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Occult precipitation as an important contribution to the wet deposition in Bohemian Forest

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Abstract
Together six active fog-water collectors and ten passive fog-water collectors were installed in various suitably chosen mountainous parts and urban regions of the Czech Republic with different pollutants loads in order to evaluate if site-to-site differences exist. Fog deposition rates is calculated with the use of the Lovett's mathematical micrometeorological model for the selected mountainous localities. Estimated gross deposition of cloud water is about 9 % of the total annual precipitation in the mountainous regions of the Bohemian Forest. Samples of cloud water obtained with the aid of the both active and passive collectors were analysed for major ions. The results from 1994–1999 obtained in the Bohemian Forest are presented here. A wide range of concentrations were encountered, most typically exceeding concentrations occurring in rain (so-called enrichment factor is ranging from 1 to 19 in the Bohemian Forest). Estimated wet deposition for example for NH_4^+, NO_3^- and SO_4^{2-} via fog and cloud droplets impaction and sedimentation represents 826, 1810 and 1900 $kgkm^{-2}year^{-1}$, respectively (i.e. 147, 85 and 88 %, respectively with respect to weighted means of precipitation). The highest values of the enrichment factors for NH_4^+ (16.4) and Pb (18.7) were reached.

Key words: Cloud and fog water deposition, occult precipitation, cloud and fog water chemistry, cloud and fog water collectors

Introduction

Remote mountain ecosystems, especially lakes and streams, are becoming increasingly attractive both from the scientific and common human point of view. Because of their sensitivity to the changing environmental conditions they have sharpened our senses and largely increased our understanding of forces and responses, of action and reaction in aquatic ecosystems in general. The importance of the cloud and fog water deposition as a major pathway for the transport of atmospheric pollutants has long been recognized. The cloud and fog water is generally more acid than rainwater and has higher levels of ionic concentrations. The composition of fog water varies greatly from one site to another, and with time. Therefore any generalisation should not be made without taking into account influence from local emission of pollutants, climate and topography.

Generally occult precipitation can be divided into deposited (dew, white dew, hoar frost, soft rime) and collected (fog, cloud-water, hard rime) precipitation (Brechtel 1990, Eliáš & al. 1995). Deposited occult precipitation condenses or sublimates directly onto plant surfaces and other acceptors. Collected occult precipitation is condensed in the atmosphere in liquid or solid form and transported by air movement to surfaces.

Especially the deposition of water and chemicals to vegetation from wind-driven clouds and fogs has long been recognized as an important hydrological input not only in many mountainous and coastal environments (LOVETT & al. 1982) but also in urban areas (BREWER & al. 1983). Since the concentration of chemical species is several times higher in cloud water than in precipitation, the chemical deposition associated with cloud and fog droplet interception by vegetation can be significant, or even predominant, with respect to deposition due to precipitation. Also in the Czech Republic the occult precipitation as a process affecting water balance and chemistry is studied. The attention is paid both to the solid (PORKERT 1998) and liquid occult precipitation (TESAŘ 1993).

The objectives of this article are to: (1) estimate the fog and cloud water deposition as a process affecting both water balance and chemistry in the mountainous region of the Bohemian Forest (and thus also watersheds of the lakes); (2) compare the above-mentioned delivery mechanisms for water and chemical species with suitably chosen mountainous regions of the Czech Republic and determine if site-to-site differences exist.

Sites description

Hydrological and ecological significance and site-to-site variation of the low cloud and fog water deposition is studied in the Czech Republic at seven localities. The individual localities are differing in the pollutants loads, situation and elevation. Four localities represent the mountainous forested regions: (i) Bohemian Forest – mountainous range forming the border between the Czech Republic, Germany and Austria (1123 and 1250 m a.s.l.); (ii) Jizerské

