ELSEVIER

Atmospheric Research 64 (2002) 19–28

ATMOSPHERIC
RESEARCH

www.elsevier.com/locate/atmos

Temporal and spatial variations of fog in the Western Sudety Mts., Poland

Marek Błaś[a,*], Mieczysław Sobik[a],
Friedrich Quiel[b], Paweł Netzel[a]

[a]*Department of Meteorology and Climatology, University of Wrocław, 8 Kosiby Street, 51-670 Wrocław, Poland*
[b]*Department of Environmental and Natural Resources Information System,*
The Royal Institute of Technology KTH, Stockholm, Sweden

Received 8 October 2001; received in revised form 11 February 2002; accepted 15 April 2002

Abstract

The ridges of the Western Sudety are well exposed to the humid maritime air masses that are mainly associated with westerly atmospheric circulation. Fog is the most frequently observed atmospheric phenomenon, being present on average 45% of the time, with 250–300 days with fog per year. This study on temporal variation of fog in both daily and annual cycles is based on 30 years of measurements (1961–1990) made on Mt. Szrenica at 1362 m a.s.l.

Based on the data from 51 meteorological stations and the results of fog deposition field measurements, a digital model of fog frequency in the Western Sudety was prepared using a Geographic Information System. The model shows that altitude is not the only important factor controlling fog frequency. Such parameters as slope aspect and position of a particular site in relation to local and regional morphology are also of crucial importance.

Keywords: Fog frequency; Mountain climatology; Geographic Information Systems; Sudety Mts.

1. Introduction

The hercynian mountains of Western and Central Europe include the Massif Central, Ardennes, Vosges, Black Forest, Bohemian Forest, Ore Mts., Harz and Sudety. The latter are notable for high frequency of observed fog existence. As far as

---

Abbreviations: LWC, liquid water content [g m^{-3}]; NDF, number of days with fog.

[*] Corresponding author. Tel.: +48-71-372-94-97; fax: +48-71-372-94-98.

E-mail address: blasm@meteo.uni.wroc.pl (M. Błaś).

PII: S0169-8095(02)00076-5

continental Europe is concerned (except for Scandinavia), the highest number of days with fog (NDF) is observed at Sudetic stations, i.e.: Śnieżka (1602 m a.s.l.), Praded (1492 m), Szrenica (1364 m) and at Brocken in the Harz Mountains (1153 m): 296, 284, 274 and 284 days/year, respectively (Błaś and Sobik, 2000). The most frequent category of fog observed at these sites is slope fog (or orographic fog) formed as humid air ascents mountain slopes. The following conditions are favourable for such high NDF:

- altitude within a range 1000–1600 m a.s.l.;
- convex landform;
- exposure to advection of humid Atlantic air masses;
- proximity to the coast;
- absence of other mountain massifs on the windward side.

The Sudetes are subjected to air pollution emitted from combustion of sulphur-rich coal in the so-called "Black Triangle"—an industrial region situated where Germany, the Czech Republic and Poland meet. The Izera Mts. and Giant Mts. (the two main massifs which comprise the Western Sudety) straddle the Polish/Czech border and form two conspicuous orographic thresholds on the way of humid and polluted air masses moving from a wide sector SW–W–NW–N. The SO_4^{2-} aerosol was found to be the most important pollutant with approximately 80% of SO_2 gas being converted into sulphate aerosol (Zwoździak et al., 1993). Investigations indicate that fog can locally be a more important factor for pollutant deposition than precipitation due to:

- high number of NDF;
- liquid water content typically 0.2–0.6 g m^{-3} (Błaś, 1997; Kmieć et al., 1998);
- contamination of fog—pollutant concentrations in cloud/fog droplets were two to seven times higher at Mt. Szrenica than those observed in precipitation (Baron and Sobik, 1995; Kmieć et al., 1998; Dore et al., 1999; Jała and Błaś, 2000);
- existence of effective fog/cloud droplets receptors—the highest ridges of Giant and Izera Mts. are covered by spruce forest stands and dwarf pine, which belong to the most effective natural receptors of fog owing to their considerable height and surface area index (Woźniak, 1991; Sobik and Migała, 1993; Sobik et al., 1998; Tesař et al., 2000).

