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The Role of Turbulent Heat Fluxes in the Energy Balance of High Alpine Snow Cover

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C. Plüss and R. Mazzoni
Swiss Federal Institute of Technology, ETH,
CH-8057 Zürich, Switzerland

Energy balance measurements over a seasonal snow cover were performed near Davos, Switzerland at 2,540 m a.s.l. The energy fluxes were studied over dry and melting snow covers. The beginning of snowmelt clearly coincides with the beginning of positive daily sums of net radiation. During snowmelt, net radiation is the dominant energy source. Latent and sensible heat fluxes do not show a significant seasonal change and remain slight over most of the measuring period. This minor contribution of the turbulent heat fluxes can be attributed to generally low wind speeds in this inner alpine region and to frequent inversions over the melting snow cover.

In a changing climate the turbulent heat fluxes could become increasingly important in the energy balance. Therefore, evaluations of the turbulent heat fluxes from profile measurements and the eddy correlation method are compared with simple approximations commonly used in snowmelt models. The conditions under which these approximations can be used for routine discharge forecasts are identified.

Introduction

The duration and height of the snow cover in alpine regions is of major importance as a water resource, for storage purposes, for protecting the vegetation cover, and for snow tourism.

The predictions of future climate changes due to the man-made greenhouse effect (IPCC 1990 and 1992) have provoked a strong interest in the alpine regions to gain a better understanding of the impacts of such changes on the energy budget of the snow cover.

Several attempts were made to parameterize the energy balance of a snow cover from routine weather data, mainly in order to predict the discharge from the snow cover (*e.g.* Braun 1985 and Rohrer 1992). Such approaches could also be useful for detecting the impact of climate changes on the snow cover, providing the accuracy of the approximations and the conditions for applicability are known.

The aims of this study are to validate energy balance models which are used for runoff prediction and to investigate the role of the turbulent heat fluxes in the energy balance.

Measurement Site and Instrumentation

The Swiss Institute for Snow and Avalanche Research (SLF) has been investigating the snow cover at a test site near Weissfluhjoch above Davos at 2,540 m a.s.l. for over 50 years. Near the institute there is also a station of the Swiss Meteorological Institute automatic network (ANETZ), which has been operating for over 10 years. In spring 1992 and 1993 additional measurements of the meteorological properties of the surface layer and of the radiative fluxes were performed.

The weather in April and May 1992 was warm (April +1.6°C, May +2.4°C above average) and very dry and sunny in May. The weather in April, May and June 1993 was also warm (April +2.4°C, May +2.1°C, June +1.6°C) with average precipitations and sunshine and frequent foehn periods.

In this study the energy balance of spring 1992 is evaluated and the results are compared with a parameterized energy balance using the ANETZ-data, following an approach proposed by Rohrer (1992).

For the comparison of sensible heat flux evaluation, also data from 1993 were used because of these foehn periods with relatively high wind speeds.

Table 1 – Energy balance related measurements at Weissfluhjoch (3 April - 18 May 1992).

Properties	Instruments test site SLF (2540 m)	Instruments ANETZ (2670 m)
Radiation		
Short-wave incoming	Pyranometer (Swissteco)	Pyranometer
Short-wave reflected	Pyranometer (Swissteco)	
All-wave incoming	Pyrradiometer (Swissteco)	
Net radiation	Net Radiometer (Swissteco)	
Meteorological Elements		
Temperature (ventilated)	4-level profile (0.3m -3m)	at 2m
Humidity (ventilated)	4-level profile (0.3m -3m)	at 2m
Wind speed	4-level profile (0.3m -3m)	at 10m
Wind speed 3-dimensional	Sonic anemometer (Gill) (selected days only)	
Synoptic Observations		
Cloud Cover		3 times daily
Snow Properties		
Snow height	daily reading	
Water equivalent	twice monthly	
Runoff	Lysimeter ($5m^2$)	

