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THE INTENSITY OF DIFFERENT KINDS OF RIME ON THE UPPER TREE LINE IN THE SUDETY MOUNTAINS

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Abstract. Based on many years of measurements and observations on the frequency and intensity of deposition of various types of rime which have been conducted by the Department of Meteorology and Climatology of Wrocław University at the top of Szrenica, Sudety mountains, a hundred meters above the tree line, the essential factors influencing this feature have been determined and are discussed. The upper parts of the Sudety mountains belong to the regions with the most frequent and heaviest rime deposits in Europe, which often appears to be hazardous to farming. It has been found that intensity of rime deposition depends clearly on air temperature and wind velocity, and it is related to certain types of weather situations characterized by types of atmospheric circulation delineated by Konček and Rein (1971).

Résumé. *L'intensité des differents types de givre à l'altitude de la limite superieure de la forêt dans les monts de Sudetes.* Depuis de longues années des mesures et des observations sur la fréquence et l'intensité du dépôt de différents types de givre sont exécutées par le Département de Météorologie et de Climatologie de l'Université de Wrocław au sommet du mont Szrenica, dans les monts des Sudety à une centaine de mètres au-dessus de la limite de la forêt. Sur les bases de ces recherches, on discute et on détermine les facteurs essentiels qui influent sur ces dépôts. Le haut des monts des Sudety confine aux régions où les dépôts de givre sont les plus fréquents et les plus abondants d'Europe, ce qui semble souvent dangereux pour l'agriculture. On a trouvé que l'intensité des dépôts de givre dépendent manifestement de la température de l'air et de la vitesse du vent et qu'elle est en relation avec certaines situations météorologiques caractérisées par les types de circulations atmosphériques décrites par Konček et Rein (1971).

Zusammenfassung. *Die Intensität verschiedener Reifarten an der oberen Waldgrenze in den Sudeten.* Auf der Basis langjähriger Messungen und Beobachtungen über Häufigkeit und Intensität der Bildung verschiedener Reifarten, ausgeführt von der Abteilung für Meteorologie und Klimatologie an der Universität Wrocław am Gipfel des Szrenica in den Sudeten, etwa 100 m oberhalb der Waldgrenze, werden die wesentlichen Einflussgrössen für dieses Phänomen bestimmt und diskutiert. Die Hochregion der Sudeten gehört zu den Gebieten häufigster und stärkster Reifbildung in Europa; die Landwirtschaft hat deshalb dort mit grossen Schwierigkeiten zu kämpfen. Die Intensität der Reifbildung erwies sich klar als abhängig von der Lufttemperatur und der Windgeschwindigkeit; sie steht in Beziehung zu bestimmten Wetterlagen, die sich durch die von Konček und Rein (1971) beschreiebenen Typen der atmosphärischen Zirkulation charakterisieren lassen.

Introduction

Atmospheric ice formation, especially clear rime, is a very serious threat to farming in the mountains. Under the weight of rime, tree branches, telephone and electric cables break. The immense permanent accumulation also disrupts chair lifts and cable cars as well as meteorological apparatus. The danger of damage increases in the presence of strong winds which in the mountains often accompany the appearance of rime.

In Poland, very few works have hitherto appeared treating the various types of rime. In addition to the early publications of Smosarski (1918) and Dobrowolski (1923), it is necessary to mention the many-sided works of Orlicz and Orliczowa (1954), Orliczowa and Samaj (1974) discussing rime in the Tatras (on Kasprowy Wierch and Lomnica), as well as the work of Sadowski (1965) delineating the frequency and weight of the various types of rime in the Polish lowlands from the point of view of energy requirements. Several authors have occupied themselves with the serious problem of the role of rime in the water balance (Ermich, 1958; Ermich and others, 1967; Woźniak, 1975). Lityńska and others (1969) discussed the problem of conditions of permanent rime appearance in Poland along with their forecasting for the purposes of communications. Several articles on the topic of damage caused by rime on energy distribution and forests have also appeared.

Until recently, very little attention has been given to the problems of rime in the Sudety mountains. In the works of Hellman (1915) and Rink (1938) information can be found on the topic of rime frequency as a result of tests carried out at the meteorlogical observatory on

Śnieżka. On the basis of materials gathered from Szrenica (west Sudety) one of the co-authors of this work carried out initial analysis on the frequency and intensity of this phenomenon (Liebersbach, 1975).

