Cold Surface Layer Dynamics on Storglaciären, Northern Sweden, 2009-2019

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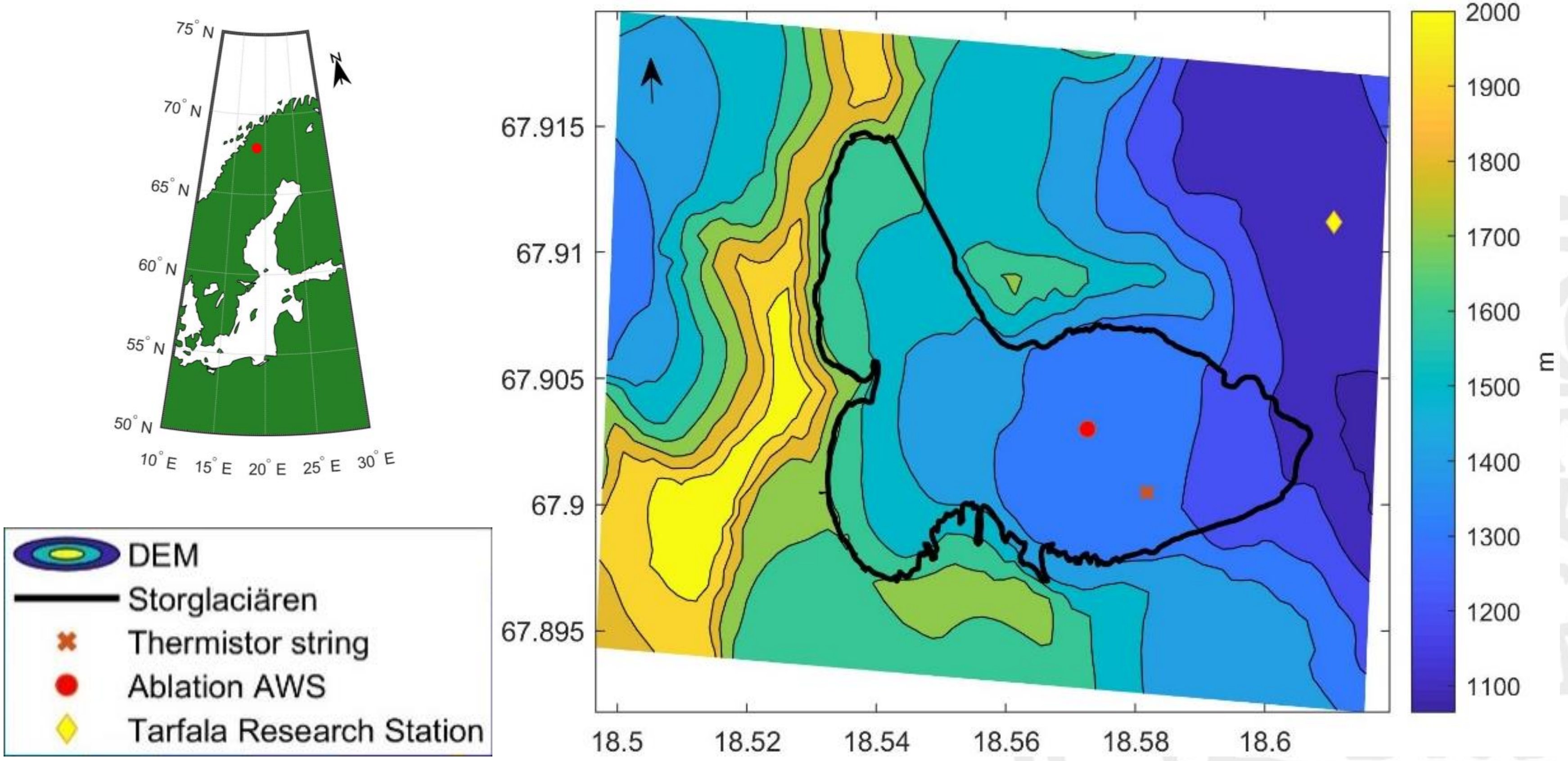
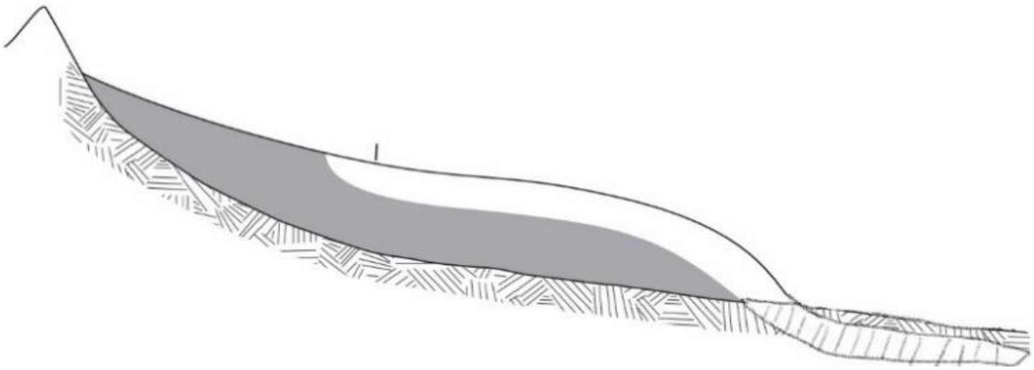
Otterborg Stipend
Linnaeus Scholarship
Uppsala University IPK Scholarship

Storglaciären



Background



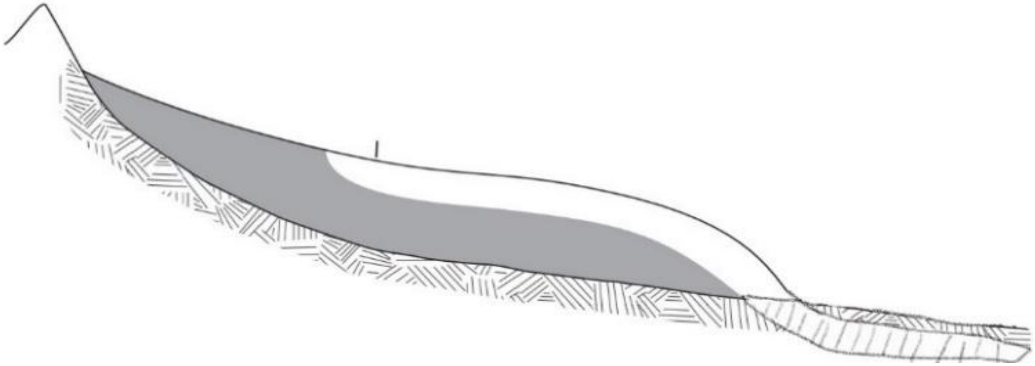
modified from (Dobiński et al., 2017; Pettersson, 2004)

- Cold–temperate transition surface (CTS)
  - The boundary between cold and temperate ice is a prominent englacial transition .
  - A hydraulic boundary for intra-granular water, separating the water-free region from the temperate region
- CTS depth decreased 8.3 m (22% of average thickness) during 1989-2001
- Storglaciären has lost one-third of its cold surface layer volume (2009)
- Average thinning rate of $0.80 \pm 0.24\ \mathrm{m} \cdot a^{-1}$

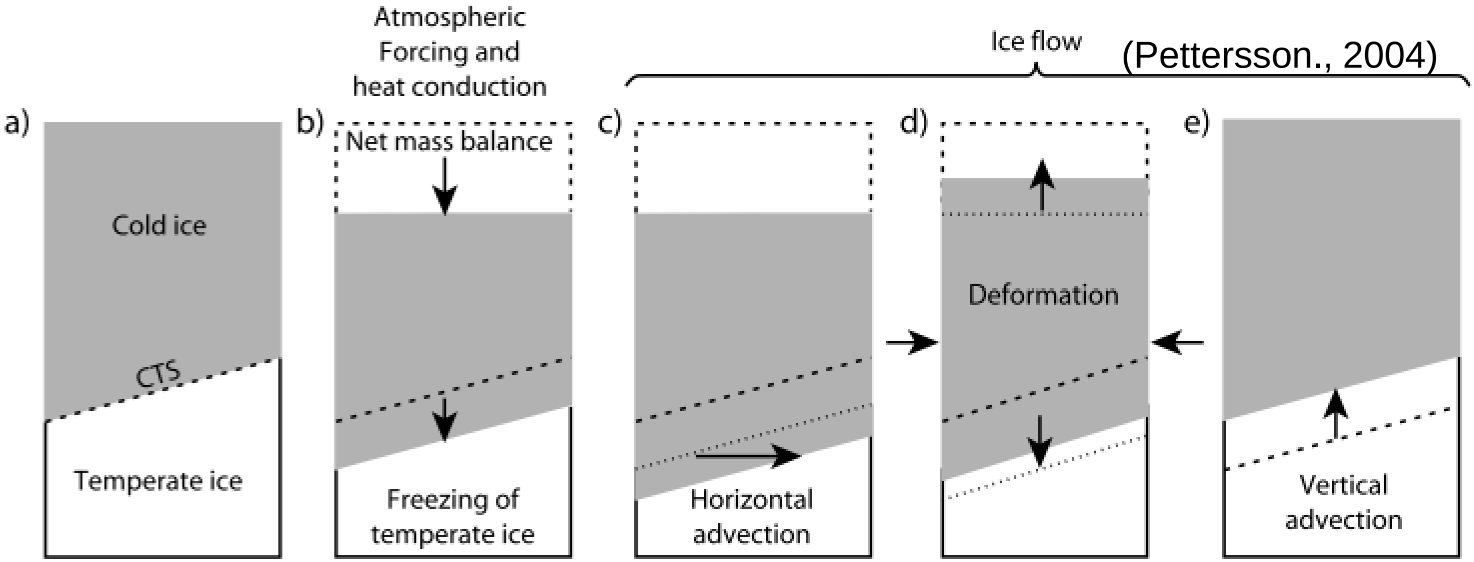
?

