Windstorm effect on forest sources of biogenic volatile organic compound emissions in the High Tatras

S. Bičárová
Geophysical Institute of the Slovak Academy of Sciences[1]

P. Fleischer
Research Station of the Tatra National Park[2]

Abstract: The 19 November 2004 windstorm caused significant forest damage in the High Tatras. The windstorm effect on forest sources of biogenic volatile organic compounds (BVOC) has been studied using BEIS2 series of GLOBEIS model for a domain of square 16 km x 16 km with grid 1 km for periods from July to September in 2004 and 2005, respectively. Differences of total emissions of native species isoprene (ISO), total monoterpenes (TMT), other VOCs (OVC) reflect land use and vegetation structure changes due to windstorm disturbance. The decrease of emissions in range 53–59% is adequate to a 59% reduction of forest vegetation area. Estimates of total BVOC quantity for the considered periods 2004 and 2005 were 606 t (ISO - 164 t; TMT - 242 t; OVC - 201 t) and 275 t (ISO - 67 t; TMT - 113 t; OVC - 95 t), respectively. The uncertainty of the BVOC emission models is substantially larger than for anthropogenic emissions. The improvement of advanced biosphere-atmosphere exchange models includes additional parameters and reproduces the seasonal cycle.

Key words: BVOC emissions, BEIS model, windstorm, forest vegetation, the High Tatras model domain

1. Introduction

Biogenic volatile organic compounds (BVOC) as isoprene and monoterpentes emitted in abundance by forest vegetation play a significant role in

[1] Stará Lesná, 059 60 Tatranská Lomnica, Slovak Republic; e-mail: bicarova@ta3.sk; Web: http://www.ta3.sk/gfu
[2] 059 60 Tatranská Lomnica, Slovak Republic; e-mail: fleischer@vstanap.sk; Web: http://www.vstanap.sk

the tropospheric photochemistry, especially in suburban and rural locations *(Chameides et al., 1992)*. Biogenic VOC are particularly important due to their high reactivity *(Kleinman et al., 2002; Paulson et al., 1997)* and quantity - at global scale they are responsible for 80% of total emissions *(Fowler and Erisman, 2003)*. The measurement and modeling of BVOC are essential for understanding regional and global atmospheric chemistry, carbon cycles, and climate. Emissions modeling systems (GLOBEIS, ENVIRON) and other global models of tropospheric chemistry (GEOS-CHEM) incorporate the algorithm developed by *Guenther et al. (1993)*. The emission rates are a function of the landcover and environmental conditions, which are characterized by user-supplied data using the most updated emissions algorithms *(Guenther et al., 1999a,b)*.

The 19 November 2004 windstorm was a severe weather event that caused considerable damages in the region of the High Tatras. In the evaluated case, wind gusts of speed over 160 km/h (44.4 m/s) were recorded in the southern (lee) slopes of the mountains even at altitudes of 800–1200 m a.s.l. what can be considered as a rare event *(Simon and Vivoda, 2005)*. The windstorm strongly damaged almost one third of the forested area - approximately 12 600 ha of the total 46 000 ha of forest vegetation of the Tatra National Park. The purpose of this paper is to estimate biogenic volatile organic compound emissions and to analyse changes due to windstorm disturbance on forest vegetation.

2. Materials and methods

2.1. Model description

GloBEIS - Global Biosphere Emissions and Interactions System.

The BEIS series of models as product of collaboration of the EPA and the National Center for Atmospheric Research (NCAR) allows users to estimate biogenic emissions of volatile organic compounds, carbon monoxide, and soil NO_x for any scale and domain. GLOBEIS runs in Microsoft ACCESS and the computer code can be downloaded from the web page at www.globeis.com. The BEIS2 estimates normalized biogenic emissions by multiplying the fraction of land use in each grid by the species specific emission factor and the corresponding biomass, and then the normalized

emissions are adjusted for ambient temperature and light levels using the above canopy meteorological parameters *(Guenther et al., 1993)*:
$E = [\Sigma(fE_sD)]\gamma$
where E is the flux of type BVOC emissions to the atmosphere [μgC m^{-2} h^{-1}] related to a unit of ground area; f is the fraction of land use in a grid; Es is the emission factor [μgC g^{-1} h^{-1}] related to dry leaf matter of specific land use class; D is foliar density [g m^{-2}] and means quantity of dry leaf matter specific vegetation for ground area, and γ is a unit-less environmental correction factor representing the effects of short-term (e.g. hourly) temperature (CT) and photosynthetic activate radiation (PAR) changes (CL) on emissions.

