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OBSERVATIONS ON RIME FORMATION IN RELATION TO ROUTINELY MEASURED METEOROLOGICAL PARAMETERS

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Abstract

An attempt to evaluate the growth rate of rime using routinely measured meteorological parameters is made. The data are from rime gauge observations in northern Finland. A significant relationship between the rate of rime formation I and the wind speed v is found. The cloud height observed in the valley area proves to be useful in determining the duration of rime formation on the hills: The wind speed multiplied by the time during which the cloud base is at a lower elevation than the rime observation point seems to be a reasonable predictor of the ice load. There is no dependence of I on air temperature t_a. However, the occurrence of glaze instead of rime is affected by t_a as well as by v. The intensity of ice accretion does not correlate with precipitation measured with a rain gauge. This indicates that rime deposition on vegetation should be treated as an independent factor when examining the water balance of regions where icing conditions are common.

1. *Introduction*

The formation of ice loads on structures due to rime deposition is a serious hazard to human activities in cold regions. Atmospheric ice accretion is often followed by heavy damage to power lines, masts, telephone cables etc. The economic impact of a single ice storm can be of the order of 100 million dollars (MCKAY and THOMP-

SON, 1969). In Finland the main problems caused by rime have been damages to forests (SOLANTIE and AHTI, 1980) and the destruction of radio-masts.

The optimum structural design and positioning of power lines, for example, require information on the probability of occurrence and on the expected intensity of ice accretion in different atmospheric conditions. Therefore data on the frequency of different types of ice deposits (soft rime, hard rime, glaze, wet snow) in different air temperatures, wind speeds and intensities of precipitation have been collected in many localities (*e.g.*, LENHARD, 1955, SADOWSKI, 1965, RUDNEWA, 1973). However, there is little quantitative information about the dependence of the ice formation intensity on these variables. Hence the possibilities of estimating or predicting the growth of ice loads are very limited – the present methods giving differences of one order of magnitude after 100 hours of deposition.

In order to develope at least a rough estimation method, and to study the ice accretion phenomena in Finland in more detail, measurements of ice accretion together with registration of meteorological conditions were made in different localities during 1970's. Some qualitative results of these measurements have been published earlier (AHTI, 1980). In this paper the results related to the quantitative estimation of ice loads are presented. The results are limited to the cases of rime formation only, since heavy deposition of clear ice was too rare for making a corresponding analysis for glaze.

2. *The measurements*

The data of this study is from three separate series of measurements. The first experiment aimed at revealing the possible connection between precipitation and the amount of accreted ice, and the second experiment at studying the dependence of the rime formation rate on air temperature and wind speed. In the third experiment the conditions in which rime formation changes to glaze formation were examined.

The measurements of the daily ice accumulation and the daily amount of precipitation were made at the Värriö Subarctic Research Station (67°45′N, 29°37′E, altitude above sea level = h = 390 m) during the winter 1972–73. The instrument for collecting rime consisted of four vertical sheets made of steel (Fig. 1a). This instrument was also compared with a vertically situated aluminium cylinder of the same projection area and was found to give, on the average, identical results. The amount of accreted ice was measured by determining its volume after melting. Precipitation was measured with a standard Finnish precipitation gauge.

