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# Contribution from biogenic organic compounds to particle growth during the 2010 BEACHON-ROCS campaign in a Colorado temperate needle leaf forest

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was to assess the accuracy of reconstructing the highly variable meteorological conditions using a column model. The second task was to compare the modeled aerosol precursor gases against the measurements. In addition to sulfuric acid ( $\text{H}_2\text{SO}_4$ ), we focused on MBO and monoterpenes because they dominate the biogenic emissions at the site (Karl et al., 2014; Kaser et al., 2013a, b; Kim et al., 2010). After assessing the model performance with respect to the meteorology and related precursor gases, we proceeded with the study on the effects of BVOC and their oxidation products on particle growth.

## 2 Materials and methods

### 2.1 Manitou Experimental Forest Observatory and BEACHON-ROCS field campaign

All observations presented in this study were obtained during the BEACHON-ROCS field campaign at Manitou Experimental Forest Observatory (MEFO) in August 2010. The campaign is part of the BEACHON project, which aims to investigate ecosystem-atmosphere exchange of trace gases and aerosols and their potential feedbacks between biogeochemical and hydrological cycles. Ortega et al. (2014) have provided a very detailed description of the BEACHON project as well as MEFO; here we only provide a summary of the site and campaign descriptions related to this study.

MEFO is located in the Front Range of the Colorado Rocky Mountains ( $39.1^\circ\text{N}$   $105.1^\circ\text{W}$  and 2370 m.a.s.l.). It is a mountainous site in close proximity to large urban centers (e.g. Denver is about 85 km northeast of the site and Colorado Springs about 40 km to the southeast). Due to shielding by the Rampart Range to the east and Pikes Peak to the south, the site normally encounters clean continental air masses from the southwest. Exceptions include episodic but frequent intrusions of anthropogenic air masses due to upslope flow during the mornings and air moving downslope from the south during the evenings. Ponderosa pine is the dominant tree species at the forested

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der clear sky conditions (Korhonen et al., 2004). It includes all basic aerosol processes, including nucleation, condensation, coagulation and dry deposition. The model performance has been validated against field measurements from Hyytiälä, Finland in various studies (Boy et al., 2013; Mogensen et al., 2011, 2014; Smolander et al., 2014).

5 The biogenic emission module based on MEGAN requires emission factors for representative vegetation types to estimate the net fluxes of BVOC from canopy to the atmosphere. The emission factors define the emission of a given compound at standard conditions and have an uncertainty of a factor of three or more when global default values are used, primarily due to the large variability in emission rates for different plants  
10 (Guenther et al., 1995). In this study monoterpene emission factors were obtained from leaf cuvette measurements (Harley et al., 2014), while the MBO emission factor is suggested by Kaser et al. (2013a), which is based on both leaf cuvette emission measurements and canopy-scale analysis.

The chemistry scheme employed by the model for this study includes the full MCM  
15 chemical paths for the following parent molecules: methane, methanol, formaldehyde, acetone, acetaldehyde, MBO, isoprene, alpha-pinene, beta-pinene, limonene and beta-caryophyllene. For other emitted organic compounds, for which no MCM chemistry path is available, we have included their first order oxidation reactions with OH, O<sub>3</sub> and NO<sub>3</sub>. Those compounds include: myrcene, sabinene, 3-carene, ocimene, cineole,  
20 and “other” monoterpenes, farnesene, and “other” sesquiterpenes (Atkinson, 1994). In the case of linalool we have included its reaction with OH and NO<sub>3</sub> to form acetone and “condensable material” and its reaction with O<sub>3</sub> to additionally produce formaldehyde. For the reactions of the stabilized Criegee Intermediates (sCI) from alpha-, beta-pinene and limonene, we have used the rates from Mauldin et al. (2012) similar to  
25 “Scenario C” in Boy et al. (2013). For the sCI from isoprene, we used the rates from Welz et al. (2012) as done in “Scenario D” in Boy et al. (2013). Sulfuric acid and nitric acid are removed from the gas phase based on the condensation sinks calculated from background aerosol loading (Pirjoja et al., 1998).

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It is not fully understood which mechanisms drive nucleation in the atmosphere. Various parameterizations have been created for predicting atmospheric nucleation (e.g. Pierce and Adams, 2009; Paasonen et al., 2010). The nucleation mechanism, however, has minor influence on the actual production rate of the observable particles compared to the subsequent growth step because the nucleated clusters have rather short lifetimes (Kulmala and Kerminen, 2008; Kulmala et al., 2013). For this reason, we opted to use only the kinetic nucleation parameterization in this study (Weber et al., 1997). It was chosen also because Zhou et al. (2014) showed that the SOSAA model with kinetic nucleation parameterization gave good predictions of NPF events at a boreal forest site in Hyytiälä, Finland. In kinetic nucleation, two sulfuric acid molecules collide to form a cluster as in the kinetic gas theory. Some of the formed clusters will break apart, but some will remain stable and then grow to become particles. The nucleation rate,  $J$ , is related to the sulfuric acid concentration,  $[\text{H}_2\text{SO}_4]$ , via

$$J = K \times [\text{H}_2\text{SO}_4]^2 \quad (1)$$

where  $K$  is the kinetic coefficient that includes both the collision frequency and the probability of forming a stable cluster after the collision (Weber et al., 1997; Sihto et al., 2006; Zhou et al., 2014). The nucleated particles were then added to the first size bin (at 2 nm) in the model. Before carrying out our modeling studies for particle growth, a sensitivity study was done to establish a suitable value for the nucleation coefficient  $K$ . By comparing the simulated and DMPS measured total number concentrations for particles between 20 and 80 nm,  $K$  was set to  $5 \times 10^{-15} \text{ cm}^{-3} \text{ s}^{-1}$ .

