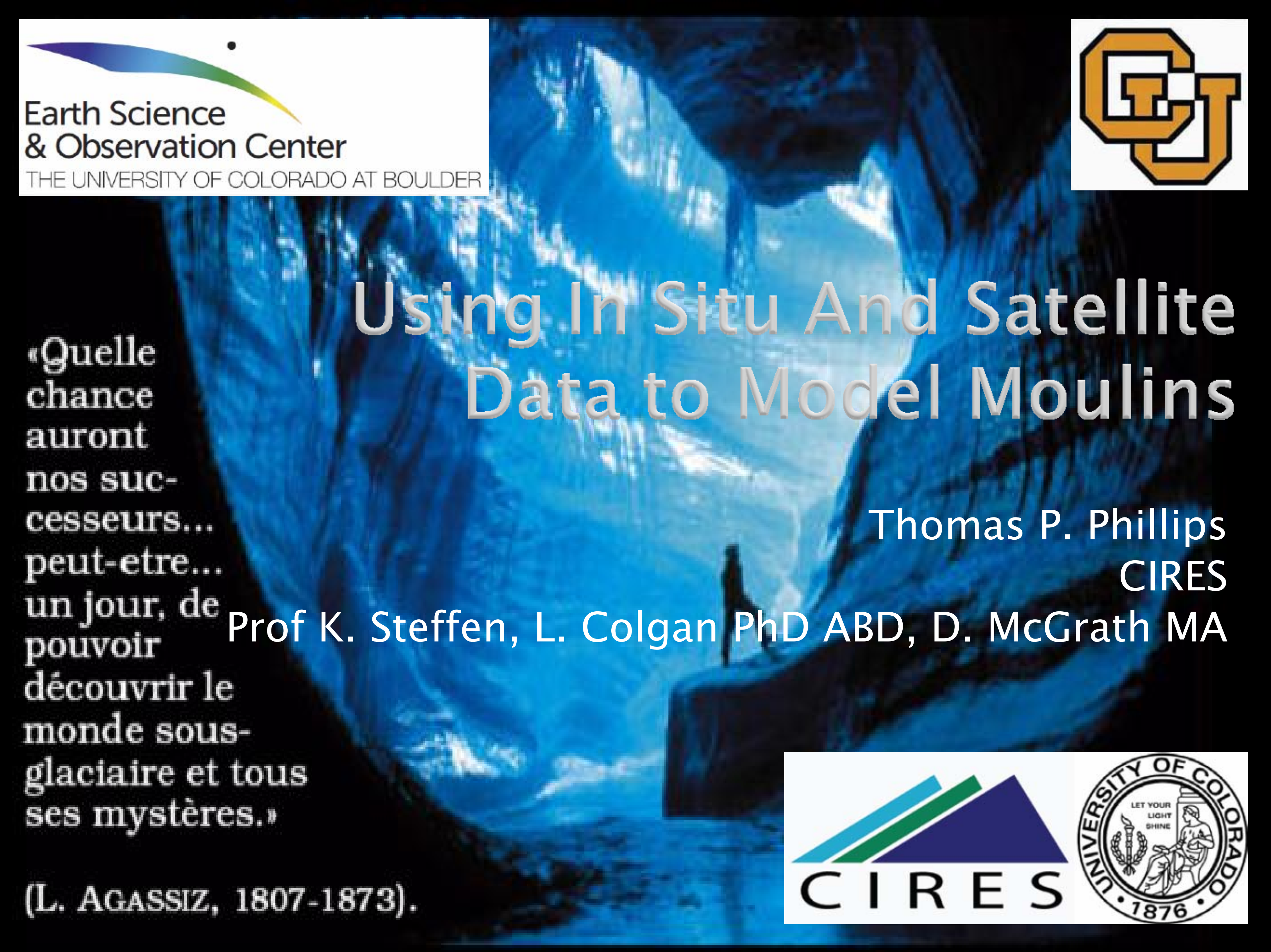

Using In Situ And Satellite Data to Model Moulins

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CIRES
Prof K. Steffen, L. Colgan PhD ABD, D. McGrath MA

«Quelle chance auront nos successeurs... peut-etre... un jour, de pouvoir découvrir le monde sous-glaciaire et tous ses mystères.»

(L. Agassiz, 1807-1873).

Earth Science & Observation Center
THE UNIVERSITY OF COLORADO AT BOULDER

Initial Condition= Initial Problem

- Problem: we know very little about the processes happening within the Greenland Ice Sheet. What is the velocity at the base? What is the temperature profile? Does it lie on bedrock or till? What is the geothermal heat gradient?
- In my case: How could the surface melt influence the ice temperature in the ice sheet
- Solution: We model the en-glacial processes using the physical processes known to us. The surface boundary condition is the only condition we can observe accurately. And even that is not easy due to the climate and the remoteness.
- Problem: We make a number of assumption in order to run the model. We do sensitivity analyses in order to understand the possible offset from reality.

Understanding the Processes...

Satellite (ex situ)

Field data (in situ)
(photo: D. McGrath)

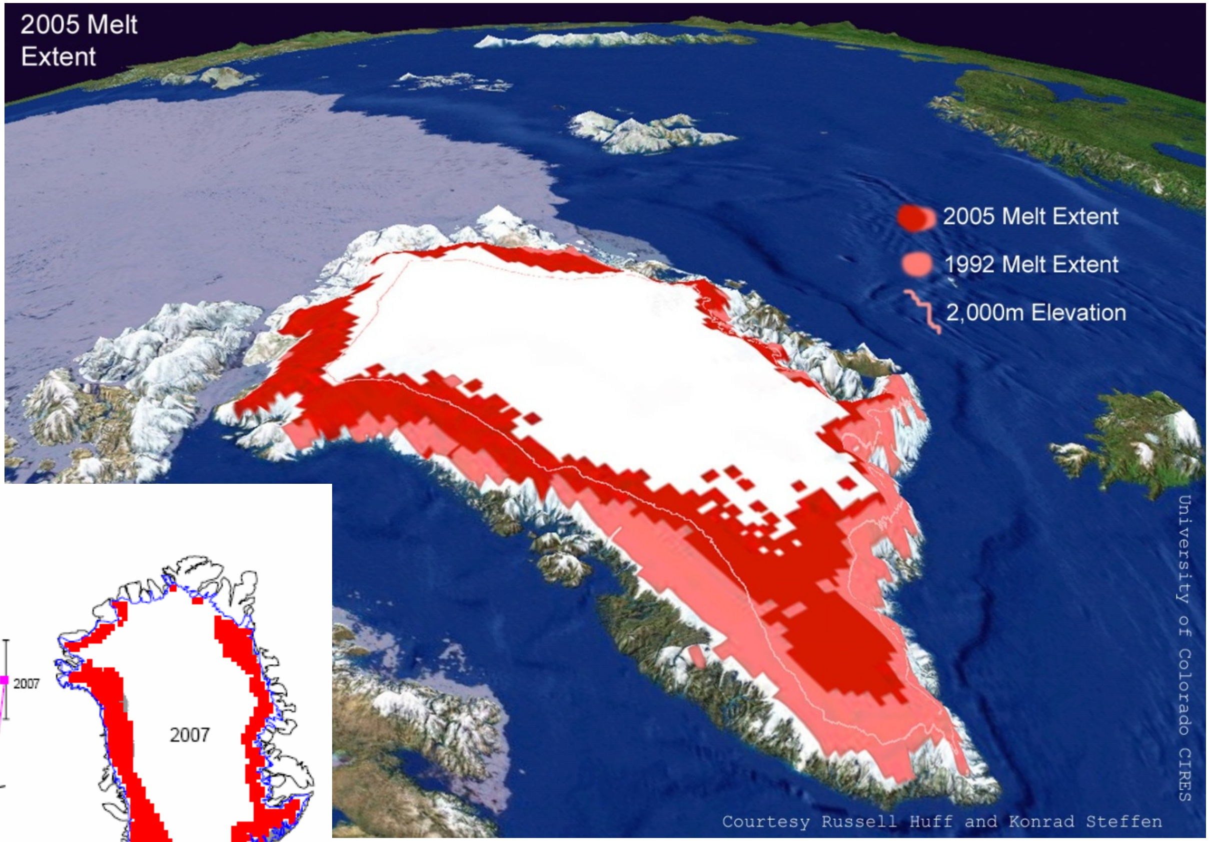
Model to understand the Processes (photo L. Colgan)

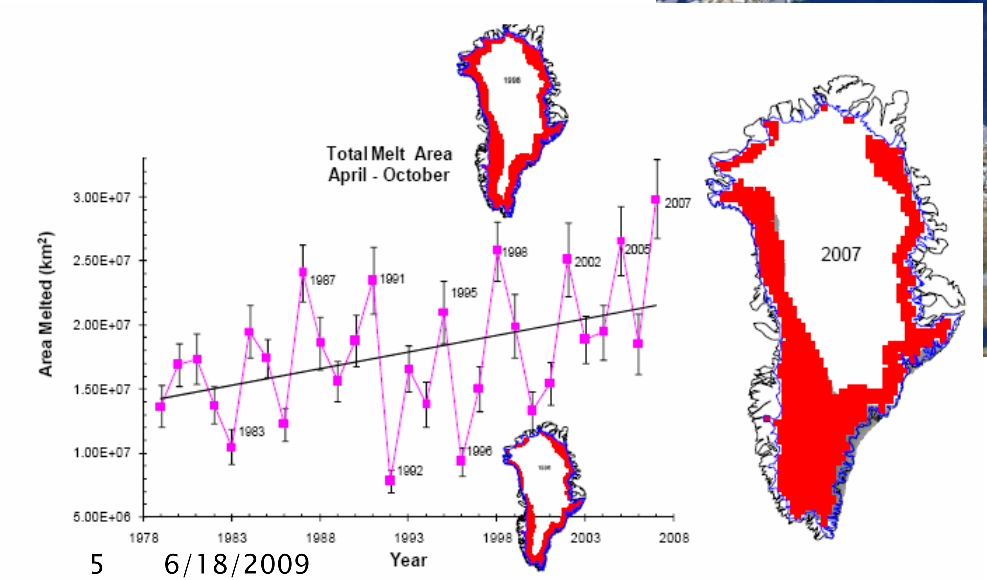
Content of talk

- Climate Change in Greenland
- Using satellite imagery to detect ice melt.
- In situ Automatic Weather Stations (AWS) data is used to calibrate the satellite data and is used as a surface boundary condition for modeling en-glacial processes.
- Moulins: The gateway to the en-glacial water system
- Modeling the impact of the melt water on the englacial temperature

Climate Change in Greenland:

The melt area for Greenland is showing An increasing trend. On average Greenland is currently losing 220 $km^3\ yr^{-1}$ (Hanna et al. Journal of Climate, 2008)



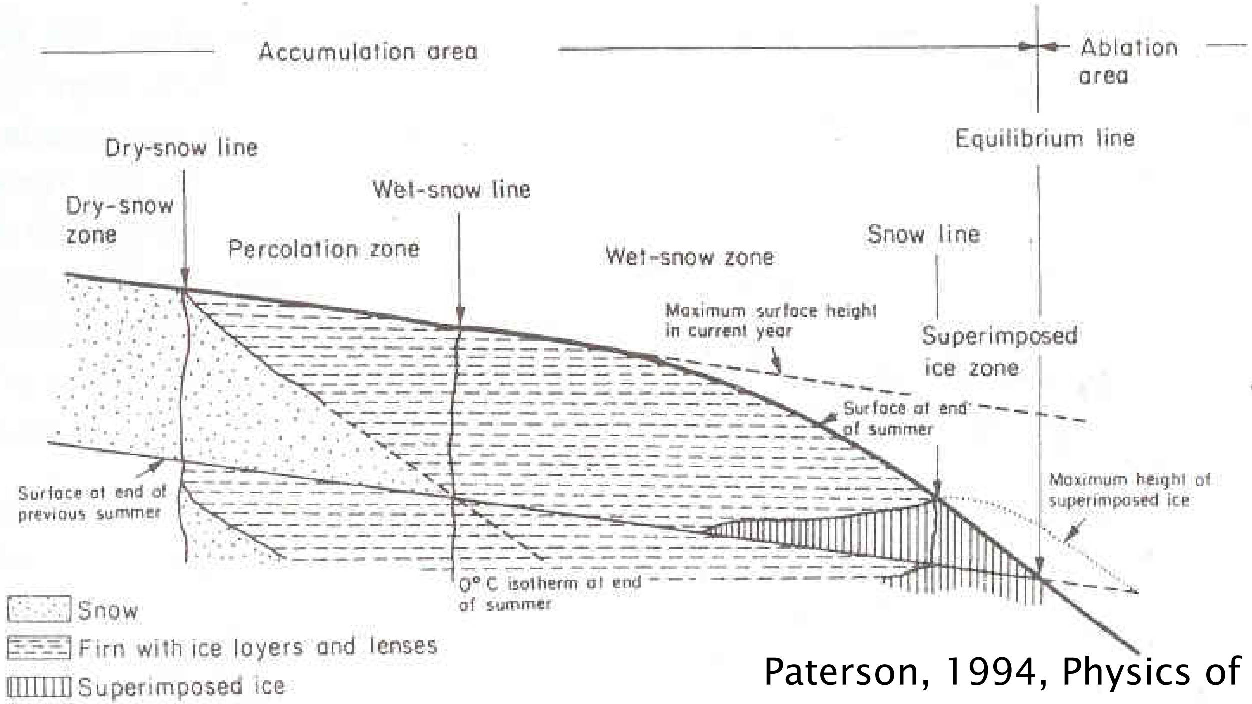


(Steffen et al. 2009, NASA Report)

Monitoring the Climate

- The Greenland Ice Sheet covers 1.7Mio km2.
- Maximum elevation: Summit 3207 m.
- Maximum ice thickness: 3600m.
- Due to its large high elevated plateau it has a large influence on weather patterns in the northern hemisphere.
- The average annual temperature at Summit is -25 Celsius => harsh conditions to maintain a weather network and to collect field data.

Monitoring the climate:

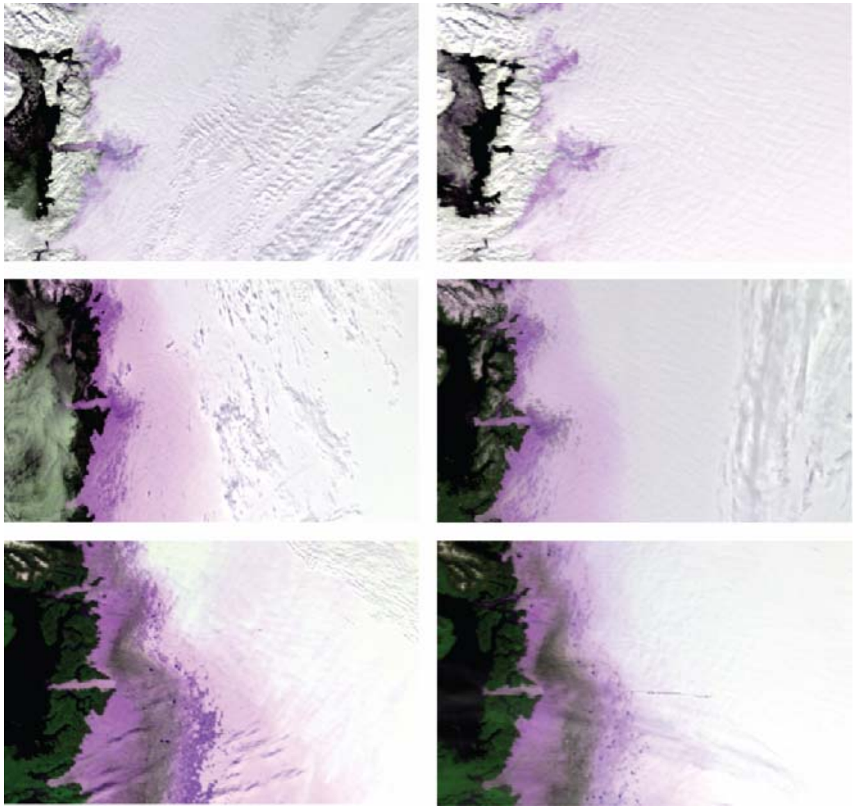


Paterson, 1994, Physics of Glaciology

- The ice sheet is divided into different ice & and snow facies: Ice, wet snow, percolation zone, dry snow.
- There is no water flow in the dry snow zone.
- There is vertical water flow in the percolation zone.
- There is large water displacement in the wet snow zone and on the blank ice.

Satellite imagery to record changes

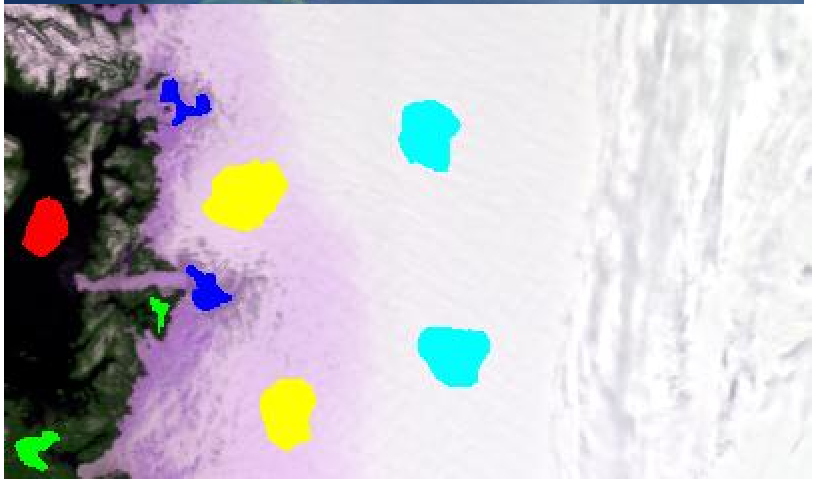
- In a warming climate we see more ice loss than ice gain.
- In a cooling climate the ice sheet grows.
- In a steady climate the mass balance is in equilibrium.
- The ice sheet has a long reacting time to the climate and hence we can see climate trends in the behavior of the ice sheet.
- How does the melt area change? How do ice sheets melt and grow? What is the energy balance?



Left column: April 22nd, June 6th, August 10th 2007
Right column: April 22nd, June 6th, August 10th 2004
Channels 1 (red), 4(green) and 7 (NIR)
Taken from Steffen et al., 2009, NASA Report.

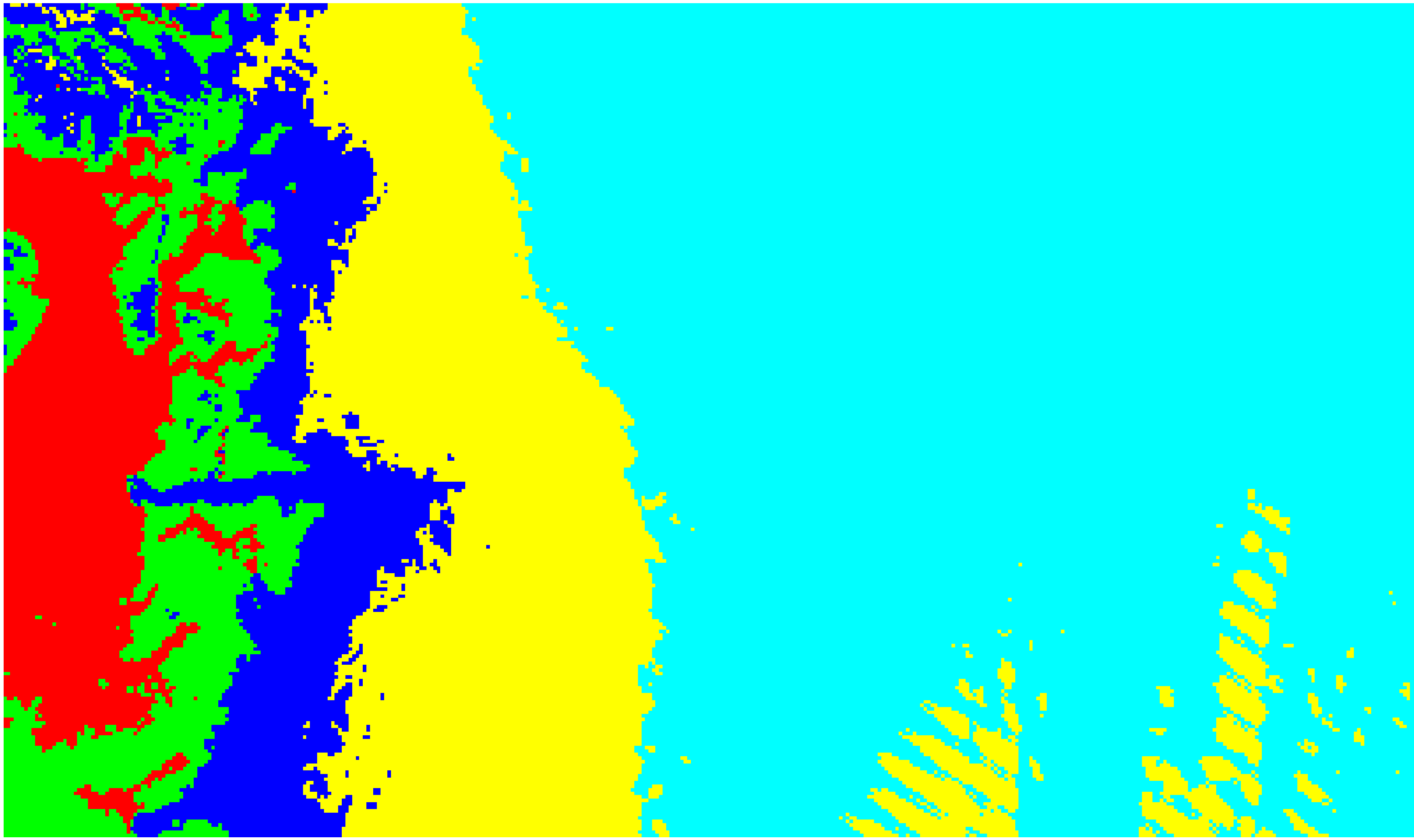
Creating ROIs

- Using a summer image the different facies are statistically analyzed for all 36 channels of MODIS. This is done by creating Regions of interest (ROI) for each of the facies and than looking at the value distribution.
- We create melt extent maps at different times and can compare the state of the surface at different times of the year.
- Automatic Weather station (AWS) data is used to verify melt.