For isoprene emission: $\gamma_{ISO} = C_{Liso}C_{Tiso}$,

$$C_{Liso} = \frac{\alpha C_{L1} L}{\sqrt{1+\alpha^2 L^2}}; \qquad C_{Tiso} = \frac{\exp(C_{T1}(T-T_S)/RT_STS)}{1+\exp\left(C_{T2}\left(T-T_M\right)/RT_STS\right)},$$

where α (0.0027) and C_{L1} (1.066) are empirically determined coefficients, and L is the PAR flux [μmol photons m^{-2} s^{-1}]; R is the universal gas constant (8.314 J K^{-1} mol^{-1}), C_{T1} (95 kJ mol^{-1}), C_{T2} (230 kJ mol^{-1}), and TM (314 K) are empirical coefficients, TS (303 K) is the standard leaf temperature, T is the actual leaf temperature. Photosynthetic activate radiation (PAR) calculation is based on the solar zenith/azimuth angle, time of day and cloud fraction. In the case of temperature, it is assumed that leaf temperature is equal to air temperature.

For monoterpene emissions: $\gamma_{MTS} = \exp(\beta(T-T_S))$,
where β (0.09 K^{-1}) is an empirical coefficient based on non-linear regression analysis of numerous measurements present in the literature. The relationship between environmental conditions and emission of OVC is even less understood than the isoprene and monoterpenes. Emissions of some of these compounds, including a group of C6 unsaturated, are strongly influenced by external factors other than light and temperature, such as plant wounding by microbes, insects or mechanical stress. For the parameterization of oxygenated hydrocarbon emission is $\gamma_{OVC} = \gamma_{MTS}$ is recommended.

The BEIS2 allows to assign values for input parameters: isoprene EF Adjustment (1); number of layers modeled within the canopy (5); time zone (-1); selection time period range of hours (0-23), julian days (183–274

