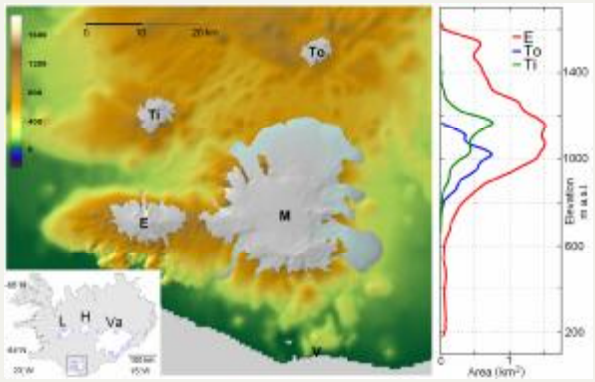
Response of glacier mass balance to regional warming, deduced by remote sensing on three glaciers in S-Iceland

Sverrir Gudmundsson[1], Helgi Björnsson[1], Eyjólfur Magnússon[1], Etienne Berthier[2], Finnur Pálsson[1], Magnús T. Gudmundsson[1], Thórdís Högnadóttir[1] and Jørgen Dall[3]
[1]Institute of Earth Sciences, University of Iceland
[2]LEGOS, Toulouse, France
[3]National Space Institute, Technical University of Denmark, Lyngby, Denmark

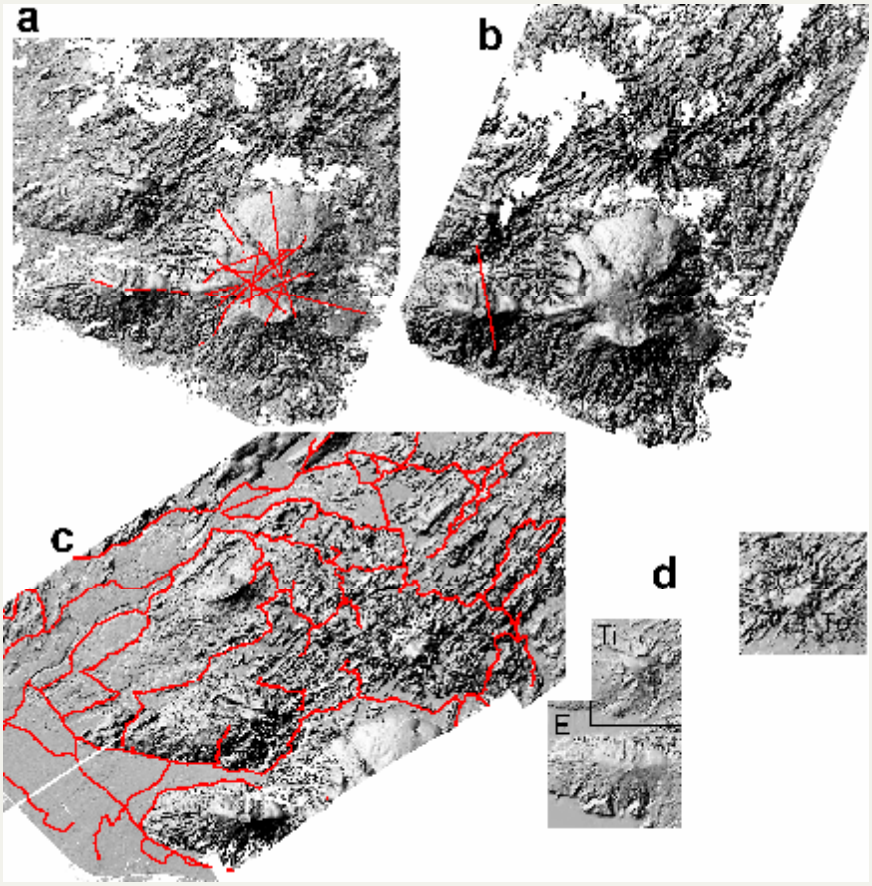
Abstract.
We assess the mean mass balance of three ice caps in South Iceland, for two periods, 1980 to 1998 and 1998 to 2004, by comparing digital elevation models (DEMs) covering the entire glaciers; Eyjafjallajökull (81 km^2), Tindfjallajökull (15 km^2) and Torfajökull (14 km^2). The DEMs were compiled 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).

