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Evaluation of forest canopy models for estimating isoprene emissions

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Abstract. During the summer of 1992, isoprene emissions were measured in a mixed deciduous forest near Oak Ridge, Tennessee. Measurements were aimed at the experimental scale-up of emissions from the leaf level to the forest canopy to the mixed layer. Results from the scale-up study are compared to different canopy models for determining the leaf microclimate as input to isoprene emission algorithms. These include (1) no canopy effects, (2) a simple vertical scaling canopy model with a leaf energy balance, and (3) a numerical canopy model which accounts for leaf-sun geometries, photosynthesis, respiration, transpiration, and gas transport in the canopy. Initial evaluation of the models was based upon a standard emission rate factor of 90 μgC g^{-1} hr^{-1} (0.42 nmol g^{-1} s^{-1}) taken from leaf cuvette measurements and a biomass density factor of 203 g m^{-2} taken from biomass surveys and a flux footprint analysis. The results indicated that predicted fluxes were consistent among the models to within approximately ±20%, but that the models overestimated the mean flux by about a factor of 2 and overestimated the maximum observed flux by 30 to 50%. Adjusting the standard emission factor and biomass density each downward by 20% yielded predicted means approximately 20% greater than the observed means and predicted maxima approximately 25% less than the observed maxima. Accounting for changes in biomass density as a function of direction upwind of the tower improved the overall model performance.

Introduction

The forest canopy is a dynamic environment which dictates the flux of a variety of trace gases to and from the atmosphere. Biogenic hydrocarbons, such as isoprene and monoterpenes, are emitted from trees at rates dependent upon the leaf level microclimate. Because these gases are a major source of reactive carbon on a regional or global basis, it is important to estimate the emissions of the compounds with as much accuracy as possible. Because the emissions are very temperature sensitive, and for isoprene, light sensitive, accurate emission estimates require accurate modeling of the forest canopy influence. For example, canopy effects decrease estimated isoprene emissions by as much as 50% due to leaf shading and cooling in the lower part of the canopy (*Lamb* et al., 1993). Scaling exercises in mixed temperate forests have been conducted successfully for CO_2 and water vapor (e.g., *Baldocchi and Harley*, 1995), but these efforts do not guarantee success in scaling isoprene emissions. The emission of isoprene is species specific; in a mixed forest only some of the trees will contribute to isoprene forest fluxes. Hence, scaling models for isoprene must be tested against independent field data before the models are used.

In this paper, different approaches are compared for determining the leaf micro-climate as input to biogenic emission inventory systems. These include: (1) no canopy effects, (2) a simple scaling model based upon empirical vertical scaling relationships and a leaf energy balance, and (3) a numerical canopy model which explicitly accounts for leaf-sun geometries, photosynthesis, respiration, and transpiration. Model-to-model comparisons and sensitivity analyses are presented to highlight the uncertainties involved in modeling leaf level biogenic hydrocarbon emissions. An evaluation of these models is also presented based upon measured isoprene fluxes from a southeastern deciduous forest. These measurements were collected as part of an intensive field study aimed at the experimental scale-up of emissions from the leaf level to the canopy and from the canopy to the mixed layer. This work was conducted jointly by the National Center for Atmospheric Research, Washington State University, and the Atmospheric Turbulence and Diffusion Division of the National Oceanic and Atmospheric Administration with the support and cooperation of the United States Environmental Protection Agency.

Isoprene Emission Scale-Up Study

Current biogenic emission models are based primarily upon leaf or branch enclosure measurements which are used to specify emission rate factors at a standard set of conditions (E_f). To predict emission fluxes over an area for a given set of conditions, empirical temperature and, for isoprene, light correction functions are used to account for observed environmental conditions. Canopy models are used to adjust these conditions for canopy effects, and biomass density

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factors (B_f) are used to extrapolate from a biomass emission rate to an areal flux. This calculation process can be written as

$$F(T,PAR) = E_f x B_f x f[T_i)z),PAR(z)] \quad (1)$$

where $f(T_i(z),PAR(z))$ is the empirical correction function to correct for temperature and light effects and $T_i(z)$ and $PAR(z)$ are the leaf temperature and photosynthetical active radiation flux density obtained as a function of height through the canopy from an appropriate canopy model. In order to evaluate this type of emission model, it is important to obtain measurements at each step of the extrapolation process.

During the summer of 1992, measurements were made near Oak Ridge, Tennessee, in a mixed hardwood forest. The mean canopy height was 24 m with a leaf area index of 4.9. A 44-m walk-up tower was used as the primary measurement location for both leaf cuvette studies and eddy correlation flux measurements. The tower was located immediately next to a mature white oak tree (*Quercus alba.*). The leaf cuvette system was placed on leaves at different heights from the tower. It was used to measure emissions at the leaf scale and to investigate the effects of light, temperature, and humidity upon isoprene emissions. Branch enclosure measurements were also made at various levels in the canopy on the primary white oak tree located next to the tower, and a survey of emissions from a variety of species was conducted with the branch enclosure system in the immediate vicinity of the tower.

At the canopy level, tower flux measurements were made using both a micrometeorological gradient method (GRAD) and a relaxed eddy accumulation method (REA). In the first case, the mean isoprene concentration gradient was measured at two heights above the canopy on a 30-min average basis. Isoprene fluxes were calculated by assuming similarity between water vapor fluxes measured with an eddy correlation system and isoprene fluxes. The following scheme outlines the calculation of isoprene flux from the measured isoprene gradient, the measured water vapor gradient, and the measured eddy flux of water vapor:

$$F_{H2O} = K_{H2O}\frac{\Delta C_{H2O}}{\Delta z} = \overline{w' C_{H2O}} \quad (2)$$

$$K_{H2O} = \frac{\overline{w' C_{H2O}}}{\Delta C_{H2O} / \Delta z} \quad (3)$$

$$F_i = K_{H2O}\frac{\Delta C_i}{\Delta z} \quad (4)$$

It is also possible to obtain eddy diffusivities for estimating isoprene fluxes using eddy correlation and gradient measurements of wind speed (momentum), temperature (heat), or carbon dioxide (CO_2). *Baldocchi et al.* [1995] have shown from a Lagrangian modeling analysis that *Ks* for water vapor are more appropriate for calculating isoprene fluxes than are *Ks* for CO_2.