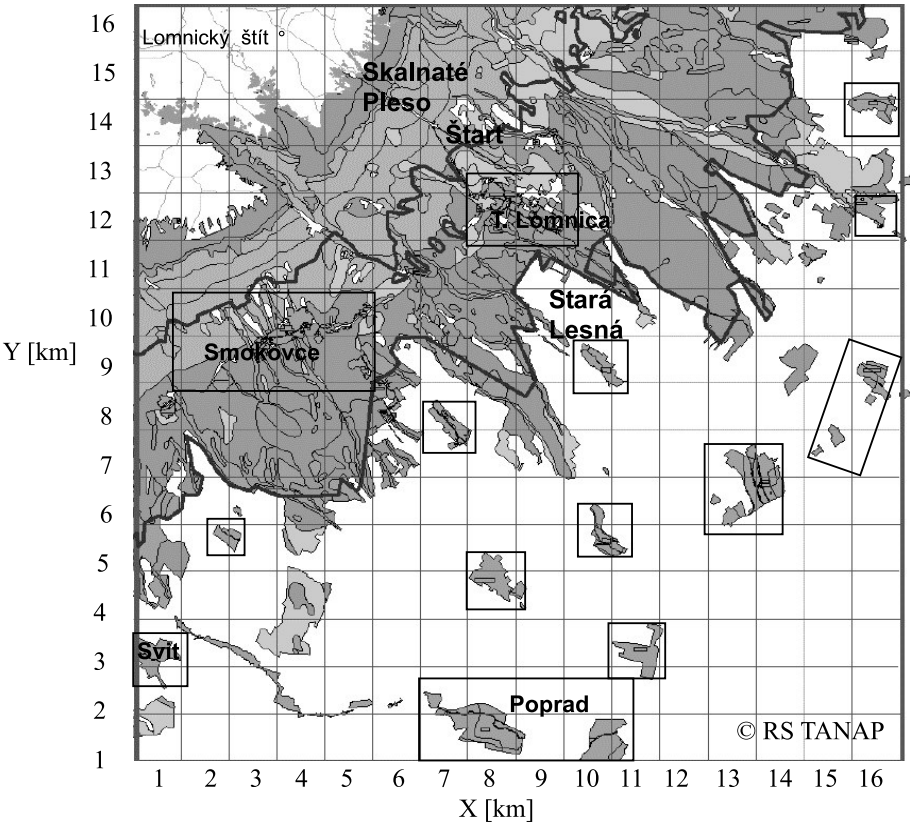

Fig. 1. The High Tatras domain definition area: square 16 km × 16 km; grid 1 km; gradate of grey color – forest vegetation before November 19, 2004 windstorm; solid grey line – border of area affected by windstorm; white color – no forest vegetation; rectangles – urban and rural settlements.

and 182–273, respectively), years (2004 and 2005, respectively) and selection of PAR input: directly or by import of cloud cover data file. Input modules realize import of domain definition, land use, cloud cover and temperatures files. Emissions are calculated for natural species isoprene (ISO), total monoterpenes (TMT) and other VOCs (OVC) in units mgC m^{-2} h^{-1}. The execute and output modules calculate, speciate and export emissions by reports of ISO, TMT and OVC in tons for each hour or each cell.

2.2. Model parameters

2.2.1. Domain definition

The domain definition file specifies a geographic area for which emissions are to be calculated. The High Tatras domain area is square 16 km × 16 km with 1 km grid situated in the central part of the mountain region (Fig. 1). The domain definition file provided five data fields: I-cell (X = 1 to 16 km), J-cell (Y = 1 to 16 km), cell area (1 km^2), cell latitude (49° 20′ N), cell longitude (19° 20′ E).

2.2.2. Land use

The land use (or land cover) file provides information about how the area of each cell is assigned to different land cover categories. Generally, land cover of the High Tatras domain involves forest (spruce, alnus, larix, pine, silver as prevailing types) and other (urban and unknown, assume grass) vegetation. Proportional structure based on GIS RS TANAP data is shown in Fig. 2. From the total area of 256 km^2 the forest vegetation covered 102 km^2 (40%) before and 42 km^2 (16.4%) after November 19, 2004 windstorm. The vegetation types (for BEIS2 coded as vegib2) are defined by isoprene, total monoterpenes and other VOC emission factor, LAI - leaf area index and LMD - leaf mass density (Table 1). The land was defined for every cell listed in the domain definition file and required four fields: I-cell, J-cell, land use code (LU code), and fraction of the cell covered by that LU code.

2.2.3. Meteorological factors

Hourly values of cloud cover and air temperature for periods from July to September in 2004 (A – before windstorm) and 2005 (B – after windstorm), respectively, were used. Data are included in measurement databases of the meteorological observatories GPI SAS at Stará Lesná and Skalnaté Pleso *(Ostrožlík, 2005; Ostrožlík, 2006)* and at meteorological station T. Lomnica – Štart (Štart) of ILTER (Fig. 1). The interpolation of cloud cover and air temperature values for each cell of model domain was based on topographical properties (altitude) and air temperature vertical gradient changes. Comparison of meteorological factors between A and B indicates less suitable cloudiness (Fig. 3) and positive temperature (Fig. 4) environment conditions in 2005 than 2004 for BVOC emissions.

Forest vegetation		Area [km^2]		Fraction [%] of forest vegetation area		Fraction [%] of total domain area	
		A	B	A	B	A	B
1	Norway spruce *(Picea abies)*	62.0	25.9	60.8	61.7	24.2	10.1
2	Pine (*Pinus sylvestris, cembra, mugo)*	17.7	7.7	16.7	18.3	6.7	3.0
3	European alder *(Alnus glutinosa)*	14.5	3.8	14.7	9.1	5.9	1.5
4	European larch *(Laryx decidua)*	4.9	3.3	4.9	7.8	1.9	1.3
5	Silver Fir *(Abies)*	2.8	1.3	2.9	3.1	1.3	0.5
Total		101.9	42.0	100	100	40.0	16.4

