Energy balance of N-Vatnajökull, Iceland, during extreme glacial river floods

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1. Introduction

We describe the daily energy balance and melting of the entire Brúarjökull outlet glacier of the Vatnajökull ice cap and the exceptional circumstances leading to three extreme floods in the main river Jökla draining the outlet, two of which occurred in August 2004 and one in July 2005. A typical July and August mean river discharge is 400–500 m³s⁻¹, but daily average flow of 700–800 m³s⁻¹ were observed during the flood events. Flood prediction is crucial because the river is presently being dammed for production of hydropower.

One to three automatic weather stations, providing the full energy balance, have been operated on the glacier outlet during the summers since 1996. The meteorological data, along with mass balance observation at stakes, observed topography and satellite optical images, where used to produce daily energy balance maps for the entire outlet glacier (Gudmundsson and others, 2006). Runoff calculated from the energy balance data satisfactorily agrees with the measured river discharge.

The results show that the first flood was related to intensive rain, but the second and third to glacial melting maintained by warm and sunny weather accompanied by unusually low glacier surface albedo. During the second and third floods, 10–40% of the total energy supplied for melting could be explained by high turbulent heat fluxes driven by exceptionally warm air advecting over the glacier. The main contribution to the glacial melting was from the high net radiation maintained by the clear sky solar radiation and low albedo. The sudden removal of the entire winter snow on large parts of the ablation area during the second flood in August 2004, dramatically reduced the albedo. The low albedo during the third flood was due to sand and dust blown over the glacier during a period of strong northern winds in July 2005.

Our analyses of the processes providing the floodwater are used to evaluate how frequent extreme flood events may be related to both exceptional weather- and glacier surface conditions that can be expected on the ice cap.

2. Study area and observation sites

Brúarjökull outlet glacier of Vatnajökull ice cap (red and magenta outlines), the river Jökla (blue), the glaciated area of the water drainage basin of Jökla (red outline), sites of the mass balance observations (black dots), meteorological stations, (red triangles, elevation in m a.s.l.) and discharge gauge for Jökla (magenta triangle).

3. The flood events

**August 3–6, 2004:**
- Following a period of intensive precipitation August 1–3.
- The rainfall did peak within the glaciated water drainage basin of the river Jökla.

**August 9–14, 2004:**
- Exceptionally high air temperatures and clear weather with high solar radiation.
- The warm air was advected over Vatnajökull from an extensive high-pressure system stretching to Mediterranean latitudes.

**July 21–25, 2005:**
- A period of warm and clear weather with high solar radiation.
- Both high temperatures and river discharge was observed most of July.

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a) Discharge of Jökla observed at Bríði Jökuldal, 40 km north of the Brúarjökull terminus. b) Precipitation at Kárahnjúkar and Akurnes, north and south of Vatnajökull, respectively. c) Temperature at Eyjafjörður north of Vatnajökull. d) Measured solar radiation at Brúarjökull compared to theoretically calculated clear-sky irradiance (Olseth and others, 1995).
3. Energy balance, melting and runoff

The AWSs on the glacier measured the incoming and outgoing short wave radiation ($Q_s$ and $Q_o$, respectively), and incoming and outgoing long wave radiation ($I_r$ and $I_i$, respectively) at 2 m above the surface. Wind speed ($u$), air temperature ($T$) and relative humidity ($r$) were measured at one to four levels.

The total energy was calculated for a melting glacier surface as
\[ M_i = R + H, \]
where $R = Q_i (1-a) + I_i - I_o$ is the net radiation ($a$ is the surface albedo) and $H$ the net turbulent heat flux (latent and sensible), calculated with one- and two-level models using stability factor (Monin and Obukhov method) and different roughness lengths for $a$, $T$ and $r$ (Andreas, 1987).

Daily energy balance maps (EBMs) were calculated for the Brúarjökull outlet by assuming the weather parameters to vary only with elevation and infering albedo by combining information from stake observations of the winter balance, observed daily albedo at the AWS sites and optical satellite images. Stake observations of the summer balance were used for calibration.

Daily ablation for each pixel in the EBMs was calculated as
\[ q_a = \begin{cases} M_i / (Lp); & M_i > 0 \\ 0; & \text{otherwise} \end{cases}, \]
with $p = 10^3$ kg m$^{-2}$ and $L = 3.3 \times 10^3$ kg m$^{-1}$, and the total melting (runoff) as
\[ q = \int q_a dS, \]
where $S$ is the glaciated water drainage basin of Jökla.

4. Processes generating the flood events

<table>
<thead>
<tr>
<th>Event</th>
<th>$q_o$ observed (m$^3$ s$^{-1}$)</th>
<th>Rain</th>
<th>Net radiation</th>
<th>Turbulent heat fluxes</th>
</tr>
</thead>
<tbody>
<tr>
<td>Aug. 3-6, 2004</td>
<td>-750</td>
<td>100%</td>
<td>0%</td>
<td>0%</td>
</tr>
<tr>
<td>Aug. 9-14, 2004</td>
<td>-690</td>
<td>0%</td>
<td>30%</td>
<td>0%</td>
</tr>
<tr>
<td>July 21-25, 2004</td>
<td>-680</td>
<td>0%</td>
<td>30%</td>
<td>25%</td>
</tr>
</tbody>
</table>

a) Six day averages of the glacial runoff ($q_o$) calculated from the energy balance maps and observed river discharge of Jökla at Brúá Jökuldal ($q_i$). $q_o$ is separated into contribution from net radiation ($q_{sr}$) and net turbulent heat flux ($q_{tr}$).

b) Wind speed ($u$), air temperature ($T$), incoming and outgoing solar radiation ($Q_s$ and $Q_o$, respectively), and albedo, averaged over the outlet.

5. Conclusions

- Circumstances leading to the floods in Jökla:
  - August 3-6, 2004: heavy rainfall 1-3 August.
  - August 9-14, 2004: exceptionally high temperatures and high solar radiation along with abruptly reduced albedo August 9 due to rapid removal of snow in the ablation area.
  - July 21-25, 2005: high temperatures and solar radiation accompanied by low albedo due to sand blown over the glacier during storm in mid-July.

- Exceptionally high meltwater runoff from Brúarjökull is a consequence of both:
  - Combined warm air and high solar radiation.
  - Low surface albedo, due to low winter accumulation and/or sand blown over the surface, increasing the absorbed solar energy.

- Our long-term mass balance- and meteorological data show:
  - Days in the July month with energy fluxes capable of producing Jökla floods have occurred during three of the ten summers of energy balance observations, but only once in August.
  - A trend of reduced winter accumulation lowering the summer albedo as well as increased temperatures at and around the glacier.

- Hence if global warming continues, reduced winter accumulation may cause more frequent meltwater floods.