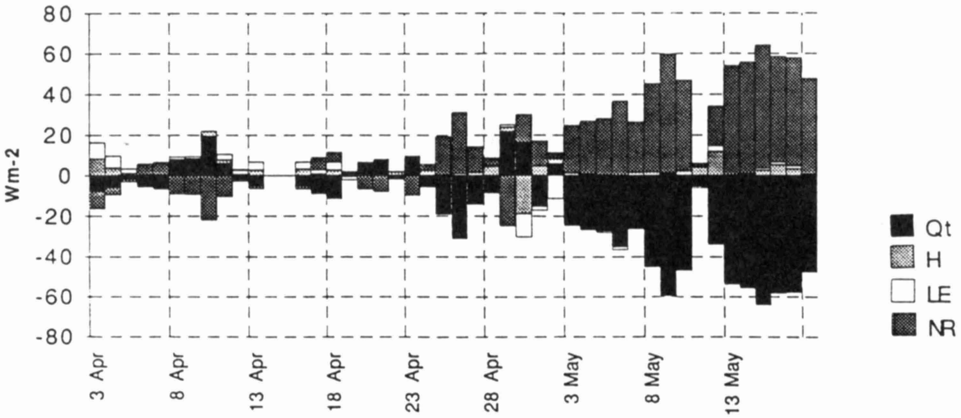

Fig. 1. Energy Balance at Weissfluhjoch (2,540 m) in spring 1992 as derived from measurements. *Qt* = total heat flux passing the surface; *H* = sensible heat flux; *LE* = latent heat flux; *NR* = net radiation.

The Energy Exchange of an Alpine Snow Cover with the Atmosphere

An overview of the energy exchange processes at the snow surface is given by Male and Granger (1981). The energy flux through a snow surface Q_t can be written as

$$G(1-\alpha) + L\downarrow - L\uparrow + H + LE + Q_t = 0 \tag{1}$$

where G – Global radiation
α – Albedo
$L\downarrow$ – Long-wave incoming radiation
$L\uparrow$ – Long-wave outgoing radiation
H – Sensible heat flux
LE – Latent heat flux

The sign of the fluxes is chosen to be positive towards the surface. Because soil and snow temperatures are usually very similar at the base of the snow cover, the ground heat flux has been neglected.

Fig. 1 shows the components of the daily energy balance derived from the measurements at the SLF test site in spring 1992. The evaluation of the quantities from the measurements and their parameterization from routine weather data (ANETZ) is discussed below.

Short-Wave Radiative Fluxes

Short-wave radiation is generally the largest energy source for the snow cover. The short-wave incoming flux may exceed 1,000 Wm^{-2} during the melt period. However, most of this energy is reflected from the surface.

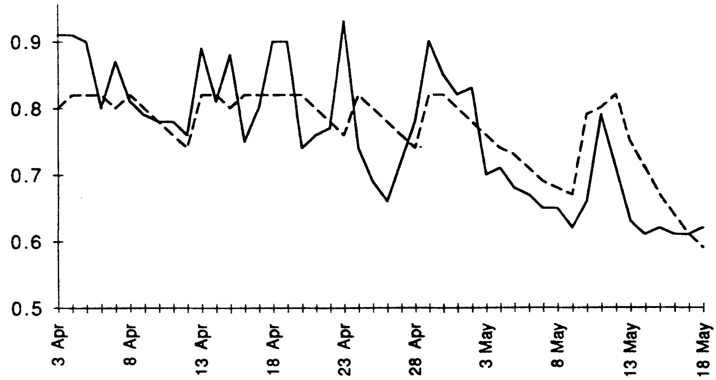

Fig. 2. Daily mean albedo measured (solid line) and parameterized (dashed line). The parameterization slightly underestimates the albedo during the premelt period and overestimates it during the melt period.

Since global radiation is measured at the ANETZ-station, modelling of the short-wave net radiation depends on the quality of albedo simulation. The albedo α is parameterized after Rohrer (1992)

$$\alpha = \alpha_0 + K e^{-npk} \tag{2}$$

with $\alpha_0 = 0.4$
$K = 0.44$
$k = 0.05$ for $T_{air} < 0°C$
$k = 0.12$ for $T_{air} > 0°C$
np – days since last snowfall (> 2 cm)

This parameterization leads to a slight underestimation of the albedo in the premelt season and to an overestimation in the melt season:

	measured albedo	parameterized albedo
average 3 - 30 April 1992	0.81	0.80
average 1 - 18 May 1992	0.68	0.72

Because of the magnitude of short-wave radiation, this small overestimation of the parameterized albedo during the melt period leads to a relatively significant underestimation of short-wave net radiation.

