European Commission: **Biogenic VOC emissions and photochemistry in the boreal regions of Europe – Biphorep**
Edited by Tuomas Laurila and Virpi Lindfors, 1999 – 158 pp. – 16.2 x 22.9 cm, ISBN 92-828-6990-3

Upscaling the BIPHOREP Results – Regional Biogenic VOC Emissions in the European Boreal Zone

V. Lindfors, J. Rinne, and T. Laurila

Finnish Meteorological Institute, Air Quality Research
Sahaajankatu 20E, FIN-00810 Helsinki

Introduction

The ultimate purpose of the BIPHOREP project is the characterisation of biogenic emissions from European boreal ecosystems. The full value of the project will be realised when the extensive range of emission data, obtained during the course of the two campaign years, is fitted into the framework of emission modeling to complement the existing species and landscape specific databases. The new results on emission factors and emission composition will improve the accuracy of global biogenic VOC emission inventories and facilitate a more detailed treatment of local emission features which may be important also in regional or global scales.

In this work, we have taken the first tentative steps towards the upscaling of the BIPHOREP emission measurements. We combine the new information on emission factors and biomasses of boreal tree species with the best available emission algorithms and detailed land cover data, based on satellite measurements, to construct a forest VOC emission inventory for specific regions in the boreal zone. The results are discussed in the context of measured biogenic VOC concentrations and compared with the direct emission flux measurements.

Biogenic emission modeling

In the European boreal zone, the dominant tree species are pine (*Pinus sylvestris*) spruce (*Picea abies, Picea abies* ssp. *obovata*), and birch (*Betula pendula* and *Betula pubescens*), with minor contributions of other coniferous species, aspen (e.g. *Populus tremula*), and alder (*Alnus* sp.). In Finland, for example, pine, spruce, and birch occupy 64.5%, 25.7%, and 7.3% of the forest land area, respectively (FFRI, 1997). The relatively narrow species distribution simplifies the construction of the VOC emission inventory for boreal forests – however, until recently comprehensive emission factor information has not been available in the North

European environmental conditions. Earlier emission assessments for this region (Simpson et al., 1995, Lindfors et al., 1995) have therefore relied on emission factor data bases (e.g. Geron et al., 1994; Guenther et al., 1994) compiled from measurements made in the United States and Central Europe and often representing species and subspecies not found in the European boreal forests.

In general, deciduous trees are considered to be the main isoprene emitters. In the European boreal forests, however, the dominant deciduous species is birch which is, at best, a low isoprene emitter. Willow and aspen are high isoprene emitters, but their relatively small share in the boreal forests makes them less important in large scale emission inventories. The prevalent boreal spruce species, *Picea abies*, on the other hand, is a low isoprene emitter (e.g. Steinbrecher and Rabong, 1994; Kempf et al., 1996), and due to its large biomass it is an important contribution to the regional emission patterns in this zone.

The isoprene emissions are under enzymatic control, and they are strongly dependent on leaf temperature and light intensity (e.g. Monson et al., 1995). Conifers emit a wide spectrum of terpenes (Tingey et al., 1991), and some of the boreal birch species are also high monoterpene emitters (Hakola et al., 1998). The most common emitted monoterpenes are α-pinene, β-pinene, Δ^3-carene and limonene. Terpene emissions are mainly regulated by leaf temperature (Guenther et al., 1993; Schuh et al., 1997; Hauff et al., 1998). Thus, unlike isoprene whose emissions are practically nonexistent at night, monoterpenes can also be emitted in the dark. In addition to the terpenoids, biogenic emissions contain numerous other VOCs (OVOCs) such as alcohols, esters, ethers, aldehydes, ketones, alkenes and alkanes. Emissions from different tree species have characteristic VOC composition and strength. However, the emissions are also strongly influenced by environmental factors and tree phenology, and there may be great variability in emission patterns between individual trees of the same genus and species depending on their growing conditions.

We base the estimation of the VOC emissions from forest foliage on the method described by Guenther (1997). The emission flux F (in μg m^{-2} h^{-1}) is given by

$$F = \varepsilon D \gamma \quad , \qquad (1)$$

Table 1. *The emission potentials (in μg g(dry weight leaf biomass)$^{-1}$ h^{-1}) of dominant boreal tree species.*

	Isoprene	**Monoterpenes**	**OVOC**
Deciduous trees			
Betula pendula and *Betula pubescens*	0.1[a]	1.0[b]	1.5[a]
Populus tremula	43[b]	1.0[b]	1.5[a]
Salix sp.	34[a,b]	0.3[b]	1.5[a]
Coniferous trees			
Pinus sylvestris	0.1[a]	1.5[a]	1.5[a]
Picea abies	1.0[c,d]	1.5[c,d,e]	1.5[a]
Picea abies ssp. *obovata*	0.1[a,c]	1.5[c,d]	1.5[a]

References: a) Simpson et al., 1999; b) Hakola et al., 1999, c) Steinbrecher et al., this volume; d) Kempf et al., 1996; e) Janson, 1993.

where ε is the emission potential in μg g(dry weight)$^{-1}$ h^{-1}, D is the foliar biomass density in g(dry weight) m^{-2}, and γ is a nondimensional environmental correction factor, which includes the effect of temperature and light conditions. The emission potential and the foliar biomass density are species specific properties, and they should be assessed individually for each tree genera and subspecies, in conditions representative of those in the actual ecosystems.

Biogenic emission potential

The emission potentials applied in this study are summarised in Table 1. Basically, we have adopted the compiled values of Simpson et al. (1999) for emissions from European ecosystems. We have also taken into account their recommendation that most tree species with no documented isoprene emissions (e.g. *Pinus sylvestris*) should be assessed a minimun emission rate when considering landscape emissions, because their isoprene emissions may be so low that they are not quantifiable, and because of the emissions of unaccounted-for vegetation within the forest area. To emphasise the boreal character of the study area, we have utilised the results obtained in the BIPHOREP emission measurement campaigns (Steinbrecher et al, this volume; Hauff et al., 1998; Hakola et al, 1998; 1999) as well as some other recent work (Janson, 1993; Kempf et al., 1996, and references therein) to complement the isoprene and monoterpene emission factor data base of Simpson et al. (1999). No new quantitative information has become available on the OVOC emission potential of boreal vegetation, and thus we have assigned the default value 1.5 μg g(leaf biomass)$^{-1}$ h^{-1} (Guenther et al., 1995, Simpson et al., 1999) for all tree species.

Foliar biomass density

The typical foliar biomass density of European deciduous trees is 320 g m^{-2} (Simpson et al., 1999). The foliar biomass densities of *Pinus sylvestris* and the *Picea* species are highly variable with latitude. The values recommended to be used in areas north of 60°N are 500 g m^{-2} and 800 g m^{-2}, respectively (Simpson et al., 1999). However, the boreal forests cover a wide range of latitudes (mostly between 50°N and 70°N), and in this inventory we have taken into account the biomass variability within the studied region.

