Volume and mass balance changes of ice caps in Iceland deduced from elevation data and *in-situ* mass balance observations

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The Nordic Climate and Energy (CE) and Climate and Energy Systems (CES) projects

Overview

- Volume and mass balance changes derived from:

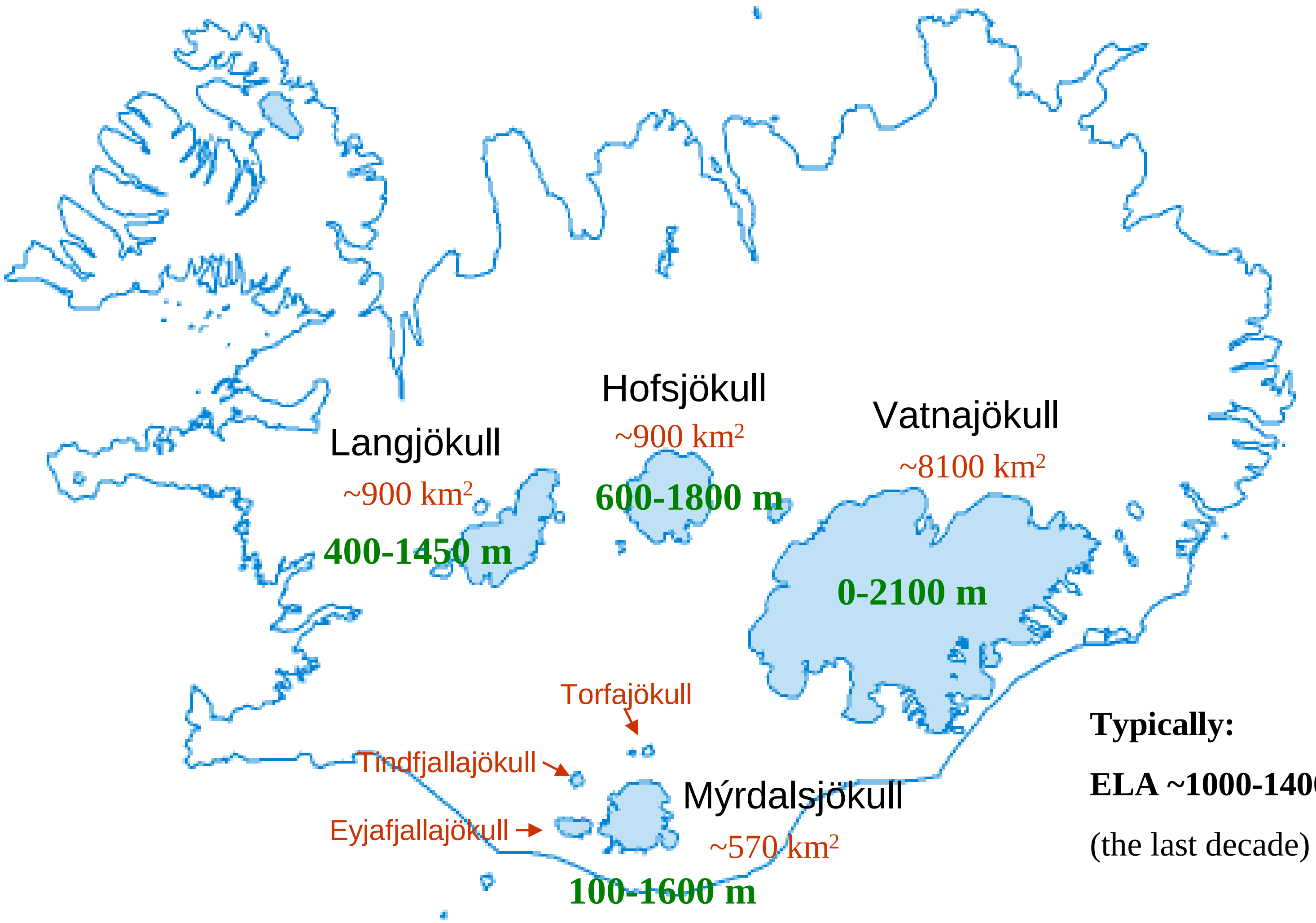
  1. ***in-situ* annual mass balance observations**
     - at snow pits and stakes
  2. **differential DEMs**
     - from dense GPS profiles and remotely sensed data
     - recent DEMs obtained within the SPIRIT project

- Results show response of glacier mass balance to regional climate changes since the 1980s to present

- Contribution to sea level changes

Size and elevation of ice caps

Glaciers cover around 11% of Iceland

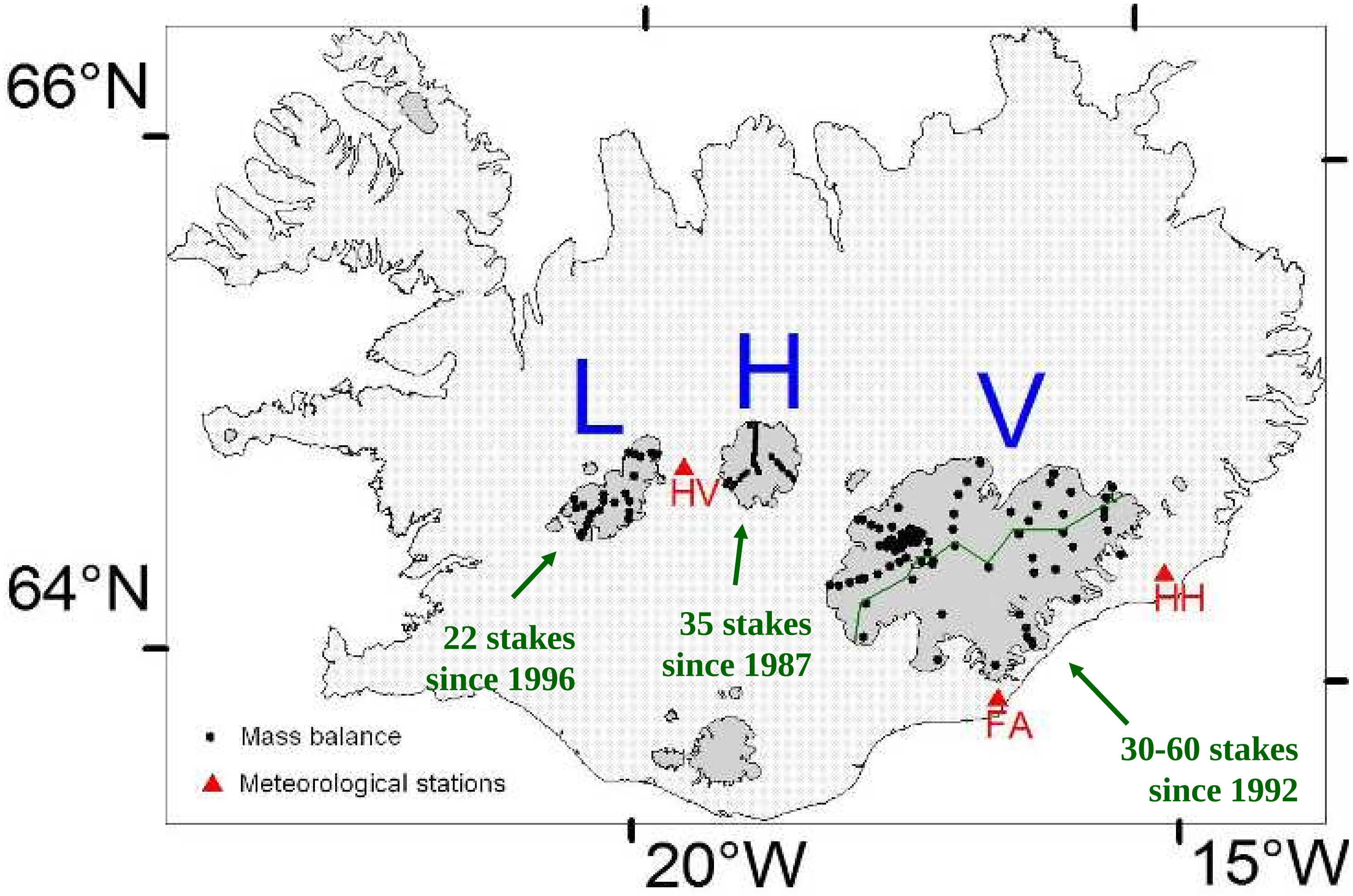


Typically:

ELA ~1000-1400 m

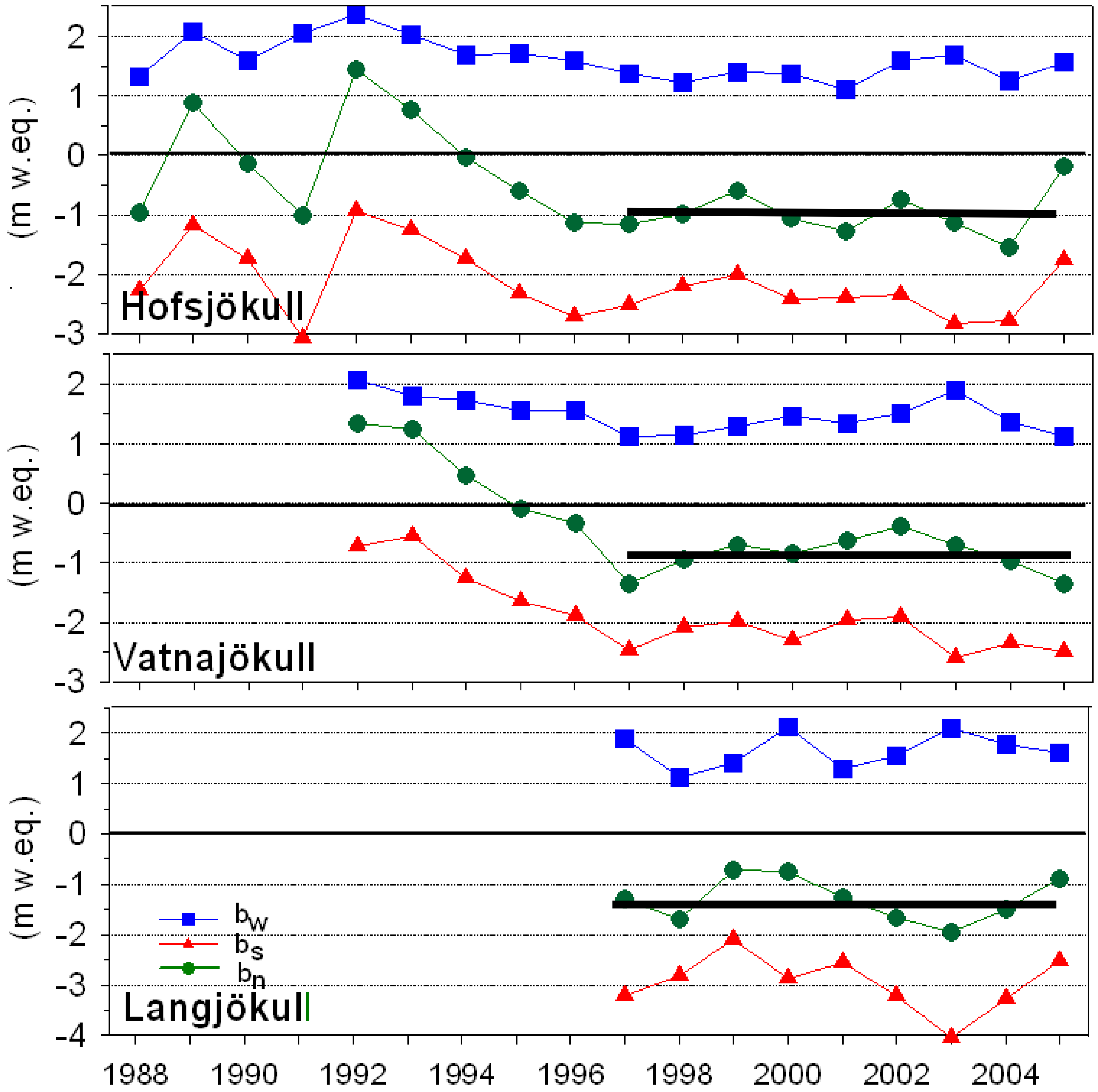
(the last decade)

Mass balance observation sites



Specific mass balance from stake observations

- Since 1997: -1 to -1.5 m/a w.e.