The SOSAA model requires four groups of input data. The first group includes the site land cover characteristics, such as the leaf density and canopy height. The second group consists of meteorological parameters including radiation, vertical profiles of wind speed, temperature and relative humidity. These inputs are available from the micrometeorology tower measurements at MEFO. ERA-Interim reanalysis data by ECMWF (Dee et al., 2011) for wind speed, temperature and humidity were used as the boundary conditions for the upper border of the model column. Since one of the

radiation inputs, the actinic flux spectrum, was not measured at MEFO, we used the scaled actinic flux spectrum from the Tropospheric Ultraviolet and Visible (TUV) Radiation Model (Madronich, 1993). The scaling factors are based on the measured NO<sub>2</sub> photolysis rates and the TUV modeled rates (Madronich and Flocke, 1998). The third group consists of five inorganic gas concentrations (NO, NO<sub>2</sub>, CO, O<sub>3</sub> and SO<sub>2</sub>) measured from the chemistry tower and the sulfuric acid sink to the background particles. The condensation sink of sulfuric acid was calculated based on the method described by Pirjoja et al. (1998). These parameters were read in every half hour with a linear interpolation in between. The last group of input data is the measured particle number size distribution. The model only reads in the measured number size distribution once a day at midnight for initialization. More detailed description of model input is available from Boy et al. (2011).

### 2.3 Modeling experiments

In order to investigate the influence of organics on particle growth, three organic vapors (Vapor I–III) were set to take part in the condensation process in addition to sulfuric acid. Since the main biogenic emissions at the site are MBO and monoterpenes, Vapor I–III were set to be the lumped sums of first stable reaction products from OH, O<sub>3</sub> and NO<sub>3</sub> oxidation of MBO or/and monoterpenes. This treatment of organic condensing vapors is similar to the approach of Lauros et al. (2011) and Zhou et al. (2014). Three model experiments were designed to study the influence of MBO and monoterpenes on particle growth:

- Experiment I: lumped sums of first stable reaction products from OH, O<sub>3</sub>, and NO<sub>3</sub> oxidation of monoterpenes were included as the organic condensing Vapor I, II, and III respectively.
- Experiment II: lumped sums of first stable reaction products from OH, O<sub>3</sub>, and NO<sub>3</sub> oxidation of MBO were included as the organic condensing Vapor I, II, and III respectively.

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- Experiment III: lumped sums of first stable reaction products from OH oxidation of both monoterpenes and MBO were included as the organic condensing Vapor I. Lumped sums of first stable reaction products from O<sub>3</sub> and NO<sub>3</sub> oxidation of monoterpenes were included as the organic condensing Vapor II and III, which were the same as Vapor II and III in Experiment I.

The aerosol module simulates particle growth by calculating the condensation flux of each condensing vapor onto the particle surfaces (Korhonen et al., 2004). An iterative method was used in each experiment to estimate the saturation vapor concentration of the condensing organic vapors, by varying the saturation vapor concentration of each compound and by comparing the modeled particle size distribution with the observed distribution. In all experiments, sulfuric acid condenses onto particles with the assumption that once it is condensed, it will not evaporate from the particles.

### 3 Model validation for meteorology and chemistry

Since the SOSAA model does not accommodate precipitation, all the observational data presented in this section have been filtered to exclude rain events. When comparing averaged diurnal profiles of a specific parameter, the modeled profile is the average of the period for which observation data are available.

#### 3.1 Meteorology

Figure 1 presents the average behavior of the modeled temperature, wind speed and relative humidity compared to the measurements above the canopy at 30 m. Because the site is situated in a north–south slope (draining to the north), the meteorology is influenced by the diurnal mountain-valley flows. While daytime wind directions are variable, nighttime winds are dominated by the drainage from the south (Ortega et al., 2014). Unfortunately the column model SOSAA cannot capture this behavior related to the topography. The model simulates a comparable temperature for daytime but fails

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to decrease the temperature sufficiently during nighttime. The big diurnal variation applies not only to the temperature but also to the relative humidity (RH). The model again simulates comparable RH levels during the day but fails to capture it at night. The underestimation in RH at night is mainly a result of the overestimation of temperature. The simulated wind speed agrees well with the measurements during daytime. At night, the wind speed was observed to fluctuate around  $2 \text{ ms}^{-1}$  above the canopy, but the modeled wind speed is around  $3 \text{ ms}^{-1}$ . As already mentioned, the model cannot simulate the drainage flows related to the topography, and a clear discrepancy of the nighttime wind speeds can be expected as the nighttime drainage has been observed to be effective at the site. In general the model gave satisfactory predictions of the three meteorological variables during daytime, though notable deviations are found during nighttime.