The throughfall volume measured at the edge of a forest stand at Stóg Izerski in the Izera Mts. (1100 m a.s.l.) was 80% higher than bulk precipitation in the deforested terrain with four times higher pollutant deposition. At the same altitude in the Giant mountains, which are partly sheltered by the Izera Mts, throughfall volume and pollutant deposition compared with bulk precipitation was respectively 13% and three times higher (Jała and Błaś, 2000). Orographic fog formed on Izera Mts. is generally more polluted than rain and washed out by particles of precipitation (the seeder–feeder effect) which causes a 50% increase of pollutant concentrations in rain and snow and a 50% enhancement of precipitation intensity (Dore et al., 1999).

Because of meteorological and environmental conditions (land use), pollutant deposition by fog is one of the main reasons, and locally even the most important reason, for deforestation in the Western Sudety. Defoliation was most intense in the western part of the mountains at sites with high elevation, particularly observed in the altitude range 800–1200 m a.s.l. Complete defoliation occurred at sites well exposed to the wind and affected 42% of spruce forest stands (Moravčik and Černy, 1995).

The aim of this paper is to present in a climatological context a detailed description of orographic fog variations on the ridge of the Giant Mts. and to propose a GIS method to calculate spatial distribution of fog frequency in a larger area of the Western Sudetes.

2. Site and method

The analysis of temporal variation of fog is based on a data set from the period between 1961 and 1990 collected at the Meteorological and Climatological Observatory of the University of Wrocław at Mt. Szrenica ($\varphi = 50°48'$, $\lambda = 15°31'$, $H = 1364$ m a.s.l.). It is situated in the Giant Mts., the highest mountain range in the Sudety. The data set incorporates hourly visual observations which contain characteristics of cloudiness and fog intensity expressed by visibility: (500 m–1 km) small, (200–500 m) medium and (below 200 m) dense. Fog at Mt. Szrenica was characterised according to atmospheric circulation assigned for the following days on the basis of Lityński's (1969) calendar. Eight main directions of circulation with distinction between cyclonic, anticyclonic and transitional were selected. Synoptic maps were used on a daily basis to define type of air mass present.

A 12-year data set (1954–1965) on number of days with fog observed at 51 meteorological stations of the Polish Weather Service (Roczniki Meteorologiczne, IMGW) and field measurements of fog frequency (1996–2000) were used to prepare a numerical map of NDF distribution in Sudety. The digital elevation model was extracted from the 30 arc sec data set prepared by the USGS EROS Data Center and resampled to a raster element size of 500 × 500 m.

3. Temporal variation of fog at Mt. Szrenica

At the top of Mt. Szrenica, fog exists during 274 days/year on average. The total time of fog duration in the period 1961–1990 reached 3900 h yearly, which corresponds to 44.5% of the year. Fog lasting the whole day was noted 53 times per year. The longest period registered at Mt. Szrenica with fog lasted for 371 h (15.5 days). A very dense fog with horizontal visibility of less than 100 m or less prevails (86%) during the total time of fog presence. Visibility during fog episodes in the Giant Mts. is inversely dependent on liquid water content—LWC (Błaś, 1997). Thus, LWC observed at Szrenica is at least significant in most episodes and varies in a range 0.1–0.6 g m^{-3} (ibid.). Observed NDF and liquid water content combined with mean wind speed accompanying fog episodes (11 m s^{-1}) show the potential role of horizontal precipitation in water balance.

As a result of the deformation of air streamlines produced by topography, orographic clouds are formed due to the adiabatic cooling and condensation of water vapour in the air

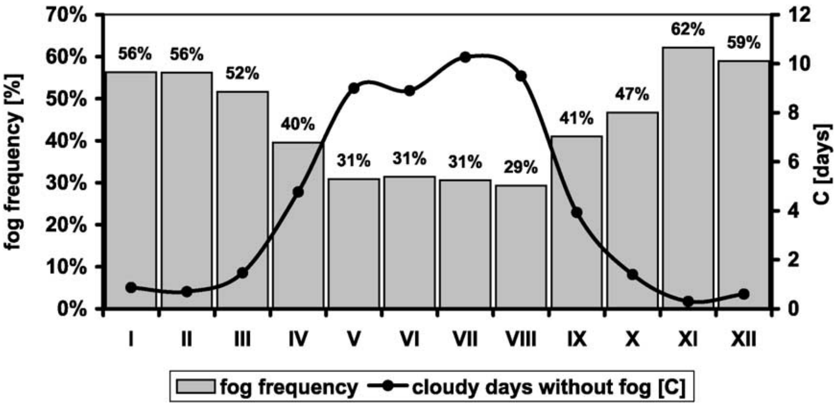

Fig. 1. Annual variation of fog frequency based on hourly data and number of cloudy days without fog (C) at Mt. Szrenica.