The difficulty in specifying the eddy diffusivity is avoided by using a relaxed eddy accumulation technique [*Businger and Oncley*, 1990]. In this case, isoprene flux is obtained directly from measuring the standard deviation of vertical velocity fluctuations, and the difference in concentration between an updraft sampling bag and a downdraft sampling bag (on a 30-min average basis):

$$F_i = b\sigma_w(C_{up} - C_{down}) \quad (5)$$

where b is an empirical constant (b = 0.6). Details of the REA method are available elsewhere [Leaf, canopy, and landscape level measurements of isoprene fluxes from a forest canopy, submitted to the *Journal of Geophysical Research*, 1995; hereinafter referred to as A. B. Guenther et al., 1995]. An REA sampler was used during the latter portion of the study period to measure isoprene fluxes immediately above the canopy. In addition to the isoprene flux measurements, eddy correlation measurements were also made for carbon dioxide and water vapor. Solar radiation measurements were made above the canopy and within the canopy as well.

Detailed biomass surveys were collected within approximately 1 km of the tower site to determine the leaf area index and biomass density of the vegetation. This included identification of the fraction of biomass which emitted isoprene.

At the boundary layer scale, tethered balloon sampling was conducted to measure vertical profiles of isoprene and other hydrocarbons from just above the canopy to well into the mixed boundary layer. These profiles were accompanied by tethersonde measurements of vertical meteorological profiles. Balloon soundings were collected several times during each test day. Results from this study are being presented in a number of papers dealing with emissions at different scales. For the present evaluation of canopy models, data from the mean concentration gradient and relaxed eddy accumulation sampling systems are used. A more complete description of the study and analysis of the overall scale-up of emissions is presented by A.B. Guenther et al. (1995).

Model Descriptions

Isoprene emission algorithm (no-canopy effects). To predict isoprene emissions, the most current algorithm is that developed by *Guenther et al.* (1993). In this approach, isoprene emission rate is calculated using an emission factor (E_f) defined for standard conditions and adjusting this standard rate using temperature and light correction functions:

$$E_i = E_f C_L C_T \quad (6)$$

where C_L and C_T are correction terms for light and leaf temperature relative to the standard conditions. *Guenther et al.* [1993] formulated these terms as

$$C_L = \frac{ac_1 L}{\sqrt{1 + a^2 L^2}} \quad (7)$$

where a (=0.0027) and c_1 (=1.066) are empirical constants, and L is the flux density of photosynthetically active radiation (PAR). The temperature correction term is written as

$$C_T = \frac{\exp\frac{c_2(T - T_s)}{RTT_s}}{1 + \exp\frac{c_3(T - T_c)}{RTT_s}} \quad (8)$$

where T_s is the temperature for standard conditions (301 K) and c_2(=95000 J/mol), c_3 (230000 J/mol), and T_c (=314 K) are empirical coefficients based upon measurements from three plant species: eucalyptus, aspen, and velvet bean. For the current study, the isoprene emission factor was taken from leaf cuvette measurements to equal 90 μgC g^{-1} hr^{-1} (0.42 nmol g^{-1} s^{-1}).

Simple forest canopy model. A simple forest canopy model for treating natural hydrocarbon emissions was first developed by *Gay* [1987] and refined for regulatory use by *Pierce et al.* [1991] as the BEIS model (Biogenic Emission

Inventory System). Results for a United States national inventory using a version of this canopy model have recently been presented by *Lamb et al.* [1993]. In this approach, above canopy conditions (PAR, temperature, humidity, and wind speed) are adjusted as a function of height through the canopy using very simple, empirical scaling functions based upon an assumed vertical biomass distribution through the canopy. The model treats the canopy in eight layers, and for each layer the ambient conditions are calculated from the above canopy conditions and the scaling functions. A simple leaf energy balance [*Gates and Papien*, 1971] is then solved for each layer to yield leaf temperature as a function of height through the canopy. Together, the calculated leaf temperature and PAR levels are used in Guenther's algorithm to calculate isoprene emissions as a function of height through the canopy. The total flux of isoprene is obtained by summing over all layers. During midday conditions, this approach yields leaf temperatures warmer than ambient in the upper levels of the canopy and at or below ambient in the lower part of the canopy. Light levels decrease exponentially through the canopy. A simplified version of this model (BEIS2) has recently been implemented with revised emission factors and biomass densities for the United States [*Geron et al.*, 1994]. With respect to simulation of canopy effects, BEIS2 assumes that the above canopy ambient temperature applies throughout the canopy, but it does adjust the available PAR as a function of height through the canopy. For application in this study, the BEIS model was used in the sensitivity analyses with both the standard vertical biomass distribution for a deciduous canopy and with a site-specific vertical biomass distribution. These versions were further used with both local National Weather Service (NWS) airport data from nearby Knoxville, Tennessee, and with site-specific data obtained from the forest tower. The BEIS2 model and a version of the BEIS2 model formulated to account for the occurrence of sun flecks within the canopy were used in the comparison of model predictions and measured fluxes.

Numerical forest canopy model. *Baldocchi and Harley* [1995a] have developed a much more complete model of the forest canopy (named CANOAK) which explicitly treats radiative transfer, turbulent diffusion of gases in the canopy, and leaf biodynamics to predict photosynthesis rates, latent heat fluxes, sensible heat fluxes, and net radiation. The radiative transfer model can be used assuming either random, spherical leaf angle distributions or a clumped leaf distribution. In both cases, the probability distribution of sunlit and shaded leaves is calculated as a function of depth in the canopy. Since the model directly calculates PAR and leaf temperature through the canopy, it can also be used with Guenther's emission equation to predict isoprene emissions as a function of height through the canopy.

