Melt and Surface Sublimation across a Glacier of the Tibetan Plateau: Distributed Energy Balance Modelling of the Parlung No. 4 Glacier

Multi – source hydrological data products to monitor High Asian River Basins and regional water security (MUSYCADHARB) 32449

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32449, Lead: Massimo Menenti, Xin LI

Observation and modelling of high elevation hydrological processes, including accumulation and ablation in glaciers

Chinese PI: Kun Yang
EU PI: Francesca Pellicciotti

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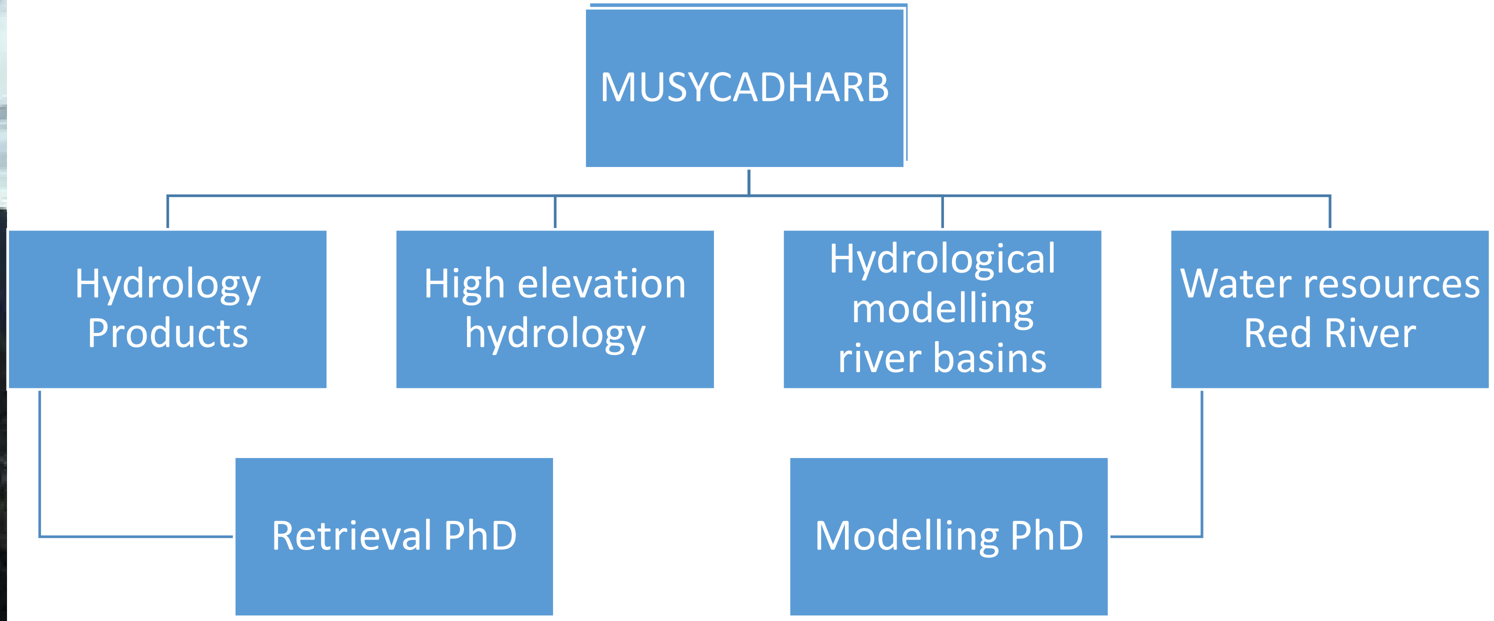

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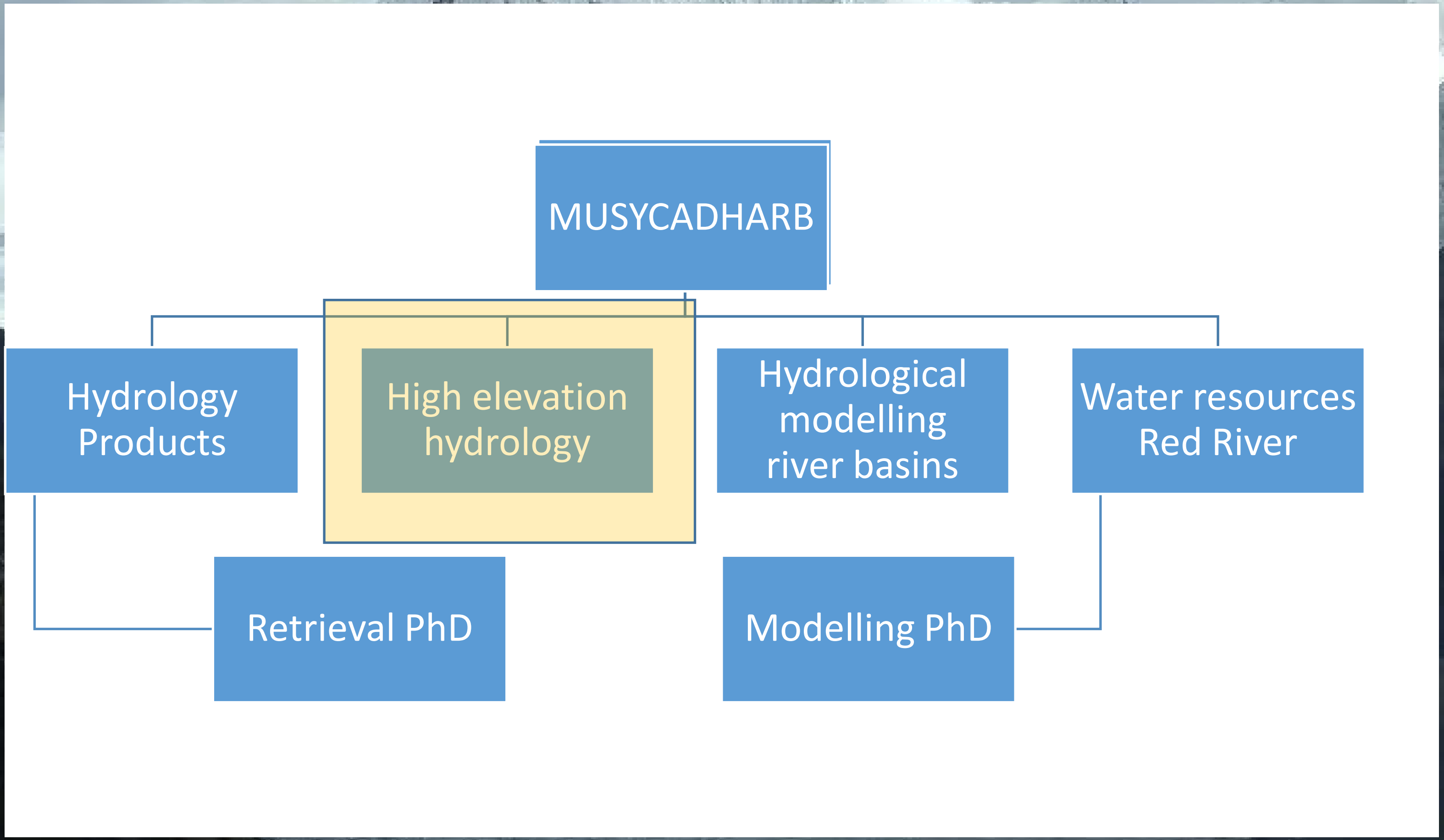
European Space Agency



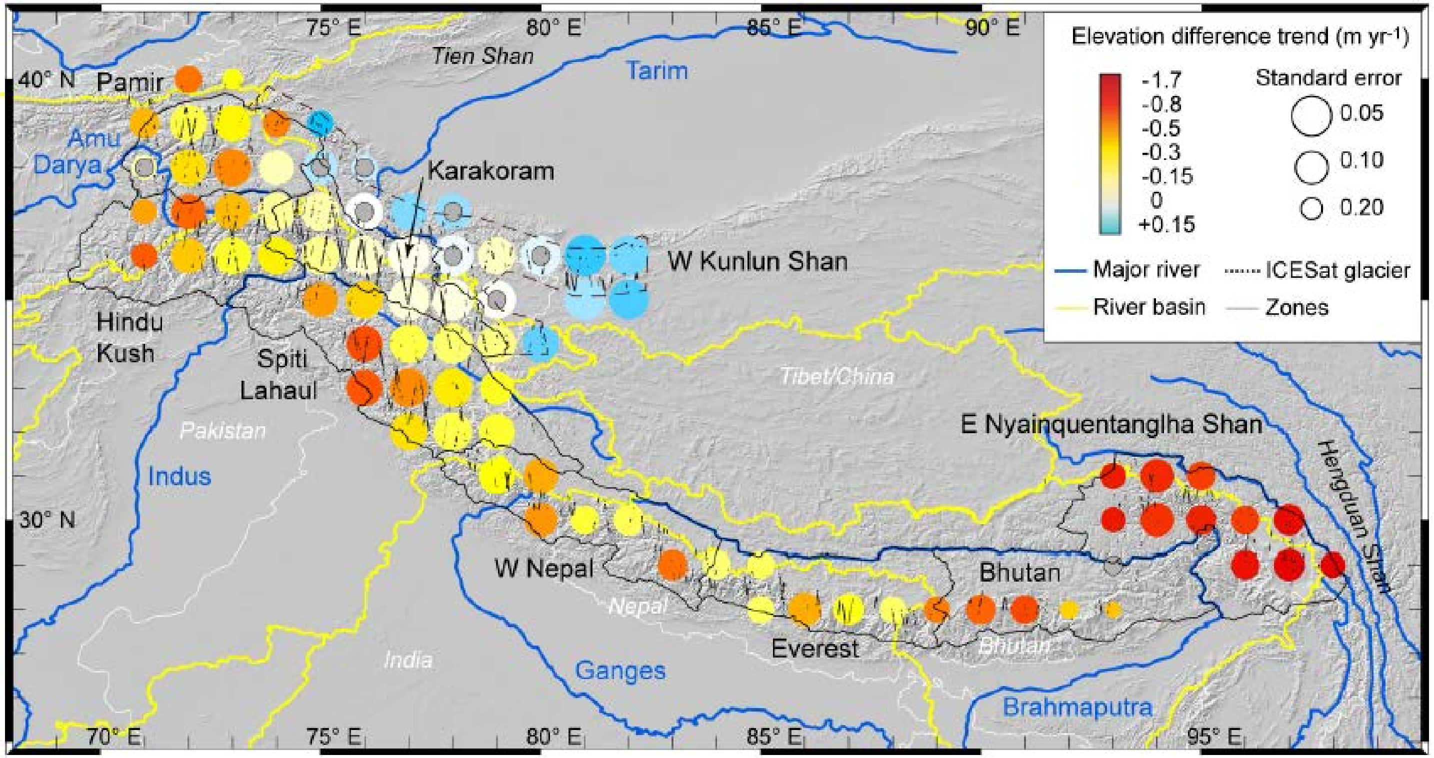
Observation and modelling of high elevation hydrological processes, including accumulation and ablation in glaciers

