

ENERGY BALANCE CALCULATIONS ON AND NEAR HINTEREISFERNER (AUSTRIA)
AND AN ESTIMATE OF THE EFFECT OF GREENHOUSE WARMING ON ABLATION

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ABSTRACT

During some 10 days in July 1986, measurements of meteorological variables and ablation were made at two sites on and near Hintereisferner (Austria), namely at GLACSTAT (2500 m), located on the glacier tongue, and at ROCKSTAT (2440 m), just in front of the tongue. In this paper energy balance calculations for both stations are presented. About 90% of the ablation energy at GLACSTAT came from radiation. This large value is a consequence of the low albedo (0.16) and the long periods of sunny, relatively cold weather. A detailed comparison is made of the surface energy budget at the two sites. While melting is important at GLACSTAT, the loss of energy by the turbulent fluxes and the outgoing long wave radiation is larger at ROCKSTAT.

Finally, the consequences of the rising concentrations of atmospheric trace gases on ablation are discussed. The data from GLACSTAT will be adapted to estimated past and projected future concentrations. If all relevant trace gases are considered and under the specific conditions of the experiment total ablation for the 10-days period will increase by 11% in the 50 years after 1986.

1. INTRODUCTION

It is a well known feature that glaciers are generally retreating since the middle or the end of the last century (e.g. Patzelt (1970), Reynaud (1983) and Meier (1984)). As most glaciers in any part of the world show this trend we may assume that the retreat is caused by climatic change. In principle in this case climatic change may be a change in any or a combination of the variables which determine the energy fluxes between atmosphere and glacier. Thus, one of the necessary steps in establishing the relation between climate and glacier length is a better understanding of the relation between climate and these energy fluxes.

From 12 till 22 July 1986 a field programme was carried out on the Hintereisferner (46°48'N, 10°56'E), a valley glacier in the Austrian Alps. Emphasis was laid on measurements of the meteorological variables

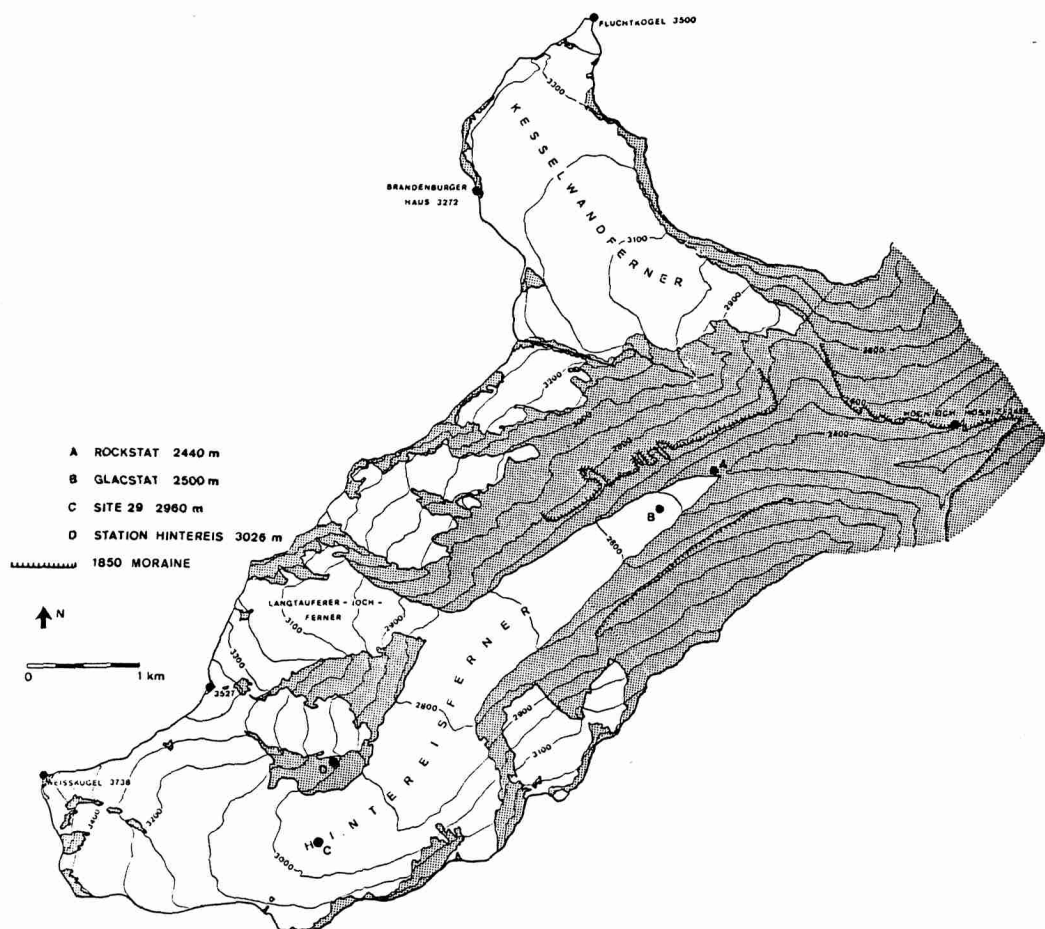


Figure 1. Catchment area of the Hintereisferner and the Kesselwandferner. White surfaces represent the 1969 glacierized area. Since 1969 the Hintereisferner has retreated so that the ice edge was about midway between GLACSTAT and ROCKSTAT in 1986, while the altitude at the site of GLACSTAT decreased to about 2500 m a.s.l.

from which the energy fluxes can be determined. Moreover, the ablation rate was measured. One of the purposes of the experiment was to obtain a better understanding of the energy balance of the glacier surface and its surroundings at different sites in exactly the same weather conditions.

