EFFECT OF GLACIERS ON ANNUAL RUN-OFF, JOHAN DAHL LAND, SOUTH GREENLAND

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ABSTRACT. Run-off data for two basins in south Greenland, one of which contains glaciers, are compared with precipitation at a nearby weather station and with ablation measured in the glacier basin. Seasonal variations of run-off for the two basins are broadly similar while run-off from the glacier basin has smaller year-to-year variations. A simple statistical model shows that this is the result of a negative correlation between ablation and precipitation, which has the effect of reducing run-off variations in basins with a moderate amount of glacier cover although run-off variations may become large again for highly glacierized basins. The model also predicts an increasing run-off with ablation correlation and a decreasing run-off with precipitation correlation as the amount of glacier cover increases. Although there are still too few data sets from other parts of Greenland for final conclusions, there are indications that the present findings may be applicable to other Greenland basins.

INTRODUCTION

Johan Dahl Land in south Greenland was chosen in 1975 as a possible site of a hydropower station, and hydrological measurements were started there in 1976 by the Greenland Technical Organization. As the basin contains an outlet from the Greenland ice sheet, glaciological measurements were also made over six summers 1978-83 by the Geological Survey of Greenland. For reasons unrelated to the physical conditions in Johan Dahl Land, plans for hydropower were shelved in 1983, although they could be taken up again in connection with future mining operations.

The glaciological work in Johan Dahl Land was started with the intention of applying standard glaciological and hydrological methods but, in the event, some concepts need modification for Greenland conditions. In particular, it is very difficult to determine areas of drainage basins on the Greenland ice sheet. The reason is that liquid water at any point on the ice sheet does not necessarily flow in the same direction as the ice flow. This is equivalent to having separate "basins" for liquid and solid water, i.e. hydrological and glaciological basins, respectively, although water on the surface does not necessarily flow in the same direction as englacial and subglacial water. The problem is further complicated because surface topography on the ice sheet is poorly mapped and there is little information about subglacial topography. The Geological Survey of Greenland is actively researching these problems, while the present paper attempts to assess the effects of glaciers on run-off in Johan Dahl Land without accurately knowing the drainage area.

PHYSICAL SETTING

Johan Dahl Land is an upland area located about 25 km north of Narsarsuaq in south Greenland (Fig. 1). The area is uninhabited and seldom visited except for back-packers and scientists.

The proposed hydropower station would have used a large lake (Nordbøsø with an area of 11 km²) as a reservoir, and water from a smaller lake (Thor Sø with an area of 5 km²) would have been piped into this reservoir. The Thor Sø basin is ice-free and is therefore a pure precipitation basin. By contrast, the Nordbøsø basin includes small isolated glaciers and a tongue of the Greenland ice sheet (Nordbogletschger). Its run-off is therefore influenced by glacier ablation as well as by precipitation.

Climate

The climate of Johan Dahl Land is Arctic as monthly mean temperatures are always below 0°C. For example,
temperatures are only above freezing for about 4 months in the year, i.e. from mid-May to mid-September. For the rest of the time, the area is covered with snow although, even in winter, there can be short sudden spells of warm weather with melting caused by Fohn-type storms. The longest climate record in the area is from Narsarsuaq which is an airport established in 1941. Climatological measurements were made at a station alongside Nordboglescher for the six summers 1978-83 (Olesen, 1978; Clement 1981, 1982, 1983, 1984[a]) as part of the glaciological research programme. Monthly mean temperature and monthly precipitation total at this station have reasonably high correlations with the corresponding values at Narsarsuaq (Clement, 1984[a]). Although there are no climatological data from the Thor So basin, there are no grounds a priori to suspect that its climate is greatly different from the lowest part of the Nordbøsø basin.

Basin characteristics

The Thor So basin covers an area of 32 km² and is ice-free. The areas of ice-free land (including lakes) and small glaciers in the Nordbøsø basin are 96 and 5 km², respectively. The terrain is very rugged and sparsely vegetated, with elevations ranging from 660 m a.s.l. at the lake Nordbøsø to 1650 m a.s.l. at Valhaldinde.