- What are the spatial and temporal changes of CTS on Storglaciären from 2009 to 2019?
- How mass balance affects the cold surface layer evolution?

Mechanism



modified from (Dobiński et al., 2017; Pettersson, 2004)

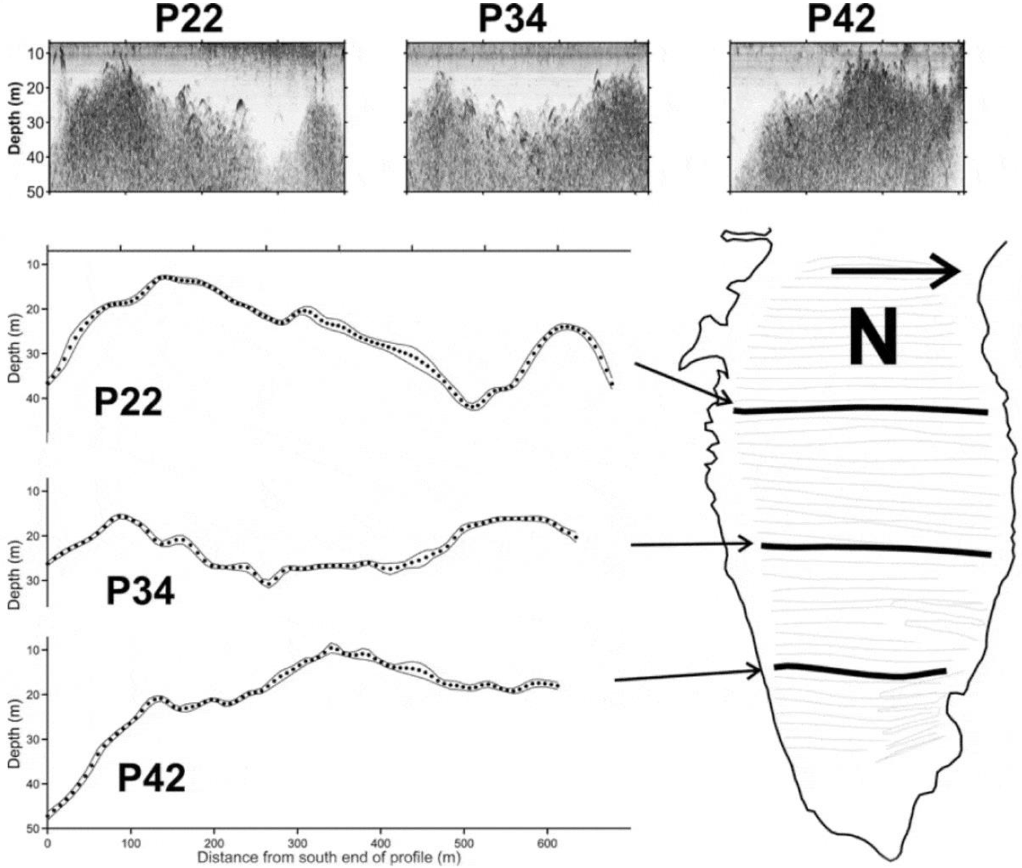


(Pettersson., 2004)

The stability and long term thickness of cold surface layer is determined by the balance between the downward migration of CTS and net ablation at glacier surface

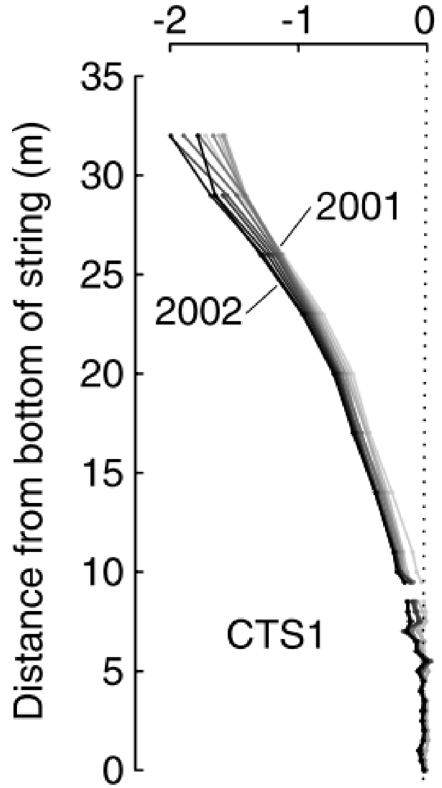
How do we know about CTS?

Ground Penetrating Radar



Gusmeroli, A., Jansson, P., Pettersson, R., Murray, T., 2012. Journal of Glaciology 58, 3–10.

Thermistor string



Pettersson, R., Jansson, P., Blatter, H., 2004. Journal of Geophysical Research: Earth Surface 109.

How do we know about CTS?

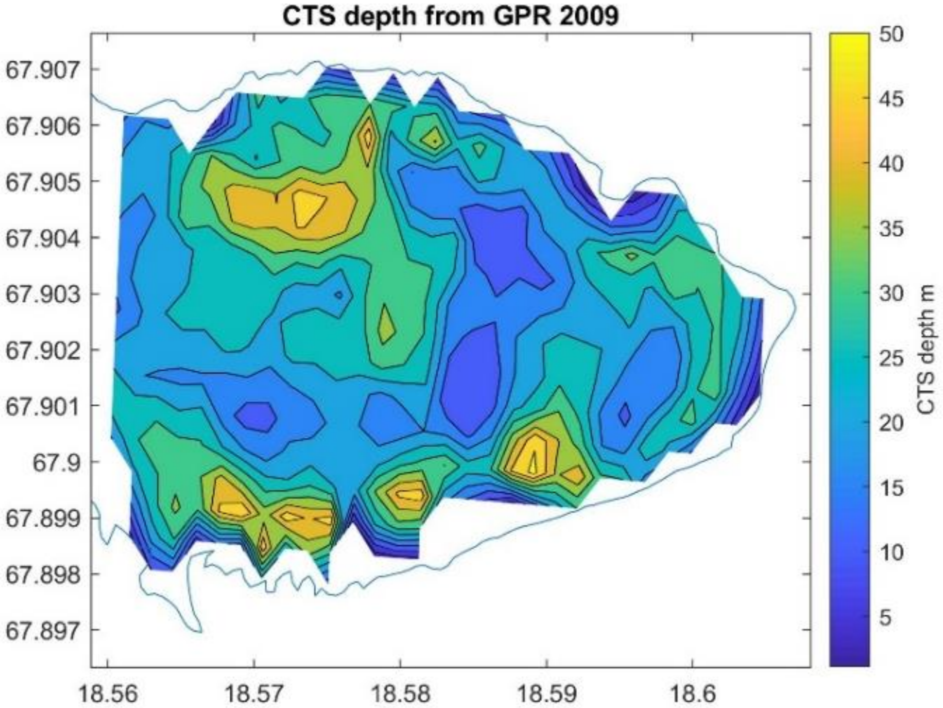
Model

- Hock and Holmgren (2005): a distributed surface energy balance model
  - subsurface melting is neglected.
- Pettersson et al. (2007): a one-dimensional model.
  - emergence velocities which is not available in the study period.
- Aschwanden and Blatter (2009): enthalpy method along the kinematic center line
  - Velocity data; computation challenging

Previous Survey

CTS Survey 1989, 2001 and 2009

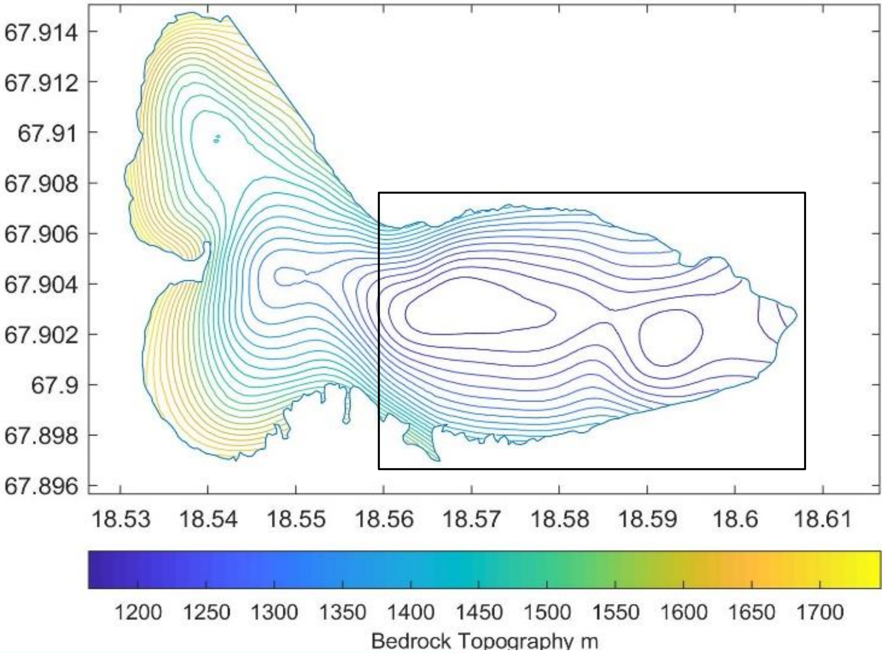
Year	CTS depth (m)		
	Min	Mean	Max
1989	23	38	64
2001	4	31	65
2009	1	25	59