In order to assess the latitudinal variability of the foliar biomass, the BIPHOREP biomass data base, created from the forest inventory data of the Finnish Forest Research Institute (Kellomäki, this volume), was filtered for ≥90% of the biomass consisting of one species only. The original data set of 1256 sample plots was thus reduced into subsets for pine, spruce and birch, with 331, 284, and 25 sample plots, respectively. The deciduous subset was small and the data was considered too inconsistent for further study. However, for pine and spruce we obtain a latitudinal dependence of the biomass, shown in Figure 1. According to this analysis, the average foliar density of *Pinus sylvestris* decreases from 400 g m^{-2} to 200 g m^{-2}, and that of *Picea abies* from 1250 g m^{-2} to 750 g m^{-2}, between the latitudes 60°N and 70°N.

In this work, a 10×10 km^2 grid analysis of LANDSAT satellite data, covering the land areas of Finland, was used to obtain the forest area distribution in different parts of the boreal zone. Besides the land cover type, the LANDSAT forests are also assorted into five growing stock volume classes, ranging from <50 m^3 ha^{-1} to >200 m^3 ha^{-1}. It is therefore possible to estimate the total volume in each main Finnish forest type (pine, spruce, deciduous) in specific regions within the study area. To convert the growing stock into total tree biomasses, we have used the average densities 420 g/l, 380 g/l, and 480 g/l for pine, spruce, and deciduous trees, respectively (Kauppi et al., 1995). The average share of foliage of pine, spruce, and deciduous trees is 5%, 15%, and 4% of the stemwood mass, respectively (Kauppi et al., 1995), which gives us an estimate of the forest biomass distribution over Finland. The average biomass

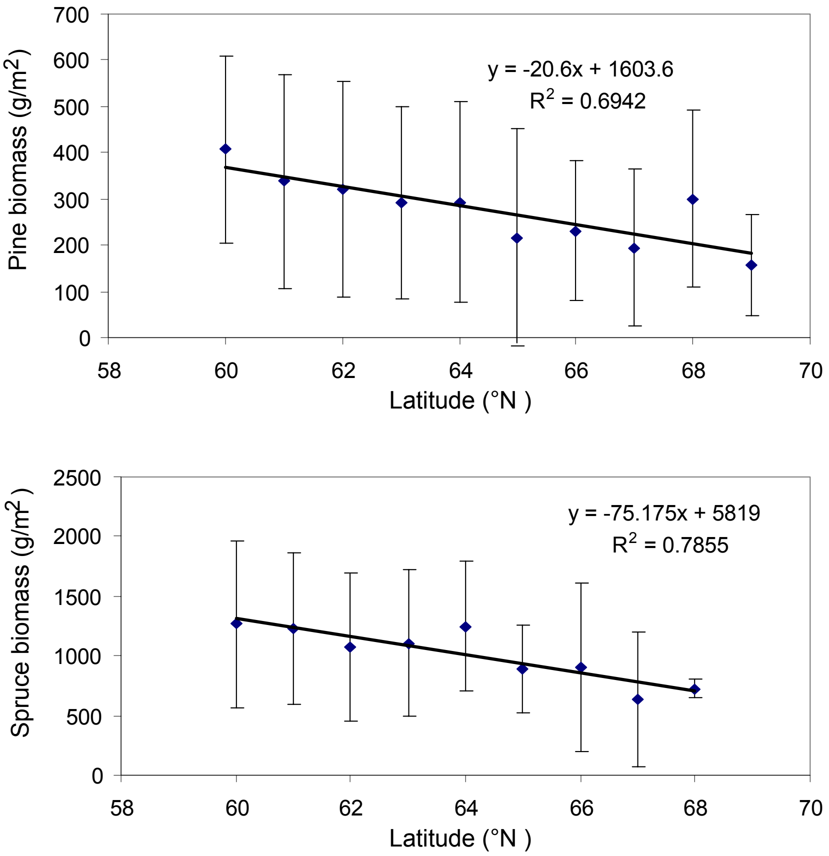

Figure 1. *Foliar biomass density of pine (upper panel) and spruce (lower panel) as a function of latitude in the North European boreal zone according to the forest inventory data of the Finnish Forest Research Institute. The error bars indicate the standard deviation.*

densities resulting from this analysis are given in Table 2. The values obtained for pine and spruce are in good agreement with the analysis of the BIPHOREP biomass data base described above. The biomass density of deciduous forests appears to be slightly higher than the average European value recommended by Simpson et al. (1999), while the foliar biomass of the boreal pine forests is considerably lower than the recommended 500 g m^{-2}.

For the purposes of this preliminary emission modeling excercise, we have adopted the values given in Table 2 for southern and northern Finland as representative of foliar biomass densities in the southern and northern parts of the boreal zone, respectively. The grand average values were applied to the Middle boreal zone.

Table 2. *The average foliar biomass densities (in g m^{-2}) of the main boreal forest types, based on the LANDSAT growing stock volume analysis.*

	Pine	**Spruce**	**Deciduous**
Southern Finland	300	900	400
Northern Finland	200	750	350
Grand average	300	900	400

Light and temperature correction

The environmental correction factor γ describes the diurnal variation of the biogenic VOC emissions. Several numerical algorithms have been developed to simulate the effect of light and temperature on isoprene and monoterpene emissions (e.g. Lamb et al., 1987, 1993; Guenther et al., 1991, 1993). In this work we have adopted the algorithms proposed by Guenther et al. (1993), which have been shown to perform extremely well when applied to different vegetation types and environmental conditions (e.g. Guenther et al., 1993; Guenther, 1997; Simpson et al., 1999). According to this approach, the terpene emissions are controlled by the volatilisation of hydrocarbons from storage pools inside the leaf (temperature control), while isoprene is emitted directly after it has been synthetised by the plant (light and temperature control).

The environmental correction factor for isoprene emissions is thus

$$\gamma_{ISO} = C_T \cdot C_L \ , \qquad (2)$$

where C_T is the temperature correction and C_L is the light correction.

The light correction has the form

$$C_L = \frac{\alpha C_{L1} L}{\sqrt{1+\alpha^2 L^2}} \ , \qquad (3)$$

where L is the photosynthetically active photon flux density (PPFD, µmol photons m^{-2} s^{-1}), and α (= 0.0027) and C_{L1} (= 1.066) are empirical coefficients (Guenther, 1997).