Location



Eyjafjallajökull (E), Tindfjallajökull (Ti), Torfajökull (To) and Mýrdalsjökull (M) ice caps. V: automatic weather station at Vík in Mýrdalur. On the inset map of Iceland: location of the study area as well as Langjökull (L), Hofsjökull (H) and Vatnajökull (Va) ice caps. The plot shows the elevation distribution of the E, Ti and To ice caps as area (km^2) per 10 m elevation interval.

Data



Digital Elevation models calculated using:

a) SPOT 5 HRS from October 5, 2004
- spatial resolution: 40x40 m
- accuracy: 10 m in elevation and 30 m in horizontal position

b) SPOT 5 HRS from August 14, 2004

c) 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

d) 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:

a) Airborne radar altimetry, observed seasonally from 2004 to 2007
- relative error within 1 m

b) 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 occurence of clouds in the area

c) GPS profiles and points observed at ice free areas
- accuracy ~1 m in elevation

Characteristics

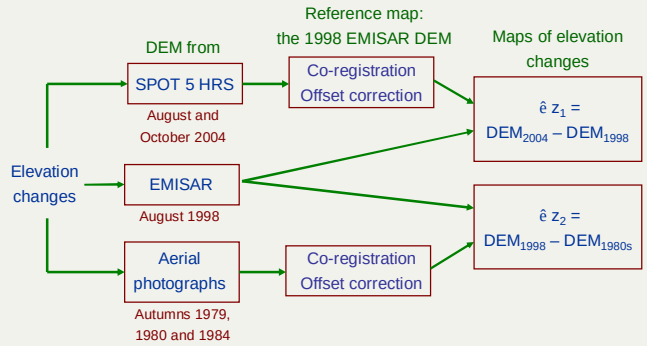
Ice cap	Area (km^2)	Range in elevation (m a.s.l.)
E: Eyjafjallajökull	81	180-1630
Ti: Tindfjallajökull	15	660-1480
To: Torfajökull	14	750-1170

AAR of the warm year of 2004

- digitized using the October 2004 SPOT 5 HRS images

Ice cap	AAR (%)
E: Eyjafjallajökull	20-25
Ti: Tindfjallajökull	<5
To: Torfajökull	0

Method



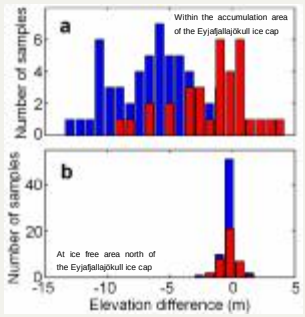
EMISAR August 1998 (reference map): Danish airborne synthetic aperture radar. DEM preprocessed using a cross-calibration of interferometer SAR data (*Dall*, 2003) and further corrected with available DGPS points and driven profiles at ice free areas (*Magnússon and others*, 2005).

Autumn aerial photographs: 20 m contour lines digitized using the best available aerial photographs from: 1979 for Torfajökull, 1980 for Tindfjallajökull and 1984 for Eyjafjallajökull. Regular 40x40 m DEMs created by a kriging method.

SPOT 5 HRS August 2004 stereo image pairs: along-track stereoscopic images (pixel size of 5 m along track and 10 m across track) with ±20° forward and backward viewing angles. From an automatic processing method developed at IGN, using no check against ground truth (e.g. *Bouillon and others*, 2006).

SPOT 5 HRS October 2004 stereo image pairs: processed with PCI-Geomatica, using as ground truth point measurements and surface profiles surveyed by kinematic GPS, and further corrected with airborne radar altimetry profiles from October 2004.