ascending the slopes. In the diurnal cycle, the maximum frequency of fog (exceeding 50%) was noted between 4 and 6 AM and the minimum during 1–3 PM, with frequency 39%. Such differences are connected with diurnal changes of air temperature. During decreasing air temperature in the morning hours, the saturation vapour pressure decreases and a reduction in the saturation mixing ratio of vapour can lead to condensation and formation of fog. The reverse phenomenon can be observed when the air temperature goes up during the day.

Similar relationships are evident in the annual cycle (Fig. 1). In the warmest months V–VIII, the frequency of fog reaches about 30% of total time and the condensation level more often occurs above the summit of Szrenica. A strong diurnal cycle in the condensation level during the summer and especially during the transitional seasons (spring and autumn) results from pronounced changes in temperature. This produces a strong diurnal signal in

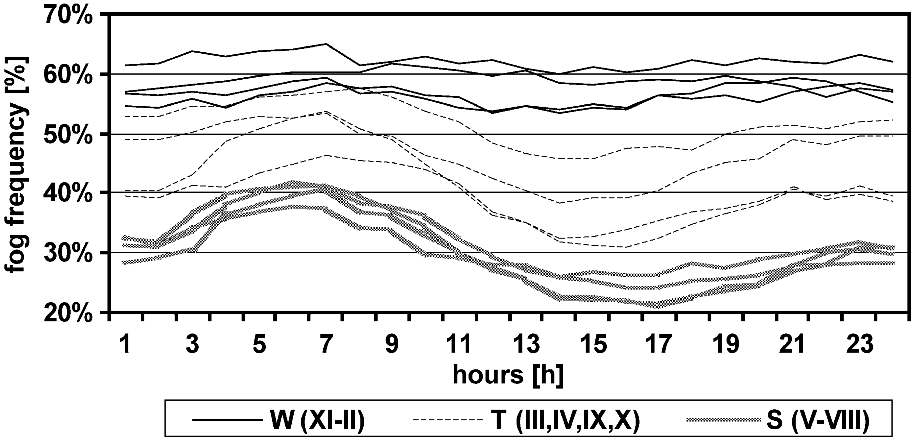

Fig. 2. Diurnal variation of fog frequency in winter (W), transitional (T) and summer (S) months at Mt. Szrenica.

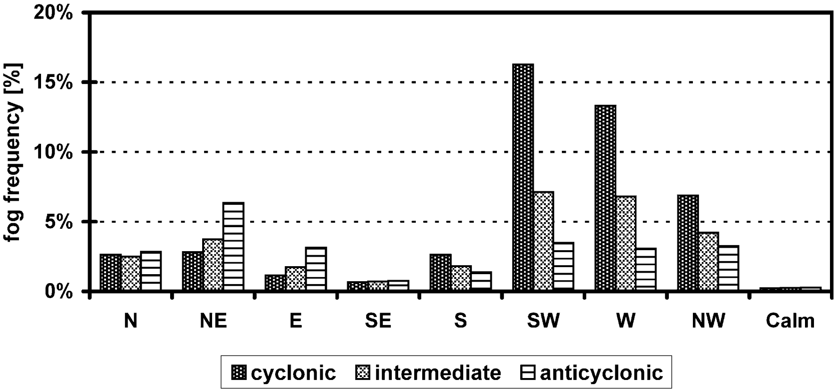

Fig. 3. Fog frequency versus wind direction and synoptic situation at Mt. Szrenica (cyclonic + intermediate + anticyclonic = 100%).

fog intensity with a more significant morning maximum (Fig. 2). In winter months XI–II, the diurnal variation of fog is much less significant. When high cloudiness in the lowest level of cloud was noted, Szrenica summit was considered to be above the frontal cloud base. The highest frequencies of 62% and 59% are typical for XI and XII, respectively, and are connected with seasonal dynamic cyclonic circulation. When the following low-pressure systems pass from W to E, fog could stay with short breaks at Mt. Szrenica for the entire weeks.