22 August 2010, day of year (DOY) 234, was selected out of the five sounding days for demonstrating vertical profiles of the potential temperature at the site (Fig. 2). Mast measurements are provided in addition to sounding data in order to extend the measured profile close to the surface. Mast measurements and sounding measurements differ because (1) the tower observations presented are half an hour averages, while the sounding can only provide an instantaneous value, (2) the instruments are not the same, (3) measurements were not made at exactly the same location. At 05:00 LT, both the model and measurements show a typical nocturnal stable boundary layer. We focus on the gradient of potential temperature that describes the stability. The model exhibits a stronger gradient at the canopy top (18.5 m) compared to both the mast measurements and the sounding observation. The modeled profile improves during daytime. At 11:00 LT, the boundary layer has developed since morning up to about 800 m in the model, while the sounding data show it may be higher than 1 km. The simulated potential temperature gradient near ground is similar to the mast measurements, despite a slight difference in magnitude. At 19:00 LT, the gradients have already become positive. The strongest gradient modeled is again a few hundred meters lower than the sounding data. This tendency of SOSAA to underestimate the height of the mixed

layer has also been observed in studies made in Hyytiälä, Finland (Mogensen et al., 2014). At 22:00 LT, the nocturnal boundary layer has built up. We see the model profile shows a gradient below the canopy at around 10 m, indicating an inversion inside the canopy. The sounding measurements show strongest potential temperature gradient above the canopy. In general, despite the underestimated daytime boundary layer height, the model at least predicted a satisfactory potential temperature profile up to the top of measurement mast.

To investigate the model performance with respect to the surface energy balance and the vertical mixing strength, we compared the modeled average diurnal profile of the latent and sensible heat fluxes and friction velocity with the eddy covariance measurements above canopy (Fig. 3). A positive flux indicates that the atmosphere is gaining heat from the surface and vice versa for the negative flux. The modeled latent heat flux is in general comparable with observations except during morning when the model underestimates the fluxes slightly. The sensible heat flux is in general overestimated during daytime. This is probably related to inaccuracies of the other components of the energy balance, namely the heat flux and storage to the soil and the net radiation. These can also cause the leaf temperature to be modeled incorrectly, which promotes the simulated sensible heat flux. The friction velocity is well simulated compared to the measurements during daytime. The nighttime overestimation is due to the overestimation of wind speed (Fig. 1), which increases vertical wind shear and thus the amount of turbulent mixing. The well modeled friction velocity suggests that the model should have reasonable vertical turbulence mixing.

To summarize, the model's meteorological performance is satisfactory during daytime. The simulated basic meteorological parameters (temperature and its gradient, humidity, and wind speed) as well as the turbulent fluxes of latent heat and momentum (which directly depends on the magnitude of the friction velocity presented in Fig. 3) agree well with the observations. The height of the boundary layer, which dictates the volume of air into which the emitted compounds are diluted, had a tendency to be underestimated by around 20%. As the difference relative to the total boundary layer

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height is not large, this is not expected to have a high impact. However, during nighttime the drainage flows down the side of the mountain cause difficulties for the model to simulate the meteorological conditions. We therefore focus on daytime conditions in the following analysis.

## 3.2 Chemistry

The chemistry analysis focuses on aerosol precursor gases (MBO, monoterpenes and sulfuric acid), OH and the oxidation products of MBO and monoterpenes. Averaged diurnal concentrations are presented in this section to show the general behavior of modeled chemistry. The averages for MBO and monoterpenes are calculated for 10–23 and 29–31 August 2010 when the PTR-MS measurements are available. The averages for OH and sulfuric acid are calculated for 13 August 2010 noon to 14 August 2010 noon and 16 to 25 August 2010 noon when the CIMS measurements are available. The averages for oxidation products are calculated for 1–8, 19–22, and 25–30 August 2010, when the aerosol particle measurements are available.

The averaged diurnal profiles show that the monoterpene concentration has a clear diurnal variation in both the observations and model simulation (Fig. 4). The concentration is high during the night and low during the day. The nighttime concentration is high mainly due to the suppressed boundary layer height and the decreased losses from oxidation. On the other hand, the concentration decreases during daytime as the boundary layer height increases and due to the presence of OH. The model simulated comparable concentrations but an increasing trend for MT during night. The main reason could be that the model overestimated the nighttime temperature up to five degrees, which possibly leads to overestimation of monoterpene emissions. On average the simulated monoterpene concentration during daytime agrees well with the measurement (Fig. 4). The MBO concentration is high during daytime and low in nighttime due to the light-dependent production. The model captures the diurnal trend of MBO concentration well (Fig. 4). Because the large SDs of the measurement dataset, Fig. 5 presents the modeled and measured MBO concentrations from 10 to 23 August 2010

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(DOY 222 to 235). It shows that the modeled concentration is comparable to the measurement except at some nights when the concentration is overestimated.