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

ICESat: Ice, Cloud,and land Elevation Satellite (e.g. *Zwally and others*, 2002)

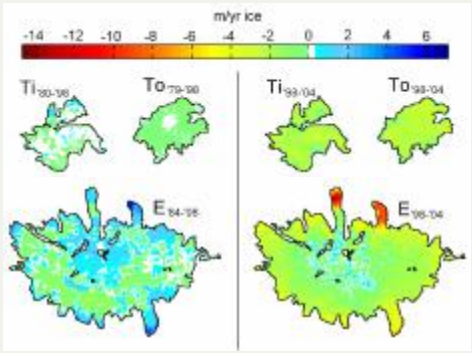
The results indicate high winter accumulation at the Eyjafjallajökull ice cap:

- § from ICESat: high seasonal elevation changes of up to 10 m are observed within the accumulation area
- § from our elevation data: negligible lowering is observed at the highest parts from 1998-2007
- § hence 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: 1 to 2 m yr^{-1} (*Pálsson and others*, 2007)

Eyjafjallajökull and Mýrdalsjökull are the most maritime ice caps in Iceland:

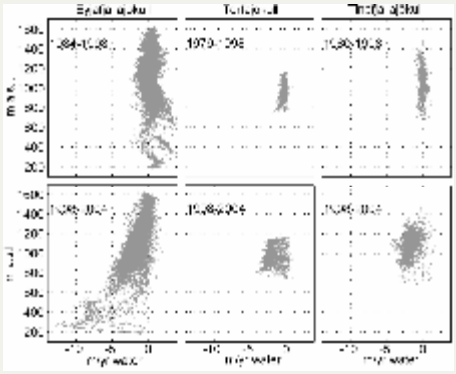
- § high seasonal elevation changes of up to 10 m have also been observed within the accumulation area of Mýrdalsjökull (*Gudmundsson and others*, 2007)
- § in contrast, the highest recorded seasonal elevation change on Langjökull ice cap located in the central Iceland, is 6 m (*Pálsson and others*, 2007)

Specific mass balance



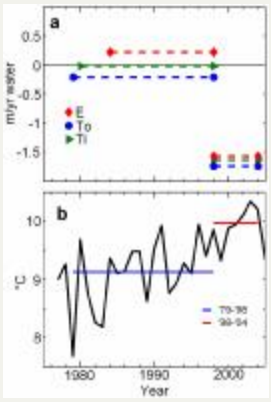
Maps of annual average elevation changes:

- E: Eyjafjallajökull, Ti: Tindfjallajökull and To: Torfajökull ice caps
- periods displayed as subscripts of E, To and Ti



Distribution with elevation:

- scaled to w. eq. by using the density 900 kg/m^3 for ice
- from the 1980s to 1998, the ice flow more or less compensated for the mass loss at the lowest parts
- In contrast, all the ice caps were in a fast retreating phase from 1998 to 2004



Average specific annual mass balance (a), compared to average May to September temperature at weather station close to the ice caps (b):

- mass balance close to zero for the average climate condition during the first period 1979/1984-1998
- mass balance declination of >1.5 m yr^{-1} w. eq. for the ~1° C warmer period from 1998 to 2004

Average specific annual mass balance (m yr^{-1} w. eq.)

- Uncertainties are cautiously estimated using the given DEM accuracies

Ice cap	1979/1984 - 1998	1998 - 2004
Eyjafjallajökull	+0.20 ± 0.20	-1.53 ± 0.10
Tindfjallajökull	-0.02 ± 0.15	-1.63 ± 0.10
Torfajökull	-0.20 ± 0.15	-1.80 ± 0.10

Concluding remarks

Estimates of mass balance:

- Average specific mass balance of three small ice caps (with areas from 15 to 80 km^2) over 6 to 20 years, were efficiently estimated from maps of glacier elevation changes deduced by SPOT 5 HRS, EMISAR and aerial photographs
- Accuracy of estimating the elevation changes, was greatly improved by using the highly precise EMISAR DEM as a reference for co-registration and offset correction

Trends in mass balance:

- The winter balance on the Eyjafjallajökull ice cap, one of the most maritime glacier in Iceland, seem to be considerable
- Period from the 1980s to 1998:
  - the average specific mass balance was close to zero on the three ice caps
  - the ice flow more or less compensated for the mass loss at the lowest parts of the glaciers
- Period from 1998 to 2004
  - ~1°C warmer than from the 1980s to 1998
  - the average specific mass balance declined by >1.5 m yr^{-1} w. eq. on the three ice caps
  - lowering rate up to 14 m yr^{-1} of ice was observed at the lowest parts of Eyjafjallajökull

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