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Measuring and Modelling Snowmelt in Dyrdalen, Western Norway, 1979 and 1980

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During spring snowmelt 1979 and 1980 the runoff from the snowpack was recorded by lysimetry from a 9 m^2 area. Wind speed, air temperature, air humidity, radiation, and precipitation data were also recorded. When the melting rate (= snowpack runoff-rainfall) and the net radiation were measured, the turbulent heat exchange between the snowpack and the atmosphere was computed as a residual from the energy balance equation of the snowpack. These computed values were used to find "optimal" empirical constants in aerodynamical equations expressing the turbulent fluxes as functions of the wind speed and the temperature/vapour pressure differences between the measurements 2 m above the ground (0.6-1.5 m above the snow surface) and the values at the surface. These empirical constants agree reasonably well with constants found by other investigators.

Averaged over the two melting seasons, sensible heat flux represents 65%, and net radiation represents 35% of the energy consumed in melting, while 13% was gained from condensation, and 13% was lost by evaporation. When the weather conditions varied during the melting season, the energy balance model yields better results than does the degree-day-model. Residual errors were 7.3 mm (42%) and 13.2 mm (76%), respectively. The maximum melting observed in 24 hours was 110 mm, and the snowmelt rate in overcast days was about 3 times the rate when the cloudiness was light, provided the same wind and temperature conditions and albedo ~ 70%.

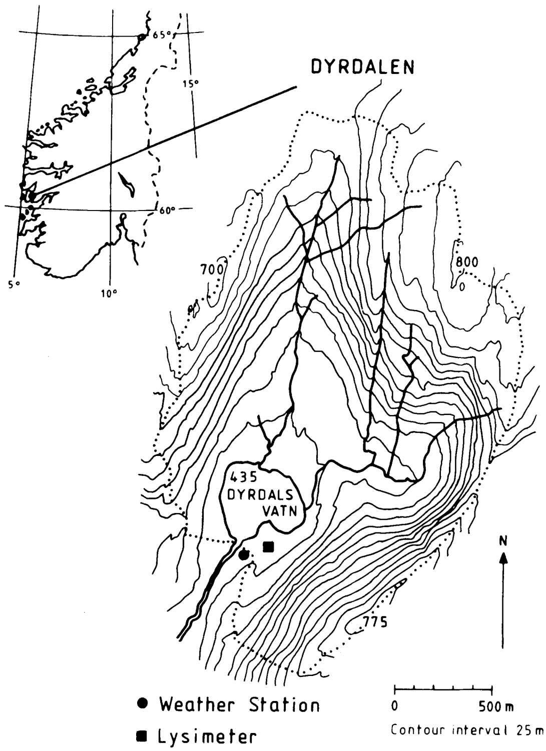

Fig. 1. Map of the Dyrdalen catchment area.

Introduction

From a hydrological point of view there is a need for better models for predicting snowmelt. Practical use is in hydroelectric power production and flood forecasting.

To a meteorologist, snowmelt is of interest because snow is melting due to energy supplied from the atmosphere. This energy exchange between the atmosphere and a melting snowpack may be measured by recording the melt water and meteorological parameters.

Field Description and Data Collection

Dyrdalen is situated 11 km ESE of Bergen (60°25'N, 5°20'E) at the western coast of Norway. The precipitation catchment area (3.5 km^2, 435-806 m a.s.l.) is a roughly mountainous area. The climate is highly variable and storms may occur throughout the year. During winter the weather changes from periods with strong snowfall to rainy periods with snowmelt, or to clear sky with air temperature drops below −20°C at the bottom of the valley. Mean precipitation is about 3,000 mm/year and mean air temperature about +3°C.

At Dyrdalsvatn (Fig. 1) runoff, air temperature, air humidity, wind speed and -direction, precipitation, global radiation, albedo, and (1980 only) atmospheric radiation were recorded during the snowmelt seasons of 1979 (April 1, to May 21) and 1980 (April 12, to May 1). The discharge from a 9 m^2 snowpack was recorded by using a lysimeter (Tveit 1977), illustrated in Fig. 2. The melting season was defined as the period in which the snowpack discharged melt water until boundary effects of the collection vats were significant (~50 mm water equivalent left in the vats, ~70% snowcover in the whole catchment area).

