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THE CONTRIBUTION OF OCCULT PRECIPITATION TO SULPHUR DEPOSITION IN THE CZECH REPUBLIC

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With 8 figures and 2 tables
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Summary: We present a spatial estimation of the contribution of occult precipitation to the true atmospheric sulphur deposition across the territory of the Czech Republic. Our estimation is based on differences in two spatially explicit, data driven geo-statistical deposition models for forested areas: 1. a throughfall sulphur deposition model and 2. a sulphur deposition model calculated from dry plus wet-only deposition (often referred to as the "total" deposition). The sulphur deposition maps for Czech forested areas at 1x1 km resolution are presented and the dependence of the contribution of occult precipitation to sulphur deposition on altitude is assessed. All available data on precipitation chemistry at disposal, results of wet-only, bulk and throughfall measurements were compiled. Our preliminary results based on geo-statistical modelling indicate that the contribution of occult precipitation to sulphur deposition is significant, varies in a wide range, and is dependent on altitude. On 68% of the Czech forested area, the occult deposition in 2008 ranged between 0–0.5 $g.m^{-2}.year^{-1}$, on 25% between 0.5–1 $g{\cdot}m^{-2}{\cdot}year^{-1}$, on 3.5% between 1–1.5 $g{\cdot}m^{-2}{\cdot}year^{-1}$, and on 0.7% it was more than 1.5 $g{\cdot}m^{-2}{\cdot}year^{-1}$. In relative terms, in 2008 the occult precipitation contribution to sulphur deposition over the Czech forested area was up to 200% of wet plus dry deposition estimates in 99% of the grid cells, and in the remaining 1% of the grid cells it even ranged between 200–400%. Across ca. 50% of the Czech forested area 50–100% of sulphur deposition was contributed by occult precipitation. Our results indicate that when using the maps of the "total deposition" derived from wet and dry deposition without accounting for occult deposition (which is hitherto a common approach), we are likely to substantially underestimate the true atmospheric deposition and consequently its possible impacts on ecosystem health. The approach and the weaknesses that still remain are discussed. The presented results are rough estimations but can be considered the best available at the moment for the Czech Republic.

Zusammenfassung: Wie präsentieren einen räumlichen Ansatz zur Abschätzung des Einflusses von Nebelniederschlägen auf den tatsächlichen Eintrag von Schwefel im Gebiet der Tschechischen Republik. Unsere Abschätzung basiert auf den Unterschieden zwischen zwei geostatistischen Modellierungen für den Schwefeleintrag bewaldeter Areale: 1. einem Bestandniederschlag-Eintragsmodell und 2. einem Schwefeleintragsmodell basierend auf kombinierten Werten der Trocken- und Nassdeposition. Karten der Schwefeldeposition in Tschechien mit einer Rasterzellengröße von 1x1 km werden für die bewaldeten Gebiete präsentiert und die Bedeutung der Nebelniederschläge auf den Schwefeleintrag in Abhängigkeit von der Höhe abgeschätzt. Dabei wurden alle verfügbaren unterschiedlichen Niederschlagsdaten und chemischen Analysen zusammengetragen und berücksichtigt. Unsere vorläufigen, auf geostatistischer Modellierung beruhenden Modellierungen, deuten daruf hin, dass die Nebelniederschläge signifikanten Einfluss auf die Menge der Schwefeldeposition haben und dass ein deutlicher Zusammenhang mit der Höhenlage besteht. In 68% der bewaldeten Gebiete in Tschechien lag der Schwefeleintrag 2008 bei 0–0,5 $g{\cdot}m^{-2}$ $Jahr^{-1}$ auf 0,7% der Fläche über 1,5 $g{\cdot}m^{-2}$ $Jahr^{-1}$. Relativ betrachtet lag damit der Schwefeleintrag durch Nebelniederschlag in 99% der betrachteten Rasterzellen bis zu 200% über der modellierten Gesamttrocken- und nassdeposition und bei dem restlichen 1% der Rasterzellen gar 200–400% darüber. Unsere Ergebnisse zeigen, dass das bisher übliche Verfahren der räumlichen Schwefeldeposition-Modellierung ohne die Berücksichtigung der Nebelniederschlagseinträge zu einer Unterschätzung der Schadstoffeinträge und der daraus folgenden ökosystemaren Auswirkungen führt. Obwohl der vorgestellte Ansatz durchaus noch Unsicherheiten aufweist und somit zunächst nur grobe Abschätzungen erlaubt, kann er als der momentan realistischste Modellierungsansatz der Schwefeldeposition für Tschechien angesehen werden.

Keywords: True atmospheric deposition, geo-statistical modelling, spatial deposition, patterns, forested area, sulphur

1 Introduction

Accurate determination of the atmospheric deposition of a chemical species is a key issue for identifying regions with deposition that are in excess of the amount expected to cause environmental damage (Brook et al. 1999). True atmospheric deposition consists of dry deposition, wet deposition by precipitation and occult deposition (fog, low cloud, dew, rime, hoarfrost). The quantification of the respective

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components significantly differs regarding the complexity, difficultness and reliability of the resulting deposition value. Wet deposition is relatively easily measured and assessed (Krupa 2002), while there is no widely accepted technique for measuring dry deposition. Hence, it is estimated using different, usually elaborate modelling approaches (Wesely and Hicks 2000; Kumar et al. 2008). Out of the three components, occult deposition is by far the most difficult to quantify (e.g., Krupa 2002; Klemm and Wrzesinsky 2007).