Four institutes took part in the experiment: the Institut für Meteorologie und Geophysik (University of Innsbruck), the Hydrological Institute (Wallingford, U.K.), the Kommission für Glaziologie (Munich) and the Instituut voor Meteorologie en Fysische Oceanografie (University of Utrecht). The latter operated two stations: one on the glacier tongue (GLACSTAT, 2500 m a.s.l.) and one just in front of it (ROCKSTAT, 2460 m a.s.l.). The other institutes carried out their measurements higher up in the firn area. Measurements and results from these stations will be reported in Harding et al. (1987). Figure 1 gives an impression of the setting.

GLACSTAT and ROCKSTAT essentially consisted of 1 mast each. Both masts supported 11 sensors (see Figure 2). The signals from each of the sensors were automatically recorded at 2 minute intervals. Moreover, twice a day ablation was measured along 11 stakes distributed across the glacier tongue and all at the elevation of GLACSTAT (2500 m).

The weather was fine with almost cloudless skies during 6 days out of 10. During 3 days the weather was variable and one day was predominantly foggy.

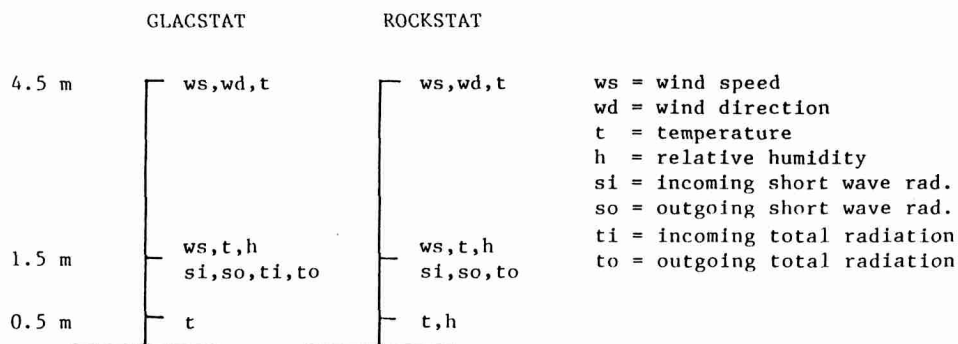


Figure 2. GLACSTAT and ROCKSTAT masts with positions of sensors. Temperature and humidity sensors are not ventilated.

In Section 2 of this paper the computer model used for the energy calculations will be discussed. Then, in Section 3 the calculations itself will be presented for the 2 stations near the terminus. Some model sensitivity experiments mainly concerning the turbulent exchange will be performed. It will also be shown that the energy gained by incoming radiation is lost in completely different ways at the 2 stations. In Section 4 the impact of the increasing concentrations of atmospheric CO_2 and other trace gases is studied. Probable changes in temperature and incoming long wave radiation due to the increasing trace gas concentrations are inferred from literature. Then, our field data are adapted accordingly and the ablation is calculated for the 1880 pre-industrial level of trace gas concentrations and for the predicted 2036 level of trace gas concentrations.

2. CALCULATION OF THE ENERGY FLUXES

If the energy transport by rain drops is neglected, the total energy flux between the atmosphere and the glacier or the soil is the sum of the radiative and the turbulent fluxes. Fluxes towards the surface will be called positive hereafter.

2.1 The radiative fluxes

At the two stations considered here the total radiative fluxes could be obtained from the measurements of incoming and outgoing short wave and incoming and outgoing total radiation through horizontal surfaces. At GLACSTAT, where the surface sloped about 10° to the north-east, the data were corrected in order to obtain the fluxes through a surface parallel to the atmosphere-glacier interface (see Mannstein, 1985). The incoming long wave radiation was not measured at ROCKSTAT. Therefore the values from GLACSTAT were used. The measurements of the outgoing long wave radiation were rejected. It appeared to be more accurate to calculate the outgoing long wave radiation from the surface temperature, which itself was also calculated (see Section 2.3).

2.2. The turbulent fluxes

Essentially, the turbulent fluxes can be calculated from profile measurements of wind velocity, temperature and humidity. In this study, starting from pairs of values of each of these variables two theories will be considered for the calculations. In both cases the fluxes are equal to the product of an exchange coefficient and the temperature or vapour pressure difference between the two levels. In the first case logarithmic profiles of the variables concerned are assumed, e.g.

$$u(z) = \frac{u_*}{k} \ln \frac{z+z_{ou}}{z_{ou}} \quad (1)$$

with u the wind velocity, z the height, u_* the friction velocity, k von Karman's constant and z_{ou} the roughness parameter of the wind velocity profile. This leads to an exchange coefficient proportional to the wind velocity difference and the height, and independent of the stratification (hereafter s.i.-theory). The second method used here is based on the Monin-Obukhov similarity theory (hereafter M.O.-theory) see e.g. Businger (1973). It takes into account the effect of the stratification on the exchange coefficient. The errors in the measurement of the temperature and relative humidity were estimated to be 0.3°C and 5%, respectively. Calculations are only reliable if the differences in temperature and vapour pressure between the levels of the measurements are much larger than the errors in the individual measurements. Often this was not the case. However, the temperature and vapour pressure differences between the levels of the measurements and the surface were much larger, even if the measurements from the lowest level were used. So, pairs of values of temperature, vapour pressure and

wind velocity were obtained from the measurements at 1.5 m in the atmosphere and from calculated surface values (see next section). The surface roughness parameters for GLACSTAT were taken from literature, while they served as tuning parameters for the calculations at ROCKSTAT.