MODIS image June August 10th 2007
Is used to define the ROI.

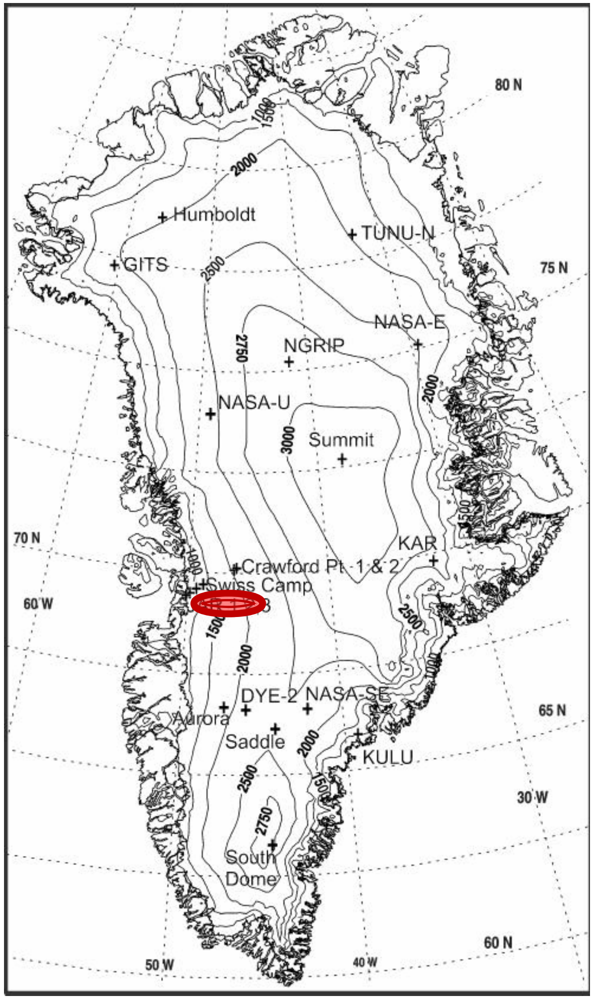
Melt Area



Red=ocean; green=mountains/ vegetation, blue=ice; yellow = wet Snow; cyan = dry snow

Surface Check: AWS GCnet:

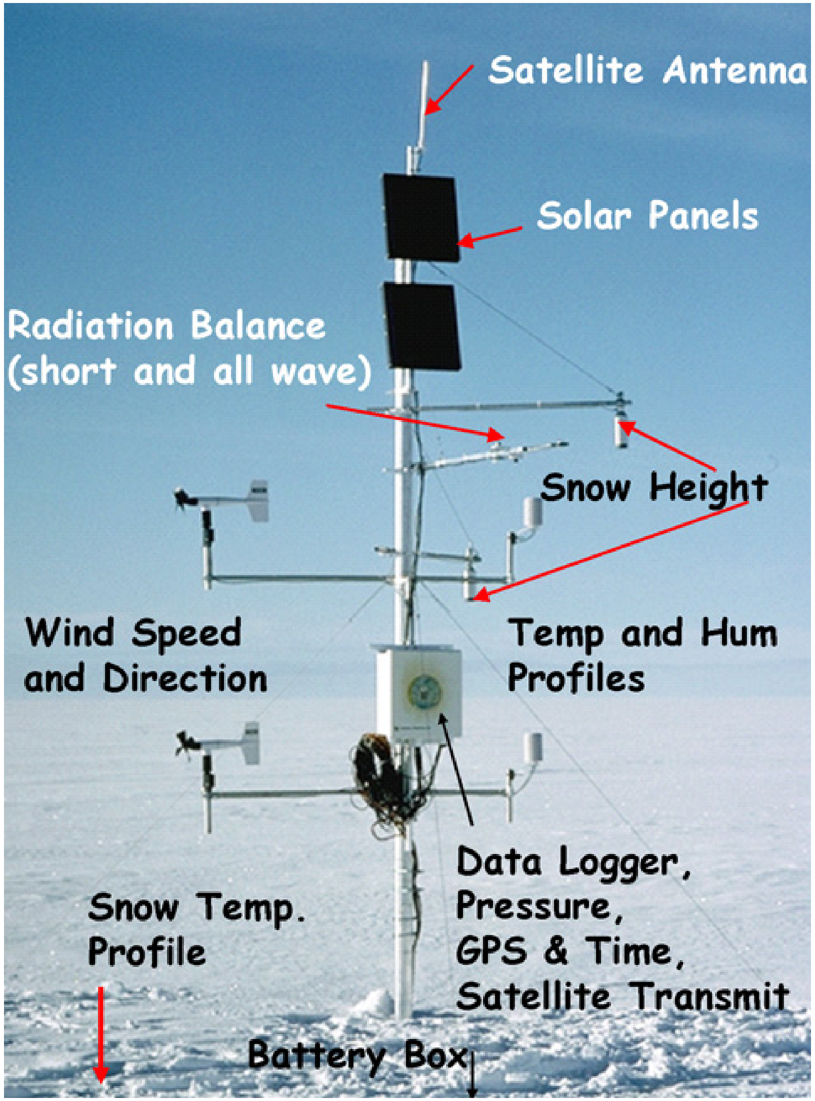
- The GCnet has a total of 22 automatic weather stations distributed over the ice sheet. Currently 16 are activated. 6 have been lost to Weather.
- Period: early 90s-current
- Highest Density of Stations in the Jakobshavn Glacier area in western Greenland.



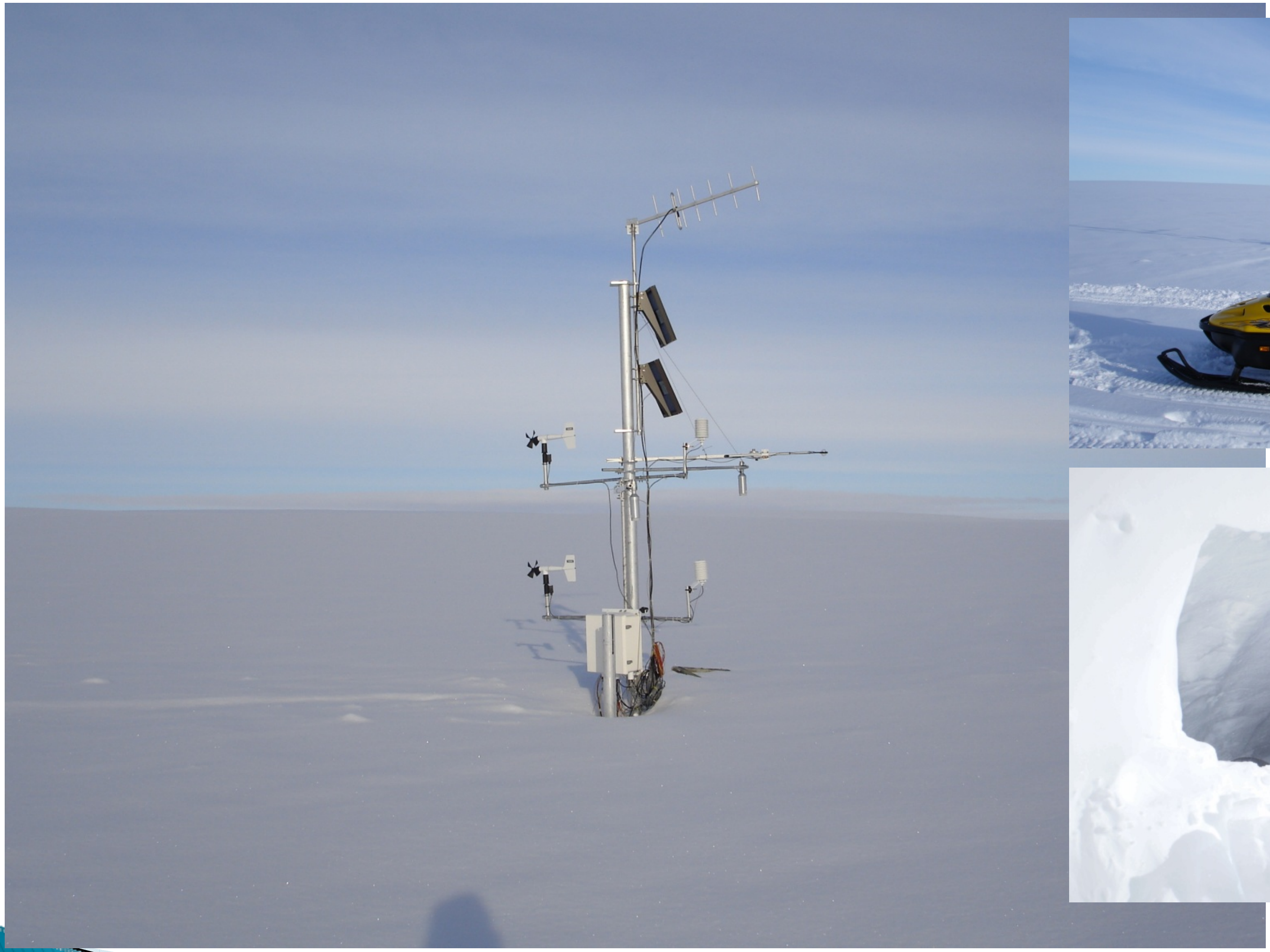
http://cires.colorado.edu/science/groups/steffen/gcnet/