Test sites

The test sites discussed in this work were located in the upper part of the main Karkonosze range—the highest and broadest massif in the Sudety.

The central ridge of the Karkonosze is a great, granite mountain massif with a noticeable flat peak at an altitude of 1 380–1 450 m a.s.l. with steep north slopes. Above these peaks rise the isolated dome-shaped pinnacles of Śnieżka (1 602 m), Smogornia (1 489 m) and Szrenica (1 362 m) covered with block-strewn slopes. The vegetation found there is characteristic of that found in high mountains. The following is the vegetation format:

480– 950 m—lower belt of sub-alpine forest presently occupied by planted spruce;
950–1 250 m—higher belt of sub-alpine forest, the domain of large, natural spruce forests; the upper limit of this belt is also the upper tree line having an altitude of 1 100–1 280 m;
1 250–1 450 m—zone of dwarf mountain pine (sub-alpine) relatively untouched by man;
1 450–1 600 m—zone floor with mountain pastures and block slopes.

In the territory of the Karkonosze mountains, forests take up 85% of the area. In most of this these are both natural forest of mixed tree types (54%) and natural high-mountain forest (25%).

The physiographical separateness of the Karkonosze mountains is among other things the result of their distinct climatic character. Owing to the great differences in heights (400–1 600 m) and the latitudinal orientation of the axes of the range, the Karkonosze mountains stand out as having noticeable differences in solar radiation, circulation, temperature, and humidity conditions.

Among the types of atmospheric circulation delineated by Konček and Rein (1971) the most common two are: (i) anticylonic type with the centre over Central Europe (13.2%); (ii) western cyclonic type with frontal zones travelling from west to east (13.1%). As a result of these two types, in the Karkonosze mountains, like the whole Sudety, west, south-west, and north-west winds prevail. In the higher parts of the mountains, south-west winds prevail, while in the foothills north-west winds are more common. The average yearly wind velocity in the lower slopes is 2 m s^{-1}, while near the peaks the velocity varies from 9 to 11.5 m s^{-1}. Typical here are the strong föhn-type winds.

The average annual air temperature in the Karkonosze territory is 4.7°C. Of course, the coolest readings are found on the peaks (Śnieżka 0.4°C, Szrenica 1.5°C). The cold half-year temperature has been found to be −4.0°C, whereas the minimum January temperature was observed to be −10.0°C. The number of days with sub-freezing temperature ranges from 40 at the base to 130 at the peak.

The Karkonosze mountains are known for high air humidity. At the peaks, the average reading was observed to be 86%, and this is 6–8% higher than at the foothill level. At the higher altitudes a great variability in this humidity can be observed. Very often several days of high humidity (98–100%) occur, and not infrequently also very low humidity conditions (below 40%). Cloud-base altitude most often occurs at the order of 1 000–1 200 m, thus fog is a very frequent phenomenon at the higher altitudes. As an example, during 1963, Szrenica found itself enveloped in fog on 261 days, and of these the condition was constant for a 24 h period for a total of 71 days.

Because the Karkonosze mountains are found in the European territory of frequent fog accompanied by low temperatures and strong winds, there is a high frequency and high intensity of icing. On Śnieżka (1 605 m) were observed an average of about 160 days with

rime; while on the much higher peak Kasprowy Wierch in the Tatras (1 988 m) about 150 days were recorded. In the higher altitudes of the Sudety, about 50% of the available water originates from this rime (in the Tatras the corresponding figure is only 25%).

Methods of measuring rime

The Department of Meteorology and Climatology of the University of Wrocław, from 1958, has conducted wide research on atmospheric ice formation in addition to standard meteorological measurements. All of this takes place on Szrenica in the Karkonosze mountain region. One observation outpost is situated at an altitude of 1 329 m in the zone of dwarf mountain pine about 80 m above the upper forest line and represents the region of flat peaks. The second point is located on the observation tower situated on the very top of Szrenica (Fig. 1), which serves to represent the pinnacles of the Sudety mountains.