The temperature correction is

$$C_T = \frac{\exp(\frac{C_{T1}(T - T_S)}{RT_S T})}{C_{T3} + \exp(\frac{C_{T2}(T - T_M)}{RT_S T})} \quad . \tag{4}$$

Here T (K) is the leaf temperature, T_S is the leaf temperature at standard conditions (= 303.15 K), R is the universal gas constant, and C_{T1} (= 95 000 J mol^{-1}), C_{T2} (= 230 000 J mol^{-1}), C_{T3} (= 0.961), and T_M (= 314 K) are empirical coefficients (Guenther, 1997).

The environmental correction for terpene emissions is

$$\gamma_{TERP} = \exp(\beta(T - T_S)) \quad , \tag{5}$$

where β (= 0.09 C^{-1}) is an empirical coefficient, and T_S is the standard temperature given above. This correction factor is generally also used for OVOCs, because experimental data on the OVOC emissions is still too scarce to facilitate the development of specific emission algorithms (Guenther et al., 1994; Simpson et al., 1999).

Recently, it has been shown that the terpene emissions of some oak species are also light and temperature controlled (Seufert et al., 1997). In addition, Steinbrecher (1994) and Steinbrecher et al. (1999) have suggested a light dependence of the terpene emissions of the *Picea* species, indicative of both storage emissions and *de novo* synthesis. However, since oak is not an important species in the North European boreal forests, and since the above mentioned emission flux measurements of spruce are also well described by the pool model (Steinbrecher et al., 1999), we have retained the simple idea of representing all terpene emissions by the γ_{TERP} algorithm in Equation 5. Given the large overall uncertainties in both the emission factors and the land cover information, this simplification is not likely to introduce any discernible bias in the emission estimates.

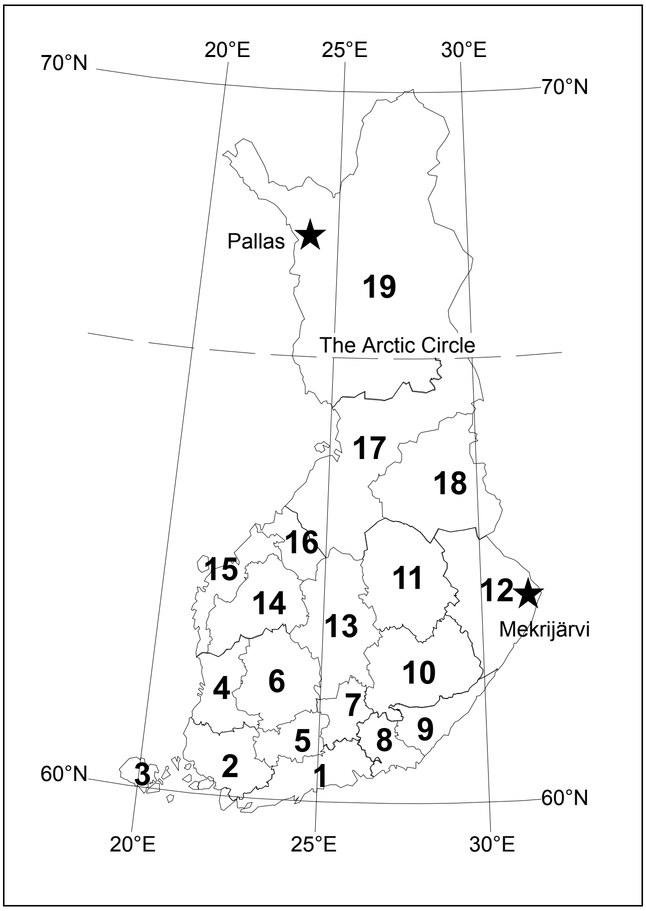

Figure 2. *The area classification of the LANDSAT land cover data set of Finland used in this study. The BIPHOREP campaign sites Pallas (1996) and Mekrijärvi (1997) are indicated with stars.*

<u>Land cover and meteorological data</u>

The 10×10 km^2 grid analysis of LANDSAT satellite data, obtained from the Finnish Environmental Information Center, was used to construct the land cover data base for the emission model. All forests were classified into pine, spruce, or deciduous category, with the allocation of mixed forests based on the assumption that mixed coniferous forests comprise of 54% pine and 46% spruce, and mixed forests of 18% deciduous, 44% pine, and 38% spruce (Kauppi et al., 1995; FFRI, 1997). The regional grouping was done on the basis of the N.U.T.S. (the *<u>N</u>omenclature des <u>U</u>nités <u>T</u>erritoriales <u>S</u>tatistiques* of the European Union) Level 3 area classification of Finland as shown in Figure 2. Since average emission potentials and broad averages of foliar biomasses were used in this study, the geographical areas were chosen to be large enough to smooth over any small-scale variability introduced by specific

Table 3. *The relative share (in per cent) of pine, spruce, and deciduous forests of the total land area of the 19 regions in Finland, based on the LANDSAT satellite data analysis. The total forest coverage (in per cent) and the geographical coordinates of the synoptic station are also given for each region. The boreal zone classification of the regions is indicated in parenthesis (S = South boreal, M = Middle boreal, N = North boreal, C = coastal) (see text).*

Region	**Synoptic station**		**Forest coverage, % of land area**			
	Lat, °N	***Lon, °E***	***Pine***	***Spruce***	**Deciduous**	**Total**
1 (S)	60.32	24.95	20	22	8	50
2 (S)	60.51	22.27	24	18	5	47
3 (C)	60.15	19.88	28	9	6	42
4 (S)	61.47	21.80	25	29	7	62
5 (S)	60.82	23.50	22	28	10	60
6 (S)	61.42	23.42	30	28	7	64
7 (S)	60.97	25.63	24	28	8	61
8 (S)	60.90	26.93	21	32	9	63
9 (S)	61.73	27.30	17	31	8	56
10 (S)	61.73	27.30	21	28	10	59
11 (S)	63.02	27.80	18	28	19	65
12 (M)	62.67	30.93	24	25	11	60
13 (S)	62.40	25.68	28	31	12	71
14 (M)	63.10	23.03	25	29	9	63
15 (C)	63.10	23.03	23	27	12	61
16 (M)	63.10	23.03	30	22	11	62
17 (M)	65.37	27.02	27	25	22	74
18 (M)	64.28	27.67	29	30	14	73
19 (N)	67.37	26.65	28	23	16	67

vegetation types or other local phenomena. The regional forest coverage, calculated from the LANDSAT data as described above, is given in Table 3 as relative shares of pine, spruce and deciduous forests of the total land area of each region.

A representative synoptic station was selected for each area, and meteorological data for the growing season (April 1 – September 30) of the years 1996 and 1997 was obtained from the database of the Finnish Meteorological Institute. The three-hourly values of temperature, relative humidity, cloudiness and wind speed were interpolated linearly to construct a continuous time series of hourly meteorological data for each area. The geographical coordinates of the synoptic stations are also given in Table 3 to indicate the latitudinal variation of the forest coverage. Note that some smaller adjacent regions may be represented by the same synoptic station (e.g. regions 14-16).