Deposition of sulphur has been attentively studied in Europe (Vestreng et al. 2007) and elsewhere in the long run due to its detrimental effects on the ecosystem health. Sulphur dioxide (SO_2) emitted from different sources is oxidised in the atmosphere to sulphates (SO_4^{2-}). Regarding the species lifetime, it is obvious that while SO_2 concentrations are affected by local or nearby sources, SO_4^{2-} concentrations are more attributable to regional air pollution transport (Seinfeld and Pandis 1998; Myles et al. 2009). Almost the entire sulphur deposition from the atmosphere is transferred to the forest floor in the form of SO_4^{2-} contained in the throughfall (Stachurski and Zimka 2002). Sulphur plays an important role in the biogeochemistry of forests as an essential plant nutrient and is indispensable for many reactions in the living cell. However, an increase in sulphur deposition cannot be considered as universally beneficial for ecosystems, particularly to the ones poorly buffered against an increase in acidity (Kravitz et al. 2009). Moreover, the sulphur cycle is closely interconnected with biogeochemical cycles of all major and some minor elements (Lindberg and Lovett 1992) and of the major elemental cycles it is one of the most heavily perturbed by human activity (Charlson et al. 2000).

SO_2, from the combustion of low-quality local lignite with high contents of sulphur, was apparently the principal ambient air pollutant in former Czechoslovakia through the 1960s–1980s (Moldan and Schnoor 1992). The high SO_2 levels were recognized as a co-factor of forest decline in Central Europe (Fanta 1997) with the worst manifestation in the former "Black Triangle", the highly industrialised region at the border of Czechoslovakia, Germany and Poland. After the profound socio-economic changes in Central Europe in the 1990s, the SO_2 emissions were substantially reduced. While the reduction in most European countries accounted for ca. 60% between 1990 and 2004 (Vestreng et al. 2007), it was even nearly 90% over the Czech Republic (CR) as reported by Hůnová et al. (2004), and resulted in a corresponding decrease in ambient SO_2 levels, and a somewhat less substantial decrease in SO_4^{2-} concentrations in precipitation and deposition of sulphur (Hůnová et al. 2004). Nevertheless, in spite of the fact that the air quality has considerably improved since the early 1990s, which was accompanied by a decreased average ionic content, the ion concentration in fog water still remains high as reported, e.g., for Saxony in Germany (Lange et al. 2003).

The air pollution and precipitation chemistry has been monitored over the Czech territory for a long while and maps of atmospheric deposition are regularly published (Ostatnická 2009). The contribution of the occult deposition has so far been neglected, however. The chemistry of occult precipitation is measured only at few sites in the CR (Fisak et al. 2002) and so the data that are available have very limited use for spatial estimation of the contribution of occult precipitation to deposition of ambient air pollutants. Nevertheless, it is widely accepted that the contribution of the occult precipitation is likely to account for a substantial portion of the total atmospheric deposition both regarding its quantity and quality, particularly at elevated sites (Aleksic et al. 2009; Bridges et al. 2002; Thalmann et al. 2002; Zimmermann and Zimmermann 2002) and can lead to significant fluxes locally (Seinfeld and Pandis 1998).

The efficiency of occult precipitation varies significantly from site to site depending on many factors such as altitude, aspect, the relative height of a windward slope, and the screening effect of surrounding relief. The highest potential efficiency of occult precipitation has been observed at high elevated slopes and ridges exposed to humid air masses with lowlands at the windward side (Sobik and Blas 2008). The phenomenon referred to as the "edge effect" further contributes to the high variability in occult deposition locally. The trees on the edge of the forest stand, well exposed to the wind, are much more efficient in collecting occult precipitation than the trees inside the forest (Weathers et al. 1995; Sobik and Blas 2008).

We present an approach for providing a spatial estimation of the contribution of the occult precipitation to the true atmospheric sulphur deposition across the territory of the CR, based on differences in two deposition models for forested area: 1. the throughfall sulphur deposition model and 2. the sulphur deposition model calculated from dry plus wet-only sulphur deposition. A map showing the difference between the two models in S deposition for Czech forested areas in 1x1 km resolution for 2008 is presented and its dependence on altitude is assessed.

2 Study area, data and methods

This paper presents our analysis for the Czech forested area, which accounts for ca. 33% (representing 26 430 km^2) of the entire surface area. Norway spruce (*Picea abies*), an important timber tree, is the dominant species covering nearly 48% of the total forested area. Pine trees (*Pinus spp.*), with 14%, rank second. The coniferous forests account for 67% of the Czech forested area. Oak (*Quercus spp.*) with 7.4% and beech (*Fagus sylvatica*) with 7.2% are the most common deciduous species (Úhúl 2007).

We collated all available data on precipitation chemistry which were available. Figure 1 presents the atmospheric deposition sampling sites; we used 19 wet-only, 30 bulk and 26 throughfall sites. The sites for monitoring precipitation chemistry are distributed unevenly across the CR. The highest density of sites is in the border mountains, particularly in the northern and western portions and in the Czech-Moravian uplands. Apart from the sites included in the national ambient air quality monitoring network run by the Czech Hydrometeorological Institute (CHMI), we also used the data from sites operated by the Czech Geological Survey, Forestry and Game Management Research Institute and T.G. Masaryk Water Research Institute. For improving the interpolation in border region we used the data provided by the German LfULG and Polish WIOS and IMGW.