Baldocchi and Harley [1995] have used data from the 1992 Oak Ridge study to evaluate CANOAK with respect to its ability to predict net radiation and the flux densities of carbon dioxide, latent heat, and sensible heat. In these cases, the model results using the clumped leaf assumption yielded better agreement with the canopy measurements than the spherical leaf distribution assumption. For the clumped leaf approach, the model predicted net radiation values to within approximately 5 W/m^2 and latent heat flux densities to within ±10% of measurements. For sensible heat flux density, the clumped leaf model agreed with the measurements for negative heat fluxes, but underestimated the fluxes by 30 to 40% for positive heat flux conditions. Calculations of CO_2 flux densities agreed to within 5% of the measured values using the clumped leaf model, while the random leaf distribution model underestimated measured CO_2 flux density by approximately 30%. In this case, the clumped leaf model appeared to provide a better prediction because the clumped leaf model is able to maintain light densities deeper into the canopy than does the random leaf model.

Results and Discussion

BEIS sensitivity analysis. Several different types of sensitivity tests were used to examine the no-canopy model and various versions of the BEIS canopy model. The first set of sensitivity tests examined systematic perturbations in air temperature, visible solar radiation, relative humidity, and wind speed. A total of 54 sensitivity tests were used: air temperatures of 15°C, 30°C, and 40°C; visible solar radiation values (top of canopy) of 250 μmol m^{-2} s^{-1}, 1000 μmol m^{-2} s^{-1}, and 2000 μmol m^{-2} s^{-1}; relative humidity of 70% and 90% (at 15°C), 48% and 63% (at 30°C), and 27% and 36% (at 40°C); and, wind speeds of 1 m s^{-1}, 3 m s^{-1} and 7 m s^{-1}.

The results for these 54 meteorological combinations show that the no-canopy model, in general, yields higher isoprene correction factors than either the standard BEIS model or the sun fleck version of BEIS. On average, isoprene correction factors from the BEIS canopy model with onsite leaf area index (LAI) are 13% lower than from the no-canopy model, while isoprene correction factors from the sun fleck BEIS model are 39% lower than from the no-canopy model. During some conditions, however, the BEIS model yielded correction factors that are higher than the no-canopy model. For example, with a temperature of 30°C and PAR equal to 1000 μmol m^{-2} s^{-1} or 2000 μmol m^{-2} s^{-1}, the BEIS canopy model yielded correction factors that are as much as 50% higher than the no-canopy model. This increase can be attributed to predicted leaf temperatures that are as much as 5°C above the ambient temperature in the upper portion of the canopy. Results from the sun fleck model are consistently lower than results from the no-canopy model or the BEIS model. It should be noted that the sun fleck model also accounts for leaf angle (which was not accounted for in BEIS) and consequently lowers the solar radiation on the leaf by as much as 50%.

A second aspect of the sensitivity analysis involves model response to meteorological conditions for one of the actual study days, August 2 1992 (Julian day 215). Figure 1 shows the isoprene correction factors computed for the no-canopy model and four versions of the BEIS canopy model. For this case, three versions of the BEIS model give higher emissions than the no-canopy calculation. This results from the predicted warming of the leaves in the upper portion of the canopy relative to the ambient temperature. The various versions of the BEIS canopy model show substantial differences that can be attributed to each model's treatment of meteorological data and solar radiation. The use of different LAI profiles can be compared with the base BEIS and the NWS BEIS (with National Weather Service data from the Knoxville airport). The base BEIS results in isoprene correction factors that are 40% lower than the site BEIS. The use of different meteorological data can be seen by comparing the results for the two site BEIS model simulations, onsite met versus NWS met.

The NWS met simulation used the Knoxville, Tennessee surface observations, with solar radiation computed using the approach of *Iqbal* [1983] with cloud attenuation from *Holtslag and van Ulden* [1983]. During the daylight hours on Julian day

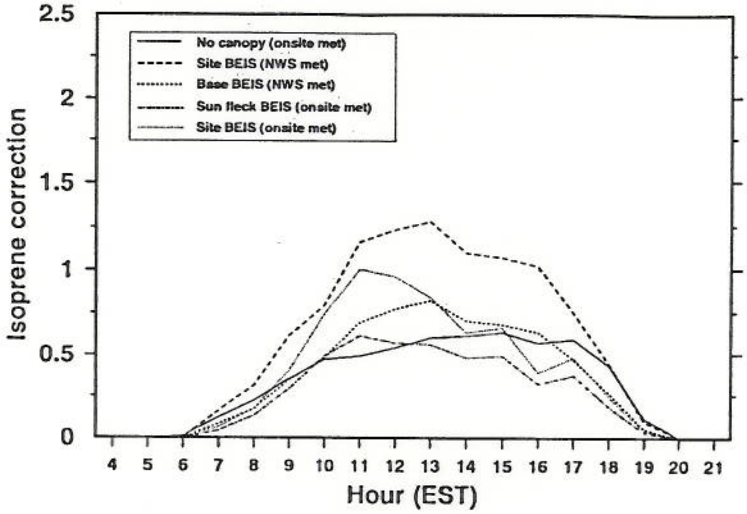

Figure 1. Predicted isoprene emission correction factors from JD 215 using different versions of BEIS.

215, the onsite data average 1.6°C cooler (24.2°C versus 25.8°C) than the Knoxville data. Solar radiation values from the tower averaged 427 μmol $m^{-2} s^{-1}$ lower with onsite data than the airport data (1297 μmol $m^{-2} s^{-1}$ versus 870 μmol $m^{-2} s^{-1}$). These differences in meteorological and solar radiation values account for the variation in the two versions of the site BEIS model. These results illustrate the potential problems associated with using standard airport observations to estimate emissions for a large region.

The sun fleck version of BEIS yielded correction factors that are 20% lower than the no-canopy correction. The sensitivity analysis for this day clearly shows that considerable variation (as much as a factor of two) can occur in isoprene flux estimates depending on the choice of canopy model.