AWS stations:

- Available Data:
- Air temperature
- Snow temperature
- Surface pressure
- Humidity
- Wind direction
- Wind speed
- Snow height
- Radiation
- Ice temperature: 1–10 meters

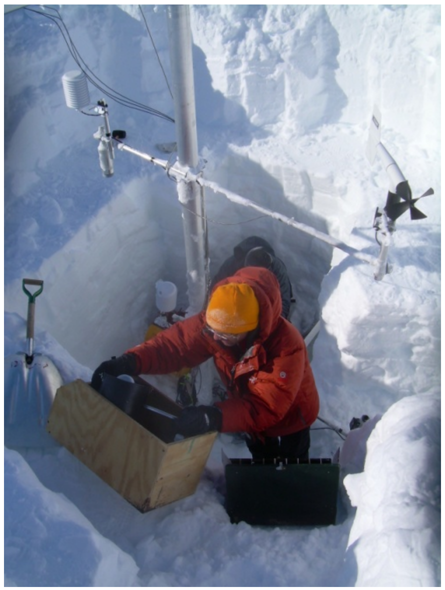


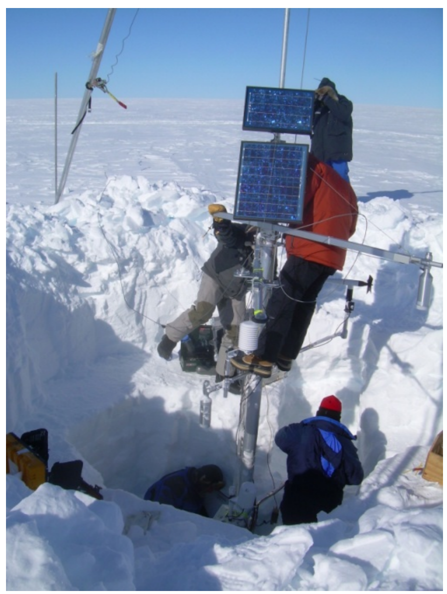
Weather Station: Maintenance



Saddle, 2007.

Working on the station

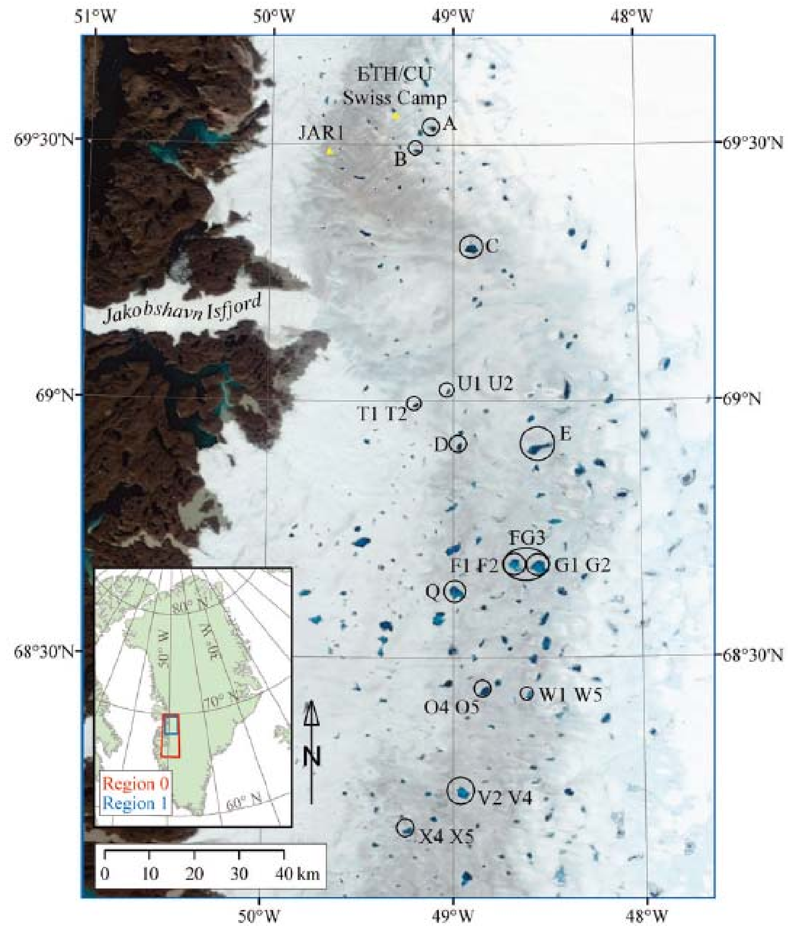




- The stations are visited on average every other year.
- The data logger is checked – the data is downloaded.
- Maintenance work is done including lowering or raising the tower.

Melt in Numbers

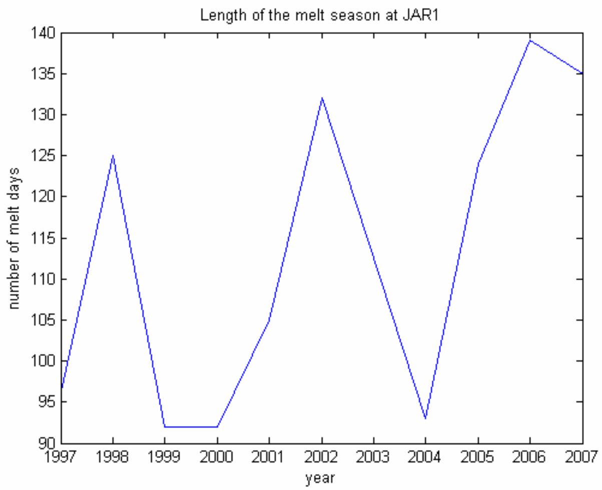
Lake	Tot. Vol.	Av. Dis.	max Dis.
	10^6 m3	m3/s	m3/s
F-G	-97.4	187.8858	1612.114
G2	-31.5	364.5833	756.7098
G1	-23.3	29.96399	618.2865
W5	-20.6	19.86883	569.3146
V4	-22.7	43.78858	607.5732
V2	-23.7	45.71759	625.3781
O4	-20.7	79.86111	571.1647
X5	-6.7	77.5463	268.2448
F2	-13.3	153.9352	424.6605
X4	-13.2	25.46296	422.5186
O5	-9.8	9.45216	346.085
T2	-6.9	13.31019	273.5837
T1	-2.9	3.729424	153.0622

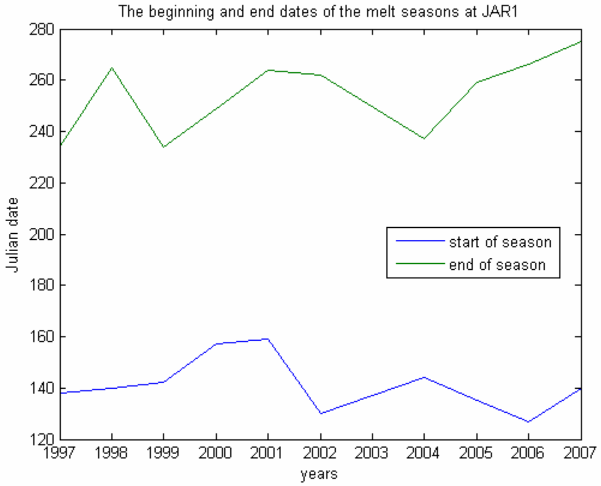


Box et. al, 2008

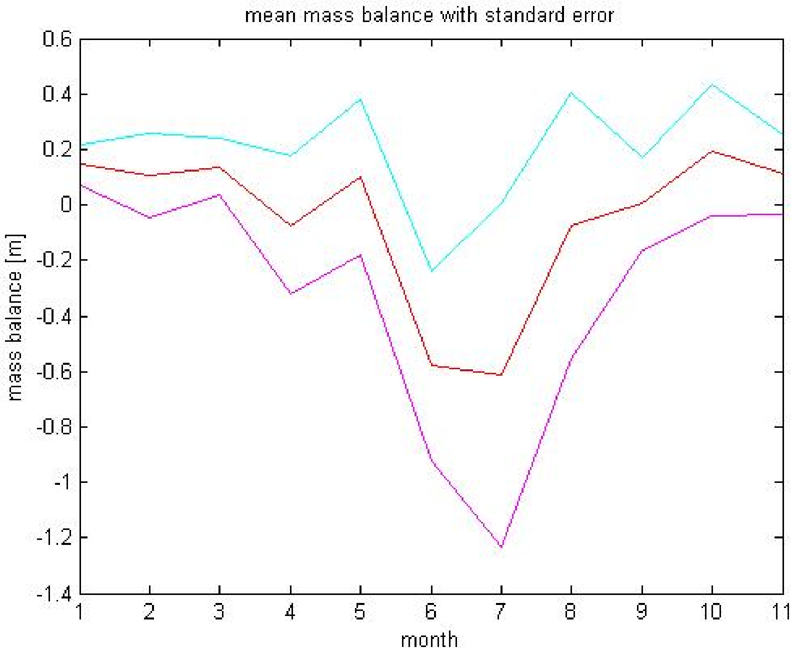
Melt Season at AWS station JAR1

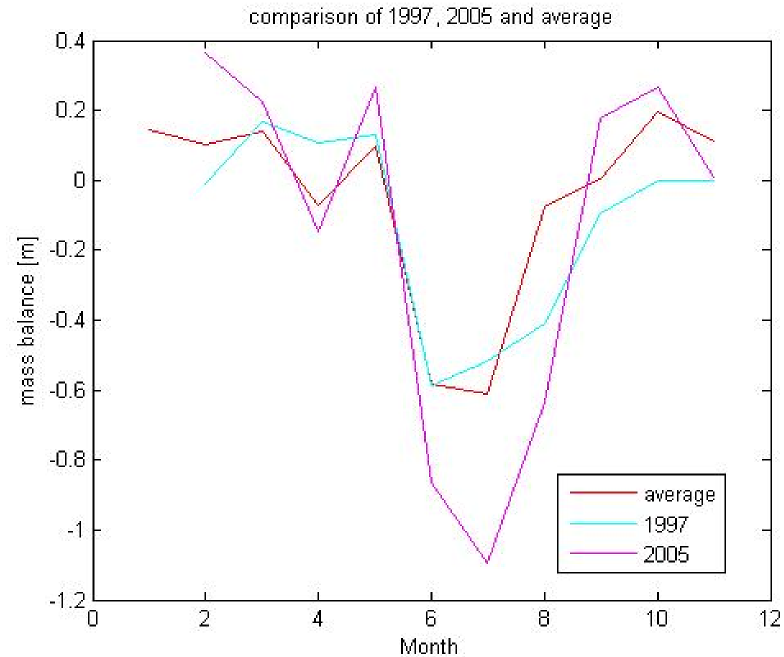
Year	Start	End	days
1996		Sept 12	
1997	May 18	Aug 22	96
1998	May 19	Sept 22	125
1999	May 22	Aug 22	92
2000	June 5	Sept 5	92
2001	June 8	Sept 13	105
2002	May 10	Sept 29	132
2004	May 23	Aug 24	93
2005	May 15	Sept 18	124
2006	May 7	Sept 22	139
2007	May 20	Oct 1	135





