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On the Values and Variability of Degree-Day Melting Factor in Finland

Esko Kuusisto
Hydrological Office, Helsinki, Finland

About 96,000 snow depth and 17,000 snow density measurements were used to study the most widely used variable in snowmelt forecasting, the degree-day factor. This data was collected on 12 stake stations each with 25 stakes in forest and 9 on open field during 1959 to 1978. The seasonal averages of degree-day factor are studied; they vary rather widely from station to station. The average for all forest sites is 2.42 mm°$C^{-1}d^{-1}$ and for all open sites 3.51 mm°$C^{-1}d^{-1}$. A 10 per cent increase of canopy cover in forest decreases the degree-day factor on the average by 0.16 mm°$C^{-1}d^{-1}$. On rainy pentades the degree-day factor is larger especially in forest sites. Finally, the seasonal course of the degree-day factor and its dependance on snow density are discussed.

Introduction

The snowmelt process is dependent on the net heat exchange between the snow pack and its environment. Thus for computing the amount of melt the only strictly correct way is using the energy budget. However, the different sources and processes influencing heat transfer to and from a snow pack are largely variable both in space and time. Because also the measuring of the variables involved is complicated, usually simplified approaches to snowmelt modelling are applied.

One of the most popular methods used to forecast snowmelt is to correlate air temperature with snowmelt data. Usually this is done with the equation

$$M = KM\,(T-KT) \qquad (1)$$

where

M = the amount of melt, mm d^{-1}
T = daily mean temperature, °C
KM = degree-day factor, mm $°C^{-1}d^{-1}$
KT = threshold temperature, °C

When this model is applied, M actually indicates the decrease of water equivalent of snow, not the true, physical amount of snowmelt. The threshold temperature is called also the critical temperature or equilibrium temperature, as the net heat exchange between the snow pack and its environment is supposed to be zero at this temperature.

Since air temperature is only one of the several meteorological parameters influencing snowmelt, neither the degree-day factor nor the threshold temperature can be truly constant. They depend on solar radiation, cloudiness, wind speed, air humidity and on the effect of forest cover. Zuzel and Cox (1975) showed that the standard error of daily snowmelt prediction could be decreased 13 per cent by using vapor pressure, net radiation and wind velocity in predictive equations instead of air temperature alone. In different environments the predictiveness of air temperature may, however, vary considerably. Even at the same site the factors affecting snowmelt may vary i.e. depending on the type of air mass.

The literature abounds with different values for the degree-day factor and the threshold temperature. Although quite often a fixed threshold temperature, KT = 0°C, is used, the range of degree-day factor still is considerable: due partly to the time variation of this factor, partly to differences in the methods of measurement and the definition of variables involved.

In this study, a comprehensive data on five-daily values of snowmelt in Finland is used. The data is gathered on 12 snow stake stations in southern, central and northern parts of the country, four in each part, during the snowmelt seasons 1959 to 1978. Several aspects related to the degree-day factor are discussed. For threshold temperature the fixed value KT = 0°C is used throughout the study.

The Data

In 1958 stake stations for measuring snow were established in different parts of Finland (Seppänen 1961). On even ground stakes were set up in squares 25 stakes ten meters apart in pine dominated forest and 9 stakes five meters apart on open field, the latter exposed to solar radiation. The measurements of snow depth and snow density 6 times monthly were started in the beginning of March and continued through spring until all snow had disappeared from around all the stakes. The snow density was measured gravimetrically at 4 points in the forest and at 2 points