CANOAK sensitivity analysis. A number of different models runs were conducted to examine the sensitivity of the numerical CANOAK model to environmental parameters. The flux of isoprene obtained with CANOAK shows an increasing dependence upon photon flux density at increasing ambient temperatures as indicated in Figure 2. At low temperatures, increasing PAR from 100 to 1500 μmol $m^{-2} s^{-1}$ increases the isoprene flux from approximately 10 to 30 nmol $m^{-2} s^{-1}$. However, at 35°C, the increase in isoprene flux over the same range of PAR is much greater from approximately 30 to almost 300 nmol $m^{-2} s^{-1}$. If isoprene flux is calculated as a function of air temperature instead of leaf temperature, this increase in sensitivity to PAR levels at higher temperatures is diminished. Calculations of isoprene flux at low and moderate wind speeds show that wind speed has little apparent effect, but it is worth noting that the model predicts leaf temperatures in the upper portion of the canopy approximately 5°C higher than ambient. Shaded leaves are cooler than sunlit leaves by approximately 1°C over most of the canopy depth.

Comparison of observations and predictions. Biomass density estimates were taken from a transect extending 500 m from the tower in the southwest direction and along each of the 8 compass radials out to a distance of 50 m from the tower. The data along the 500-m transect show that isoprene emitting biomass was highest very near the tower and decreased with distance away from the tower as indicated in Figure 3. Along this transect in the fetch immediately upwind, the isoprene biomass was estimated to be 260 g m^{-2}, at distances out to approximately 135 m the biomass was 150 g m^{-2}, and for distances from 165 to 485 m, the biomass was approximately 50 g m^{-2}. The arithmetic average biomass for the transect was 110 g m^{-2}, but the distance weighted ($1/d^2$) average was 220 g m^{-2}. There were also significant differences in isoprene-emitting biomass along the different compass radials out to 50 m. Generally, the isoprene emitting biomass was higher toward the eastern half of the fetch and lower toward the western half of the fetch surrounding the tower.

A more accurate approach for determining the appropriate biomass density to use with the standardized emission factor is to define the isoprene emitting flux footprint upwind of the tower. In recent years, a number of investigators have developed models to predict the along wind extent of this footprint. *Horst and Weil* [1992] developed an analytical expression for the footprint from surface layer similarity theory, while *Leclerc and Thurtell* [1990] first employed a Lagrangian stochastic particle model to estimate the footprint,

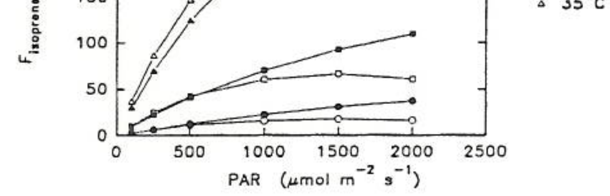

Figure 2. Predicted isoprene fluxes from the CANOAK clumped leaf distribution model as a function of photosynthetically active radiation (PAR) for different ambient temperatures. Predictions based only upon light and ambient temperature are shown for comparison.

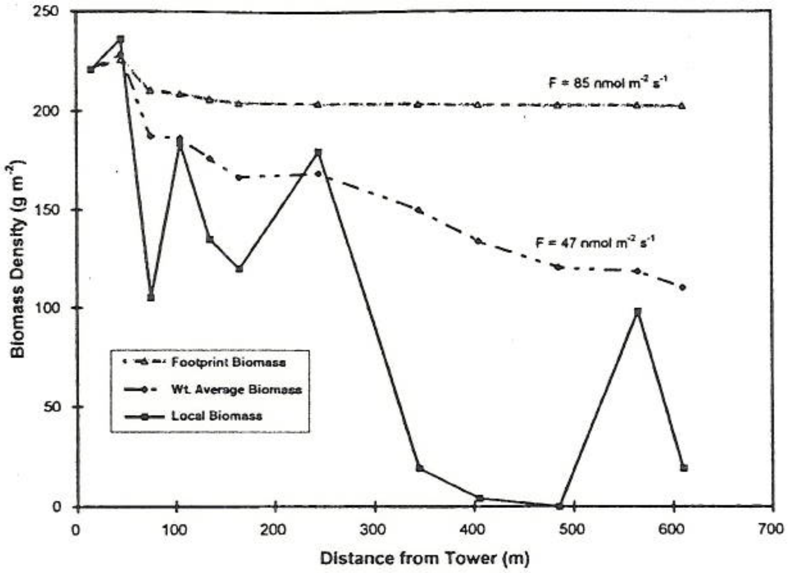

Figure 3. Transect of leaf biomass densities (g m^{-2}) measured southwest of the measurement tower and weighted upwind average biomass densities based upon the cumulative scalar source footprint for typical convective conditions and upon a simple distance average. The indicated standard emission fluxes assume a standard emission rate factor equal to 90 μgC g^{-1} hr^{-1}. (0.42 nmol m^{-2} s^{-1}).

and then developed a large eddy simulation model to determine the footprint (M.Y. Leclerc et al., Large-eddy simulations of footprints in the convenience boundary layer, submitted to the *Journal of Geophysical Research*, 1995; hereinafter referred to as M.Y. Leclerc et al., 1995). *Finn et al.* [1996] conducted a tracer study over a sagebrush canopy and used the data to evaluate analytical expressions from *Horst and Weil* [1992] and the Lagrangian stochastic model from M.Y. Leclerc et al. The results indicated that the footprint was relatively well predicted by all of the models during convective conditions. For our purposes, the simpler analytical expression from *Horst and Weil* [1992] can be used to provide an estimate of the footprint. It should be noted, however, that this expression has not been evaluated versus field measurements over a tall forest canopy. The predicted footprint and cumulative flux are shown as a function of distance upwind of the tower in Figure 4 for conditions from JD 218. The footprint is sharply peaked within 50 m of the tower with 70% of the total flux within 100 m of the tower. At 300 m upwind, the cumulative flux is predicted to equal 95% of the total flux. These estimates yield a footprint weighted biomass density of 203 g m^{-2}. As shown in Figure 3, this corresponds to a standardized flux of 85 nmol m^{-2} s^{-1}, while the biomass density averaged over the transect (110 g m^{-2}) leads to a standardized flux of 46 nmol m^{-2} s^{-1}. It