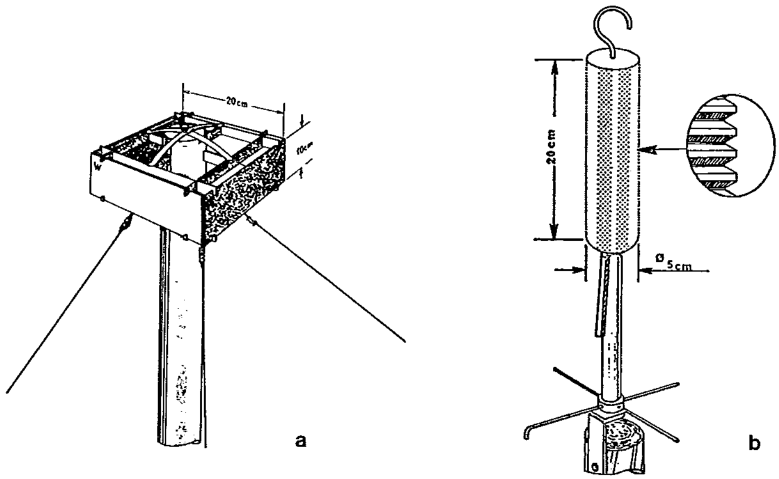

Fig. 1. The rime measurement instrument used at Värriö 1972–73 (a) and the instrument used at the Finnish rime measurement stations after 1976 (b).

The experiment for studying the dependence of rime formation intensity on air temperature and wind speed was made at Pyhätunturi (67°01′N, 27°13′E, h = 477 m) during the winter 1976–77. In this experiment a 5 cm diameter aluminium cylinder (Fig. 1b) was used to collect the ice deposit. The wind speed was recorded with an integrating cup-anemometer. The ice accumulation and the average wind speed were observed once a day, and the time of accumulation was determined as the time at which the cloud base observed at the Rovaniemi airport (80 km to the south-west, 66°31′N, 25°50′E, h = 197 m) and Sodankylä Geophysical Observatory (45 km to the north-west, 67°22′N, 26°39′E, h = 190 m) was lower than the elevation of the observation point. There were no temperature measurements at Pyhätunturi but air temperature was determined from the synoptic observations and from the temperature soundings at Rovaniemi and Sodankylä. The error introduced by this procedure presumably did not exceed ±2 °C because of the uniform structure of the temperature profiles in the observed icing situations.

In addition to the measurements directly related to the rate of rime formation, measurements were made to determine the meteorological conditions in which the change from the formation of rime to the formation of clear ice, *i.e.*, glaze, occurs. The data are from three localities where ice accretion is quite common but where the intensity of accretion is too small for studying its connections with meteorological conditions. In these locations (Rovaniemi, Sodankylä and Jyväskylä airport, 62°24′N, 25°40′E, h = 143 m) wind speed and air temperature were measured in the vicinity of the ice collector (cylinder in Fig. 1b). The type of the ice deposit was determined visually.

3. *Estimation of the rate of rime formation*

3.1 Precipitation

The amount of precipitation measured with a rain gauge has often been used in examining the intensity of ice accretion (LENHARD, 1955, GRUNOW and TOLLNER, 1969, MCKAY and THOMPSON, 1969, CHAINE, 1973, MCLEOD, 1981). Following this approach the correlation coefficient between the daily amount of precipitation and the measured ice deposit was calculated for the data from Värriö. No correlation was found ($r = -0.08$). Ice deposit and precipitation data is given in Fig. 2.

Our results may be affected by local factors which play an important role in determining the frequency of precipitation during ice accretion (LOMILINA, 1977). However, it should be pointed out that actual data from other localities, too, do not support the usefulness of precipitation in estimating the rate of formation of ice loads: WAIBEL (1956) found no connection between precipitation and icing intensity in Feldberg, West Germany and the correlation coefficient obtained by LENHARD (1955) was not more than 0.41 for the data from Pennsylvania, USA. It has also been shown by RINK (1938), SADOWSKI (1965) and LOMILINA (1977) that the majority of cases of rime formation occurs during days with no precipitation.