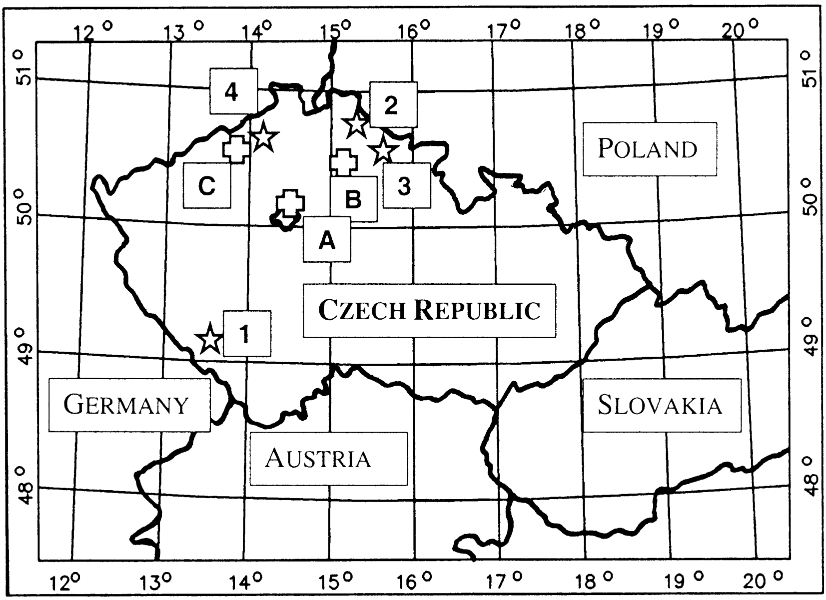

Fig. 1. – Situation of the cloud and fog water measuring localities in the Czech Republic. Mountainous regions: 1 – Bohemian Forest, 2 – Jizerské hory Mts., 3 – Krkonoše Mts., 4 – Milešovka Mts., Urban regions: A – Prague, B – Jablonec, C – Kopisty.

hory Mts. – the border between the Czech Republic and Poland (from 730 to 890 m a.s.l.); (iii) Krkonoše Mts. – the range between the Czech Republic and Poland (1350 and 1550 m a.s.l.) and (iv) Milešovka Mt. – Northwestern part of the Czech Republic (835 m a.s.l.). Three localities were selected to describe the urban areas of the Czech Republic: (i) the capital of the Czech Republic – Prague (300 m a.s.l.); (ii) Jablonec – Northern part of the Czech Republic (550 m a.s.l.) and (iii) Kopisty by Most – Northwestern part of the Czech Republic (240 m a.s.l.). Situation of the measuring localities is shown in the Fig. 1.

The chemical and hydrological significance of occult precipitation over the Czech Republic will be demonstrated in this paper for the higher elevation zones of the Bohemian Forest. Only for a comparison the results from the Jizerské hory and Krkonoše Mts. (Northern Bohemia) will be presented here. These zones, especially above the elevation of 1000 m above sea level, are characterized by high wind speeds, lengthy periods of cloud and fog immersion, and coniferous vegetation, all of which contribute to high potential rates of cloud droplet capture. The first locality (Bohemian Forest) represents the cleanest part of the Czech Republic while the second and third ones (Jizerské hory and Krkonoše Mts.) belong to the heavy polluted regions. In the each of the selected above-mentioned localities the experimental watershed was equipped and the long-term data sets on the basic hydrological and hydrometeorological parameters are available. All the catchments represent hydrologicaly closed basins with a continuous measurement of the precipitation throughfall in order to permit future estimates of the fog water amount by the use of the water balance method (LOVETT 1988).

The sampling site for the cloud and fog water collection in the Bohemian Forest is located at an elevation of 1123 m a.s.l. on the hilltop Churáňov, the precipitation gauge and bulk precipitation and throughfall samplers were installed in the Liz catchment (0.99 km^2, 828–1074 m a.s.l.) where also the discharges in the closure profile were continuously measured. The second sampling site described in this article was created in the Uhlířská basin (1.87 km^2, 775 – 886 m a.s.l.) at an elevation of about 800 m a.s.l. The sampling site for the observation and evaluation occult precipitation created in the Krkonoše Mts. was established in the Modrý potok basin (2.62 km^2, 1010–1554 m a.s.l.) at the highest point of the watershed.

Methodology

The statistical analysis of the individual types of the occult precipitation was done and so-called climatological normals were obtained for the 1961–1990 time period. Further the same statistical analyses were done for the 1960–1999 time period and for its individual quarters (i.e. decades: 1960–69, 1970–79, 1980–89 and 1990–99).

A resistance model of the deposition of cloud droplets to a spruce forest canopy (LOVETT 1984) was tested. This model is composed of two submodels, the first simulating a turbulent diffusion of cloud droplets into the forest and their deposition onto foliar and branch surfaces, and the second simulating the evaporation/condensation process under cloud-immersion conditions in the forest. Both the cloud deposition model and the evaporation/condensation model have been described (LOVETT & al. 1982, LOVETT 1984, LOVETT 1988). Although these models depend on the estimation of a number of parameters whose accurate measurement is difficult (the leaf-area index, the droplet-size distribution and the cloud-liquid-water content), it represents a very instructive tool enabling us to estimate both gross and net deposition (total cloud-water deposition minus total evaporation) and examine their reactions to changes in meteorological and canopy-structure parameters. For calculating the ion deposition via cloud water a direct estimate of gross water input is needed, and that is why we have applied the above-mentioned model. Some canopy structure parameters are described in literature (THORNE & al. 1982, LOVETT & REINERS 1986).