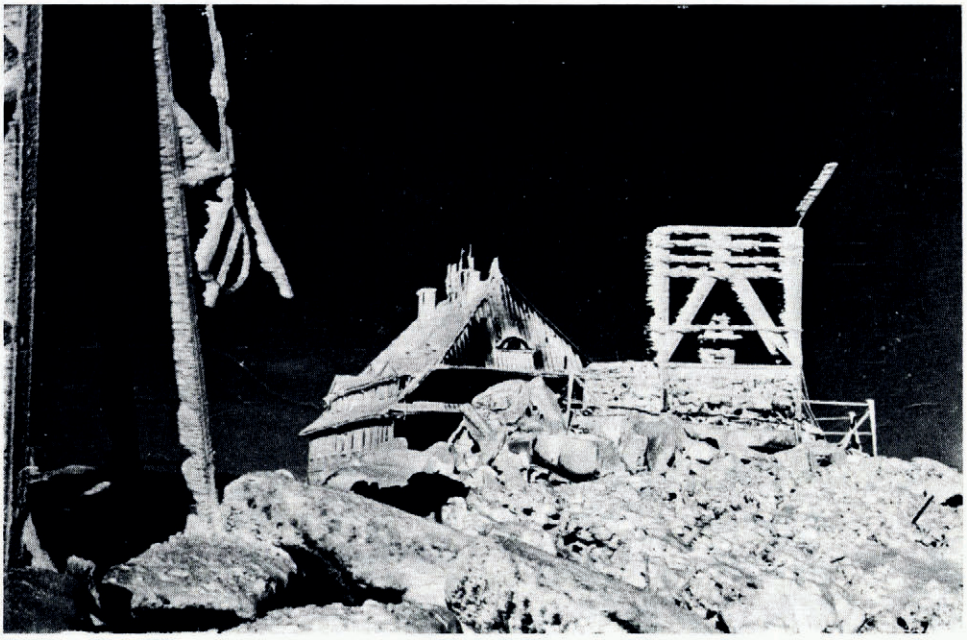

Fig. 1. The summit of Szrenica with tourist house and tower on which measurements of rime deposition were conducted.

Grunow nets (tubes of wire netting 20 cm long and 10 cm in diameter) and aluminium pipes (45 cm long and 3 cm wide) are used to measure icing conditions. At times of climatological observations (7.00 h, 13.00 h, 21.00 h), the layer thickness is measured in addition to the ice mass accumulated on the apparatus. Visual observations are also made as to the accretion direction and the type of ice in accordance with the morphological-meteorological classification (Grunow, 1953; Zamorski, 1955). In this present work, the most complete and most reliable data from the years 1965–70 has been used.

In addition to the above systematic procedures, in the area of Szrenica, series of special measurements have been taken under chosen weather conditions. They were normally carried out each hour with the aid of the Grunow net, a straight-forward ice direction determinator, along with an "artificial tree" imitating a dwarf spruce. In addition, the character of rime was tested in relation to terrestrial, natural objects—especially tree branches, dwarf mountain pine, rocks and boulders, and snow cover.

Research results

A six-year series of this systematic observation in the region of Szrenica, upon which this report is based, has yielded rich material allowing for the determination of the essential factors in atmospheric ice formation in the higher altitudes of the Sudety mountains.

It has been observed that at altitudes higher than the upper forest line the most frequent type of ice formation is hard rime (54% of observation time); secondly clear rime (9%); and finally soft rime (8%). In 29% of the observation time a mixture (mixed rime) was observed, in which the greatest portion was that of hard and clear rime (13%). The average number of days in which total rime formation (of all types) occurred was found to be 150 during the course of the whole year. This result supports the earlier research of Hellmann (1915) and Rink (1938). The greatest number of days with rime formation occur during January and December, the most sporadic rime formation occurring in July and September. Rime formation was never noticed during the month of August (Fig. 2). In the higher altitudes of the Sudety mountains rime formation occurs for periods lasting from 1 to 48 days. As in the Tatras, periods of 1–3 days were recorded most often (50% of the recorded time).

