Volume changes of Langjökull and Mýrdalsjökull deduced from elevation data

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1. Introduction

We evaluate volume changes and mass balance of ice caps in Iceland by comparing digital elevation maps (DEMs), airborne altimetry and GPS field measurements. DEMs of the ice caps Langjökull and Mýrdalsjökull (in late August 2004 and 2006) were constructed from high resolution SPOT5 stereo pairs obtained by the across-track high-resolution-geometry (HRG) sensors. Spatial resolution up to 20x20 m and accuracy better than 2 m in elevation is achieved by using accurate ground control points on and around the ice caps. The elevation on Langjökull 1997 and 2007 is known from GPS-measurements in several points (mass balance stakes) and profiles. On Mýrdalsjökull annual elevation changes have been monitored since 1999 from airborne radar altimetry along several profiles across the ice cap. The SPOT5 derived DEMs accurately describe the spatial variability and the *in-situ* elevation data changes with time.

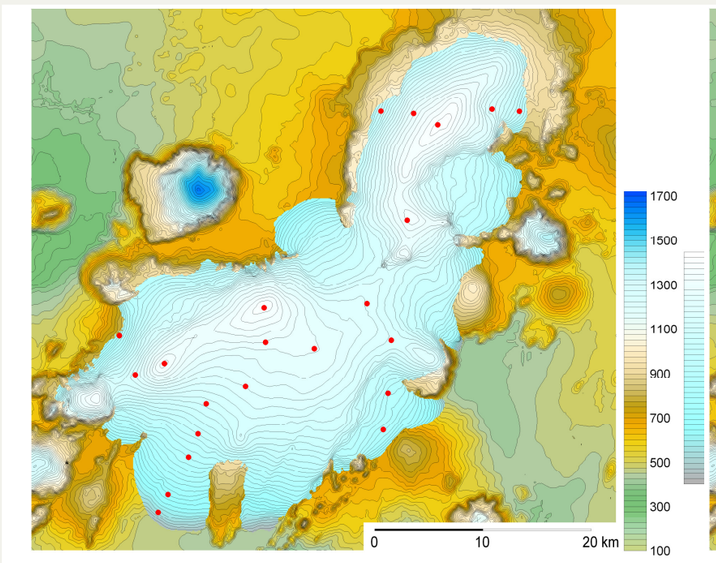
We apply Markov random field regularization and simulated annealing optimization to efficiently produce maps of elevation changes. On Langjökull, comparison of DEMs 1997 to 2004 give a volume loss of 11.5 km^3 w.eq. which is close to the 11.8 ± 1 km^3 w.eq. obtained from independent annual mass balance observations. The mean specific mass balance over the period 1997 to 2007 is -1.3 m/a. The annual net mass balance of Mýrdalsjökull is estimated from the maps of elevation changes. The mean specific mass balance over the period 1999 to 2006 is -1 m/a, but on this most maritime glacier in Iceland annual variations are found to be considerable.