The total area of the Nordbøsø basin is uncertain because the area of Nordboglescher from which liquid water drains into the Nordbøsø lake is problematic. Olesen (1978) stated that Nordboglescher is a "branch" of the glacier Eqalorutsit kangigdlit sermiat with an area of 35 km² within the perimeters of the Nordbøsø hydrological basin. The delineation of Nordboglescher was extended on to the ice sheet to give a total area of 208 km² during the course of the glaciological investigations by Olesen (1978) and Clement (1981, 1982, 1983, 1984[a], [b]). However, it was gradually realized that this represents the glaciological area of Nordboglescher, the area from which liquid water flows to Nordbøsø must be much smaller. For example, Clement (1984[a]) gave an area of 57 km² for this hydrological basin. The area estimates of Olesen (1978) and Clement (1984[a]) are equivalent to a glacier cover of 29–39% of Nordbøsø basin with a total area of 136–138 km².

Using the above area, the Nordbøsø basin has only 7–8% of lake cover compared with 17% for the Thor So basin.

THE DATA

The data used in the present study are annual run-off from Nordbøsø and from Thor So, annual precipitation at Narsarsuaq, and annual ice ablation on the tongue of Nordboglescher, which are summarized in Table I.

### Table I. SUMMARY OF HYDROLOGICAL CONDITIONS IN JOHAN DAHL LAND, SOUTH GREENLAND 1976-85. Q₁ is ANNUAL RUN-OFF OF NORDBØSØ BASIN, Q₂ is ANNUAL RUN-OFF OF THOR SO BASIN, P is ANNUAL PRECIPITATION IN NARSSARSSUAQ, AND A is ANNUAL ICE ABLATION ON THE TONGUE OF NORDBOglescher

<table>
<thead>
<tr>
<th>Year</th>
<th>Nordbøsø run-off × 10⁶ m³ a⁻¹</th>
<th>Thor So run-off × 10⁶ m³ a⁻¹</th>
<th>Narsarsuaq precipitation m a⁻¹</th>
<th>Nordboglescher ablation m a⁻¹</th>
</tr>
</thead>
<tbody>
<tr>
<td>1976</td>
<td>198 (13%)</td>
<td>26 (11%)</td>
<td>0.74</td>
<td>0.38</td>
</tr>
<tr>
<td>1977</td>
<td>168 (13%)</td>
<td>15 (19%)</td>
<td>0.74</td>
<td>1.72</td>
</tr>
<tr>
<td>1978</td>
<td>181 (11%)</td>
<td>16 (0%)</td>
<td>0.45</td>
<td>2.66</td>
</tr>
<tr>
<td>1979</td>
<td>161 (0%)</td>
<td>24 (2%)</td>
<td>0.66</td>
<td>2.34</td>
</tr>
<tr>
<td>1980</td>
<td>169 (0%)</td>
<td>16 (0%)</td>
<td>0.38</td>
<td>2.07</td>
</tr>
<tr>
<td>1981</td>
<td>177 (0%)</td>
<td>24 (2%)</td>
<td>0.85</td>
<td>1.16</td>
</tr>
<tr>
<td>1982</td>
<td>144 (1%)</td>
<td>16 (26%)</td>
<td>0.81</td>
<td>0.23</td>
</tr>
<tr>
<td>1983</td>
<td>214 (0%)</td>
<td>36 (14%)</td>
<td>0.64</td>
<td>2.05</td>
</tr>
<tr>
<td>1984</td>
<td>198 (0%)</td>
<td>25 (16%)</td>
<td>0.64</td>
<td>2.05</td>
</tr>
<tr>
<td>1985</td>
<td>136 (18%)</td>
<td>10 (15%)</td>
<td>0.64</td>
<td>2.05</td>
</tr>
</tbody>
</table>

Mean 174 22 0.64 2.05
s.d. ±23 ±8 ±0.18 ±0.53
c.v. ±13% ±36% ±28% ±26%

Mean, standard deviation s.d., and coefficient of variation c.v. refer to the 6 years 1978-83.
rating curve is little changed by the addition of extra measurements. The calculations in Braithwaite (1985) are based on an older data set which has been slightly updated to that shown in Table I of this paper.

There are times when the recording instruments break down so that missing water-level values must be filled in by estimation. This is done as part of the data analysis by the GTO (1986[b]) and the figures in brackets in Table I give percentages of the annual run-off accounted for by estimated rather than measured water-level values. With the exception of 1978, the 1978–83 record for Nordbøsø is almost complete, while there are substantial periods of missing records for Thor Sø in 4 out of 6 years of interest. Run-off from Thor Sø is probably less accurate than run-off from Nordbøsø.