The 19 regions were classified into the South, Middle and North boreal zones according to Solantie (1990) and Ahti et al. (1968). The classification is indicated in Table 3 with capital letters. The BIPHOREP campaign site in 1996 was Pallas in Lapland (region 19), which is representative of the climatic conditions in the North boreal zone. In 1997 the campaign was carried out in Mekrijärvi in North Karelia (region 12). The site is located on the Middle boreal side of the border between the South and Middle boreal zones. In the LANDSAT biomass analysis described above, the coniferous forest biomasses in North Karelia were approximately 270 and 750 g m^{-2} for pine and spruce, respectively, which is notably lower than the southern Finland averages given in Table 2. In this emission modeling excercise, we have therefore assigned the whole region 12 to the Middle boreal zone.

<u>Calculation of hourly emissions</u>

The calculation of the hourly emissions from each region was done using the FMI/BEIS emission model. The model is based on the updated version of the Biogenic Emissions Inventory System (BEIS, version 2.2) developed at the Environmental Pollution Agency (EPA) of the U.S.A. (Birth and Geron, 1995; Pierce, 1996). For application in North European areas, the model code has been completely rewritten to treat only the dominant boreal forest types, with two coniferous forest classes and one deciduous class. To facilitate the use of the LANDSAT land cover database, where the average fraction of allocated pure pine, spruce, or deciduous forests is less than 50% of the total forest area, we have developed species profiles for each forest type. The profiles, similar to those used in a previous version of the EPA BEIS model (Lamb et al., 1987; Pierce and Waldruff, 1991), take into account the mixing of species within coniferous and deciduous forests, according to the Finnish forest statistics (FFRI, 1997).

Lacking more specific information about the relative abundance of the main *Picea* species in different parts of the country, we have treated all spruce as *Picea abies*, except for the

Table 4. *Per cent contribution of deciduous and coniferous species in the boreal forest types. The deciduous species are classified into high isoprene, low isoprene, and non-isoprene emitters, as explained in the text.*

Forest type	**Deciduous species**			**Coniferous species**	
	high-iso	*low-iso*	*non-iso*	*pine*	*spruce*
Pine	1.0 %	16.0 %	1.0 %	82.0 %	0.0 %
Spruce	0.5 %	10.0 %	0.5 %	0.0 %	89.0 %
Deciduous	3.5 %	64.0 %	3.5 %	16.0 %	13.0 %

northernmost region (Lapland, region 19), where the spruce foliar biomass is assumed to be divided equally between *Picea abies* and *Picea abies* ssp. *obovata* (Hämet-Ahti et al., 1992). The deciduous tree types are divided into three classes, based on their isoprene emission potential, to reflect the relative share of high isoprene emitters (e.g. *Populus* and *Salix* sp.), low isoprene emitters (e.g. *Betula* sp.) and non-isoprene emitters (e.g. *Alnus* sp.). Deciduous forest is assumed to contain a small fraction of coniferous trees, and coniferous forests have a share of deciduous species. The ensuing distribution of the total forest biomass between the tree species is presented in Table 4.

The emission fluxes of isoprene, total monoterpenes and OVOCs were calculated for each forest type according to Equation (1)

$$F_{ISO,TERP,OVOC} = \varepsilon_{ISO,TERP,OVOC} \cdot D \cdot \gamma_{ISO,TERP,OVOC}(T,L) \ ,$$

using the environmental correction factors given in Equations (2) (isoprene) and (5) (monoterpenes and OVOCs). The FMI/BEIS model includes the original EPA/BEIS program code for the calculation of the photosynthetically active photon flux density (L, PPFD) from the cloudiness information of the hourly meteorological time series (Birth and Geron, 1995). Measured PPFD can also be used as model input when available. A simple canopy model with five vertical levels is used to adjust the PPFD within the forest canopy (Geron et al., 1994).

Table 5. *Calculated annual (April 1 –September 30) average biogenic emission fluxes (in kg per km^2 of total forest area) in different parts of the boreal zone in 1996 and 1997.*

Boreal zone	**South**	**Middle**	**North**
1996			
Isoprene	112	89	40
Monoterpene	762	642	403
OVOC	817	694	441
Total VOC	**1691**	**1426**	**883**
1997			
Isoprene	159	126	58
Monoterpene	902	753	473
OVOC	967	814	518
Total VOC	**2028**	**1694**	**1049**

Using the land cover information, the emissions were calculated for each region on hourly and daily basis over the growing season (April 1 – September 30) in 1996 and 1997. Total annual emissions were obtained by summing the daily totals over the calculation period.

Results

The calculated average annual isoprene, monoterpene, and OVOC emission fluxes from coniferous and deciduous forests in the South, Middle, and North boreal zone are presented in Table 5. The combined total biogenic VOC emissions in the 19 regions during the whole growing season were 291 kilotonnes and 347 kilotonnes in 1996 and 1997, respectively. This is considerably higher than the estimated Finnish annual anthropogenic VOC emissions of 193 kilotonnes (Mroueh, 1994). In 1996, isoprene, monoterpenes and OVOCs contributed 18, 131, and 142 kilotonnes, which is 6%, 45%, and 49% of the total emissions, respectively. In 1997 the total isoprene, monoterpene, and OVOC emissions were 25, 154, and 167 kilotonnes, i.e. 7%, 45%, and 48% of the total emissions, respectively.

Coniferous forests are the most important emitters in the North European boreal region, even with respect to isoprene, due to the large biomass of the low emitting spruce species. This can

Table 6. *Average contribution of coniferous forests to biogenic VOC emissions in different parts of the boreal zone.*

Boreal zone	**South**	**Middle**	**North**
	conifers	*conifers*	*conifers*
Isoprene	82 %	76 %	59 %
Monoterpene	91 %	88 %	84 %
OVOC	89 %	86 %	80 %
Total VOC	**90 %**	**86 %**	**80 %**

be seen in Table 6, where we give the coniferous forest contribution to the total isoprene, monoterpene, and OVOC emissions. The relative importance of deciduous species appears to increase when moving from the southern boreal zone to the North. This is especially evident when considering the isoprene emissions where the coniferous contribution in the North boreal zone is only 60 %.