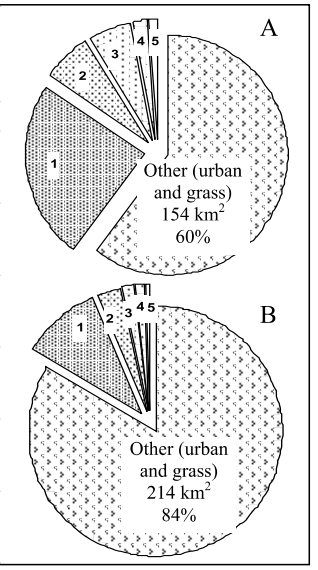

Fig. 2. Structure of the forest vegetation fraction of the High Tatras model domain: A – before windstorm; B – after windstorm.

Table 1. Vegetation code characteristics *(Guenther et al., 1993)*

LU - vegib2	Name	Emission factor [μgC m^{-2} h^{-1}]			Leaf area index LAI [m^2 m^{-2}]	Leaf mass density LMD [g m^{-2}]
		ISO	TMT	OVC		
Forest vegetation						
98001 - Abie	Abies (fir)	170	5100	2775	7	1500
98008 - Alnu	Alnus (European alder)	43	43	694	5	375
98052 - Lari	Larix (larch)	43	43	694	5	375
98077 - Pice	Picea (spruce)	23800	5100	2775	7	1500
98078 - Pinu	Pinus (pine)	80	2380	1295	3	700
Other						
98117- urba	Urban (.2 grass/.2 forest)	409	162	201	4	108
98070- othe	Other (unknown, assume grass)	56	141	84	4	150

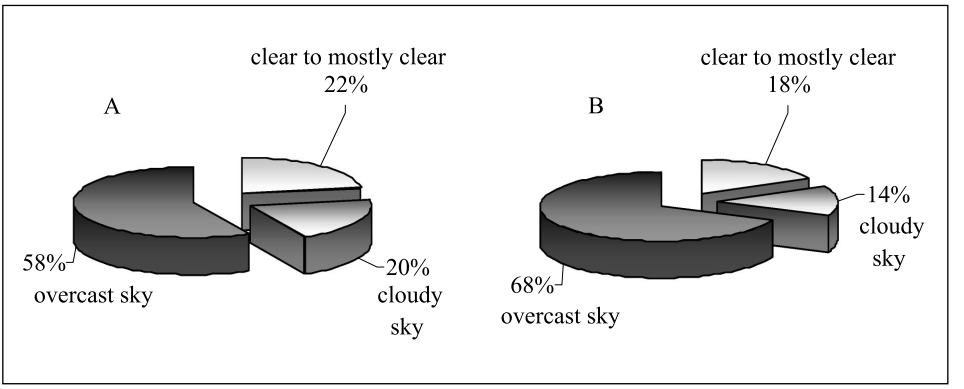

Fig. 3. Frequency of cloudiness day [%] after categories based on cloud fraction of sky cover: clear to mostly clear (N < 2/10); cloudy sky (2/10≤N≤8/10); overcast sky (N > 8/10) for the High Tatras region and periods: A – before windstorm, B – after windstorm.

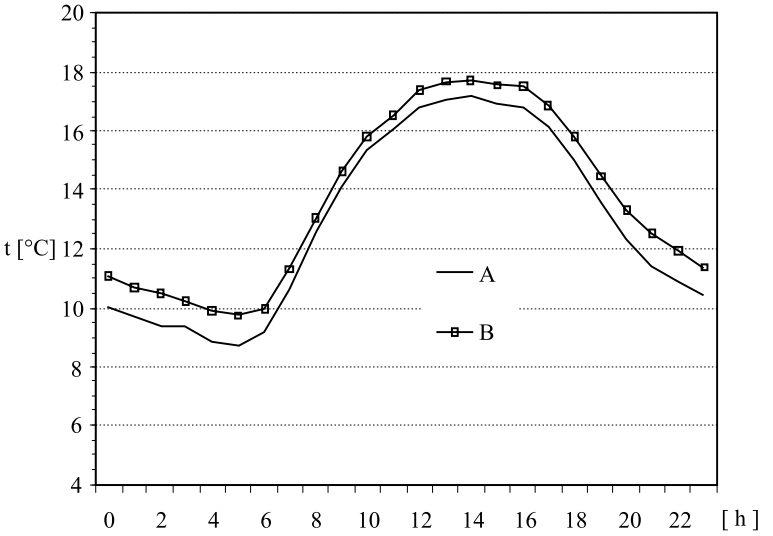

Fig. 4. Daily course of air temperature [° C] for the High Tatras model domain and periods: A – before windstorm, B – after windstorm.