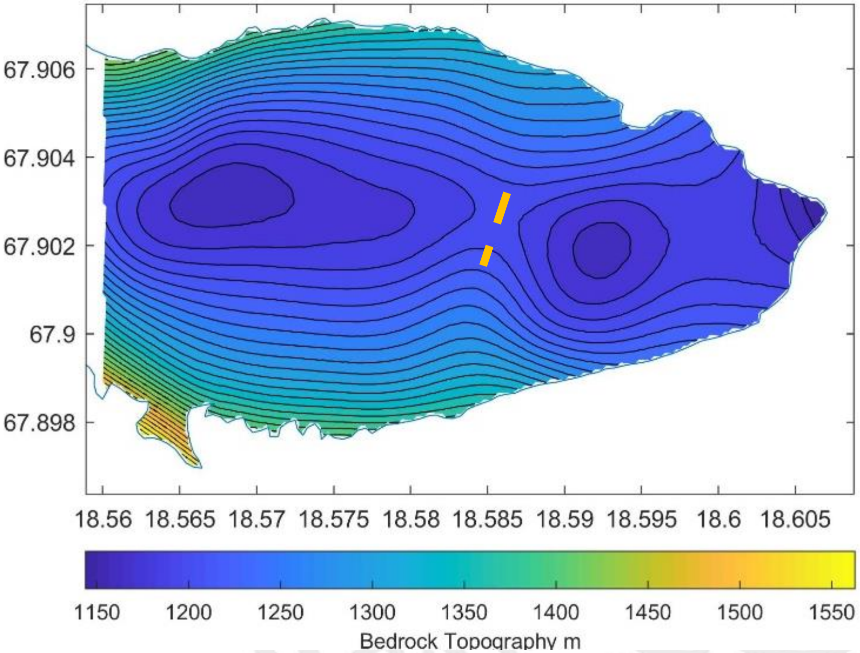


Previous Survey

A bedrock threshold separates the ablation zone to upper and lower part

Ice flows faster over this threshold → thinner snow cover





Method

Thermistor string

- A 20-meter thermistor string
- 24 thermistors

↓

- Extrapolate subsurface temperature (point scale)

Model

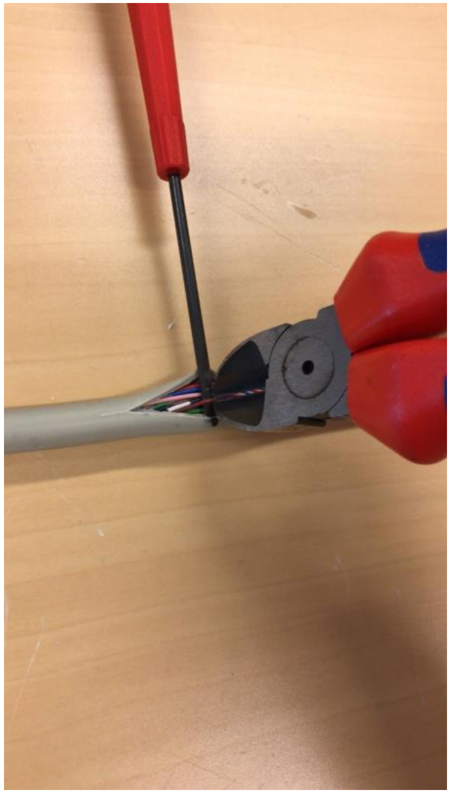
- A coupled surface energy balance-snowpack model

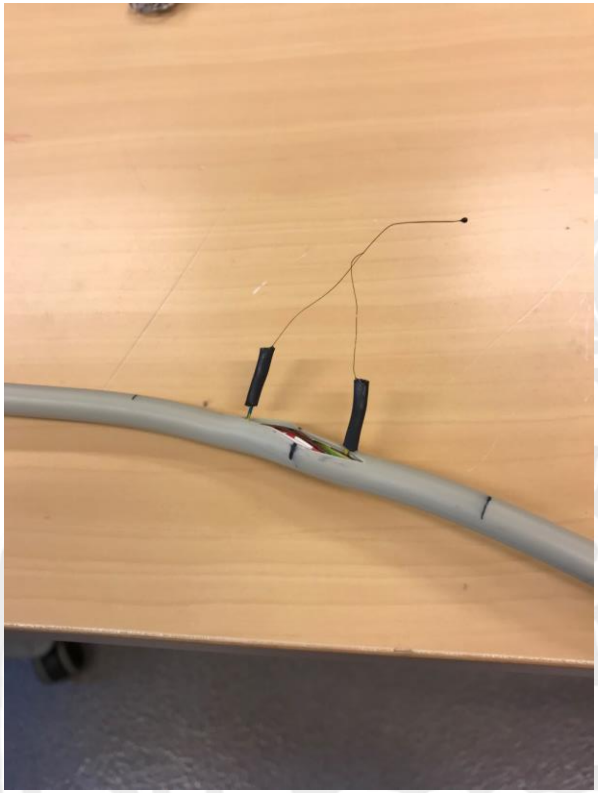
↓

- Simulate subsurface temperature evolution (glacier scale)