In order to estimate the cloud-liquid-water content (LWC) and to gain cloud water samples, the sample-taking device was constructed. Two methods of sampling were used. In one, fog-water was collected by drawing air with a fan across 10 rows of vertical Teflon strands of 0.5 mm diameter. The strands were fixed to a support which was placed inside a Plexiglass box with the fan at one end. Air entered the box through the opening in the bottom of the box. These so-called active CWP collectors as described in literature (DAUBE & al. 1987) were installed in the Bohemian Forest on the hilltop Churáňov and in the Jizerské hory Mts. at the dam of the water reservoir Josefův Důl. Collector of this type have been used during a relatively extensive fog research in the U.S.A. (WEATHERS & al. 1988). The collected volume of sampled water was from a few centilitres to approximately two litres – depending on the duration of the fog events and their cloud liquid water content (CWP).

In the second method, fog water was collected passively, i.e. fog droplets were captured on Teflon strings of 0.5 mm diameter mounted longside to form a curtain in the form of a truncated cone. This „Grunow" type of fog gauge (GRUNOW 1952; NAGEL 1956) was shielded against direct rainfall incidence by 0,5 m^2 roofing. These so-called passive cloud and fog water collectors were installed in the Bohemian Forest on the hilltop Churáňov (1123 m a.s.l) and on the slope of the Mokrůvka Mt. (1250 m a.s.l.), in the Jizerské hory close to the spring of the Černá Nisa river (810 m a.s.l.), in the Krkonoše Mts. on the slope of the Labská louka locality (1350 m a.s.l.) and on the top of the Studniční hora Mts. (1550 m a.s.l.).

Samples collected were stored in 500 or 1000 ml polyethylene bottles at 4 °C in the dark. Prior to use, storage bottles were washed with 6N HCl, followed by several distilled water rinses. Chemical analytical methods: pH of the samples was measured with a Radiometer GK2401C electrode, fluoride was determined by ion selective electrode, chloride, nitrate and sulphate by high performance liquid chromatography (HPLC), ammonia spectrophotometrically, main cations by flame AAS and trace metals by graphite furnace AAS (ETAAS).

Results and discussion

Data sets describing the occurrence and duration of the individual kinds of the occult precipitation events (i.e. fog, hard rime, hoar frost, soft rime, dew and white dew) were analyzed in full detail and so-called climatological normals for the time period 1961–1990 were obtained (Table 1). Fig. 2 shows the duration of the low cloud and fog events in the individual months of the evaluated time periods (i.e. 1960–69, 1970–79, 1980–89, 1990–99, 1961–90 and 1960–99). The same elaboration was done for the other type of occult precipitation (i.e. hard rime, hoar frost and soft rime, dew and white dew). From the statistical analysis of the individual types of the occult precipitation in the region of the Churáňov observatory for the period 1961–1990 (this period was selected to describe so-called climatological standards of a evaluated phenomena in the Czech Republic) a surprising homogeneity of the phenomena

Table 1. – Climatological normals (standards) for the 1961–1990 time period of the frequency and duration of the individual types of the occult precipitation in the Bohemian Forest.

Type of occult precipitation	Number of days with the event	Duration of individual phenomenon [hour]			
		Intensity 0	Intensity 1	Intensity 2–3	Total
Fogs, Low Clouds	147	122	223	899	1245
Hard Rime	32	309	142	89	539
Dew, White Dew	104	273	356	125	755
Hoar Frost, Soft Rime	44	180	122	45	348