The differences in the annual emissions are mainly explained by the temperature and light conditions of the campaign years. The progress of the growing season in 1996 and 1997 is presented in Figure 3, where we show the accumulated temperature > 5 °C for representative synoptic stations in the different boreal zones. In Finland, the summer of 1996 was cold, rainy, and short. In the southernmost parts of the country, the thermal growing season progressed close to normal in spring, while being about a week late and two weeks late in the central and northern parts of the country, respectively. July was exceptionally cold in the whole country, while August was warmer than normal. In 1997, spring was late, and the thermal growing season progressed very slowly due to severe cold spells in May. However, the whole summer was warmer than normal, with exceptionally high temperatures during the nights. The thermal growing season lasted until the third week of September in the North, and to the beginning of October in the central and southern parts of the country (statistics of the Finnish Meteorological Institute). The climatic variations are clearly reflected in the biogenic emissions which are also shown in Figure 3 as intergrated isoprene and monoterpene emission fluxes over the growing season in regions 5, 18, and 19, chosen to characterize the South, Middle and North boreal zones, respectively.

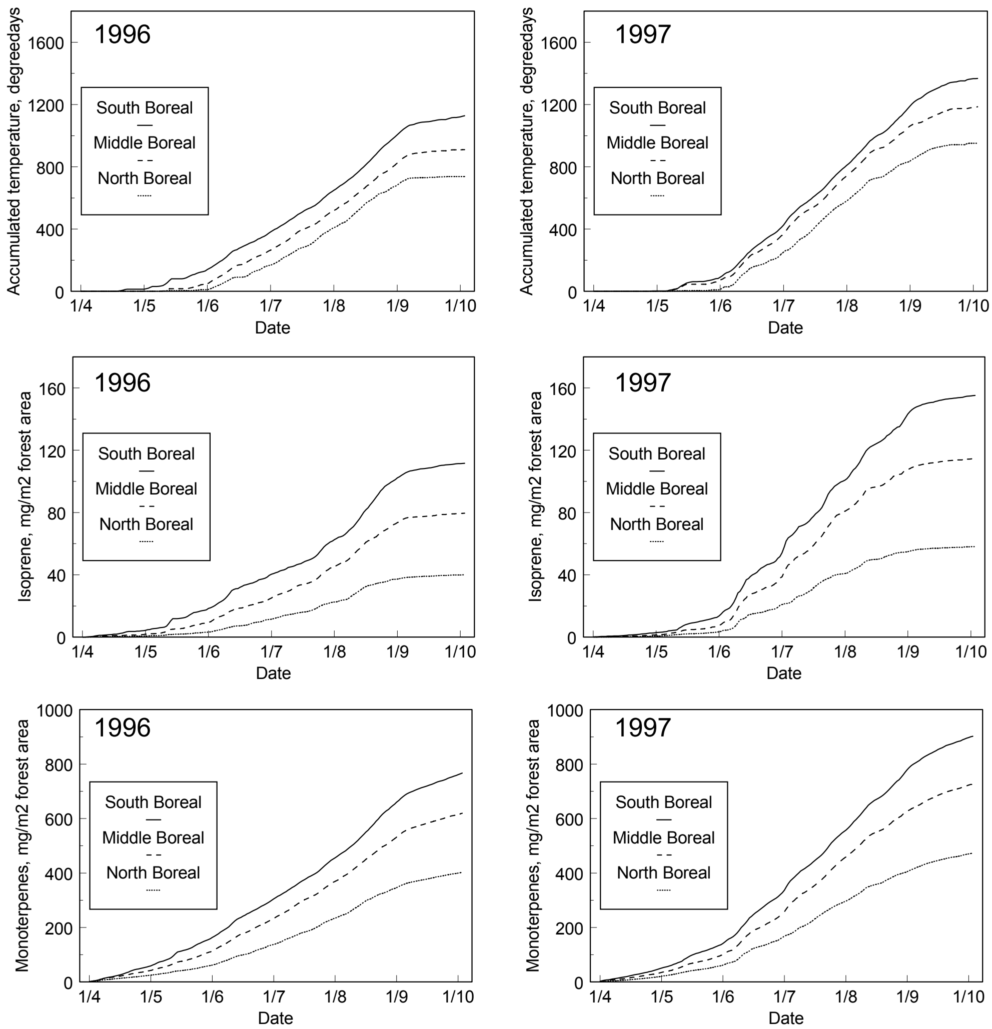

Figure 3. *Accumulated temperature (upper panels) and integrated isoprene (middle panels), and monoterpene emission fluxes (bottom panels) during the growing season in different parts of the boreal zone in 1996 (left) and 1997 (right).*

In Figure 4 we present the seasonal variation of the isoprene emissions in the Middle boreal zone in 1997, together with the daily average temperatures. The isoprene emissions follow closely the temperature variability, and the warm spells during the summer are clearly evident as emission maxima in the time series. The sharper variability of the daily emissions reflects the great sensitivity of the isoprene emission mechanism to the environmental conditions (Equations 3 and 4). In the beginning and at the end of the growing season, both the greater variability of the temperature (from below zero values at night to high afternoon values) and the reduced availability of solar radiation limit the daily emissions, even though the average

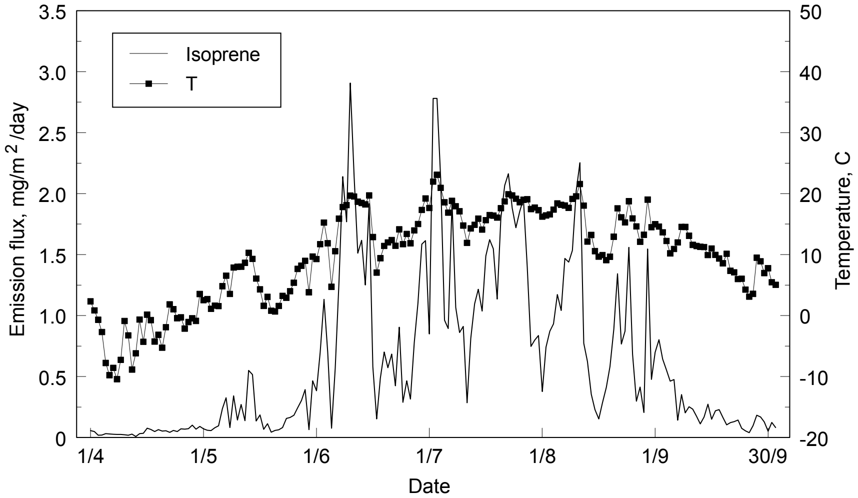

Figure 4. *Seasonal variation of isoprene emission flux (in mg per m² forest area per day, left axis) and the daily average temperature (right axis) in the Middle boreal zone (region 18) in 1997.*

temperatures may be close to the midsummer values. The average isoprene emission fluxes in the representative areas of the South, Middle and North boreal zone in 1996 were approximately 610, 435, and 220 g/km^2(forest area)/day, respectively. In 1997 the corresponding numbers were 850, 630, and 320 g/km^2(forest area)/day. During the warmest days of 1997, however, the maximum emissions could be close to 4 kg/km^2(forest area)/day in the South boreal zone, and about 3 and 2 kg/km^2(forest area)/day in the Middle and North boreal zones, respectively.