Preparation of Thermistor String

Solder the sensors





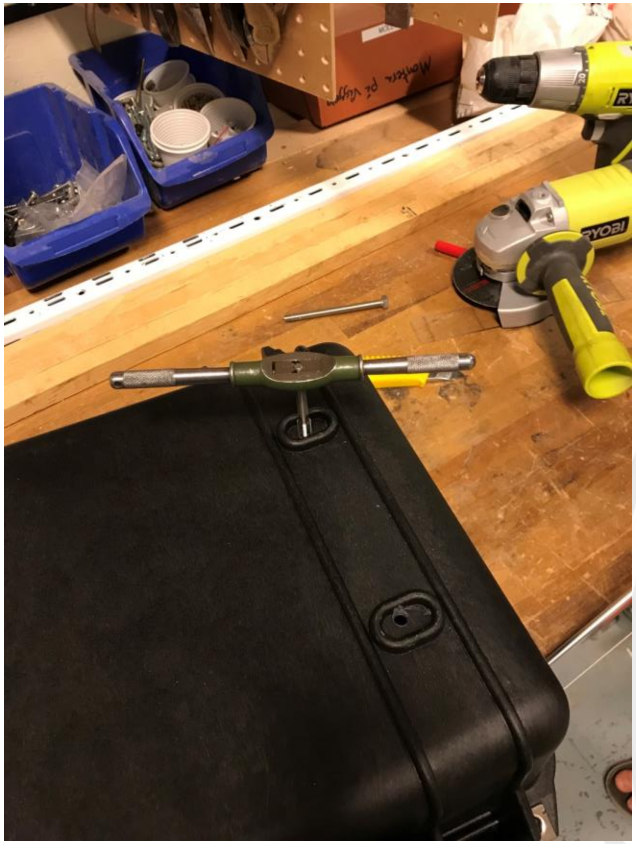
Preparation of Thermistor String

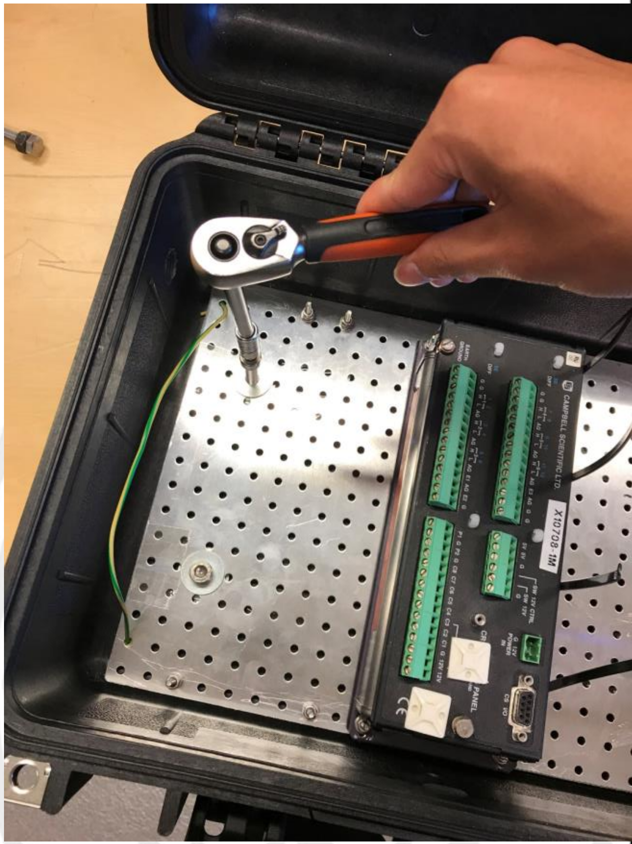
Thermistor String

Preparation of Thermistor String

Preparation of Logger Box

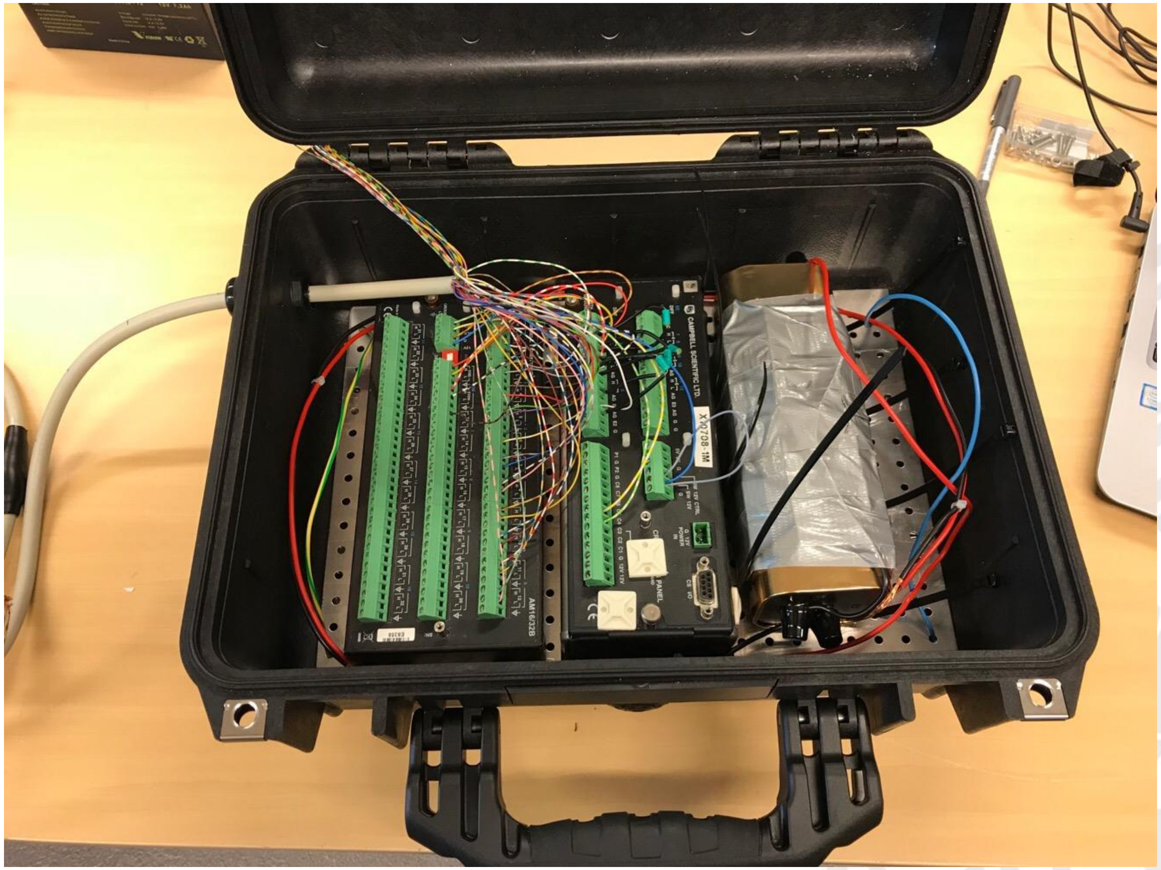
Logger box





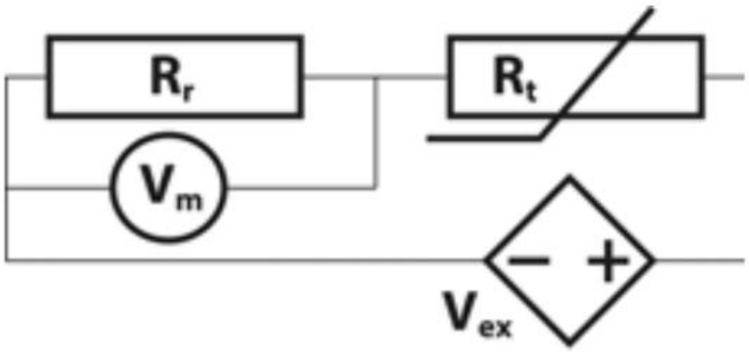
Preparation of Logger Box

Logger box



Calibration of Thermistor String

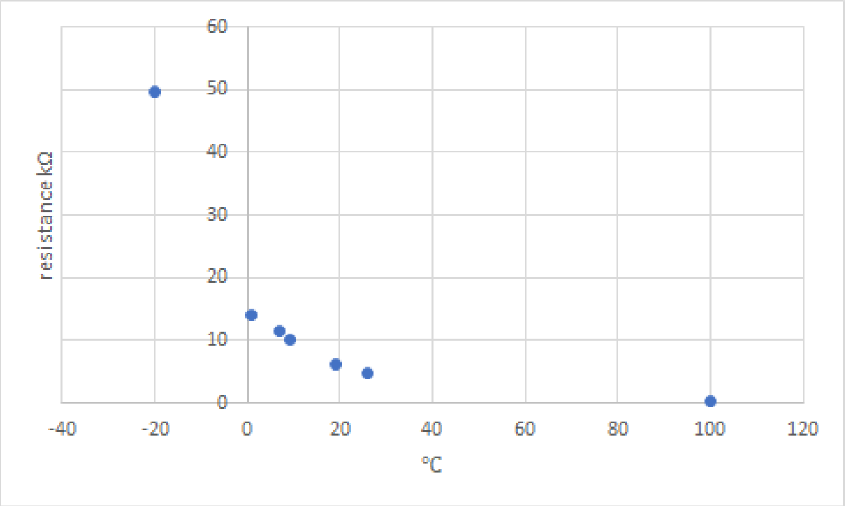
- $\frac{U_{ex}}{R_t+R_f} = \frac{U_m}{R_\mathrm{f}}$



(Marchenko, 2018)

- $\frac{1}{\mathrm{T}} = a + b\left(ln\frac{R_t}{R_{25}}\right) + c\left(ln\frac{R_t}{R_{25}}\right)^2 + d\left(ln\frac{R_t}{R_{25}}\right)^3$

Calibration of Thermistor String

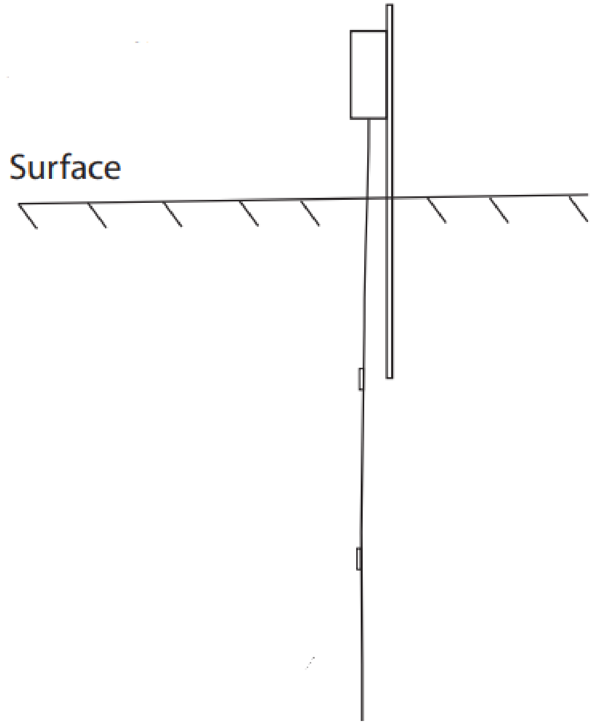


- $\frac{U_{ex}}{R_t+R_f} = \frac{U_m}{R_\mathrm{f}}$

- $\frac{1}{\mathrm{T}} = a + b\left(ln\frac{R_t}{R_{25}}\right) + c\left(ln\frac{R_t}{R_{25}}\right)^2 + d\left(ln\frac{R_t}{R_{25}}\right)^3$
- $\ln\left(\frac{R_t}{R_{25}}\right) = A + B \times T^{-1} + C \times T^{-2} + D \times T^{-3}$

Installation of Thermistor String

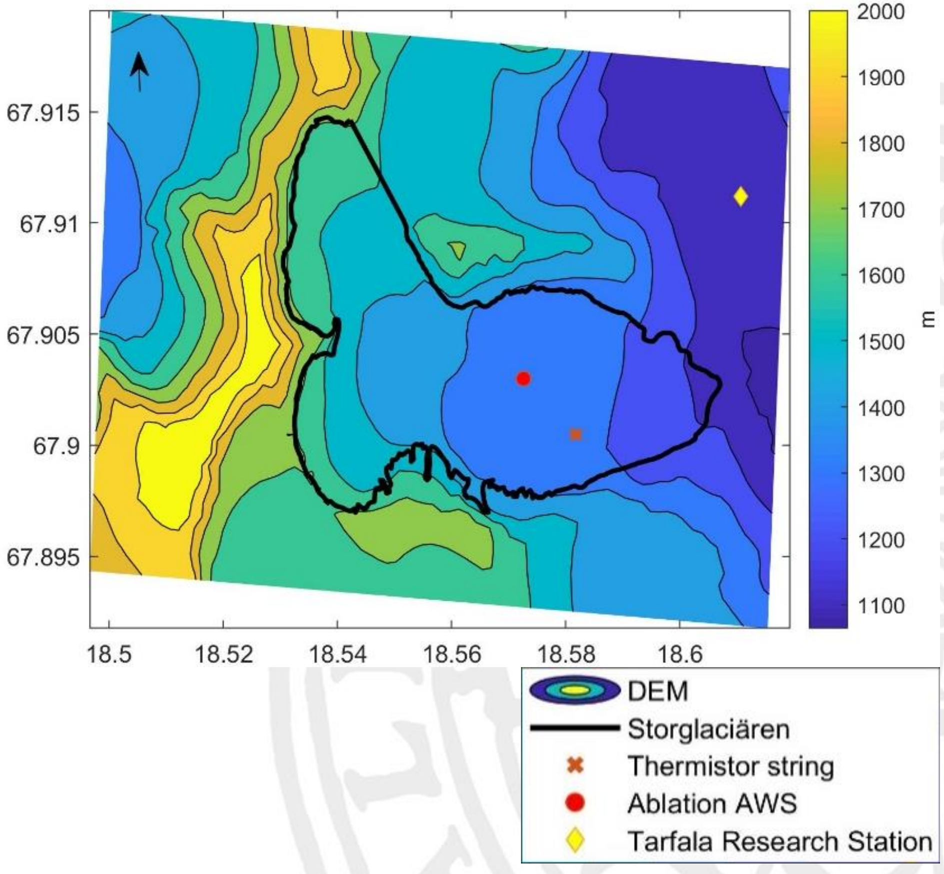
Installation of Thermistor String



provided by Rickard Pettersson

Installation of Thermistor String

- (67° 90'N, 18° 57'E)
- Reference resistance: 100 kΩ or 10 kΩ?
- Drilled through a water channel?
  - Stopped at 14.3 m
  - Lost additional 1 m during installation