From: IMO

<u>~ -1.0 m/a w.e.</u>
1997-2005

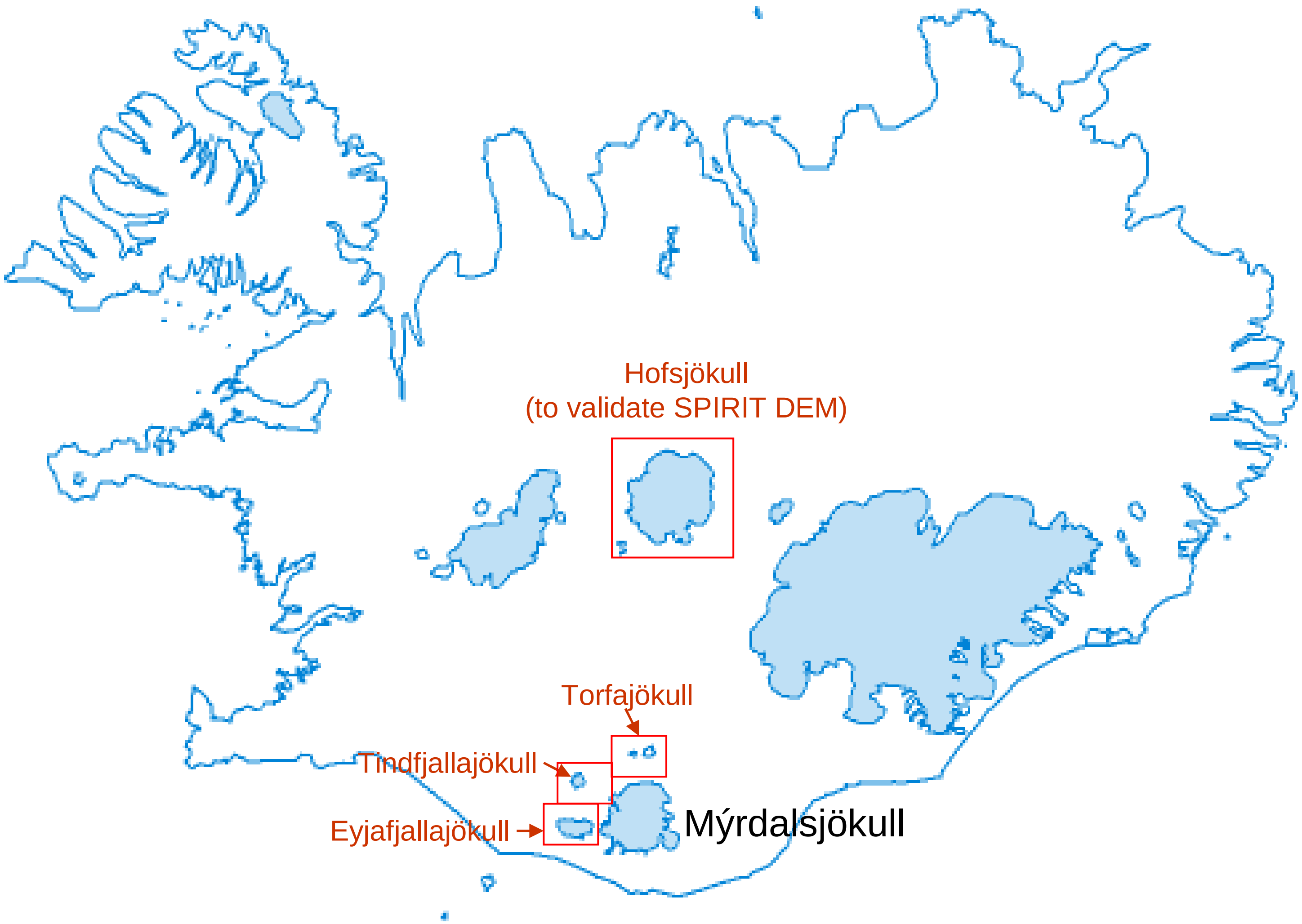
<u>~ -0.9 m/a w.e.</u>
1997-2005

<u>~ -1.3 m/a w.e</u>
1997-2005

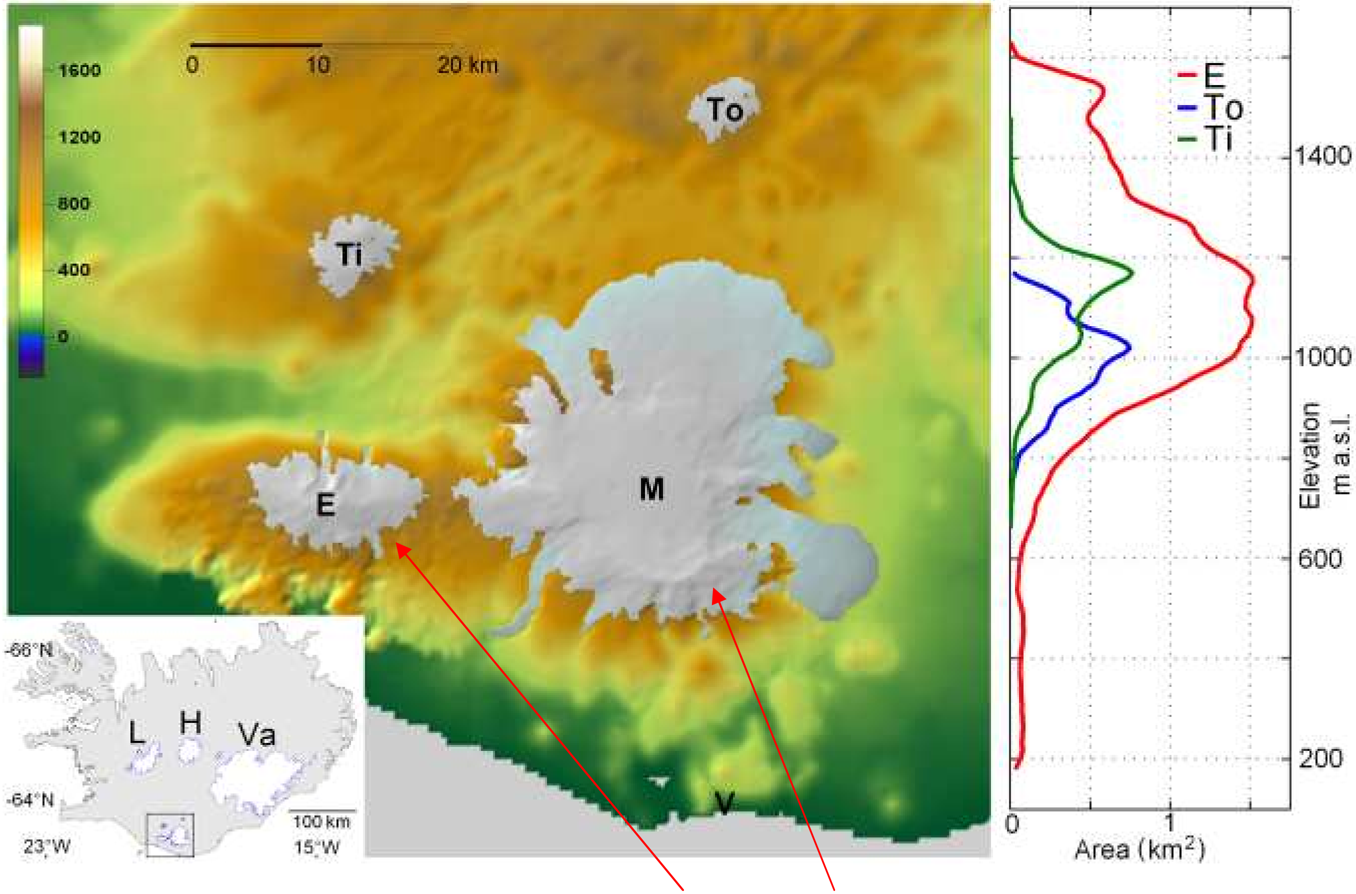
Elevation data

- **Aerial photographs**
  - **since in the 1980's**
- **EMISAR** (The National Space Institute, DTU, Denmark):
  - **Very accurate airborne stereo InSAR images, 1998**
- **SPOT 5 stereo images** (SPIRIT and OASIS projects)
  - **HRG and HRS sensors, since 2004**
    - **HRG: stereo image pairs with few days separation**
    - **HRS: back and forward looking stereo image pairs**
- **Lidar** (collaboration between IES and IMO)
  - **Highly accurate airborne laser altimetry, since 2007**
- **Dense elevation profiles**
  - ***in-situ* GPS profiles, since 1997**
  - **airborne radar altimetry, since 1999**

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



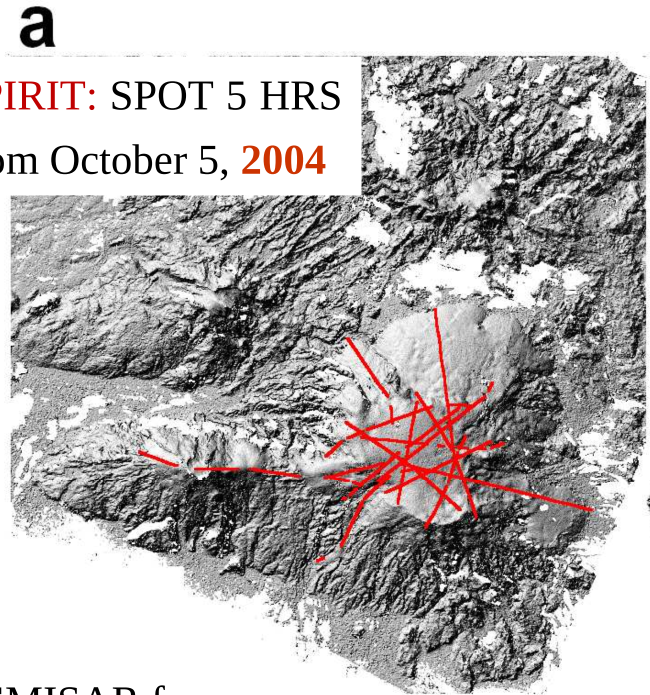
Location



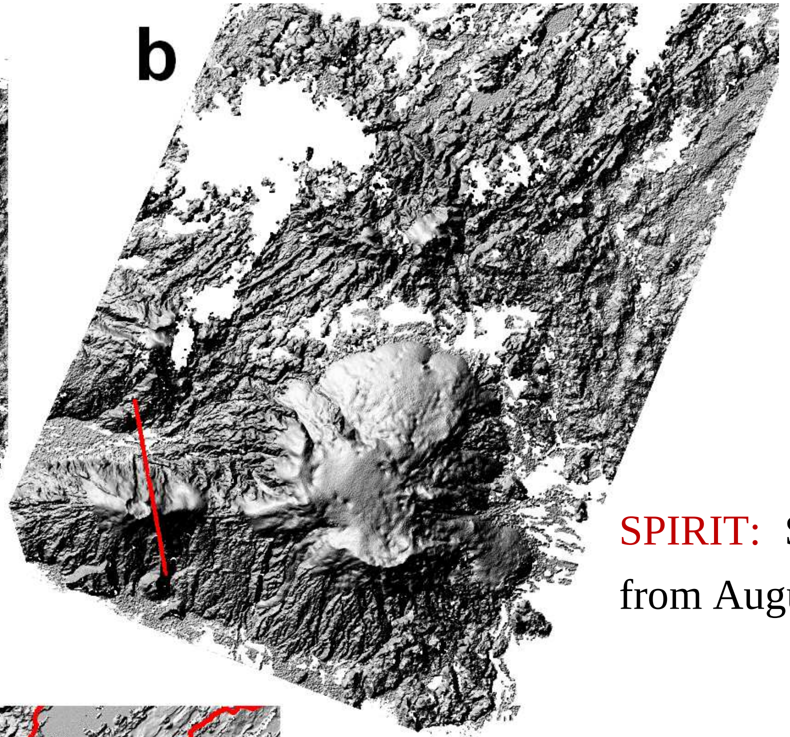
- **M: ~570 km^2**
- **E: ~80 km^2**
- **Ti: ~15 km^2**
- **To: ~15 km^2**