Another problem is posed by the structure of the glacier wind. This wind is characterized by a low level wind velocity maximum (0.5-3 m above the glacier) and a thermocline at about the same level (see Holmgren, 1971). Turbulent exchange theories, like the two used in this study, are not valid close to such a wind velocity maximum. They should be applied only to the layer clearly below the maximum (Holmgren, 1971). Nevertheless, the values from 1.5 m were used for the calculations. This level is likely to be below the wind maximum and the associated thermocline when turbulent exchanges are large. As indicated by more detailed measurements of the wind profiles on the glacier high temperatures tend to cause large wind velocities, which in turn are associated with a higher wind velocity maximum. Even in cases where the wind velocity maximum and thermocline are situated below 1.5 m, the error in the calculation of the sensible heat flux introduced by this phenomenon will be restricted. The effects of taking a smaller wind velocity and a higher temperature oppose each other. However, the stability is overestimated so that calculations with the M.O.-theory are affected more than the calculations with the s.i.-theory.

The vapour pressure over the ice is simply calculated by taking the saturation vapour pressure corresponding to the surface temperature. A similar procedure does not work for ROCKSTAT, since the vapour pressure might be well below its saturation value. The availability of water in the soil is not calculated. It depends on factors like precipitation, evaporation, horizontal advection of water, water holding capacity and permeability of the soil. Thus, another method had to be used for the calculations of the latent heat flux. The values of temperature and humidity at the middle and the lower level were used to calculate the sensible and the latent heat flux and the Bowen ratio (ratio of the sensible and the latent heat flux). Then, the sensible heat flux was calculated once again from the temperatures at 1.5 m and the surface, and the latent heat flux was obtained by dividing this last calculated sensible heat flux by the Bowen ratio.

2.3 The surface temperature

In fact, the modelling of the englacial temperature was derived from an energy balance model including the calculation of englacial temperatures. This model is described by Greuell and Oerlemans (1986). The temperature profile in the uppermost layers of the glacier and the soil was calculated from:

$$\rho c \frac{\partial T}{\partial t} = K \frac{\partial^2 T}{\partial z^2} + W \quad (2)$$

with ρ the density, c specific heat and K the conductivity of the ice or the soil, T the temperature, t the time, z the depth below the interface

and W the production or consumption of energy. W includes the formation and refreezing of melt water (only at GLACSTAT) and the total energy flux from the atmosphere. Melt water does not penetrate into the ice. However, the ice close to the surface contained some water, so that a water holding capacity (C) was assumed. Equation 2 was solved numerically on a grid of 50 points extending downwards to about 4 m and with a downwards increasing grid point distance. The timestep was the same as used for the energy flux calculations, namely 2 minutes.

3. RESULTS

3.1 Results from GLACSTAT

Firstly, the total ablation calculated was compared with the amount of ablation measured along the stakes, which was 510 ± 20 mm w.e. for the whole period (see Table I).

Table I: Calculated ablation for the whole period in mm w.e.

"Standard run": $z_{ou} = 1.33$ mm; $z_{ot} = z_{oe} = 0.01$ mm; s.i.-theory;
 $C = 10$ mm; temperature, vapour pressure and wind
velocity from 1.5 m.

Measured ablation	510 \pm 20
"Standard run"	550
$C = 0$ mm	573
No turbulent fluxes	505
Roughness lengths $\times 5$	569
Temperature from 50 cm	545
M.O.-theory	539

In a first run, called "standard run" hereafter, the roughness parameter for the wind profile, z_{ou} , was taken to be 1.33 mm and the roughness parameters for the temperature (z_{ot}) and the humidity (z_{oe}) profiles were 0.01 mm. These values are taken from Hogg et al. (1982) and should be valid for ice in the ablation zone. The value for z_{ou} agrees well with the value obtained from detailed wind velocity profile measurements ($z_{ou} = 1$ mm), which we performed at GLACSTAT. In this "standard run" the s.i.-theory was applied and the water holding capacity of the ice was assumed to be 10 mm. Calculated ablation amounted to 550 mm w.e., which is evidently too much.

In the next run the effect of the water holding capacity was studied. With some water present the surface temperature decline associated with negative energy fluxes is delayed until the water in the ice is frozen. The higher surface temperature reduces the total energy flux through the outgoing long wave radiation and the turbulent fluxes. Comparing experiments with $C = 0$ mm and $C = 10$ mm in Table I we see that the water holding capacity of 10 mm reduces the total ablation by 23 mm.

In fact the surface temperature never drops below the melting point if $C = 10$ mm. According to our field observations a water holding capacity of at least 10 mm seems to be realistic.

In the next runs some sensitivity experiments regarding the turbulent fluxes were performed. Firstly, the turbulent fluxes were put equal to zero during the whole period. The resulting amount of ablation then equals the measured amount of ablation.

If the values of the 3 roughness parameters are each multiplied by 5, the turbulent fluxes are multiplied by a factor 1.5. An inspection of values for the roughness parameters in literature (e.g. Holmgren (1971) and Kuhn (1979a)) and estimates from our field data indicate that such a multiplication by 5 is certainly more than the upper limit in the uncertainty in the roughness parameters.

Temperature was also measured at a lower level (50 cm). If the values from this level are taken instead of the values from 1.5 m, total ablation decreases by 5 mm w.e. This decrease is caused by the existence of the thermocline.

In a further experiment the M.O.-theory was used. In this case the turbulent fluxes cause about 29 mm w.e. of ablation. For the s.i.-theory this was 40 mm w.e. The quotient of these values, 0.725, is a measure of the damping of the turbulent fluxes by the stability of the stratification. However, this damping is certainly overestimated by the use of wind velocity and temperature data from above the wind velocity maximum and its associated thermocline (see Section 2.2).