The season of 1979 may be divided into two separate melting periods (April 1 to 30, and May 1 to 21) due to the length of the melting season and different meteorological conditions of the two periods.

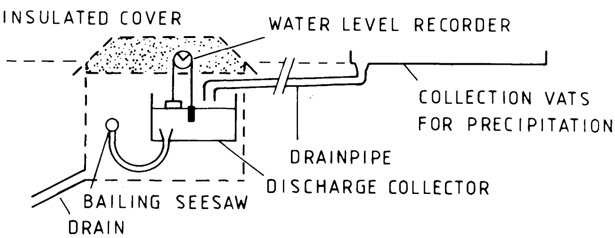

Fig. 2. Principle of the snow lysimeter used at Dyrdalen 1979 and 1980.

Modelling Snowmelt

Degree-Day Model

Using the degree-day model, snowmelt, S_m (mm day^{-1}) is expressed as a linear function of daily mean air temperature, T_m(°C)

$$S_m = k(T_m - T^*) \tag{1}$$

where k(mm day^{-1} °C^{-1}) and T^*(°C) are to be determined by regression analysis, and $S_m = 0$ when $T_m < T^*$. The method may be evolved by computing different constants to different seasons and/or weather types.

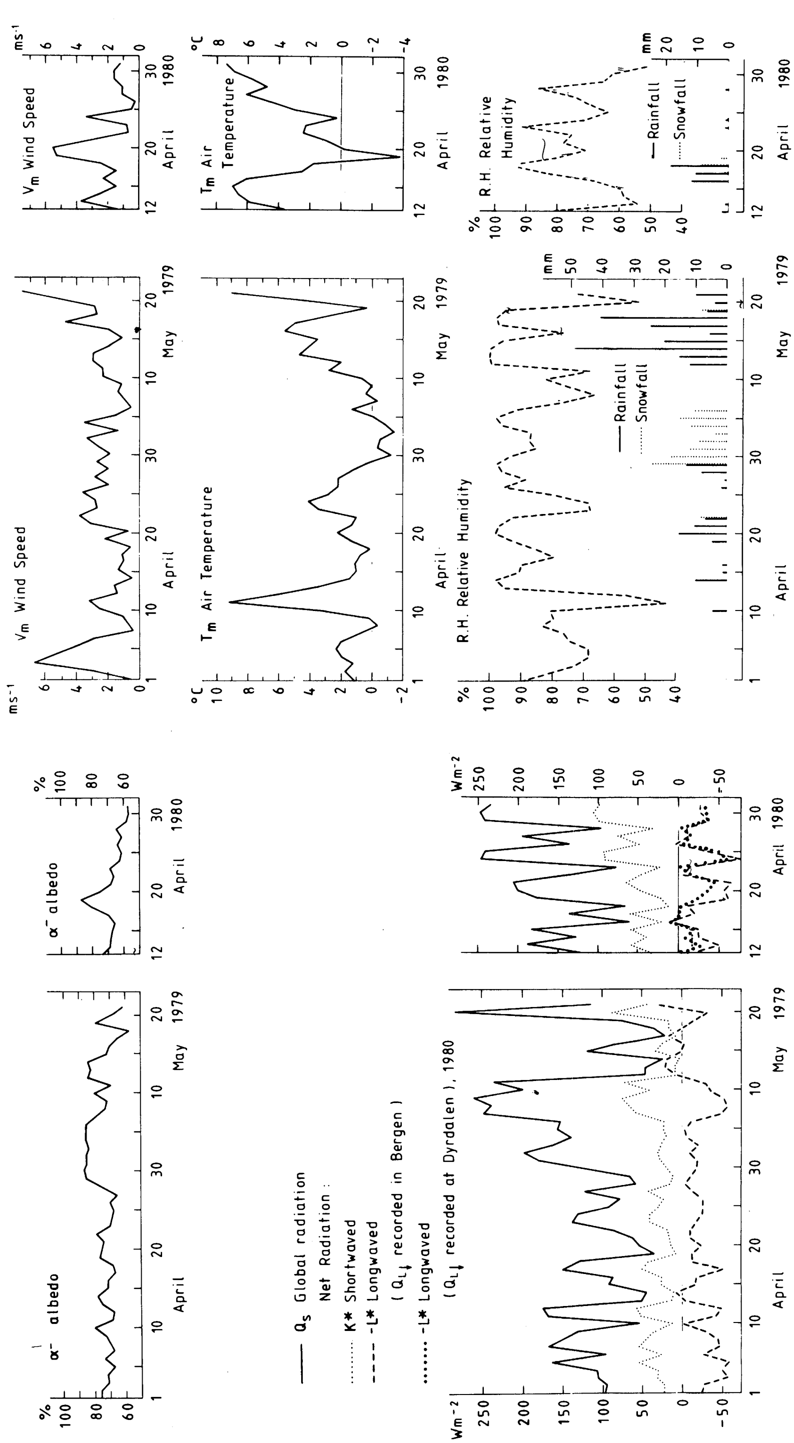

Fig. 3. Some meteorological data recorded at Dyrdalen.

Energy Balance Model

The energy supply used in melting the snow Q_M is mainly due to net radiation Q_N, and the turbulent fluxes of sensible and latent heat Q_H and Q_E

$$Q_M = Q_N + Q_H + Q_E \tag{2}$$

Ground heat flux, gain of energy by rain and change of internal energy in the snowpack are ignored, giving only minor contributions to the spring snowmelt.

Net radiation, Q_N, is defined by

$$Q_n \equiv (Q_S(1-\alpha)) + (Q_{L\downarrow} - \sigma T_0^4) = K* + (-L*) \tag{3}$$

where Q_S is global radiation, and α is the albedo of the snow cover. $\sigma T_o{}^4$ is longwaved radiation from the snow surface where the unit of T_o is °K and the emission coefficient of the snow cover approximates unity. By computing the snow surface temperature T_o the following considerations are taken into account: $T_o = 0$°C(273°K) when the air temperature $T > 0$°C, and $T_o = 2\,T$ when $T < 0$°C (Schieldge and Halberstrom 1978, Fig. 5). Incoming longwave radiation $Q_L\downarrow$ is measured in Bergen and subtracted 23.6 $\mathrm{Wm^{-2}}$ due to difference in altitude (400 m). In the melting season of 1980, there were also used values of $Q_L\downarrow$ measured in Dyrdalen. When used in the computations this is stated separately in the text.