- **The two most maritime glaciers in Iceland**
- **“High” precipitation**
- **Up to 12 m winter accumulation of snow observed**
- **Considerable annual mass balance variations**


The eruption site
7 April 2010
few days before the Eyjafjallajökull eruption



SPIRIT: SPOT 5 HRS
from October 5, **2004**

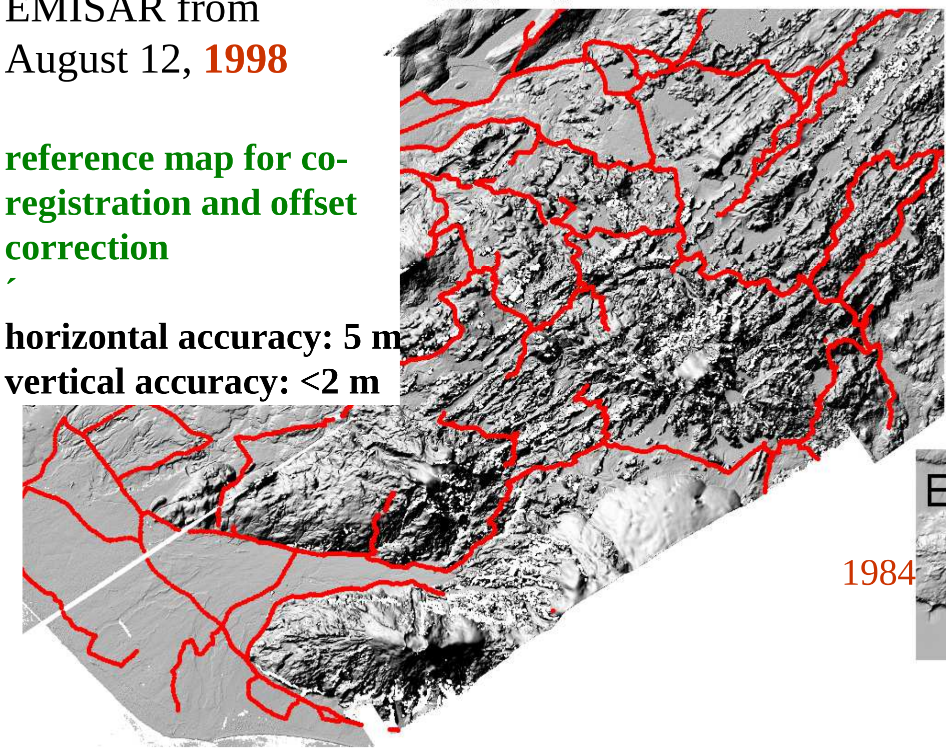


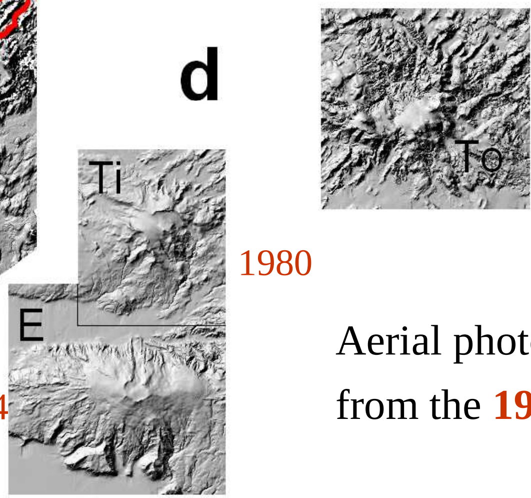
SPIRIT: SPOT 5 HRS
from August 14, **2004**

EMISAR from
August 12, **1998**

reference map for co-registration and offset correction

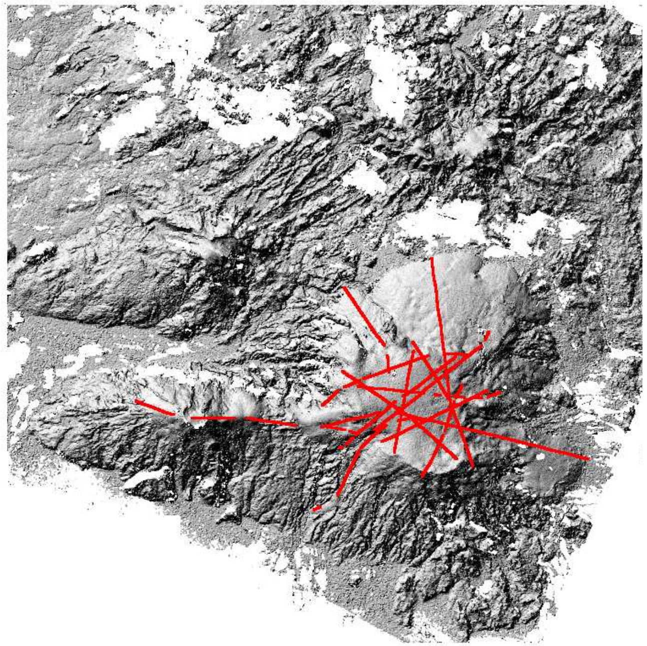
horizontal accuracy: 5 m
vertical accuracy: <2 m

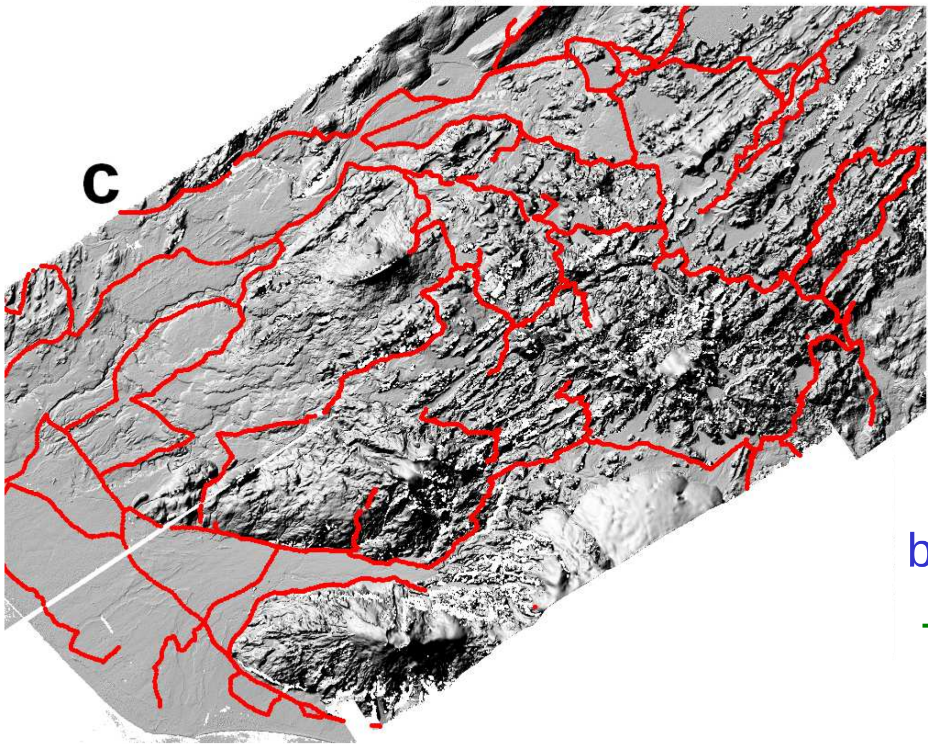




Aerial photographs
from the **1980s**

a





Imprinted profiles:

a) Airborne radar altimetry (4.3 GHz / 7 cm; C-band)

- seasonally since 1999
- relative error within 1 m

b) GPS profiles and points

- accuracy ~1 m in elevation

Validation of the August 2004 SPIRIT DEM

- Relative to the 1998 EMISAR DEM
  - (<2 m in elevation; ~5 in location)

	East (m)	North (m)	μ / σ (m)
E	15	5	+0.2 / 4.1
To	15	10	-1.0 / 4.7
Ti	20	5	-0.6 / 6.0

From : Sverrir Gudmundsson and others (in press)

- Relative to a 2008 Lidar DEM close to the Hofsjökull ice cap
  - (<20 cm in elevation; <<5 m in location)

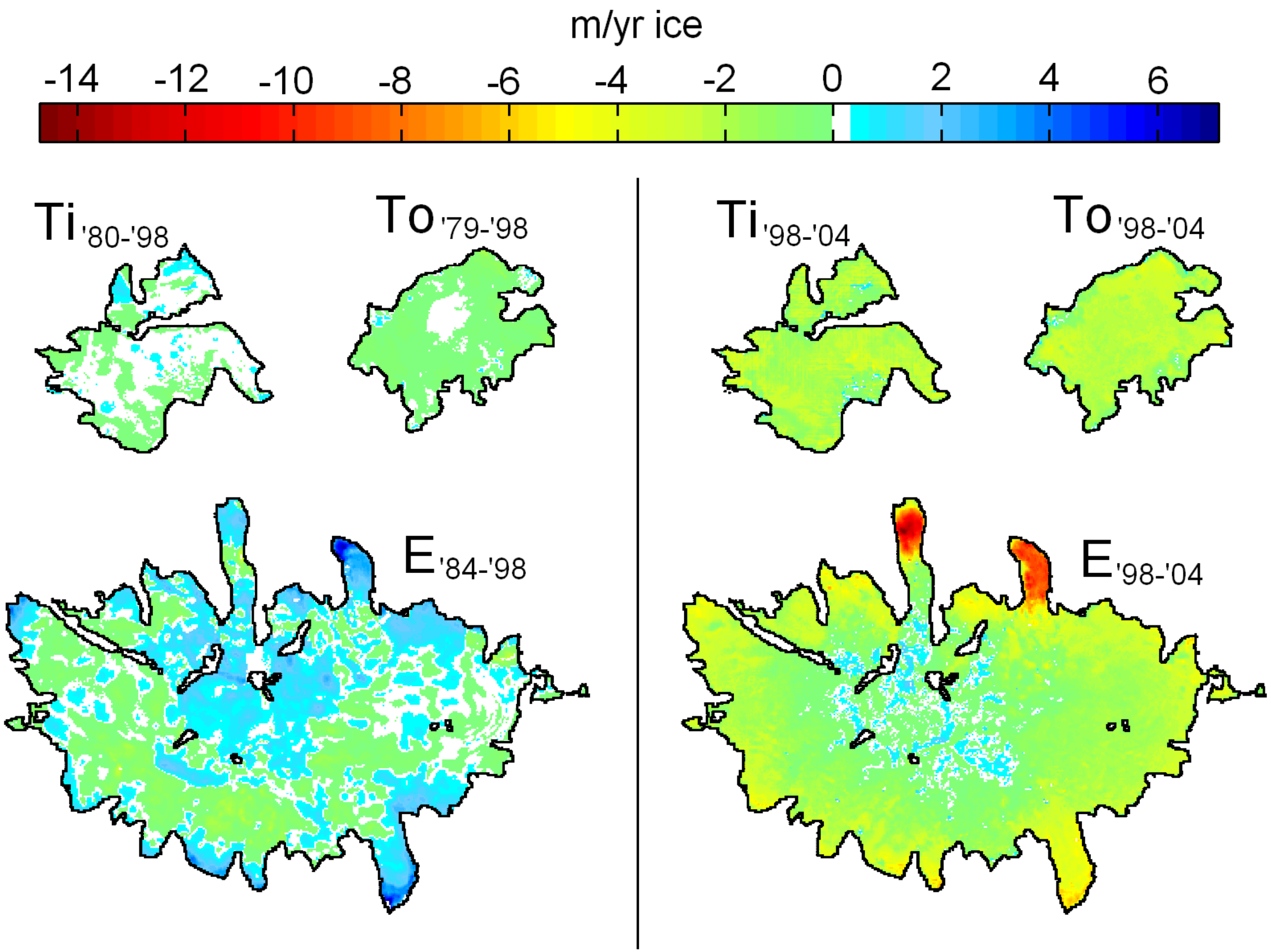
	East (m)	North (m)	μ / σ (m)
H	5	0	+0.3 / 5.6

From : Eyjólfur Magnússon and others (in prep.)