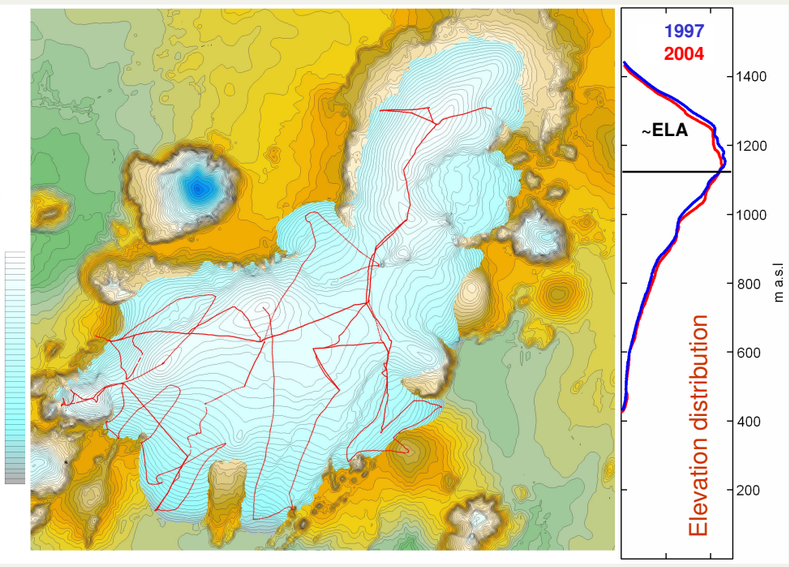
2. Location

Glaciers cover 11% of Iceland. Red boxes: Langjökull and Mýrdalsjökull ice caps

3. Data

Langjökull ice cap (920 km^2)





DEM in May 1997

- **Using DGPS profiles**: along profiles less than 1 km apart
- **Accuracy**: ~1 m

Red dots: locations of mass balance and DGPS observations

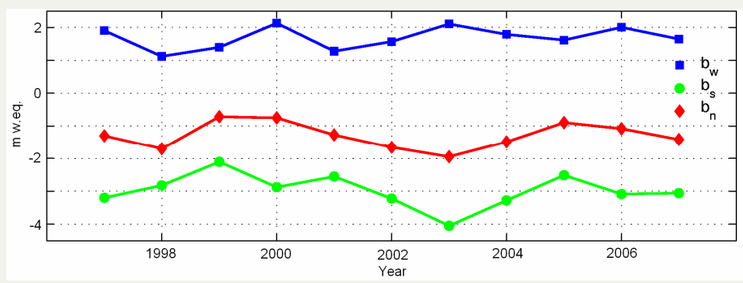
- Winter and summer balance have been observed every year since 1997

DEM in August 2004

- **Using 3 stereo image pairs from the SPOT5 HRG sensors**
- Using good ground control points (GCP)
- Noise and error reduced
- **Accuracy**: 1-2 m, compared to GPS observations at locations of mass balance stakes

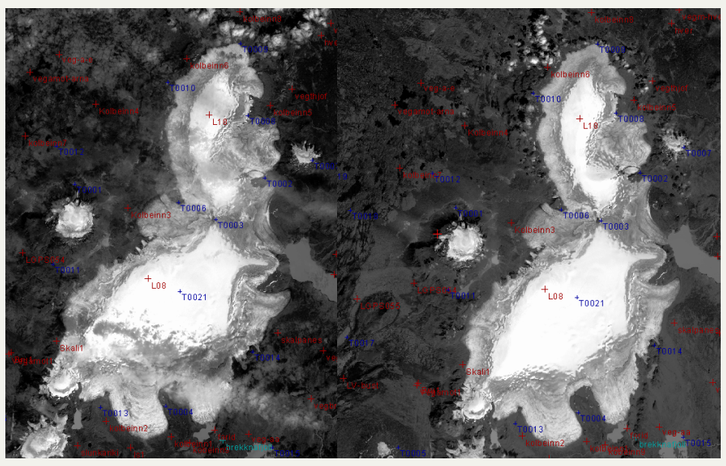
Red lines: kinematic GPS elevation profiles in May 2007