Chinese PI: Kun Yang
EU PI: Francesca Pellicciotti

Main goal: Unravel the **hydrological functioning** of representative **high elevation glacierised catchments** across the Tibetan Plateau and identify the causes for different **glacier mass balances** and **contribution to basin runoff** in individual climate regimes

Background

Complex patterns and large variability of glacier mass balance and glacier response to climate in High Mountain Asia (Kääb et al., 2012; Bolch et al., 2012; Gardelle et al., 2012, 2013)



Kääb et al. (2015), *TC*; Kääb et al. (2012), *Nature*

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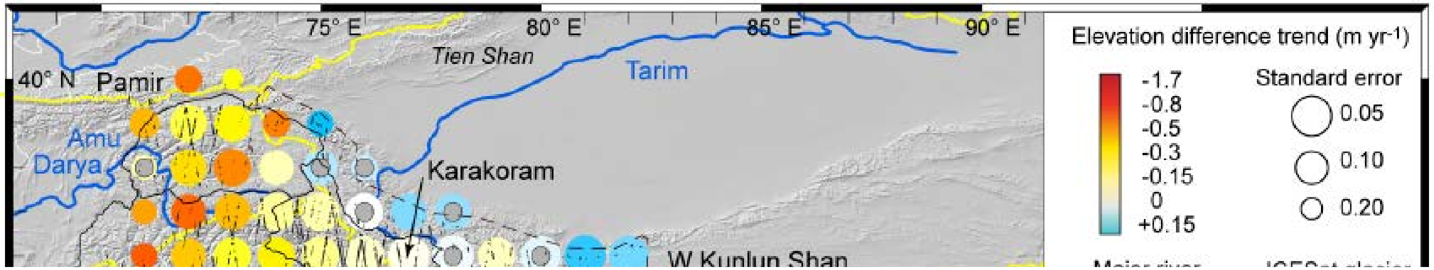
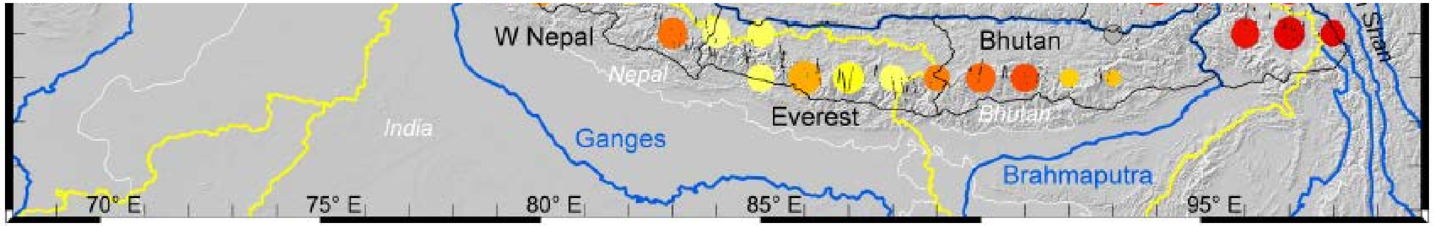


Contrasting patterns of early twenty-first-century glacier mass change in the Himalayas

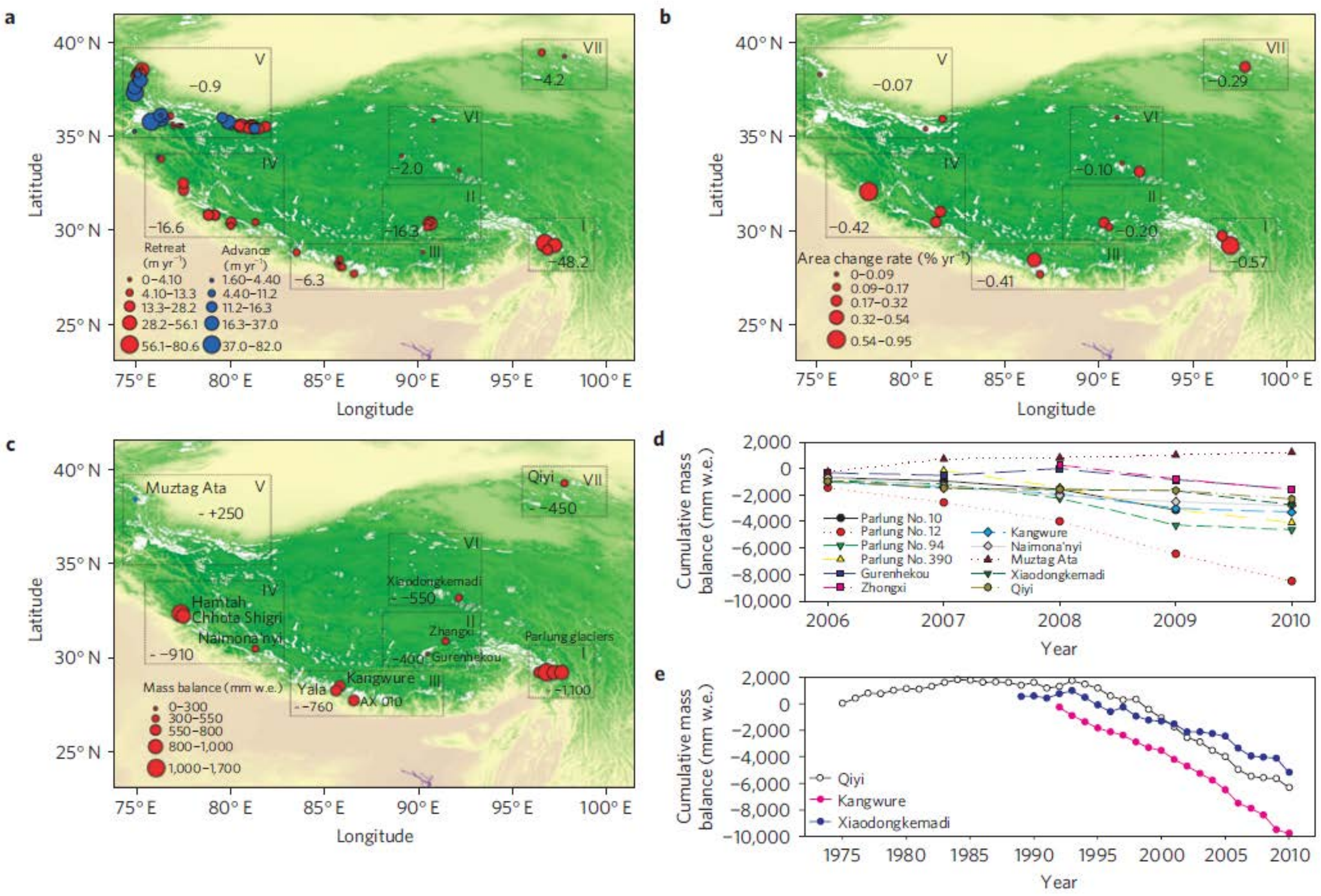
Andreas Kääb[1], Etienne Berthier[2], Christopher Nuth[1], Julie Gardelle[3] & Yves Arnaud[4]



Kääb et al. (2015), *TC*; Kääb et al. (2012), *Nature*

Background

Complex patterns and large variability of glacier mass balance and glacier response to climate in High Mountain Asia: **Tibetan Plateau**

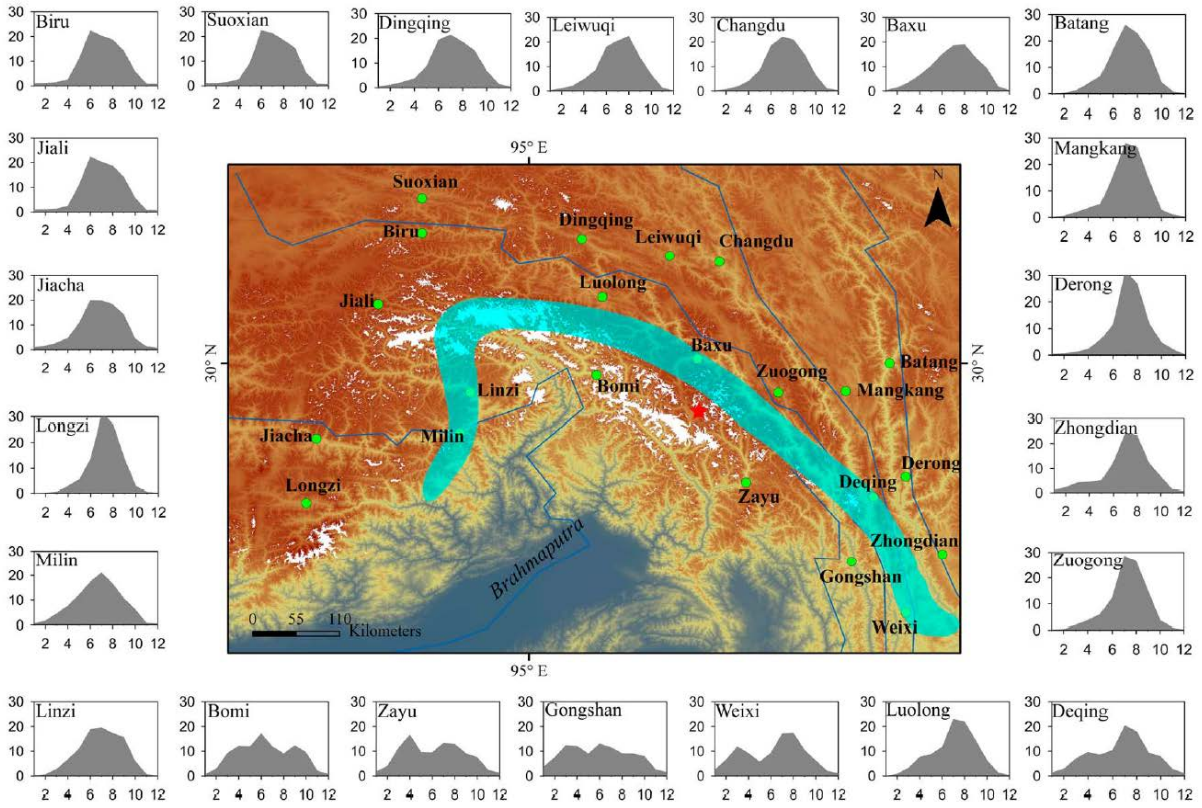


Yao et al. (2012), Nature Climate Change: *Different glacier status with atmospheric circulation in Tibetan Plateau and surroundings*

Background

Complicated by heterogeneity of climatic conditions across the TP due to the presence of the monsoon and summer-accumulation type glaciers

Few studies have assessed present day glacier behaviour on the TP, mainly because of a lack of glacio-meteorological field data.



