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Is Evaporation an Important Component in High Alpine Hydrology?

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The knowledge of evaporation in the high mountain areas of the European Alps is still rather poor. It is generally regarded as a component of secondary importance in the water balance. The available mean areal evaporation data are based on conventional water balance estimations and suffer from inaccuracies in the determination of precipitation. This is also obvious from the rate of decrease in mean annual evaporation with altitude indicated by different authors; these values range from 71 mm to 356 mm pro 1,000 m of altitude. From heat balance studies on glaciers it is evident that evaporation/condensation as a process of high specific energy exchange can be a determinative factor in the shortterm variations of melt rates. The scale width of the daily latent heat fluxes reaches at magnitudes equal to or larger than those of net radiation and sensible heat flux.

Introduction

The average annual areal evaporation figures in the high mountain regions of the Alps have been calculated up to now from the water balance equation

$$E = P - R - \Delta S$$

In basins of mean altitudes > 2,000 m, various water balance calculations have indicated for E (evaporation plus transpiration) values in the range of 300 to 150 mm (Binggeli 1974; Koehl 1971; Luetschg 1944; Steinhäusser 1952). The discussion and interpretation of these figures is difficult because of the great uncertainty

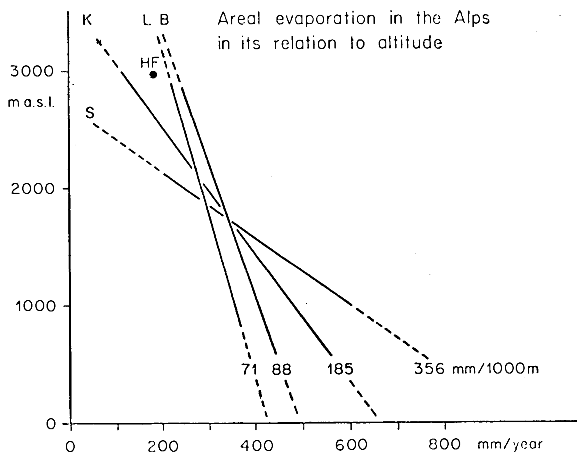

Fig. 1 .Compilation of present knowledge on mean annual areal evaporation of catchment basins in the European Alps in relation to their mean altitudes, based on water balance computations for different regions and by different authors (L: O. Luetschg 1944; S: H. Steinhäusser 1952; K: A. Koehl 1971; B: V. Binggeli 1974; HF: H. Hoinkes and H. Lang 1962)

due to the inaccuracy in the corresponding precipitation values.

The vertical gradients of *E* given by the above mentioned authors for different regions, range from 71 mm to 356 mm decrease of *E* per 1,000 m increase in altitude (see Fig. 1). These great differences are far beyond what can be expected from the hydroclimatic differences between these regions. It confirms the uncertainty in our knowledge of high alpine evaporation. A two year ice- and water balance study in the Hintereisferner basin (Oetztal Alps), which used corrected precipitation measurements (including direct observation of snow cover water equivalent) provided a rather well founded areal evaporation figure of 180 mm, corresponding to a mean altitude of the 58% glaciated basin of 2981 m (Hoinkes and Lang 1962).

Taking this as our present knowledge of evaporation in the high mountain areas of the Alps, it seems justified to regard it as a component of minor importance in the hydrological regime, being in the order of approximately 10% of precipitation. At the same time the means: the magnitudes of precipitation inaccuracy and of evaporation estimates are of the same order.

Based on water balance estimations currently available and on physical considerations, precipitation generally increases with attitude, while evaporation is generally assumed to decrease with altitude. These "facts" may be the further arguments to regard evaporation as an unimportant quantity in high altitude regions.

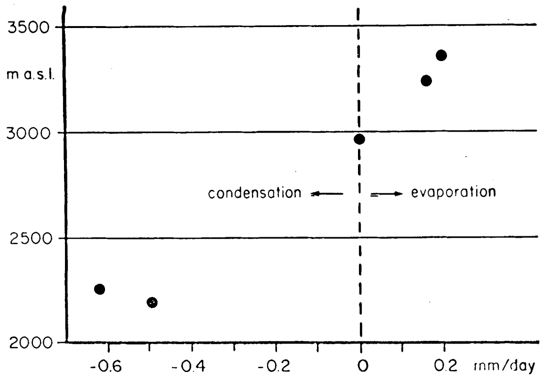

Fig. 2. Mean daily values of evaporation and condensation on alpine glaciers, resulting from different heat balance studies in the ablation period on different glaciers (H. Hoinkes and N. Untersteiner 1952; H. Hoinkes 1953; W. Ambach and H. Hoinkes 1963; H. Lang and M. Schönbächler 1968; H. Lang, B. Schädler and G. Davidson 1977).