At Szrenica, fog is most often noted during circulation from the western sector SW–NW (Fig. 3). This involves advection of cool and humid polar-maritime or arctic air masses and the condensation level remains below Szrenica for the entire day (lack of the diurnal cycle in fog frequency). Fog was most infrequently registered when the direction of air flow was from sectors S and SE. These directions are associated with dry and warm tropical air of continental origin. Notably, the character of the pressure system (cyclone/anticyclone) was found to change the direction with the highest fog frequency.

In the days with anticyclonic situations, the peak of fog frequency was from the NE because in this sector, the Giant Mts. represent the highest relative height (1000–1200 m). In cyclonic situations with airflow from the NW, relative height is not so important because from this direction typically comes cool and humid oceanic air with condensation level below Szrenica.

4. Spatial variation of fog in Sudety

GRASS, a raster-based Geographic Information System, was used to implement a model for the spatial variation of fog in the Sudety. Based on the original digital elevation model, new raster maps were generated with a number of GRASS modules. These new layers reflect topographic properties (e.g. relative altitude, convexity/concavity, aspect) and provide independent variables $X_1 \ldots X_{10}$ to determine the frequency of NDF. Mean annual NDF at 51 meteorological stations, versus independent variables, was analysed using regression technique to estimate the significance of these variables for the overall spatial fog frequency.

Listed below are crucial parameters, which determine NDF from a statistical point of view and which were used in the model:

(1) Altitude above sea level—the forced ascent of humid air leads to the creation of stationary cap clouds covering the highest parts of mountains;

- (X_1)—true elevation value (m a.s.l.);
- (X_2)—average elevation within a 5 × 5 window;
- (X_3)—elevation squared [$X_3 = (X_1)^2/10\,000$];

(2) Form indicator (convexity/concavity)—radiation fog is typical for concave landforms and orographic or frontal fog for convex landforms, respectively;

- (X_4)—difference between true elevation (X_1) and median elevation in a 9 × 9 window;
- (X_5)—difference between true (X_1) and average elevation on a 5-km diameter circle (Fig. 4A);
- (X_6)—indicator of larger concave landforms calculated as the difference between the average in a 5 × 5 window (X_2) and average elevation on a 5-km diameter circle (Fig. 4B); this parameter considers only values below zero (Z) and is finally expressed as $X_6 = (Z)^2/100$;
- (X_7)—difference between the maximum in a 9 × 9 window and true elevation (X_1);

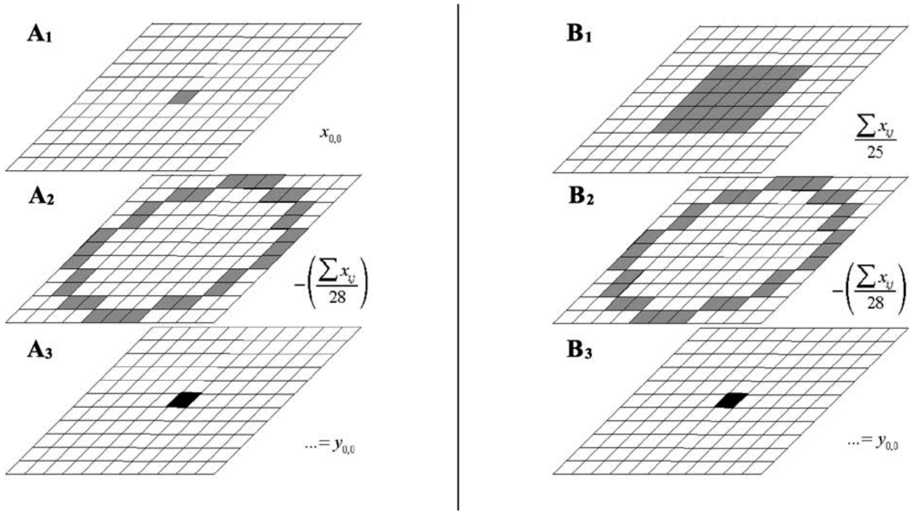

Fig. 4. Calculation procedure of concavity/convexity landform indicator: $A_1 - A_2 = A_3$ and $B_1 - B_2 = B_3$; where: A_1 and B_1—altitude and average altitude of an individual raster element, respectively; A_2 and B_2—average altitude on the 5-km diameter circle; A_3 and B_3—new raster layer; A_3 or $B_3 < 0 \Rightarrow$ concave landform; A_3 or $B_3 > 0 \Rightarrow$ convex landform.