2.1 Sulphur deposition

2.1.1 Wet-only sulphur deposition

Automated wet-only samplers (Fig. 2) that were placed in open areas and operated on weekly/daily basis provided the concentration of SO_4^{2-} in rain and snow. These data are supported by the measurements of bulk samplers operating on a monthly basis. The concentration of SO_4^{2-} was determined by ion chromatography. The bulk S/SO_4^{2-} data were corrected using the empirical factor of 0.83 derived from collocated samplers to enable merging of the results of wet-only and bulk samplers. The spatial pattern of the wet-only deposition was derived from the annual mean concentration of S/SO_4^{2-} measured at individual sites monitoring the chemical composition of precipitation and annual precipitation totals recorded at 750 precipitation gauging sites by standard gauges.

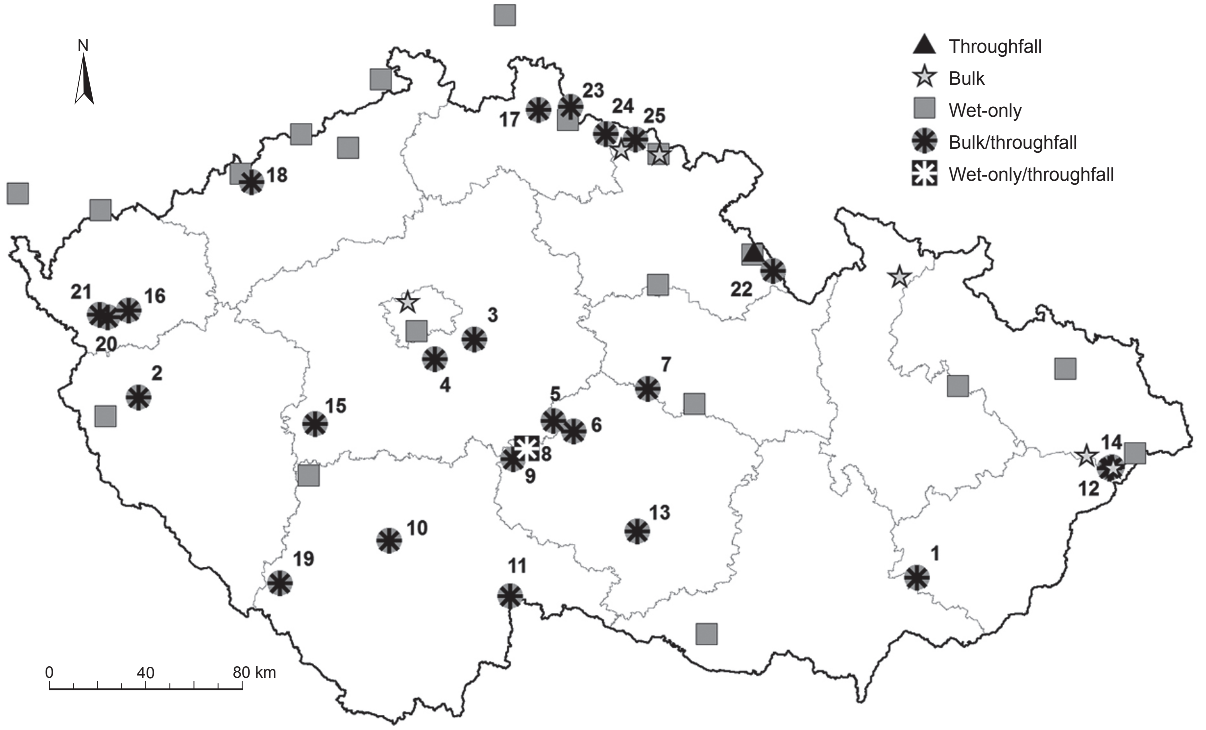

Fig. 1: Monitoring network of the atmospheric deposition, 2008. The sites which are numbered measure both throughfall and bulk/wet-only deposition and were used for estimation of the contribution of occult precipitation to sulphur deposition presented in table 1

Fig. 2: Wet-only sampler, site Kocelovice

2.1.2 Throughfall sulphur deposition

The throughfall deposition is measured under the forest canopy. It is a relatively simple and economically feasible method, well applicable in a complex terrain. 26 monitoring sites across the CR sample throughfall (Fig. 3); most of the sites are situated in the spruce forests, two are in oak, one in pine and one in beech forests. The precipitation amount of throughfall in winter is measured volumetrically by buckets. For developing the spatial pattern of the throughfall deposition of S/SO_4^{2-}, the field of annual precipitation totals is corrected by the empirical coefficient derived as a ratio between the water quantity (precipitation volume) in throughfall and bulk samples for individual sites.

2.1.3 Dry sulphur deposition

We calculated the dry sulphur deposition from the field of annual mean concentration of SO_2 and SO_2 deposition velocity of 0.7 $cm \cdot s^{-1}$ (0.35 $cm \cdot s^{-1}$) for forested (unforested) areas. SO_2 is measured by UV fluorescence (at stations measuring in real-time) and by West-Gaeke or ion chromatography techniques (at manually operated sites).