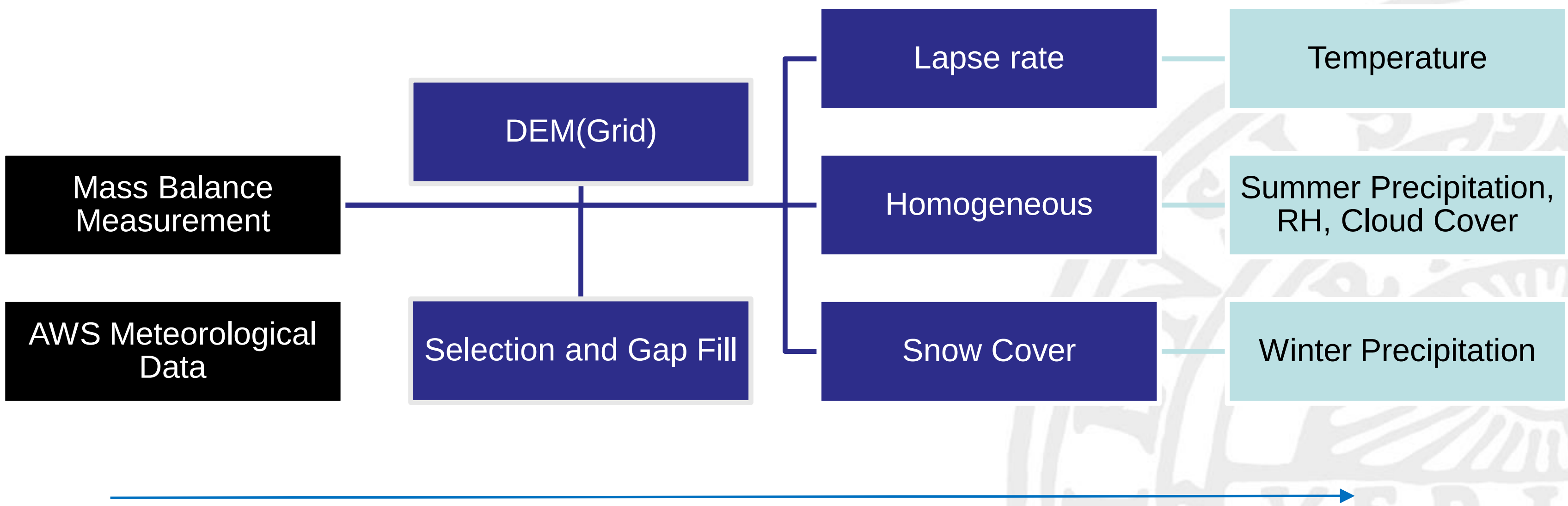
Model Setup

- Surface energy model → Multi-layer snowpack model → update the liquid water storage, gravitational densification and heat conduction
- Requires:
  - 1) air temperature, 2) precipitation, 3) relative humidity (RH) and 4) cloud cover
- Simulation period:
  - 2009-04-01 00:00 to 2018-04-01 00:00
- Model Update:
  - Moving grid (add new layers from the bottom):
    - constant water content 8 mm w.e.
    - temperature (273.15 K)

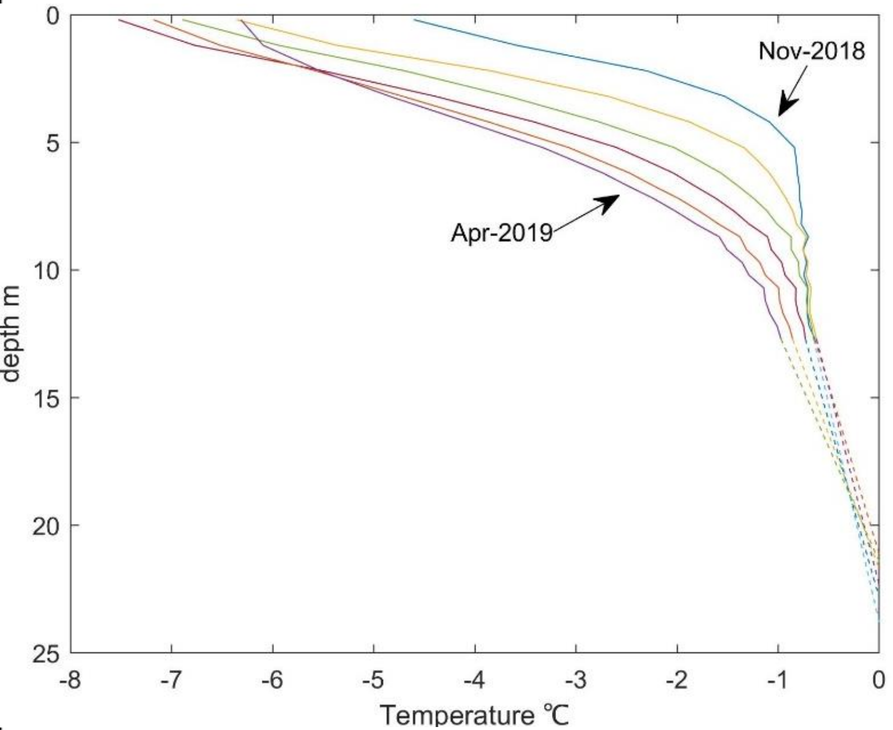
Data Input

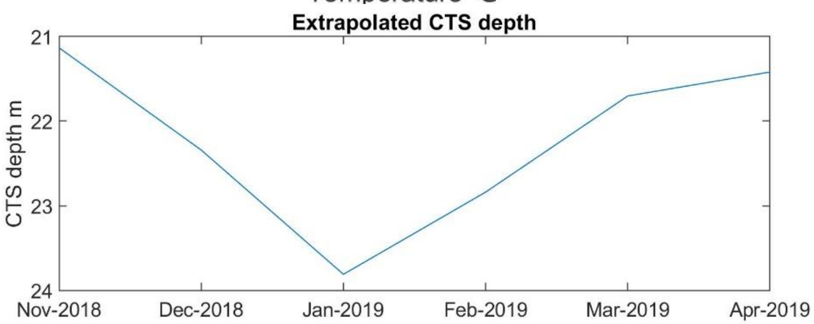
Data	Date	Parameter	Source
mass balance	1946-2018	Stake measurement Snow density	https://bolin.su.se/data/tarfala/tarfalaglaciaren.php
TRS AWS	1988-2018	temperature, RH, precipitation, global radiation, wind, air Pressure	https://su.figshare.com/TRS
Storglaciären AWS **Storglaciären Snow**	2013-2018	temperature, RH, precipitation	Provided by TRS at request
SLU DEM		2 m resolution DEM	https://maps.slu.se/
SMHI AWS	*	Temperature, RH Cloud cover	https://www.smhi.se/klimatdata/meteorologi/

Data Input


Mass Balance Measurement
AWS Meteorological Data
DEM(Grid)
Selection and Gap Fill
Lapse rate
Homogeneous
Snow Cover
Temperature
Summer Precipitation, RH, Cloud Cover
Winter Precipitation