(3) Exposure to the frequency of fog formation—the most humid air masses are associated with W–NW–N atmospheric circulation when the occurrence of cap clouds is more probable;

- (X_8)—applied when $X_4 > 0$ according to eight-aspect category of raster elements; FFα—contribution of fog frequency with airflow from direction α in total fog frequency at Szrenica [$X_8 = X_4 \mathrm{FF}\alpha$];

(4) Co-ordinates (W–E)—gradual decrease of moisture while air masses moving inland;

- (X_9)—distance from the western edge of the map in raster elements (500 m);

(5) Indicator of the frontal cloud base position versus a distance from the WNW edge of Sudety, that is, NDF depends on morphology in a large neighbourhood;

- (X_{10})—result of Eq. (1)

$$X_{10} = 226.51 S^{-0.9598} - 15 \tag{1}$$

with S: distance from NW edge of Sudety in number of raster elements calculated for areas above 800 m a.s.l., which is an average frontal cloud base height on the upwind slope of Izera Mts. This parameter was introduced to correct for underestimated NDF values in the western and overestimated NDF in the eastern part of Sudety.

The final Eq. (2) describes the distribution of NDF with determination coefficient $R^2 = 0.99$ and standard error of estimation 7 days.

$$\begin{aligned} \mathrm{NDF} = {} & -0.60369X_1 + 0.55466X_2 + 1.03713X_3 + 0.49098X_4 - 0.01886X_5 \\ & + 0.00135X_6 - 0.07163X_7 + 0.68659X_8 - 0.03277X_9 + 1.14403X_{10} \\ & - 84.66 \end{aligned} \tag{2}$$

Based on this equation, a map with estimates of NDF for the Western Sudety was generated. The fog is most frequent in two areas (Fig. 5): on the highest ridges in Giant Mts. (about 1300–1600 m a.s.l.) and at the westernmost orographic threshold in the Izera Mts (1000–1100 m a.s.l.). At Śnieżka (1602 m a.s.l.), the highest point in the Giant Mts., the model predicted 304 days with fog versus 303 observed. At Stóg Izerski in the Izera Mts. (1110 m a.s.l.), the model predicted 261 days versus 265 observed. The secondary maximum of NDF in Izera Mts is connected with both slope fog formation at the first significant orographic barrier and frequent immersion in sub-inversion clouds, which are formed in autumn and winter during anticyclonic situations, below the height of Giant Mts. ridges.

According to model predictions and observations, NDF is three times higher (50–60 days) at the bottom of concave terrain forms than in the lower parts of slopes (15–20