Annual precipitation

Precipitation is measured at Narsarsuqqu, about 25 km south of the Nordbøsø and Thor Sø basins, by the Danish Meteorological Institute. The data in Table I refer to annual precipitation for the hydrological year 1 September–31 August. Precipitation in September–December is assumed to fall mainly as snow and to contribute to run-off in the calendar year 1 January–31 December. This cannot be exactly true as Fohn storms can cause strong melting of snow at any time. For convenience in calculating annual precipitation from monthly totals, the hydrological year is assumed to be of fixed duration and to include only complete months. However, more correctly the hydrological year is of irregular duration starting in early or mid-September. Despite these simplifications, the plot in Figure 2 indicates that the present choice of hydrological year is not unreasonable, especially as some of the indicated run-off in September may be drawn from lake storage rather than being provided by precipitation.

Annual ice ablation

Snow accumulation and ice ablation were measured for the six summers 1978–83 at many stakes on the tongue of Nordbogletcher by Olesen (1978) and Clement (1981, 1982, 1983, 1984[a]). In this paper, ablation is taken to be positive, instead of negative as in Anonymous (1969), as this seems more logical for hydrological purposes. The ablation values given in Table I are averages of measurements from 14 stakes which were maintained throughout the 6 years of measurements (the mean elevation for the 14 stakes is about 870 masl). According to Braithwaite (1985), the year-to-year variations of annual balance at these stakes represent about three-quarters of the total variance (14 stakes and 6 years) with errors accounting for a further 18% of variance. As the stakes were located in the lower ablation area, the ice ablation is essentially identical to annual balance (measurement year from early September to early September) with its sign reversed, and is also comparable with the "Eis-Nettoablation" in Ambach (1972).

RUN-OFF VARIATIONS

Run-off from Thor Sø is caused by rainfall and snow melt, while run-off from Nordbøsø is supplemented by ice melt. Assuming uniform precipitation variations in the area, differences in run-off between the two basins reflect effects of glaciers on run-off. On the other hand, differences between run-off from Thor Sø and precipitation at Narsarsuqqu reflect the effects of snow accumulation and melt. This simple picture could be partly obscured by effects of errors in the data, e.g. measurements of solid precipitation are notoriously inaccurate.

Seasonal variations

Seasonal variations of run-off from the two basins and of Narsarsuqqu precipitation are compared in Figure 2. Means of monthly totals of the three series are plotted as cumulative percentages of the annual values for 1978–83. The curve for Narsarsuqqu precipitation is fairly straight, indicating that precipitation rate is roughly constant throughout the year, although there is slightly higher precipitation for June–October.

The run-off curves for Nordbøsø and Thor Sø follow each other quite closely and are very different from the precipitation curve. This shows that water-storage changes are important for the annual hydrological cycle while the contribution of ice melt is less important.

The curves in Figure 2 show that the effect of glaciers on run-off is relatively small on a seasonal basis. However, there are some interesting differences between the two run-off curves. For example, run-off from Nordbøsø in August and September is proportionally higher than run-off from Thor Sø as well as higher than precipitation. This is probably a glacier effect whereby the extra run-off from Nordbøsø is provided by melting ice, while the run-off from Thor Sø is essentially the same as precipitation as all snow has been melted away. From October until April, the two run-off curves are parallel and their lower gradients compared with the precipitation curve indicates that most precipitation in the period falls as snow and does not contribute to run-off. Both curves start to rise in May, indicating the onset of melting. However, Thor Sø run-off rises faster than Nordbøsø run-off in May and June, partly reflecting the lower average elevation of the Thor Sø basin, which will therefore be warmer, but another important factor is an ice-dammed lake in the Nordbøsø basin (Clement, 1984[b]) which fills up in May and June and thus reduces run-off from Nordbøsø. This lake starts to drain in early to middle July, thus causing the Nordbøsø run-off curve to rise faster than the Thor Sø curve for July and August.

The difference in seasonal run-off patterns between glacier-free and glacier-covered basins, e.g. the delay in run-off from a glaciated basin (Meier, 1969; Futter and Tangborn, 1965), probably increases with increasing glacier cover. The fairly small differences in seasonal run-off between Nordbøsø and Thor Sø are therefore consistent with a small to moderate amount of glacier cover in the Nordbøsø basin.

Year-to-year variations

Annual values of run-off from the two basins and of Narsarsuqqu precipitation are plotted in Figure 3. The data are expressed as percentage deviations from their respective mean annual values for 1978–85.