Long-Wave Radiative Fluxes

Long-wave radiation is the major source of energy loss in the snow cover. The long-wave incoming radiation strongly depends on the properties of the lowest

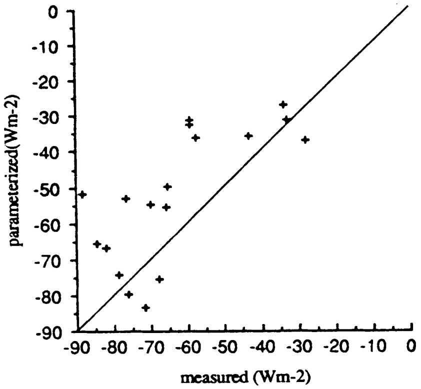

Fig. 3. Daily mean long-wave net radiation: Measured values compared with parameterization (1-18 May 1992).

atmospheric layers and the cloud cover, whereas the long-wave outgoing radiation is a function of surface temperature and emissivity.

The long-wave incoming radiation measurements were corrected for the underestimation of unshaded pyrradiometers as described by Ohmura and Gilgen (1993).

To estimate the long-wave net radiation L^* from the ANETZ-data, an approximation as used by Braun (1985) and modified after Kuhn (1984) was employed

$$L^* = L_0 (1-C) \tag{3a}$$

$$L_0 = 0.7\,\sigma T_{air}^4 - \sigma T_{surf}^4 \tag{3b}$$

L_0 is the clear sky longwave net radiation, σ the Stefan-Boltzman constant and C the cloud cover in 1/10. The surface temperature T_{surf} was taken as 0°C during the entire melt period. This parameterization leads to useful results with a slight underestimation of the long-wave radiative loss compared to the measurements (Fig. 3). The reason for this underestimation might result from

- the incomplete information about the cloud cover, with only three daily readings;
- the influence of the surrounding relief;
- the low humidity of the boundary layer, only part of which is included.

Turbulent Fluxes

The contribution of the turbulent fluxes of sensible and latent heat to the energy balance is very variable and depends mainly on the local scale meteorological conditions. Direct measurements are very difficult to perform. The turbulent fluxes are usually derived from temperature, relative humidity and wind speed measurements in the lowest boundary layer. A review of current methods of their evaluation over snow and ice is given by Morris (1989). For comparison purposes the turbulent heat fluxes were calculated using several approaches.

Profile Methods:
The turbulent fluxes are derived from 4 level measurements which were located at z = 0.3 m, 0.8 m, 1.8 m and 3.2 m above the snow surface, the exact height depending on the snow height. It was assumed that the profiles can be described by the Businger-Dyer equations (see Stull 1988 and Holtslag and van Ulden 1983)

Sensible heat flux

$$H = -\rho C_p u_* \theta_* \tag{4}$$

Latent heat flux

$$LE = -\rho L_v u_* q_* \tag{5}$$

with

$$\begin{aligned} u_* &= k(u_2-u_1)\{\ln(\frac{z_2}{z_1}) - \Psi_m(\frac{z_2}{L}) + \Psi_m(\frac{z_1}{L})\}^{-1} \\ \theta_* &= k(\theta_2-\theta_1)\{\ln(\frac{z_2}{z_1}) - \Psi_h(\frac{z_2}{L}) + \Psi_h(\frac{z_1}{L})\}^{-1} \\ q_* &= k(q_2-q_1)\{\ln(\frac{z_2}{z_1}) - \Psi_e(\frac{z_2}{L}) + \Psi_e(\frac{z_1}{L})\}^{-1} \end{aligned} \tag{6}$$

The Obukhov length is defined by

$$L = \frac{\theta u_*^2}{\mathrm{kg}\theta_*} \tag{7}$$

u, θ and q are the wind speed, the potential temperature and the specific humidity of the air as they are measured at different levels z. k is the van Kàrmàn constant, taken as $k = 0.4$, g is the acceleration due to gravity, C_p specific heat for air and L_v latent heat of vaporization of water.