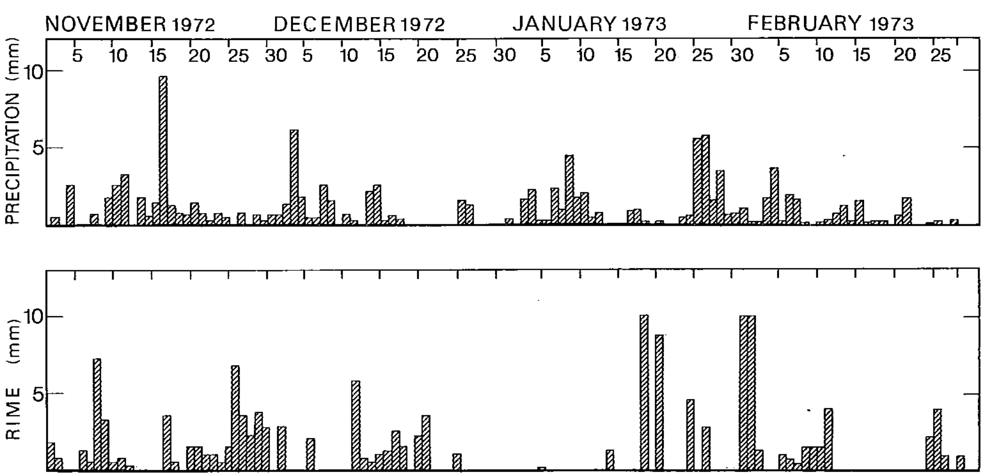

Fig. 2. The daily amounts of rime and precipitation at Värriö (from Ahti, 1976).

3.2 Air temperature

One might suppose that air temperature t_a has an effect on the rate of rime formation I, because of the possible connection between air temperature and liquid water content of air, for example. In order to test this assumption the correlation coefficient between I and t_a was calculated for the data from Pyhätunturi. No correlation was found ($r = 0.08$). This was not due to the compensating effect of wind speed v, since there was no correlation in the data between t_a and v.

The fact that there seems to be no correlation between I and t_a is in agreement with the results of WAIBEL (1956), and with the theoretical considerations (see *e.g.*, MAKKONEN, 1981). Also RINK's (1938) data coincide with the present result in the temperature regime of rime formation. BARANOWSKI and LIEBERSBACH (1977) have found a slight dependence of air temperature for hard rime and soft rime separately, but as a whole their data do not indicate a connection between the intensity of rime formation and air temperature either.

3.3 Wind speed

Ice is accreted on a vertical surface when supercooled water droplets moving with the wind strike the surface (snow accretion is not considered here and was not observed in our data). Obviously the vertical component of the motion of these droplets is very small, since precipitation does not correlate with the rate of ice formation. In the case of rime (dry growth) all the droplets striking the surface actually freeze (see *e.g.*, MACKLIN and PAYNE 1968), and there is no direct connection with the icing intensity and air temperature as in the case of glaze (wet growth, see MAKKONEN, 1981). Therefore, the intensity of rime formation I on a measurement cylinder can be calculated according to eq. (1).

$$I = E w v \,, \qquad (1)$$

where E is the collection efficiency, *i.e.*, the ratio of the mass flow of droplets striking the cylinder to the mass flow of droplets that would strike it if the droplets were not deflected following the air stream around the object, w is the liquid water content in air and v is the wind speed. The collection efficiency E is dependent mainly on wind speed, droplet size distribution and the dimensions of the icing object (see *e.g.*, MCCOMBER and TOUZOT 1981).

The liquid water content of air and the droplet size spectrum are extremely difficult to measure or to predict. These parameters are probably related to *e.g.*, the direction of the wind, but the dependence of I on wind direction could not

