Evaluating the Austre Lovén and its bedrock topography using Ground Penetrating Radar and differential GPS measurements.

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September 21, 2010

Intoduction

Objective [1]: estimate the mass balance and area of a polar glacier exhibiting typical average thickness variations of a few tens of centimeters/year

1. classically, a few stakes measurements/year at best, with coarse spatial accuracy
2. complement with fine spatial accuracy using historical Digital Elevation Models (DEM) ?

⇒ what is the resolution of DEMs when used for estimating mass balance ?

"... an absolute requirement of using glacier maps is that they are of a very high accuracy. Otherwise it is a doubtful task to try to determine volume changes over periods of 10-12 years.",

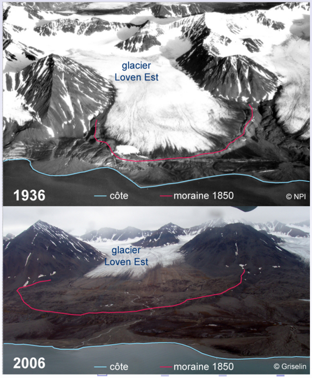
N. Haakensen, Annals of Glaciology **8** (1986)

[1] sequel to the presentation given by Griselin *& al* at 10th International Circumpolar Remote Sensing Symposium, Whitehorse, Canada (2008)

Relationship between area and volume

1. Air temperature might appear as the most obvious (most commonly available) climate index.
2. The delay between area and volume changes has been estimated to 31 years for the neighbour Middre Lovénbreen (S. Hansen, Master Thesis, 1999)

- How to relate these measurements with actual glacier mass balance ?
- compare historical temperature records with historical DEMs (1965-2010)
- All discussion will focus on thickness (altitude) measurements rather than water equivalent thicknesses.
- Application to Austre Lovenbreen, 79°N, Svalbard (selected for its hydrological properties)



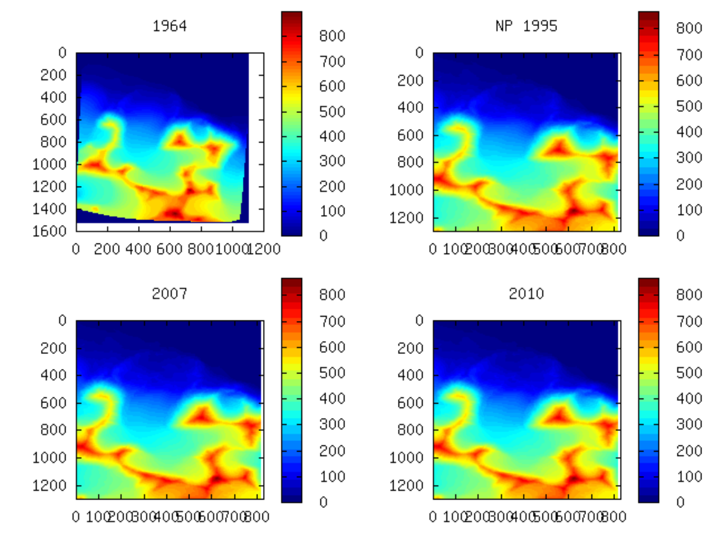
Available data: DEMs from 1965 to 2010

DEMs are generated from a **wide variety of sources**

1. 1/25000 **map** traced by the German scientists between 1962 and 1965 in the framework of the "Deutschen Spitzbergen-Expeditionen 1962-1965 des Nationalkomitees für Geodäsie und Geophysik der DDR".
2. 1995 from the Norsk Polarinstitutt was derived from six stereo-overlapping **aerial photographs** taken in August 1995 (Rippin et al., 2003).
3. **airborne LiDAR** data from the Scott Polar Institute Cambridge (Rees, 2003, 2005) [2] working on the Middre Lovénbreen (15 cm vertical accuracy).
4. 2007 SPIRIT (CNES) dataset was obtained from stereography of couples of September 2007 **SPOT satellite** HRS images (high stereoscopic resolution)
5. skidoo tracked **(D)GPS** in 2007 and 2010 over glacier surface only