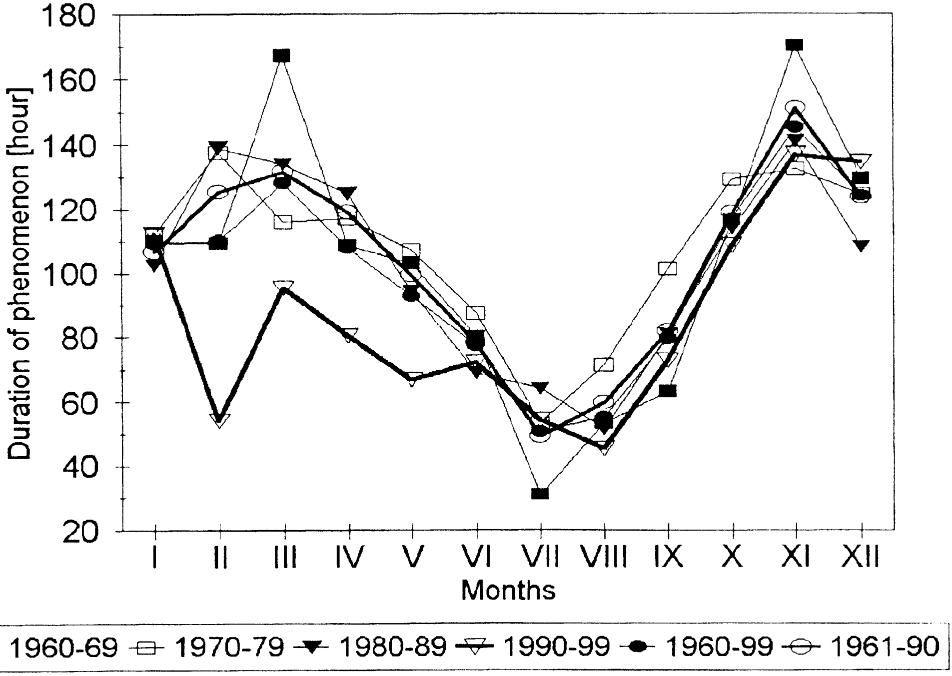

Fig. 2. – Mean monthly duration of the low cloud and fog events at the Churáňov station (1123 m a.s.l., Bohemian Forest) for the climatological normal time period (1961–90), for the 1960–99 time period and for its individual decades (1960–69, 1970–79, 1980–89, 1990–99).

duration for the whole period and the individual decades (1960–1969, 1970–1979,1980–1989) can be seen. The only exception is presented by the last evaluated decade 1990–1999. In this period the course of time duration of fog and low cloud events is significantly different (mostly lower i.e. shorter; see Fig. 2). The same finding is valid for the hard rime but in contrast to this two cases the duration of hoar frost, soft rime, dew and white dew was longer in the mentioned period. With respect to this finding it could be assumed that the observed change of behaviour besides the antropogenic activities is partly due to the proceeding global changing of climate. The occult precipitation and its frequency and duration could be taken into account as a sensitive indicator of the climate changes because its appearance is typical for the air temperature instability conditions in the atmosphere close to the Earth surface. On the other hand the possible influence of the changes of the hydrometeorological station staff and observation methodology should be also taken into account.

The results of model predictions of gross cloud droplet deposition, net cloud droplet deposition and simulated cloud water deposition velocity (gross flux divided by the liquid water content) are $0.505*10^{-3}$ $gcm^{-2}min^{-1}$, $0.175*10^{-1}$ $cmhour^{-1}$ and 20.9 cms^{-1}, respectively. Model predictions were made for canopy structure parameters and for annual mean meteorological conditions during cloud and fog events typical for the Bohemian Forest region, with wind speed 3.2 $msec^{-1}$, relative humidity 96 %, cloud-water content 0.4 gm^{-3}, mean droplet diameter 10 mm, net radiation 0.071 $calcm^{-2}min^{-2}$ and air temperature –0.2 °C. If we take into account this elaboration and assume that the spruce forests in the Bohemian Forest are immersed in clouds and fogs for 322 $hoursyear^{-1}$ (only fogs of very heavy intensity 3 for the evaluated time period 1994–1999) on the average and that, for 104 hoursyear^{-1}, rime-ice accretion reduces the deposition rate by 50 % according to LOVETT & al. (1982), then our estimated annual gross deposition of cloud-water is 81 mmyear^{-1} (9 % of the annual vertical precipitation total), while the net deposition is 47 mmyear^{-1}. These estimates are admittedly crude, but they certainly are the best estimates available. On the basis of these calculations the estimates of cloud water deposition in the Jizerské hory and Krkonoše Mts. were made.