All but one of the runs mentioned in Table I give too high values for the total ablation. The exception is the run during which the turbulent fluxes were zero. However, this is certainly an unrealistic situation. Thus, it seems that changing model assumptions like the ones mentioned in Table I cannot produce a calculated amount of ablation equal to the measured amount of ablation. Therefore, the discrepancy will probably be due to instrumental error. An analysis of the effects of the possible errors in the data on the calculation of the total ablation was performed. It appeared that an error in the incoming total radiation measurements seems by far the most likely cause of the discrepancy.

Average values of the fluxes and some of the meteorological variables for the whole period along with maximum and minimum hourly means can be found in Table II. About 90% of the calculated ablation is due to radiation. This is an amazingly high value. According to Hoinkes and Steinacker (1975) this value varies between 50% and 80% in the Alps. The relatively large contribution of the radiation must be attributed to: a. the abnormally high percentage of cloudless skies. The sun impinged on the instruments during about 63% of the maximum possible time; b. the extremely low albedo, 0.16 (a similar value was found by Dirmhirn and Trojer (1955) at the very end of the Hintereisferner); c. an average temperature equal to 4.0°C . In spite of the cloudless skies this is almost equal to the long year average (see Kuhn et al., 1979b).

The daily courses of the temperature, the vapour pressure, the wind velocity and the fluxes are shown in Figures 3 and 4. Figure 3 is an average for 5 almost cloudless days; Figure 4 is an average for 3 days with poor weather. In this case this is a designation for days with

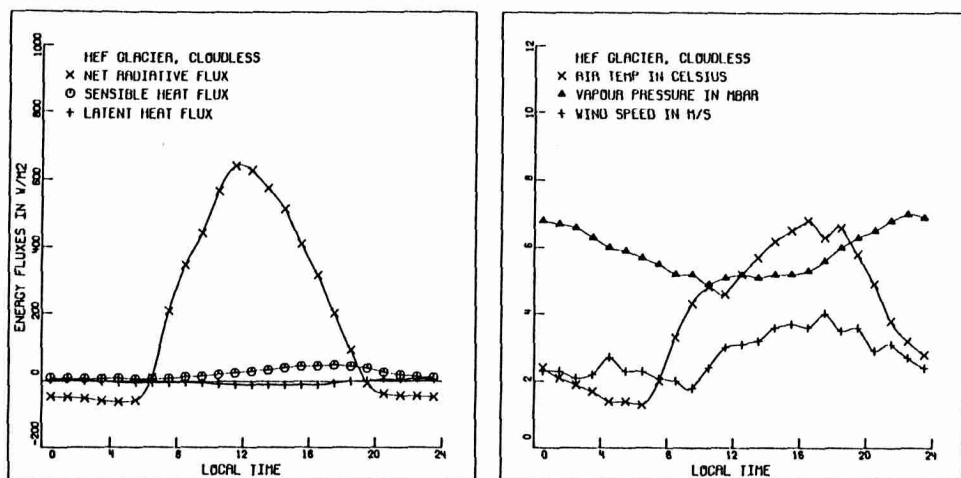


Figure 3. Daily variations of the fluxes calculated during the "standard run", and daily variations of temperature, vapour pressure and wind velocity at the middle level of the measurements (1.5 m). These are average values for 5 almost cloudless days (14, 15, 16, 17 and 21 July 1986) at GLACSTAT.

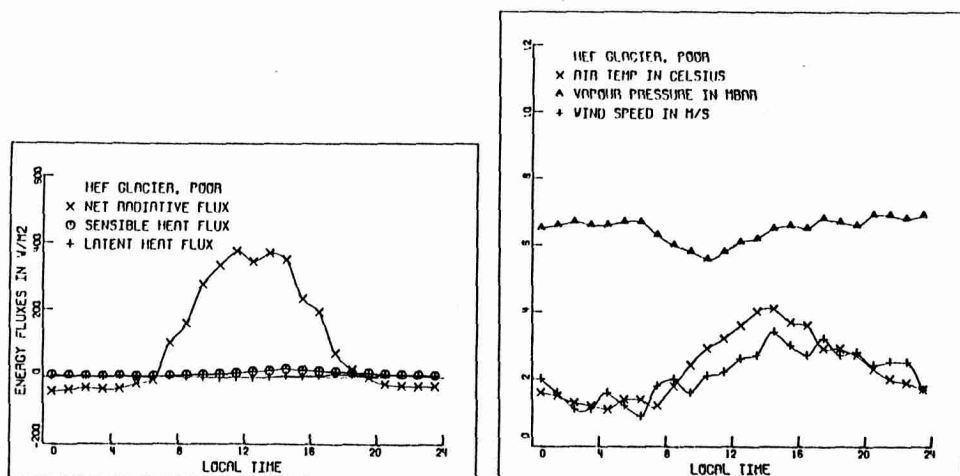


Figure 4. See Figure 3. However, these are average values for 3 "poor weather days" (13, 19 and 20 July 1986).

overcast skies and rain fall and fog during much of the time. To point out some characteristics of the daily variations we turn to the cloudless days. We find that the wind velocity and the temperature are continually rising during day-time. The rise of the temperature is interrupted at about 11 a.m. This can be understood by the movement of the thermocline associated with the glacier wind. During the early morning the thermocline is generally below 1.5 m, the height of the temperature sensor. Then, along with the increasing wind velocity the thermocline is rising. During 4 out of the 5 cloudless days considered here the thermocline passed the sensor at about 11 a.m. and thus caused a temporary decline of the temperature. The vapour pressure has a daily cycle with minimum values around noon.

Table II: Means for the whole period (12-22 July 1986) and maximum and minimum hourly means for the whole period. Variables marked with an asterisk are calculated.