In contrast to the seasonal variations, there is closest agreement between Narsarsuqqu precipitation and Thor Sø run-off, while the run-off from Nordbøsø follows a different pattern. Braithwaite (1979) with a large difference between the first two series, possibly due to errors in estimating missing data for that year.

In order to examine the above patterns, correlation coefficients were calculated between the two annual run-off series and the precipitation and ablation series in Table I. The results are given in Table II where all correlations refer to the 6 year period 1978–83. The run-off from Nordbøsø and from Thor Sø have similar correlations with annual precipitation p, i.e. correlation coefficients of +0.77 and +0.72, respectively, which indicate moderately large correlations. The correlation between the two run-off series is even higher (ρ = 0.93). However, as already seen in

Fig. 2. Seasonal variations of run-off from Nordbøsø, Thor Sø, and precipitation at Narsarsuqqu. Data are expressed as cumulative percentages of their respective monthly averages for 1978–83.

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Fig. 3. Annual departure from mean of run-off from
Nordbø, Thor Sø, and precipitation in Narsarsuaq. Data
are expressed as percentage deviations from their respective
averages for 1978–83.

Table I, the run-off from Nordbø is proportionally less
variable than the run-off from Thor Sø, e.g. the standard
deviations of the two series constitute ±13% and ±36% of
their respective mean values. Run-off from the Nordbø
basin therefore follows the variations of Thor Sø run-off
and Narsarsuaq precipitation with reduced amplitude.

From the foregoing it is clear that the major effect of
.glaciers in this case is on the year-to-year variations of
run-off rather than on seasonal variations. The hydrological
effect of glaciers in Johan Dahl Land is therefore to
smooth year-to-year variations in run-off as in other areas,
e.g. western North America (Meier, 1969; Krimmel and
Tangborn, 1974; Fountain and Tangborn, 1985), Scandinavia
(Tvede, 1983), the Alps (Kasser, 1959; Collins, 1985;
Röthlisberger and Lang, 1987), Pakistan (Ferguson, 1985),
and China (Lai Zuming, 1982; Yang Zhenniang, 1982). The
possible mechanisms of this effect are examined later.

Long-term variations

Measurements were only started in 1976, so the
question of long-term variations in annual run-off is specu-
lative. However, a possible source of such variations is
change in volume of Nordbøgletscher as the tongue has
been advancing steadily since at least 1942. According to
Clement (1984[a]), the total advance into the lake Nordbø
in the period 1942–81 is 0.4 km². Assuming an ablation rate
of about 3 m a⁻¹ at the tongue of Nordbøgletscher, the total
increase in annual run-off due to increased tongue area
over the 40 year period is 1.2 \( \times 10^6 \) m³a⁻¹. This figure
should be increased for expansion of Nordbøgletscher along
its flanks, but the increase in run-off is still small compared
with the 1978–83 average of 174 \( \times 10^6 \) m³a⁻¹
given in Table I. Long-term changes in run-off due to the
advance of Nordbøgletscher are therefore neglected compared
with seasonal and annual run-off variations.

Table II. Correlation coefficients between
annual run-off from Nordbø, Q₁, annual
run-off from Thor Sø, Q₂, precipitation in
Narsarsuaq, P, and ablation a on
Nordbøgletscher for the 6 years 1978–83

<table>
<thead>
<tr>
<th>Q₁</th>
<th>Q₂</th>
<th>P</th>
<th>a</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.00</td>
<td>0.93*</td>
<td>0.77*</td>
<td>-0.51</td>
</tr>
<tr>
<td>1.00</td>
<td>0.72</td>
<td>-0.56</td>
<td></td>
</tr>
<tr>
<td>1.00</td>
<td>-0.63</td>
<td></td>
<td></td>
</tr>
<tr>
<td>1.00</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

* Significant at 5% level.

ANNUAL RUN-OFF MODEL

In the following, changes in annual storage of liquid
water in ground water and in lakes as well as in the
subglacial and englacial systems are ignored. Run-off can
come from rainfall, ablation of glacier ice, ablation of snow
from the current hydrological year, and ablation of firn
stored in perennial snow patches and in the accumulation
area of glaciers. It is convenient to re-group these different
terms so that annual precipitation appears in the
water-balance equation. The annual precipitation is divided
between rainfall and snow accumulation where the latter
contributes to snow ablation and to the accumulation of firn
and superimposed ice which are stored into the following
hydrological year. The appropriate ablation term to use

Consider a basin of area \( F \) of which an area \( G \) is
governed by glaciers. The glacier cover \( \alpha = G / F \). The annual
specific run-off in the year \( t \) is \( q_t \), which is given by:

\[
q_t = p_t + a_q - (1 - \alpha) e_t
\]

where \( p_t \) is the annual precipitation averaged over the
whole basin, \( a_q \) is the net ablation at the glacier surface
averaged over the glacier cover within the basin, and \( e_t \) is
the annual evaporation averaged over the glacier-free area
with evaporation from the glacier assumed to be zero.