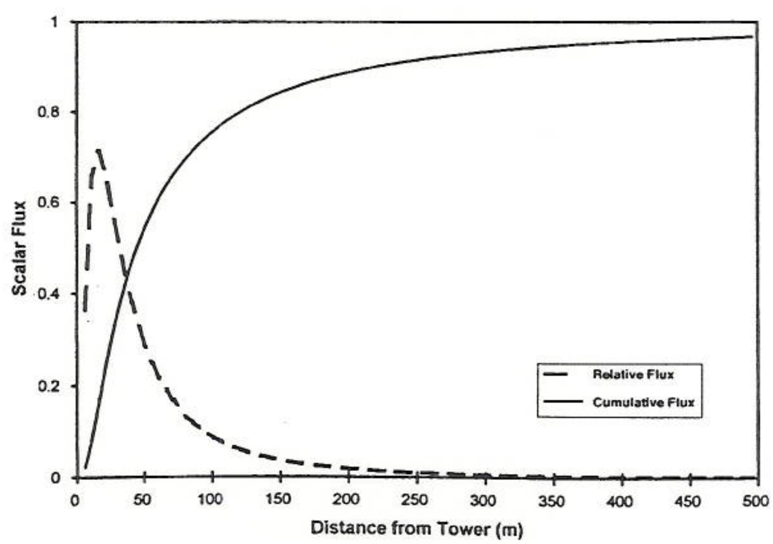

Figure 4. Scalar source footprint and cumulative footprint upwind of the measurement tower during typical midday convective conditions estimated using an analytical expression from Horst and Weil (1992).

should be emphasized that this footprint calculation is based upon typical midday convective conditions. For other periods and other conditions, the footprint can be quite different.

To illustrate the ability of the models to predict representative isoprene diurnal emission patterns, results can be used from JD 218 when the most complete set of flux measurements was obtained. The measured fluxes for this day were obtained using the REA flux system only. The temperature, PAR, and wind direction observations for JD 218 are shown in Figure 5. The environmental conditions on JD 218 were optimal for isoprene production with ambient temperatures increasing until late afternoon to a maximum temperature of 27 °C. The solar radiation levels exhibited more variability apparently due to passing clouds. Values of PAR reached a maximum of almost 1800 μmol m^{-2} s^{-1} at approximately 1430. Wind direction is included in Figure 5 because the biomass surveys showed that isoprene emitting biomass upwind of the tower was quite dependent upon the wind direction. The relative amounts of isoprene emitting biomass from these data are shown as a function of wind direction in Figure 6 along with an estimate of the variation in the relative emission flux.

Predicted fluxes from each of the models are compared to REA flux measurements for JD 218 in Figures 7 and 8 for the case with the standardized flux equal to the midpoint of the range of standardized fluxes: 65 nmol m^{-2} s^{-1}. The observed isoprene fluxes on JD 218 increased from near zero at 0800 to a maximum of approximately 35 nmol m^{-2} s^{-1} at 1300. In midafternoon the observed fluxes decreased to less than 17 nmol $m^{-2} s^{-1}$ at 1430 and then abruptly increased again to near 35 nmol $m^{-2} s^{-1}$ by 1530. Emissions dropped back to zero by approximately 1800. The general trend of emissions increasing into midafternoon and then decreasing to zero in early evening is consistent with maximum light and temperature levels during midday. The reason for the abrupt decrease in midafternoon could be due to a change in wind direction as shown in Figure 5, although the factor of 2 change in isoprene flux is larger than can be explained by variations in isoprene emitting biomass around the tower as shown in Figure 6. It should be noted that the biomass survey was restricted to the nearest 50 m at each compass point, except for the 500 m transect conducted along the southwest radial.

Model predictions for this day, based upon a constant isoprene biomass (independent of wind direction), correctly simulated the diurnal pattern of isoprene flux, except for the midafternoon minima. For the BEIS2 standard and sun fleck models (both using on-site LAI and meteorological data), the predicted fluxes were between 25% and 5% less than the measured maximum flux as shown in Figure 7. During the morning and late afternoon, the emissions estimated with no-canopy effects were significantly higher than either of the BEIS2 versions and higher than observed. During midafternoon, there was very little difference between the sun fleck model and the no-canopy estimate. For the numerical CANOAK model using either the clumped leaf distribution or the random spherical distribution, the emission fluxes appeared to be overestimated as shown in Figure 8. Using a standardized emission flux of 65 nmol m^{-2} s^{-1}, the predicted fluxes for the clumped leaf and spherical distributions at the time of the maximum measured flux were within 20% of the measured flux.

Results from all of the measurement days are summarized in Figures 9a, 9b, and 9c in terms of the mean, maximum, and normalized mean square error between measured and modeled fluxes for a range of standardized emission fluxes. This evaluation is based upon the combined GRAD and REA flux measurements. Although it was not possible to make simultaneous GRAD and REA flux measurements during the study, the overall mean flux from the GRAD measurements during the first half of the study equaled 14.8 ± 14.0 nmol m^{-2} s^{-1}, which agrees very closely with the overall mean flux from the REA measurements (13.5 ± 12.5 nmol m^{-2} s^{-1}) obtained during the second half of the study. Further analysis of the results from the different measurement techniques are given by A.B. Guenther et al. (1995).