2.2 Model/map

For elucidation of preparing the two deposition models, we present the scheme with all the input maps used to create Model 1 corresponding to the throughfall deposition and Model 2 corresponding to the dry plus wet-only deposition, often referred to as the "total" deposition (Fig. 4). The maps of S/SO_4^{2-} concentrations in throughfall and wet-only/bulk, as well as the map of throughfall/bulk water quantity ratio, were prepared using the Inverse Distance Weighted (IDW) spatial interpolation technique (e.g., Isaaks and Srivastava 1989). The network for monitoring the precipitation chemistry is sparse. Therefore the spatial interpolation was run in two steps. The values resulting from the first run were extracted to the regular 20 x 20 km point network and the secondary interpolation round was applied on the newly generated regular network 1 x 1 km for smoothing purposes. In contrast, the network measuring the precipitation totals is fairly dense (750 sites) so it was possible to apply more sophisticated interpolation method, the universal linear kriging taking into account the dependence of precipitation totals on altitude (Tolasz et al. 2007). The field of annual mean SO_2 concentration was constructed based on IDW interpolation of the values recorded at 117 measuring sites in combination with the Gaussian dispersion model SYMOS 97 (EEA 2010), a reference modelling method in the CR, calculating the concentrations using the detailed emission inventories for the CR and relevant meteorological data (Ostatnická 2009). The SO_2 map was derived using assimilation

Fig. 3: Throughfall sampling, site Košetice

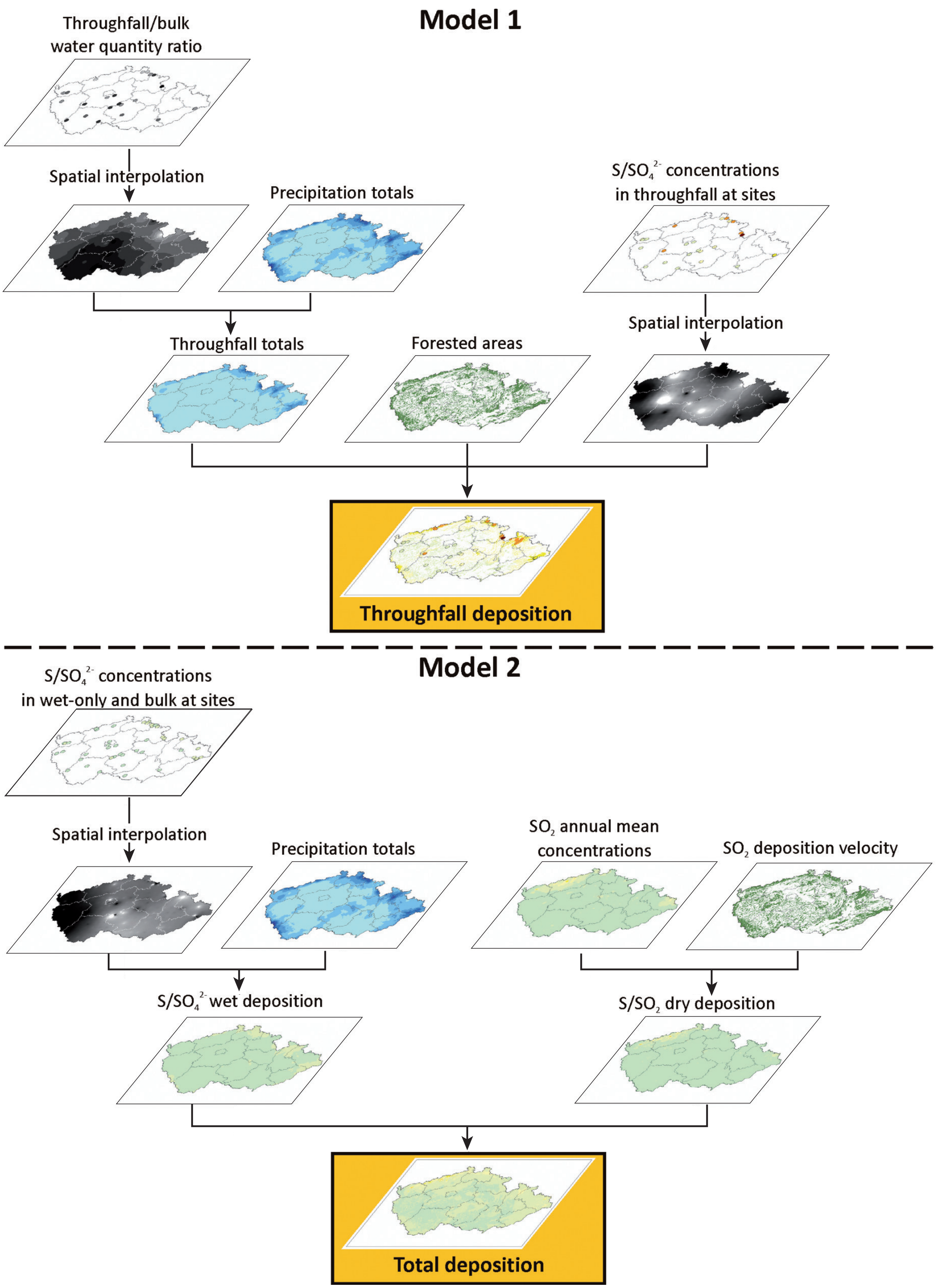

Fig. 4: Diagram showing the inputs into the Model 1 and Model 2

of measured and modelled data with subsequent interpolation of residuals. All maps were prepared with the ArcGIS Geostatistical Analyst (Johnston et al. 2001).

2.3 Dependence of sulphur deposition difference on altitude

The relation between the difference in sulphur deposition between the two models at 1 x 1 km resolution (n = 26,479 cells) was assessed by linear regression.

3 Results

The information about the role played by the occult precipitation in water as well as chemical input based on the measurements at individual sites, ranked according to the altitude, is given in table 1. Records from 25 sites measuring both throughfall and bulk/wet-only deposition are presented. The contribution of occult precipitation to sulphur deposition varies widely among the sites.