- Within the estimated 27 m accuracy in position and 5 to 10 m in elevation (90% confidence) given by Bouillon and others (2006)

Maps of annual average elevation changes

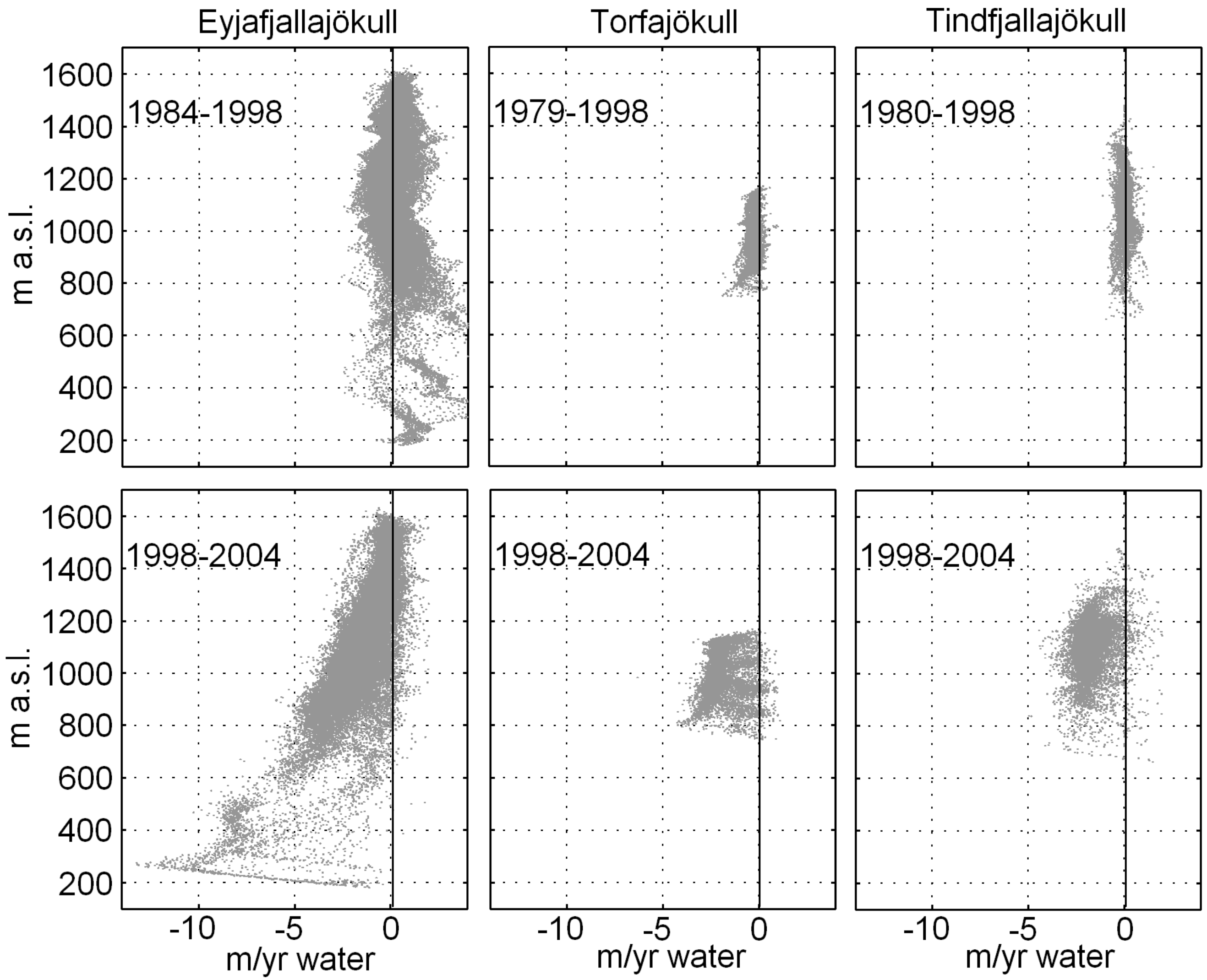
- E: Eyjafjallajökull, Ti: Tindfjallajökull and To: Torfajökull ice caps
- periods displayed as subscripts of E, To and Ti



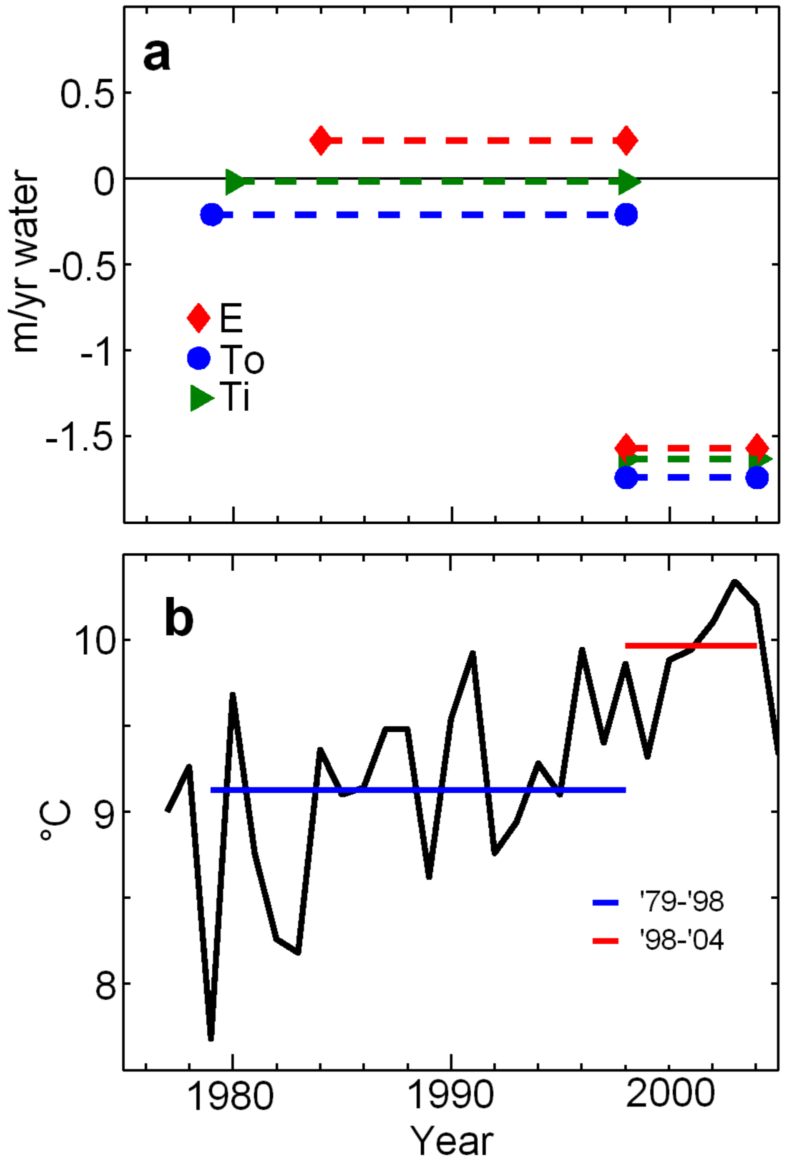
Distribution of mass changes with elevation:

1) 1980s to 1998: Ice flow compensated for the mass loss at the lowest parts

2) 1998 to 2004: In contrast, all the ice caps in a fast retreating phase



Mass balance and mean summer temperature



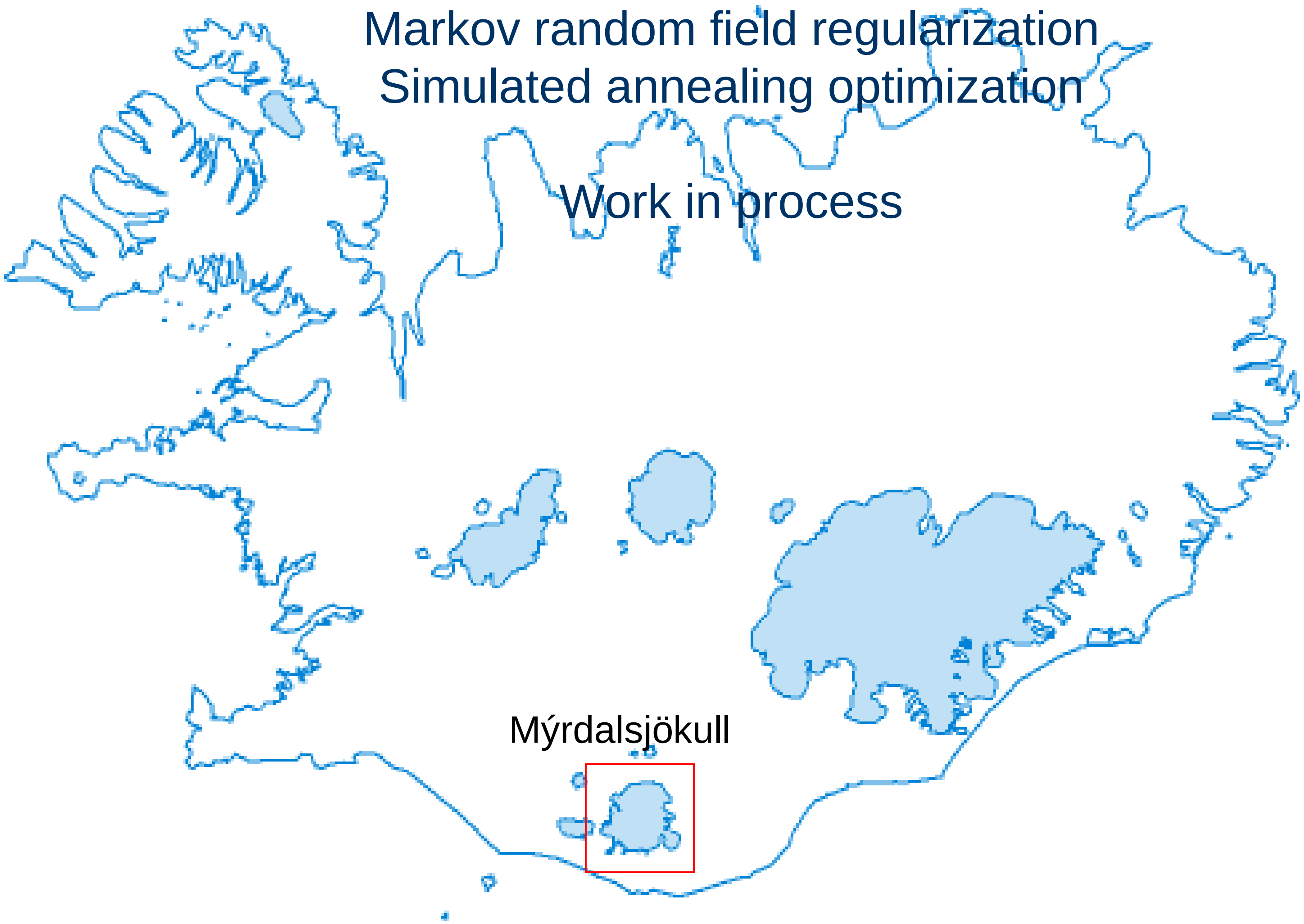
Average specific annual mass balance ($\bar{b}_n$)

Mean summer temperature at weather stations close to the ice caps (Vik in Mýrdalur)