Yang et al. (2013), JGR

Background

Energy balance models can provide *accurate* simulations of **energy fluxes** and **ablation** to improve understanding of the **main processes** at the glacier-atmosphere interface.

Most estimates of melt and surface sublimation rates for the glaciers of the TP at the **point scale**

- Moelg et al. (2012), TC
- Huintjes et al (2015), AAAR

Not established yet how ablation components vary **across the entire extent** of a glacier in this environment.

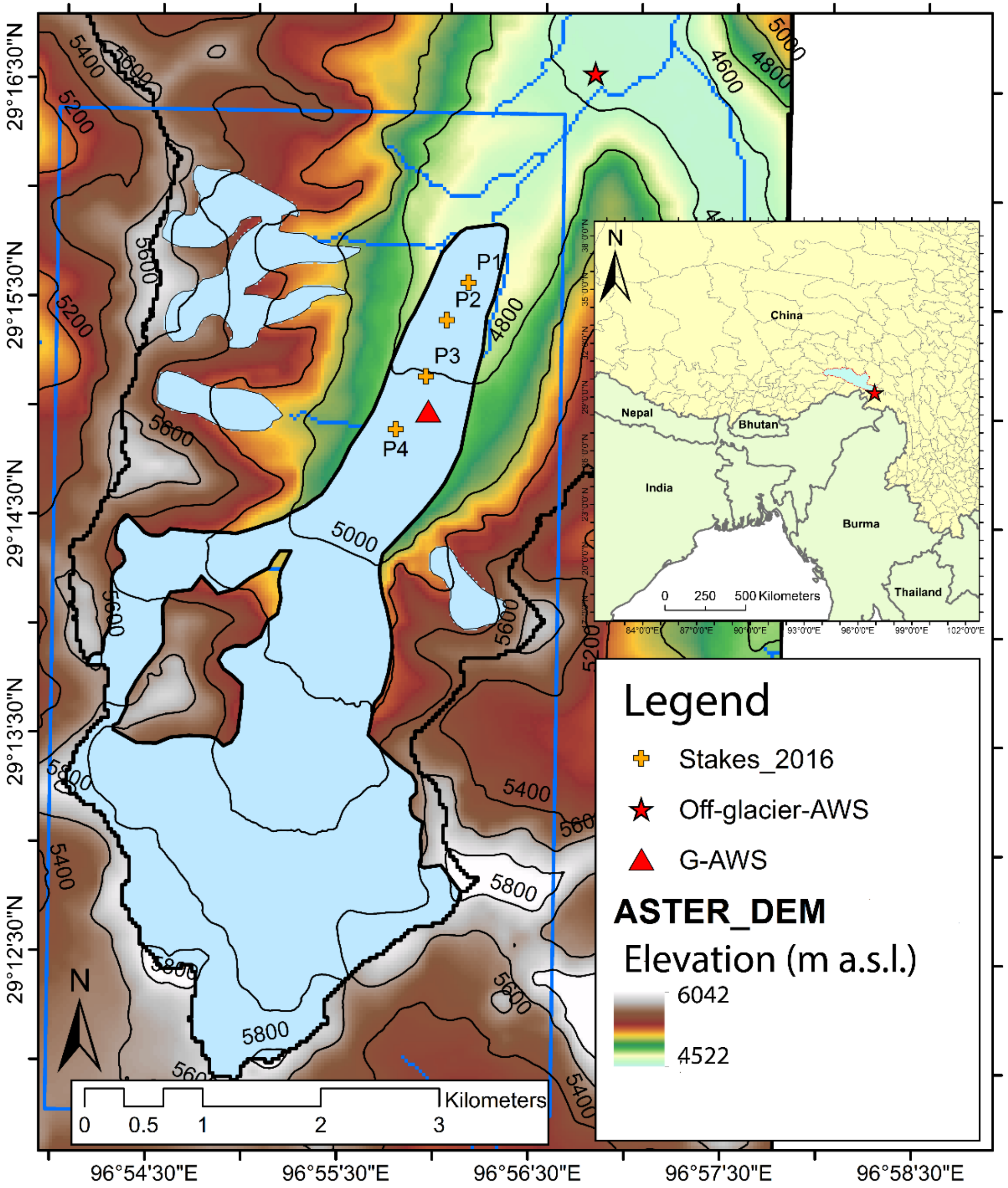
Study Site: Parlung N° 4 Glacier

Size: 10.84km^2

Elevation range: 4659-5939 m a.s.l. (median = 5397 m a.s.l.)

Glacier length: ~7.5 km, North-NorthEast facing.

Mean slope: 15° (0.3-62° range)



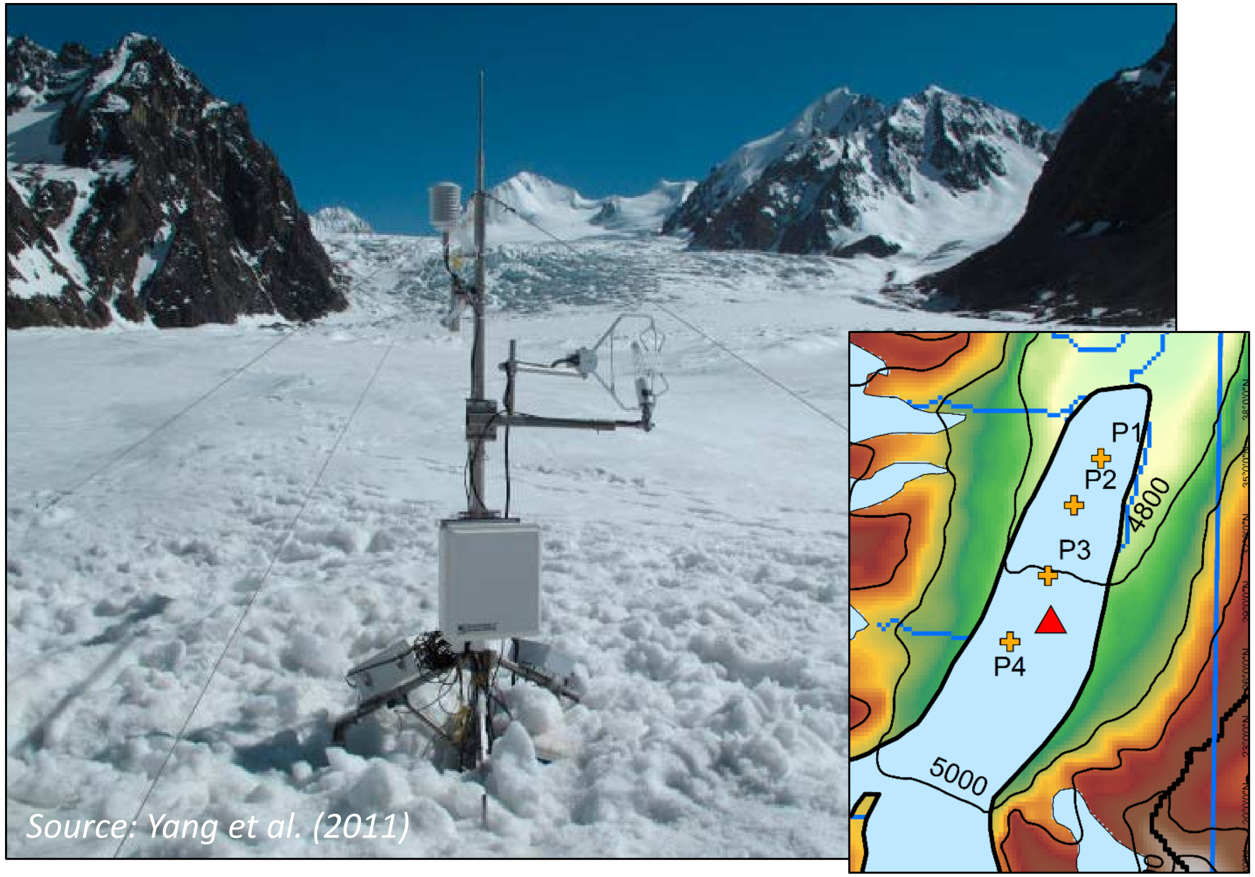
Data

- Automatic weather station (AWS) at 4808 m a.s.l. on the glacier. More than 18,000 hourly observations for:

1st June – 8th September 2009
Full EB, Eddy Cov., Precipitation
10.6% of hourly data is missing