The intensity of total rime formation measured on the Grunow net with an area of 200 cm^2 was found at the Szrenica peak observatory to average 35.5 g h^{-1}, which roughly equals 1.8 kg m^{-2} h^{-1}. The greatest intensity was found during November and December (about 2.0 kg m^{-2} h^{-1}). Amongst the three main types of rime, the most intensive formation was

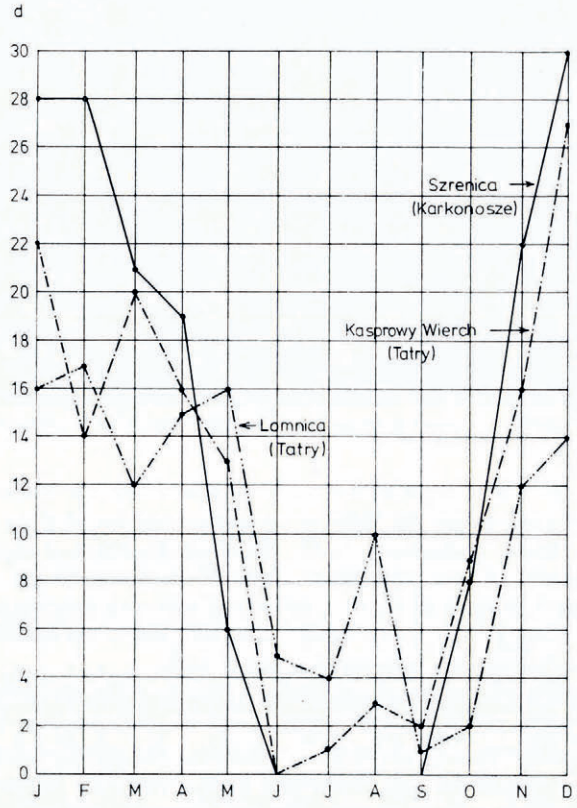

Fig. 2. Number of days with rime (icing) on Szrenica, as comparated with Kasprowy Wierch and Lomnicki Stit (after Orliczowa and Samaj, 1974).

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that of clear rime (averaging 2.0 kg m^{-2} h^{-1}); followed by hard rime (1.8 kg m^{-2} h^{-1}); and finally, soft rime (0.7 kg m^{-2} h^{-1}). An annual intensity graph of these types is shown in Figure 3. In the zone of dwarf mountain pine near the upper forest limit, the rime formation intensity is almost four times smaller.

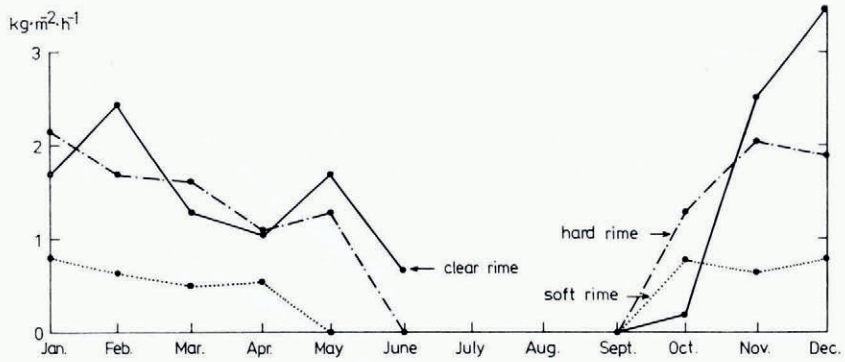

Fig. 3. Annual course of deposition intensity of soft rime, hard rime and clear rime on Szrenica.

At both observation points located on Szrenica, the bulk of the atmospheric ice accumulation occurs at air temperatures from −6 to 0°C, especially so when the temperature lies between −3 to −2°C. The maximum intensity of rime formation also takes place in this −3 to −2°C range; but the greatest frequency of rime formation is associated with the temperature range of −6 to −3°C. The dependence of the various types of rime formation on temperature is shown in Figure 4. Most probably this type of dependence is characteristic for the whole Sudety mountain range.