The modeled average diurnal profile of OH is in good agreement with the observations before noon (Fig. 6). After this time, the model results become higher than the observations, likely related to an overestimation of photolysis production in the afternoon. Since a scaling factor based on the modeled clear sky and measured NO<sub>2</sub> photolysis rate was used to scale the actinic flux spectrum for whole solar radiation wavelength, the overestimated NO<sub>2</sub> photolysis rate in the afternoon suggests the photolysis production of OH may also be overestimated (Fig. 7). The modeled sulfuric acid concentration is only half of the observed value (Fig. 6). One reason could be that the condensation sink of sulfuric acid is overestimated. Another reason should relate to the unknown sulfuric acid production term missing from the chemistry scheme (Eisele and Tanner, 1993; Boy et al., 2013; Berresheim et al., 2014). Because the underestimation is observed both during night and daytime, the missing production term is likely not related to photolysis. It should also be noted that the CIMS measurements may have uncertainties of 30 to 60% (Plass-Dülmer et al., 2011). Importantly, the diurnal trend in sulfuric acid concentrations is well captured, which seems to be crucial for correctly simulating new particle formation events.

The modeled diurnal concentration profiles of the sum of first stable reaction products from OH, O<sub>3</sub> and NO<sub>3</sub> oxidation of monoterpenes and MBO are shown in Fig. 8. The concentrations of reaction products from MBO oxidation are 10 to 100 times higher than the concentrations of reaction products from monoterpenes, except in case of NO<sub>3</sub> oxidation. The concentrations of O<sub>3</sub> oxidation products are about two to three orders of magnitude greater than that of OH oxidation products, irrespective of the precursor species. Comparing to the concentrations of first stable O<sub>3</sub> oxidation products of MBO, which are fairly stable at a level of  $3\text{--}6 \times 10^{11}$  molecules cm<sup>-3</sup>, the concentrations of NO<sub>3</sub> oxidation products of MBO are negligible. The nighttime concentrations of NO<sub>3</sub> oxidation products of monoterpenes are comparable with the daytime concentrations of OH oxidation products of monoterpenes. The concentrations of NO<sub>3</sub> oxidation products

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gases present, for example, monoterpenes. Experiment III combined the contributions from the oxidation products of both monoterpenes and MBO – the OH oxidation products from MBO enable the freshly nucleated particles in the daytime to grow large and fast enough while the nighttime  $\text{NO}_3$  oxidation products from monoterpenes allow particles to grow up to 100 nm. The simulated growth of particles above 15 nm compares well with the DMPS measurements. These simulations are also consistent with results from Levin et al. (2012, 2014) for hygroscopicity measurements at the BEACHON-ROCS site; these authors showed that growth of new particles was likely driven by biogenic secondary organic species, and the NPF events ultimately impacted aerosol chemical and physical properties for particles up to cloud condensation nuclei (CCN) sizes.

Since lump sums of different oxidation products were used as the condensing vapors in this modeling study, it was not possible to assign exact physical properties to the vapors. Based on the implemented chemistry scheme, the molar mass of the three condensing vapors should range from 200 to 300 Da. The saturation vapor concentration of  $10^6$  molecules  $\text{cm}^{-3}$  would thus correspond to approximately  $0.0001\text{--}0.0005 \mu\text{g m}^{-3}$ , which is close to the saturation vapor concentration of the extreme low volatility compounds suggested by Donahue et al. (2011). The three experiments suggest the importance of extremely low volatility compounds for growing particles, especially the role of monoterpenes and MBO as precursor gases in different time of a day.

Particle number size distributions are shown together with above canopy wind direction observations for the period of 19 to 22 August 2010 (DOY 231 to 234, Fig. 10), when continuous sulfuric acid, MBO and monoterpene concentration measurements were available (Fig. 11). We see that the modeled onset of nucleation, the first appearance of sub-3 nm particles in simulated number size distribution, usually starts when the wind direction changes from south to north. This is consistent with the fact that the source of anthropogenic influence is from the Denver area northeast of the site. Anthropogenic  $\text{SO}_2$  is advected to the forest and is oxidized to  $\text{H}_2\text{SO}_4$  on the way. The  $\text{H}_2\text{SO}_4$  then triggers nucleation. We see the  $\text{H}_2\text{SO}_4$  concentration rise in tandem with