When considering the latitudinal dependence of the emission densities, we find that between the South boreal zone and the North boreal zone, both isoprene and monoterpene emissions are reduced by approximately 50%. This is shown in Figure 5, where the annual emission fluxes in 1996 and 1997 are presented as a function of the latitude of the synoptic station used in the model calculations.

The validation of the emission model estimates is very difficult due to the scarcity of direct biogenic VOC flux measurements, representative of the modelled time periods and the different geographical locations. Indirectly, one can compare the variability of the modelled

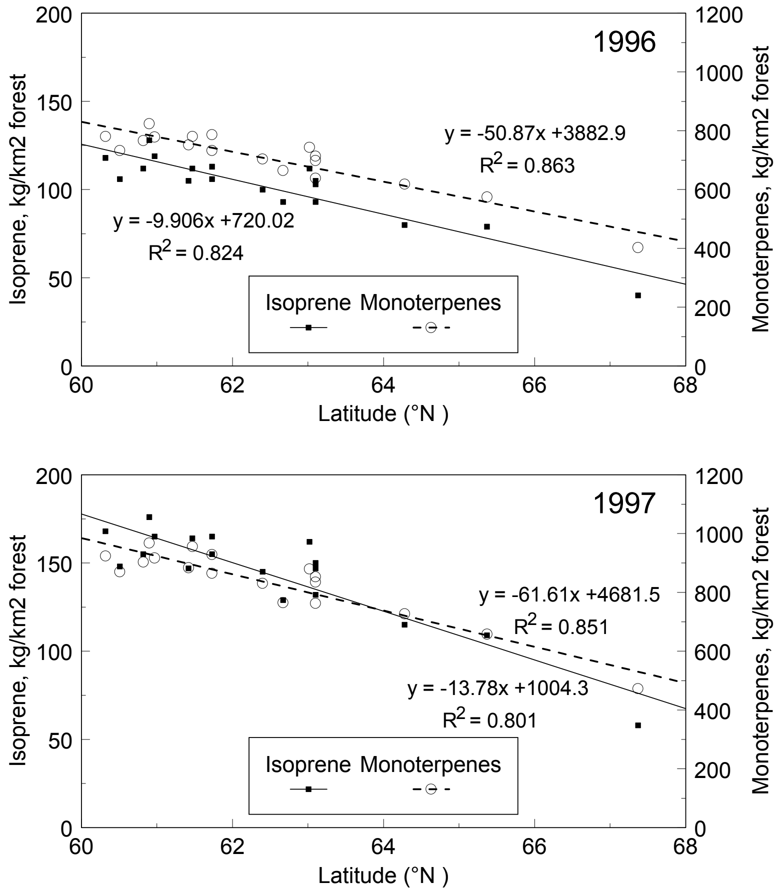

Figure 5. *Annual isoprene (left axis) and monoterpene (right axis) emission fluxes (emitted hydrocarbon mass per km^2 of forest land) as a function of latitude in the European boreal zone in 1996 and 1997.*

fluxes with that of observed biogenic VOC concentrations in background areas, where the local emission patterns are the main factor affecting the concentration fluctuations.

In Figure 6 we present the modelled isoprene and total monoterpene emission fluxes in North Karelia (region 12) in 1997, together with concentration data obtained at the Mekrijärvi Research Station during the BIPHOREP Project (Laurila et al., this volume). This comparison shows that the variability of the atmospheric concentrations is closely connected to the modeled emission variability. Both the duration of the intense emission period and the occurrence of the strong emission maxima are reflected in the measured concentrations.

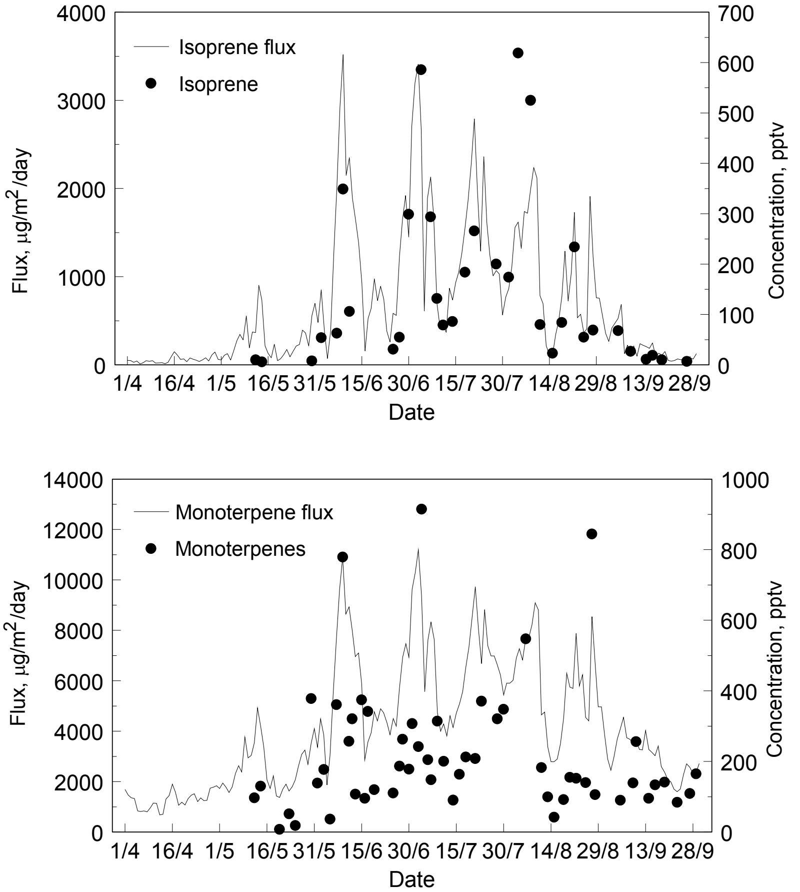

Figure 6. *Modelled isoprene (upper frame) and monoterpene (lower frame) emission fluxes together with the respective measured concentrations in North Karelia (region 12) during the growing season in 1997.*

Unfortunately, no measurements were available prior to May 15, and it is therefore not possible to judge the performance of the emission model with respect to the onset of terpene emissions. However, it seems clear that the present isoprene emission model somewhat overestimates the early spring emissions. This can be partly explained by the model assumption of constant biomass throughout the modeling period, which is clearly not the case with the deciduous species in the boreal zone, where the onset of leafing generally occurs in May - July, depending on the latitude. As explained above, in 1997 the spring was late, and according to the measurement data, isoprene was first detected in the air at the very end of May in the Middle boreal zone. It has been shown by Hakola et al. (1998; 1999) that in North

European environmental conditions the deciduous isoprene emitters do not start to synthesize the compound until about two weeks after the leaves have opened.