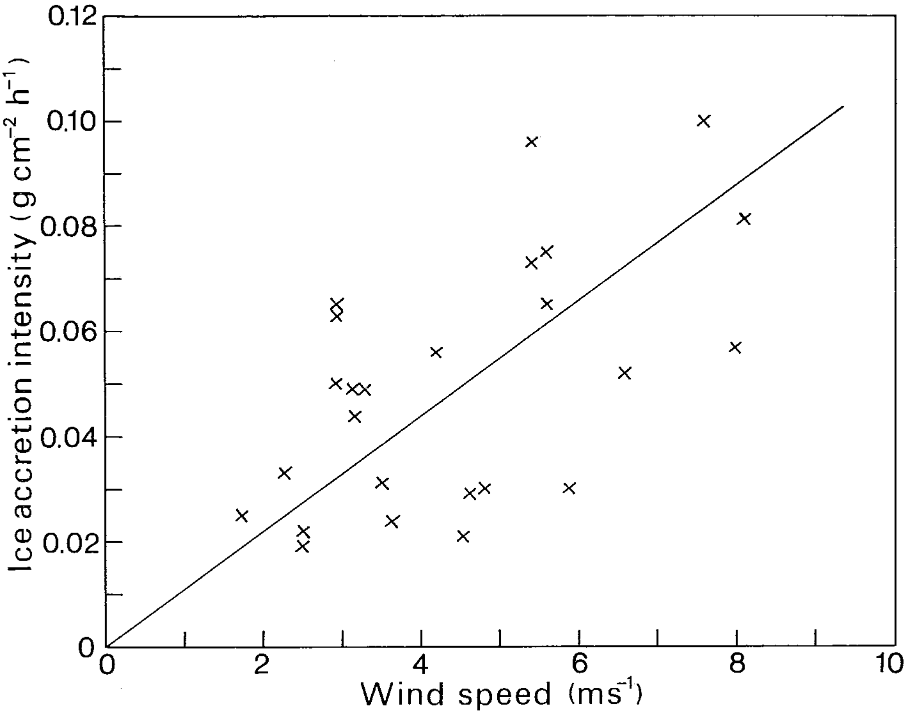

Fig. 3. The intensity of rime formation versus wind speed at Pyhätunturi.

be examined in our data due to the predominance of south-westerly winds during ice accretion. Therefore, the only practical possibility to construct an estimation method for I based on Eq. (1) seems to be to neglect the variation of liquid water content and droplet size and to find out if I and ν covary. This was attempted using the data from Pyhätunturi, neglecting the few cases of glaze for which Eq. (1) is not expected to be valid (MAKKONEN, 1981). The correlation coefficient 0.58 was obtained between I and ν. This is significant at the 0.5 % -level (t-test). The data are given in Fig. 3.

In Fig. 3 also the linear regression line for the data is presented. The regression line is forced through the origin, since the results of SADOWSKI (1965) and VOLOBUEVA (1975) (see also Fig. 5) show that rime is formed down to the wind speed values as small as the starting speed of the anemometer and since, on the other hand, the rate of accretion in zero wind speed (sublimation) is negligible in the fog conditions which prevailed during the deposition.

The regression equation in Fig. 3 is

$$I = 11.0 \cdot 10^{-3}\, v \tag{2}$$

where I is in g $cm^{-2}h^{-1}$ and v in ms^{-1}. The standard deviation of the proportionality factor in Eq. (2) is $0.9 \cdot 10^{-3}$.

The scatter of the points in Fig. 3 is considerable, probably mainly because of the changes in liquid water content, droplet size and duration of icing. However, it is interesting to note that also the data of RINK (1938) from Germany and of BARANOWSKI and LIEBERSBACH (1977) from the Sudety Mountains show a linear relationship within a much larger range of wind speed values. The linear regression equation between I and v for a 10 cm diameter cylinder was calculated by BARANOWSKI and LIEBERSBACH (1977) separately for soft rime and hard rime and yielded $I = 7.5 \cdot 10^{-3}\, v$ for soft rime and $I = 15 \cdot 10^{-3}\, v$ for hard rime, the correlation coefficients being $r = 0.60$ and $r = 0.50$, respectively. Also WAIBEL's (1956) data for a 2.3 cm diameter wire supports the near-linear relationship, giving $I \approx 8.0 \cdot 10^{-3}\, v$ for the wind speed range 1–20 ms^{-1}.