As it stands, Equation (1) is reasonably general and
applies to both basins containing self-contained glaciers and
those containing sectors of the ice sheet. However, in the
former case the net ablation \( a_q \) refers to whole glaciers,
while in the latter case it refers only to the parts of
.glaciers within the hydrological basin. In the particular case
of Johan Dahl Land, the upper boundary of the Nordbø
hydrological basin, according to both Olesen (1978) and
Clement (1984[a]), lies below the average equilibrium line,
so there is little accumulation of firn or superimposed ice
at the end of the hydrological year and the net ablation is
the same as ice ablation measured by stakes drilled into the
glacier surface.

In principle, the glacier cover \( \alpha \) changes as glaciers
advance and retreat but in the present case it is known that
Nordbøgletscher has advanced very little during the period
of record compared with the uncertainty in \( \alpha \) itself. More
subtly, \( \alpha \) could change on a seasonal or year-to-year basis
if shifts in the internal hydraulics of glacier sectors cause
changes in the boundaries of hydrological basins. This
possibility cannot be included in the present treatment but
is being investigated by new field work. The following
treatment also assumes stationary climatic conditions.
Whether or not this is exactly true, it is certain that any
climatic trend is small compared with seasonal and year-to-
year variations.

Standard deviation

The average annual run-off \( \langle q \rangle \) for an \( N \) year period
is given by:

\[
\langle q \rangle = (1/N) \sum_{i=1}^{N} q_t
\]

and the deviation of run-off from this average in the year
\( t \) is given by:

\[
q_t' = q_t - \langle q \rangle.
\]

Averages and deviations are defined in similar ways for
annual precipitation, net ablation, and annual evaporation.
Neglecting evaporation deviations compared with precipita-
tion deviations gives:

\[
q_t' = p_t' + a_q'.
\]
By definition, the run-off variance for an $N$ year period is given by:

$$S_q^2 = \frac{1}{N-1} \sum_{t=1}^{N} (q_t - \bar{q})^2$$

(5)

where $S_q$ is the standard deviation of the annual run-off. Squaring both sides of Equation (4) and averaging over $N$ years gives the run-off variance as:

$$S_q^2 = S_p^2 + 2\alpha S_p S_a S_{pa} + \alpha^2 S_a^2$$

(6)

where $S_p$ and $S_a$ are the standard deviations of annual precipitation and net ablation respectively, and $R_{pa}$ is the correlation coefficient between precipitation and ablation defined by:

$$R_{pa} = \frac{1}{N-1} \sum_{t=1}^{N} (p_t - \bar{p})(q_t - \bar{q})$$

(7)

According to Equation (6), if $R_{pa}$ is zero, i.e. if net ablation is not correlated with precipitation, the variance of the annual run-off is simply equal to the sum of the variances of precipitation and ablation. However, in the present case $R_{pa}$ is negative with a correlation coefficient of $-0.63$ so that the variance of the annual run-off is less than this sum, i.e. the negative correlation between precipitation and ablation smoothes year-to-year variations in annual run-off, depending upon the glacier cover $\alpha$.

The negative correlation between ablation and precipitation arises because increased precipitation is associated with increased accumulation of snow during the winter and the melting of this uses energy in the summer which would otherwise be available for melting ice. This effect is accentuated by the fact that a certain amount of snow accumulation inhibits a greater amount of ice melt (Braithwaite and Olesen, in press). Increased ablation therefore reduces ice ablation.