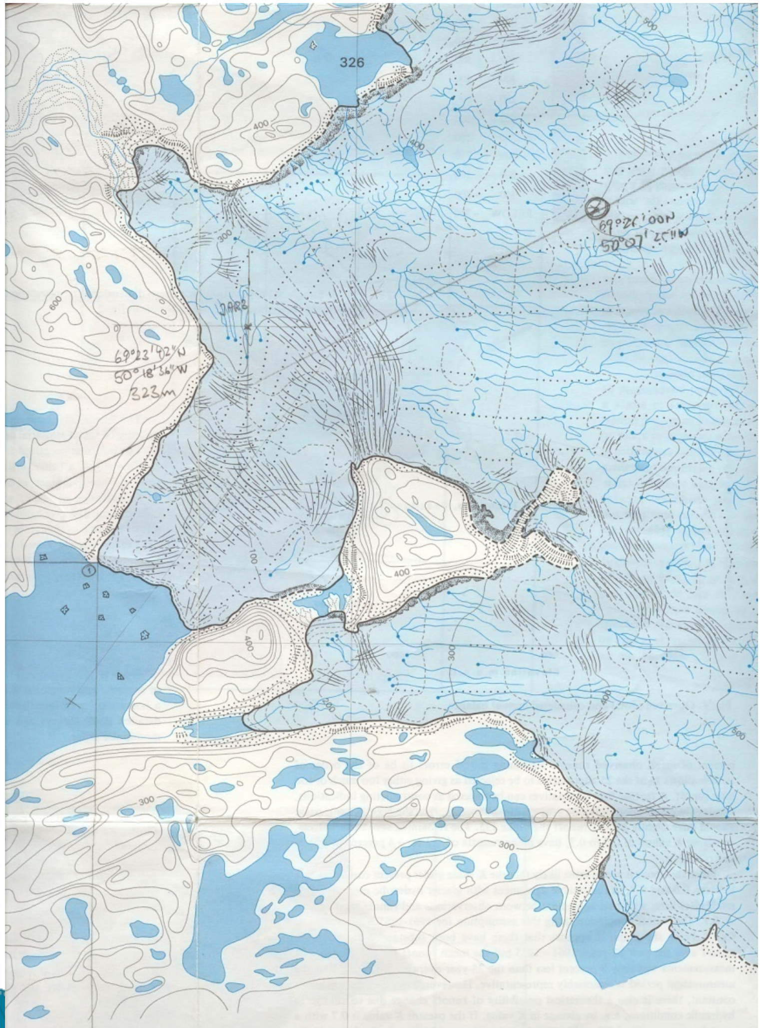
Monthly Variation:

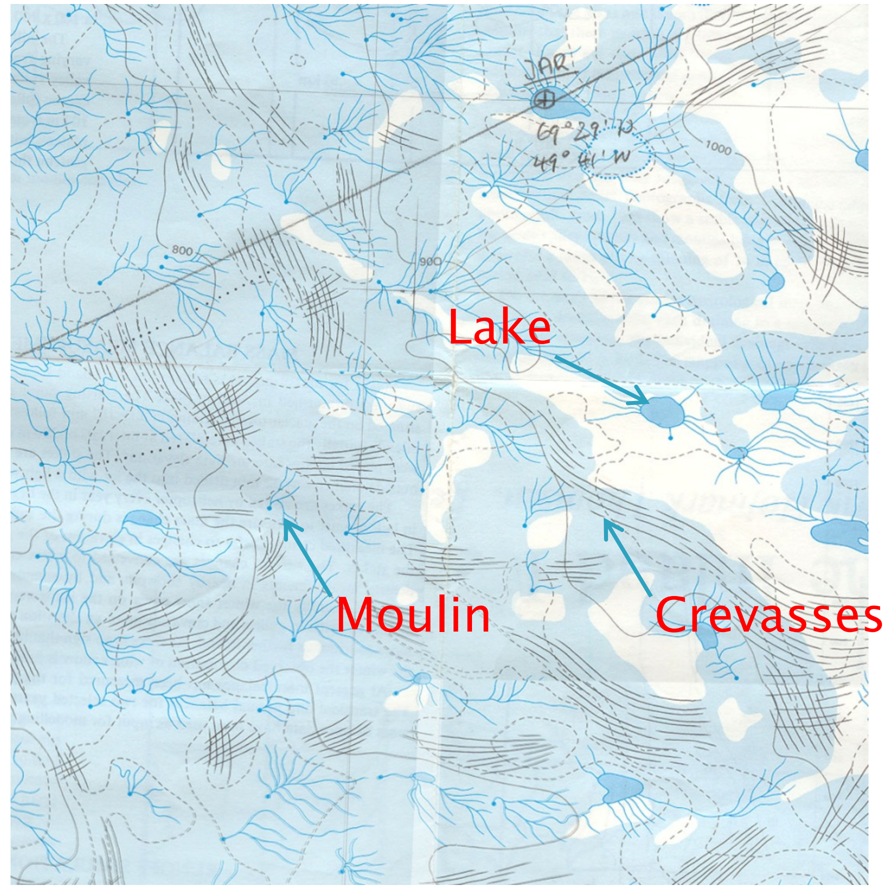




- The variability during the melt season is larger than during the accumulation season
- Strong melt seasons are often followed by above average snowfall during the early accumulation.

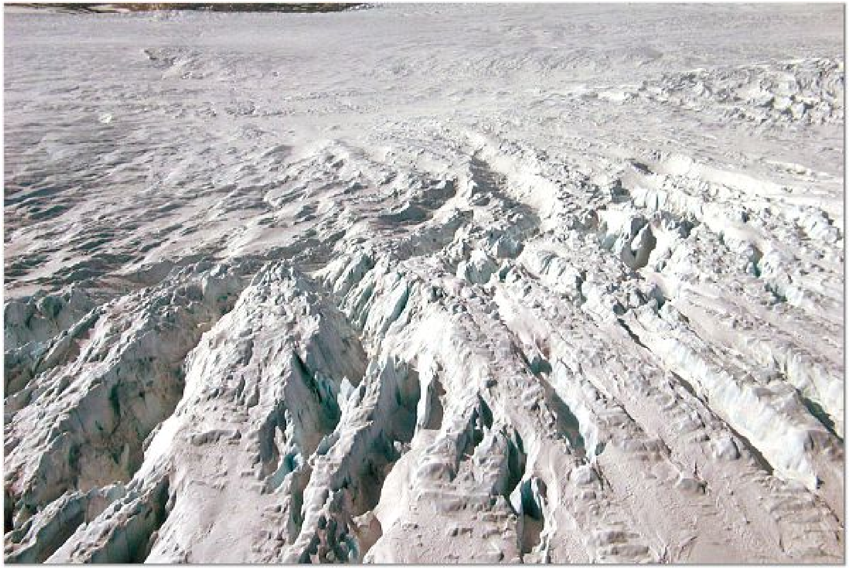
Where does the water go…



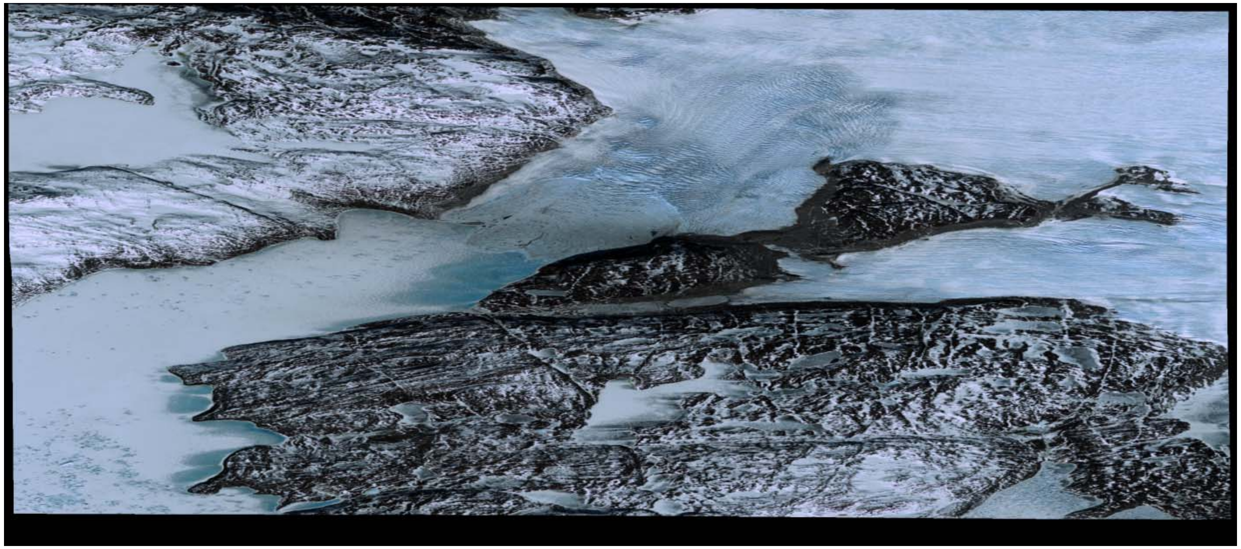


Thomsen Map showing crevasses, lakes and moulins.