[2]
- Arnold, N.S., Rees, W.G., Devereaux, B.J. and Amable, G. 2006. Evaluating the potential of high-resolution airborne LiDAR in glaciology. International Journal of Remote Sensing **27** (5-6), 1233-1251.
- Rees, W.G. and Arnold, N.S. (2007) Mass balance and dynamics of a valley glacier measured by high-resolution LiDAR. Polar Record **43** 311-319

DEM source comparison



X-Y: 5 m/pixel interpolation of all DEMs

DEM source comparison

Comparison of a few static refence points on historical DEMs:

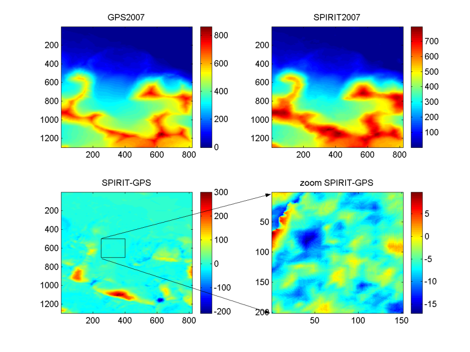
DEM	moraine1	moraine2	moraine3	moraine4	bird cliff
map 1964	67	111	35	111	21
LiDAR 2005	61	121	30	87	24
NPI 1995	62	116	33	86	21
SPIRIT 2007	54	121	34	129	29
max-min	13	10	5	43	8

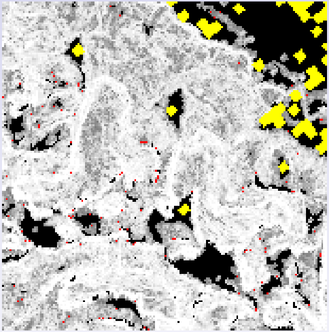
→ Offset is not constant

We complement these data with skidoo-tracked GPS units (C/A in 2007, phase corrected in 2010 – Trimble Geo XH)

DEM source comparison (2)

Within a year: C/A GPS v.s SPIRIT (stereography of satellite images)

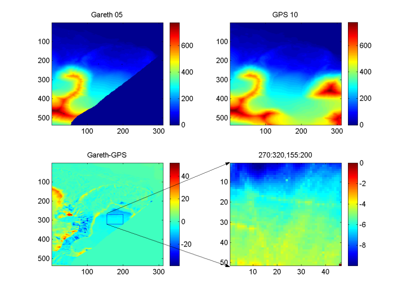


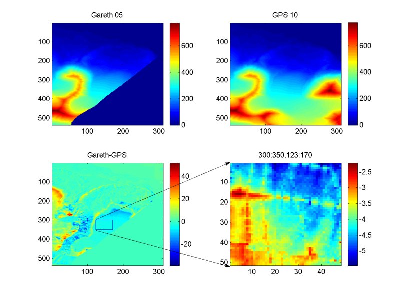


- >15 m differences in the flattest part of the glacier, consistent with C/A GPS elevation errors
- + missing parts due to shadows in the SPIRIT DEM (steep slopes)

DEM source comparison (3)

2010 DGPS - 2005 LiDAR (partial coverage)

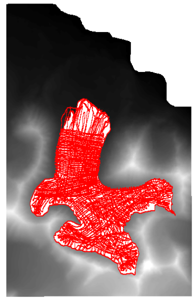


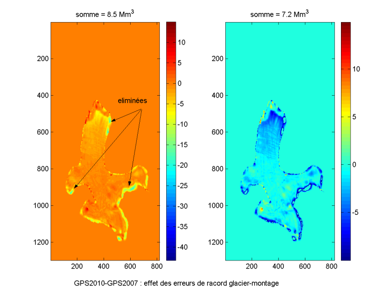


- Most consistent dataset: elevation errors <1 m, remaining error due to environment (snow) or measurement procedure (antenna height)
- We are interested in elevation *differences*: offset might be removed using a constant correction over the whole image based on a few reference points