Mass balance of Mýrdalsjökull since 1997, deduced from elevation data

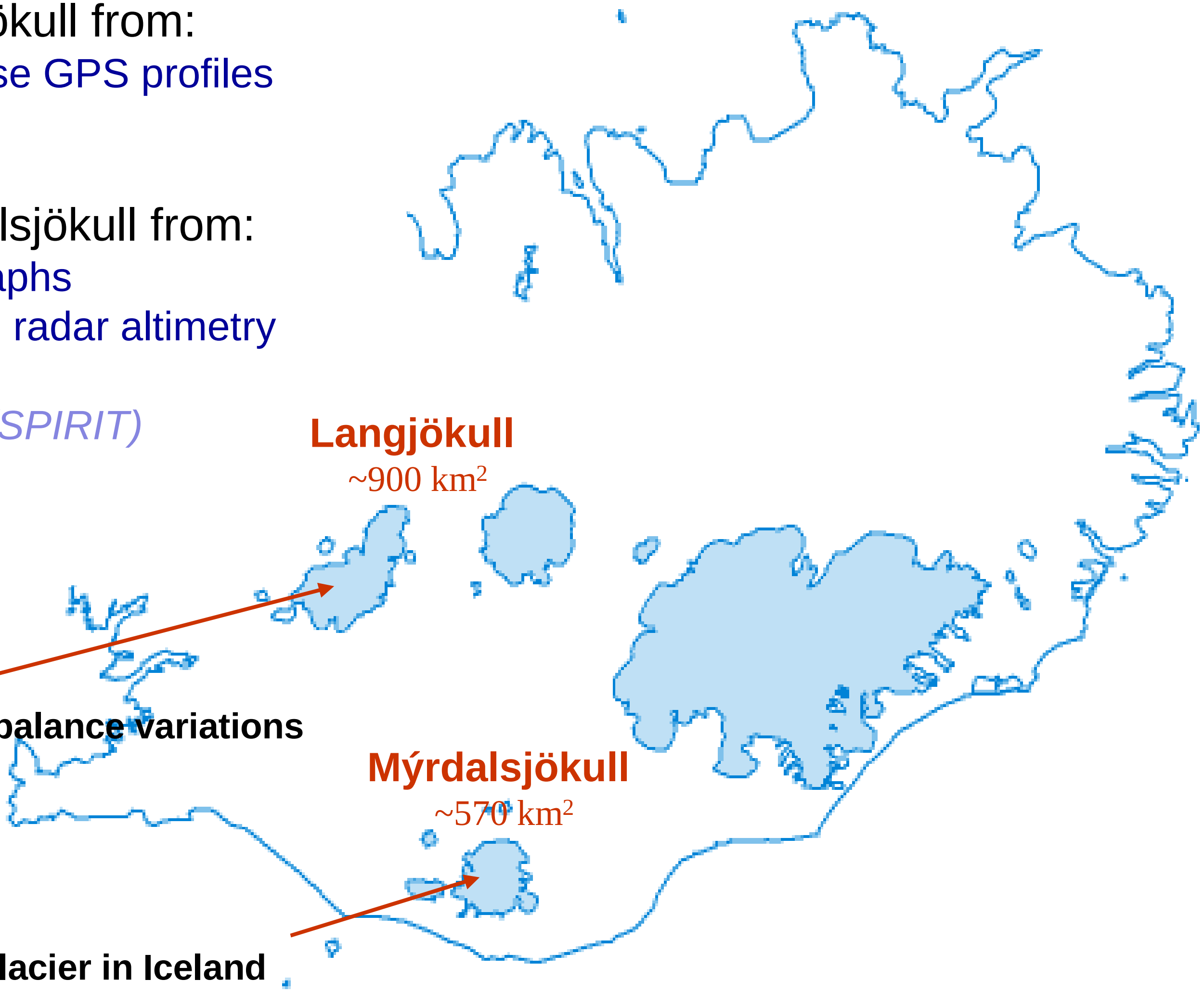
Data fusion using:
Markov random field regularization
Simulated annealing optimization

Work in process



Study area

- Langjökull: *In-situ* mass balance to validate results
- Elevation of Langjökull from:
  1) multi-year dense GPS profiles
  2) SPOT 5 HRG
- Elevation of Mýrdalsjökull from:
  1) Aerial photographs
  2) dense airborne radar altimetry
  3) SPOT 5 HRG
  4) SPOT 5 HRS (SPIRIT)



- **“Low” precipitation**
- **“Low” annual mass balance variations**

- **The most maritime glacier in Iceland**
- **Annual mass balance variations are considerable**

Volume loss and mass balance

Volume loss

Langjökull	Spring 1997 to autumn 2004 (km^3 w.eq.)	Spring 1997 to spring 2007 (km^3 w.eq.)
1) Δz maps	11.5	12.1
2) Annual mass balance observations	11.8	12.0

Mass balance

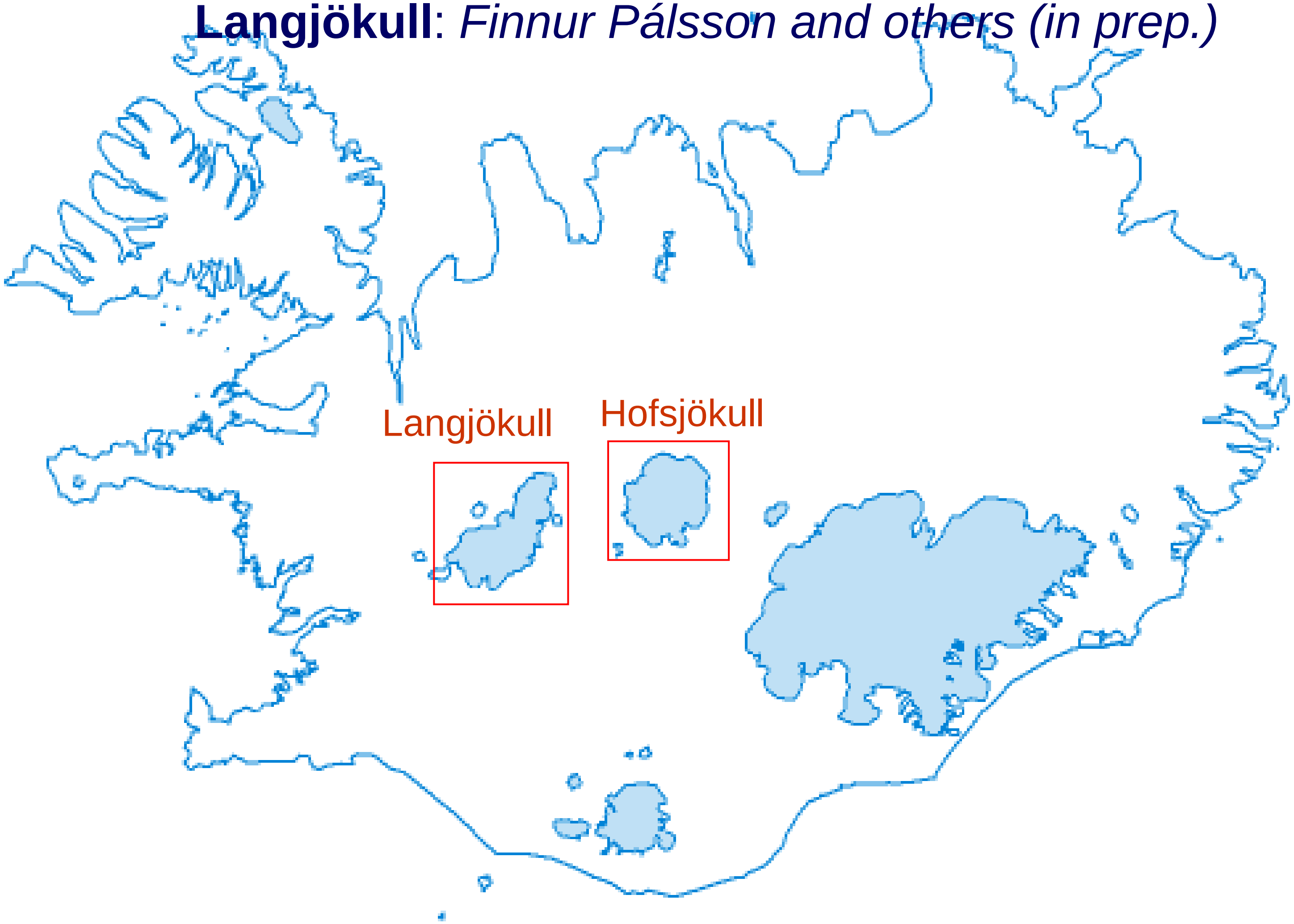
Glacier	Autumn 1999 to autumn 2006 (m/a w.eq.)	Autumn 1999 to autumn 2005 (m/a w.eq.)	Autumn 1999 to autumn 2007 (m/a w.eq.)
1) Mýrdalsjökull; Δz maps	-0.93	-0.99	-0.99

2004 SPIRIT DEM: will improve the data fusion

Specific mass balance of Langjökull and Hofsjökull from 1986 - 2008

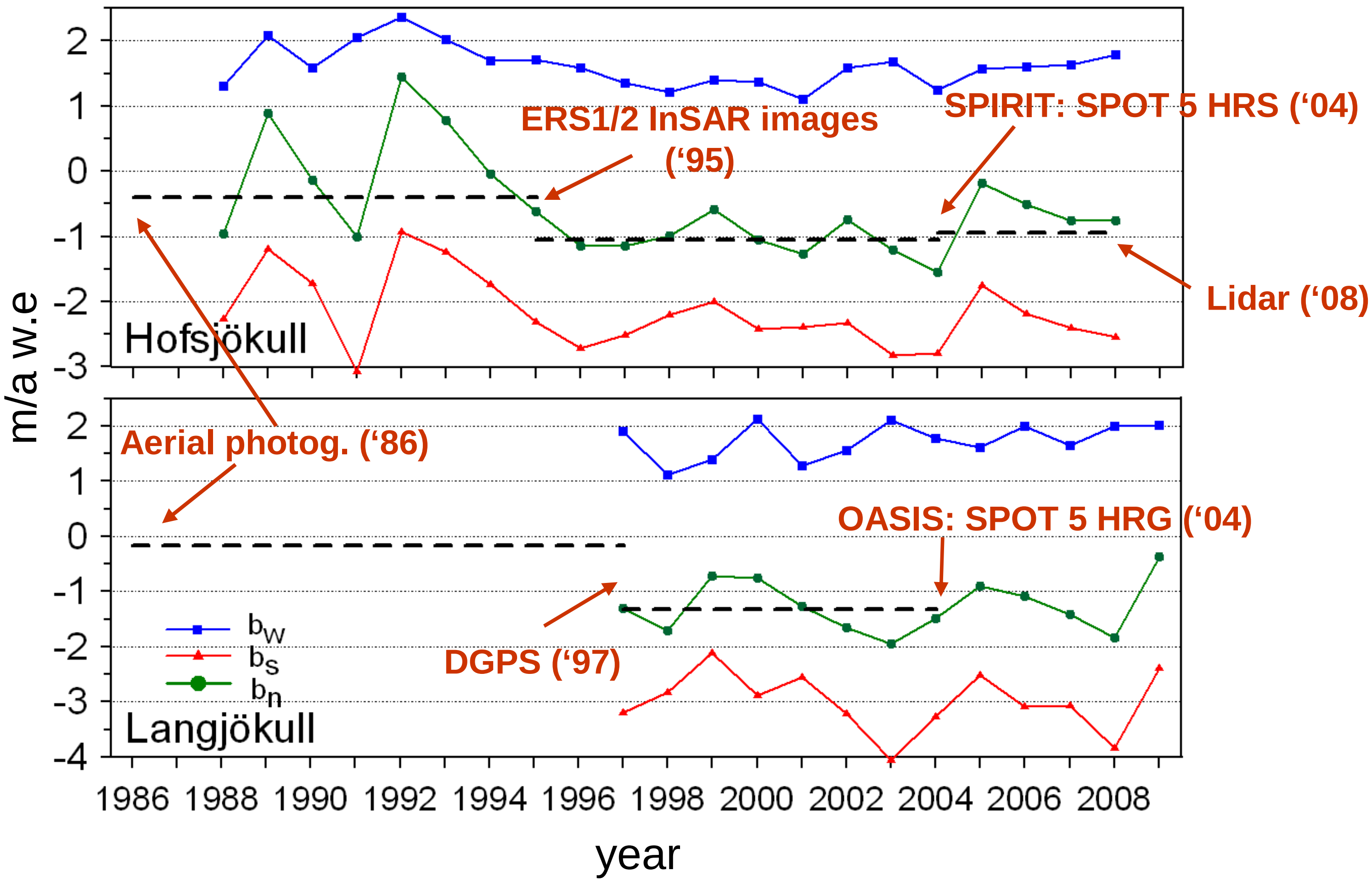
Hofsjökul: *Eyjólfur Magnússon and others (in prep.)*