3. Results and discussion

Maps of total BVOC emissions (sum of isoprene, total monoterpenes and other VOCs) using BEIS2 results and natural neighbor interpolation

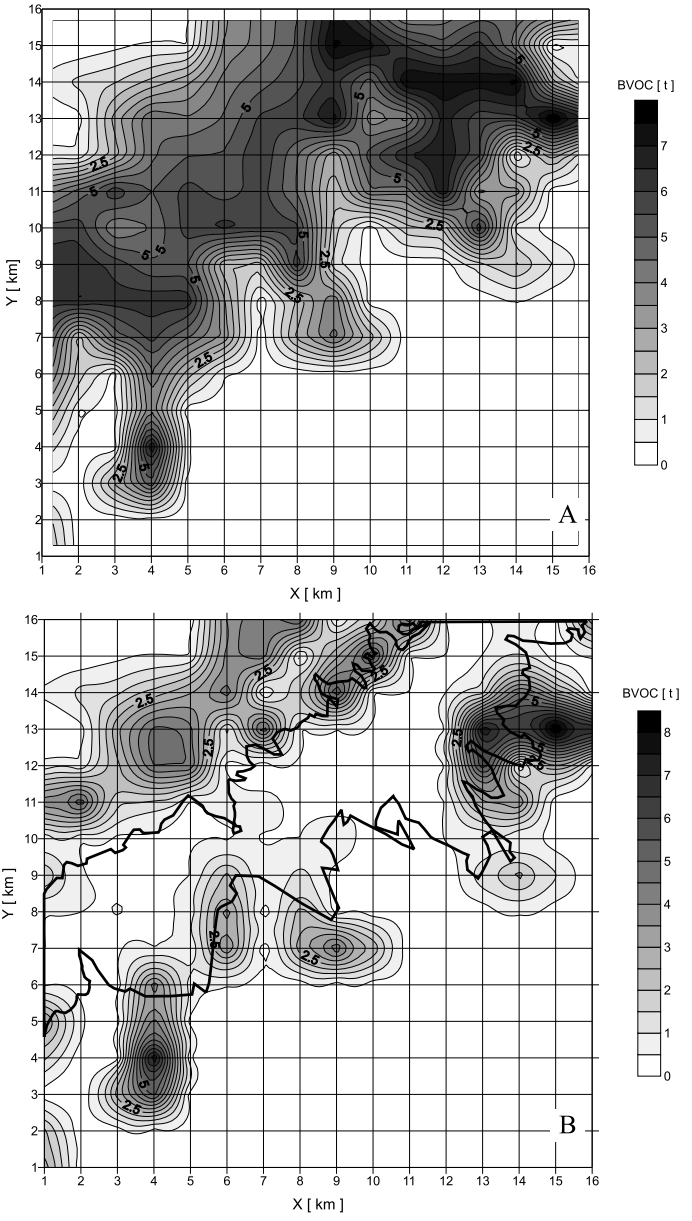

Fig. 5. Spatial distribution of total BVOC emissions (isoprene, total monoterpenes and other VOC) for the High Tatras model domain of periods: A – before windstorm, B – after windstorm (solid black line – border of damaged forest area).

Fig. 6. Variability of daily flux of estimate emissions [mg m^{-2} d^{-1}] for isoprene (ISO), total monoterpenes (TMT) and other volatile organic compound (OVC) emitted by area of the High Tatras model domain for periods: A – before windstorm, B – 2005 after windstorm.