Ice Sheet Surface



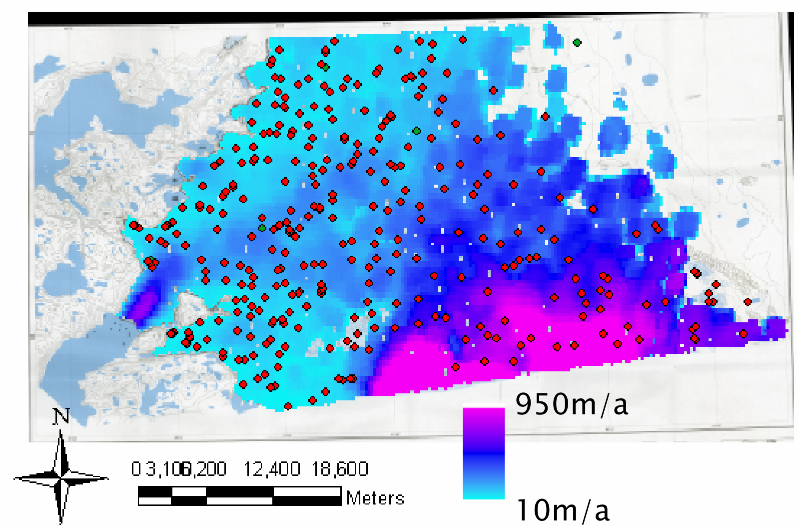
Known Moulin Locations



QuickBird image, DigitalGlobe Inc., 2009

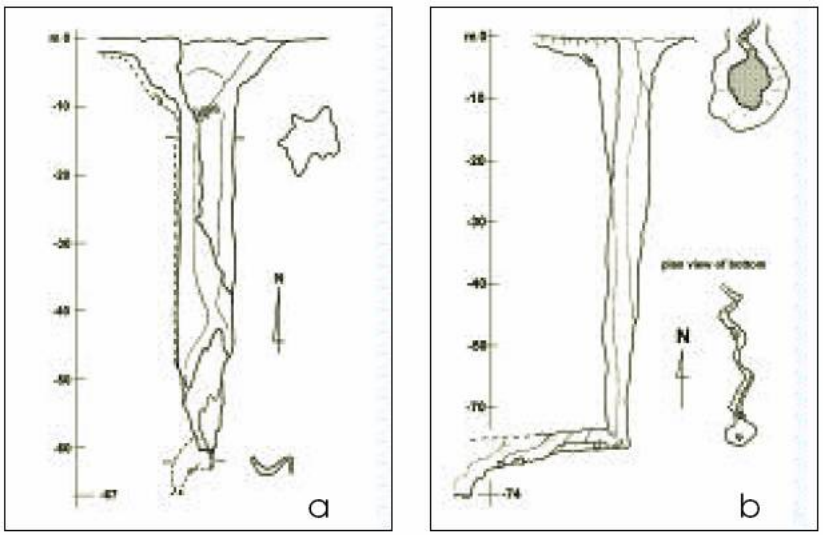
Thomsen Map, July 9th, 1985

Moulin Locations



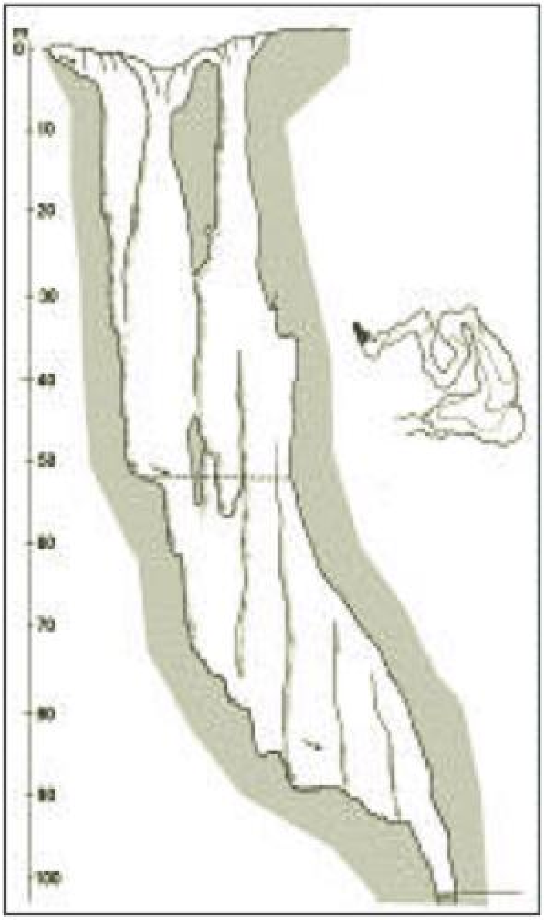
Historical data from the Thomsen map (right) is compared to present imagery captured by QuickBird (0.6m resolution) or WorldView images (0.5 m resolution at nadir).

The Geometry of a Moulin

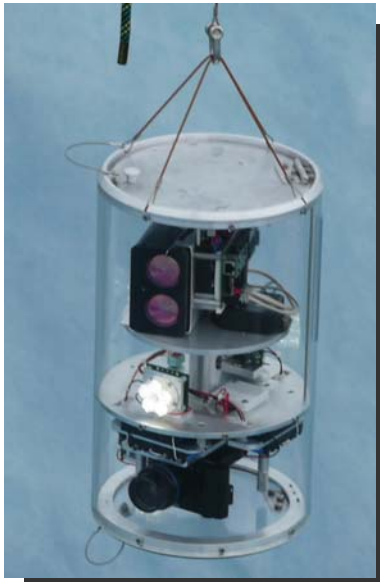


Above: Gorner Glacier (Badino, 2002)

Right: Grand Moulin on Mont Blanc, first described and climbed in 1897. Same location and approx. geometry every year. (Raymond, 1989)



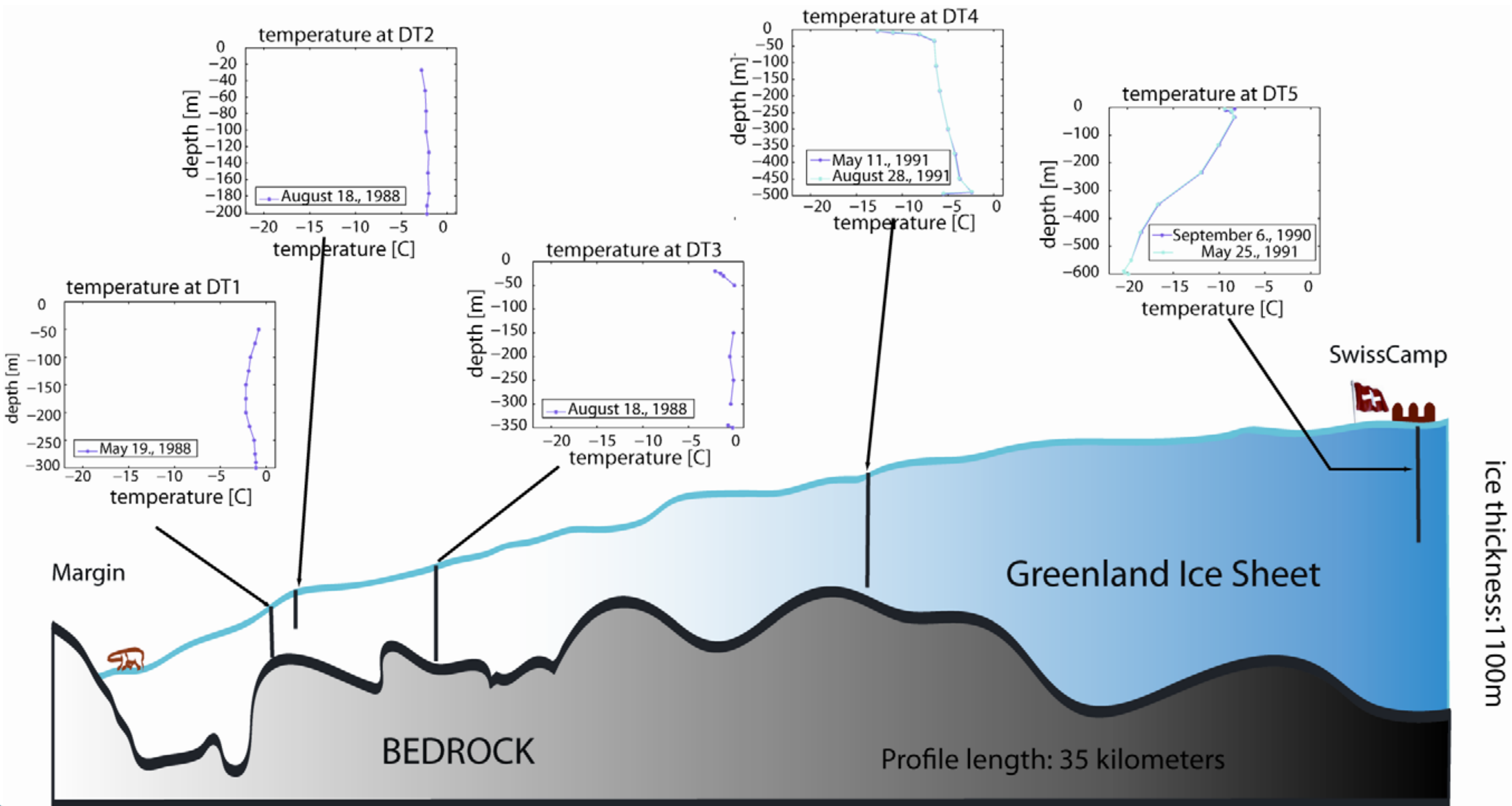
The Steffen Moulin



Moulins

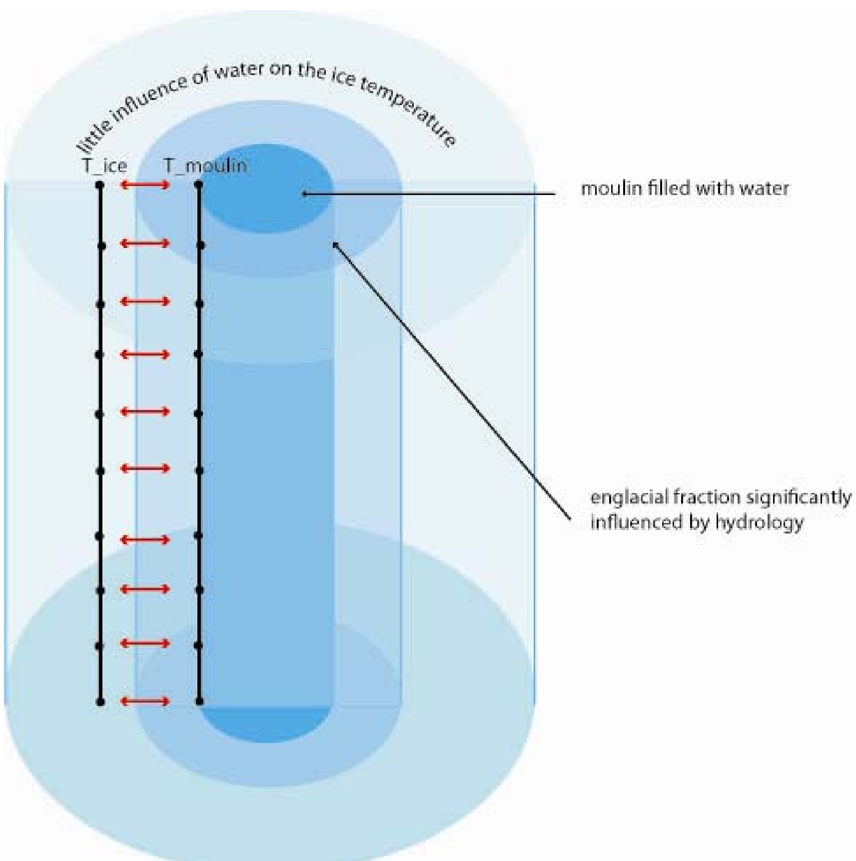
By D. McGrath, CIRES, 2008

Data: ice temperature profiles:



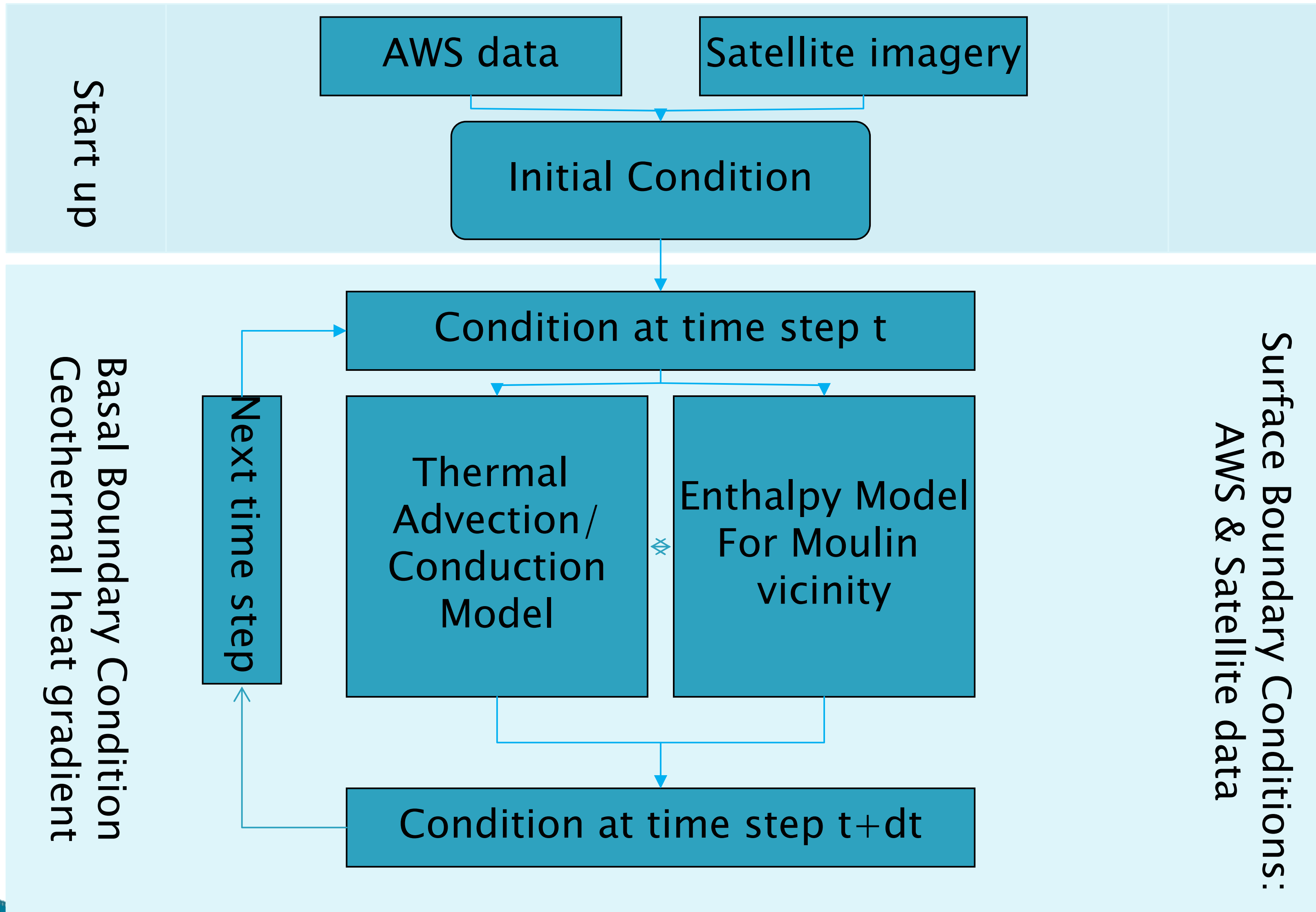
Thomsen, unpublished

Thermal Dynamics Model



- Add a second column in the moulin vicinity that is influenced by the water flow.
- This column interacts with the ice column by ways of heat conduction.
- Include a snow cover in winter that insulates the ice.

Model Concept:

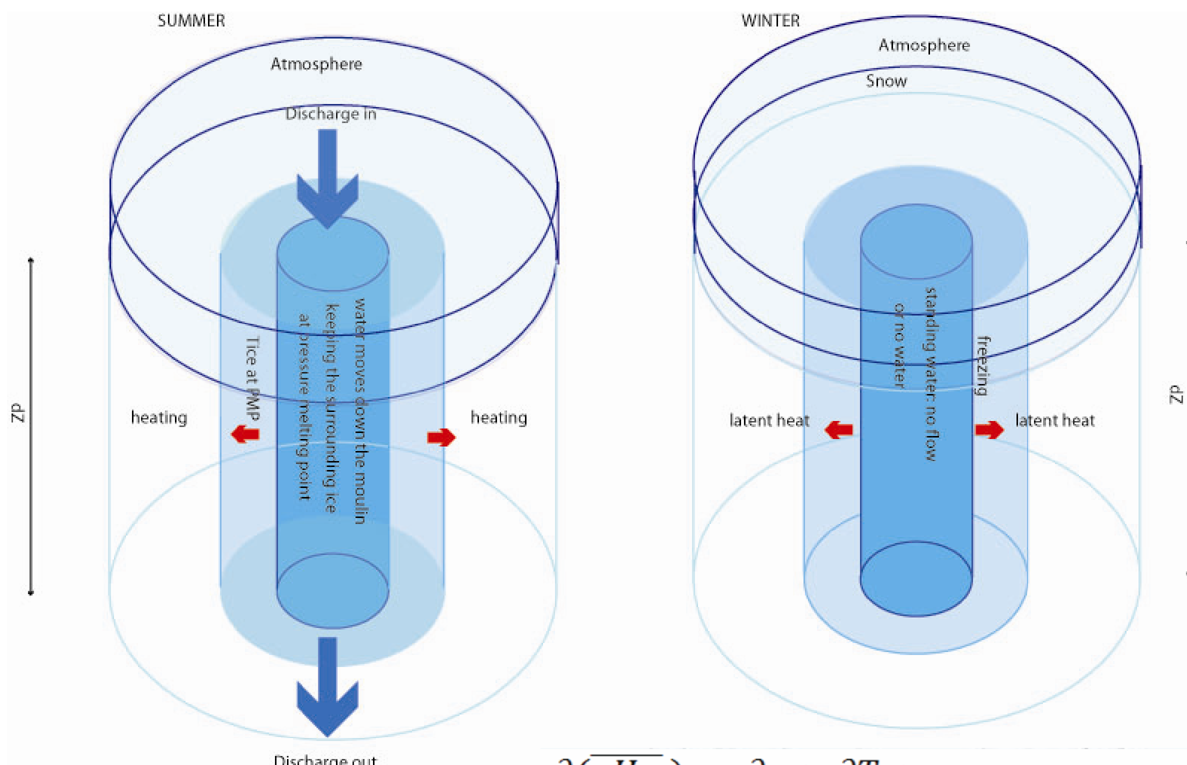


Model set up: winter summer modes

Ice

Moulin Vicinity

$$0 = \frac{\partial \Theta_{ice}}{\partial t} - \kappa \frac{\partial^2 \Theta_{ice}}{\partial^2 z} - u \frac{\partial \Theta_{ice}}{\partial x} - w \frac{\partial \Theta_{ice}}{\partial z} + \frac{Q}{\rho_{ice} c_{pice}} - \alpha(\Theta_m - \Theta_{ice})$$

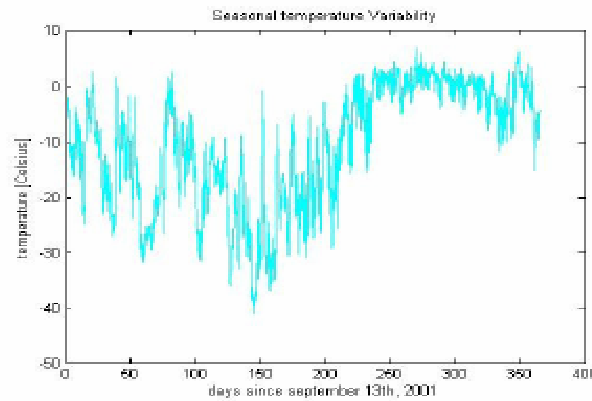


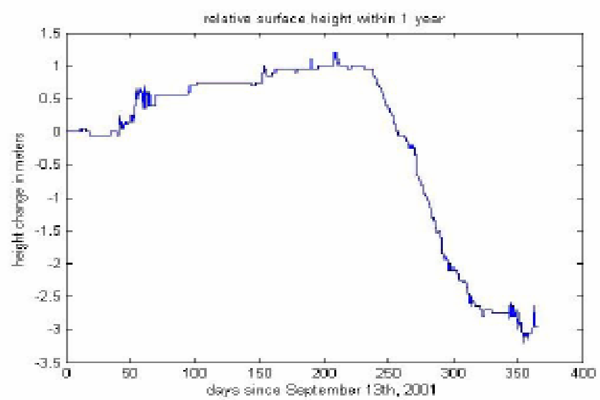
$$\Theta_m = \Theta_{pmp}$$

$$\frac{\partial(\overline{\rho H_m})}{\partial t} - \frac{\partial}{\partial z}\left(\bar{k}\frac{\partial T_m}{\partial z}\right) - \alpha_E(T_{ice} - T_m) = 0$$

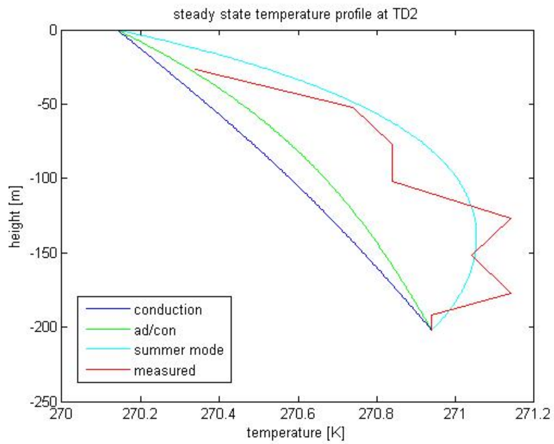
Ground Truth and Boundary Conditions

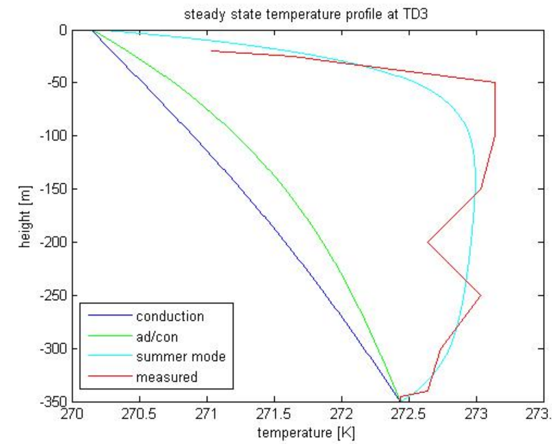
- The geothermal heat flux is used as the basal boundary condition => guess
- The physical properties for snow and ice are calibrated using the AWS temperature profiles.
- This would result in the release of energy during the freezing process and a warming of the ice.
- In addition the snow cover insulates the ice sheet from the harsh Arctic winter.