The Ψ -functions Ψ_m for mass, Ψ_h for heat and Ψ_e for water vapour are given by Paulson (1970)

for $L < 0$ (unstable):

$$\begin{aligned} \Psi_m &= 2\ln(\frac{1+x}{2}) + \ln(\frac{1+x^2}{2}) - 2\tan^{-1}(x) + \frac{\pi}{2} \\ \Psi_h &= \Psi_e = 2\ln(\frac{1+y}{2}) \end{aligned} \tag{8}$$

with

$$x = (1 - 15\frac{z}{L})^{1/4}, \quad y = (1 - 9\frac{z}{L})^{1/2}$$

for $L > 0$ (stable):

$$\Psi_m = \Psi_h = \Psi_w = -6\,\frac{z}{L} \tag{9}$$

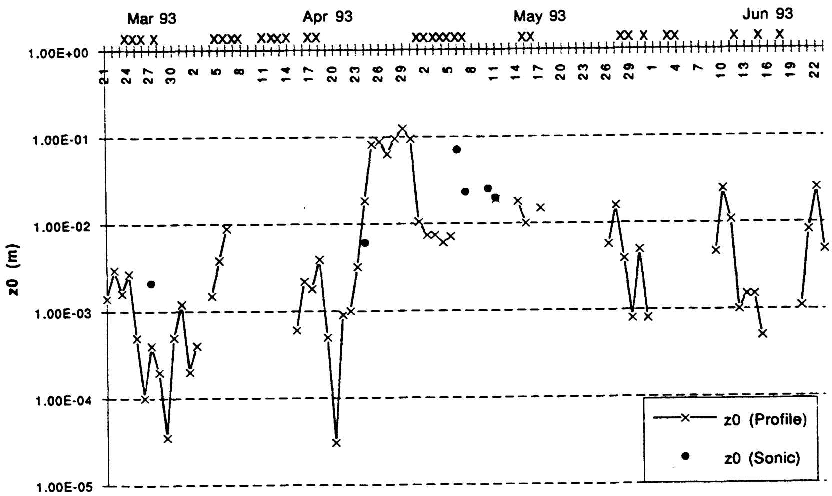

Fig. 4. Daily mean roughness lengths for momentum calculated from 4-level profile measurements or from sonic anemometer measurements in near neutral conditions. A daily average value was calculated if more than 4 runs were available during the respective day. The 'X' on the time axis indicates snowfall events (> 2 cm).

The calculations were performed iteratively between any 2 measurement levels z_1 and z_2. The roughness length z_0 is calculated using Eq. (6) in near neutral conditions where the Ψ -functions can be neglected. For each near neutral run (where $z/L<0.05$), z_0 was calculated as the height z_1 where $u_1=0$. The roughness lengths obtained in this manner where averaged over a day. The variation of z_0 during the measurement period is shown in Fig. 4. The average of z_0 during the premelt period is 1.9×10^{-3} m and 4.4×10^{-3} m during the melt period. There is also some indication of z_0 declining after periods of snowfall (see Fig. 4). The large values of z_0 at the end of April occured during strong foehn wind periods and may be influenced by the topography around the measurement site.

The calculation of the roughness lengths for temperature (z_{0t}) and for humidity (z_{0q}) is possible over melting snow, when the surface conditions are known. In near neutral conditions, however, the gradient of temperature is near zero and therefore z_{0t} cannot be determined from profile measurements. Using corrected profiles for non-neutral conditions (Eqs. (8) and (9)), the resulting z_{0t} is very small (mean value around 10^{-6} m) with large scatter. For z_{0q} the scatter is too large, to calculate an average.

Many authors (*e.g.* Oke 1987) suggest a roughness length around 10^{-3} m for snow for all properties. This value fits quite well the conditions found at the test site.