Using Equation (6) and the results in Tables I and II ($S_p = 0.18$, $S_a = 0.53$, and $R_{pa} = -0.63$), together with a glacier cover $\alpha$ of 0.30-0.39, gives a range of 0.15-0.17 m water for the standard deviation of specific run-off from Nordbøgletsh. With a basin area of 135-157 km$^2$, the corresponding standard deviation of run-off volume is 20-27 × 10$^6$ m$^3$ a$^{-1}$, which is in good agreement with the value of 23 × 10$^6$ m$^3$ a$^{-1}$ for observed run-off volume for Nordbøgletsh. On the other hand, according to Equation (6), the specific run-off from a glacier-free basin should have the same standard deviation as precipitation. This assumption gives a standard deviation of 6 × 10$^6$ m$^3$ a$^{-1}$ for the volumetric run-off compared with the observed value of 8 × 10$^6$ m$^3$ a$^{-1}$ for Thor $S_o$, i.e. the model underestimates by about 25%.

In order to apply the results to other basins, the variation of standard deviation is plotted in Figure 4 as a function of $\alpha$ using data from Johan Dahl Land. As before, $S_p = 0.18$ and $R_{pa} = -0.63$, but it is more difficult to choose a general value for $S_a$ because the available ablation data from Nordbøgletsh refers to the lowest part of the glacier. Basins with higher-lying glaciers have lower ablation and $S_a$ might be lower in proportion. Values of the ratio $S_a/S_p$ equal to 1 and 2, as well as 3 for the present case, are therefore assumed to cover the range of likely $S_a$ values.

### Minimum standard deviation

The plots in Figure 4 predict that increasing glacier cover reduces the standard deviation of annual run-off down to a certain minimum after which it increases again, possibly to a very large value if ablation has a high variability. By differentiating $S_q$ in Equation (6) with respect to $\alpha$ and setting the derivative $dS_q/d\alpha$ equal to zero, the glacier cover $\alpha$, giving the minimum standard deviation is found to be:

$$\alpha_1 = -\frac{S_p}{S_a} R_{pa}$$

(8)

With the present values, $\alpha_1 = 0.21$ but this minimum is shifted towards higher values of glacier cover with decreasing variability of ablation relative to precipitation, i.e. by decrease in $S_a/S_p$. This can be compared with 0.3 in Krimmel and Tangborn (1974), 0.5 in Fountain and Tangborn (1985), 0.20 in Tvede (1983), 0.3-0.4 in Kasser (1959), 0.3-0.6 in Röthlisberger and Lang (1987), and 0.1-0.2 in Ferguson (1985).

The minima in the curves in Figure 4 look rather shallow compared with similar curves from other regions (personal communication from M.F. Meier). Substitution of $\alpha_1$ from Equation (8) back into Equation (6) gives the minimum standard deviation as $S_q(1 - R_{pa}^2)$, which means that the depth of the minimum in the curve of standard deviation versus glacier cover is controlled by the correlation between precipitation and ablation. In the present case, $R_{pa} = -0.63$, so that the minimum standard deviation is 0.78$S_q$, which represents a fairly shallow minimum. The deeper minimum found in other areas, e.g. as shown in figure 10.4 in Röthlisberger and Lang (1987), suggests that $R_{pa}$ may be more negative than found here. It is also possible that the value $R_{pa} = -0.63$, based upon ablation data from the lowest part of the glacier, is an underestimate of the correlation for basins containing whole glaciers.

As a low standard deviation of annual run-off is desirable for water management, the most attractive basins for exploration are ideally those with a moderate amount of glacier cover.

### Run-off with precipitation correlation

The correlation between annual run-off $q_t$, and precipitation $p_t$ is $R_{qp}$ given by:

$$R_{qp} = \frac{S_p/S_a}{1 + \alpha S_a/S_q R_{pa}}$$

(9)

which is obtained by multiplying both sides of Equation (4) by the precipitation deviation $p_t'$, averaging over an $N$ year period, and applying the definitions in Equations (5) and (7).

The dependence of the run-off with precipitation correlation on glacier cover is plotted in Figure 5 for the same assumptions as for Figure 4. Naturally, the equation refers to an "ideal" correlation in the absence of errors which generally reduce correlations calculated for real data. However, the equation predicts that the highest correlation between run-off and precipitation occurs for glacier-free basins and that the correlation decreases with increasing glacier cover. The correlations given in Table II do not exactly agree with this as run-off from Nordbøgletsh has a slightly higher correlation with precipitation than does run-off from Thor $S_o$, i.e. correlation coefficients of 0.77 and 0.72, respectively. This might partly reflect the effects of proportionally larger errors in the Thor $S_o$ data but the run-off with precipitation correlation from Nordbøgletsh is also higher than that predicted by Equation (9). For example,
Several authors, e.g. Collins (1985) and Ferguson (1985), have noted this possibility and, as will be shown in a later section, there are highly glacierized basins in Greenland with negative run-off with precipitation correlations.