In terms of the mean flux, the various models yield agreement with the mean measured flux only over the range of standard emission fluxes from 33 to 47 nmol m^{-2} s^{-1}. This range of standard emission fluxes corresponds to the lower end of estimated biomass density factors. At the midpoint of the range of standard emission fluxes, the model mean values ranged from 22 to 25 nmol m^{-2} s^{-1} in comparison to the measured mean flux of 17 nmol m^{-2} s^{-1}. The mean based upon no-canopy effects was predicted to equal 28 nmol m^{-2} s^{-1} or

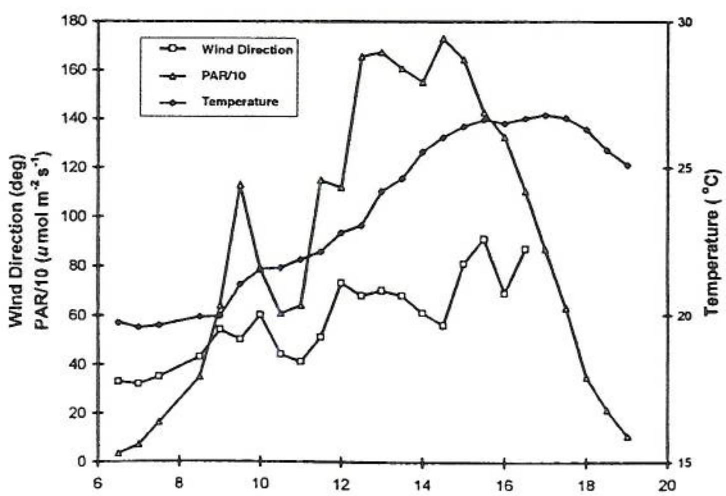

Figure 5. Measured ambient temperature, photosynthetically averaged radiation (PAR), and wind direction during Julian day 218.

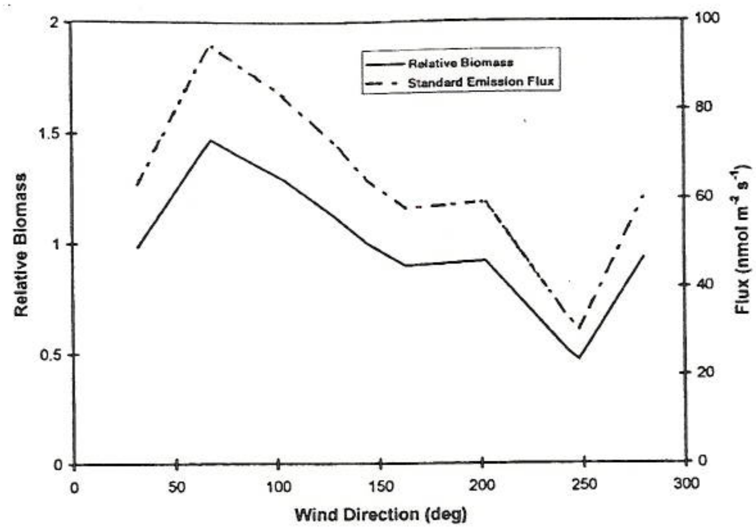

Figure 6. Relative biomass distribution and estimated standard emission factor as a function of wind direction. Biomass distributions based upon surveys within 50 m of the tower at each of the eight compass directions.

almost a factor of 2 larger than observed. Use of the canopy model thus yields a significant improvement in the predicted mean flux.

The maximum measured flux was 48 nmol m^{-2} s^{-1} which was matched by the different models over the range of 58 to 73 nmol $m^{-2}s^{-1}$ standard emission factors. In this case, the range of standard emission factors corresponds to the middle portion of the range of biomass density factors. At the midpoint of the standard emission factors, the CANOAK model with the clumped leaf distribution was only 5% higher than the measured maximum, and the CANOAK model with the random spherical distribution was essentially equal to the measured maximum. Both of the BEIS2 versions were approximately 10% less than the measured maximum flux. Ignoring canopy effects yields an overestimate of the maximum flux of approximately 15% at the midpoint of the standard emission fluxes.

The normalized mean square error (NMSE) is a common measure of overall model performance; good model performance is indicated by NMSE <0.4 and poor model performance is indicated by NMSE > 4. The NMSE is calculated as

$$NMSE = \frac{\overline{(O_i - P_i)^2}}{\overline{O}\,\overline{P}} \quad (9)$$

where O is the observed flux, P is the predicted flux, and the overbars indicate average values. In Figure 9c, the range of estimated standard emission fluxes yields NMSE for the

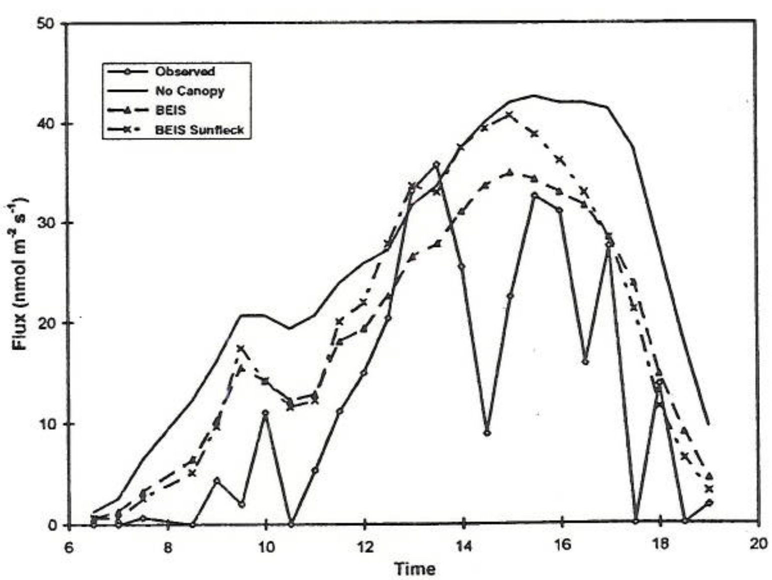

Figure 7. Comparison of observed isoprene fluxes for JD 218 with isoprene fluxes predicted with the standard and sun fleck BEIS2 models for a standard emission flux factor of 65 nmol m^{-2} s^{-1}. The predicted emissions with no-canopy effects are also shown.