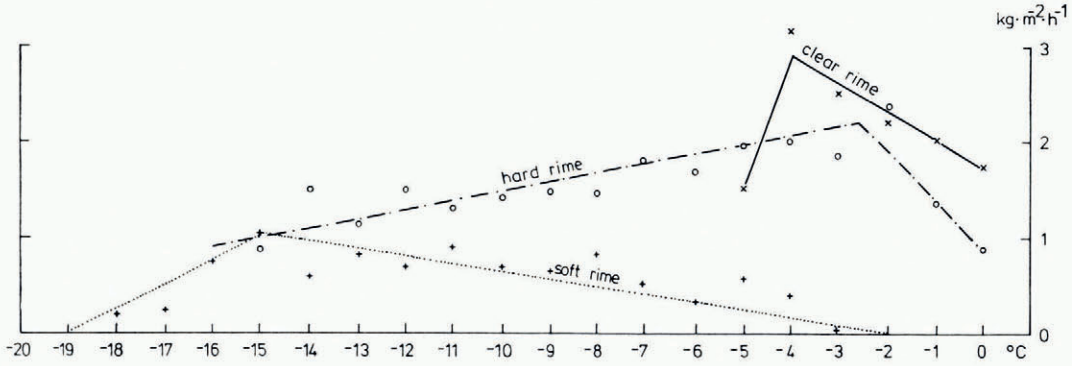

Fig. 4. Dependence of intensity of deposition of various types of rime on air temperature on Szrenica.

Measurements taken at the Szrenica site show that the intensity of rime formation i is a clear function of wind speed v, but it is different for the various types of rime (Fig. 5). The following are the regression functions:

soft rime: $i = 0.075v$;
hard rime: $i = 0.15v$;
clear rime: $i = 0.21v$;

the correlation coefficients respectively being: 0.60, 0.50 and 0.45. The greater the rime density, the greater the growth intensity of its formation with increasing wind velocity. The

correlation would not be expected to be higher because temperature, liquid-water content and droplet size are neglected.

Considering the average wind velocities which accompany the wind directions that bring to the Sudety the various rime types, one can determine the optimal meteorological conditions for their formation, and these are given in Table I.

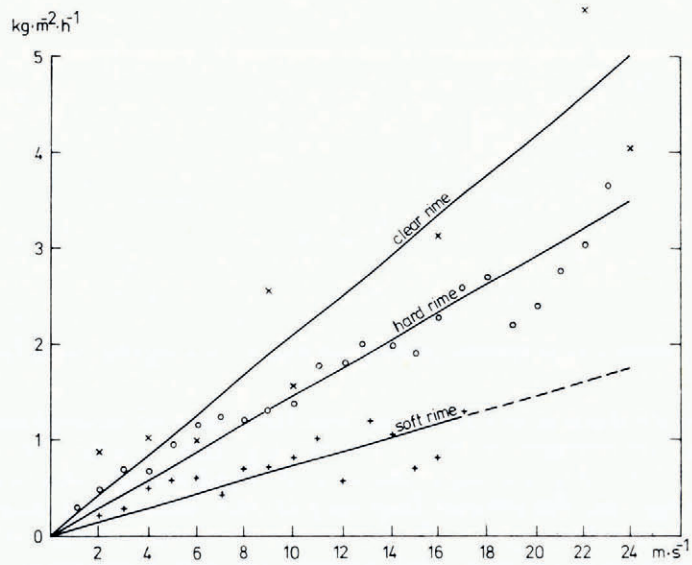

Fig. 5. Dependence of intensity of deposition of various types of rime on wind velocity on Szrenica.

TABLE I. OPTIMAL METEOROLOGICAL CONDITIONS FOR RIME FORMATION

	Temperature °C	*Wind direction*	*Rime formation intensity* kg m^{-2} h^{-1}
Hard rime	−2 to −3	S.W., N.E.	2–2.5
Soft rime	−14 to −15	N.E.	1–1.2
Clear rime	−3 to −4	S.S.W., S.S.E.	2.5–3

In the Sudety mountains, intensive riming is associated with a certain type of atmospheric circulation. Using the Konček and Rein classification (1971), it has been proved that for hard rime the most conducive conditions are the western-cyclonic type Wc (Fig. 6a). As an example, in Figure 7 is presented the synoptic situation in Europe for 18 March 1970, relating to this type of circulation when an especially intense hard rime occurred in the Sudety. The investigated region then found itself under the warm sector of a depression centred over the North Atlantic, which caused an intensive flow of air from the west. This type of circulation is most common in the Sudety mountains. As mentioned earlier, its yearly average frequency is 13.1%, but during the cold half of the year this increases to 15.6%. Associated with this western-cyclonic circulation is: (i) the greatest amount of rime formed (36% of the overall mass); (ii) the greatest recorded frequency of formation (22% of all cases); (iii) average intensity of the overall icing formation (2.75 kg m^{-2} h^{-1}). In this hard rime is mainly found.