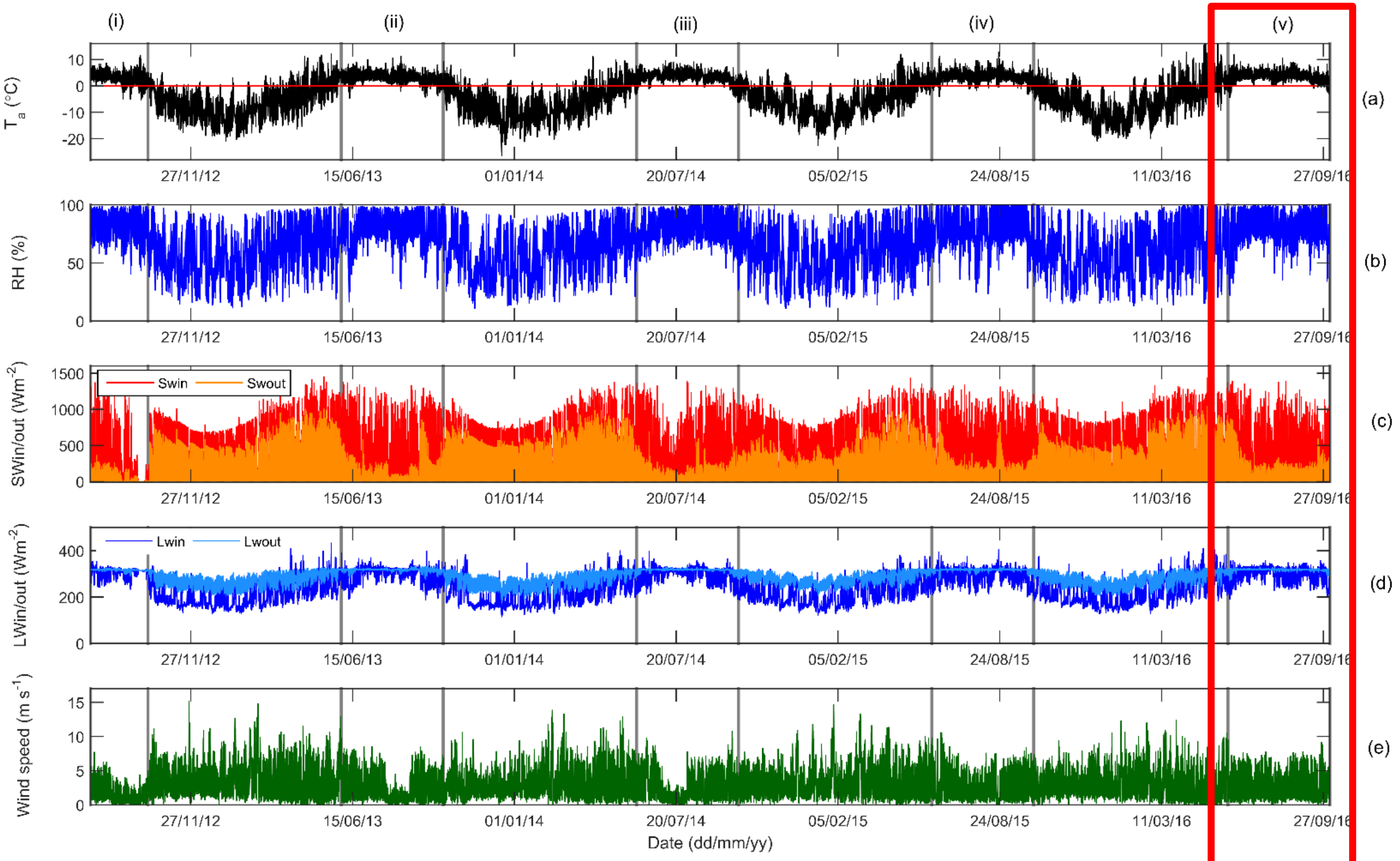
25th July, 2012 - 4th October, 2016
Full EB, precipitation, stake data in 2016
Minor data gaps

- Ablation stakes on the glacier tongue



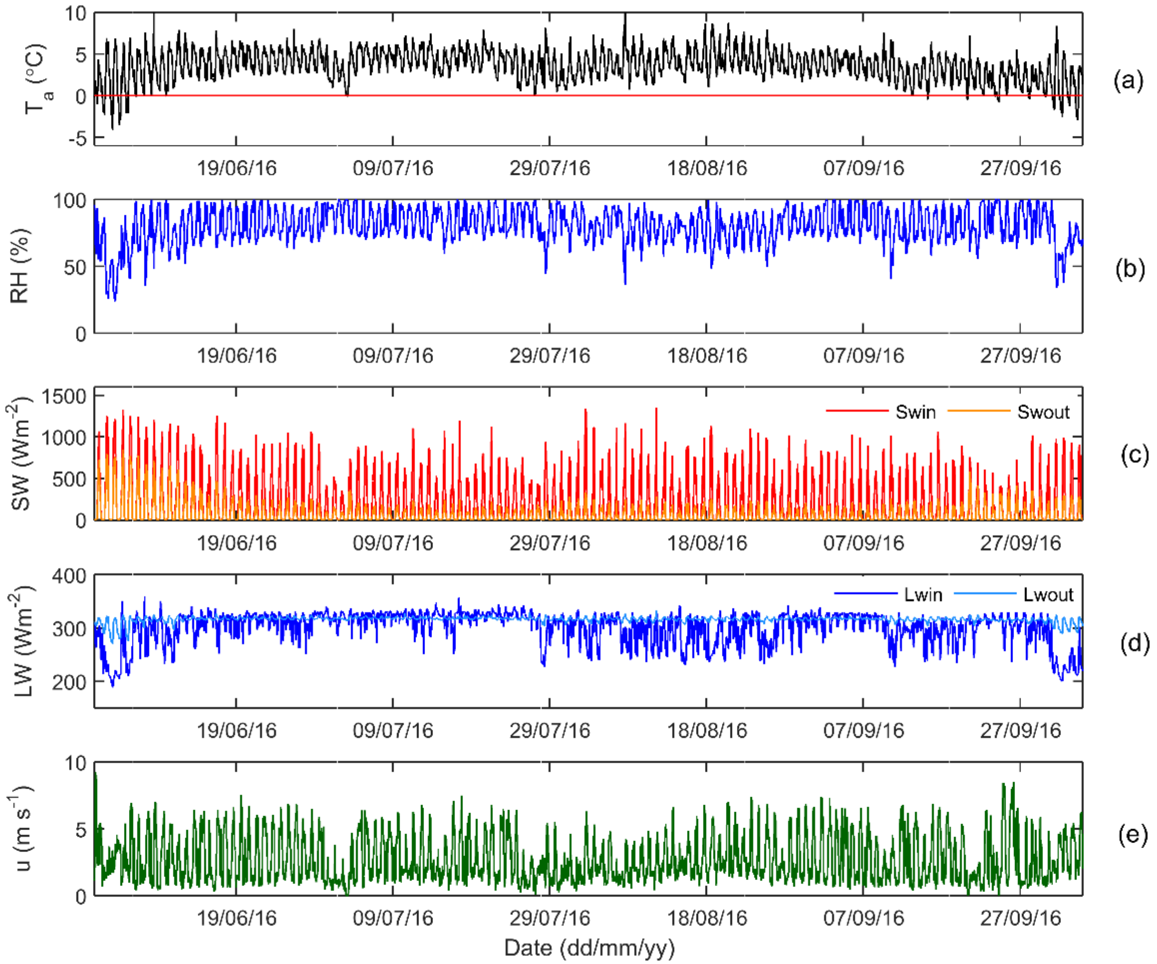
Source: Yang et al. (2011)

Meteorological conditions over the glacier (2012-2016)



Current focus on summer 2016

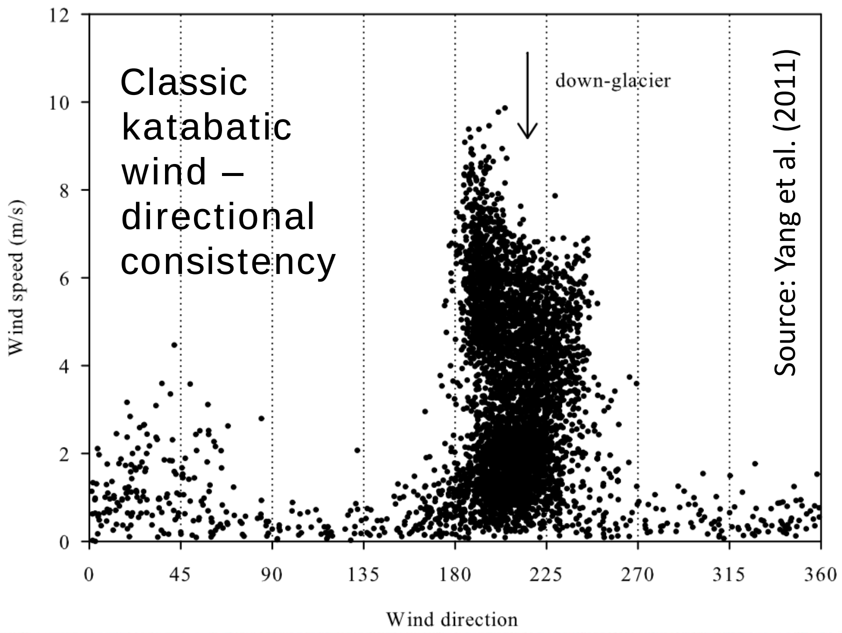
Meteorological conditions over the glacier (2016)



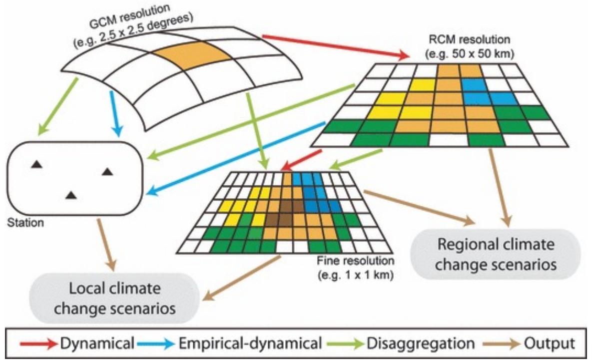
2016 summer season on Parlung Number 4 Glacier

Few sub-zero air temperature fluctuations (mean summer (JJAS) temperature: 3.65°C)

Diurnal cycle of wind speeds typically exceeding 4-5 m s^{-1}



Reanalysis input data



ERA Interim reanalysis - multiple pressure levels

- Specific humidity, u/v wind components, relative humidity and air pressure - linearly interpolated from the 0.125° grid to the elevation of the glacier grid cell.

Wind speed is adjusted to surrounding topography from 450 hPa pressure level following Peleg et al. (2017) and Ayala et al. (2017).