Langjökull: *Finnur Pálsson and others (in prep.)*



Specific mass balance of Langjökull and Hofsjökull from 1986 - 2008

- Solid lines: stake observations
- Dashed lines: averages from DEMs



Specific mass balance of Langjökull and Hofsjökull from 1986 - 2008

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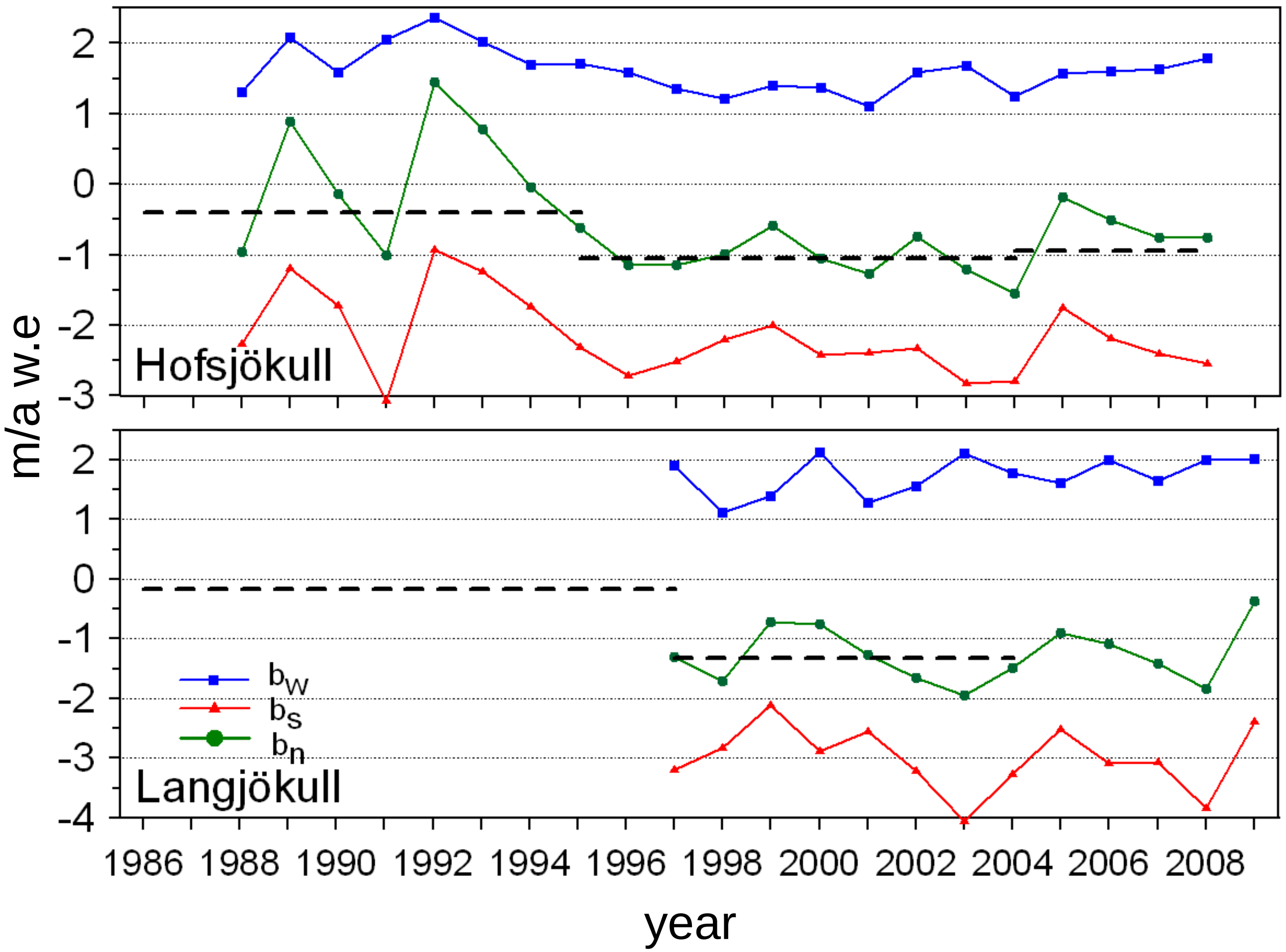


From the DEMs:

Hofsjökull:

- 0.4 m/a w.e. 1986 - 1995

- 1.05 m/a w.e. 1995 - 2004

- 0.95 m/a w.e. 2004 - 2008

Langjökull:

- 0.16 m/a w.e. 1986 - 1997

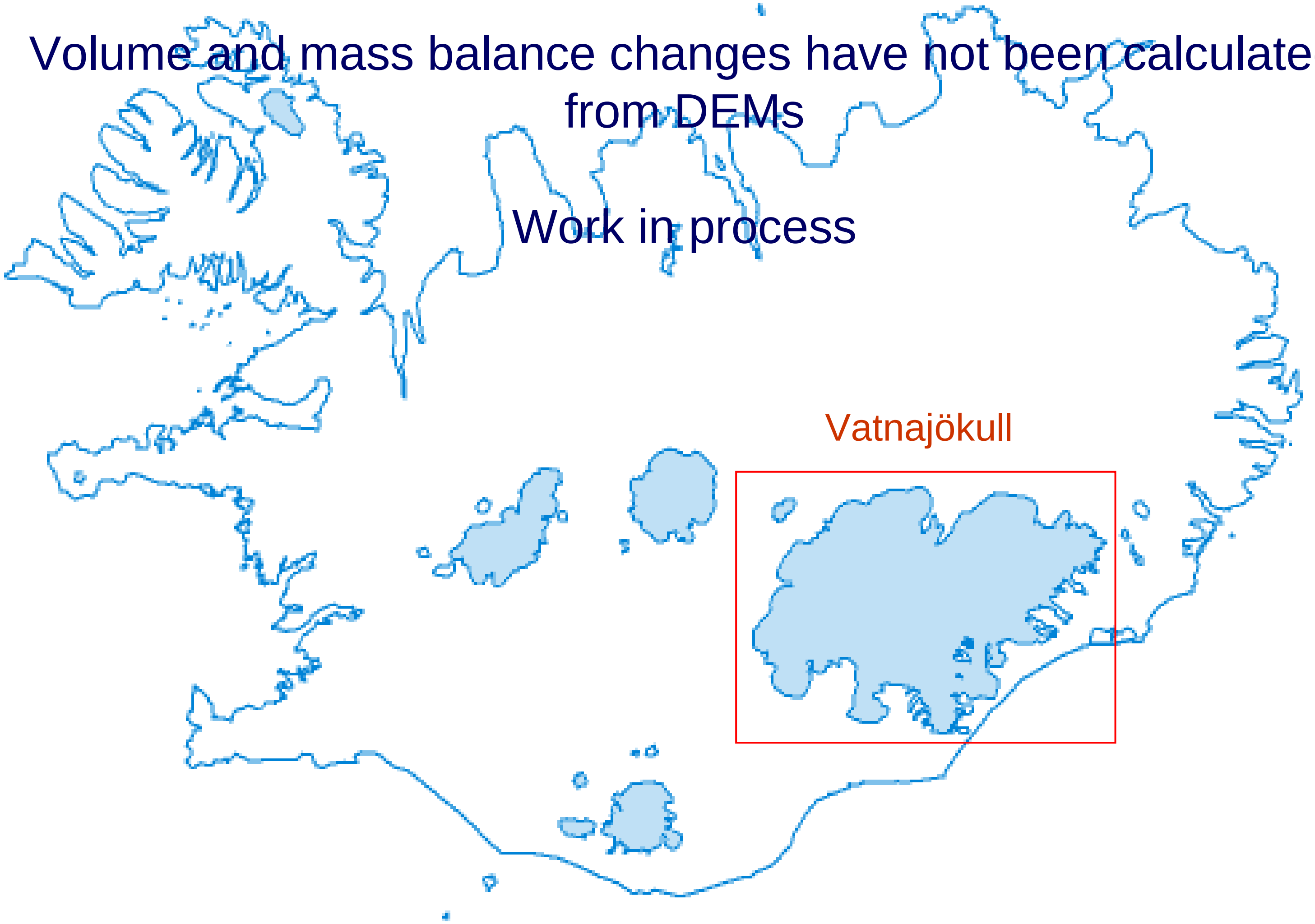
- 1.32 m/a w.e. 1997 - 2004

SPIRIT DEMs from Vatnajökull

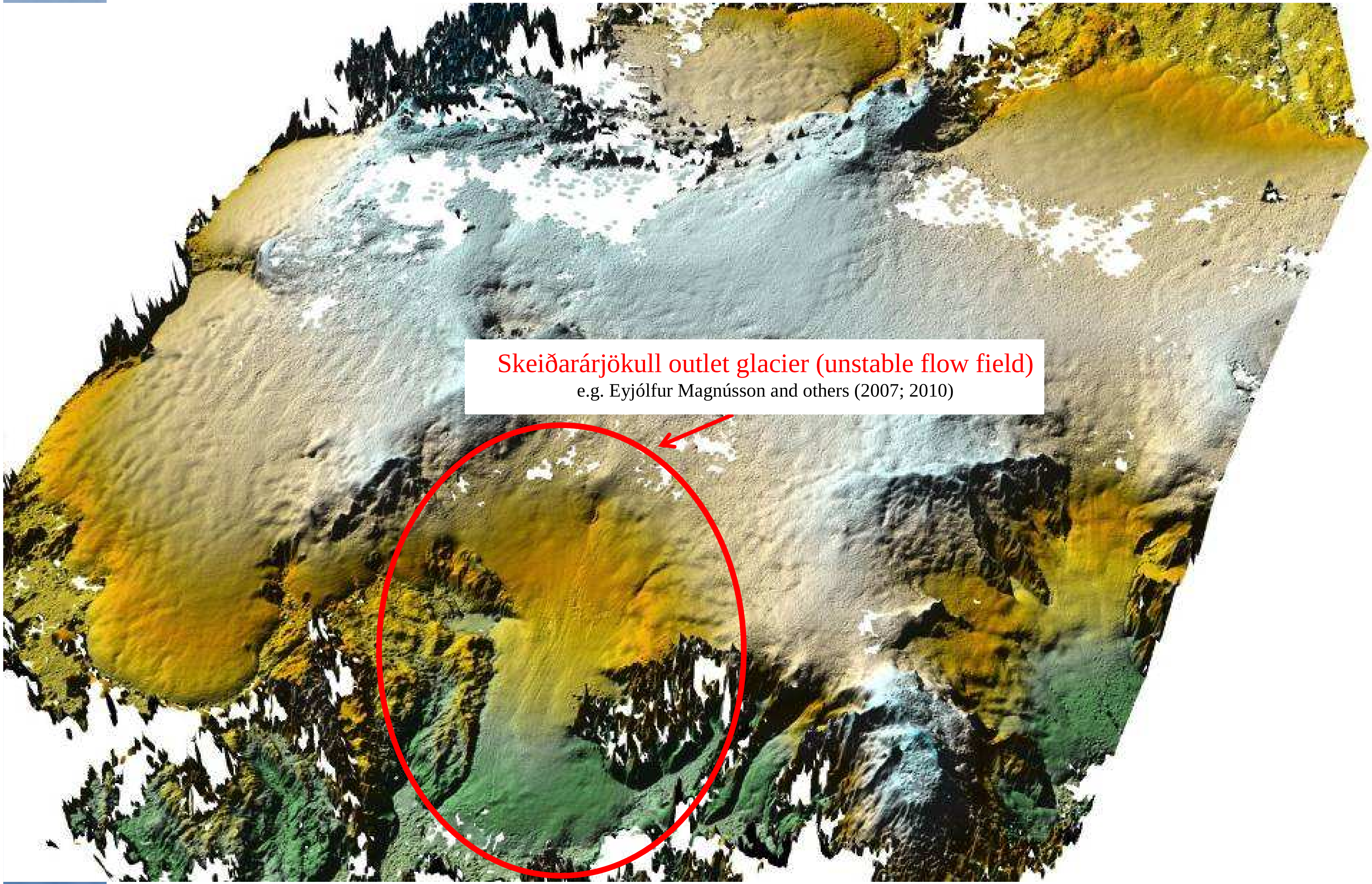
Close to have a full differential DEMs coverage of the ice cap (thanks to SPIRIT)