the change in wind direction. On 19 August 2010 (DOY 231) around noon the wind direction changed from west to northeast and to north. At the same time as the air mass changed, we see a decrease in the concentration of measured background particles larger than 100 nm. At that time a burst of particles between 20 to 50 nm was observed. These particles were likely formed north of the measurement site and then brought to the site through advection. A few hours later at about 19:00 LT, a short rain quickly washed out most particles. This burst of particles before the rain matched well with the simulated particle number size distribution for the same time period. We suspect that a new particle formation event did occur in the forest on that day, but was just not captured by the measurement instrument. In the evening, particles were removed by precipitation. Similarly on 20 August 2010 (DOY 232), when the wind direction fluctuated between north and south and the air mass was transported around the forest, we see a burst of particles between 20 to 50 nm in the afternoon. For the rest of the day the particles were observed to continue growing while wind persisted blowing from the south. The southern wind was likely to bring polluted air to the site at late evening, which appeared as the high concentration of particles over between 50 and 100 nm. Apart from this abrupt increase in concentrations of 50–100 nm particles, which cannot be captured by the column model, the observed number size distribution is well simulated. Although no new particle formation was observed on 21 August 2010 (DOY 233), the model simulated a weak formation event. This tendency of the model to predict new particle formation events when none are observed has already been reported in the previous SOSAA model study by Zhou et al. (2014). It likely results from our incomplete understanding of the NPF phenomenon, especially in cluster nucleation. Kinetic nucleation parameterization by sulfuric acid is indeed too simple to account for the process, which makes the simulated nucleation too sensitive to sulfuric acid concentration. On 22 August 2010 (DOY 234), the DMPS instrument captured Aitken mode particles for just a short period of about an hour and the model simulation shows the same distribution at the same time. The high MBO concentration observed on that day also favored SOA formation. We thus suspect that the particles were forming in

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to the particle loading during nighttime could be important. Due to the anthropogenic origin of SO<sub>2</sub>, which is the precursor gas of sulfuric acid that triggers nucleation, the model study suggests that new particle formation events are likely to happen locally in the forest and meantime under the influence of anthropogenic pollution.

The SOSAA model has been shown as a good tool for studying various atmospheric processes including SOA formation constrained by observations. The model is expected to improve in several aspects, one of which is the growth parameterization. At the moment the chosen condensing molecules are lumped to several condensing vapor classes and assigned with approximated properties. A new parameterization that calculates the exact physical properties, such as saturation vapor pressure, for each specific condensing molecule is being developed.

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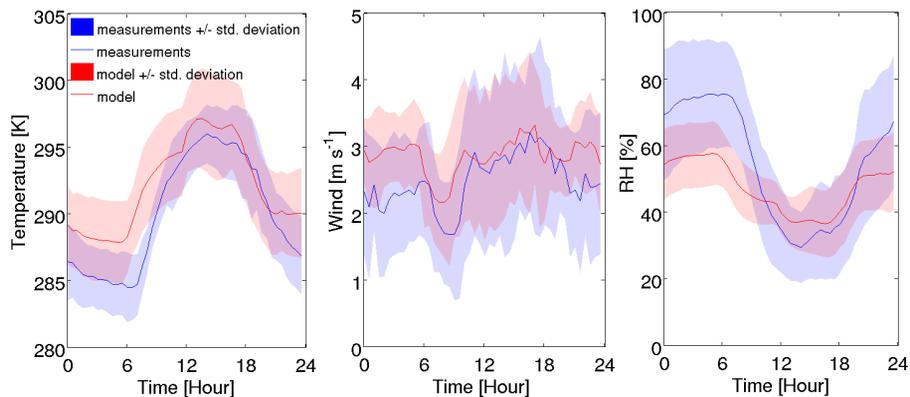
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**Table 1.** Saturation vapor concentration of each organic condensing vapor, unit:  $\text{cm}^{-3}$ .

	Vapor I	Vapor II	Vapor III
Experiment I	1	$10^{10}$	1
Experiment II	$10^6$	$10^{11}$	1
Experiment III	$10^6$	$10^{11}$	$10^6$

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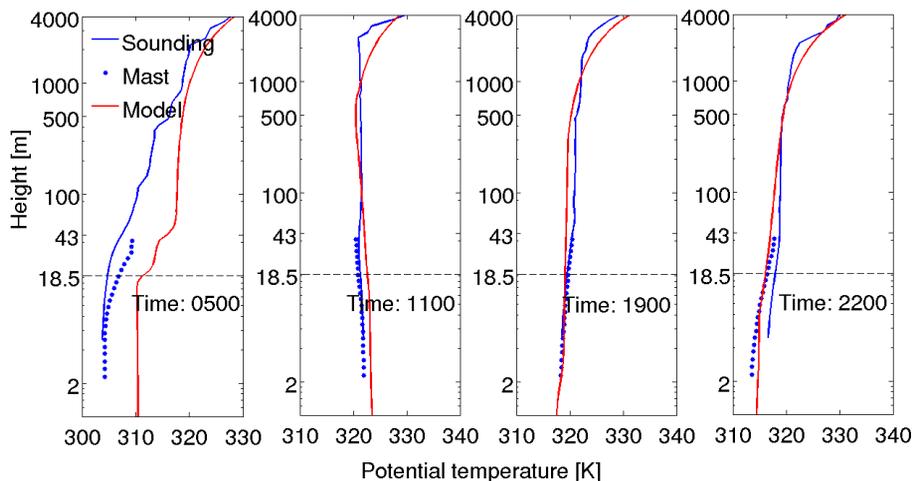


**Figure 1.** Averaged modeled and measured diurnal cycles of temperature (left), wind speed (middle), and relative humidity (RH, right). Measurement average (line) and  $\pm 1$  SD (shaded area) are in blue, model average (line) and  $\pm 1$  SD are in red. The comparisons are made above canopy at 30 m.