The present results suggest that, if liquid water content is not connected to wind speed, the collection efficiency E in Eq. (1) can as a first approximation be considered independent of the wind speed on the average. This would not be in agreement with the theoretical prediction that E increases with wind speed, other conditions being unchanged (see MCCOMBER and TOUZOT, 1981). However, the amount of data is too small to reveal a slightly non-linear relationship, and there are several reasons which make it possible for the linear relationship to be valid on the average in spite of the variable nature of E. These are for example the compensating effects of changes in average liquid water content and droplet size with changing wind speed, the more rapid increase of deposit diameter in higher wind speeds and turbulent motion of the droplets. These are all factors which should be examined in future studies.

For practical purposes the weight of ice after some time of accretion is most important. Because of the lack of information of the effects of meteorological conditions on ice accretion the time of deposition has sometimes been used as the only predictor when estimating the formation of ice loads (*e.g.*, DIEM, 1956). In our data, too, the ice load correlated more strongly with the time τ ($r = 0.70$) than with any of the meteorological predictors, although τ was not directly observed but was determined from the cloud height observations. This makes it easy to see why the severity of ice accretion is clearly dependent on the elevation (PIEHL, 1973, GLUKHOV, 1974, LOMILINA, 1977).

Since the wind speed explains a noticeable part of the variation of the intensity of rime formation and since I seems to be approximately proportional to v, it is to be expected that τ multiplied by v is a better index for the ice load than τ alone.

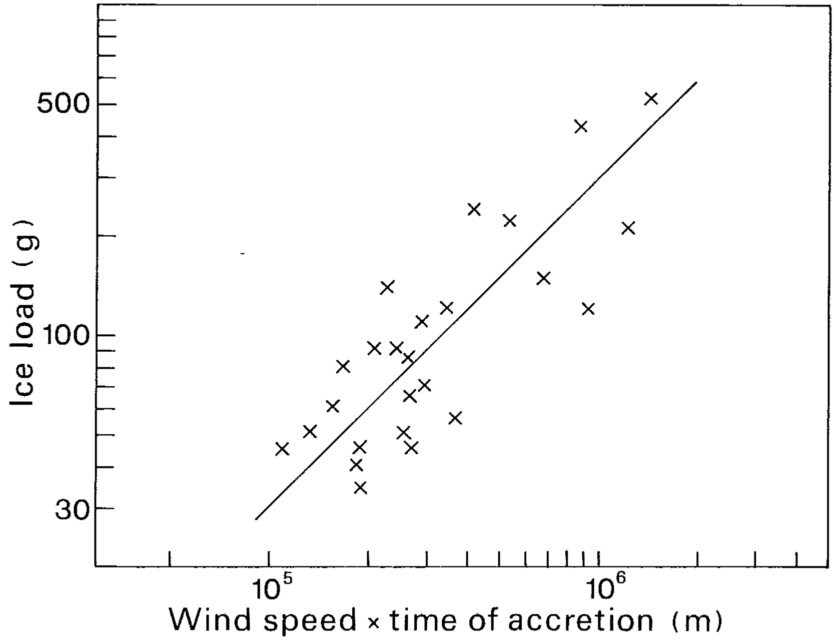

Fig. 4. The ice load versus wind speed multiplied by the time of ice accretion at Pyhätunturi. The time of accretion is estimated from cloud height observations in the valley area.

Therefore the correlation coefficient between the ice load and $\nu\tau$ was calculated, yielding $r = 0.81$. The data and the linear regression line are given in Fig. 4. Due to the large variation of the ice load a much larger data set would be required in order to find out whether the exponents α and β different from unity should be used in the predictor $\tau^{\alpha}\nu^{\beta}$ as suggested by DIEM (1956).

In spite of the relatively large scatter in Fig. 4 the results can be seen encouraging since they indicate that at least rough estimates of the ice load can be made using the average wind speed and the time during which the cloud height in the near-by valley area is lower than the elevation of the location considered. For long-term averages this method should provide a useful tool for calculation of the expected ice loads using climatological data, for example.