	GLACSTAT			ROCKSTAT		
	mean	max	min	mean	max	min
global radiation in W m^{-2}	281	1053	0	268	1072	0
albedo	0.16	-	-	0.12	-	-
inc. long wave r. in W m^{-2}	271	316	210	271	316	210
surface temperature in $^{\circ}\text{C}^*$	0.0	0.0	0.0	10.1	29.8	-1.8
net radiation in W m^{-2*}	191	905	-106	138	769	-118
sensible heat f. in W m^{-2*}	22	118	-6	-40	47	-211
latent heat f. in W m^{-2*}	-4	36	-40	-88	12	-570
temperature in $^{\circ}\text{C}$	4.0	12.2	-1.1	6.1	16.0	-0.3
vapour pressure in mbar	5.9	8.8	2.4	6.9	8.9	4.5
wind velocity in m s^{-1}	2.8	6.8	0.4	2.5	5.6	0.7
total energy flux in W m^{-2*}	209	946	-130	10	345	-184
ablation in mm w.e.*	550	10.2	0.0	-	-	-

The daily cycles of the turbulent heat fluxes are directly related to the daily cycles of temperature, vapour pressure and wind velocity, as the surface temperature always remains at the melting point. The dominance of the net radiative flux is evident, irrespective of the type of weather.

3.2 Results from ROCKSTAT

The method used for the calculations of ROCKSTAT has been explained in Section 2.2. The calculations were tuned by comparing calculated surface temperatures with a sequence of surface temperatures measured with a thermo-eye. Two kinds of tuning parameters were available: a. variables describing the thermal properties of the soil, notably ρ , c and K (Equation 2) and b. the surface roughness parameters. By varying the

thermal properties (essentially $(\rho c K)^{\frac{1}{2}}$) the amplitude of the daily variation of the surface temperature can be tuned. By varying the roughness parameters (essentially z_{ou} as the quotient z_{ou}/z_{ot} and $z_{ot} = z_{oe}$ are prescribed) the magnitude of the turbulent fluxes change. In that way the daily mean of the surface temperature can be tuned. The following values were found to give a good result: $\rho = 2000 \text{ kg m}^{-3}$, $c = 927 \text{ J kg}^{-1} \text{ K}^{-1}$, $K = 0.966 \text{ J m}^{-1} \text{ K}^{-1}$, $z_{ou} = 10 \text{ mm}$, $z_{ot} = z_{oe} = 0.1 \text{ mm}$. The values of the thermal parameters agree quite well with the values given by Carslaw and Jäger (1947) for an average soil ($\rho = 2500 \text{ kg m}^{-3}$, $c = 840 \text{ J kg}^{-1} \text{ K}^{-1}$ and $K = 0.966 \text{ J m}^{-1} \text{ K}^{-1}$).

Averages for the whole period can be found in Table II. It seems to be of special interest to compare these values with those for GLACSTAT. The average temperature ($\Delta T = 2.1^\circ\text{C}$) and the vapour pressure ($\Delta e = 1.0 \text{ mbar}$) are somewhat higher at ROCKSTAT due to the large negative turbulent fluxes during day-time. The wind velocity is slightly reduced (about 10%) at ROCKSTAT.

In Table III it is demonstrated how the incoming total radiation is lost at the 2 stations. The available amounts are almost equal and put

Table III: Loss of the available incoming radiative energy. Averages for the whole period of the measurements.

	GLACSTAT	ROCKSTAT
Gain by: incoming total radiation	100% (552 Wm^{-2})	100% (539 Wm^{-2})
sensible heat flux	4%	—
Loss by: outgoing short wave radiat.	-8%	-6%
outgoing long wave radiat.	-57%	-68%
sensible heat flux	—	-7%
latent heat flux	-1%	-16%
melting	-38%	—
storage	—	-2%

to be 100%. At both stations most of the available energy is lost by the outgoing long wave radiation. However, the percentage is definitely larger at ROCKSTAT (-68%) than at GLACSTAT (-57%) due to the higher surface temperature. For the same reason the turbulent fluxes are clearly negative at ROCKSTAT (-23%), while their sum is slightly positive at GLACSTAT (+3%). Thus, at ROCKSTAT much more of the incoming energy is returned to the atmosphere. At GLACSTAT a large part of the available energy is lost by melting (-38%). The remaining energy is lost by reflection in the short wave part of the spectrum and stored in the soil at ROCKSTAT. It should be remarked that this storage is determined by the assumed initial temperature distribution of the soil.

Like for GLACSTAT the daily variations of the fluxes are averaged over the cloudless days and the "poor weather days" (Figures 5 and 6). Turning to the cloudless days we see that the turbulent fluxes are very small during night-time, so that the energy lost by radiation is nearly

balanced by the positive soil heat flux. During day-time about half of the energy gained by radiation is lost by evaporation, while the rest is in about equal parts lost by the sensible heat flux and stored in the soil.