To calculate the turbulent fluxes over melting snow, the iterations made best progress when z_0 (10^{-3} m was used for all properties) was included in the calcula-

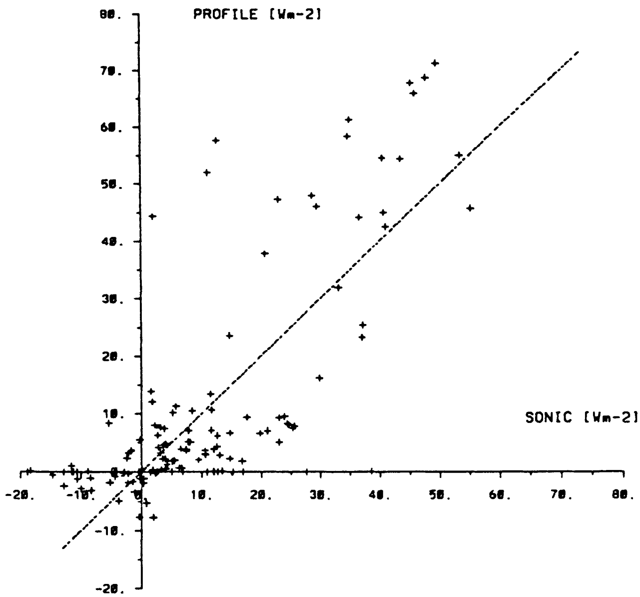

Fig. 5. Sensible heat flux (30 min means) derived from 4-level profile measurements (vertical axis) compared with eddy correlation (horizontal axis). Data from 21 March, 24 April, 11 May and 12 May 1993 were compared.

tions. The same result was attained by Nieuwstad (1978). Fig. 6 shows a comparison of 30 min average sensible heat fluxes calculated using profile and bulk methods.

Eddy Correlation Method – An acoustic anemometer was used for high-frequency wind speed measurements on selected days. These measurements enable the sensible heat flux to be determined directly

$$H = \bar{\rho} C p \overline{w'T'} \tag{10}$$

$\overline{w'T'}$ = vertical kinematic eddy heat flux

The roughness length z_0 can also be calculated from the sonic measurements for near neutral conditions from Eq. (6)

$$z_0 = \frac{z}{\exp\left(\frac{ku(z)}{u_*}\right)} \tag{11}$$

using $u_*^2 = -\overline{u'\,w'}$ from the sonic measurements.

There are only few data in near neutral conditions available, but they are in the same order of magnitude as the values calculated from the profile data (Fig. 4).

A comparison between the sensible heat flux calculated from the profile method

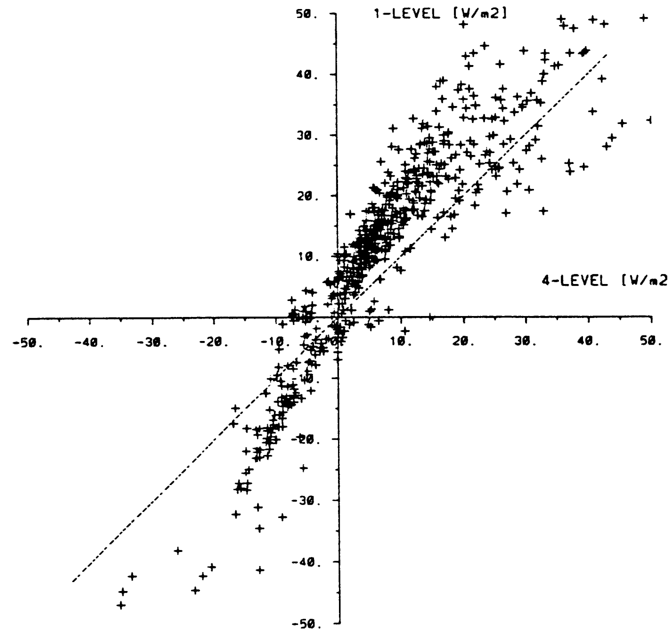

Fig. 6. Sensible heat flux (30 min means) derived from 4-level profile measurements compared to a bulk approach for wind speeds > 2 m/s. May and June 1993.

and derived from eddy correlation (Fig. 5) shows some underestimation using the profile method for small fluxes and some overestimation for the larger fluxes.