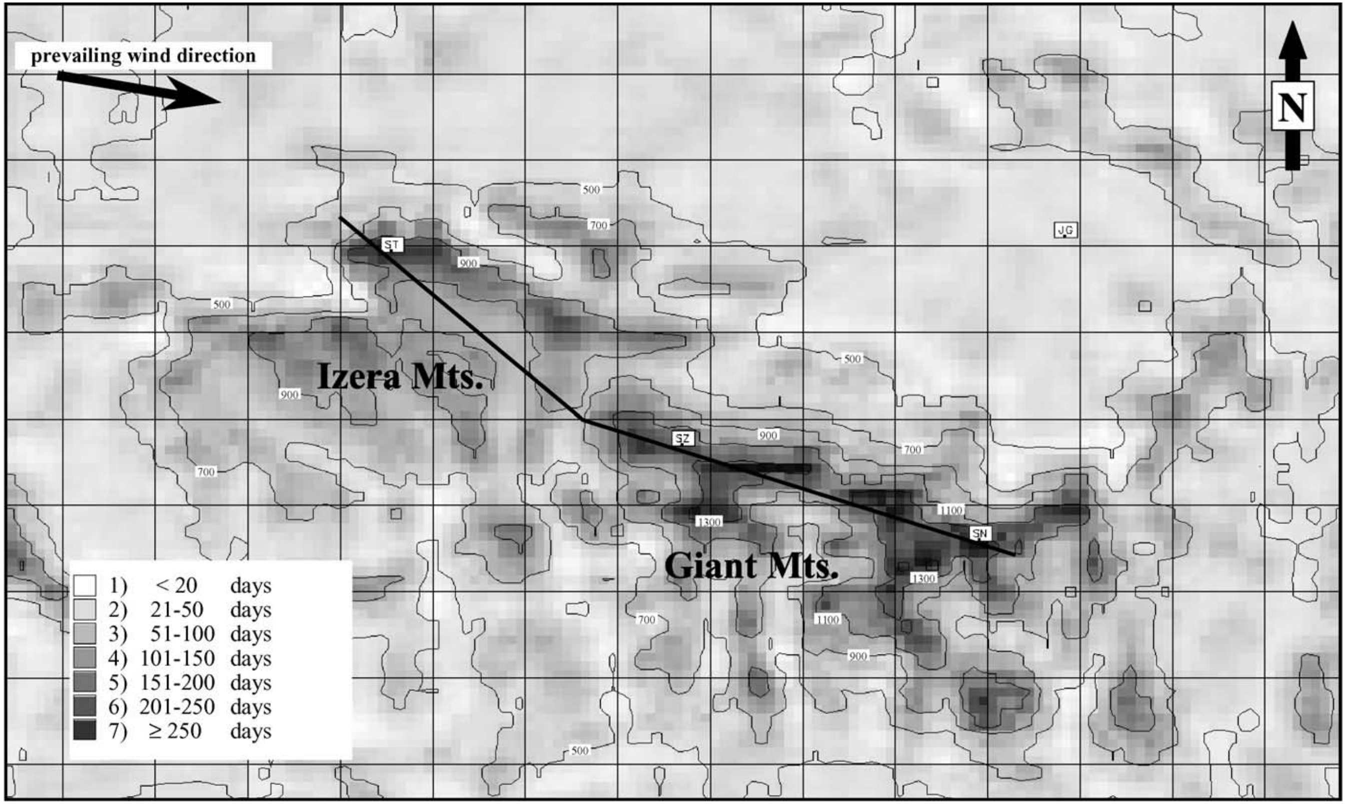

Fig. 5. Spatial distribution of annual number of days with fog in Western Sudety (grid resolution 5 km); marked points: JG—Jelenia Góra (342 m n.p.m., $\lambda = 15°48'$, $\varphi = 50°54'$); ST—Stóg Izerski (1110 m n.p.m., $\lambda = 15°17'$, $\varphi = 50°53'$); SZ—Szrenica (1364 m n.p.m., $\lambda = 15°31'$, $\varphi = 50°48'$); SN—Śnieżka (1602 m n.p.m., $\lambda = 15°44'$, $\varphi = 50°44'$).

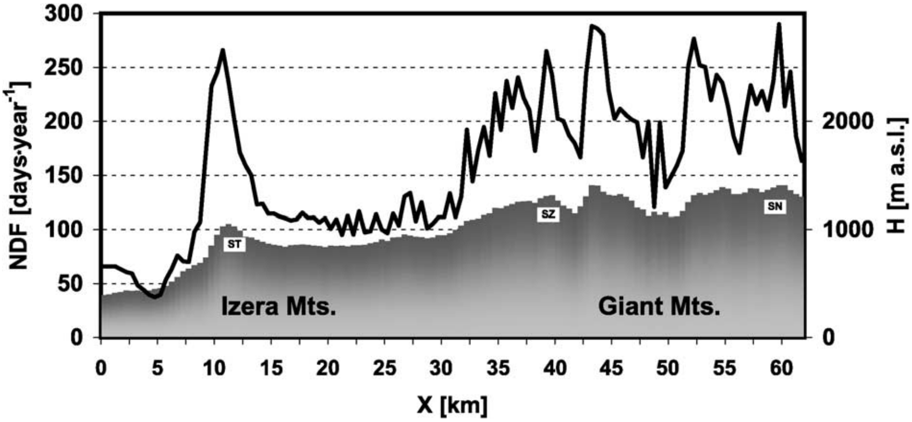

Fig. 6. Number of days with fog (NDF) in Western Sudety along NW–SE profile marked at Fig. 5.

days). Slopes with 100–150 m of relative height above the bottom of concave landforms are situated above the range of radiation fog and on the other hand, the base of frontal clouds seldom falls so low.

To clarify the role of the main factors controlling fog, values of NDF along NW–SE profile were extracted from the described GIS model (Fig. 6). It is clearly visible that in addition to altitude, other factors control NDF, e.g. relative height of a landform (mountains at 10, 43 and 52 km of the profile). On the other hand, sites situated quite high but screened by prominent landforms show relatively low NDF (see areas at 12 and 45–55 km of the profile). Such features are very important for slope fog formation at a given site during a given air flow type. This profile shows also some side effects due to the quality of the digital elevation model and processing steps. The fluctuations, e.g. between 15 and 35 km are caused by averaging of three values perpendicular to the profile and systematic effects in the interpolated digital elevation model. Due to the limited number of observation series at higher elevations, the statistical base for this part of the area is fairly small. Nevertheless, the overall picture corresponds fairly well to the observations made in the Sudety.