4. *The regime of applicability*

The observational relationship between the rate of ice accretion and wind speed in our data could be determined for rime only. Theoretically it is to be expected that

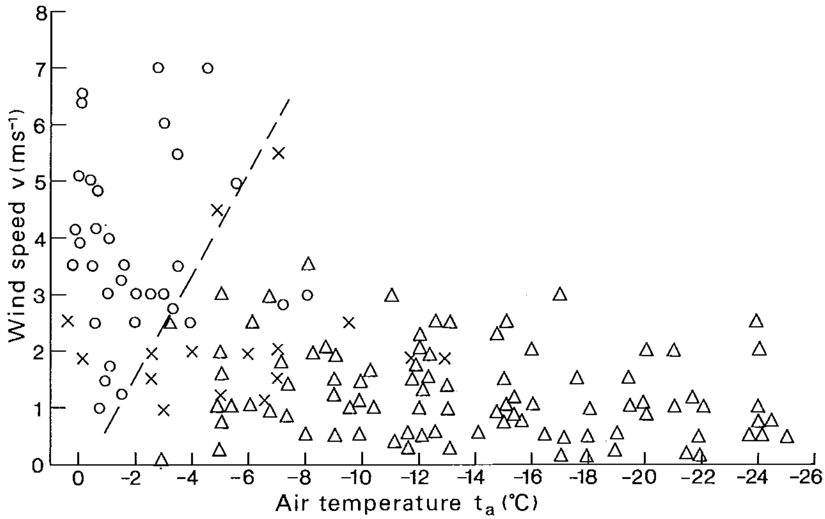

Fig. 5. Observations of soft rime (Δ), hard rime (x) and glaze (o) in different air temperatures and wind speeds at Rovaniemi, Sodankylä and Jyväskylä.

this relationship is weaker for glaze due to the temperature dependence of glaze accretion intensity (MAKKONEN, 1981). Therefore, it is important for the application of the estimation method presented to know the conditions in which the resulting ice deposit is glaze instead of rime. These critical conditions were studied simply by plotting the data of glaze, hard rime and soft rime on the v versus t_a diagram (Fig. 5).

According to Fig. 5, the change from rime to glaze seems to occur approximately when $-t_a$ (in °C) is equal to v (in ms^{-1}), the overlap of the points being, however, considerable. This is comparable to the results of VOLOBUEVA (1975), but shows glaze formation in much lower values of air temperature than observed by KUROIWA (1965). It is suggested by the theory that the increase of liquid water content makes it possible for glaze to occur in lower air temperatures. Hence, it is probable that the differences in the critical air temperature in various data are mainly due to the different frequency of precipitation during ice accretion. This is supported by the fact that also SADOWSKI (1965) and GLUKHOV (1974) have observed glaze in air temperatures as low as –10°C, whereas according to the data of GAPONOV (1939) glaze is formed only in the temperature range from 0°C to –2.2°C when the observations with simultaneous precipitation are excluded.

5. *Conclusions*

The data from the ice accretion measurements in northern Finland indicate no dependence of rime intensity on precipitation and air temperature. Air temperature, however, affects the type of the ice deposit so that rime instead of glaze is formed in higher air temperatures when the wind speed is smaller. The lack of correlation between ice accretion intensity and the amount of precipitation indicates that rime should be treated as an independent variable in the hydrological balance in the regions with considerable ice accretion.

There is a significant relationship between the intensity of rime formation and the mean wind speed. The reason why this connection is not very strong, is probably mainly that there are considerable variations in the liquid water content of air and in the droplet size distribution. Estimation methods of these factors should be developed in order to improve the accuracy of ice load calculations.

The average wind speed multiplied by the time of accretion estimated from cloud height observations seems to be the best available predictor of the ice load. This parameter can be used in calculation of the ice load on power lines, trees etc., at least for rough climatological estimates.

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