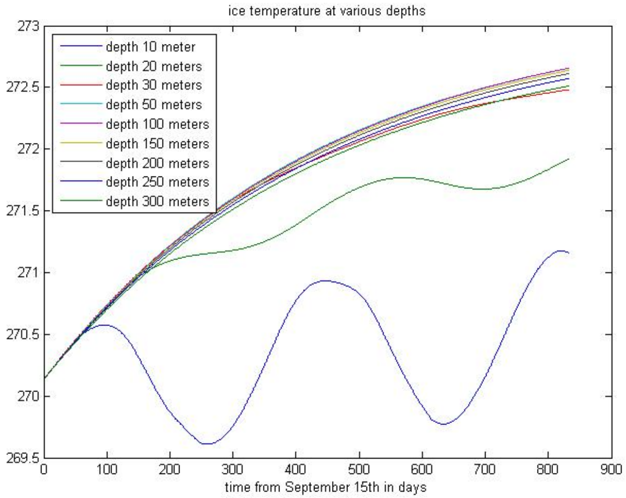
Results for the temperature profiles:

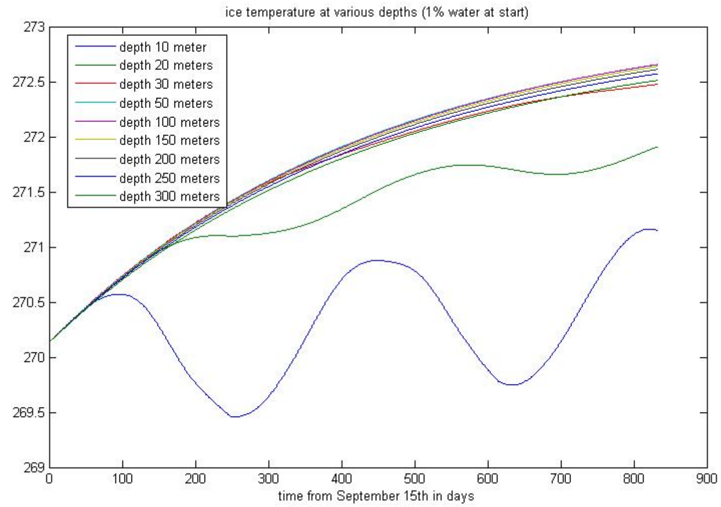


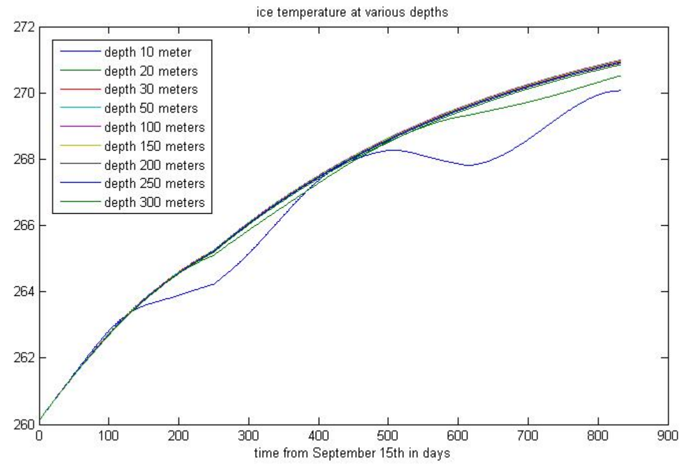


- The two bore hole data sets described here have a convex form with englacial temperatures above the surface and the base ice temperatures. This may be caused by a well developed hydraulic system.

Results: results for different temperatures and water content







Upper left: 5% water content, 270.14 K ice Temperature
lower left: 5% water content, 260.14 K ice Temperature
Upper right: 1% water content, 270.14 K ice Temperature.
$\alpha = 0.0005$ for all runs.

Programming

- Currently different programs are used to study different aspects:
- ArcGIS for spatial analysis (such as velocity, distance, etc.)
- R is used for stats
- IDL for AWS station data
- ENVI for satellite imagery
- MatLab for numerical

- We are trying to combine all for the future using Python.
- ArcGIS for spatial
- R for statistics
- C++ for numeric model
- GDAL for satellite imagery or ENVI.

Conclusions

- The melt area is increasing
- The length of the melt season is increasing
- There is a highly developed englacial water network that is active for approximately of 80 days a year.
- The peak values of water pouring down these holes are 20m3/s!
- The melt water is a large source of energy into the ice if any of the water is stored within the ice.
- This changes the physical properties and the flow behavior.
- The snow cover at the surface insulates the ice during the winter months.
- In situ data as well as satellite imagery are useful data to calibrate the model at the surface.

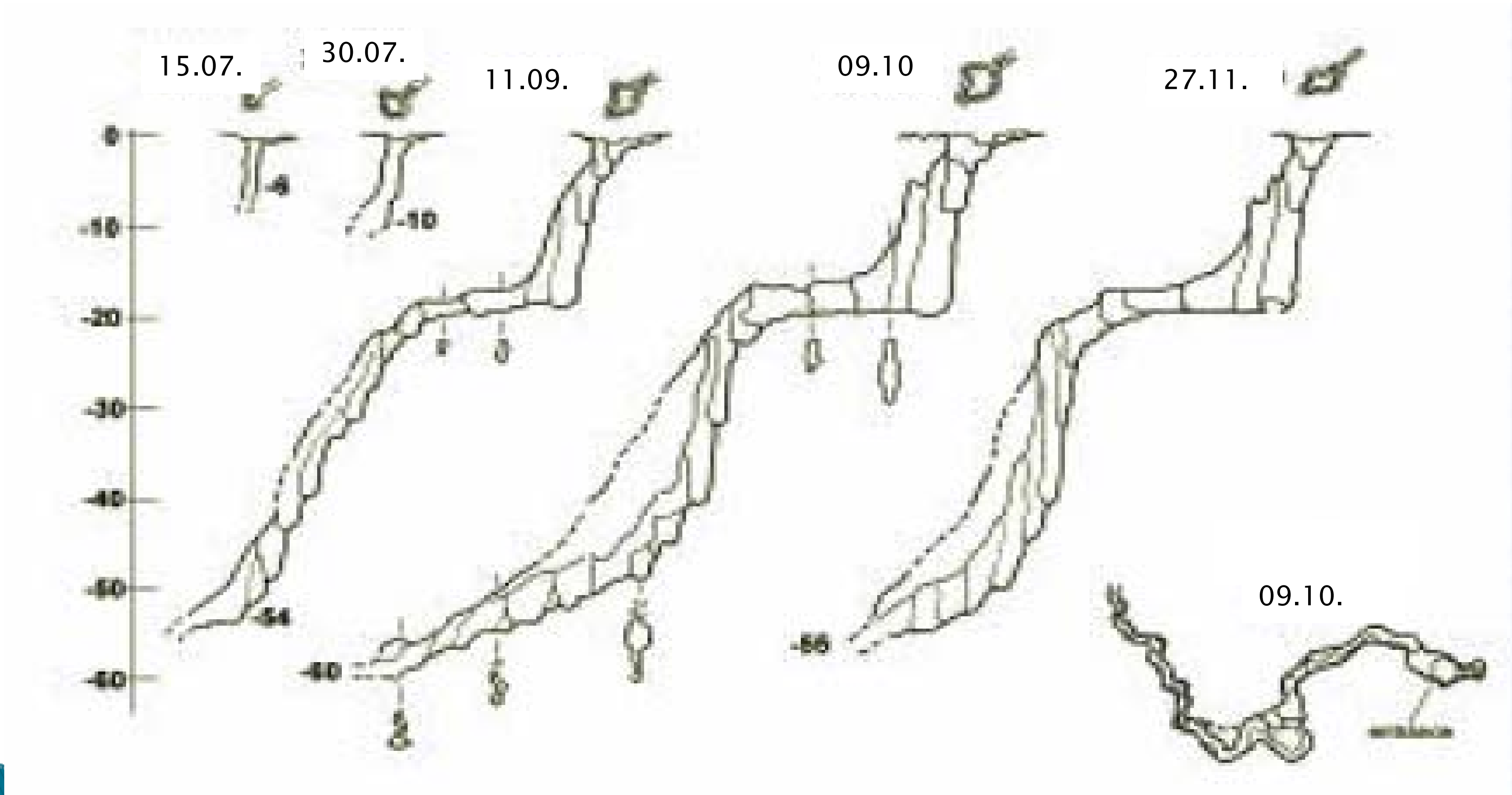
Thanks for listening…

Images: MODIS, Moulin (D. McGrath), Ice Sheet Modeler

General Water Supply to a Moulin at JAR1 (hypothetical)

Year	melt	Total [10^5m3	Max [m3/s]	Mon.	Av. [m3/s]
1996	Low	9.4	19.7	June	
1997	Low	10.3	21.0	June	1.7
1998	High	15.6	19.3	June	2.1
1999	Low	11.1.	20.7	July	1.9
2000	Low	11.3	15.0	June	1.9
2001	Low	11.9	20.3	July	1.8
2002	High	18.5	23.3	July	2.4
2004	Low	12.8	19.4	June	2.2
2005	high	19.2	26.6	July	2.6
2006	Low	5.6	15.7	July	0.7
2007	high	> 21.1	25.1	July	>2.6

Geometry of the moulin



Badino & Piccini, 2002