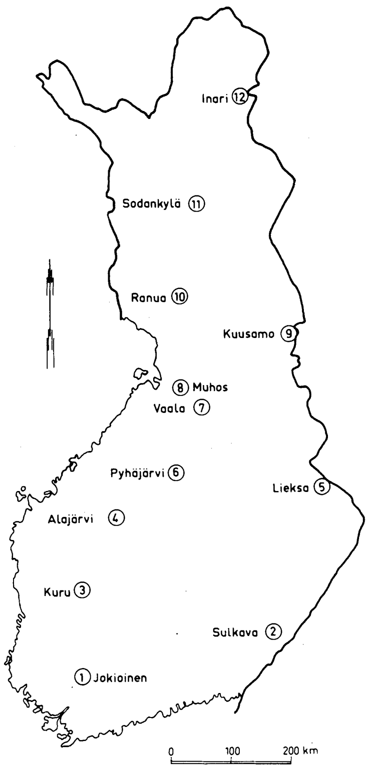


Fig. 1. The network of stake stations used in this study.

in the open field on each observation date. The water equivalent of snow was calculated on the basis of the average of snow depth and density.

Data from twelve stations were used in this study; their locations are shown in Fig. 1. They were selected from the whole network of about 25 stations on the basis of the homogeneity of data; thus stations which had experienced several changes of location, considerable changes in the forest density etc. were omitted. However, during the 20 years period even in the selected stations some changes have necessarily occurred especially on the forest sites. Also there are some differences between the stations: i.e. the density of forest and the diameter of the open field vary considerably.

Table 1 gives the means and the coefficients of variation of annual maximum water equivalents at different stations. In southern and central Finland these maxima are between 80 and 180 mm, in northern Finland between 120 and 250 mm. The coefficients of variation are rather low in northern Finland, but increase considerably southwards due to frequent thaws and considerably less stable accumulation periods.

Table 1 - The means (WE) and coefficients of variation (CV) of maximum annual water equivalents of snow at different stations.

Station	Forest		Open	
	WE (mm)	*CV*	*WE* (mm)	*CV*
Jokioinen	83	0.54	110	0.43
Sulkava	132	0.41	169	0.30
Kuru	99	0.41	159	0.31
Alajärvi	99	0.27	97	0.32
Lieksa	162	0.26	178	0.26
Pyhäjärvi	138	0.33	172	0.27
Vaala	154	0.23	198	0.24
Muhos	135	0.22	144	0.20
Kuusamo	179	0.21	210	0.18
Ranua	242	0.20	244	0.26
Sodankylä	163	0.22	152	0.27
Inari	122	0.19	142	0.19

Seasonal Degree-Day Factors

The date of the maximum water equivalent was considered as the initial date of the snowmelt season. The definition of the end of the season was rather difficult: actually some snow still should be found around each stake at the final date of the season so that the entire melting capacity of the degree-days could be utilized. However, because of the relatively long time interval, 5 days, between the observations, this was too strict limitation for years with a short snowmelt season. Besides, in forest, while the mean snow depth still measured about 25 cm at the site, around some stakes the snow had quite disappeared. Thus the final date of snowmelt season was somewhat arbitrary, but almost always there was some snow at the station on that date.

The amount of snowmelt for each five-day period was determined on the basis of water equivalent of snow and precipitation observations in the immediate neighbourhood. The amount of liquid and solid parts of the precipitation were determined on the basis of the notes of the observer and on the basis of the investigations of the Finnish Meteorological Institute (Hankimo 1976). Considering rain gauge errors the liquid and solid parts of precipitation were corrected separately: the value of correction coefficient was 1.10 for liquid and 1.30 for solid precipitation.

The averages of the seasonal degree-day factors for all the stations are shown in Table 2. From station to station a considerable variation exists especially on forest sites: the largest average degree-day factor for forest is 92 per cent higher than the smallest one. For open sites the corresponding difference is 75 per cent.

Table 2 – The seasonal degree-day factors (mm $°C^{-1}$ d^{-1}) and their coefficients of variation.