The greatest intensity of soft-rime formation, occasionally reaching 3 kg m^{-2} h^{-1}, occurs during north-easterly-cyclonic circulation type NEc (Fig. 6b). Although this circulation type is not found in the Sudety mountains at all frequently (averaging only 3.3% over the year),

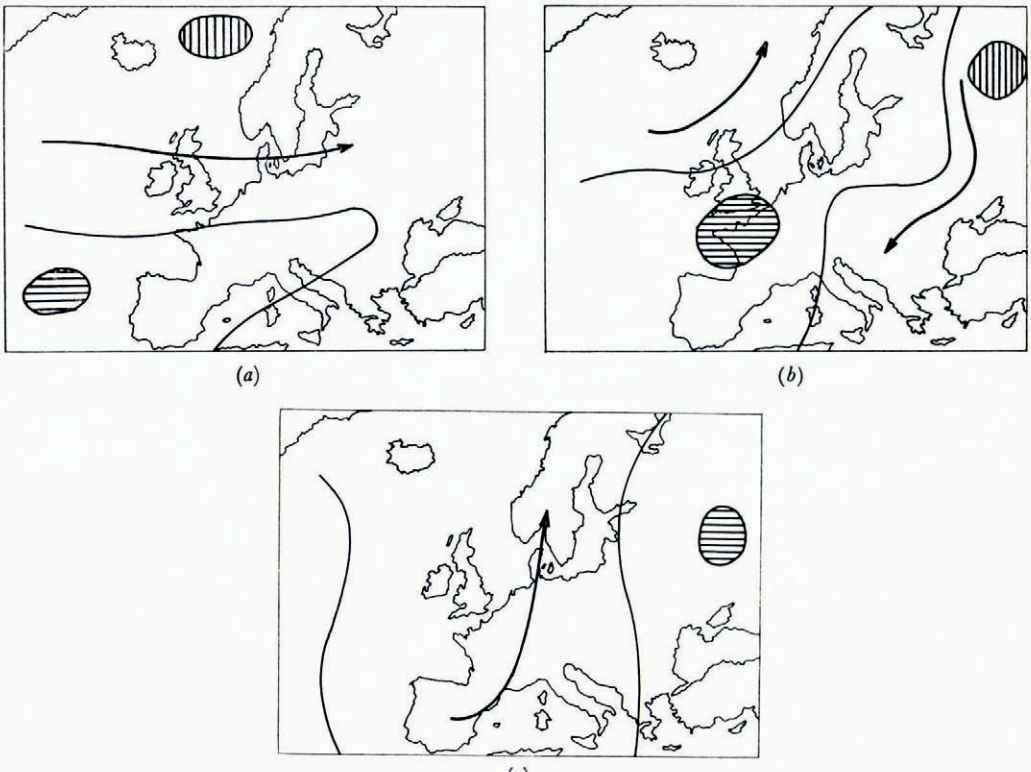

Fig. 6. Chosen types of circulation (after Konček and Rein, 1971) for Central Europe. Patches hatched horizontally show predominant location of anticyclonic centers, patches hatched vertically show predominant location of depression centres, arrows give routes of depressions and atmospheric fronts at sea-level. (a) type Wc, (b) type NEc, (c) type SWc_1.

it gives almost 22% of the total bulk of soft rime. It occurs when the northern European sector of the Soviet Union along with the region of the Mediterranean Sea occupy shallow lows, whereas in Central Europe, where weak gradients prevail, cool old maritime polar air masses flow in from the north.

Weather conditions leading to immense formation of clear rime are especially hazardous to trees and technical apparatus near the upper tree line. Such conditions occur most frequently when the circulation type is south-western-cyclonic (SWc_1) as defined by Konček and Rein (Fig. 6c). This is when warm and humid air comes slowly from the south and climbs the southern slopes of the Sudety ridge cooling adiabatically to temperatures close to 0°C. It was under such circumstances that the formation intensity of clear rime reached a record level of 7.5–12.5 $kg\,m^{-2}\,h^{-1}$, although great fluctuations in the intensity were usually observed during the deposition.