The accuracy of Q_S, $Q_S\alpha$, $Q_L\downarrow$ and σT_o^4 are all within ±5%, and the accuracy of Q_N should be within ±15 W $\mathrm{m^{-2}}$.

As a measure of Q_M, Q_M', the discharge from the lysimeter minus rainfall, is used. Some inaccuracies are connected to the free water content, the movements and capture time of the liquid water in the snowpack, and determination of rainfall. The accuracy of Q_M' should be within ±10-15%.

The turbulent fluxes of sensible and latent heat, Q_H and Q_E, are computed as half-empirical equations

$$Q_H = \sum_{i=1}^{48} \frac{1}{48} (a\,v_i + b)(T_i - T_{0_i}) \tag{4}$$

$$Q_E = \sum_{i=1}^{48} \frac{1}{48} \gamma^{-1} (a\,v_i + b)(e_i - e_{0_i}) \tag{5}$$

where v_i, T_i, and e_i are half-hourly values of the windspeed, the air temperature, and the water vapour pressure, measured 0.6-1.5 m (dependent on the thickness of the snowpack) above the snow surface. T_{o_i} is the surface temperature and e_{o_i} is the saturation water vapour pressure at the surface. The psychrometer constant γ is 0.6 mb $°\mathrm{C}^{-1}$ when the air pressure is 960 mb (Dyrdalen).

Eqs. (4) and (5) presuppose that the turbulent diffusion coefficients of sensible and latent heat are equal. The empirical constants, a (mm $\mathrm{day^{-1}}$ $(\mathrm{ms^{-1}})^{-1}$ $°\mathrm{C}^{-1}$) and b (mm $\mathrm{day^{-1}}$ $°\mathrm{C}^{-1}$) are computed by minimising the residual error, $\sigma = ((Q_M$'-

$Q_M)^2N^{-1})^{1/2}$, where Q_M' is measured and Q_M computed snowmelt. N is number of observation days.