Figure 5 shows the annual throughfall deposition of sulphur S/SO$_4^{2-}$ (Model 1), figure 6 presents the annual deposition of sulphur calculated from dry and wet deposition (Model 2). The difference between the two models, reflecting the contribution of occult deposition, is presented in figure 7. On 68% of the Czech forested area, the occult deposition in 2008 ranged between 0–0.5 g·m^{-2}·year^{-1}, on 25% between 0.5–1 g·m^{-2}·year^{-1}, on 3.5 between 1–1.5 g·m^{-2}·year^{-1}, and on 0.7% it was above 1.5 g·m^{-2}·year^{-1}. On ca. 3% of the Czech forested area, the difference between the two models was less than 0 g·m^{-2}·year^{-1}. These negative values are an artefact. Figure 8 shows the relation between sulphur deposition attributed to occult precipitation and altitude.

4 Discussion

It is evident there are many uncertainties linked to estimating individual components of atmospheric

Tab. 1: Precipitation amounts and sulphur deposition measured at the individual sites, 2008 annual values

	Site		Precipitation amount [mm]			Sulphur deposition [g·m^{-2}]				
		Altitude [m a.s.l]	Throughfall (TH)	Outside the forest (O)	Difference TH-O [%]	Throughfall (TH)	Wet only	Dry	Total (T)	Difference TH-T [%]
1	Buchlovice	350	379	591	36	0.6	0.4	0.3	0.7	-17
2	Benešovice	385	484	663	27	0.6	0.3	0.3	0.6	0
3	Lesní potok	400	282	566	50	0.9	0.2	0.4	0.7	22
4	Březka	435	390	492	21	0.5	0.3	0.4	0.7	-40
5	Želivka	440	328	562	42	0.6	0.4	0.3	0.7	-17
6	Loukov	500	439	589	25	1.2	0.4	0.1	0.6	50
7	Polomka	512	572	771	26	1.3	0.3	0.2	0.6	54
8	Košetice	535	265	505	48	0.9	0.2	0.1	0.3	67
9	Salačova Lhota	557	271	550	51	0.9	0.7	0.3	0.9	0
10	Kamýk-Všeteč	593	395	573	31	0.5	0.3	0.2	0.5	0
11	Vojířov-Lásenice	595	418	771	46	0.9	0.5	0.2	0.7	22
12	Červík	640	795	970	18	1.1	0.4	0.2	0.6	45
13	Nová Brtnice	640	411	633	35	1.5	0.4	0.2	0.7	53
14	Klepačka	650	948	1180	20	1.6	0.6	0.2	0.8	50
15	Litavka	710	380	669	43	2.1	0.2	0.2	0.4	81
16	Pluhův bor	753	561	812	31	0.9	0.3	0.2	0.5	44
17	Uhlířská	780	1046	1243	16	1.5	0.7	0.4	1.1	27
18	Jezeří	820	681	780	13	2.8	0.4	1.1	1.6	43
19	Na lizu	828	528	895	41	0.7	0.3	0.2	0.5	29
20	Lysina	867	772	1033	25	0.6	0.5	0.2	0.7	-17
21	Lazy	875	714	813	12	1.4	0.4	0.2	0.7	50
22	U dvou louček	880	1366	1186	-15	4.8	0.6	0.2	0.8	83
23	Jizerka	910	1275	1312	3	2	1	0.3	1.3	35
24	Mísečky	940	1362	1740	22	1.1	0.9	0.2	1.2	-9
25	Modrý potok	1010	1084	1877	42	2.4	0.5	0.2	0.7	71

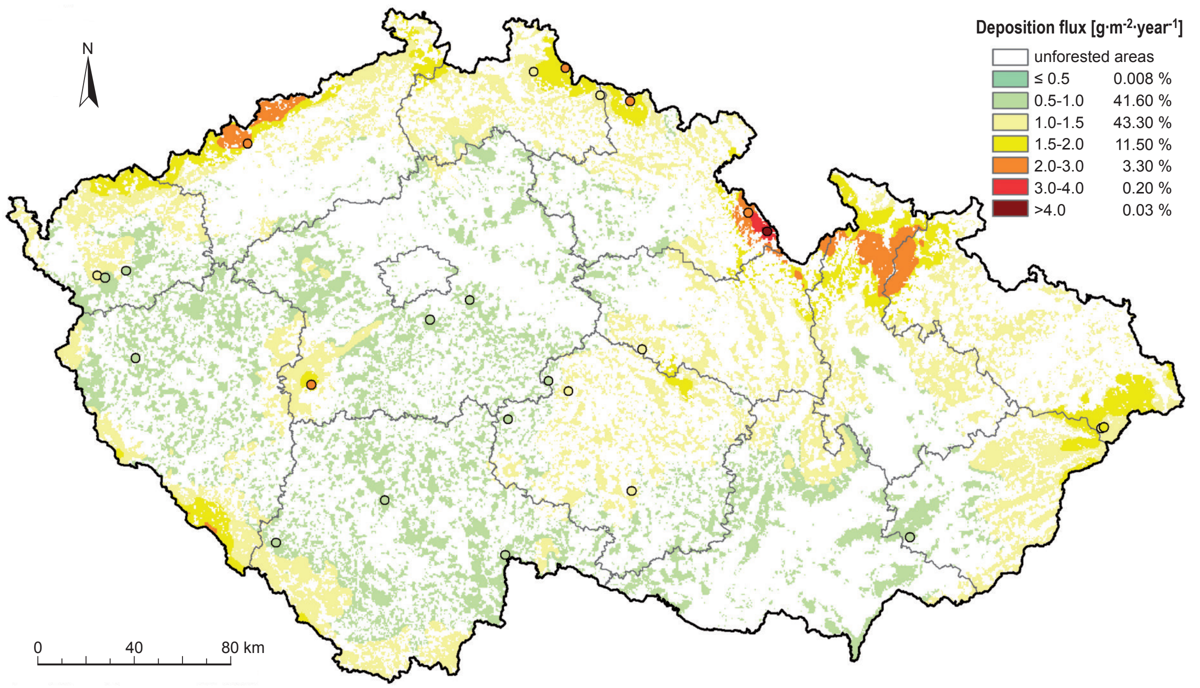

Fig. 5: Annual throughfall deposition of sulphur (Model 1) for forested area, 2008