In the natural, strongly diverse terrain conditions occurring in the upper altitudes of the Sudety mountains, immense variations in the intensities of icing formations naturally exist. The results of rime tests on instruments of various shapes (pipes, tiles, nets, artificial trees) and similarly the observations of rime growth rates on natural objects (trees, bushes, boulders) and man-made objects (towers, buildings, overhead cables) lead to the opinion that the rime formation intensity depends very strongly on the degree of branching of a given object. The highest degree of branching is shown by spruce tree branches, so rime accumulates most

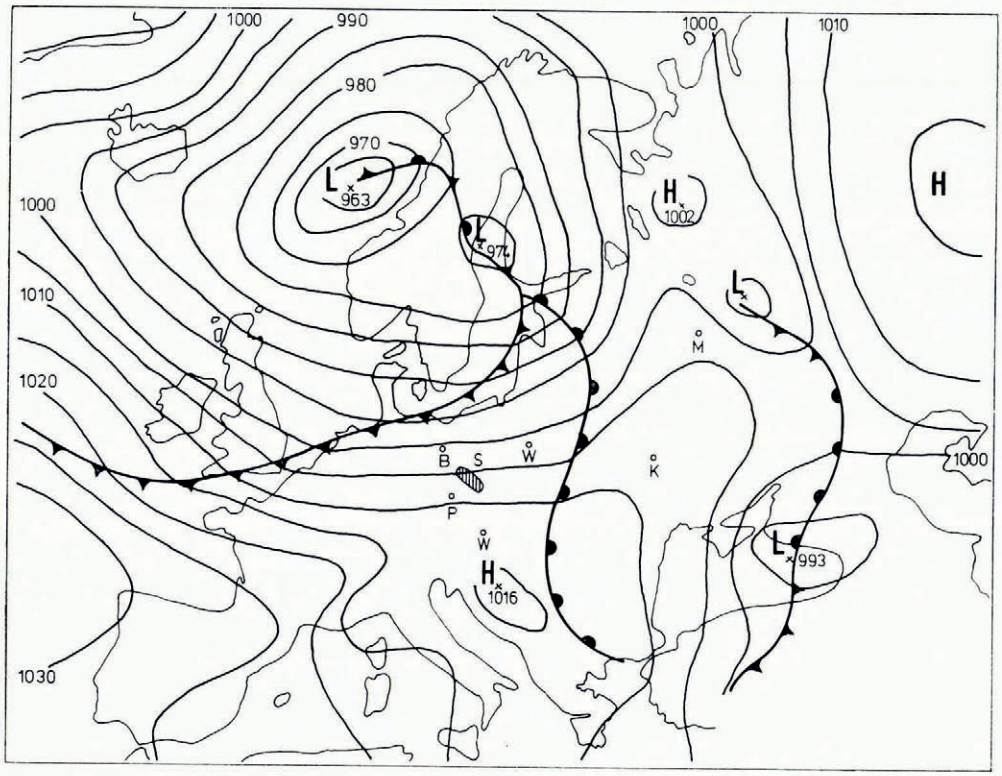

Fig. 7. Synoptic situation in Europe on 18 March 1970, 00.00 h GMT, relating to the Wc type of circulation. In the Sudety mountains particularly intense hard rime occurred.

intensively on them. For example, on one spruce tree, 70 cm tall with a diameter at the tree base of 40 cm, one of a series of measurements conducted under moderately intensive accumulation of rime (1.5 kg m^{-2} h^{-1}, as shown by the Grunow net) revealed that during one hour roughly 750 g of rime was deposited. It has, however, been proved that under conditions of stable potential intensity of rime formation (as shown by a systematically cleaned apparatus) the rate of rime deposition on permanently exposed branched objects falls rapidly after several hours. This is because rime formation lessens the degree of branching at first diminishing the effective surface area of such objects. However, if deposition of rime is prolonged, a secondary gradual increase in intensity of rime deposition may be observed, because in the course of rime accretion to the object the overall effective area of accumulation increases. Such a type of rime formation is characteristic to spruce branches, dwarf mountain pine, as well as strongly branched technical constructions. Whereas the rate of rime deposition on overhead cables and lines grows gradually; in case of buildings, compact constructions and exposed rocks this rate remains much the same, although it is distinctly smaller. Still smaller and more constant is the rime formation rate on uniform snow cover. Compared with the rime deposition on tree branches 2–3 m above the surface, it is 10 to 20 times smaller.

Great diversity in the intensity of icing accumulation in the mountains is also the reason for serious difficulties in establishing the role played by rime in the water balance of these regions.

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