Energy balance model

A two-layer, distributed energy balance model (Ayala et al., 2017)

First layer:

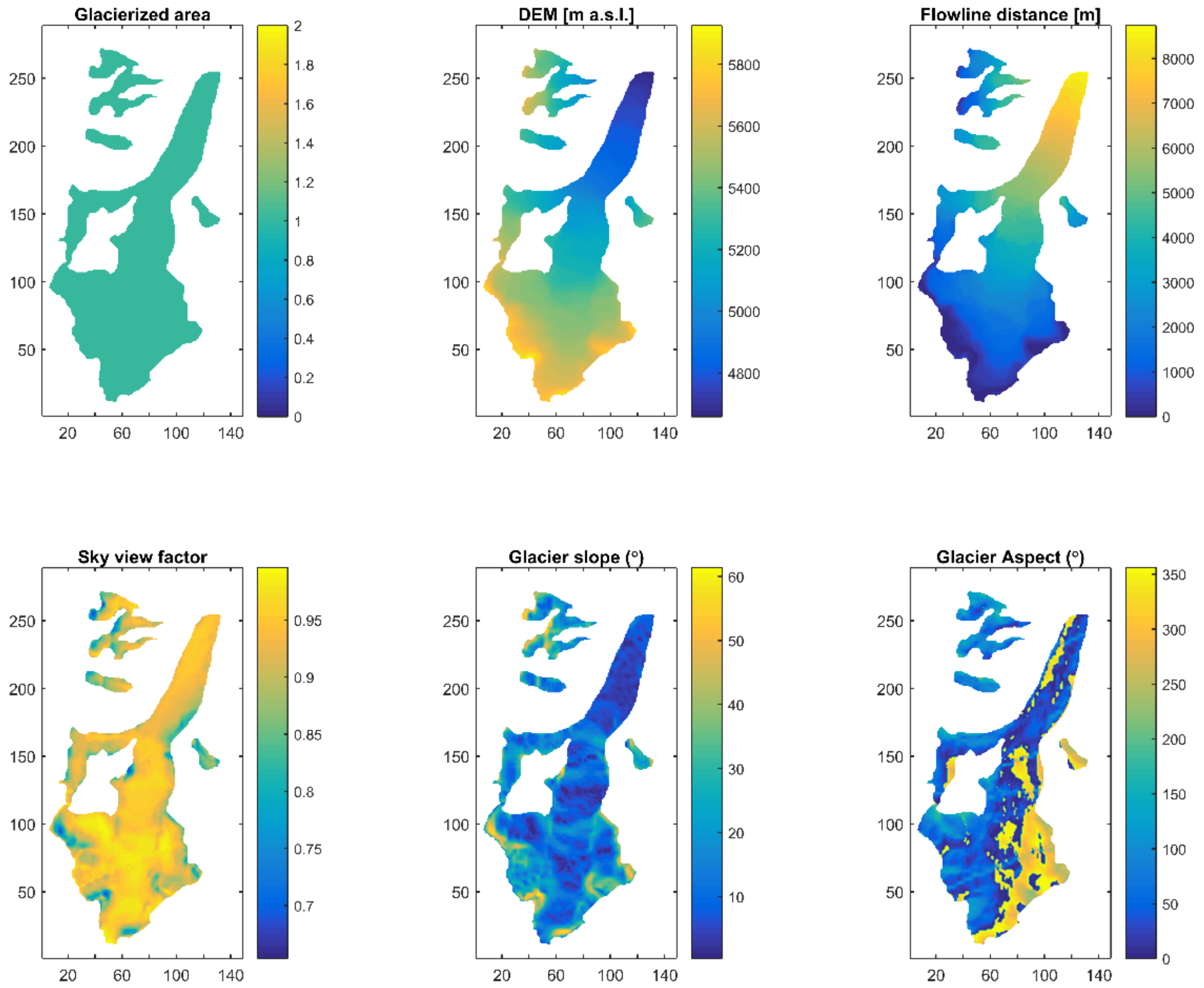
$$\int_0^{z_1} \rho c_s \frac{\partial T}{\partial t} dz = (1-\alpha)S_{in} + L_{net} + Q_H + Q_L + Q_{S(i=1)} + Q_{M(i=1)} + Q_{R(i=1)}$$

Second layer:

$$\int_{z_1}^{z_2} \rho c_s \frac{\partial T}{\partial t} dz = Q_{S(i=2)} + Q_{M(i=2)} + Q_{R(i=2)}$$

Ayala, A., F. Pellicciotti, N. Peleg and P. Burlando. 2017. Melt and surface sublimation across a glacier in a dry environment: Distributed energy balance modelling of Juncal Norte Glacier, Chile, *in press in Journal of Glaciology.*

Model setup: distributed gridded input



1) Digitised glacier outline from Digital Globe imagery

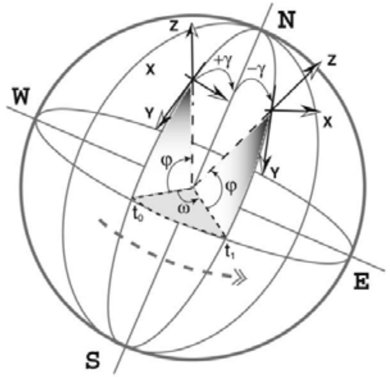
2) Elevation (DEM) from ASTER GDEM: 30 m resolution

3) Flowline distance (m), Slope and Aspect (°) calculated using DEM from topotoolbox in Matlab®

4) Sky view factor calculated from Saga GIS® using DEM

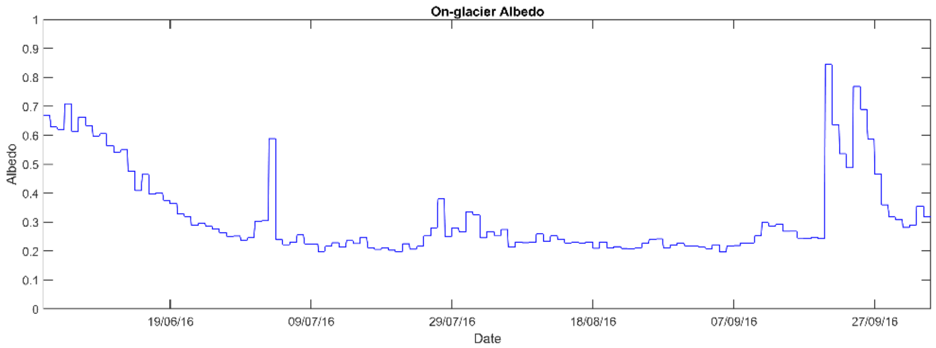
Model setup: parameterisations of meteorological and surface variables

Shortwave radiation – modelled using DEM and vectoral algebra following Iqbal (1983), Corripio (2003) and Pellicciotti et al. (2011)



Longwave radiation - estimated using modelled emissivity as in Dilley and O'Brien (1998) and a cloud correction from Unsworth and Monteith (1975) following Juszak and Pellicciotti (2013)

Snow albedo - parameterised following Oerlemans and Knap (1998)

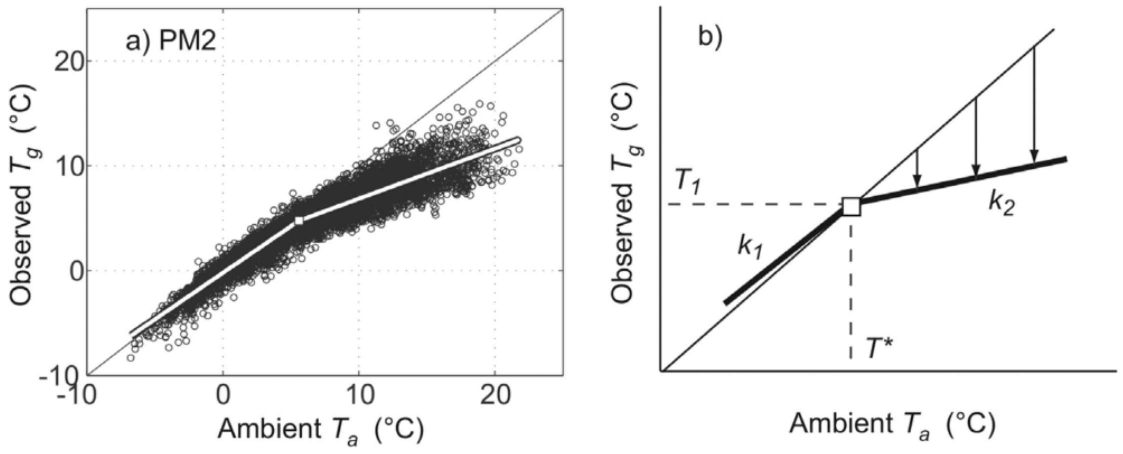


Extrapolation of meteorological variables

We tested different options to model two key meteorological variables input to the model:

Air temperature:

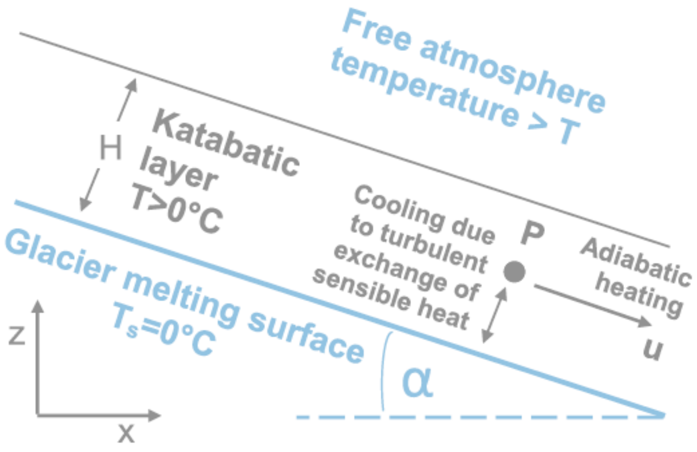
1. Distributed from the on-glacier AWS using the environmental lapse rate (-0.0065°C m^{-1}) to the elevation of the remaining grid cells
2. Distributed using ERA Interim reanalys at the location of the off-glacier AWS using the environmental lapse rate (-0.0065°C m^{-1})
3. A statistical approach (Shea and Moore, 2010) accounting for the cooling effect of the glacier and for the Katabatic Boundary Layer (KBL) indirectly



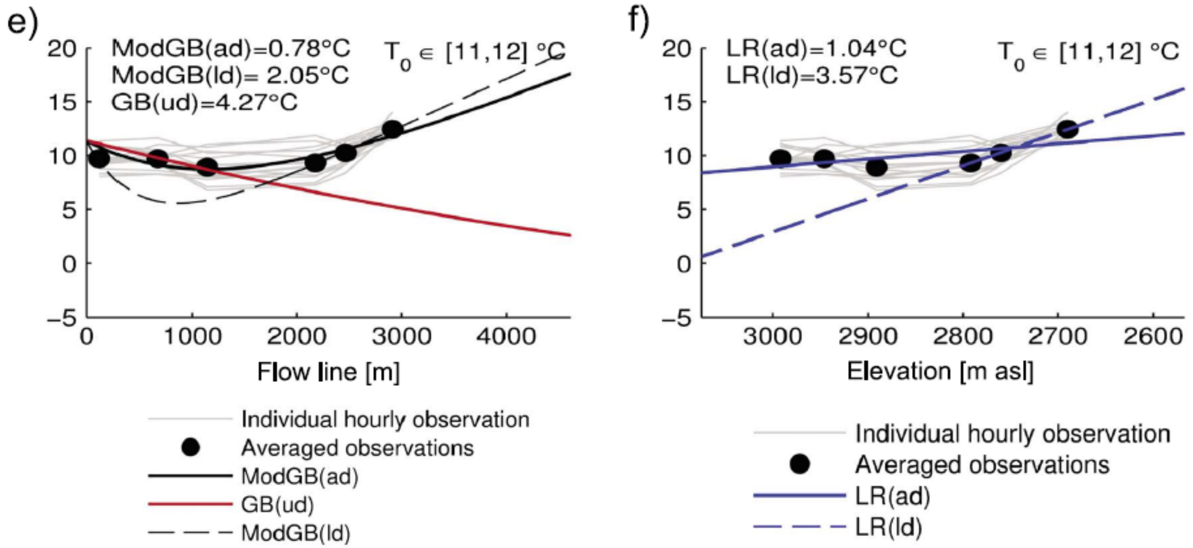
Extrapolation of meteorological variables