Result: thermistor derived CTS

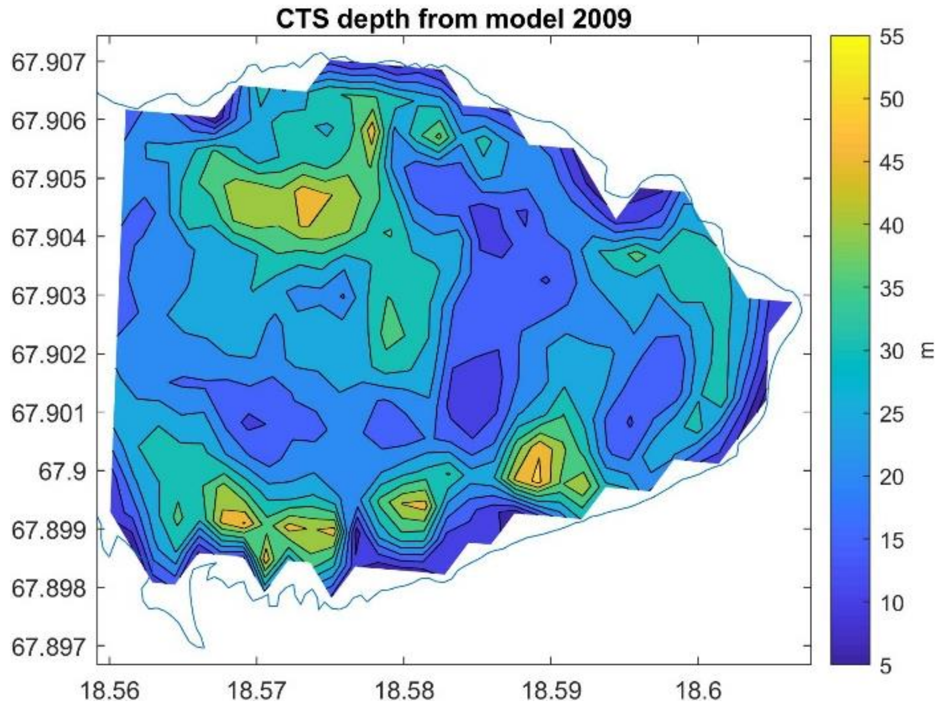


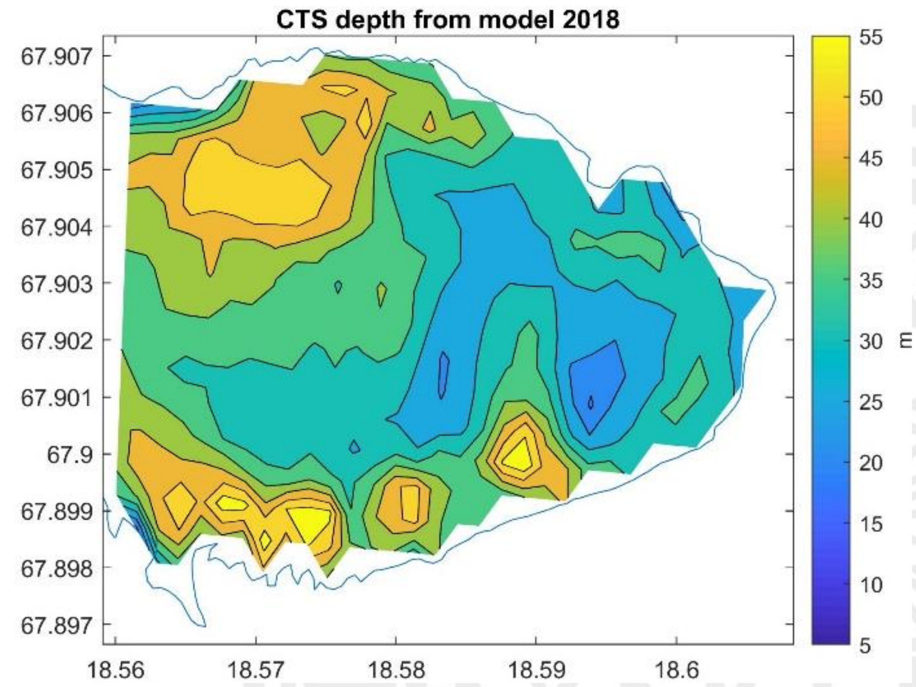


Extrapolated by linear regression of three thermistors at the bottom

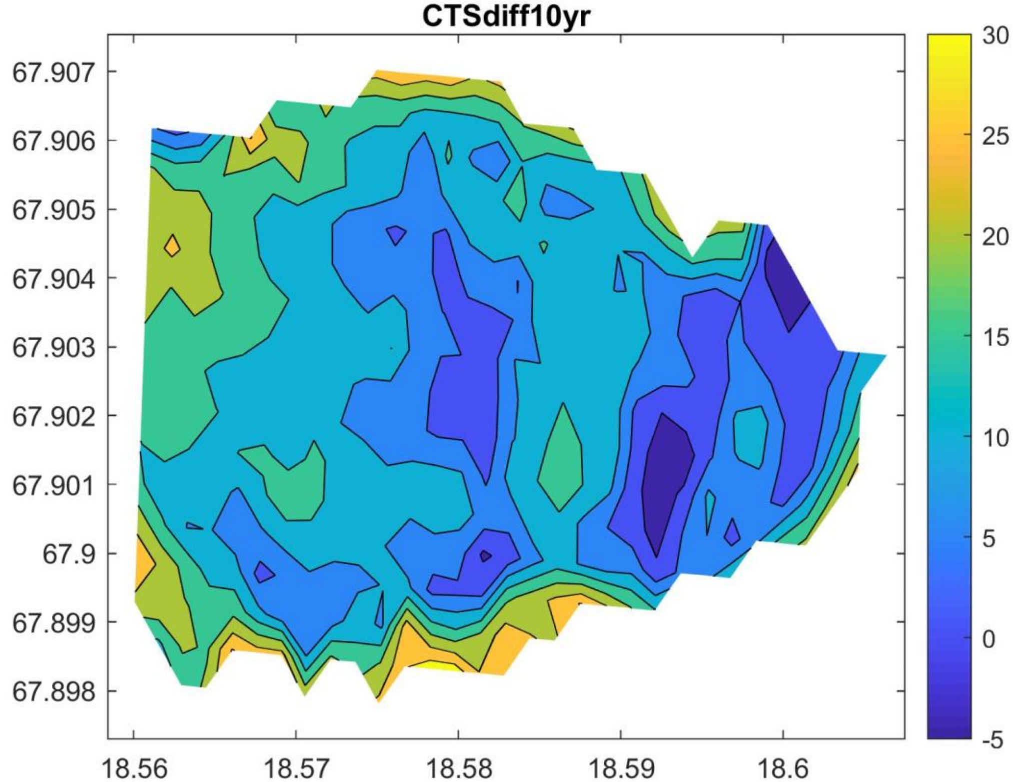
~ 1.3 m/month → 23.8 m in January

Result: model derived CTS

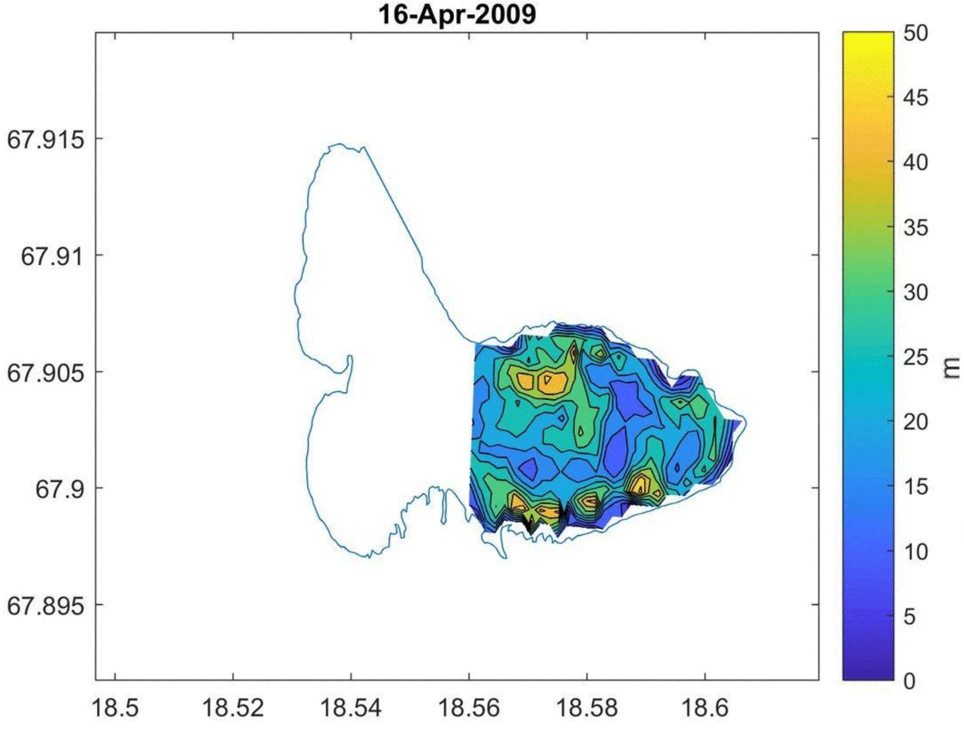


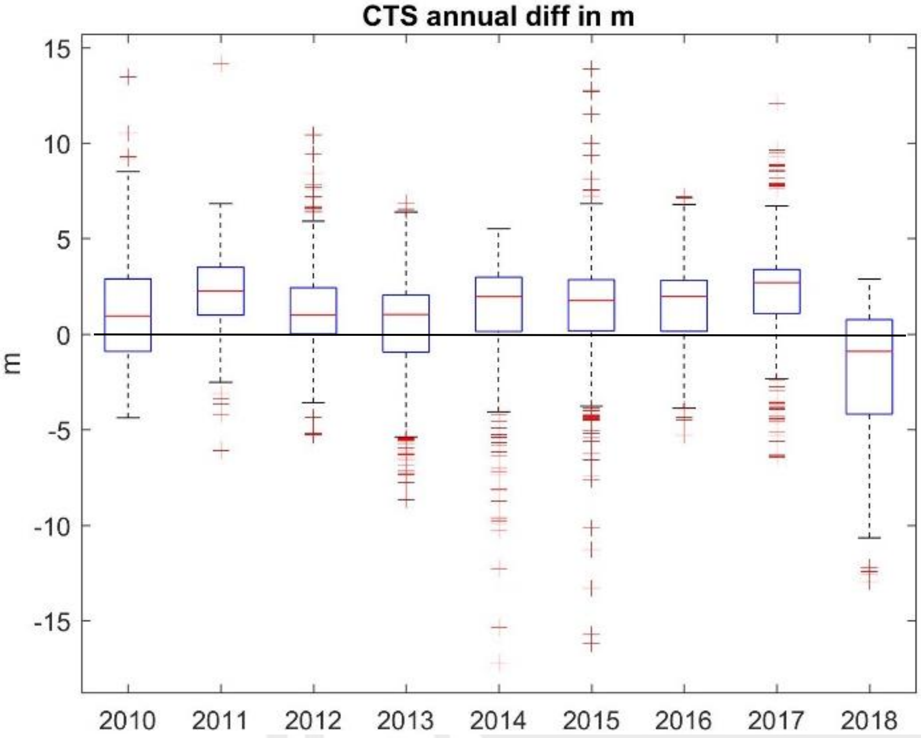


Results:
model derived CTS



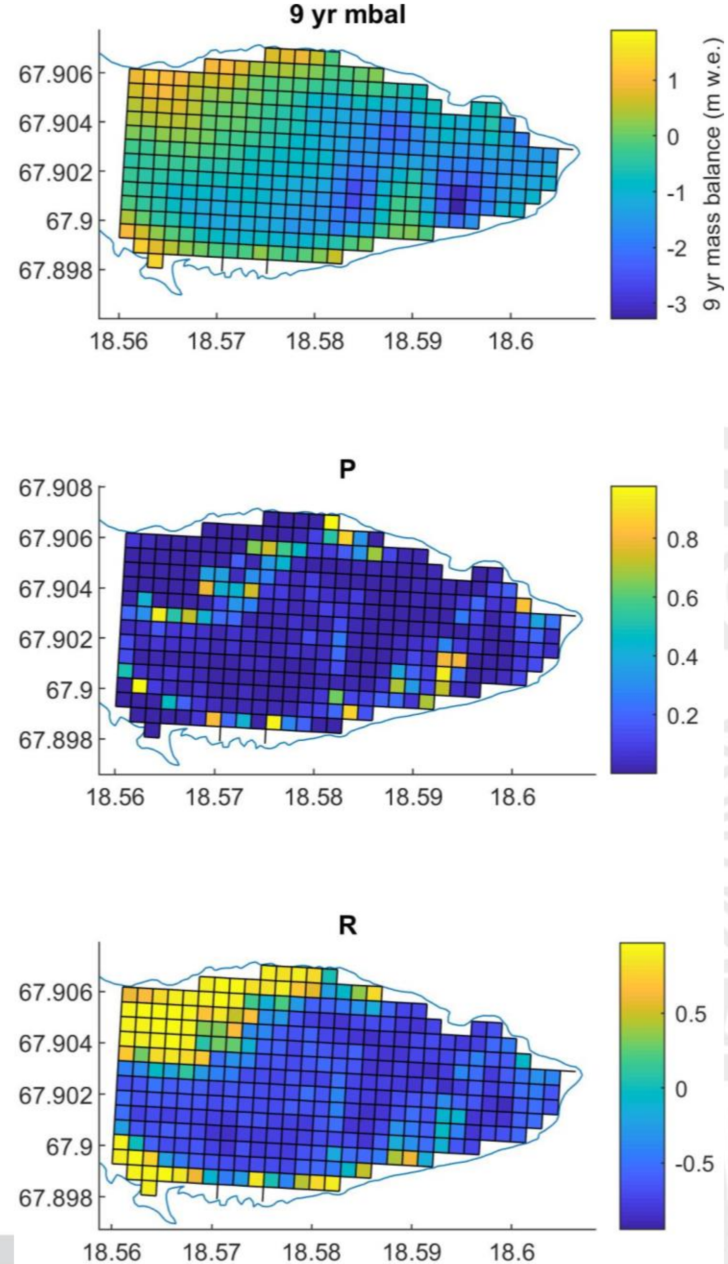
Result: model derived CTS





Correlation map: mass balance