Run-off with ablation

The correlation between annual run-off $q_i$ and net ablation $\Delta q_i$ is $R_{qa}$ given by:

$$R_{qa} = \left(\frac{S_p}{\Delta q_i}\right) R_{pa} + \alpha \left(\frac{S_a}{S_p}\right)$$

(10)

which is obtained by multiplying both sides of Equation (4) by the ablation deviation $\Delta q_i$, averaging over an N year period, and applying the definitions in Equations (5) and (7).

The dependence of the run-off with ablation correlation on glacier cover is plotted in Figure 6 for the same assumptions as for Figures 4 and 5. The equation predicts a negative correlation between run-off and net ablation for basins with little glacier cover, increasing and becoming positive with increasing glacier cover. The run-off with ablation correlations given in Table II are both negative with the Thor So value slightly more negative than the Nordbogsliefs value. However, the run-off with ablation correlation for Nordbogsliefs should be positive according to Equation (9). For example, present results ($S_p = 0.18, S_a = 0.53, R_{pa} = -0.63$, and $\alpha = 0.30 - 0.39$) give a calculated run-off with ablation correlation of $-0.31$ to $-0.56$. This theoretical correlation could be made negative according to Equation (6) by either decreasing the glacier cover or by reducing $S_a$ compared with $S_p$.

The existence of a negative correlation between run-off and ablation is at first surprising for a basin like Nordbogsliefs as ablation from Nordbogletscher is supposed to be a major source of run-off. For example, one of the main purposes of the glaciological work in Johan Dahl Land was to measure glacier mass balance as a step in calculating run-off. It is therefore disappointing to find that the run-off with ablation correlation is not only fairly weak but also that it is negative. The ablation measurements can be used to explain the low variability of Nordbogsliefs run-off but the calculation of run-off itself must use precipitation as the more important variable.

An interesting case arises when the run-off with standard deviation is a minimum, i.e. for a glacier cover $\alpha = \alpha_i$, as according to Equation (10) the correlation between run-off and ablation is zero.

Although the present results cannot apply exactly to these basins, it would be interesting to see if the main conclusions are broadly correct.

Out of a total of 19 basins, there are 12 with at least 4 years of record up to and including 1985 (GTO, 1986(a)). Annual run-off data for these basins were used for calculating coefficients of variation of annual run-off and correlations between run-off, annual precipitation, and summer mean temperature, and the results are given in Table III together with the glacier cover $\alpha$.

The precipitation and temperature data for the correlations are taken from the nearest weather station to the basin in question. The correlations between run-off and summer temperature are used as substitutes for correlations between run-off and ablation because few data for the latter are available from the basins.

The present results, with 4–9 years of record, have very sparse statistically bases compared with similar studies in other areas, e.g. Tvede (1983). This raises the interesting possibility that an unwary investigator might incorrectly conclude on the basis of the zero correlation that run-off was "totally unrelated to ablation", whereas in fact ablation has the useful effect of smoothing run-off variations.

In contrast to the Johan Dahl Land situation, Equation (10) predicts a fairly strong positive correlation between run-off and ablation in highly glacierized basins and preliminary results from the PAAK 437 basin near Ilulissat/Jakobshavn in central West Greenland support this (Thomsen and Braithwaite, 1987).

OTHER GREENLAND BASINS

Hydrological measurements have been made in other basins in Greenland for the planning of hydropower to supply electricity to towns. The locations of these basins are shown on a map in Thomsen and Braithwaite (1987). Although the present results cannot apply exactly to these basins, it would be interesting to see if the main conclusions are broadly correct.

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TABLE III. COEFFICIENT OF VARIATION c.v., CORRELATION $R_{\text{QP}}$ BETWEEN ANNUAL RUN-OFF AND ANNUAL PRECIPITATION, AND CORRELATION $R_{QT}$ BETWEEN ANNUAL RUN-OFF AND SUMMER TEMPERATURE VERSUS GLACIER COVER $\alpha$ FOR 12 BASINS IN WEST GREENLAND, LOCATIONS OF THE BASINS GIVEN BY THOMSEN AND BRAITHWAITE (1987)