Air temperature:

4. A physically-based thermodynamic model of air temperature (Greuell and Bohm, 1998, JG; Ayala et al., 2015, JGR)



$$T(x) = (T_0 - T_{eq})\exp\left(-\frac{x - x_0}{L}\right) + T_{eq} + \underbrace{K\left(\frac{x - x_0}{L}\right)}_{\text{NEW TERM}}$$



Ayala, A., F. Pellicciotti and J. Shea. 2015. Modeling 2m air temperatures over mountain glaciers: Exploring the influence of katabatic cooling and external warming, *Journal of Geophysical Research.*

Extrapolation of meteorological variables

We tested different options to model two key meteorological variables input to the model:

Wind speed

1. Uniform in space wind speed equal to the one recorded at AWS (variable in time)

2. ERA Interim synoptic flow **topographically adjusted** to surrounding topography from 450 hPa pressure level following Peleg et al. (2017) and Ayala et al. (2017).

Reference run

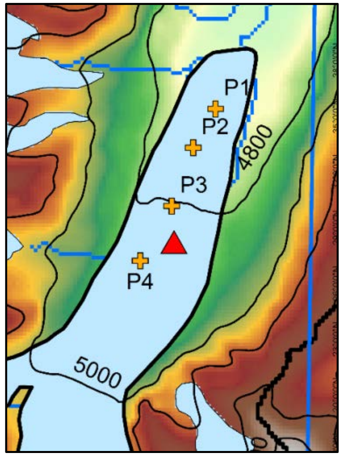
- *Air temperature*: Distributed from the **on-glacier AWS** using the **environmental lapse rate** (-0.0065°C m^{-1})
- *Wind speed:* **uniform in space** and equal to the one recorded at the **on-glacier AWS**

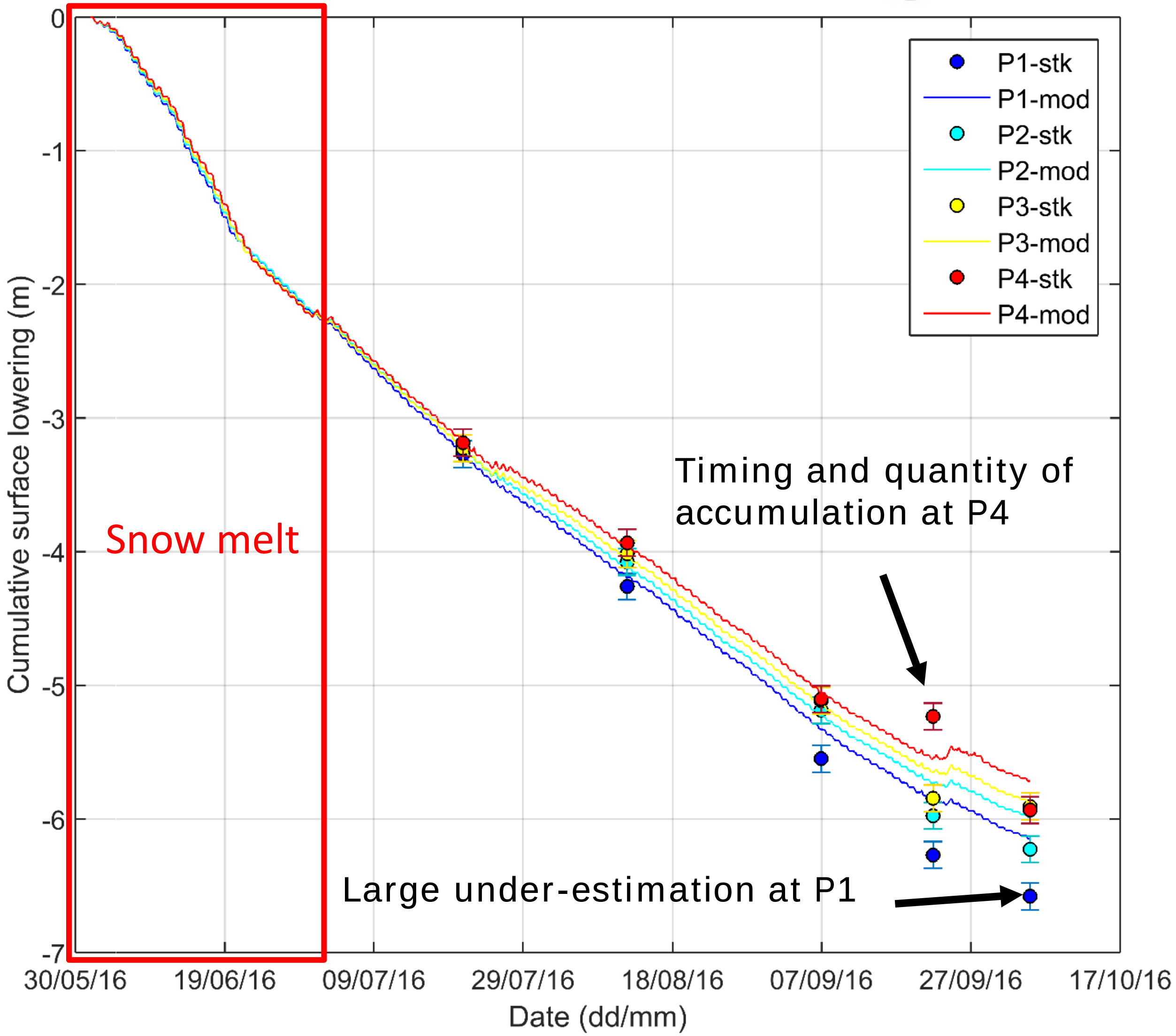
Results: Reference run

Validation at the stakes

Simulations of hourly melt from 1st June to 4th October, 2016

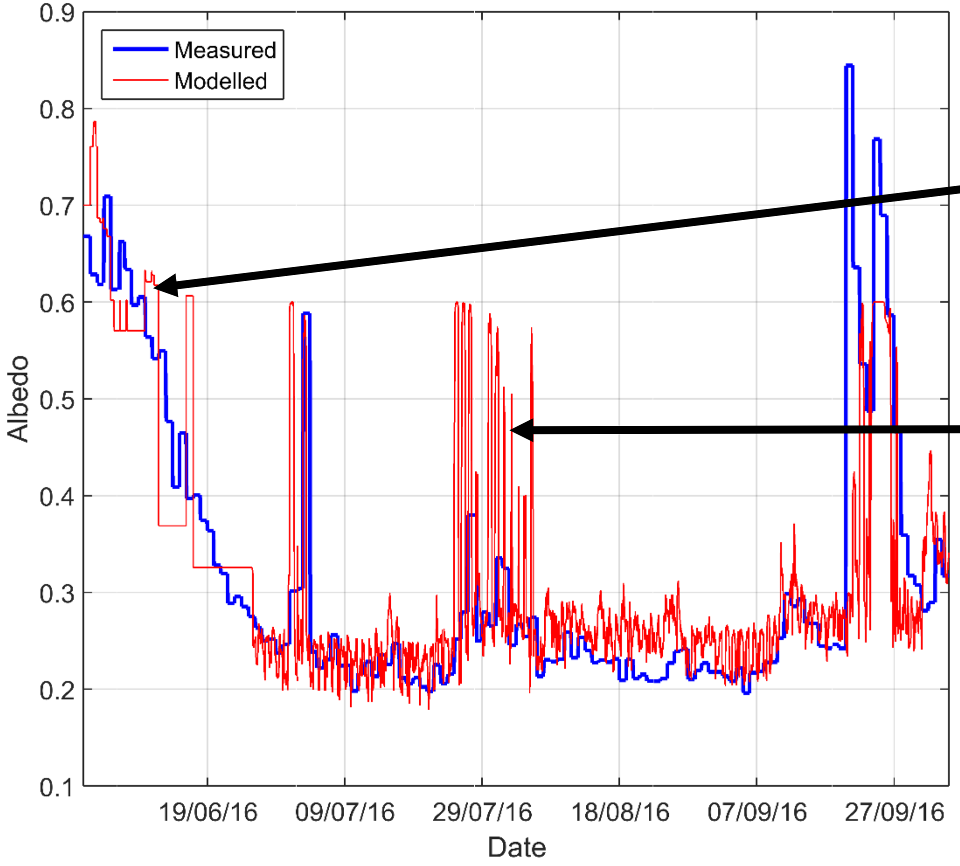
- **Good overall estimation** of ablation at Stakes P3 (yellow) and P4 (red)
- Small under-estimation at P2 (turquoise)
- Large **under-estimation** at P1 on the **glacier tongue:** due to constant in time z_0 and wind speed?





Reference run: Albedo validation

Albedo: similar parameters as to those reported by Yang et al. (2013) for 2009

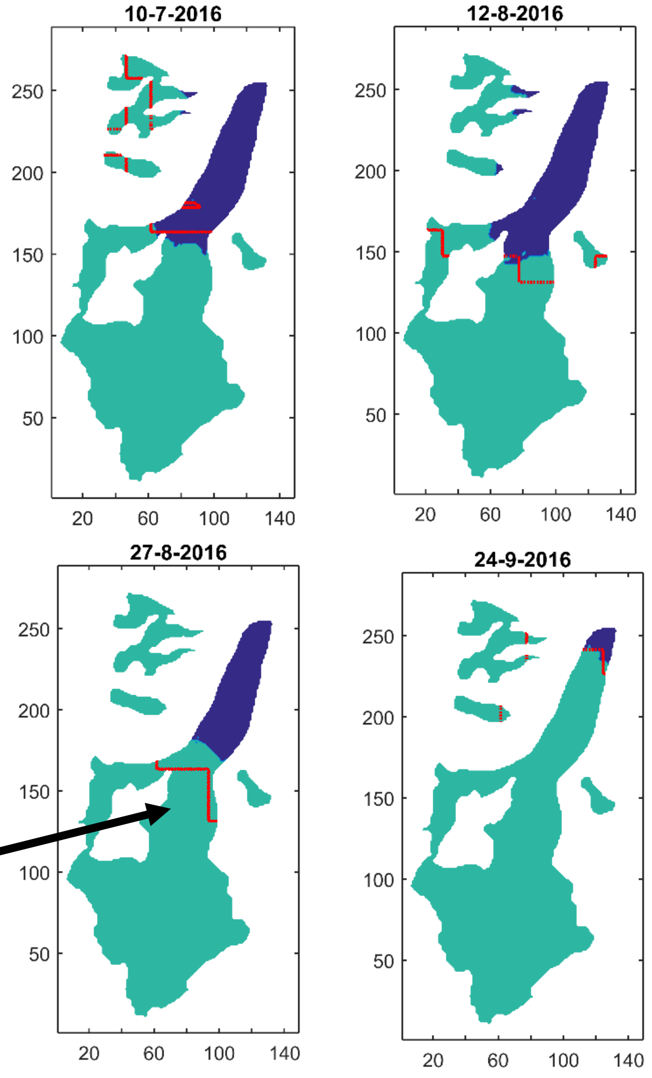


Jump changes in initial albedo decay

Albedo of fresh snowfalls accounted for but not always accurately simulated.