DEM source comparison

2007-2010 (D)GPS





1. 2010 dataset was RINEX-corrected using the reference station in Ny Ålesund (6 km away)
2. Most significant errors on the borders of the glacier, where the slopes are steepest (cannot be reached by skidoo)
3. depending on the assumption in the circuses and ice-rock junction, volume loss between 2007 and 2010 would be between 8.5 and 7.2 Mm^3 (over a 4.8 km^2 basin: 1.8 to 1.5 m on average)
4. significant altitude loss (-5 to -7 m/3 years) in the glacier front

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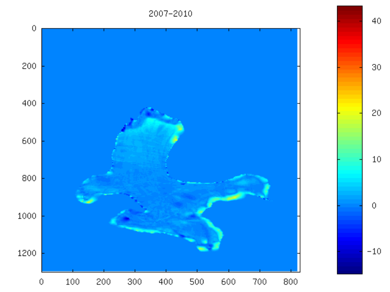

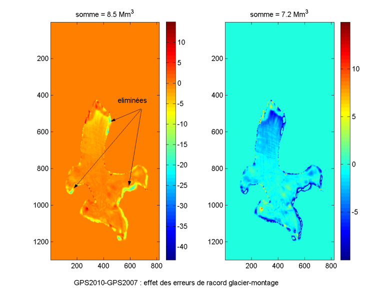

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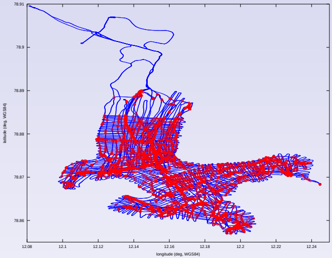
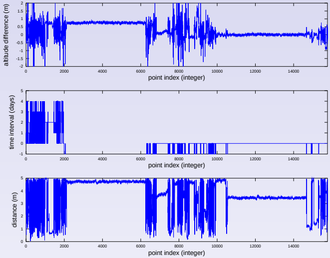
DGPS 2010 analysis

Search all neighbours within 5 m of each point: what is the elevation difference ?





Elevation difference standard deviation: ± 50 cm describes $> 66\%$ data $\Rightarrow$ if DGPS altitude error is no longer significant, what other sources of error ?

- bias (altitude of receiving antenna)
- snow height/weight of skidoo

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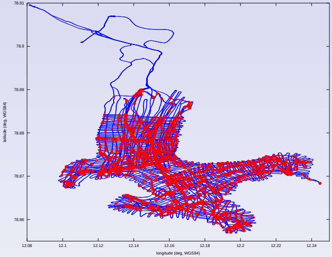

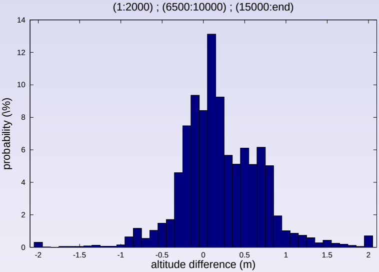

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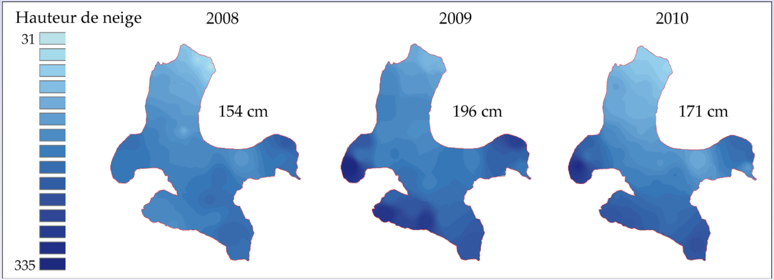
Snow cover influence