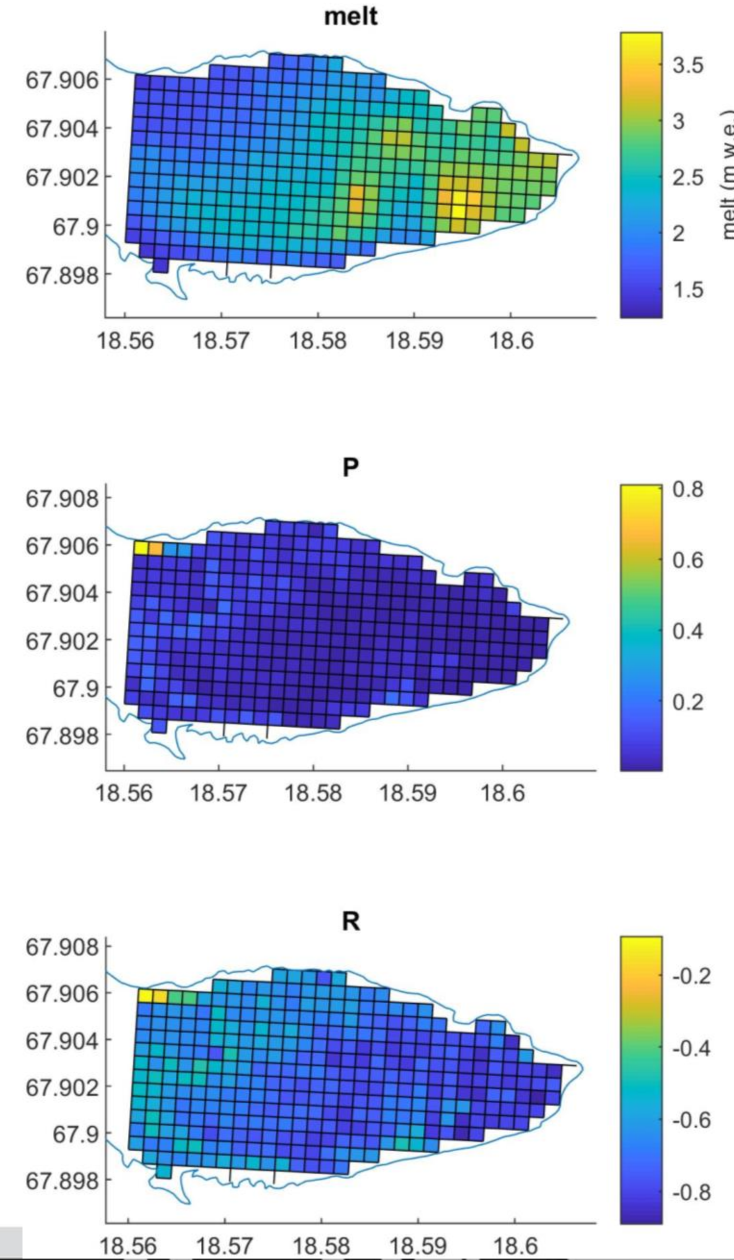
- R>0.5: positive mass balance
  - Higher mass balance
    → thicker cold surface layer
- R<-0.5: negative mass balance
  - More net loss of ice mass
    → shallower CTS
- Not significant: mass balance close to equilibrium



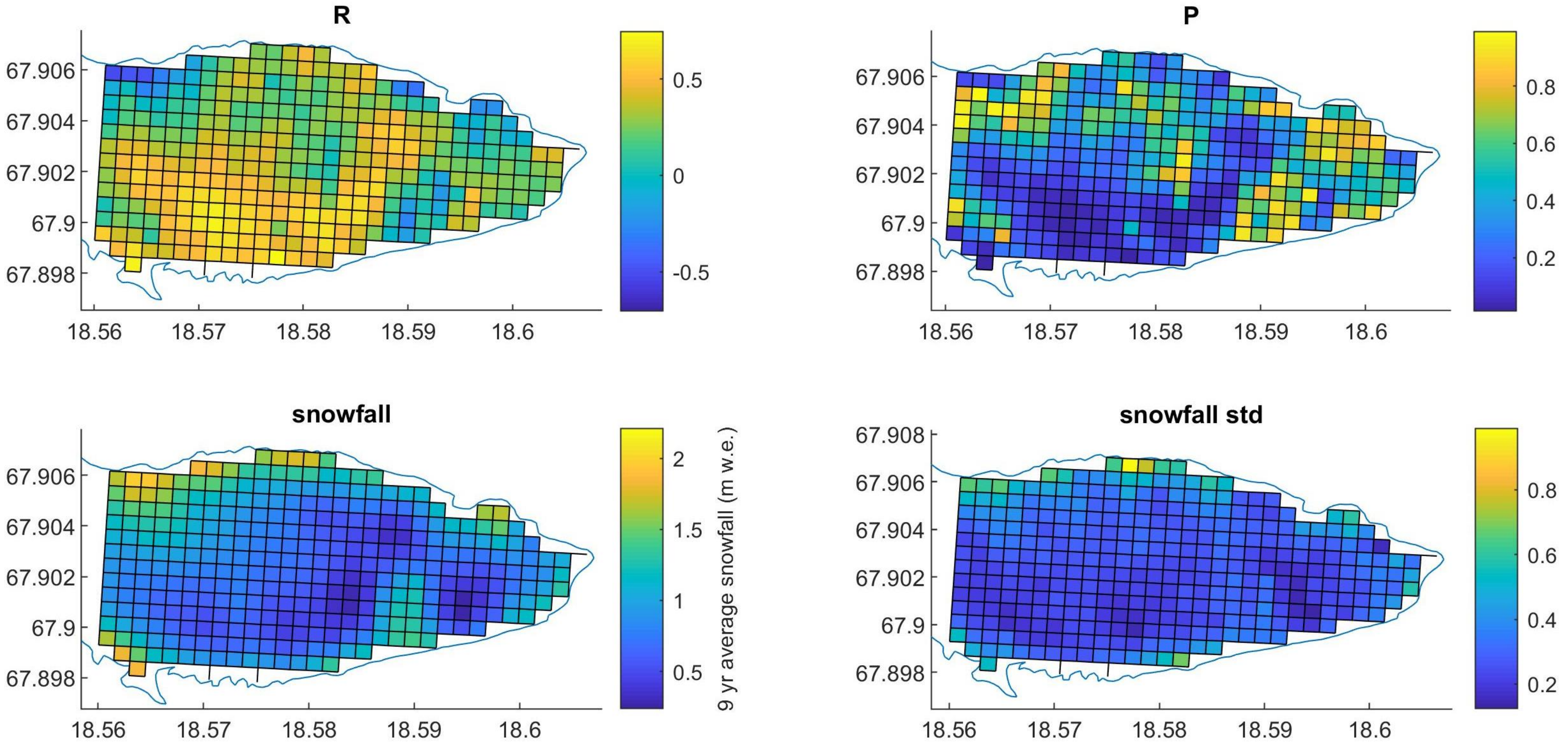
Correlation map: melt

- Negative correlation
  - More melt → thinner cold surface layer

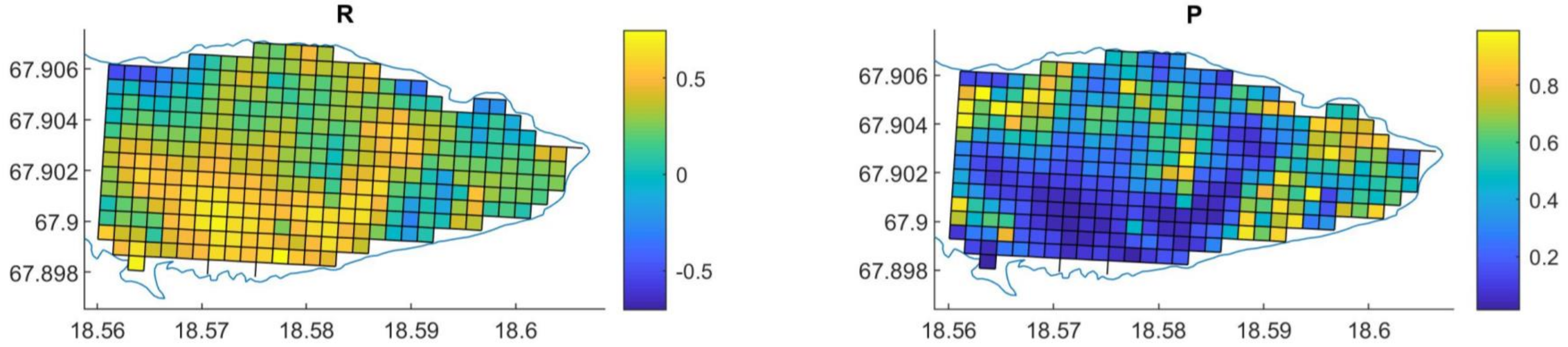
- The correlation gets stronger as melt rate increases