method of Surfer software were generated (Fig. 5). Reduction of BVOC emissions for damaged area approximately from level of 3-7 tons (A) to level of 0–3 tons (B) reflect land use and vegetation structure changes due to November 19, 2004 windstorm. Variability of estimate ISO, TMT, OVC natural emissions daily fluxes (Fig. 6) also indicates evident lower values during the considered period in 2005. While emission extremes reached 12-20 mg m^{-2} d^{-1} before the windstorm (A) on the other hand a rapid decrease to 8-10 mg m^{-2} d^{-1} in spite of temperate favourable temperature environment conditions (Fig. 4) after windstorm (B) occurred. The results are within the right order of magnitude of various model calculations and field measurements of biogenic emission fluxes *(Guenther et al., 2006; Lee et al., 2005; Ruuskanen et al., 2005)*. The total quantity of BVOC for period A and B was 606 t (ISO-164 t; TMT-242 t; OVC-201 t) and 275 t (ISO-67 t; TMT-113 t; OVC-95 t), respectively (Fig. 7). The decrease of emissions in the range of 53–59% is adequate to the reduction (59%) of the forest vegetation area (Fig. 2).

The results (Fig. 7) showed that monoterpenes with a contribution about of 40% were the main component of the BVOC emitted from the domain. Although many types of monoterpenes exist, most plants release only 2-3 major species, with the reactive α-pinene often dominating the emissions from species such as the Norway spruce *(Janson, 1993)*. The ratio of one compound to another is very variable, both with season and temperature, so it is very difficult to specify the speciation in a quantitative way. Table 2 includes the ratios of several monoterpenes to total monoterpenes obtained from *(Guenther et al., 1999b, 2003)* and the emission contribution of selected species. The main components α-pinene, β-pinene, 3-carene represent more than 60% of total monoterpenes. The quantity of monoterpenes after the windstorm decreased by about 53%: from 68.2 to 32.0 t (α-pinene), from 49.2 to 23.1 t (β-pinene), from 30.1 to 14.1 t (3-carene). The identification and quantification of OVC is also a demanding task due to the content of a wide variety of compounds, many of which have been difficult to measure. The conversion of OVC emissions to output VOC species using the VOC speciation scheme described by *Guenther et al. (1999a; 2003)* is also shown in Table 2. The OVC reduction of 53% for dominant species: methanol (from 100.5 to 47.5 t), ethanol (from 12.1 to 5.7 t), acetone (from 20.1 to 9.5 t), ethene and acetaldehyde (from 10.1 to 4.8 t), propene (from

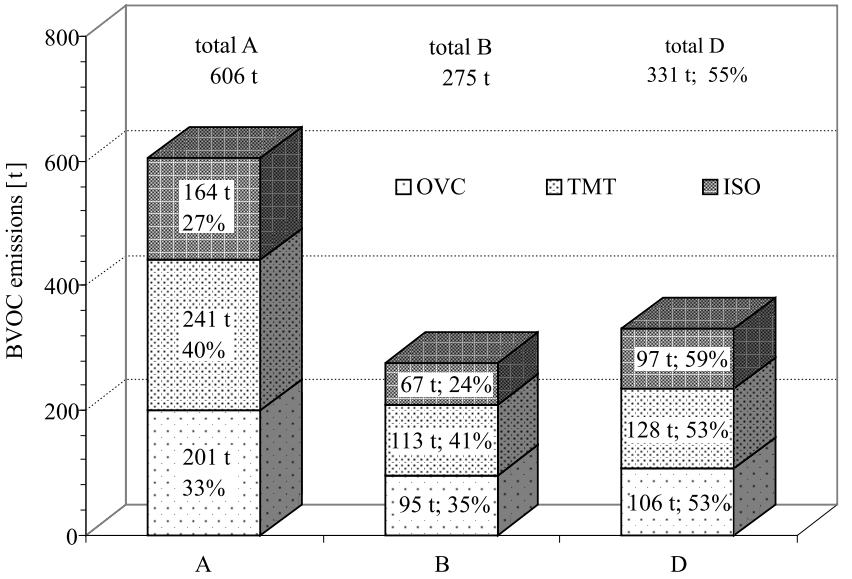

Fig. 7. Summary of estimate isoprene (ISO), total monoterpenes (TMT), other volatile organic compound (OVC) BVOC emissions [t] for the High Tatras domain and periods: A – before windstorm, B – after windstorm, D - decrease B [t] in relation to A [%].

8.0 to 3.8 t) was calculated.