deposition. We can reasonably assume that the highest uncertainties are in modelling dry deposition, particularly in dry deposition velocity. The deposition velocity varies temporally and spatially and depends on underlying surface type, meteorological conditions, season and time of day (Brook et al. 1997). The deposition velocity is measured experimentally using technically demanding micrometeorological methods (Baldocchi et al. 1988). The practical way of quantifying the dry deposition is the application of inferential models (Brook et al. 1997). The deposition velocity for SO_2 ranges between 0.1–4 $cm{\cdot}s^{-1}$ depending on the type of surface (Brook et al. 1999). The highest values are reported over water surfaces; for coniferous forests, the velocity ranges between 0.1–2.5 $cm{\cdot}s^{-1}$ (Tab. 2).

The value of 0.7 $cm{\cdot}s^{-1}$ for forested areas, which we used in our calculations, corresponds to the value reported for coniferous forests in Netherlands (Erisman 1994). It is obvious that using one value across all Czech forested area is a significant simplification and even a minor change in used deposition velocity value is likely to result in substantial change in dry deposition.

The wet-only S deposition is, to our best knowledge, fairly reliable. The field of annual precipitation totals was generated from data measured by standard methods at 750 sites across the CR, taking into account the altitude's effect on precipitation. We integrated the altitude, which is beneficial for improvement of the precipitation map, as was shown earlier for example for Great Britain (Lloyd 2005). The precipitation totals are much more variable as compared to the S/SO_4^{2-}concentration in wet-only and bulk samples across the CR (Hůnová 2003).

Based on the equation of canopy water balance method suggested by Lovett (1988), it would be correct also to account for the input by stemflow deposition (Levia and Frost 2003). For Northern Italy, Bini and Bresoli (1998) reported that the SO_4^{2-} concentration is enriched in stemflow by a factor of 2 for spruce forests and by a factor of 2.5 for beech forests. In a review of 19 papers reporting on the quantity of water deposited by stemflow, the estimate for spruce forests ranges between 0.5–3% of the precipitation amount in an open area (Kantor 1983). Considering the above data, we estimated that the stemflow deposition in our spruce forests accounted for less than 5% of the throughfall deposition. Consequently the stemflow deposition was neglected in our analysis in agreement with many other studies focusing on deposition in spruce forests (e.g., Jost et al. 2004). We are aware, however, that for the beech forests (and likely for other deciduous species) the stemflow deposition must be higher (Kantor 1983) and thus by neglecting it, our estimate may be biased and too low for the 15% of the area with deciduous forests.