<table>
<thead>
<tr>
<th>Basin</th>
<th>Years</th>
<th>c.v.</th>
<th>$R_{\text{QP}}$</th>
<th>$R_{QT}$</th>
<th>$\alpha$</th>
</tr>
</thead>
<tbody>
<tr>
<td>TSSK 428</td>
<td>4</td>
<td>22</td>
<td>0.64</td>
<td>0.26</td>
<td>0</td>
</tr>
<tr>
<td>KILA 419</td>
<td>4</td>
<td>19</td>
<td>0.95</td>
<td>-0.80</td>
<td>0</td>
</tr>
<tr>
<td>TASAQ 431</td>
<td>4</td>
<td>38</td>
<td>0.57</td>
<td>-0.93</td>
<td>0</td>
</tr>
<tr>
<td>ITLA 420</td>
<td>4</td>
<td>35</td>
<td>0.87</td>
<td>0.19</td>
<td>0</td>
</tr>
<tr>
<td>KNNQ 422</td>
<td>4</td>
<td>30</td>
<td>0.99</td>
<td>0.01</td>
<td>1</td>
</tr>
<tr>
<td>TSUQ 106</td>
<td>9</td>
<td>17</td>
<td>0.41</td>
<td>0.05</td>
<td>3</td>
</tr>
<tr>
<td>AMNG 426</td>
<td>4</td>
<td>26</td>
<td>0.98</td>
<td>-0.24</td>
<td>9</td>
</tr>
<tr>
<td>TSSK 124</td>
<td>4</td>
<td>25</td>
<td>0.91</td>
<td>-0.27</td>
<td>15</td>
</tr>
<tr>
<td>QAPI 113</td>
<td>5</td>
<td>19</td>
<td>0.5</td>
<td>0.56</td>
<td>31</td>
</tr>
<tr>
<td>ISTA 305</td>
<td>8</td>
<td>11</td>
<td>-0.03</td>
<td>0.54</td>
<td>7</td>
</tr>
<tr>
<td>KSTA 421</td>
<td>5</td>
<td>15</td>
<td>-0.92</td>
<td>0.96</td>
<td>48-73?</td>
</tr>
<tr>
<td>PAAK 437</td>
<td>5</td>
<td>25</td>
<td>-0.73</td>
<td>0.92</td>
<td>89-96?</td>
</tr>
</tbody>
</table>

For what they are worth, the results in Table III generally indicate high values of the coefficient of variation c.v. and correlation $R_{\text{QP}}$ between run-off and precipitation at very low values of $\alpha$ together with low positive, or large negative, values of the correlation $R_{QT}$ between run-off and temperature. For example, of the first eight basins in Table III with small amounts of glacier cover ($\alpha$ from 0 to 15%) there are six basins that fit this pattern reasonably well. The other two basins (KILA 419 and TSUQ 106) both have low coefficients of variation despite their lack of glacier cover and do not agree with Figure 4.

There are three basins (QAPI 113, ISTA 305, and KSTA 421) with moderate to large glacier cover which have low coefficients of variation of annual run-off, low or negative correlations between run-off and precipitation, and reasonably high correlations between run-off and temperature. These results fit the predictions of Figures 4-6. There is a fourth basin (PAAK 437) with a relatively high coefficient of variation which may be caused by the high (estimated!) glacier cover as predicted by Figure 4.

CONCLUSIONS AND OUTLOOK

There is a qualitative agreement between the results from Johan Dahl Land and the model. For example, variations in annual run-off for Nordbøse are relatively small compared with those for Thor Sa. The model also correctly predicts the existence of other basins in Greenland with negative run-off with precipitation correlations. However, the qualitative agreement of the model with field data from Johan Dahl Land is not always good. For example, assuming the glacier cover $\alpha$ in the Nordbøse basin equals 0.30-0.39, gives theoretical run-off with precipitation and run-off with ablation correlations which are respectively too low and too high. It is tempting to remove these contradictions by claiming that the amount of glacier cover in the Nordbøse basin is over-estimated but it is difficult to justify an $\alpha$ value much less than 0.3, although the exact area of the hydrological basin cannot be determined. Another possibility is to remove the contradiction by suggesting a lower value of the ratio $S_p/S_{\text{QP}}$ than used here but the available data do not justify this.

Other possibilities are to blame the contradictions on errors in the data or shortcomings in the model. For example, inter-annual storage of precipitation in snow patches might cause glacier-free basins to mimic glacier basins, while negative correlations between precipitation and evaporation might reduce contrasts between glacier-covered and glacier-free basins.

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