Station	Forest		Open	
	KM	*CV*	*KM*	*CV*
Jokioinen	1.91	0.27	4.94	0.39
Sulkava	2.42	0.20	3.43	0.16
Kuru	2.72	0.22	3.90	0.13
Alajärvi	3.24	0.20	4.19	0.22
Lieksa	2.13	0.21	2.96	0.26
Pyhäjärvi	1.75	0.21	2.82	0.29
Vaala	2.55	0.18	2.97	0.20
Muhos	1.84	0.17	3.42	0.24
Kuusamo	2.20	0.21	3.45	0.25
Ranua	3.36	0.21	3.89	0.27
Sodankylä	2.57	0.21	3.29	0.18
Inari	2.40	0.20	2.82	0.22
Mean	2.42	0.21	3.51	0.23

The annual variation of the degree-day factor is less pronounced. The average coefficient of variation of the seasonal degree-day factor is 0.21 for forest sites and 0.23 for open sites. The largest annual variation occurs in Jokioinen in southwestern Finland where the snow cover is relatively thin.

For open sites the average degree-day factor for the four southernmost stations and for the four northernmost stations were 4.10 and 3.34 mm $°C^{-1}$ d^{-1}, respectively. However, from station to station the variation is so large that this difference cannot be considered regional.

For forest sites the possible regional differences in degree-day factor are obviously obscured by other factors such as the density of the forest. The following equation was obtained between the average degree-day factor *KM* and the canopy cover *F* (in per cent)

$$KM = 2.92 - 0.0164\,F \quad (2)$$

Thus with canopy covers 10 per cent and 70 per cent, KM-values equal 2.76 and 1.77 mm$°C^{-1}$ d^{-1}, respectively. These values of canopy cover can be considered as limits of the validity of the equation; it has, however, a relatively low correlation coefficient ($r = 0.51$).

The Influence of Precipitation

The amount of heat transfer from rain water to the snow is small in general. However, the liquid water content of the snow pack may increase considerably and thus a false increase of degree-day factor may occur. It is also likely that with relatively high air humidity sensible and latent heat transfer are large.

The pentades of the snow melt seasons were divided into three groups according to the amount of precipitation. For the whole data consisting of several thousend pentades the following results were obtained

Average degree-day factor (mm°C^{-1} d^{-1})

Precipitation (mm)	Forest	Open field
0...1.0	2.16	3.21
1.0...10.0	2.33	3.33
10.0...	2.79	3.38

Thus with increasing precipitation there was an increase of degree-day factor both in forest and on open field. In Fig. 2 the values of degree-day factor in the first and third precipitation class are shown for the forest sites of all the stations. Only at two stations the difference is insignificant.

The interception by trees obviously causes an error, which could explain partly these differences in degree-day factor. However, there is no correlation between the canopy density and the differences in degree-day factor.

It might be expected that the larger amount of solar radiation on clear days could lead to a higher degree-day factor. According to the results of this study, this is not the case, but the degree-day factor slightly increases with precipitation.

The Seasonal Course of Degree-Day Factor

It is well-known that the degree-day factor is not constant throughout the snow-melt season. It usually increases when snow ripens and solar radiation becomes more intensive.

In Fig. 3, the average seasonal development of the degree-day factor is shown for forest and open sites. Each of the three curves for both sites is based on the measurements on four stake stations. The ordinate scale gives the ratio of the degree-day factor to its seasonal mean.

In March the degree-day factor is only 30 to 70 per cent of its seasonal mean in central and northern Finland. It starts to increase sharply in the beginning of April and it roughly doubles during this month. The seasonal mean of the degree-day factor is reached between the 10th and the 20th of April in southern and central Finland and at the end of the month in northern Finland. The increase of the factor is more pronounced on open field than in forest; this might be due to the larger effect of increased solar radiation.

The degree-day factor has also been correlated to the density of snow (Martinec

Fig. 2. The values of degree-day factor for forest sites on rainy and dry pentades.