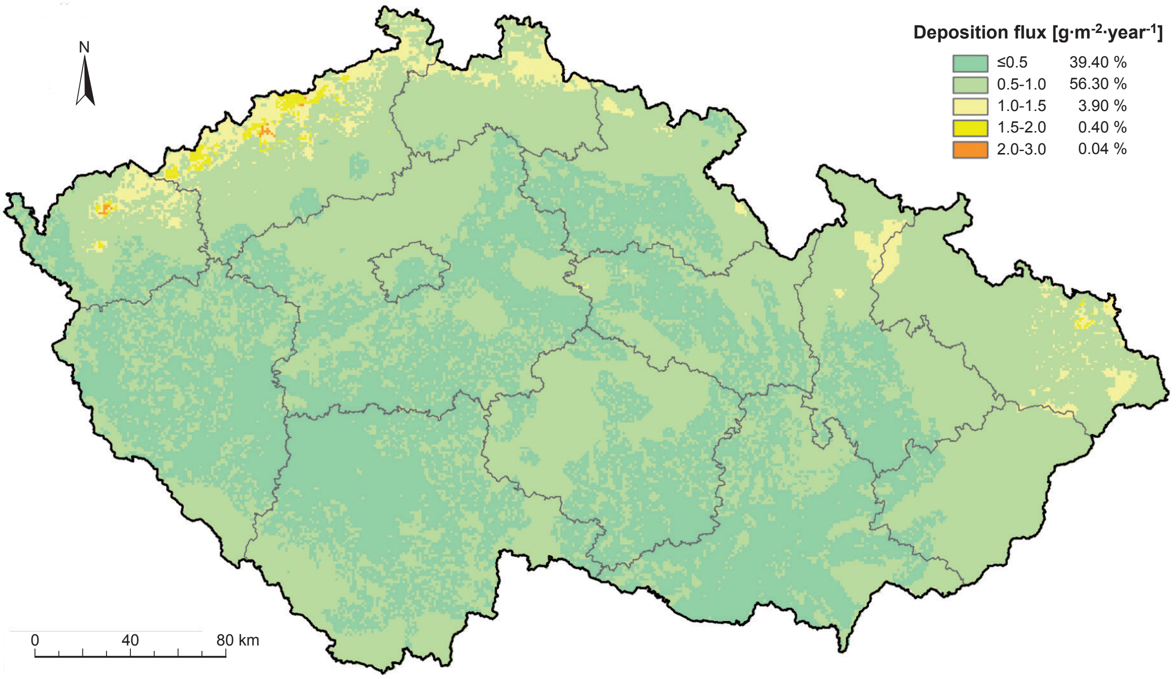

Fig. 6: Annual total deposition of sulphur (Model 2), 2008

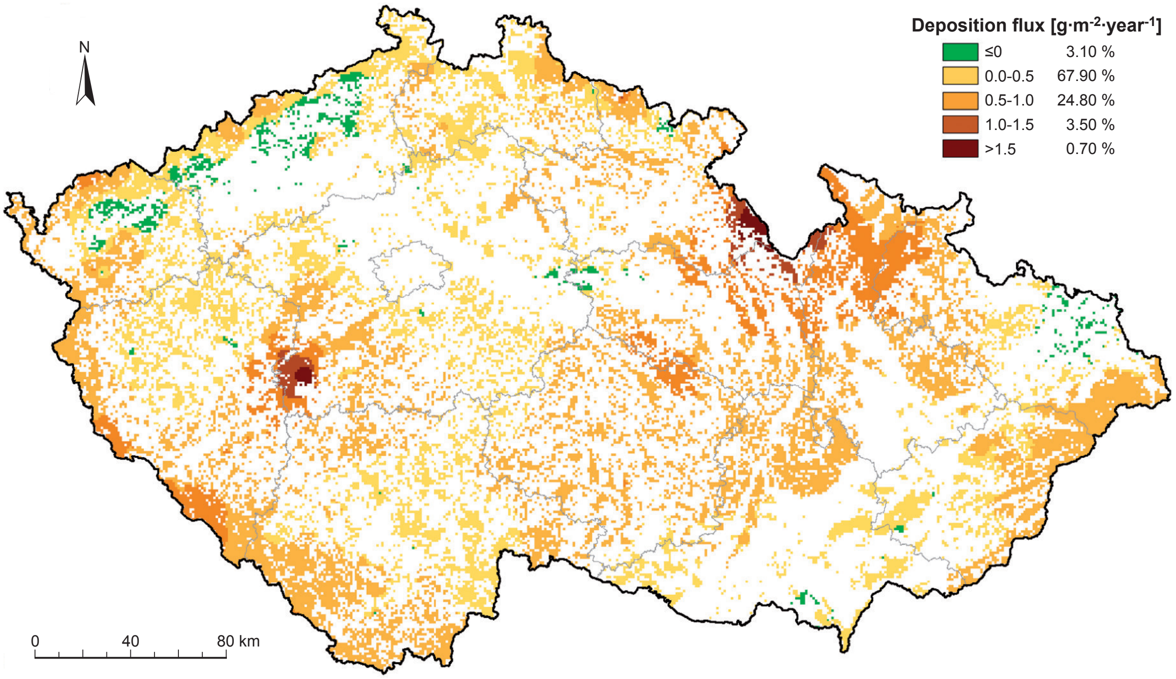

Fig. 7: Occult deposition determined from the difference between Model 1 and Model 2 for forested area, 2008

Precipitation interception was not treated in our model. The interception of forests is an important component of the hydrological budget, varies widely and depends on storage capacity of the canopy and the nature of precipitation (Whelan et al. 1996; Levia and Frost 2006; André et al. 2011). The meteorological factors (precipitation amount and intensity, evaporation rate, wind speed, time intervals between successive events) and biological factors (canopy structure affected by stand density and species composition) are important modifiers of the interception. The share of precipitation interception at our sites, given as a difference between the throughfall and precipitation amount outside the forest, is presented in table 1. Due to the complication of the interception process, we did not attempt to estimate it in our interpolation. We are aware, however, that neglecting the interception results in underestimation of the share of occult precipitation and our results, consequently, are lower than the real values. The phenomenon of the "edge effect" was not accounted for due to the spatial resolution of the model.

For spatial interpolation of the values measured at individual sites, we applied different interpolation techniques regarding the density of the measuring network. Caution is required when inferring regional deposition from a network of sparse monitoring sites (Sickles et al. 2009). For interpolation of the precipitation chemistry, we used a relatively simple deterministic IDW method since with respect to the geo-statistics, the number of sites is very low. The advantage of this method is that after interpolation, the values measured at the sites remain the same. For interpolation of precipitation totals, kriging was used as the network is fairly dense.

Theoretically, the difference in the two models includes – apart from the occult deposition – also the S/SO_4^{2-} from aerosol. We could not account for sulphate aerosol when estimating the dry deposition, because our measurements are strongly limited. Based on the information from the only three sites we have, we assumed that S/SO_4^{2-} from aerosol at forested sites is so low that it can be neglected. We are aware, however, that it is a very rough estimation.

Our result that the deposition of sulphur attributable to the occult deposition increases with increasing altitude (Fig. 8) meets the assumption based on scientific literature (e.g., Seinfeld and Pandis 1998; Zimmermann and Zimmermann 2002). Interestingly, we have found the largest scatter in occult S deposition in the altitude range between ca. 550–1000 m a.s.l. Geographically, the highest flux is found in the Orlicke hory Mts. and Jeseniky Mts., adjacent to the border with Poland. The plausible explanation might be the different processes leading to occult precipitation at these altitudes, particularly the mountain valleys, where the occult deposition may be related either to radiation fog, orographic slope fog or low clouds (Dore et al. 1999). Blaš et al. (2010) report significant differences in chemistry depending on fog origin for Polish sites. The explanation of this phenomenon will require further analysis, however.