Bulk Method – The turbulent heat fluxes are often approximated over melting snow with only one measurement of temperature, relative humidity and wind speed above the snow surface. The so called 'bulk method' (see *e.g.* Kuhn 1984) is widely used because of its simplicity. Over melting snow at height z_{0t} the surface temperature is taken as 0°C and at height z_{0q} the saturation vapour pressure as 6.1 mbar. With this assumptions the Businger-Dyer relations can be used to calculate the fluxes.

Despite a systematic overestimation, the calculation of the *sensible heat flux* using the profile level 3 (at 1.8 m) for the bulk method leads to results comparable to the profile method (Fig. 6 and Table 2).

Table 2 – Mean turbulent heat fluxes 1 - 18 May 1992 calculated using different methods.

Method	H (Wm-2)	LE (Wm-2)
4-level Profile (test site)	2.5	-0.6
1-level bulk (test site)	3.8	-4.4
Bulk with ANETZ data	-5.3	-14.0

Table 3 – Comparison of different methods for determining the melt energy and runoff. Average values 1 - 18 May 1992.

Method	Melt energy (Wm^{-2})	Runoff (mmd^{-1})
1) Energy Balance Method	38	10
2) Measured Runoff (readings from the lysimeter calculated into melt energy)	51	13
3) Parameterized from ANETZ data and 1-level profile	35	9
4) Degree-Day model	33	9

Comparison of the *latent heat flux* calculated using the bulk method and using the profile method leads to less satisfactory results (Table 2). This difference could result from relatively large measurement errors.

Using the ANETZ temperature, humidity and wind speed data for the calculations, the fluxes become much larger in magnitude and differ largely from the fluxes measured at the test site SLF (Table 3). This large difference can be explained by the location of the ANETZ station on a small summit, which is much more exposed to wind than the test site below, and to the elevation difference of 130 m which causes melt conditions to occur later in the year.

The above results suggest that the bulk method is a useful approach for qualitative estimations of the turbulent fluxes, if short time accuracy is of secondary importance. To obtain acceptable results, however, it is necessary to know reasonably well the surface conditions (roughness length, surface temperature) and to perform the measurements at a site where the wind conditions are representative for the area of interest. Extrapolation in space of the turbulent fluxes should therefore only be done with great care.

Melt Energy and Runoff

Once the entire snow cover becomes temperate, nearly all the energy flux through the surface is transferred into melting (Ohmura 1981). This condition was reached around 30 April in 1992 and 27 April 1993.

Table 4 and Fig. 7 show different methods for determining the runoff.

The degree-day approach is still used at times for rough approximations of runoff from a snow cover. For the Weissfluhjoch area the parameterization after deQuervain (1979) was used

$$A = a\,T \tag{12}$$

where A – runoff (mmd^{-1})

a – degree day factor taken as a=4.0 $mm°C^{-1}d^{-1}$

T – daily mean temperature above 0°C

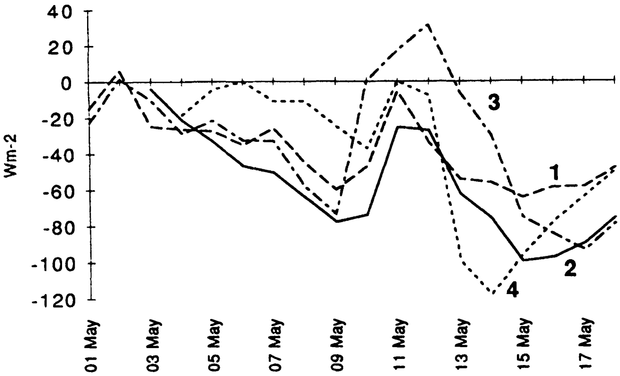

Fig. 7. Melt energy at Weissfluhjoch calculated using different methods: 1) Measured energy balance, 2) Measured runoff, 3) Parameterized energy balance, 4) Degree-day.

DeQuervain points out that the correlation is only valid for long-term predictions (weeks, months).

The day-to-day runoff can be predicted rather well using the energy balance measurements, despite a systematic underestimation of about 20 % compared to the readings from the lysimeter (Fig. 7). This may be the result of water storage in the snow cover during early melt period or of water flow from the slope above the test site.