Some Evidences from Heat Balance Studies and from Direct Observations

Several heat balance studies during the main ablation season i.e. approx. June-August on glaciers in the Austrian and Swiss Alps pointed out, that evaporation over periods of several days and weeks is obviously counterbalanced to a great part by condensation. (Hoinkes and Untersteiner 1952; Hoinkes 1953; Ambach and Hoinkes 1963; Lang and Schönbächler 1968; Lang, Schädler and Davidson 1977).

In Fig. 2 the mean daily rates of evaporation/condensation from these temporary observations on glaciers are plotted in relation to altitude. In contrast to the general situation, evaporation is increasing with a altitude on glaciers, due to the physical upper limitation of temperature i.e. saturation vapor pressure at the melting point of snow and ice surfaces. In summer the vapor pressure of the air frequently exceeds this value, causing condensation, which is regularly observed on glaciers in altitudes up to approximately 3,000 m.

Furthermore, available point observations made by different authors at sites in the altitude range of 2,000 m to 2,500 m are summarized in Fig. 3 together with our own findings (de Quervain 1947; Rott 1979; Turner, 1975; Lang and Schönbächler 1968). The graph gives an idea of the seasonal variation of evaporation. In the spring, low atmospheric vapor pressure causes evaporation from the snow cover up to ca. 16mm/month in April/May – a value of *monthly evaporation loss,* which is frequently exceeded by *melt ablation rates of single days.* During the main

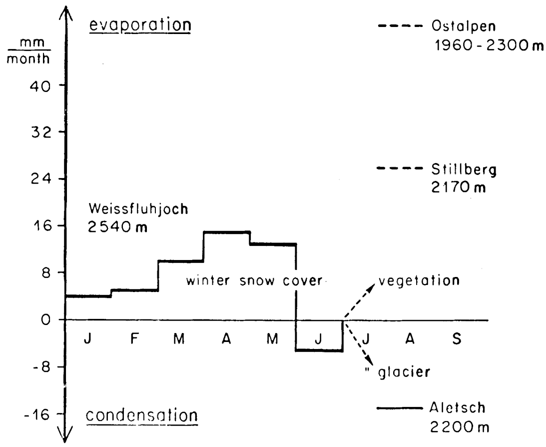

Fig. 3. Conception of the seasonal course (January to August) of monthly evaporation in altitudes between 2000 m and 2500 m, derived from direct measurements and from heat balance studies in the Alps. January to June: Evaporation/condensation from the snow cover. July/August: Evaporation from alpine vegetation cover, condensation from a glacier surface; vegetation – free areas unknown. (Weissfluhjoch: M. de Quervain 1948; Ostalpen: H. Rott 1979; Stillberg: H. Turner et al. 1975; Aletsch: H. Lang and M. Schönbächler 1968).

ablation season snow and ice surfaces in these altitudes seem to show more condensation than evaporation due to increased moisture content of the atmospheric sublayer. Evapotranspiration values of high alpine vegetation are known only from two heat balance studies (Rott 1979; Turner 1975); they give an idea of the evaporation loss during the very short vegetation period. Although this valuable information is limited, it seems evident, that *ET* values of these orders of magnitude (1-2 mm per day) must be accounted for in short-term water balance computations during the vegetation period. Even less is known about evaporation from vegetation-free areas in the Alps.

Hydrological Significance of Evaporation as a Process of High Specific Energy Turnover.

Evaporation is a process of high specific energy requirement of 597.3 cal/gr of water (at 0°C, resp. 677 cal/gr for ice and snow); the other hydrologic process, melting of snow and ice, needs only a specific energy of 79.7 cal/gr. It seems evident, that even small and in the water cycle secondary quantities of evaporation loss, can gain importance due to their relative high energy turnover, if melt rates are to be determined on the basis of estimations of available energy.