For partial verification of our results, we used the data from direct measurements of fog chemistry measured by the Institute for Hydrodynamics, Academy of Science of the CR. The fog deposition of S/SO_4^{2-} accounted for 0.49 $g{\cdot}m^{-2}{\cdot}year^{-1}$ for the Šumava, 0.72 $g{\cdot}m^{-2}{\cdot}year^{-1}$ for the Krkonoše and 1.57 $g{\cdot}m^{-2}{\cdot}year^{-1}$ for the Jizerské hory Mts. (Tesař, personal communication), which corresponds fairly well with our results.

Our results can be considered as the first step of the presented methodological approach. In an outlook, it would be of interest to analyze the temporal trends in occult precipitation contribution to the atmospheric deposition of sulphur. Moreover, it would be most interesting to identify the likely factors driving the expected high inter-annual variability in this contribution.

A question arises to what extent this approach is applicable for other chemical species in atmospheric deposition. Particularly, the analysis for nitrogen deposition would be of interest due to the remaining high loads (Lorenz et al. 2008), despite large reduction of

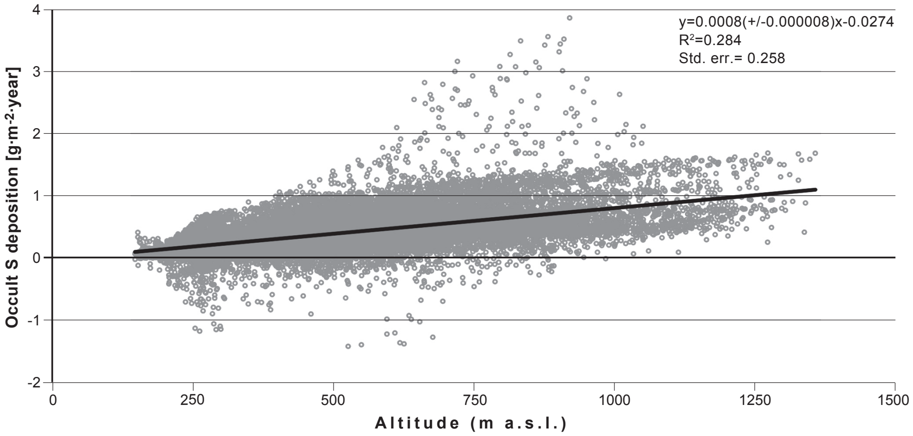

Fig. 8: Relation between occult S deposition and altitude

Tab. 2: Review of SO$_2$ deposition velocities

Type of Vegetation	Detail information	SO$_2$ deposition velocity [cm·s^{-1}]	Reference
Coniferous forest			
Coniferous forest	Winter	0.1	Johansson et al. (1983)
Coniferous forest (pine)	Dry autumn Sweden	0.33	Granat and Richter (1995)
Coniferous forest (spruce-fir)	USA	0.39	Miller et al. (1993)
Coniferous forest	Summer	0.5	Johansson et al. (1983)
Coniferous forest (fir)	Dry day Netherlands	0.7	Erisman (1994)
Coniferous forest (fir)	Dry night Netherlands	0.7	Erisman (1994)
Coniferous forest (spruce)	Denmark	1.1	Hovmand and Kemp (1996)
Coniferous forest (spruce)	Germany (Ore mountains)	1.32	Zimmermann et al. (2006)
Coniferous forest (fir)	Netherlands	1.5	Erisman et al. (1999)
Coniferous forest (fir)	Wet day Netherlands	2.3	Erisman (1994)
Coniferous forest (fir)	Wet night Netherlands	2.5	Erisman (1994)
Deciduous forest			
Deciduous forest	Winter night Canada	0.1	Erisman (1994)
Deciduous forest	Dry winter day Canada	0.3	Erisman (1994)
Deciduous forest (oak)	Austria	0.31	Puxbaum and Gregori (1998)
Deciduous forest	Wet winter day Canada	0.6	Erisman (1994)

NO$_x$ emissions throughout Europe (Fagerli and Aas 2008). It is generally accepted, however, that many ions participate in inner cycle of trees. While some ions (Ca^{2+}, K$^+$, Mg^{2+}) are released from vegetation during precipitation, in contrast, others (NO$_3^-$, NH$_4^+$, H$^+$) enter the vegetation. SO$_4^{2-}$ alongside with Na$^+$ and Cl$^-$ do not interact with vegetation (Lindberg and Lovett 1992). This approach, however, might give at least the estimation of lower occult deposition value for ions entering the vegetation and upper occult deposition value for ions released by vegetation.

The presented results are rough estimations, but can be considered the best available at the moment for the Czech Republic.

5 Conclusions

Our preliminary results, based on a geo-statistical modelling approach, indicate that the contribution of occult precipitation to sulphur deposition is significant, varies in a wide range, and is dependent on altitude. On 68% of the Czech forested area, the occult deposition in 2008 ranged between 0–0.5 g·m^{-2}·year^{-1}, on 25% between 0.5–1 g·m^{-2}·year^{-1}, on 3.5% between 1–1.5 g·m^{-2}·year^{-1}, and on 0.7% it was above 1.5 g·m^{-2}·year^{-1}. In relative terms, in 2008 the occult precipitation contribution to sulphur deposition over the Czech forested area was up to 200% in 99% of the grid cells, and in the remaining 1% of the grid cells it even ranged between 200–400%. Across ca. 50% of the Czech forested area 50–100% of sulphur deposition was contributed by occult precipitation. Our results indicate that when using the maps of the "total deposition" derived from wet and dry deposition without accounting for the occult deposition, we are likely to underestimate substantially the true atmospheric deposition and consequently its possible impacts on ecosystem health and nutrient status.

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