A frequently discussed issue associated with BVOC model calculation is the substantially larger uncertainty of estimates compared to anthropogenic emissions. However, the validation of model results of this study is not possible due to absent field measurements. The semiempirical BVOC model based on similar driving parameter as BEIS2 applied to forests in Poland and tested by the Monte Carlo method shows an uncertainty of -71% to 73% (isoprene), -57% to 140% (monoterpenes) and -55% to 57% (OVC) *(Smiatek and Bogacki, 2005)*. The improvement of the methodology was incorporated into modified version of BEIS2 in the canopy light model by specification of extinction (used to estimate decreases in PAR within the canopy) and cosla (the cosine of the mean leaf angle) coefficients. Advanced biosphere-atmosphere exchange models include additional parameters and reproduce the seasonal cycle *(Guenther, 2000)*.

Table 2. Species assignment of monoterpenes and other volatile organic compound emissions [t] for the High Tatras model domain and periods: A – before windstorm, B – after windstorm

Monoterpene emissions				Other volatile organic compound emissions			
Species name	Fraction	A [t]	B [t]	Species name	Fraction	A [t]	B [t]
α-pinene	0.283	68.2	32.0	methanol	0.50	100.5	47.5
β-pinene	0.204	49.2	23.1	ethanol	0.06	12.1	5.7
3–carene	0.125	30.1	14.1	acetone	0.10	20.1	9.5
sabinene	0.073	17.6	8.2	butanone	0.02	4.0	1.9
d-Limonene	0.066	15.9	7.5	ethane	0.01	2.0	1.0
B-phellandrene	0.053	12.8	6.0	hexenyl acetate	0.03	6.0	2.9
r-cymene	0.040	9.6	4.5	ethene	0.05	10.1	4.8
myrcene	0.026	6.3	2.9	hexenal	0.03	6.0	2.9
camphene	0.013	3.1	1.5	hexenol	0.03	6.0	2.9
camphor	0.013	3.1	1.5	acetaldehyde	0.05	10.1	4.8
bornyl acetate	0.013	3.1	1.5	propene	0.04	8.0	3.8
α-thujene	0.013	3.1	1.5	butene	0.02	4.0	1.9
terpinolene	0.013	3.1	1.5	formaldehyde	0.02	4.0	1.9
α-terpinene	0.013	3.1	1.5	hexanal	0.02	4.0	1.9
γ-terpinene	0.013	3.1	1.5	acetic acid	0.01	2.0	1.0
ocimene	0.013	3.1	1.5	formic acid	0.01	2.0	1.0
1,8-cineole	0.013	3.1	1.5				
piperitone	0.013	3.1	1.5				
Total	1.000	241.0	113.0	Total	1.00	201.0	95.0
Difference (A - B) in relation to A : - 53.1%				Difference (A-B) in relation to A : - 52,7%			

4. Conclusions

In the present study, estimations of BVOC emissions for the High Tatras region before and after the 19 November 2004 windstorm using BEIS2 series of GLOBEIS model were calculated. The land cover of the model domain (16 km × 16 km, 1 km grid) involves forest (spruce, alnus, larix, pine, silver as prevailing types) and other (urban and unknown, assume grass) vegetation. The forest vegetation covered 102 km^2 (40%) before and 42 km^2 (16.4%) after the windstorm. Meteorological factors indicate less suitable cloudiness and more positive temperature environment conditions in 2005 than in 2004 for the BVOC emissions.

Differences of total emissions for native species isoprene (ISO), total

monoterpenes (TMT), other VOCs (OVC) reflect the land use and vegetation structure changes due to the windstorm disturbance. The estimation of the total quantity before and after the windstorm were 606 t (ISO - 164 t; TMT - 242 t; OVC - 201 t) and 275 t (ISO - 67 t; TMT - 113 t; OVC - 95 t), respectively. A decrease of emission production range between 53 and 59% is adequate to the reduction of the forest vegetation (59%). The dominant component of BVOC is a group of monoterpenes ($\sim$ 40%).

The uncertainty of BVOC emission models based on similar algorithm as BEIS2 is substantially larger than for anthropogenic emissions. The improvement of the advanced biosphere-atmosphere exchange models involves the inclusion of additional parameters and the reproduction of the seasonal cycle.

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