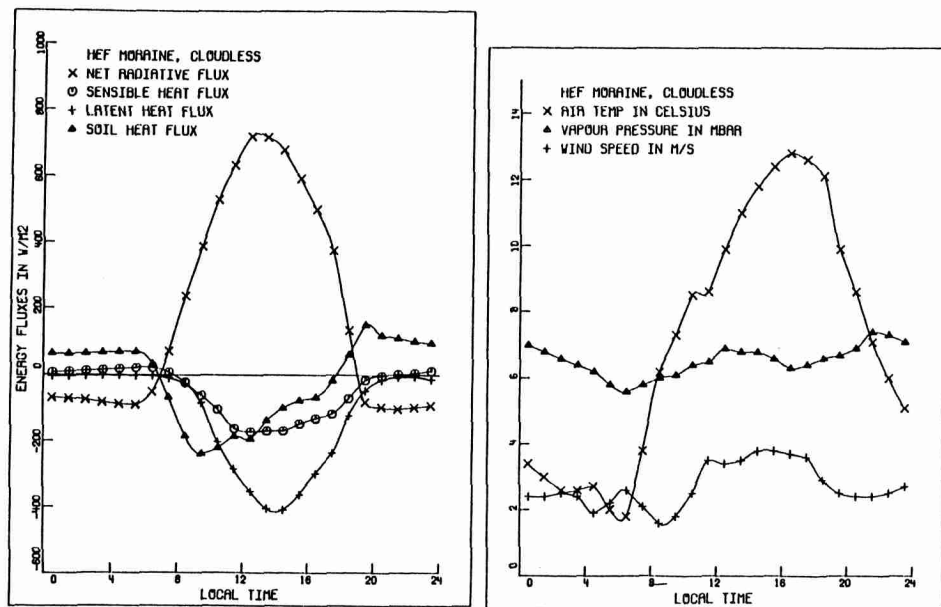


Figure 5. See Figure 3. However, these are average values for ROCKSTAT.

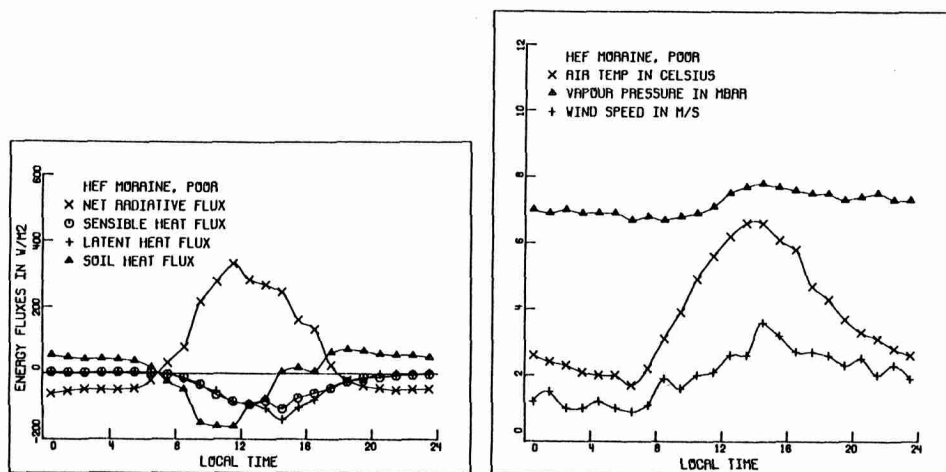


Figure 6. See Figure 5. However, these are average values for the "poor weather days".

While the method used for the calculations gives some confidence in the sum of the turbulent fluxes, the division between the sensible and the latent heat flux should be interpreted carefully. The Bowen ratio used for this division has been calculated from profile values of temperature and vapour pressure as explained in Section 2.2. The error in the measurements of these variables causes large errors in the Bowen ratio. However, the results agree quite well with those obtained by Rott (1979) in a nearby valley. Large evaporation fluxes as found in this study are only possible if the soil is wet. Observations of the soil wetness were not made.

4. INCREASING CONCENTRATIONS OF CO₂ AND OTHER TRACE GASES

4.1 Qualitative analysis of the effect on ablation

The possible climatic effects of the increasing concentrations of CO₂ only (e.g. Ramanathan, 1981 and Hansen et al., 1981) and of all relevant trace gases (Ramanathan et al., 1985) are treated in the cited literature. For the calculations 'radiative-convective' models are used. In this sub-section the consequences for the individual components of the energy balance and the resulting ablation of a glacier will be considered in a qualitative way. Then, in the next sub-section a calculation will be presented to arrive at a quantitative estimate of the 'CO₂-effect' on the energy budget and its components.

Table IV gives the changes of the variables and the fluxes affected by the increasing trace gas concentrations. Six locations are considered. In the horizontal we distinct a glacier (G) and a location (N) beyond the thermal influence of glaciers (let us say the Netherlands). In the vertical we have the surface itself (0), a level (1) about 1.5 m above the surface and a level (2) where the air is beyond the thermal influence of glaciers (let us say 2 km above the surface). Let ΔT_a be the temperature change at level 2. The corresponding change of the vapour pressure (Δe_a) is calculated with the assumption of fixed relative humidities. According to Hansen et al. (1981) this is more realistic than fixed absolute humidities. By definition ΔT_a is the same at G₂ and N₂. Let us now turn to turn to N₀ and N₁. The 'radiative-convective' models cited above provide vertical profiles of ΔT . It appears that the ΔT 's at N₀ and N₁ are almost equal to ΔT_a . The same is valid for Δe and Δe_a . So temperature and vapour pressure difference between levels N₀ and N₁, and consequently the turbulent fluxes, hardly change (see Hansen et al., 1981).

The incoming long-wave radiation increases (ΔL_i) due to the higher emissivity of the atmosphere directly related to the increasing trace gas concentrations. The positive feedback mechanisms $\Delta T_a \leftrightarrow \Delta L_i$ and $\Delta e_a \leftrightarrow \Delta L_i$ enhance the effect. The feedback mechanisms are very important. According to Hansen et al. (1981) they even multiply the ΔL_i only due to the higher emissivity of the trace gases themselves by a factor of about 15. It should be borne in mind that with the 'radiative-convective' models it is not possible to calculate ΔL_i from ΔT_a . This is due to the feedback mechanism between these variables.

Table IV: Qualitative analysis of the effect of the increasing trace gas concentrations on some meteorological variables and surface fluxes.