With the parameterized energy balance the prediction of the daily variations of the runoff is less accurate, but – averaged over the entire observed melt period – the runoff calculated from parameterization is only 10 % less than from the measured energy balance (Table 3). This indicates a need for better parameterizations if short-time accuracy is important.

Surprisingly, the degree-day approach allows a reasonable runoff prediction, despite the fact, that it mainly describes the sensible heat flux component of the energy balance.

Energy Balance Studies in Alpine Environments

There have been a large number of energy balance studies in alpine climate conditions, but most were performed on glaciers over melting surfaces. Table 4 shows the summarized results of some studies in a temperate climate.

Net Radiation dominates the energy balance in most studies, but its absolute value varies considerably. The *sensible heat flux* ranges from negligible to equal in importance to net radiation. The *latent heat flux* is negative and relatively small in most investigated areas, but can be of some importance for reducing melt in a dry climate.

Table 4 – Energy balance studies in alpine climate over a melting snow cover.

Investigator	Location, Period	NR Wm^{-2}	LE Wm^{-2}	H Wm^{-2}	Melt Energy Wm^{-2}
Seasonal Snow Cover					
Harding (1986)	Finse (Norway) 1000m, 15 days in May	25	0.3	21.4	-46.7
Olyphant&Isard (1988)	Niwot Range, Colorado, late-lying snowffields			>100	
Marks & Dozier(1992)	Emerald Lake, Sra Nevada, California May	44	-54	50	-41
	June	93	-71	92	-115
Plüss & Mazzoni (this study)	Weissfluhjoch, Swiss Alps, 18 days in May (measurements)	36	-1	3	-38
	(Parameterization)	34	-4	4	-34
Alpine Glaciers					
Föhn (1973)	Peyto Glacier, Canada, 2510m, 14 days in July	79.8	14.5	87	-181.3
La Casiniere (1974)	Mt. Blanc, French Alps, 3550m, 23 days in July	20.8	- 4.9	5.0	-20.9
Martin (1975)	St.Sorlin Glacier, France, 2700m, 11 days Summer	32.0	-3.5	24.3	-52.8
Funk (1984)	Rhonegletscher, Swiss Alps, Summer	90	-2	81	-169
Calanca & Heub.(1990)	Urumqi Glacier No 1, Tien Shan, China, 3900m	60	-15	17	-62

The latent heat flux is frequently opposite in sign but of similar magnitude as the sensible heat flux, hence the *net turbulent heat flux* is very small. This might be one reason why the bulk approach leads to good averaged results for melt energy determination, despite relatively large short-time errors of single components.

Conclusions for Snow Melt Modelling

In high-alpine environments *net radiation* generally dominates the energy balance and is the major energy source for snow-melt. In the investigated area at Weissfluhjoch, using data from automatic measurements and cloud cover observations, the net radiation could be parameterized within good accuracy compared to radiation measurements. Improvements could be possible for the albedo over melting snow and long-wave incoming radiation modelling.

The contribution of the *turbulent heat fluxes* to snow-melt can also be of major importance in some climatic conditions. Their magnitude is extremely variable and depends largely on the wind speed. For the inner alpine region of Davos, the wind speeds are generally low and hence the turbulent fluxes relatively small. At periods of high wind speeds or in windy environments, their contribution increases rapidly and they should be included in snow melt models with good accuracy.

The often used *bulk method* to calculate the sensible heat flux leads to good results, provided that data from the investigation site are included and the roughness length is known with good accuracy. On the other hand, the latent heat flux seems to be more difficult to determine. The one-level approach is therefore only recommended where the turbulent fluxes are expected to be of minor importance (*e.g.* in areas with little wind).

If the data from a distant and more elevated automatic measurement station are used to calculate the turbulent fluxes, their magnitude is considerably overestimated. Such extrapolations of the turbulent fluxes require further investigation.

The results presented in this paper are encouraging as they show that runoff prediction from an alpine snow cover is possible using an energy balance approach with good accuracy. While average runoff can be modelled with relatively simple models, the daily variations are more sensitive to the exact knowledge of the energy balance. For this purpose parameterizations should be improved.

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Address:
Department of Geography,
Swiss Federal Institute of Technology,
Winterthurerstr. 190,
CH-8057 Zürich,
Switzerland.