Snow cover might be significant, yielding a bias on the height measurements

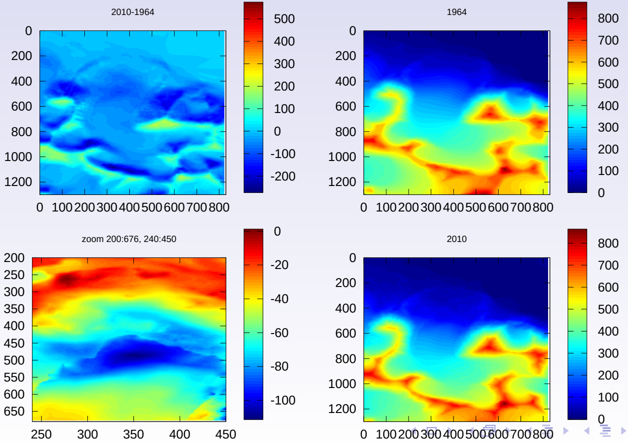


Interpolated snow (drill) thickness from 2008 to 2010

Hardly an issue for airborne measurements (july-august), but april is most favorable for skidoo tracked GPS

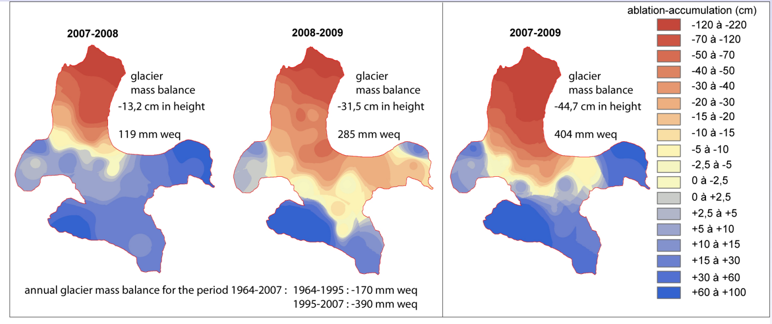
2010-1964

- Focus on the dataset extremes, where measurement errors might be small with respect to ablation
- most significant error still visible on the ice-rock boundaries
- in the flattest part of the glacier, ablation maximum would be -100 m : is this result reasonable ?



Ablation stake results

Comparison of the DEM values with field measurements using ablation stakes + interpollation ($\sim$ cm uncertainty on thickness measurements)

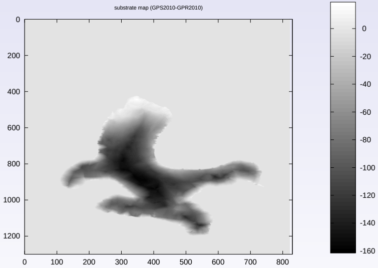


100 m/45 years=2.2 m/year average, consistent with ablation stake measurements at the glacier snout + litterature[3].

[3]N.E. Barrand & *al*, J. Glaciology (2010) **56** (199), 771-780

GPR bedrock mapping

- Purpose: estimate the glacier volume, and relate the ablation to total volume (52000 points collected using 100 MHz antennas)
- Deepest parts of the glacier: 160 m
- Thickness error (100 MHz antenna): 1 wavelength=1.7 m $\Rightarrow$ 1%
- Borders: the glacier is still 15-20 m deep on the steepest slopes $\Rightarrow$ 13% error



The largest ablation value would be at the glacier snout, where the current thickness is -20..-60 m

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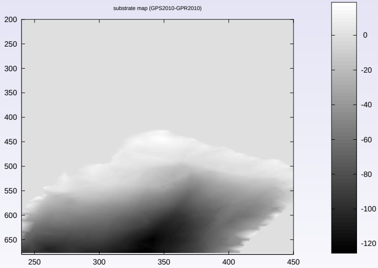

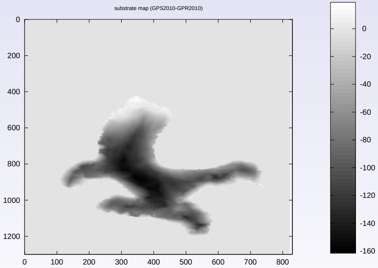

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Glacier evolution

- Strong ablation on most of the glacier, accelerating in the latest years
- Rich information from DEM: which area is accumulating ?