- **Accuracy**: relative error within 0.5 m



Specific mass balance of Langjökull

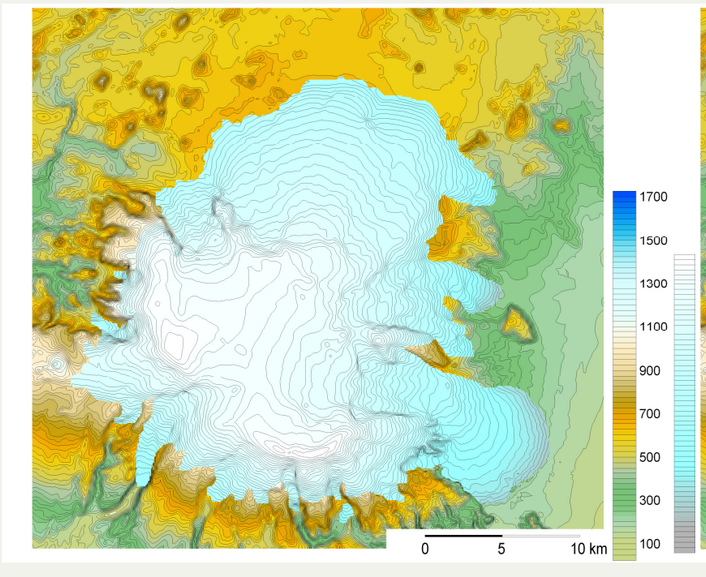
- Winter- (b_w), summer- (b_s) and annual net balance ($b_n = b_w + b_s$)

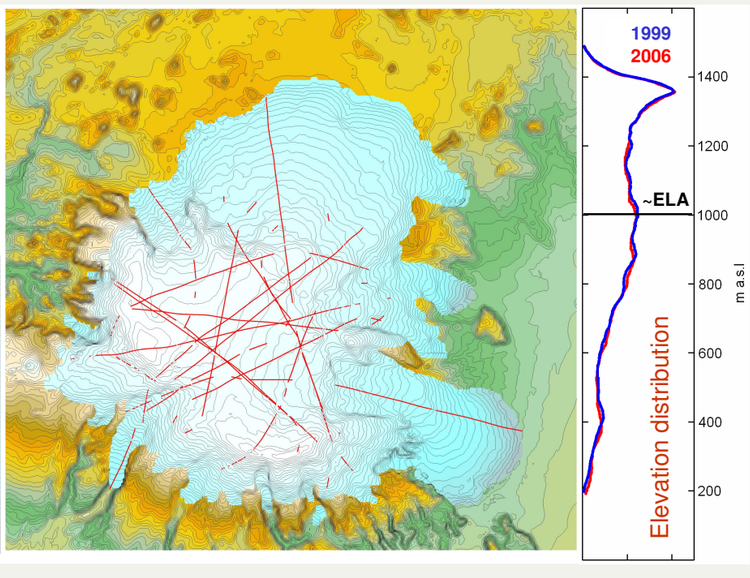


SPOT5 stereo image pair (17 and 19 August 2004)

- Spatial resolution: 2.5 m
- Red: ground control points (GCP) and blue: tie points (TP)
- Incident angular difference: 30°

Mýrdalsjökull ice cap (570 km^2)





DEM in August/September 1999

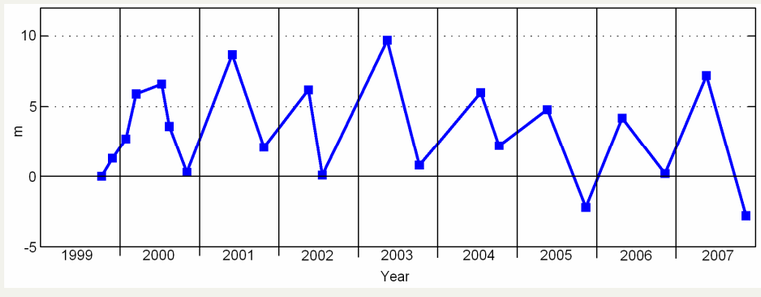
- **Using aireal photographs** (below 1200 m) **and dense profiles from GPS and airborne radar altimetry** (above 1200 m)
- Noise and error reduced
- **Accuracy**: 1-2 m

DEM in August/September 2006

- **Using 2 stereo image pairs from the SPOT5 HRG sensors**
- Using good GCP
- Noise and error reduced
- **Accuracy**: 1-2 m

Red lines: airborne radar altimetry

- **Accumulation areas**: observed in May and September to November each year since October 1999
- **Ablation areas**: observed in September-November each year since 2004
- **Accuracy**: relative error within 1 m