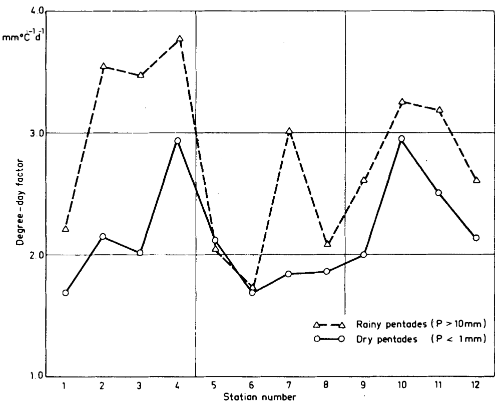
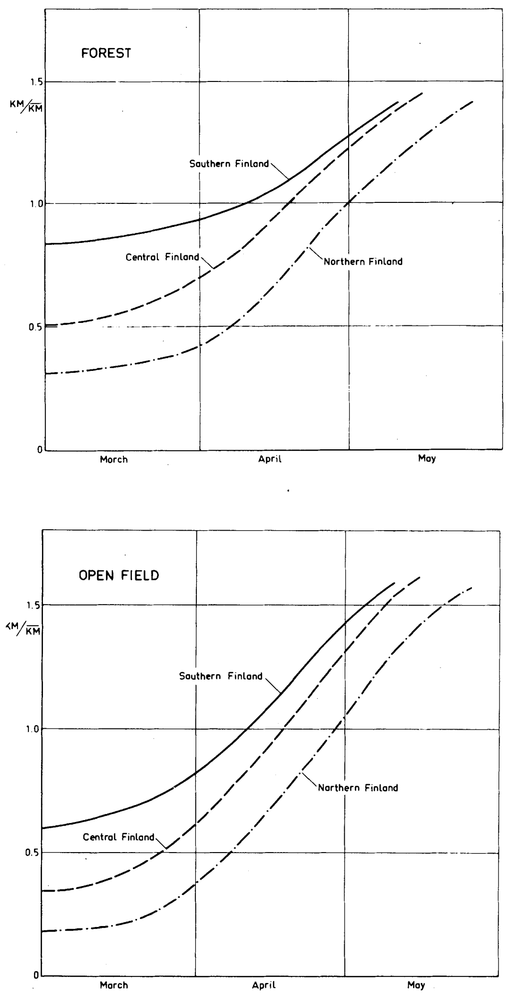


Fig. 3. The average seasonal development of the degree-day factor in southern, central and northern Finland.



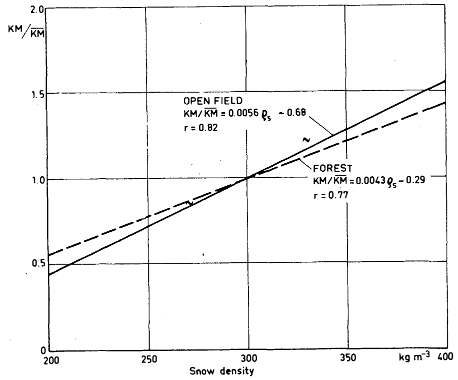


Fig. 4. The dependance of the degree-day factor on the snow density.

1976). This relationship is very clear, because the snow density represents several factors affecting snowmelt, such as lower albedo and higher liquid water content.

In Fig. 4, the regression lines between the snow density and the normalized degree-day factor are shown for forest and open sites. They are based on half-monthly averages of the variables on all the stake stations. On open field the degree-day factor increases more sharply as a function of snow density than in forest. If the regression lines are multiplied by the average degree-day factors of all the forest and open sites, the following equations are obtained

$$\text{Forest:} \quad KM = 0.0104\,\rho_s - 0.70 \qquad (3a)$$

$$\text{Open:} \quad KM = 0.0196\,\rho_s - 2.39 \qquad (3b)$$

In these equations, KM is in mm°C^{-1} d^{-1} and ϱ_s in kg m^{-3}. The equation for forest corresponds rather closely to that by Martinec (1976), which has, however, been calculated for a wider range of snow densities.

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Address: Hydrological Office,
Vuorikatu 24,
SF-00100 Helsinki 10,
Finland.