	Glacier (G)	Location beyond thermal influence of glaciers (N)
2. Atmospheric level beyond the thermal influence of glaciers:		
temperature	ΔT_a	ΔT_a
vapour pressure	Δe_a	Δe_a
1. Atmosphere (1.5 m):		
temperature	$0 < \Delta T < \Delta T_a$	$\approx \Delta T_a$
vapour pressure	$0 < \Delta e < \Delta e_a$	$\approx \Delta e_a$
wind speed	$\Delta u > 0$	≈ 0
0. Surface:		
temperature	$= 0$	$\approx \Delta T_a$
vapour pressure	$= 0$	$\approx \Delta e_a$
Fluxes:		
incoming long wave rad.	$\approx \Delta L_i$	$= \Delta L_i$
outgoing long wave rad.	$= 0$	$\approx -\Delta L_i$
sensible heat flux	> 0	≈ 0
latent heat flux	> 0	≈ 0
total energy flux	> 0	$= 0$

Calculated changes in the global radiation as a consequence of changing trace gas concentrations are insignificant compared to the changes in the long wave radiative fluxes (Hansen et al., 1981). Because the turbulent fluxes and the short wave radiative fluxes hardly change, the larger energy gain corresponding to ΔL_i must be balanced by an increase of the outgoing long wave radiation of the same amount. At the same time the long wave outgoing radiation is related to the surface temperature. Thus:

$$\Delta L_i \approx \Delta(\sigma T_a^4) \quad (3)$$

However, in the literature only ΔT_a is given in most cases, so that ΔL_i had to be recalculated for this study using Equation (3).

Let us now turn to the glacier site. In summer many locations on glaciers have a surface at the melting point. Such a location is considered here. Increasing trace gas concentrations cannot cause surface temperatures above the melting point, of course. However, temperature and vapour pressure in the adjacent air layer will increase, though by smaller amounts than ΔT_a and Δe_a . As on the average the katabatic wind speed increases with T_a , the wind may also be expected to become stronger. These changes lead to larger turbulent fluxes while the incoming long wave radiation increases by nearly ΔL_i . A small reduction of ΔL_i as calculated from Eq. (3), neglected in this study, is caused by

the fact that temperature and vapour pressure just above the glacier change by smaller amounts than ΔT_a and Δe_a . Thus, both the turbulent fluxes and the incoming long wave radiation contribute to a larger total energy flux. So ablation increases, since parallel to the surface temperature the outgoing long wave radiation does not change.

4.2 Quantitative estimate of the effect on ablation

In this sub-section a best estimate will be made of the effect of the rising trace gas concentrations on ablation in an imaginary case. The field data from GLACSTAT will be used. According to Ramanathan (1985) the CO_2 effect is magnified by the rising concentrations of other trace gases. Therefore, experiments were done both for an increase of the CO_2 concentration only and for an increase of the concentrations of all relevant trace gases. For 1880 (representative for the pre-industrial level of concentrations) and for 2036, ΔT_a relative to 1986 was inferred from literature. Then, starting from the field data the resulting changes in the surface energy fluxes were estimated. In some more detail the following steps were taken (see Table V):

Table V: Input and output of the trace gas experiments with the 1986-GLACSTAT data.

		[CO_2] in ppm	ΔT_a in $^{\circ}\text{C}$	ΔL_1 in Wm^{-2}	ablation in mm w.e.	relative to 1986
only CO_2	1880	275	-0.52	-2.8	531.1	-3.0%
	1986	339*	0.0	0.0	549.6	
	2036	449*	0.71	3.8	578.9	5.0%
all trace gases	1880		-0.79	-4.3	521.7	-5.1%
	1986		0.0	0.0	549.6	
	2036		1.54	8.4	613.8	11.3%

* values for 1980 and 2030 from Ramanathan (1985)

- Estimate of the equilibrium ΔT_a 's relative to 1980 for 1880 and 2030. These values are provided by Ramanathan et al. (1985)
- The heat capacity of the oceans causes a time lag of the real temperatures relative to the equilibrium temperatures as they are calculated by Ramanathan et al. (1985). Although a reliable estimate of this time lag is not possible according to Ramanathan et al. (1985), Hansen (1981) gives a value of 6 years that is used in this study. Thus, the equilibrium ΔT_a -values for 1980 and 2030 correspond to real ΔT_a -values for 1986 and 2036. ΔT_a is the independent variable from which the changes in those energy fluxes, that are affected by the greenhouse warming, are derived.
- ΔL_1 is simply obtained from Eq. (3). For each sample ΔL_1 is added to the measured L_1 .

c2. Estimate of the disturbed sensible heat flux (H').

If we would have a functional relationship $H(T_a)$, H' could simply be obtained by substituting $T_a + \Delta T_a$ for T_a . However, T_a was not measured. Therefore, the temperature from the highest level of the measurements (4.5 m) was taken instead of T_a . Figure 7 gives a schematic picture of the temperature profiles for T_a and $T_a + \Delta T_a$ at level 2. Profile measurements showed that the thermocline generally is below 4.5 m. In that case $T_{4.5}$ and $\Delta T_{4.5}$ should be close to T_a and ΔT_a , respectively.

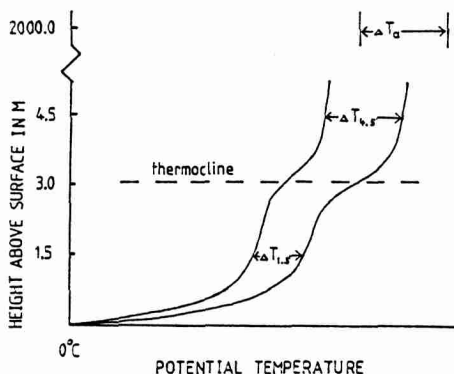


Figure 7. Schematic picture of temperature profiles for T_a and $T_a + \Delta T_a$ at a level beyond the thermal influence of the glacier. The surface is melting. ΔT decreases monotonically towards the surface and $\Delta T_{4.5}$ is almost equal to ΔT_a .