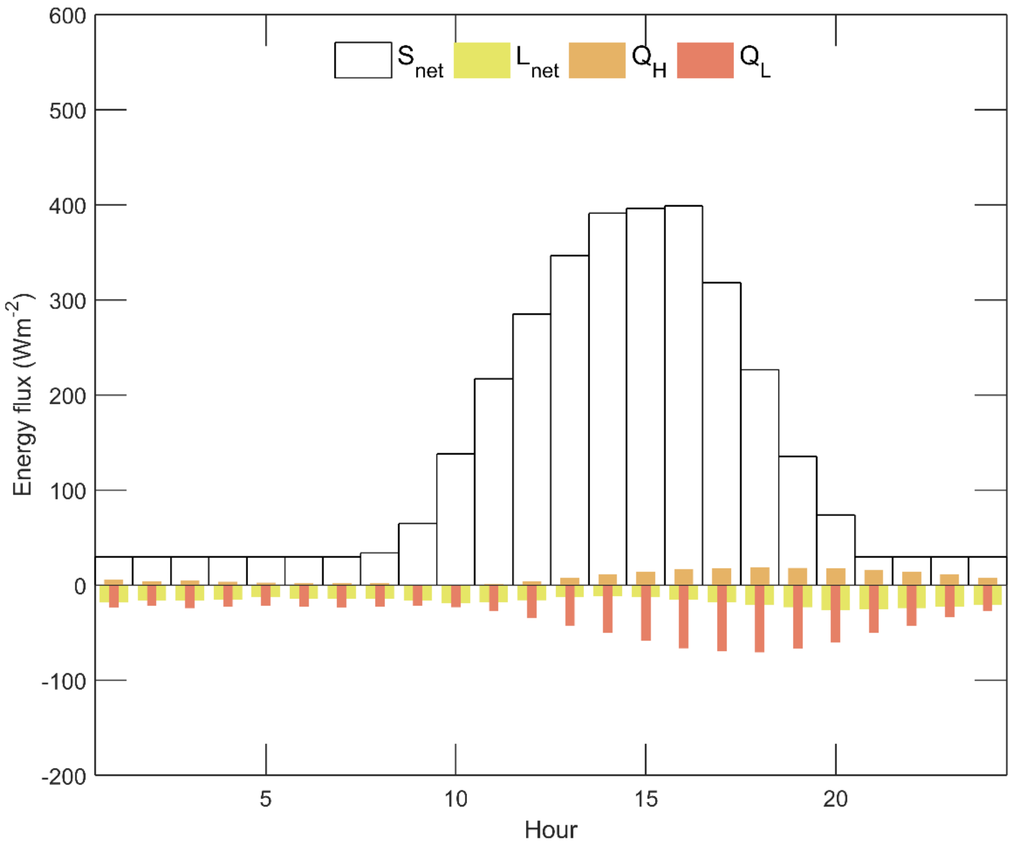
Effect of ice albedo under thin snowfall and function of snow depth?

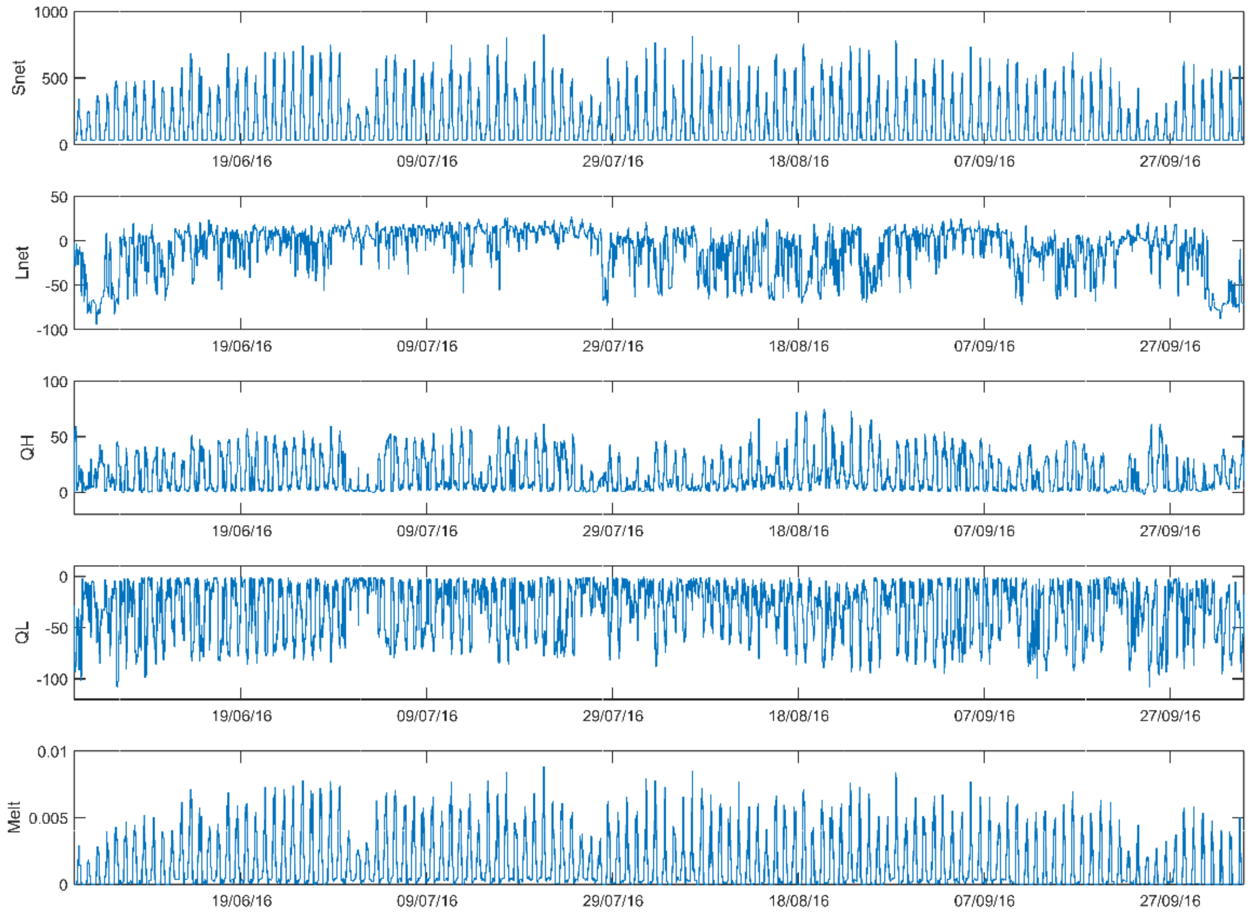
Problems related to initial snow depth and unknown precipitation gradients



Reference run: energy fluxes

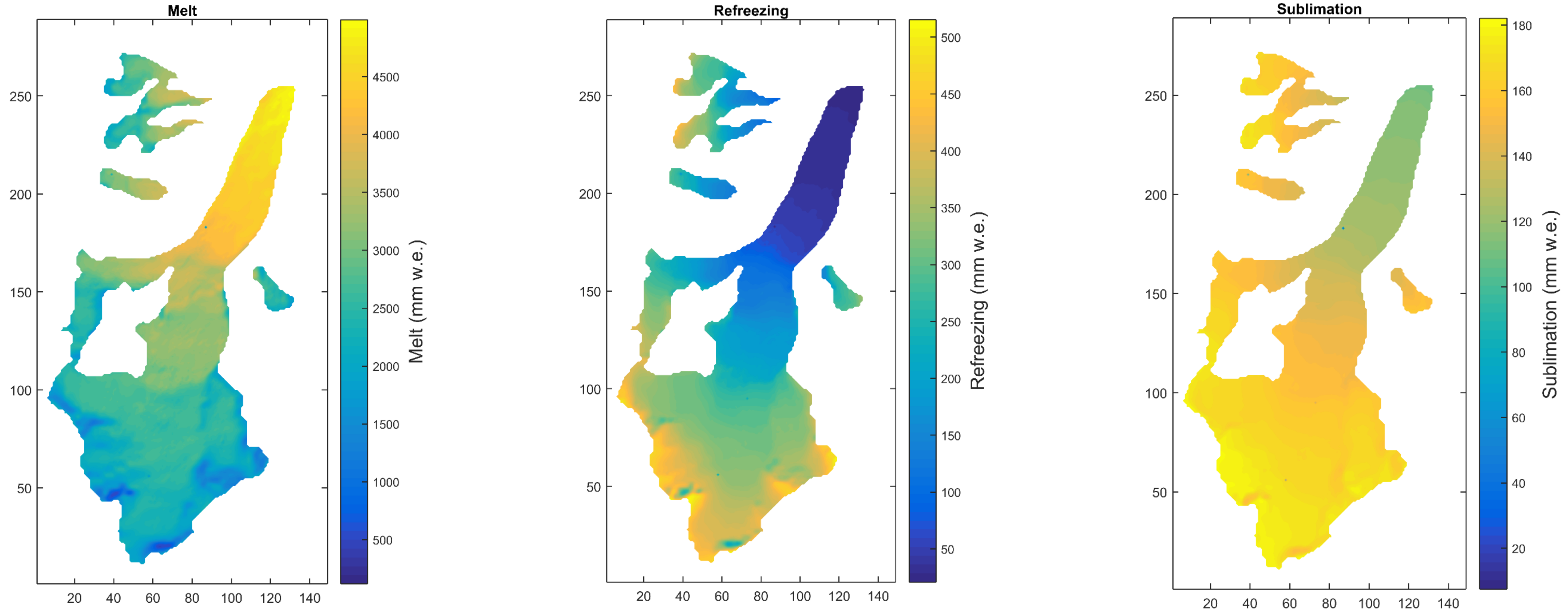
Dominated by the *shortwave radiative flux*
QL noteworthy into the late afternoon following peak Ta