The accuracies in measuring v_i, T_i, and e_i are good relative to other discrepancies using Eqs. (4) and (5). Schieldge and Halberstrom (1978) found Q_E+Q_H to be about 15Wm^{-2} on clear nights with $T < 0$°C and $v \sim 1$ ms^{-1}. In the melting seasons of 1979 and 1980 in Dyrdalen there was only one day with $T < 0$°C in more than 12 hours; very light winds (<0.5 ms^{-1}) occurred mostly at night when T <0°C. The accuracies in stating $Q_H + Q_E \approx 0$ when T <0°C should then be within 5-10 Wm^{-2} (~ 2 mm melt equivalent).

If $Q_N+Q_H+Q_E < 0$, the surface temperature T_o would drop. If the model computes negative daily values of Q_M, T_o is corrected to a lower value such that the model predicts $Q_M = 0$.

Model Adaptions

The empirical constants *a* and *b* of the wind function used in the energy balance model show small variations when computed from different parts of the data set (Table 1). The adjustment to the measured values shows only minor improvement by using *a* and *b* separately computed to different melting periods (Table 2). Andersson (1976) has computed $a = 0.88$ and $b = 0.0$ (same units as Table 1), and refers to other investigations where *a* is within 0.84-1.87 and *b* is near zero. The values of *a* and *b* computed in Dyrdalen are in reasonable good agreement with those found by other investigators.

It seems that the energy balance model yields a realistic modelling of the

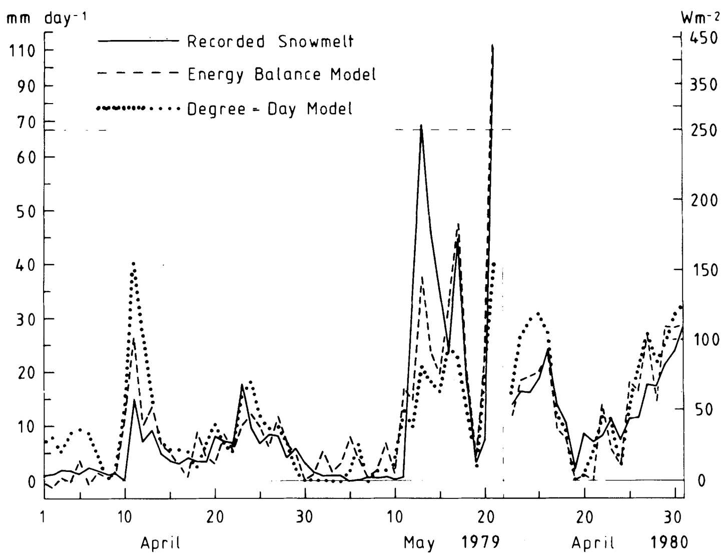

Fig. 4. Daily mean values of the snowmelt recorded and com

Table 1 – The degree-day coefficients k(mm day^{-1} °C^{-1}) and T^*(°C). The coefficients a(mm day^{-1}(ms^{-1})$^{-1}$ °C^{-1}) and b(mm day^{-1} °C^{-1}) when computing the fluxes of sensible and latent heat (mm day^{-1}) for the energy balance model used in the melting periods in 1979 and 1980.

Model	April 1979	May 1979	April 1980	1979-1980
Degree-Day	k=1.4, T*=1.9	k=9.1, T*=−0.1	k=2.0 , T*=−3.5	k=4.2 , T*=−0.4
Energy-Balance	a=0.8, b =0.0	a=1.0, b = 0.5	a=0.95, b = 0.3	a=0.95, b = 0.3
Energy Balance $Q_L\downarrow$ Measured in Dyrdalen			a=0.75, b = 0.2	

Table 2 – Recorded snowmelt together with snowmelt calculated by the degree-day-model and the energy balance model when 1) the coefficients are computed from all data, 2) computed from each of the three melting periods, separately, and 3) for $Q_L\downarrow$ recorded at Dyrdalen.