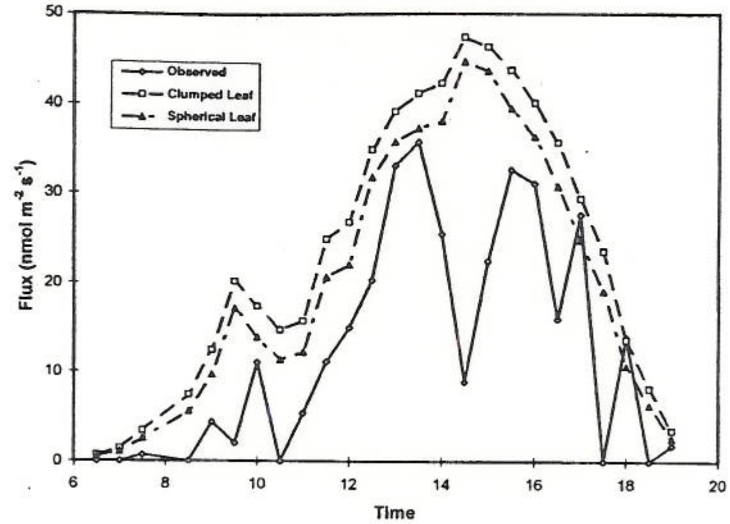

Figure 8. Comparison of observed isoprene fluxes for JD 218 with isoprene fluxes predicted with CANOAK using clumped leaf and random spherical distributions for a standard emission flux factor of 65 nmol m^{-2} s^{-1}.

various models in the range from 1.3 to 0.4. The minimum value of NMSE for each model occurs for standard emission fluxes from approximately 40 to 60 nmol m^{-2} s^{-1}. This range, which represents best model performance, is between the range of standard factors which provided the best performance in terms of the mean flux (E_f=33 to 47 nmol m^{-2} s^{-1}) and in terms of the maximum flux (E_f=58 to 73 nmol m^{-2} s^{-1}).

The differences in the range of standard emission factors which yield agreement with measured statistical parameters suggests that the models, given an optimal biomass or emission factor estimate, will over(under)estimate the mean while under(over)estimating the maximum flux. This is reflected in the differences between the shapes of the cumulative frequency distributions of measured and modeled isoprene fluxes from all of the measurement periods as shown in Figure 10. At the fiftieth percentile, the predicted fluxes exceed the measured flux by as much as a factor of 3, while at the ninety-nineth percentile, the measured flux is bounded to within approximately 10% by the predicted fluxes. If the magnitude of the standard emission factor were adjusted downward there would be better agreement at the fiftieth percentile and much worse agreement at the ninety-nineth percentile.

Some of the discrepancy in the shapes of the cumulative distributions can be accounted for by changes in isoprene biomass as a function of wind direction. If the relative biomass distribution shown in Figure 6 is used to adjust the predicted isoprene fluxes for each of the models, the model cumulative frequency distributions become much more similar in shape to the measured cumulative frequency distribution as illustrated for BEIS2 in Figure 11. It is quite apparent that the shapes of the measured curve and the modeled curve based upon biomass dependent wind direction are quite similar.

These comparisons between modeled and measured fluxes can be summarized as follows:

1. Using the initial standard emission factor of 90 μgC g^{-1} hr^{-1} with the biomass density of 203 g m^{-2} weighted by the estimated flux footprint cause the models as a group to overestimate the mean observed fluxes by approximately a factor of 2 and to overestimate the maximum observed flux by 30 to 50%;

2. Adjusting the standard emission factor and the weighted biomass density factor each downward by approximately 20% yields predicted means approximately 20% greater than observed and predicted maxima approximately 25% less than observed;

3. The shape of the cumulative frequency distribution of measured fluxes was matched by the shape of the cumulative frequency distribution of modeled fluxes only when the model estimates were adjusted to account for the relative biomass distribution along different radials upwind of the measurement point;

4. Among the models, for a given standard emission factor, the CANOAK clumped leaf and spherical distributions tended to yield higher isoprene fluxes than either the standard or sun fleck BEIS2 models; however, differences among all of the models were within approximately 20% which is small relative to the uncertainties in the measured fluxes and biomass densities.

The results from the scale-up emission study and the analysis of different canopy models compared to measured fluxes demonstrates the importance which must be placed upon correct specification of the standard emission rate factor and the associated biomass density factor. These results also emphasize the need to know the source scalar footprint for any type of flux measurement study. This knowledge is particularly crucial in a heterogeneous forest environment where trace gas emissions can be species specific.

Conclusions

Measured isoprene emission factors, isoprene fluxes, and biomass densities from an intensive forest emissions scale-up study provide a basis for quantitative analysis of the performance of both simple and complex canopy emission models. It is apparent that predicted values based upon either simple or complex canopy models agree with measured fluxes given the large uncertainty which accompanies standard emission factors, biomass density factors, and the effects of the scalar source footprint. A sensitivity analysis of the BEIS models showed that there can be a factor of 2 difference in