Volume and mass balance changes have not been calculated from DEMs

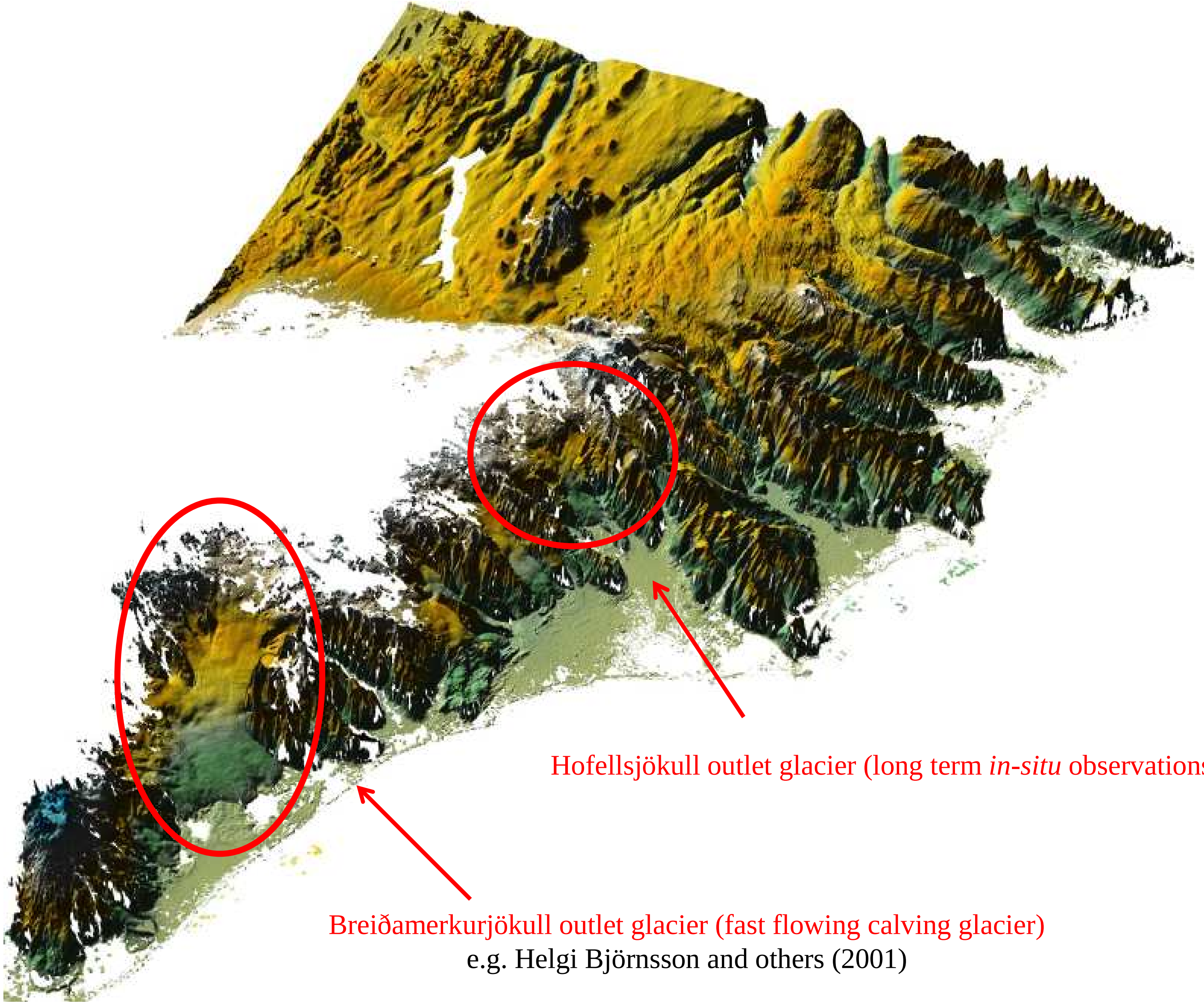
Work in process



SPIRIT: DEM from SPOT 5 HRS 2003



SPIRIT: DEM from SPOT 5 HRS 2008

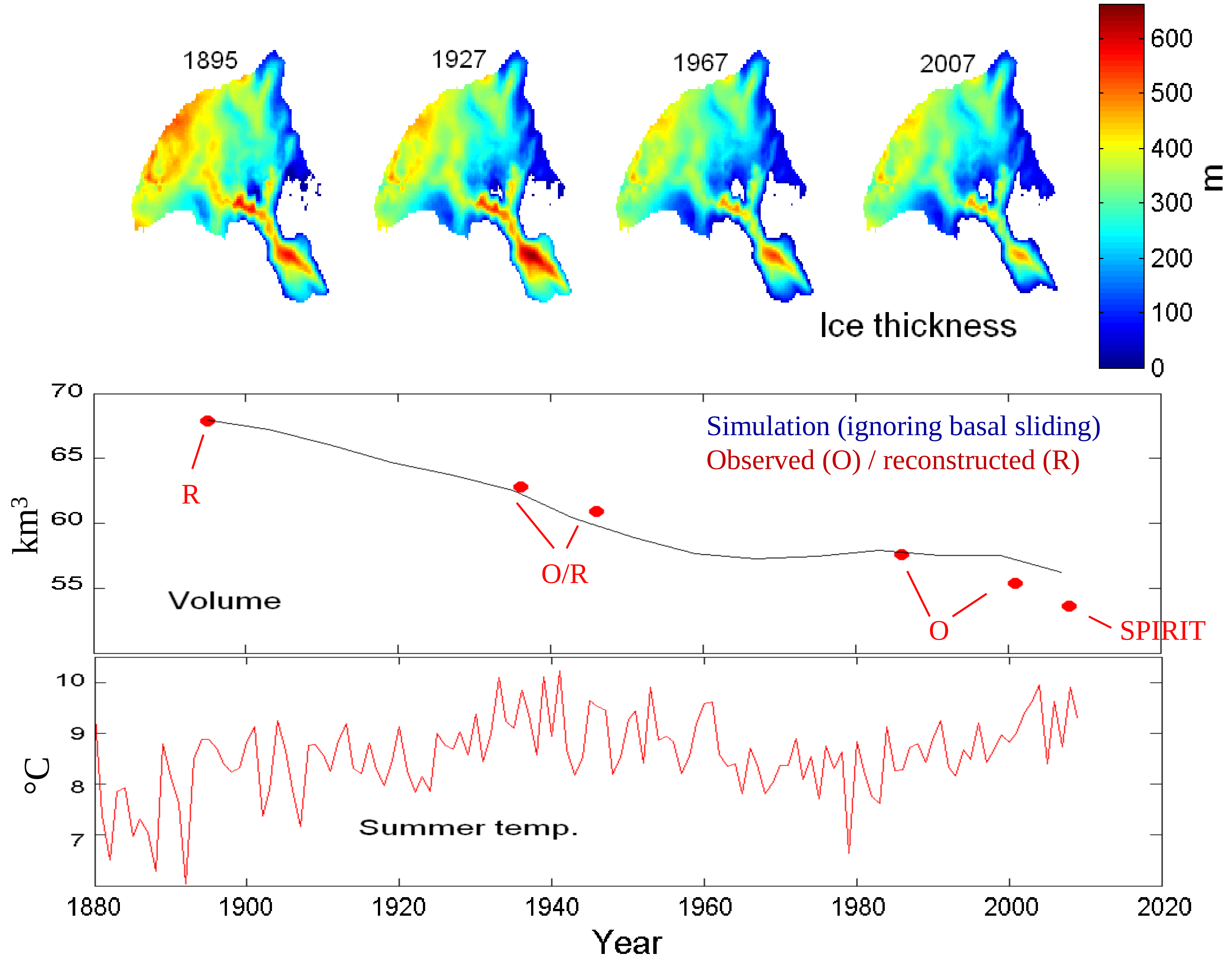


Hofellsjökull outlet glacier (long term *in-situ* observations)

Breiðamerkurjökull outlet glacier (fast flowing calving glacier)

e.g. Helgi Björnsson and others (2001)

Hofellsjökull outlet glacier of Vatnajökull ice cap

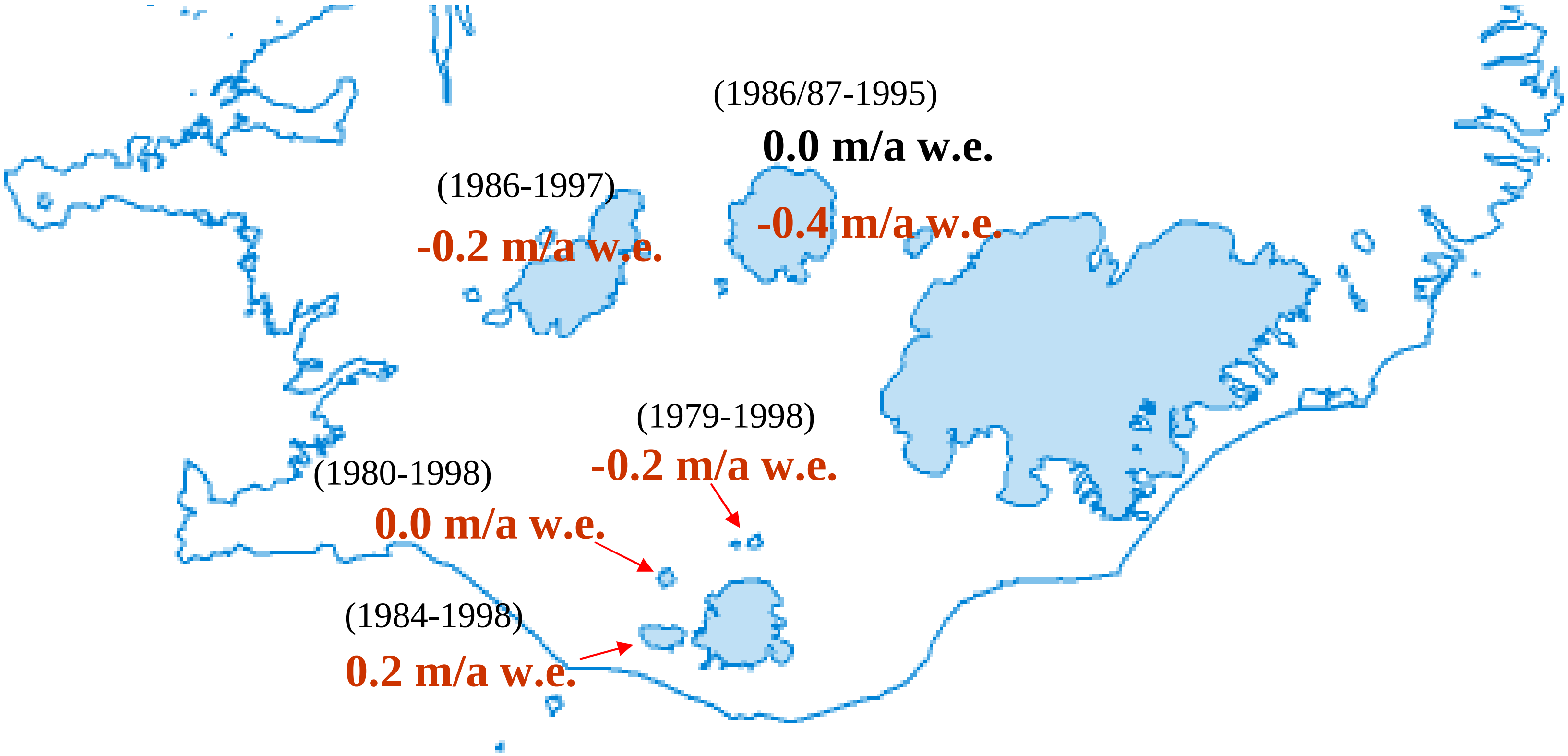


Conclusion

Specific mass balance in the 1980s to 1990s:

- **<u>Black</u>**: from the *in-situ* observations:
  0.0 m/a w.eq. for Hofsjökull 1987 to 1995

- **<u>Red</u>**: from the differential DEMs:
  near balance (close to zero)

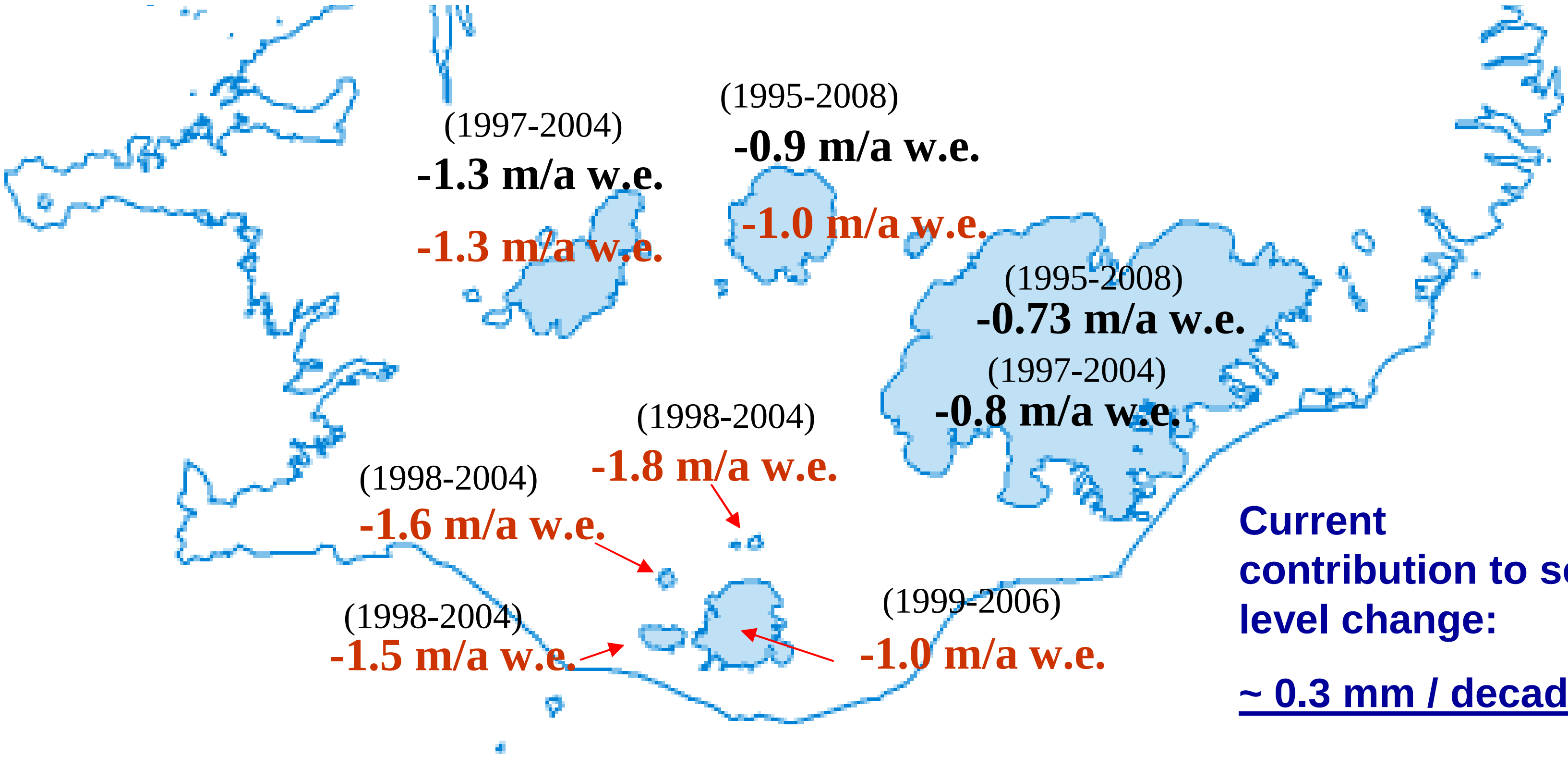


Conclusion

Specific mass balance during the past 10 to 15 years

- **Black**: from the *in-situ* observations:
  -1.3 to -0.9 m/a w.eq.

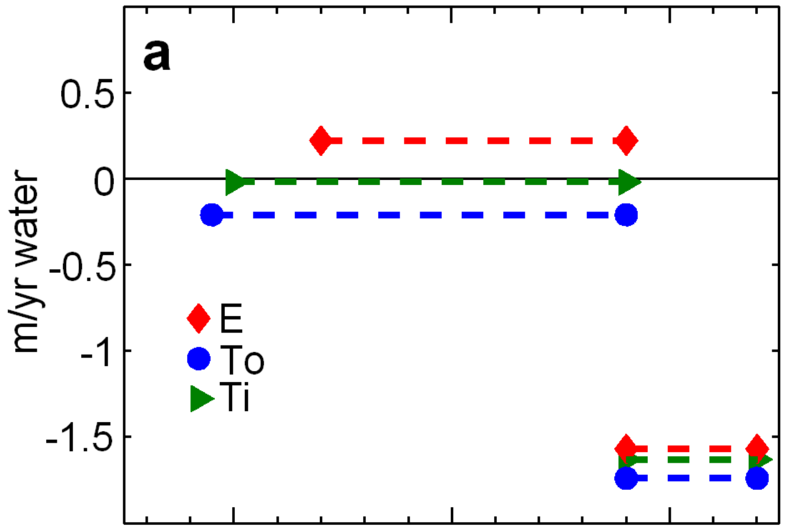
- **Red**: from the differential DEMs:
  -1.8 to -1.0 m/a w.eq.



Current contribution to sea level change:

~ 0.3 mm / decade

Mass balance and AAR



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

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 ± 0.15	-1.55 ± 0.15
Tindfjallajökull	-0.20 ± 0.10	-1.80 ± 0.30
Torfajökull	0.00 ± 0.10	-1.60 ± 0.30

Mass balance sensitivity to 1°C temperature rise

	$\partial b_n / \partial T$ (m yr^{-1} °C^{-1})
E	-3.00 ± 0.40
To	-2.10 ± 0.25
Ti	-2.25 ± 0.25

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Climate sensitivity of a high-precipitation glacier in New Zealand

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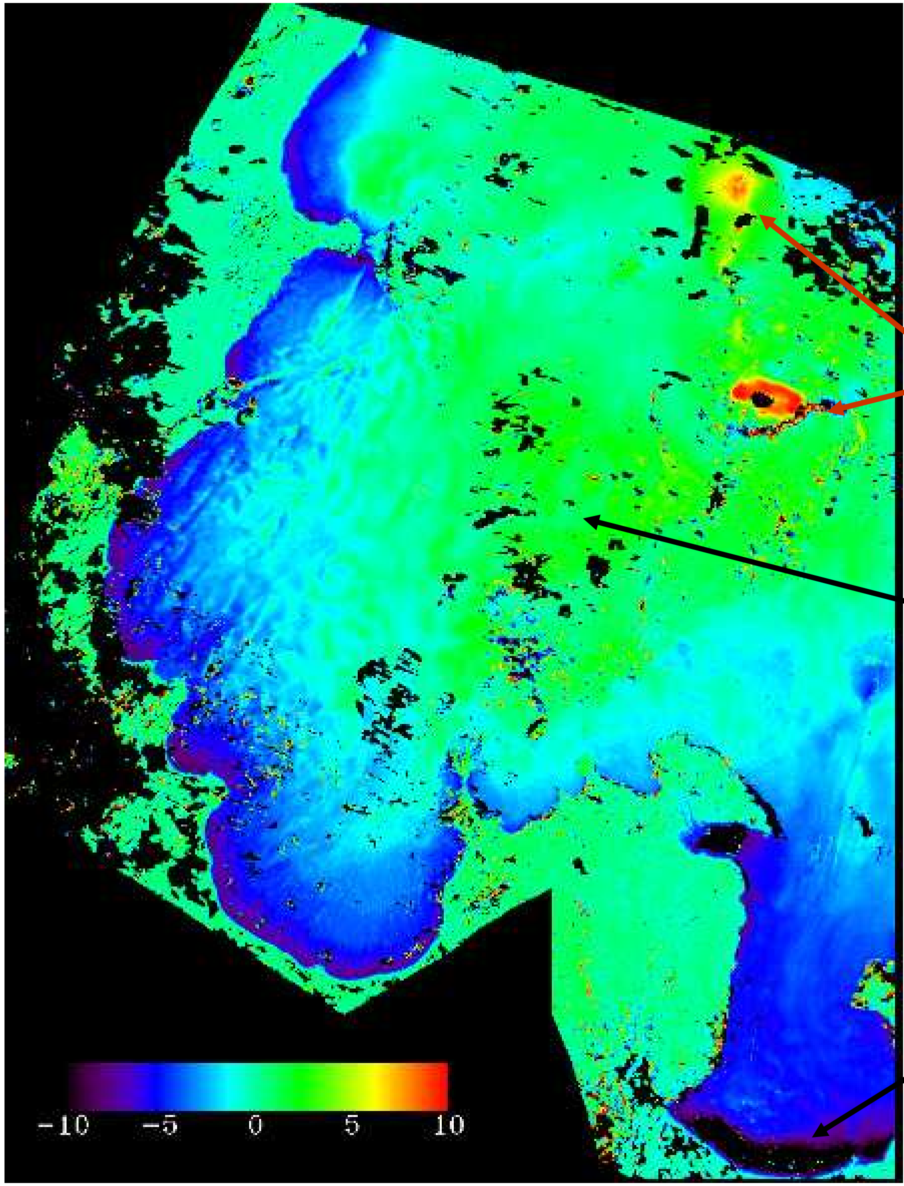
ABSTRACT. The sensitivity of glaciers to climatic change is key information in assessing the response and sea-level implications of projected future warming. New Zealand glaciers are important globally as an example of how maritime glaciers will contribute to sea-level rise. A spatially distributed energy-balance model is applied to Brewster Glacier, New Zealand, in order to calculate glacier mass balance, run-off and sensitivity to climate change. The model successfully simulates four annual mass-balance cycles. Close to half (52%) of the energy available for melt on the glacier is supplied by turbulent heat fluxes, with radiation less important, except during the winter. Model sensitivity to temperature change is one of the largest reported on Earth, at –2.0 m w.e. a^{-1} °C^{-1}. In contrast, a 50% change in precipitation is required to offset the mass-balance change resulting from a 1°C temperature change. Meltwater run-off sensitivity is also very high, increasing 60% with a 1°C warming. The extreme sensitivity of mass balance to temperature change suggests that significant ice loss will occur with even moderate climate warming.

Surface elevation change, SW-Vatnajökull

Rate of thickness change of SW-Vatnajökull

Difference between DEMs:
1998 (EMISAR)
2004 (SPOT5 HRG)

From: Eteinne Berthier *et al*., 2006



Subglacial volcanic activity

Post-surge thickening

Climatically induced thinning