In the course of hydrological years 1994–1999 115 samples of fog water were collected at Churáňov station. Analytical results are summarized in Table 2 together with data on bulk precipitation chemistry measured in the Liz station. The concentrations of chemicals in the low clouds and fogs have not been weighted for sample volume. A direct comparison of the means or medians with precipitation-weighted means for rain given in the Tables 2 has no exact quantitative significance. Nevertheless, it is of interest to note high concentrations of the major ions in cloud and fog water. Cloud water was enriched in all major ions compared to rainwater. Concentrations of major solutes in cloud and fog water and enrichment factor (cloud/rain ratios) are shown in Table 2. In Table 3 the comparison between calculated deposition due to fog and measured deposition via precipitation both on an annual basis in the Bohemian Forest (1994–1999), Jizerské hory Mts. (1998–1999) and Krkonoše Mts. (1999) is shown. The obtained results of chemical analyses are in general agreement with the known

Table 2. – Fog water (115 samples) and bulk precipitation (72 samples) chemistry in the Bohemian Forest (1994–1999).

Ion	Units	Cloud and fog water chemistry				Bulk precipitation chemistry			Enrich. Factor 1)/2)
		Min value	Max value	Men value	Median value[1)]	Min value	Max value	Weight. mean[2)]	
pH	[-]	3.36	7.10	4.20	3.98	3.60	6.65	4.64	1.2
H^+	[$\mu g l^{-1}$]	0.00	724.00	146.00	110.00	0.22	251.00	35.50	3.1
Cond.	[μS/cm]	3.48	567.00	182.00	157.00	1.00	209.00	24.60	6.4
Na^+	[$mg l^{-1}$]	0.01	9.65	1.34	0.76	0.04	0.83	0.17	4.5
K^+	[$mg l^{-1}$]	0.00	6.71	0.84	0.58	0.01	1.65	0.16	3.6
NH_4^+	[$mg l^{-1}$]	0.00	42.30	11.60	10.20	0.01	9.10	0.62	16.5
Mg^{2+}	[$mg l^{-1}$]	0.00	3.01	0.39	0.24	0.01	0.44	0.06	4.0
Ca^{2+}	[$mg l^{-1}$]	0.01	19.90	2.48	1.22	0.01	2.35	0.32	3.8
F^-	[$mg l^{-1}$]	0.00	0.45	0.10	0.09	0.01	0.20	0.02	4.5
Cl^-	[$mg l^{-1}$]	0.00	13.30	2.24	1.48	0.07	1.96	0.34	4.4
NO_3^-	[$mg l^{-1}$]	0.32	179.00	28.40	22.30	0.15	26.10	2.37	9.4
SO_4^{2-}	[$mg l^{-1}$]	0.31	76.60	25.40	23.50	0.25	27.30	2.38	9.9
Mn	[$\mu g l^{-1}$]	0.20	530.00	69.30	33.20	2.00	57.00	8.22	4.0
Zn	[$\mu g l^{-1}$]	29.00	885.00	212.00	157.00	5.00	81.00	20.30	7.7
Fe	[$\mu g l^{-1}$]	50.00	680.00	195.00	155.00	5.00	260.00	33.60	4.6
Al	[$\mu g l^{-1}$]	11.00	98.00	76.60	95.00	5.00	210.00	43.00	2.2
As	[$\mu g l^{-1}$]	0.50	7.50	2.79	1.90	0.25	7.70	0.55	3.5
Cd	[$\mu g l^{-1}$]	0.04	33.20	3.15	1.07	0.02	12.80	0.36	3.0
Pb	[$\mu g l^{-1}$]	1.00	525.00	67.10	42.60	0.20	19.50	2.28	18.7
Cu	[$\mu g l^{-1}$]	0.20	395.00	41.00	17.30	0.10	294.00	16.00	1.1
Ni	[$\mu g l^{-1}$]	1.00	230.00	17.40	7.00	0.00	3.00	0.68	10.3

Table 3. – Deposition of water and chemicals via fogs, bulk precipitation, throughfall and surface runoff in the Bohemian Forest (1994–1999) and the deposition of water and chemicals via fogs and bulk precipitation in the Jizerské, hory Mts. (1998–1999) and Krkonoše Mts. (1999).