Model	Mean Daily Snowmelt, mm				Residual Error (R) Standard Deviation (S)				Residual Error, %				Correlation Coefficients			
	Apr. 1979	May 1979	Apr. 1980	1979/ 1980	Apr. 1979	May 1979	Apr. 1980	1979/ 1980	Apr. 1979	May 1979	Apr. 1980	1979/ 1980	Apr. 1979	May 1979	Apr. 1980	1979/ 1980
1) Degree-Day	9.3	10.4	17.8	12.0	7.5	21.6	6.3	13.2R	179	75	94	76	0.66	0.86	0.90	0.62
2) Degree-Day	5.0	20.4	14.6	12.3	3.2	14.6	2.9	8.3R	76	51	43	48	0.64	0.85	0.90	0.87
1) Energy Balance	5.8	18.3	14.3	11.9	4.2	11.6	4.9	7.3R	100	40	72	42	0.70	0.91	0.89	0.92
2) Energy Balance	4.6	19.9	14.3	11.9	3.4	11.4	4.9	7.2R	81	40	72	42	0.69	0.92	0.89	0.92
3) Energy Balance	–	–	13.9	–	–	–	3.0	– R	–	–	44	–	–	–	0.92	–
Recorded Snowmelt	5.0	19.1	14.6	11.8	4.2	28.8	6.7	17.3S	–	–	–	–	–	–	–	–

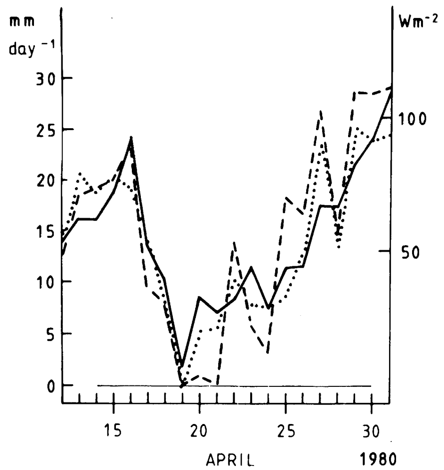

Fig. 5. Recorded snowmelt at Dyrdalen April 12, to May 1, 1980. Computed melting using atmospheric long-wave radiation, $Q_{L\downarrow}$, recorded at Dyrdalen and Bergen, respectively.

physical processes controlling the snowmelt, and that such a model may be used during other conditions than those it is tested for.

Table 2 and Fig. 4 show that there is a rather low correlation between computed and measured snowmelt rates using the degree-day-model with the same set of constants during all three melting periods in 1979 and 1980. This is due to the representation of the model as a statistical connection between weather parameters (represented by the air temperature) and the melting rate. Important physical processes are not explicitly modelled. The degree-day-model, therefore, is not successful when used during different conditions from the tested ones. Calibrating the model separately to each of the three melting periods, the improvement of the method is considerable (Table 2). When using different degree-day-constants to days with and without heavy precipitation (>5.0 mm, ≤5.0 mm), there will be a corresponding improvement (σ = 8.7 mm (50%), r = 0.87) with degree-day-constants 9.2, – 0.1 and 2.2, – 1.0, respectively.

Energy Fluxes

In Table 3 the daily values of the weather parameters and energy fluxes are placed on two main groups depending on the cloud cover (observed every 3 hours in Bergen). Cloudy weather often means maritime influence, light cloudy weather means continental influence.

Even with few observations in the statistical mean, there are some striking points:

Observed snowmelt rates on cloudy days are several times the rates of that of light cloudy days. Computed energy fluxes show that this difference is mainly due to differences in the latent heat flux, Q_E (Table 3). When the weather is cloudy,

Table 3 – Energy fluxes during overcast days and days when the cloudiness is light, April 1, to May 21, 1979, and April 12, to May 1, 1980.