Correlation map: accumulation

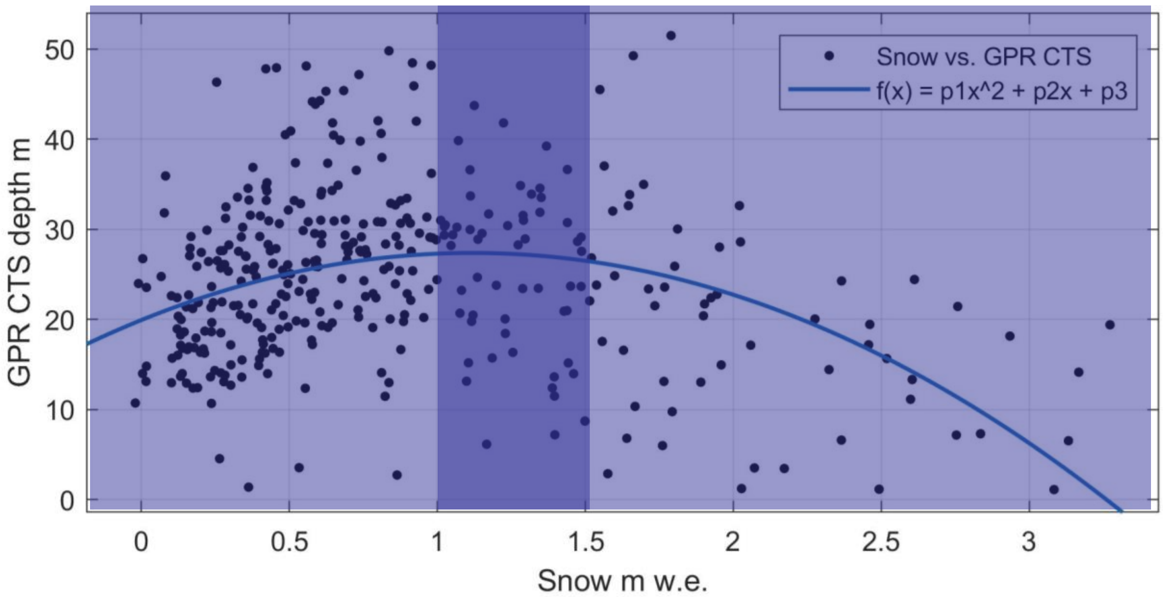


Correlation map: accumulation



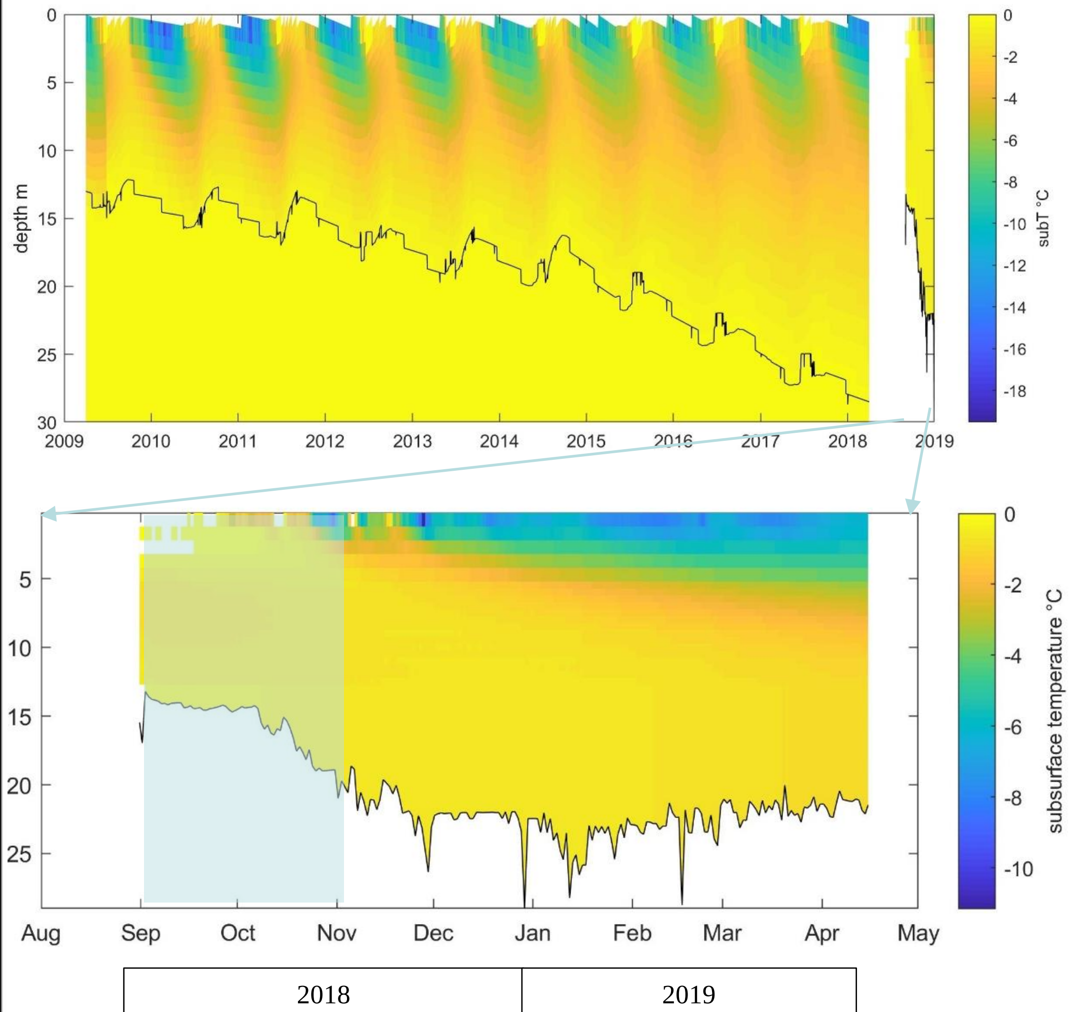
- R>0.5: (< 1 m w.e.)
  - Higher accumulation → thicker cold surface layer
- R<-0.5: (> 1.5 m w.e.)
  - Higher accumulation → thinner cold surface layer
- Not significant: (1-1.5 m w.e.)

Correlation map: accumulation



- Snowpack winter mass balance vs CTS 2009 survey
- Non-linear relation
- Similar threshold as the spatial correlation.

Time Series CTS Evolution at Study Site



- The average CTS depth estimated from thermistor data is 22.41 ± 1.56 m, about 5.59 m shallower than the last simulated CTS position.
- an average thickening rate of ~ 0.9 m·a^{-1} compared to the initial condition of CTS in 2009.

Discussion

- **CTS at Point Scale**
- Contradicting thickening trend
  1) Thermistor string didn't reach CTS (9 m shallower the thermistor estimated CTS depth)
  2) Calibration of thermistor string
- Large discrepancy between model and thermistor derived CTS depth (~5.59 m)
  1) less than 1 year time span
  2) Model stops before installation of thermistor string

Discussion

- **CTS at Glacier Scale**
- Contradicting results: trend of thickening of cold surface ice
  1) Model performance limitation
  2) Lack of model calibration
  3) Uniform water content assumption.
  4) No horizontal advection of ice (bedrock threshold)
  5) Homogeneous assumption when interpolating climate forcing data
  6) Fresh snow during the entire winter (higher albedo ~0.89)

Discussion

- **Spatial Correlation and Analysis**
- correlation mode change for mass balance and accumulation

1) Snowpack ablation protection effect vs insulation effect?
2) Model didn't take the bedrock topography into account.

Conclusion

- CTS derived from both extrapolated thermistor string data and model results shows an overall increasing trend of CTS.
  - ~ 0.9 $m \cdot a^{-1}$ at study site.
- The **spatial pattern** of the cold surface layer thickness from previous surveys were **preserved** in the model results. The overall spatial extent of the simulated cold surface layer tends to become **smoother**.

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- CTS migration gradient is higher during the ablation season and lower during the accumulation season.
- Seasonal variations of CTS migration gradient have a time **lag** in response to the temperature changes at glacier surface.
- The correlation map finds that mass balance, accumulation, and melt are closely connected to the cold surface layer evolution. Different factors account for the CTS variations differently and the strength also changes.

Conclusion

- Melt is negatively correlated with CTS in the whole study area
- Mass balance and snow accumulation exhibit a change of correlation pattern depends on a certain threshold
- The bedrock threshold is identical on the spatial pattern of CTS and plays an important role in the correlation map experiment.
- The selected coupled surface energy balance-snowpack model needs to be validated before implementing it to Storglaciären.

Thanks

Storglaciären and Kebnekaise in August 2018 Photo: Shunan Feng