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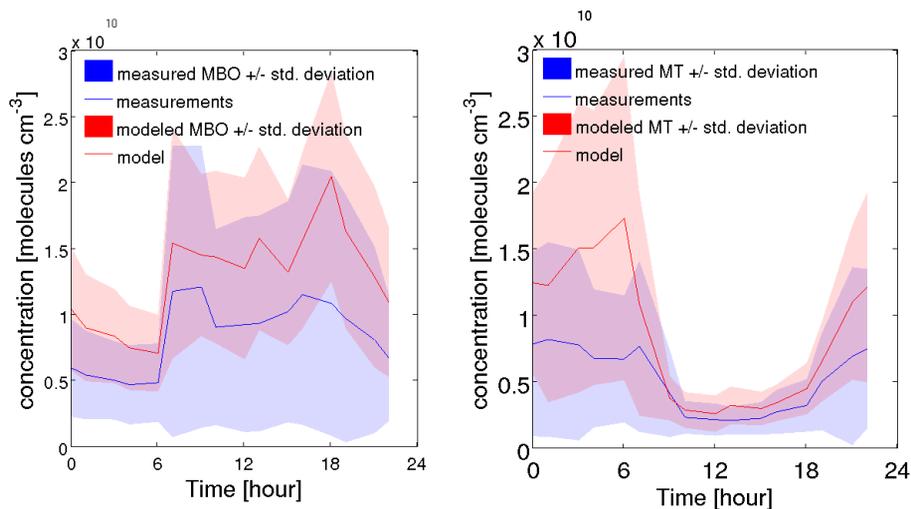
**Figure 2.** Observed and modeled vertical profiles of potential temperature at different time on 22 August 2010 (DOY 234). The y axis (height) is in logarithmic scale.

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**Figure 4.** Averaged modeled and measured diurnal cycles of MBO (left) and monoterpenes (MT, right) concentrations. Measurement average (line) and  $\pm 1$  SD (shaded area) are in blue, model average (line) and  $\pm 1$  SD (shaded area) are in red. The comparison is made at 3.5 m.

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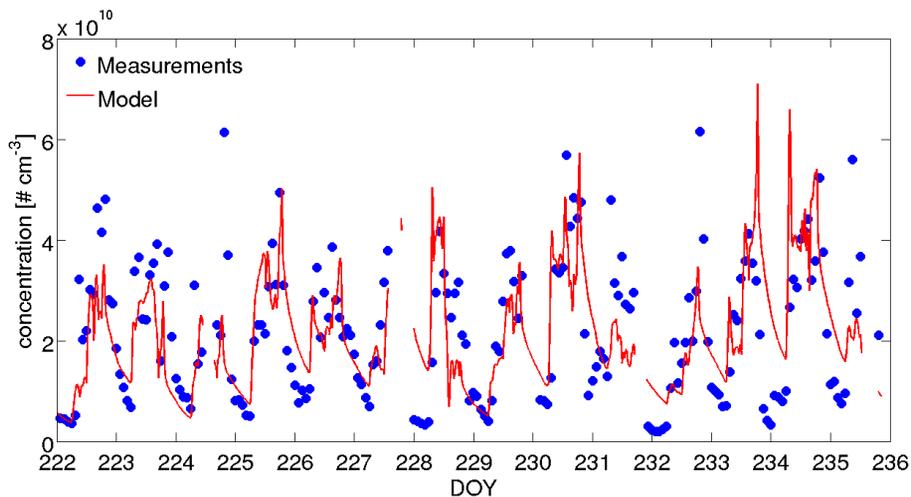
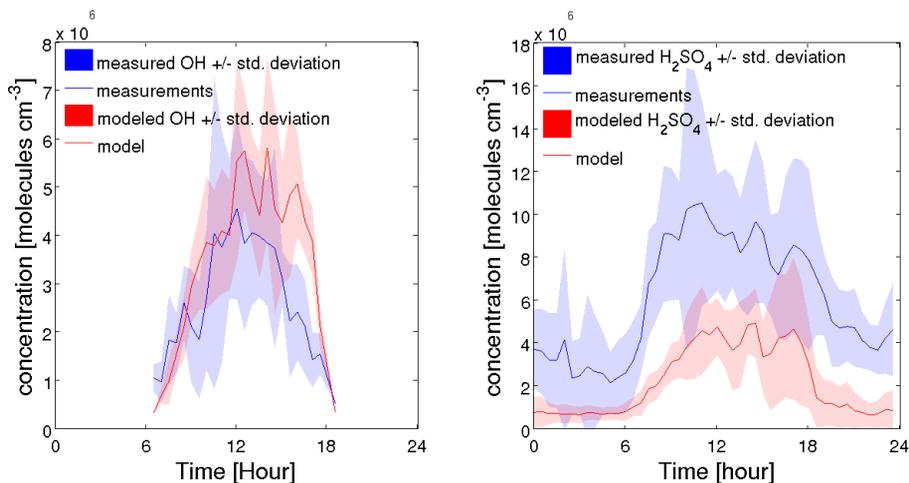


Figure 5. Measured and modeled MBO concentration at 3.5 m.