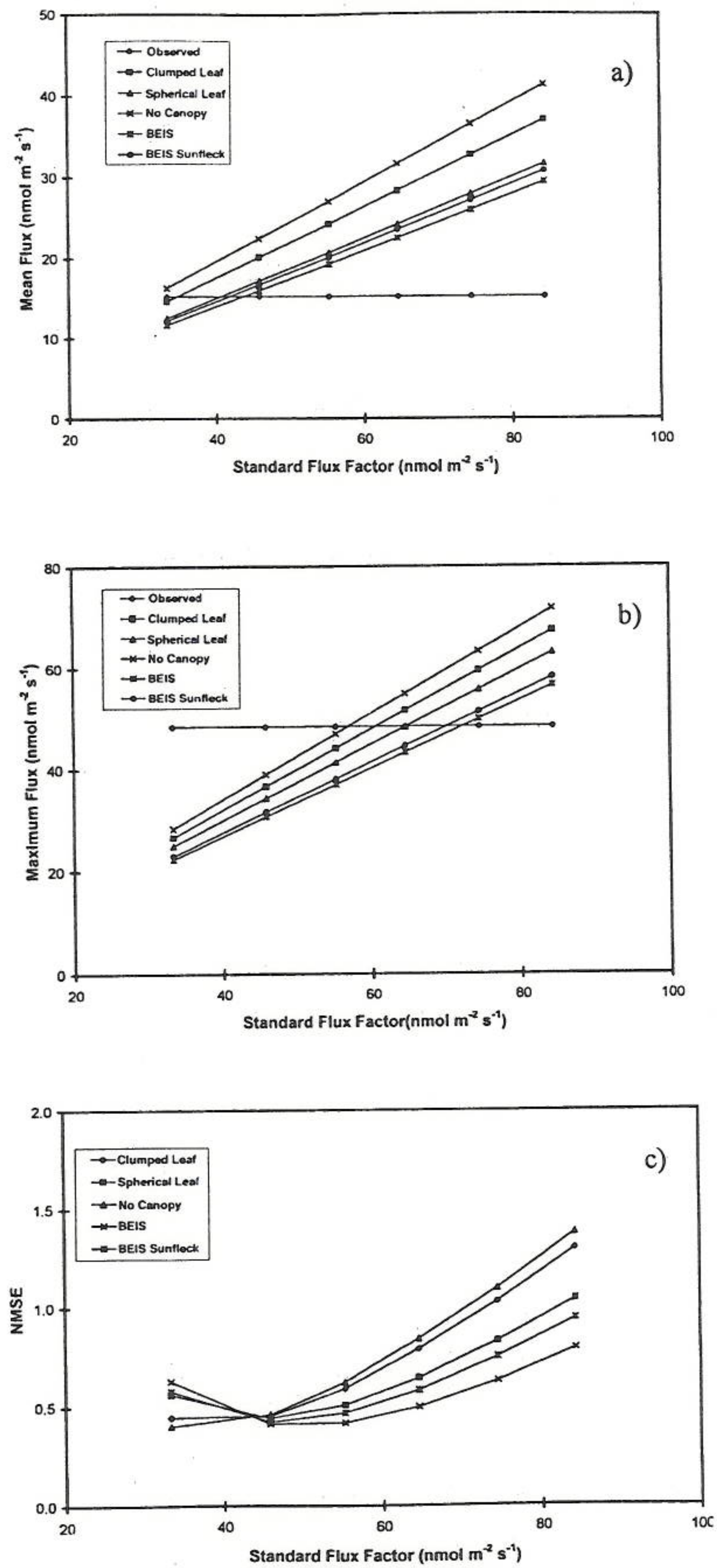

Figure 9. Measured and modeled (a) mean and (b) maximum isoprene fluxes and (c) normalized mean square error between observed and predicted fluxes as a function of standard emission flux factor.

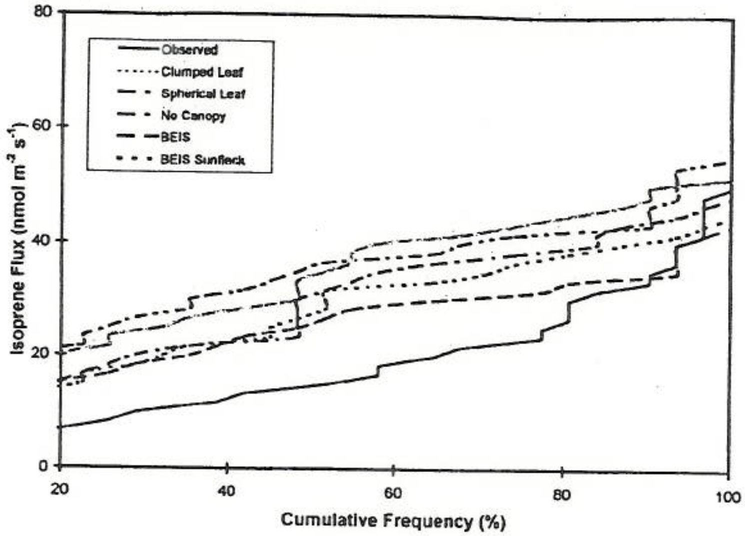

Figure 10. Cumulative frequency distribution of observed isoprene fluxes compared to the frequency distributions predicted with each canopy model using a standard emission flux factor of 65 nmol $m^{-2} s^{-1}$.

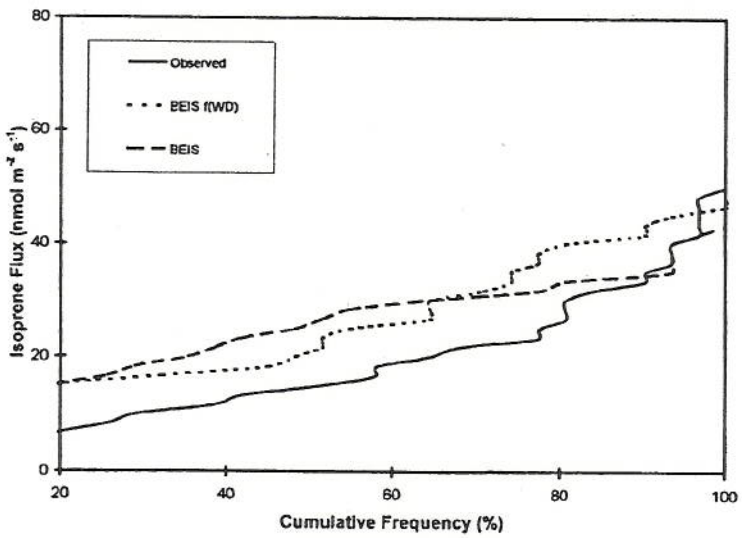

Figure 11. Cumulative frequency distribution of observed isoprene fluxes compared to the frequency distributions predicted with BEIS2 using a constant standard emission flux factor of 65 nmol $m^{-2} s^{-1}$ and using a standard emission flux factor which varies as a function of wind direction to account for variations in biomass density upwind of the tower.

emission estimates depending upon whether a canopy model is used, whether on-site or local NWS data are used, or whether a sun fleck modification is incorporated.

The agreement between measured and predicted fluxes suggest a degree of confidence in recent developments for modeling biogenic hydrocarbons from forests, but there remains further work to eliminate remaining uncertainties. In particular, more flux measurements are needed in combination with more detailed biomass surveys, and biomass data must be linked to footprint calculations. At the present stage, the uncertainties in biomass distributions and the variation in measured eddy fluxes of isoprene overwhelm any call for greater sophistication in canopy models.

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