Average elevation changes of the accumulation area of Mýrdalsjökull, since 1999

- Obtained by interpolating dense airborne radar altimetry profiles
- **Winter accumulation of 6 to 12 m of snow has been observed on the highest parts** - significantly higher than the maximum 6 m of snow observed on Langjökull

4. Method

Constraints to minimize

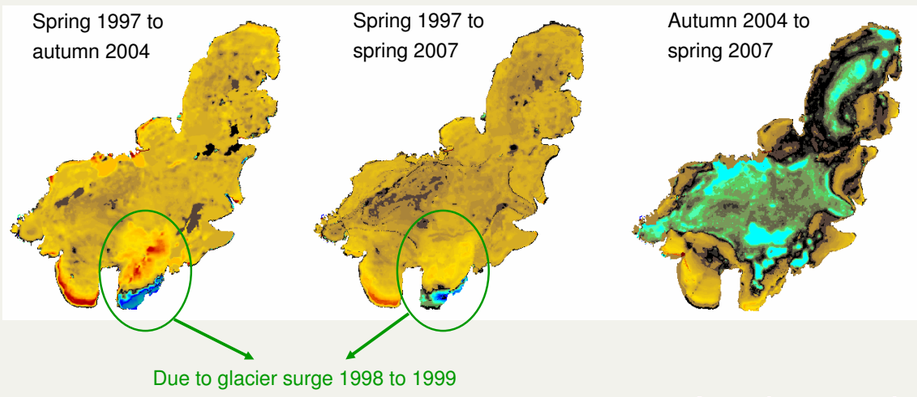
Relation to the surface elevation profiles:

1. $(\Delta z_{12} - \Delta z_{i12})^2$	Strong at and close to location of profiles, weak otherwise
2. $(\Delta z_{23} - \Delta z_{i23})^2$	Strong at and close to location of profiles, weak otherwise
Relation to the elevation maps :	
3. $(\Delta z_{12} + \Delta z_{23} - \Delta z_{13})^2$	Strong
4. $((\Delta z_{12})'' - (t_1-t_2)/(t_1-t_3)\cdot(\Delta z_{13})'')^2$	Moderate if $(t_1-t_2) \approx (t_1-t_3)$, weak otherwise
5. $((\Delta z_{23})'' - (t_2-t_3)/(t_1-t_3)\cdot(\Delta z_{13})'')^2$	Moderate if $(t_2-t_3) \approx (t_1-t_3)$, weak otherwise
6. $(\Delta z_{12} - (t_1-t_2)/(t_1-t_3)\cdot\Delta z_{13})^2$	Weak if $(t_1-t_2) \approx (t_1-t_3)$, 0 otherwise
7. $(\Delta z_{23} - (t_2-t_3)/(t_1-t_3)\cdot\Delta z_{13})^2$	Weak if $(t_2-t_3) \approx (t_1-t_3)$, 0 otherwise
Smoothness constraints:	
8. $((\Delta z_{12})'' - 0)^2$	Moderate
9. $((\Delta z_{23})'' - 0)^2$	Moderate

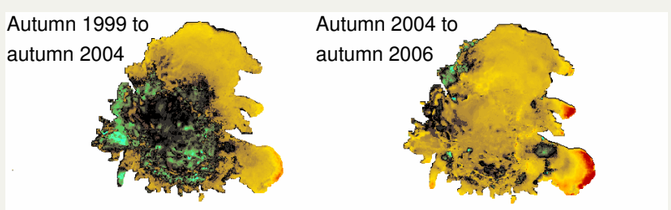
Markov random field model is used to regularize the construction of Δz_{12} and Δz_{23}. The regularization is optimised with simulated annealing (e.g. S. Gudmundsson *et al.*, 2002)