5. Conclusions

In the course of a year, frontal fog is more typical for the cold season (XI–IV), when fog occurs 50–60% of the time. The average frequency during the course of a day is very high with a weak diurnal cycle. This is connected to the predominance of humid air masses and the small diurnal periodicity of temperature. Such situations are not so frequent during the warm season (V–X), and the influence of the daily cycle of temperature is much more visible, producing significant morning maximum and early afternoon minimum of fog frequency. The diurnal cycle of fog frequency is reversed in comparison with temperature.

Generally, the occurrence of fog and clouds on a mountain range is affected by altitude. The derived map shows that locally parameters such as landform type, slope aspect, island mountain morphology and position at the windward side of a larger massif can be more important for spatial fog variability than altitude.

Acknowledgements

The authors would like to express thanks to Dr. Robert S. Schemenauer and sponsors of the 2nd Conference "Fog and Fog Collection" in St. John's, Canada, who supported our participation and to the Swedish Institute supporting the co-operation between the Institutes in the framework of the Visby Program.

References

Baron, H., Sobik, M., 1995. The function of precipitation in acidification of upper parts of the Karkonosze. Acta Universitatis Wratislaviensis 1705, 59–73.

Błaś, M., 1997. Experimental measurements of cloud liquid water content in summer and winter conditions. Acta Universitatis Wratislaviensis, t. IV, 147–153.

Błaś, M., Sobik, M., 2000. Fog in Giant Mts. and Selected European Massifs, vol. 1. Opera Corcontica, Prague, Czech Republic, pp. 35–46.

Dore, A.J., Sobik, M., Migała, M., 1999. Patterns of precipitation and pollutant deposition in the western Sudetes mountains, Poland. Atmospheric Environment 33, 3301–3312.

Jała, Z., Błaś, M., 2000. Wybrane Właściwości Chemiczne Gleb na tle Mokrej Depozycji Zanieczyszczeń Atmosferycznych w Sudetach, 2001, vol. 1. Opera Corcontica, Prague, Czech Republic, pp. 69–78.

Kmieć, G., Zwoździak, A., Kacperczyk, K., Zwoździak, J., 1998. Influence of liquid water content on chemical composition of clouds and precipitation. Geoekologiczne Problemy Karkonoszy - Materiały z sesji naukowej w Przesiece 15-18.X.1997, 163–170.

Lityński, J., 1969. Liczbowa klasyfikacja typów cyrkulacji i typów pogody dla Polski. Prace PIHM 97, 3–15.

Moravčik, P., Černy, M., 1995. Forest die-back affected regions of Czech Republic. Acid Reign '95, Proc. from the 5th Int. Conf. on Acid Deposition, Goeteborg, Sweden, 26–30 June 1995; Acidification in the Black Triangle (excursion comments), pp. 11–22.

Roczniki Meteorologiczne, IMGW.

Sobik, M., Migała, K., 1993. The role of cloud water and fog deposits on the water budget in the Karkonosze mountains. Alpex-Regional-Bulletin 21, 13–15.

Sobik, M., Błaś, M., Quiel, F., 1998. Contribution of fog precipitation in water flux and pollutant deposition in montane ecosystems, western Sudetes, Poland. Geoekologiczne Problemy Karkonoszy - Materiały z sesji naukowej w Przesiece 15-18.X.1997, 151–162.

Tesař, M., Šir, M., Fottová, D., 2000. Long-term cloud and fog water deposition monitoring in southern Czech Republic. Silva Gabreta 4, 87–96.

Woźniak, Z., 1991. Osady z mgły w Sudetach (znaczenie osadów i sposób pomiaru przychodu wody z mgły). Prace Karkonoskiego Towarzystwa Naukowego 53, 24–34.

Zwoździak, J., Zwoździak, A., Kmieć, G., Kacperczyk, K., 1993. Przyczyny zanieczyszczenia atmosfery w wyższych partiach SudetówKarkonoskie Badania Ekologiczne I Konferencja Wojnowice, pp. 19–32.