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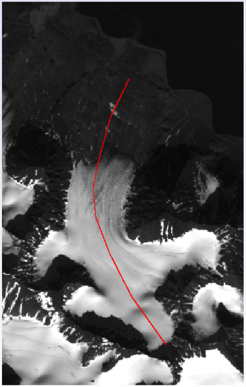

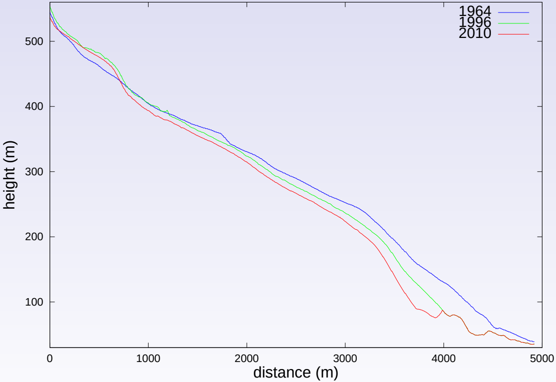

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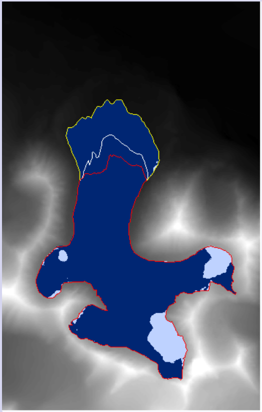
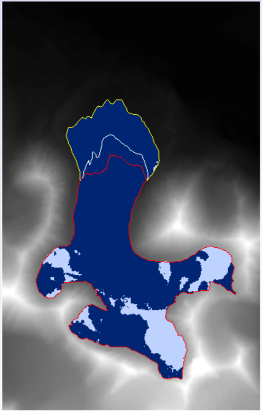
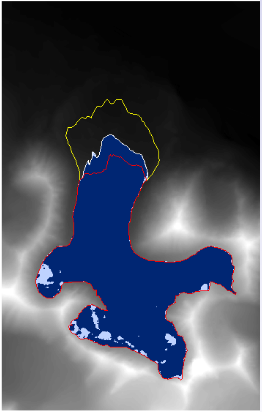


2010-1964
$\Delta h_{64-10} = -43$ cm/a
surf_{64}=5.73 km^2



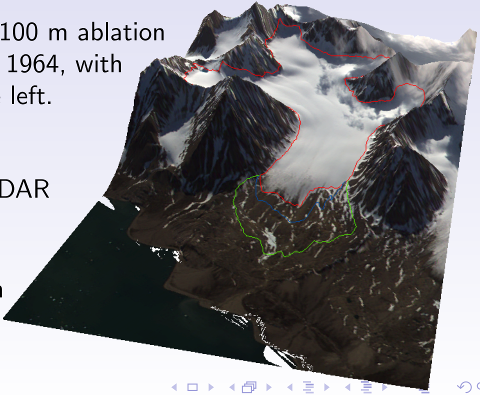
1996-1964
$\Delta h_{64-96} = -35$ cm/a
surf_{64}=4.84 km^2



2010-1996
Δh_{96-10}=-63 cm/a
surf_{64}=4.57 km^2

Conclusion

- Based on more recent measurement technologies (**(D)GPS**), snow balance over 3-years periods is accessible through DEM,
- at an average ablation rate of 63 cm/year, 3 σ DEM elevation error is reached every **3 years** + high **spatial resolution**
- beyond intrinsic height measurement errors (instrument), experimental procedures (antenna height, snow thickness) remain a source of bias,
- from this analysis, up to 100 m ablation in the glacier snout since 1964, with only 20 to 60 m-thick ice left.



Perspectives

ASTER beyond GDEM + RADAR

Acknowledgements:

- Hydro-Sensors-FlOWS French National Research Agency (ANR) funding,
- IPY #16 program,
- IPEV