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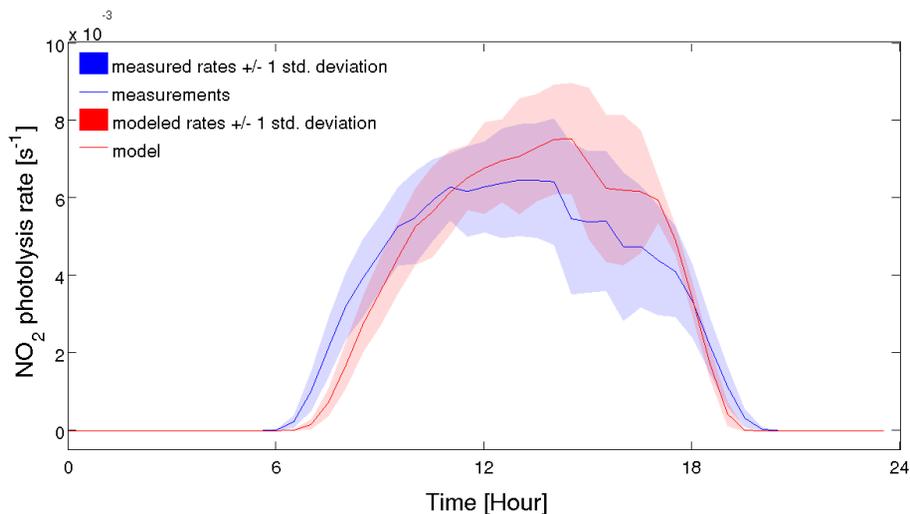


**Figure 6.** Averaged modeled and measured diurnal cycles of OH concentration (left), and sulfuric acid concentration (right). Measurement average (line) and  $\pm 1$  SD (shaded area) are in blue, model average (line) and  $\pm 1$  SD (shaded area) are in red. The comparisons for OH and sulfuric acid are made at 2 m.

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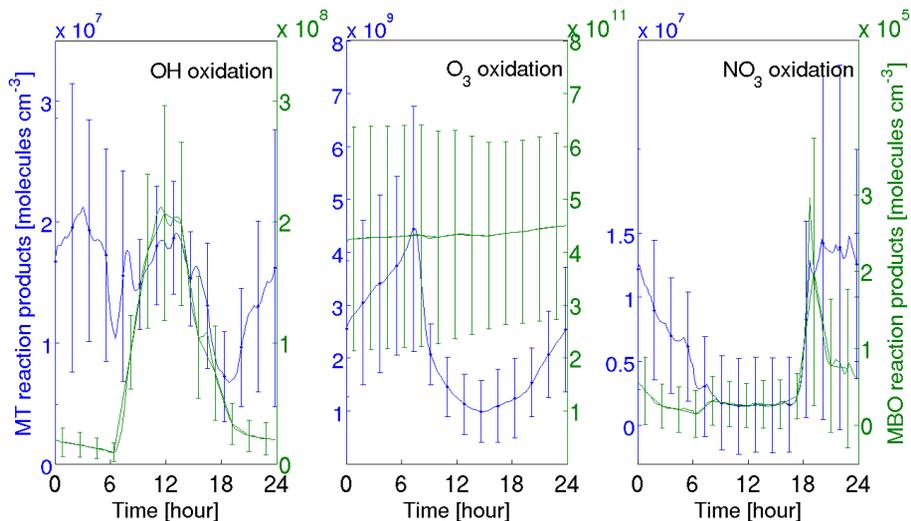


**Figure 7.** Averaged modeled and measured diurnal cycles of photolysis rate  $\text{NO}_2$ . Measurement average (line) and  $\pm 1$  SD (shaded area) are in blue, model average (line) and  $\pm 1$  SD (shaded area) are in red. The comparison for photolysis rate is made above the canopy at 25 m.

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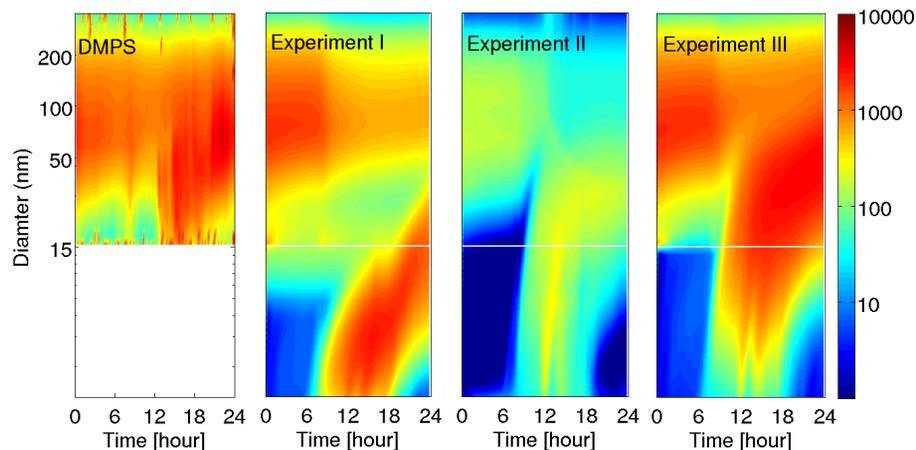