	Bohemian Forest 1994–1999					Jizerské hory Mts. (1998–1999)			Krkonoše Mts. (1999)		
Ion	**FG**	**BP**	**TH**	**RF**	**FG/BP**	**FG**	**BP**	**FG/BP**	**FG**	**BP**	**FG/BP**
	[kgkm^{-2} year^{-2}]				[%]	[kgkm^{-2} year^{-2}]		[%]	[kgkm^{-2} year^{-2}]		[%]
H^+	8.91	32.10	21.50	0.24	27.8	1.24	38.70	3.2	21.10	32.70	64.5
Na^+	61.60	154.00	214.00	1350.00	40.0	627.00	462.00	135.7	289.00	446.00	64.8
K^+	47.00	145.00	1370.00	382.00	32.4	201.00	147.00	136.7	54.60	327.00	16.7
NH_4^+	826.00	561.00	501.00	4.93	147.2	1030.00	372.00	276.9	769.00	1440.00	53.4
Mg^{2+}	19.40	54.30	188.00	581.00	35.7	122.00	78.90	154.6	60.20	89.10	67.6
Ca^{2+}	98.80	290.00	662.00	1680.00	34.1	627.00	474.00	132.3	116.00	461.00	25.2
F^-	7.29	18.10	22.90	23.60	40.3	56.40	33.80	166.9	24.50	14.90	164.4
Cl^-	120.00	309.00	520.00	475.00	38.8	548.00	1040.00	52.7	716.00	1070.00	66.9
NO_3^-	1810.00	2140.00	2150.00	938.00	84.6	3900.00	2660.00	147.0	2770.00	2840.00	97.5
SO_4^{2-}	1900.00	2150.00	3650.00	4810.00	88.4	2470.00	3260.00	75.8	1370.00	2480.00	55.2
Mn	2.67	7.44	78.80	8.57	35.9	7.39	7.20	102.5	1.56	9.40	16.6
Zn	12.70	18.30	18.80	143.00	69.4	20.60	69.50	29.6	10.00	210.00	4.8
Fe	12.60	30.40	40.90	73.20	41.4	20.30	49.50	41.0	14.50	41.60	34.9
Al	7.70	38.90	38.70	88.70	19.8	11.10	57.50	19.3		41.60	
As	0.15	0.50	0.35	0.13	30.9	0.90	0.48	185.0		0.52	
Cd	0.09	0.33	0.11	0.02	26.6	0.30	0.33	90.4		0.21	
Pb	3.45	2.06	3.28	0.32	167.2	2.02	4.09	49.5		1.41	
Cu	1.40	14.50	15.20	5.61	9.7	2.71	4.45	60.9		5.20	
Water [mm]	81.00	905.00	480.00	369.00	9.0	112.80	1127.5	10.0	222.9	1485.7	15.0

Notice: FG - estimated fog and low cloud water yearly deposition; BP - weighted bulk precipitation yearly deposition; TH - weighted throughfall deposition measured under the forest canopy; RF - surface runoff deposition measured in the closure profile of the LIZ watershed.

pattern of the chemical composition of European occult precipitation if the specific site conditions are taken into account (FUZZI & ORSI 1985 – valley fog in Po valley in Italy ; FUHRER 1986 – agricultural area of central Switzerland; OGREN & RODHE 1986 – clean air site in central Scandinavia; HERCKES & al. 1998 – three different sites in an urban and mountainous regions in France).

The data on low cloud and fog water deposition and bulk precipitation deposition are completed with data on yearly deposition measured under the forest canopy (throughfall precipitation) and surface runoff deposition measured in the closure profile of the Liz catchment. These data sets are presented here in order to demonstrate the importance of the occult precipitation both for the water and matter balance of the small forested catchment and to be available for the future deeper evaluation of the evaluated phenomena by environmental scientists.

There is insufficient number of chemical analyses of cloud water collected in the Jizerské hory and Krkonoše Mts. for the time being to be able to work out some deeper evaluation. Although these results are only preliminary ionic concentrations in cloud and fog water are apparently higher with comparison to precipitation.

Conclusions

Comparison of data for major, minor and trace elements in cloud water and bulk rain water samples collected at the Bohemian Forest shows that cloud water is much more concentrated in most elements than rain water. The importance of low cloud and fog water deposition as a major pathway for the transport of major, minor and tracer elements was demonstrated.

From the above results these conclusion can be drawn:

1) The cloud and fog water deposition is important delivery mechanism for pollutants both in relatively very clear part of the Czech Republic (the Bohemian Forest) and in polluted region (Jizerské hory and Krkonoše Mts.).

2) The gross water input via cloud and fog water represents about 9–15 % of the total annual vertical precipitation in the examined mountainous areas.

3) Concentrations of major ions in cloud and fog water are approximately 9 times greater (so called enrichment factor reaches values from 1 to 19) in the Bohemian Forest, 15 times greater (from 2 to 30) in the Jizerské hory Mts., 6 times greater (from 1 to 10) in the Krkonoše Mts.

4) The cloud and fog water droplets deposition significantly increases wet deposition of SO_4^{2-}, NO_3^- and NH_4^+ and pollutants long range transport in monitored mountains.

5) Any study of acid deposition in an upland afforested system would be incomplete without estimates of cloud water deposition.

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