From hourly means of the data and the calculations we obtained:

$$H = 2.23 + 1.098 T_{4.5} + 0.5164 T_{4.5}^2 \quad (4)$$

H' for each sample is then calculated by replacing $T_{4.5}$ by $T_{4.5} + \Delta T_a$ in this equation. In fact, by using this method to obtain H' it is assumed that a future climate disturbance (ΔT_a) will affect the sensible heat flux in the same way as variations in $T_{4.5}$ (representative of T_a) affected the sensible heat flux during the 10 days of these measurements.

c3. Estimate of the disturbed latent heat flux (E'). Again we are looking for a relation between E and T_a . As for the sensible heat flux, $T_{4.5}$ has to be used instead of T_a . There is, however, an extra complication. In the field data high temperatures are correlated with low relative humidities. This is not the kind of correlation expected for averages over longer periods (let us say one year). Relative humidities are expected to remain unchanged. Thus, a regression formula between E and $T_{4.5}$ based on the calculations and measurements of this study should not be used for the prediction of

long term fluctuations in E . Instead, hourly means of $T_{4.5}$, and of temperature (T) and wind speed (u) at 1.5 m were used to obtain:

$$T = 0.19 + 0.861 T_{4.5} \quad (\text{corr. coeff.} = 0.96) \quad (5)$$

$$u = 1.84 + 0.223 T_{4.5} \quad (\text{corr. coeff.} = 0.52) \quad (6)$$

These relations may be expected to hold also for the averages over longer periods. Now, for each sample T' and u' were obtained by substituting $T_{4.5} + \Delta T_a$ in these equations. The disturbed vapour pressure (e') is then calculated from T' and fixed relative humidity, whereafter E' is obtained from e' and u' .

Individual values of L_i' , H' and E' obtained this way certainly have no significance. Only their mean values over the whole period should be considered. This should be no disadvantage because we are dealing with climatic, thus long term average changes.

- d. Determination of the total ablation for the 10-day period.

This way ablation reductions of -3.0% and -5.1% were obtained for the '1880-CO₂' and the '1880-all trace gases case', respectively, while for the corresponding '2036 cases' ablation increases by +5.0% and +11.3%, respectively. It is clear that the magnification of the CO₂-effect by the other trace gases is expected to increase. In the '2036-all trace gases case' the mean total energy flux increases by 24.5 Wm⁻² relative to the '1986-case'. The contributions of the incoming long wave radiation, the sensible heat flux and the latent heat flux to this increase are 34%, 41% and 25%, respectively.

It is evident that the calculations contain a lot of uncertainties and assumptions. A few of them were mentioned before, but it seems worthwhile to add some remarks:

1. Though the Northern Hemisphere surface air temperature rose by about 0.5°C over the period of instrumental recording (Ellsäßer et al., 1986), most authors treating this subject conclude that 'CO₂-warming did not yet rise above the noise level of natural climate variability' (Hansen et al., 1981). One might ask whether glaciers are more appropriate as a detector of the greenhouse warming. They are particularly sensitive to higher trace gas concentrations and the noise to signal ratio of snout variations is relatively low.
2. The calculations were made for the specific 10-days period and location of this study. Certainly, the Eqs. (4), (5) and (6) are sensitive to changes in time and location. Therefore, conclusions may not unthinkingly be used at other times and locations. Furthermore, according to 3-dimensional climate models (e.g. Manabe and Wetherald, 1980) the CO₂-warming will exhibit regional differences while global means were used here.
3. According to Hansen et al. (1981) climate models do not yet accurately simulate cloudiness. Therefore, it was assumed that cloudiness remains unchanged.

4. H' and E' are estimated by a kind of black box method. Hardly any physical insight into the relevant processes is used.
5. Retreat of the glacier in question and neighbouring glaciers results in a smaller glacierized to non-glacierized area ratio. The width of the glacier will also decrease. These geometric changes enhance the turbulent fluxes, even if the climate would remain unchanged (see Oerlemans, 1987). This positive feedback mechanism is not considered here.

5. CONCLUSIONS

In the case studied in this paper the radiative fluxes cause about 90% of the total ablation. This is due to the abnormally low albedo (0.16) and sunny, but relatively cold weather. Calculated and measured ablation differ by about 10%, probably due to an error in the measurements of the incoming total radiation.

While the mean turbulent fluxes are positive and relatively small at GLACSTAT (3% of the incoming total radiation), a large part of the energy gained by the incoming total radiation (-23%) is lost by turbulent fluxes at ROCKSTAT. The loss of energy by the outgoing long wave radiation is also larger at ROCKSTAT (-68% compared -57% at GLACSTAT). The extra energy available at GLACSTAT is mainly consumed by melting of the ice (-38%).

In Section 4.1 the consequences of the rising trace gas concentrations on ablation were explained in a qualitative way. It was shown that the mean incoming long wave radiation, the mean sensible heat flux and the mean latent heat flux will all increase. Thereafter, the relative contributions of these fluxes to the increased ablation for the imaginary '2036-all trace gases case' were estimated to be about 34, 41 and 25%, respectively. In that experiment ablation increased by 11%. Two kinds of problems force to interpret the results carefully. Firstly, there are a lot of uncertainties in the chain future release of trace gases \rightarrow their atmospheric concentrations \rightarrow climate \rightarrow energy fluxes at the atmosphere - glacier interface. Secondly, the calculations were made for a specific 10-days period at a single location. The same kind of calculations should be done for longer periods and other places. The last part of the first problem and the second problem especially concern glaciologists and they might be topics for future studies.

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