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 August 2004
- Using 5 stereo image pairs from the SPOT5 HRG sensors
- Noise and error reduced
- Accuracy: 1-2 m

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 ($b_n = b_w + b_s$)

Myrdalsjökull ice cap (570 km$^2$)

DEM in August/September 1999
- Using aerial photographs (below 1200 m) and dense profiles from GPS and airborne radar altimetry (above 1200 m)
- Noise and error reduced
- Accuracy: 1-3 m

DEM in August/September 2006
- Using 2 stereo image pairs from the SPOT5 HRG sensors
- 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
- Observed by integrating 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

5. Maps of elevation changes

6. Estimated volume changes

7. Concluding remarks

**Observations:**
- Elevation maps of year \( t_1 \) (DEM1) and \( t_2 \) (DEM2)

**Elevation changes**
- Surface elevation profiles of year \( t_2 \) \((z_{t2})\)

**At all pixels:**
- \( \Delta z_{12} = DEM_{t1} - DEM_{t2} \)

**At location of profiles:**
- \( \Delta z_{12} = DEM_{t1} - z_{t2} \)
- \( \Delta z_{13} = DEM_{t1} - DEM_{t3} \)
- \( \Delta z_{23} = DEM_{t2} - DEM_{t3} \)

**Data fusion:**
- Markov random field regularization and simulated annealing optimization

**Optimized:**
- \( \Delta z_{12} = DEM_{t1} - DEM_{t2} \)
- \( \Delta z_{13} = DEM_{t1} - DEM_{t3} \)
- \( \Delta z_{23} = DEM_{t2} - DEM_{t3} \)

**Maps of elevation changes**
- Constraints to minimize:
  - Relation to the surface elevation profiles:
    - \( \Delta z_{12} \) and \( \Delta z_{13} \) at strong elevation changes
    - \( \Delta z_{12} \) and \( \Delta z_{13} \) at weak elevation changes
  - Relation to the elevation maps:
    - \( \Delta z_{12} \) and \( \Delta z_{13} \) at strong elevation changes
    - \( \Delta z_{12} \) and \( \Delta z_{13} \) at weak elevation changes

**Warm colors:**
- Decreased elevation

**Cold colors:**
- Increased elevation

**The same colorbar applies to all the images**

**Comparison of volume loss on Langjökull, deduced from 1) maps of elevation changes (\( \Delta z \)) and 2) mass balance field observations on Langjökull:**
- Water equivalent of the \( \Delta z \) maps is calculated by assuming density of ice (900 kg m\(^{-3}\)) for the whole glacier
- Inaccurate assumption when calculating volume loss over 3 years

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<tbody>
<tr>
<td>1) ( \Delta z ) maps</td>
<td>11.5</td>
<td>12.1</td>
<td>-0.3</td>
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<td>2) Annual mass balance observations</td>
<td>11.8</td>
<td>12.0</td>
<td>0.3</td>
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**Comparison of long term annual mass balance \( b_{a1} \), deduced from 1) \( \Delta z \) 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

**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 (800 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 0.2 m a\(^{-1}\) in the central accumulation areas of Mýrdalsjökull
- The snow compaction is roughly estimated as -0.5 m a\(^{-1}\)

**Reference**
- Björnsson H., Palsson F. and Gudmundsson M.T. Surface and bedrock topography of the Myrdalsjökull ice cap, Iceland: The Katla caldera eruption site and routes of jökulhlaups.

**Acknowledgement**
- We acknowledge the support of the National Power Company of Iceland, the Public Roads Administration, The Research-Found of Iceland (Rannís), and the University Research Fund. SPOT images were made available by the two OASIS (Optimizing Access to Spot Infrastructure for Science) projects number 36 and 94.