Response of glacier mass balance to regional warming, deduced by remote sensing on three glaciers in S-Iceland

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Abstract.
We assess the mean mass balance of three ice caps in South Iceland, for two periods, 1980 to 1998 and 1998 to 2004, by comparing digital elevation models (DEMs) covering the entire glaciers; Eyjafjallajökull (81 km²), Tindfjallajökull (15 km²) and Torfajökull (14 km²). The DEMs were compiled by using i) aerial photographs taken between 1979 to 1984 by the American Defense Map Agency (DMA) and the Icelandic Geodetic Survey, ii) airborne EMISAR radar images obtained in 1998 by the Electromagnetic system (EMI) of the Technical University of Denmark, and iii) two image pairs from the SPOT 5 high resolution stereoscopic (HRS) instrument from 2004. The ice-free part of the EMISAR-DEM (5x5 m spatial resolution with accuracy <2 m in elevation) was used as a reference map for co-registering and offset-correction of the HRS-DEMs (40x40 m) and the DMA-DEMs (40x40 m interpolated from 20 m contour lines). The average specific mass balance was estimated as the mean elevation difference between glaciated areas of the DEMs. The glacier mass balance declined significantly between the two periods: from -0.2 to 0.2 m yr⁻¹ w. eq. during first period 1979/1984-1998 to -1.8 to -1.5 m yr⁻¹ w. eq. for the more recent period 1998 to 2004. This declining mass balance takes place at the same time as the average regional temperatures increased by ~1 °C from the first to the second period (1980-1998 to 1998 to 2004).

Data

Digital Elevation models calculated using:
- SPOT 5 HRS from October 5, 2004
  - spatial resolution: 40x40 m
  - accuracy: 10 m in elevation and 30 m in horizontal position
- SPOT 5 HRS from August 14, 2004
- EMISAR from August 12, 1998
  - reference map for co-registration and offset correction
  - spatial resolution 5x5 m
  - accuracy <2 m in elevation and 5 m in horizontal position
- aerial photographs from the 1980s:
  i. Torfajökull ice cap (To) from the autumn 1979
  ii. Tindfjallajökull ice cap (Ti) from the autumn 1980
  iii. Eyjafjallajökull ice cap (E) from the autumn 1984
  - spatial resolution 40x40 m
  - accuracy <10 m in elevation

Imprinted profiles:
- Airborne radar altimetry, observed seasonally from 2004 to 2007
  - relative error within 1 m
- ICESat elevation data (e.g. Zwally and others, 2002), observed seasonally from 2004 to 2007
  - accuracy on cm scale at gentle sloping terrain
  - higher errors at rough and steep sloping terrain
  - often false values due to frequent occurrence of clouds in the area
- GPS profiles and points observed at ice free areas
  - accuracy ~1 m in elevation

Characteristics

<table>
<thead>
<tr>
<th>Ice cap</th>
<th>Area (km²)</th>
<th>Range in elevation (m a.s.l.)</th>
</tr>
</thead>
<tbody>
<tr>
<td>E: Eyjafjallajökull</td>
<td>81</td>
<td>180-1630</td>
</tr>
<tr>
<td>Ti: Tindfjallajökull</td>
<td>15</td>
<td>660-1480</td>
</tr>
<tr>
<td>To: Torfajökull</td>
<td>14</td>
<td>750-1170</td>
</tr>
</tbody>
</table>

AAR of the warm year of 2004

<table>
<thead>
<tr>
<th>Ice cap</th>
<th>AAR (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>E: Eyjafjallajökull</td>
<td>20-25</td>
</tr>
<tr>
<td>Ti: Tindfjallajökull</td>
<td>&lt;5</td>
</tr>
<tr>
<td>To: Torfajökull</td>
<td>0</td>
</tr>
</tbody>
</table>
**Estimated winter accumulation**

- **Distribution:** The ICESat elevation data minus the August 1998 EMISAR DEM:
  - a) at gently sloping profile location above 1300 m.a.s.l. on the Eyjafjallajökull ice cap
  - b) at horizontal sloping profile location at ice-free area
- **Blue:** using only spring ICESat data
- **Red:** using only autumn ICESat data

The results indicate high winter accumulation at the Eyjafjallajökull ice cap:
- Enorm: ICESat: high seasonal elevations of up to 10 m are observed within the accumulation area
- Enorm: our elevation data: negligible lowering is observed at the highest points from 1998-2007

Elmeg: from (a), the peak in the distribution indicates a winter accumulation of >10 m of snow, typical vertical balance velocity on observed on other ice caps in Iceland.

Eyjafjallajökull and Myrdalsjökull are the most maritime ice caps in Iceland.

Ethnic seasonal elevation changes of up to 10 m have also been observed within the accumulation area of Myrdalsjökull (Magnússon and others, 2007)
- Ein inset, the highest recorded seasonal elevation change on Langjökull ice cap located in the central Iceland, is 6 m (Pálsson and others, 2007)

**Average specific annual mass balance (a):** compared to average April to September temperature at weather station close to the ice caps (b):
- <1° C warmer than from 1998 to 2004
- mass balance: close to zero for the average climate condition during the first period 1973/1984-1998
- mass balance declination of >1.5 m yr⁻¹ eq. for the -1°C warmer period from 1998 to 2004

**References**
- Korona J., Berthier E., Bernard M., Rémy F. & Thouvenot E. SPIRIT. SPOT 5 stereoscopic survey of Polar Ice: Reference Images and Topographies during

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