The modelled monoterpene emission fluxes can also be compared with the canopy scale flux measurements of Rinne et al. (1998; 1999) over a Scots pine stand at the BIPHOREP campaign site in Mekrijärvi. They found a mean total monoterpene emission rate of 190 ng m^{-2} s^{-1}, normalised to 30°C, on July 31 and August 2, 1997. From Figure 6 we see that the calculated regional monoterpene emissions in North Karelia during these days were approximately 6000 µg m^{-2} day^{-1}. According to the synoptic data, the afternoon temperatures in North Karelia in the beginning of August were around 20°C. The daily emission of 6000 µg m^{-2} corresponds to an average flux of 70 ng m^{-2} s^{-1}, or approximately 170 ng m^{-2} s^{-1}, when normalised to 30°C. Even though this is only a very rough comparison, the result is encouraging, considering the fact that the terpene emission algorithm, as well as the emission potentials used in this study, are greatly simplified, and that the terpene emission mechanism itself is less well understood than that of isoprene.

Conclusions

We have applied the results obtained during the BIPHOREP measurement campaigns in biogenic emission modeling, using the well established Guenther emission algorithms and satellite land cover data. In addition, we have studied the biomass variability in the European boreal zone, based on the extensive biomass data base created for the BIPHOREP project and an analysis of the LANDSAT data. Both the forest biomass and the emission fluxes have a clear South-North gradient, with the forest VOC emission capacity in the North boreal zone approximately half of that in the South boreal zone.

Coniferous trees, due to their larger biomasses dominate the biogenic emissions from boreal forests. The principal isoprene emitter in the boreal region is the low emitting *Picea abies*. On an annual level, the isoprene emission contribution is 6-7% of the total biogenic VOCs emitted by the boreal forest.

In the North European environmental conditions, climatological factors determine the annual variability of the biogenic emissions. Compared to Central Europe, the vegetation period is short, and the development of the growing season is immediately reflected in both isoprene and monoterpene emissions.

A comparison of the modeled isoprene and monterpene emissions and the observed ambient concentrations in background areas indicates that the emission model is capable of reproducing the seasonal variability of the biogenic emissions.

It is obvious that the modeled isoprene emissions are slightly overestimated in the beginning and at the end of the growing season because the seasonal pattern of deciduous biomass in the boreal region is not taken into account in the present model version. However, due to the strong dominance of the coniferous species, the error thus created is probably not very large, given the overall uncertainties related both to the emission potentials and the land cover information used to initialise the emission model. On the other hand, the seasonal behaviour of isoprene emissions by *Picea abies* in the boreal region has not been established experimentally, and it needs to be resolved before any conclusive judgement can be made about the emission model performance.

The few data available of direct emission flux measurements in the boreal zone, obtained during the course of the BIPHOREP campaigns, compare well with the modeled terpene emissions. Considering the fact that the emission model is based on a very general selection of boreal emission factors, and that the model was not adjusted to the local biomass or meteorological conditions at the BIPHOREP sites, it is encouraging that the modeled and observed emission rates are within the same order of magnitude.

The logical next step in terpene emission modeling will be the development of emission algorithms for each monoterpene species emitted by the boreal trees at various phases of the growing season. This will allow the creation of compound specific emission inventories which is important for the future assessments of e.g. the aerosol producing capacity of biogenic VOCs and the role of forests as regulators of the atmospheric chemical composition.

The great uncertainty connected with the OVOC emissions is the single largest drawback of the present biogenic emission models. While it is known that this category comprises of many reactive compounds, there is only scant data available of the OVOC emission potentials. Janson and De Serves (1998) report light carbonyl emissions of comparable magnitude with the monoterpene emissions for *Pinus sylvestris* and *Picea abies* from measurements made during the BIPHOREP campaigns. The light aldehydes and ketones only account for part of the emitted compounds, however, and thus the total OVOC emissions of these trees may actually be much higher. Nothing quantitative is known of the OVOC emissions of the main boreal deciduous species. In this inventory, we have adopted the 'generic' OVOC emission potentials with the result that almost half of the VOCs emitted by boreal forests belong to this bulk emission class.

In this work, we have only modeled the emissions from the boreal forests. While wetlands are generally considered important only with respect to methane emissions (e.g. Simpson et al., 1999), it has recently been that the boreal *Sphagnum* wetlands have substantial isoprene emission potential shown (Janson and De Serves 1998 and this volume; Janson et al., 1998). The highest observed fluxes can be as high as 2000 $\mu g\ m^{-2}\ h^{-1}$ (Janson and De Serves, this volume) which is about five times the maximum isoprene emission flux of a typical South boreal forest. Wetlands may thus also contribute significantly to the reactive VOC budget in the boreal zone.

Acknowledgement

We thank Hannele Hakola from the Finnish Meteorological Institute, Robert Janson from Stockholm University, and Rainer Steinbrecher from the Fraunhofer-Institut für Atmosphärische Umweltforschung in Garmisch-Partenkirchen for the use of their emission measurement data. Seppo Kellomäki is thanked for the initial analysis of the Finnish Forest Inventory Data. We wish to express our gratitude for David Simpson from the EMEP MSC-West for fruitful discussions. The financial support of the European Commission through the R&D Programme for Environment and Climate (contract ENV4-CT95-0022) is gratefully acknowledged.

References

Ahti, T., Hämet-Ahti, L., and Jalas, J., 1968. Vegetation zones and their sections in northwestern Europe, Annales Botanici Fennici 5, 169-211.

Birth, T. L. and Geron, C. D., 1995. User's guide to the personal computer version of the Biogenic Emissions Inventory System (PC-BEIS), Version 2.0. U.S. Environmental Protection Agency, Research Triangle Park, NC 27709, U.S.A.

FFRI, 1997. Finnish Statistical Yearbook of Forestry 1997, Finnish Forest Research Institute.

Geron, C. D., Guenther, A. B., and Pierce, T. E., 1994. An improved model of estimating emissions of volatile organic compounds from forests in the eastern United States. Journal of Geophysical Research 99(D6), 12773-12791.

Guenther, A., 1997. Seasonal and spatial variations in natural volatile organic compound emissions, Ecological Applications 7(1), 34-45.

Guenther, A. B., Zimmerman, P. R., Harley, P. C., Monson, R. K., and Fall, R., 1993. Isoprene and monoterpene emission rate variability: Model evaluation and sensitivity analyses. Journal of Geophysical Research 98(D7), 12609-12617.

Guenther, A., Zimmerman, P., and Wildermuth, M., 1994. Natural volatile organic compound emission rate estimates for U.S. woodland landscapes. Atmospheric Environment 28(6), 1197-1210.