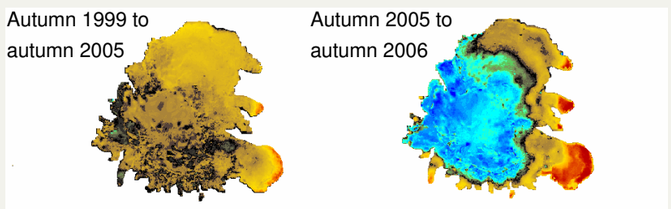
5. Maps of elevation changes

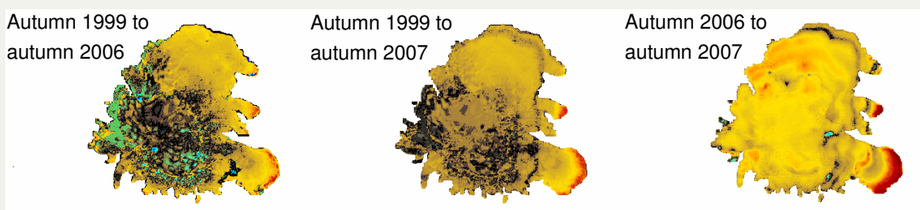
Langjökull ice cap



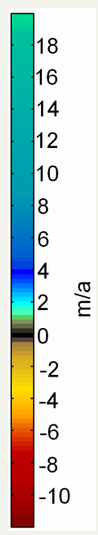
Mýrdalsjökull ice cap







Annual average elevation changes in m/a



Warm colors:
- **Decreased elevation**

Cold colors:
- **Increased elevation**

The same colorbar applies to all the images

6. Estimated volume changes

Comparison of volume loss on Langjökull, deduced from 1) maps of elevation changes (Δz) and 2) mass balance field observations

- Water equivalent of the Δz maps are calculated by assuming density of ice (900 kg m^{-3}) for the whole glacier
- Inaccurate assumption when calculating volume loss over only 3 years

Langjökull	Spring 1997 to autumn 2004 (km^3 w.eq.)	Spring 1997 to spring 2007 (km^3 w.eq.)	Autumn 2004 to spring 2007 (km^3 w.eq.)
1) Δz maps	11.5	12.1	-0.3
2) Annual mass balance observations	11.8	12.0	0.3

Comparison of long term annual mass balance (b_n), deduced from 1) Δz maps on Mýrdalsjökull and 2) mass balance field observations on Langjökull

- Water equivalent is calculated by using density of ice (900 kg m^{-3})
- 25% lower mass balance is observed on Mýrdalsjökull than Langjökull

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
2) Langjökull; annual mass balance observations	-1.30	-1.33	-1.31

Maps of elevation changes to estimate annual mass balance on Mýrdalsjökull

- Knowledge of mass density distribution, vertical velocity and snow compaction is essential – not available
- We use density of ice (900 kg m^{-3}) in the ablation areas and (600 kg m^{-3}) in the accumulation area (rough assumption)
- By using long term summer balance observations at 1200-1400 m on the nearby Vatnajökull ice cap and 4 to 6 m w.eq. accumulation that has been observed on Mýrdalsjökull, we estimate the vertical velocity to be >2 m/a at in the central accumulation areas of Mýrdalsjökull
- The snow compaction is roughly estimated as ~0.5 m/a

Preliminary results indicate high annual variations in mass balance on the coastal Mýrdalsjökull

7. Concluding remarks

Mapping volume changes:

- Maps of elevation changes, derived by SPOT5, airborne altimetry and GPS field observations, are useful tools for estimating glacier volume change over period of some years
- Volume change, derived from DEMs over 8 years on Langjökull are in good agreement with annual mass balance observations
- Annual mass balance could not be accurately estimated from the maps of elevation changes
  - Further information is needed to estimate the mass density distribution, vertical velocity and snow compaction
- The method will be further investigated and errors evaluated

Mass balance and volume changes:

- 25% lower mass balance deficit is observed on Mýrdalsjökull than Langjökull
- Annual variations of the mass balance on Mýrdalsjökull, the most maritime glacier in Iceland, seem to be considerable

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