No. of days	Classification N=Cloud Cover	$\bar{T}_m$,°C	$\bar{v}_m$,ms^{-1}	$\bar{e}_m$,mb	Energy Fluxes (Melt Equivalents, mm day^{-1}) Q_E	Q_H	K^*	$-L^*$	Q_N	Q_M	Rec. Snowmelt, mm day^{-1}
22	N≥90%	2.9	2.5	6.9	4.8	10.1	4.3	-0.4	3.9	18.8	22.8
49	N<90%	2.2	2.2	5.2	–2.2	7.0	12.2	–8.0	4.2	9.0	7.0
71	$\bar{N}$=71%	2.4	2.3	5.8	0.0	8.0	9.1	–5.9	4.2	12.1	11.9

$Q_E > 0$ (condensation), while evaporation ($Q_E < 0$) dominates in less cloudy weather. Evaporation and condensation contributes significantly to the energy budget of the snowpack (Table 3), while the contributions to the mass budget are negligible (Table 4).

Absorbed global radiation K^* and effective outgoing radiation L^* both increase when the cloudiness decreases. K^* decreases by increasing albedo, while L^* is independent of it. At lower albedo conditions than those of the melting conditions of 1979 and 1980 (~70%) the difference between the melting rate in cloudy and light cloudy weather would be less.

The sensible heat flux Q_H is more independent of the cloudiness and provides the highest contribution to the snowmelt in both weather types. During the spring of 1979 Q_H was considerably greater than Q_N (Fig. 6). The albedo values were then high (~74%, Fig. 3). During the last part of the melting season of 1980, Q_N was greater than Q_H, the albedo values being lower (~60%), the global radiation high and the wind speed low.

Mean melt-rate was 11.9 mm/day with a standard deviation of 17.3 mm/day. In four days the snowmelt exceeded 40 mm day^{-1}. May 21, 1979, there was measured 110 mm (corresponding to an energy supply of 430 Wm^{-2}) and the melting rate was 8 mm hour^{-1} in the middle of the day (Fig. 7b). Fig. 7a shows that the air temperature T varied through the day, and that the windspeed v was varying, but

Table 4 – Snowmelt, evaporation and condensation on a snow area at Dyrdalen.

Period	Recorded Snowmelt	Computed (Net Daily Values added) Evaporation	Condensation
April 1,- May 21,1979	550 mm	10.3 mm	13.4 mm
April 12,- May 1, 1980	291	4.4 mm	1.2 mm

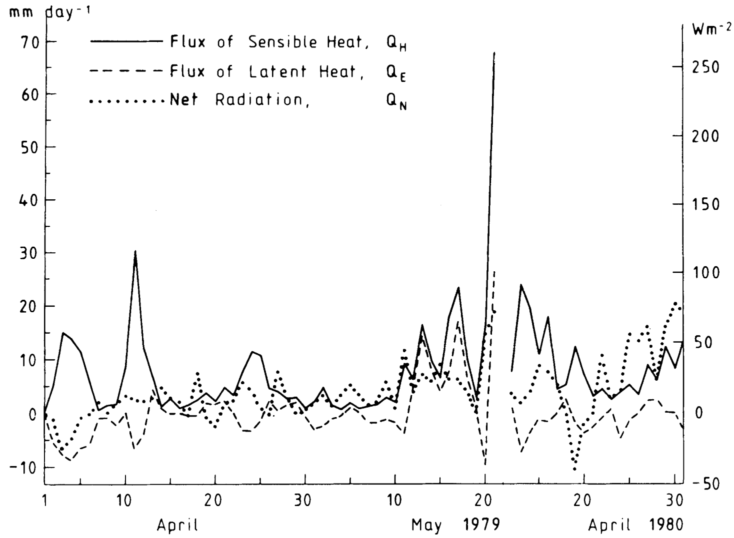

Fig. 6. The variations of the energy fluxes Q_H, Q_E and Q_N at Dyrdalen in the snowmelt periods of 1979 and 1980.