Guenther, A., Hewitt, C. N., Erickson, D., Fall, R., Geron, C., Graedel., T., Harley, P., Klinger, L., Lerdau, M., McKay, W. A., Pierce, T., Scholes, B., Steinbrecher, R., Tallamraju, R., Taylor, J., and Zimmerman, P., 1995. A global model of natural volatile organic compound emissions, Journal of Geophysical Research, 100(D5), 8873-8892.

Hakola, H., Rinne, J. and Laurila, T., 1998: The hydrocarbon emission rates of tea-leafed willow (*Salix phylicifolia*), silver birch (*Betula pendula*) and European aspen (*Populus tremula*). Atmospheric Environment, 32, 1825-1833.

Hakola, H., Rinne, J. and Laurila, T., 1999: The variation in VOC emission rates of boreal deciduous trees during the growing season. Atmospheric Environment, submitted.

Hauff, K., Rössler, J., Hakola, H., Steinbrecher, R. (1998) Isoprenoid emission in European Boreal forests. in: Proceedings of EUROTRAC Symposium '98, eds. Borrell P. M. and Borrell P., WITpress, Southampton, 1999.

Hämet-Ahti, L., Palmén, A., Alanko, P., Tigerstedt, P. M. A., and Koistinen, M., 1992. Woody Flora of Finland, Publications of the Finnish Dendrological Society 6: 1-373.

Janson, R. W., 1993. Monoterpene emissions from Scots pine and Norwegian spruce. Journal of Geophysical Research 98(D2), 2839-2850.

Janson, R. and DeServes, C., 1998. Isoprene emissions from boreal wetlands in Scandinavia, Journal of Geophysical Research 103(D19), 25513-25517.

Janson, R., C. De Serves, and R. Romero, 1998. Emission of isoprene and carbonyl compounds from a boreal forest and wetland in Swede, Agricultural and Forest Meteorology, accepted.

Kauppi, P. E., Tomppo, E., and Ferm, A., 1995. C and N storage in living trees within Finland since 1950s. Plant and Soil 168-169, 633-638.

Kempf, K., Allwine, E., Westberg, H., Claiborn, C., and Lamb, B., 1996. Hydrocarbon emissions from spruce species using environmental chamber and branch enclosure methods, Atmospheric Environment 30(9), 1381-1389.

Lamb, B., Guenther, A., Gay, D., and Westberg, H., 1987. A national inventory of biogenic hydrocarbon emissions, Atmospheric Environment 21, 1695-1705.

Lamb, B., Gay, D., Westberg, H., and Pierce, T., 1993. A biogenic hydrocarbon emission inventory for the U.S.A. using a simple forest canopy model, Atmospheric Environment 27A, 1695-1705.

Lindfors, V., Laurila, T., and Hongisto, M., 1995. Estimation of hydrocarbon emissions from forests in Finland, in: Proceedings of the 10th World Clean Air Congress, Volume 1, Emissions and Control, Tolvanen, M. et al. (Eds.), The Finnish Air Pollution Prevention Society.

Monson, R. K, Lerdau, M. T., Sharkey, T. D., Schimel., D. S., and Fall, R., 1995. Biological aspects of constructing volatile organic compound emission inventories. Atmospheric Environment 29(21), 2989-3002.

Mroueh, U.-M., 1994. Inventory of volatile organic compound (VOC) emissions, 1993. Technical Research Centre of Finland, VTT-Research Notes 1609.

Pierce, T. E. and Waldruff, P. S., 1991. PC-BEIS: A personal computer version of the biogenic emissions inventory system, Journal of the Air and Waste Management Association 41, 937-941.

Pierce, T. E., 1996. Update to PC-BEIS: Release of Version 2.2. U.S. Environmental Protection Agency, Research Triangle Park, NC 27711, U.S.A.

Rinne, J., Hakola, H. and Laurila, T., 1998. Vertical fluxes of monoterpenes above a Scots pine stand in the boreal vegetation zone, Physics and Chemistry of the Earth, accepted.

Rinne, H. J. I., Laurila, T. and Hakola, H., 1999. Measurements of vertical fluxes of VOCs above boreal forests. In P. M. Borrell and P. Borrell (Eds.): Proceedings of EUROTRAC Symposium '98. WITpress, Southampton. In press.

Seufert, G., Bartzis, J., Bomboi, T., Ciccioli, P., Cieslik, S., Dlugi, R., Foster, P., Hewitt, C. N., Kesselmeier, J., Kotzias, D., Lenz, R., Manes, F., Perez-Pastor, R., Steinbrecher, R. Torres, L., Valentini, R., and Versino, B., 1997. The BEMA-project: An overview of the Castelporziano experiments, Atmospheric Environment 31(SI), 5-18.

Schuh, G., Heiden, A. C., Hoffmann, Th., Kahl, J., Rockel, P., Rudolph, J., and Wildt, J., 1997. Emissions of volatile organic compounds from sunflower and beech: dependence on temperature and light intensity, Journal of Atmospheric Chemistry 27, 291-318.

Simpson, D., Guenther, A., Hewitt, C. N., and Steinbrecher, R., 1995. Biogenic emissions in Europe: 1. Estimates and uncertainties, Journal of Geophysical Research 100(D11), 22875-22890.

Simpson, D., Winiwarter, W., Börjesson, G., Cinderby, S., Ferreiro, A., Guenther, A., Hewitt, C. N., Janson, R., Khalil, M. A. K., Owen, S., Pierce, T. E., Puxbaum, H., Shearer, M., Steinbrecher, R., Tarrasón, L., and Öquist, M. G., 1999. Inventorying emissions from nature in Europe, Journal of Geophysical Research, in press.

Solantie, R., 1990. The climate of Finland in relation to its hydrology, ecology and culture. Finnish Meteorological Institute Contributions No. 2, Finnish Meteorological Institute, Helsinki, Finland. 130 p.

Steinbrecher, R., 1994. Emission of VOCs from selected European ecosystems: The state of the art. In: The Proceedings of EUROTRAC Symposium '94, Borrell P. M. et al. (Eds.), SPB Academic Publ., The Hague, 448-454.

Steinbrecher R. and Rabong R., 1994. Emission of terpenoids and C2-C6 hydrocarbons by Norway Spruce: Phytotron experiment and field studies. In: The Proceedings of EUROTRAC Symposium '94, Borrell P. M. et al. (Eds.), SPB Academic Publ., The Hague, 502-505.

Tingey, D. T., Turner, D. P., and Weber, J. A., 1991. Factors controlling the emissions of monoterpenes and other volatile organic compounds. In: Sharkey, T. D., Holland, E. A., and Mooney, H. A. (Eds.), Trace gas emissions by plants. Academic Press, Inc., San Diego, 93-119.