Table 1

Site	altitude	*NR* (cal	Q_S cm^{-2}	Q_L d^{-1})	available for melt
Firn area 3.-19. Aug. 1973	3,366 m	91	24	-14	101
Glacier tongue 2.-27. Aug. 1965	2,220 m	267	78	29	374

NR net radiation Q_S sensible heat flux Q_L latent heat flux

The following results of two heat balance studies at the Aletsch Glacier (Swiss Alps) may show the significance of latent heat fluxes when dealing with meltwater runoff estimations.

a) Average Conditions During the Ablation Period

Heat balance studies at the Aletsch Gletscher (Lang and Schönbächler 1968; Lang, Schädler and Davidson 1977) provided mean daily heat fluxes (cal cm^{-2} d^{-1}) which are given in Table 1.

Both field studies represent characteristic conditions during the ablation season at the accumulation area (average albedo of the firn 0.74) and at the ablation area (average albedo of ice surface 0.27).

At both sites the mean latent heat flux appears to be of secondary importance. Evaporation predominates condensation at the high altitude site and requires appr. 12% of the mean daily energy supply due to net radiation and sensible heat. The mass balance is characterized by ca. 0.2 mm average evaporation per day. At the glacier tongue, the mean latent heat flux is a heat source due to the prevailing condensation conditions at this altitude; it provides in the average appr. 8% of the heat for melt, and in the mass balance ca. 0.5 mm of condensation water per day.

b) Daily Values and Scale Width of the Energy Fluxes

Short-term forecasting of meltwater and glacier runoff in general is based on estimates of the daily meltrates. From the results of the heat balance studies one would, at first glance, expect net radiation and air temperature to be the most important factors for the purpose of estimating melt rates. In this context the method, which uses the temperature-degree-day-factor, seems a well based practical solution, provided that daily air temperature and net radiation are closely correlated.

On the other hand, former analyses clearly pointed out vapor pressure as an important variable in the estimation of daily meltrates (Lang 1968, 1980*). This is to a great extent caused by the large variation in the latent energy fluxes in the

* New computed, revised results

time scale of days. This can simply be outlined by comparing the scale-width within which the daily energy fluxes of each component vary. The above mentioned field studies on the Aletsch Gletscher provided the following values

Table 2 – Aletsch Gletscher: Scale width of daily heat fluxes (cal $cm^{-2}d^{-1}$).

Site	altitude	component	max	min	scale-width
*Firn area**	3,366 m	NR	136	37	99
3.-19. Aug. 1973		Q_S	90	4	86
		Q_L	14	-160	174
Glacier tongue	2,220 m	NR	407	45	362
2.-27. Aug. 1965		Q_S	157	10	147
		Q_L	*177*	*-183*	*360*

NR net radiation $\quad$ Q_S sensible heat flux $\quad$ Q_L latent heat flux

At both sites the maximum observed daily evaporation rates reach about the same magnitude of 160 respectively, 183 cal/cm^2 per day, equivalent to a maximum waterdepth of 2.4 respectively, 2.7 mm/d evaporation. Without evaporation conditions, the same energy would have been available for melting 20 mm of snow at the firn area additional 23 mm of ice at the glacier tongue (water equivalent). In the firn-area, in fact, all energy available from net radiation and from sensible heat flux at this very day was completely used by evaporation; the scale width between maximum and minimum daily values of the latent heat flux is significantly larger than for the other heat fluxes.

Due to the lower albedo of the ice surface (0.27), net radiation provides most of the energy for ablation; in the lower part of the glacier, at the same time, condensation rates of the same magnitude as evaporation rates are observed, and the scale width of the latent heat flux matches that of net radiation and is more than double the value of the sensible heat flux.

From this we should conclude that evaporation and condensation processes are important controlling factors in the time scale of the daily variations of the water balance in snow and ice areas under the existing climatic conditions in the Alps.

Final Remarks

The intention of this paper is twofold: 1) to contribute to avoiding misunderstandings between those involved in glacier – heat balance relations, and practising hydrologists by pointing out that the importance of the single components is very much a factor of the time scale. 2) to point out that evaporation in general seems to be of secondary importance in high alpine water balances, but may well play a significant role in controlling short-term variations of meltwater runoff.

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