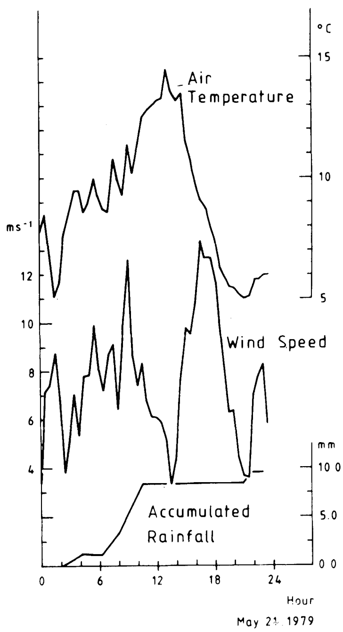

Fig. 7a. The distribution of wind speed, air temperature and precipitation on May 21, 1979.

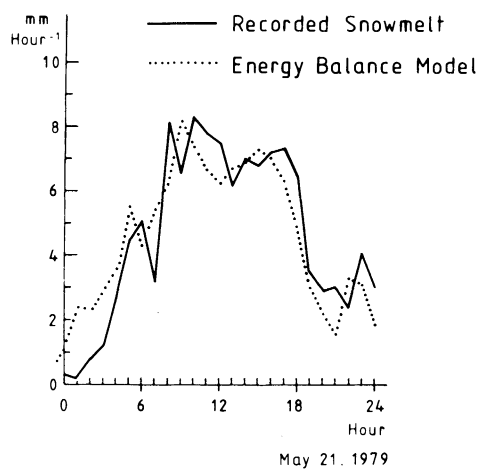

Fig. 7b. Computed and recorded snowmelt in

Table 5 - Meteorological parameters and energy fluxes during the maximum snowmelt, May 21, 1979.

Date	T_m,°C	V_m,ms^{-1}	e_m,mb	α,%	Rain-fall mm	Energy Fluxes (Melt Equivalents, mm day^{-1}) Q_H	Q_E	Q_N	Q_M	Rec. Snow-melt mm day^{-1}
May 21, 1979	9.0	7.6	8.2	61	9.6	68	26	19	113	110

v and T were high through the whole day. The air was moist, the albedo low, and the weather cloudy except in the middle of the day, yielding positive values of K^* and $-L^*$ (Table 5). There was much less rainfall than snowmelt that day, and the snow magazine in the collection vats was 170-60 mm, that is of the same order of magnitude as the snowmelt of the day. The physical properties of the snow did not vary through the day. Therefore, there seems to be good reason to believe that the accuracies of the measurements of the melting are good.

The model adaption was good throughout the day (r = 0.88, σ = 1.21 mm (46%)) by using a and b values computed from all of the 71 days of snowmelt in 1979 and 1980. When using hourly melting values there is a need for correcting the values due to the movements of the meltwater through the snow. Fig. 7b. suggests a phase displacement of 1 hour. That may be used in the computations, giving r = 0.94 and σ = 0.92 mm (35%).

Summary and Conclusions

During spring snowmelt 1979 and 1980 the runoff from the snowpack was recorded by lysimetry from a 9 m^2 area. Wind speed, air temperature, air humidity, radiation, and precipitation data were also recorded.

When the melting rate (= snowpack runoff-rainfall) and the net radiation were measured, the turbulent heat exchange between the snowpack and the atmosphere was computed as a residual from the energy balance equation of the snowpack. These computed values were used to find "optimal" empirical constants in aerodynamical equations expressing the turbulent fluxes as functions of the wind speed and the temperature/vapour pressure differences between the measurements 2 m above the ground (0.6-1.5 m above the snow surface) and the values at the surface. These empirical constants agree reasonably well with constants found by other investigators.

Averaged over the two melting seasons sensible heat flux represented 65% of the energy consumed in melting, while net radiation represented 35%. The energy gained from condensation was 13%, and 13% was lost by evaporation. The percental contributions to the melting from the various fluxes varied from one day to another, especially that from the latent heat flux.

When the weather conditions are varying during the melting season, the energy balance model yields better results than does the degree-day-model, and it needs no re-calibration to each season. A simple degree-day-method gives good results only when there is no considerable variability in meteorological conditions during snowmelt. The model should be calibrated to each season, and will show improved results using different melt factors for days with and without significant precipitation.

For albedo ~70%, the snowmelt in overcast days is about 3 times the melting in days when the cloudiness is light, provided the same wind and temperature conditions.

Acknowledgement

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