**Figure 8.** Averaged modeled diurnal cycles of OH, O<sub>3</sub>, and NO<sub>3</sub> oxidation products of monoterpenes (plotted against left y axis in blue) and MBO (plotted against right y axis in green). The error bars are  $\pm 1$  SD.

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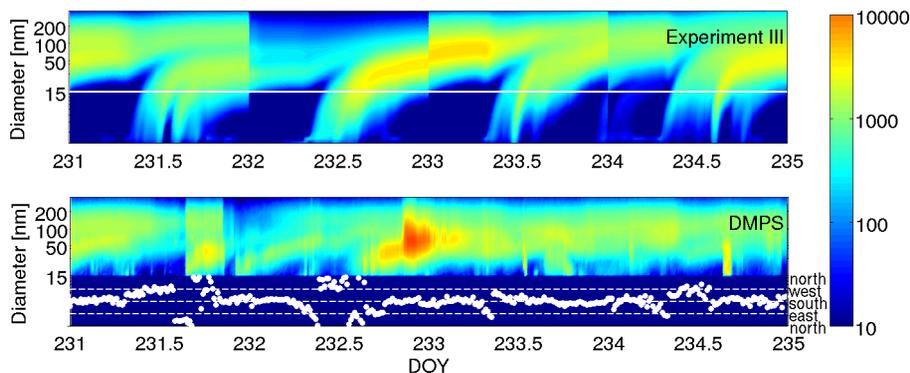


**Figure 9.** Averaged one-day number size distributions based on the DMPS measurements and model Experiment I–III. The concentration unit is molecules  $\text{cm}^{-3}$ . DMPS instrument has cutoff size at 15 nm. The averages are made only for periods when measurements are available.

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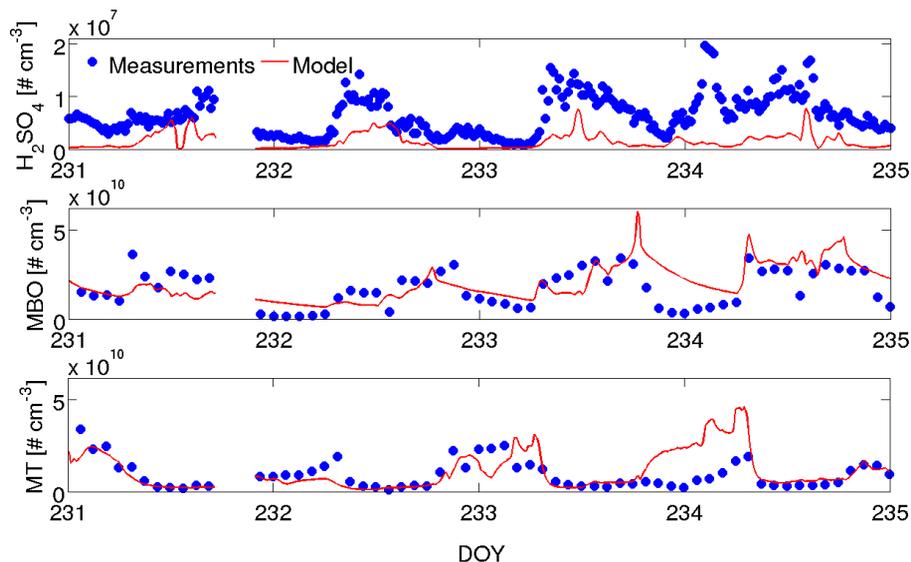
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**Figure 10.** Particle number size distribution from 19 August 2010 (DOY 231) to 22 August 2010 (DOY 234) based on the model Experiment III (top) and DMPS measurements (bottom). The DMPS instrument has a 15 nm lower detection limit. Particle concentration units are molecules  $\text{cm}^{-3}$ . Observation of wind direction at 30 m is plotted as white dots in the lower portion of the bottom figure.

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**Figure 11.** Modeled and measured  $\text{H}_2\text{SO}_4$  (top), MBO (middle) and monoterpenes (MT, bottom) concentrations from 19 August 2010 (DOY 231) to 22 August 2010 (DOY 234). Data was removed for late afternoon early evening of day 231 to exclude influence from precipitation for two hours after precipitation ended. Measurements are shown as blue circles and the model simulations are indicated by the red line. Comparisons for sulfuric acid are made at 2 m; comparisons for MBO and MT are made at 3.5 m.

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