Reference run: Mass balance components

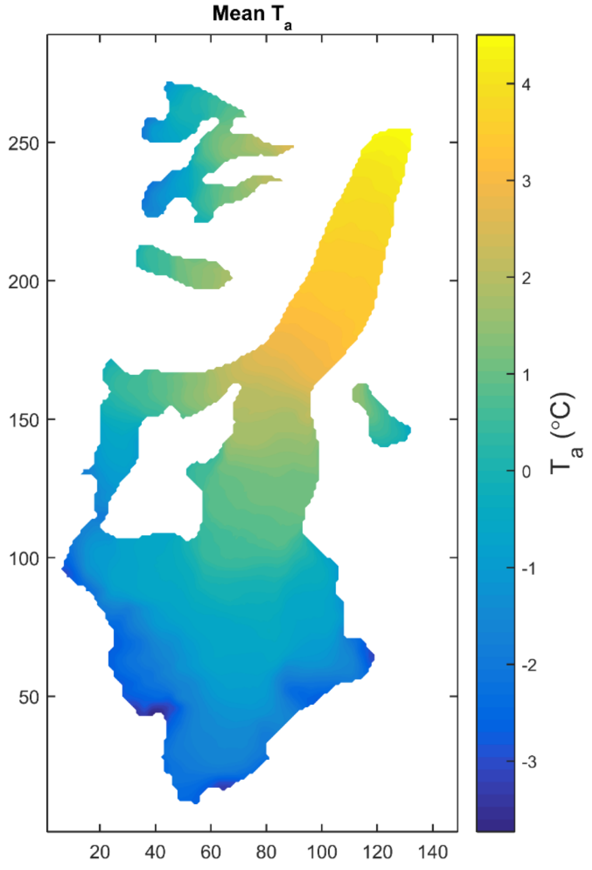
Total mass balance components at the end of the ablation season



- Spatial patterns dominated by the temperature patterns and shortwave radiation variability

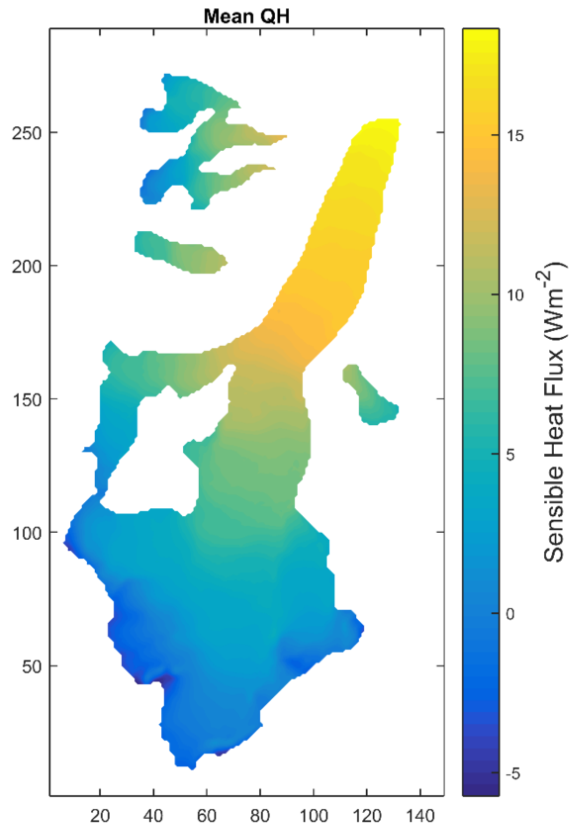
Reference run: Turbulent fluxes

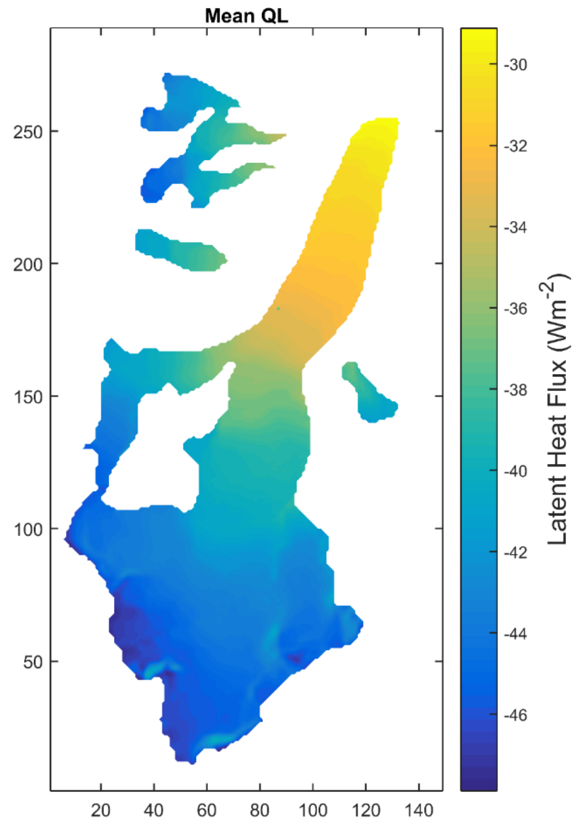
- **Uniform** spatial patterns **dominated by Ta-elevation relation** (uniform in space wind speed).



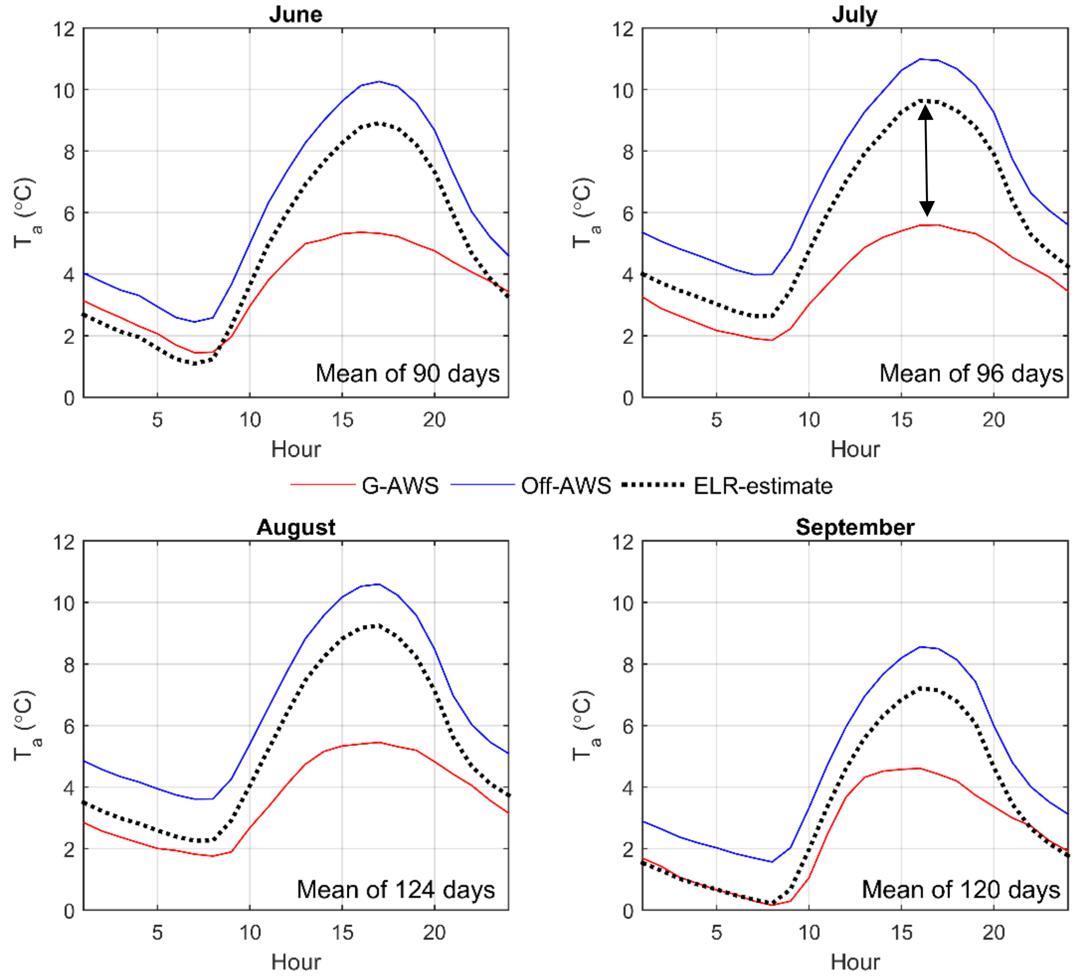
Some variability (especially in latent heat flux) in upper accumulation zone.

Mean QH/QL at AWS = 14Wm² / -33Wm²





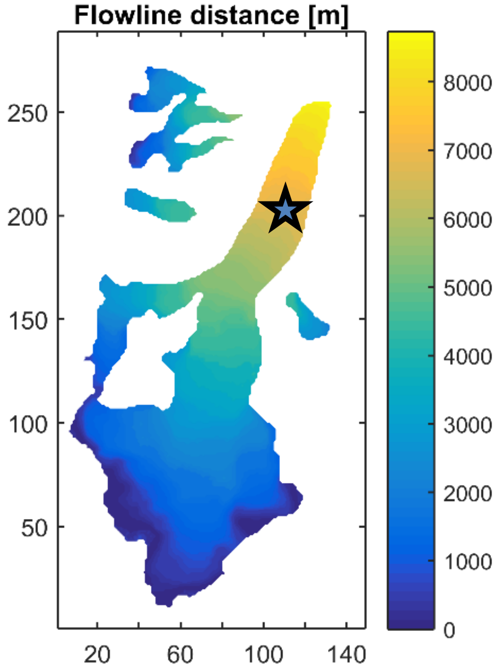
Run 1: Air temperature extrapolation from off-glacier ERA Interim Ta



Mean differences in measured and extrapolated temperature ~ 4°C for mid-summer.

Consistent with the down-glacier katabatic wind expected over a flow-line distance of > 6500 m.

Uncertain if the glacier tongue exhibits a cooler on-glacier temperature than AWS for katabatic conditions



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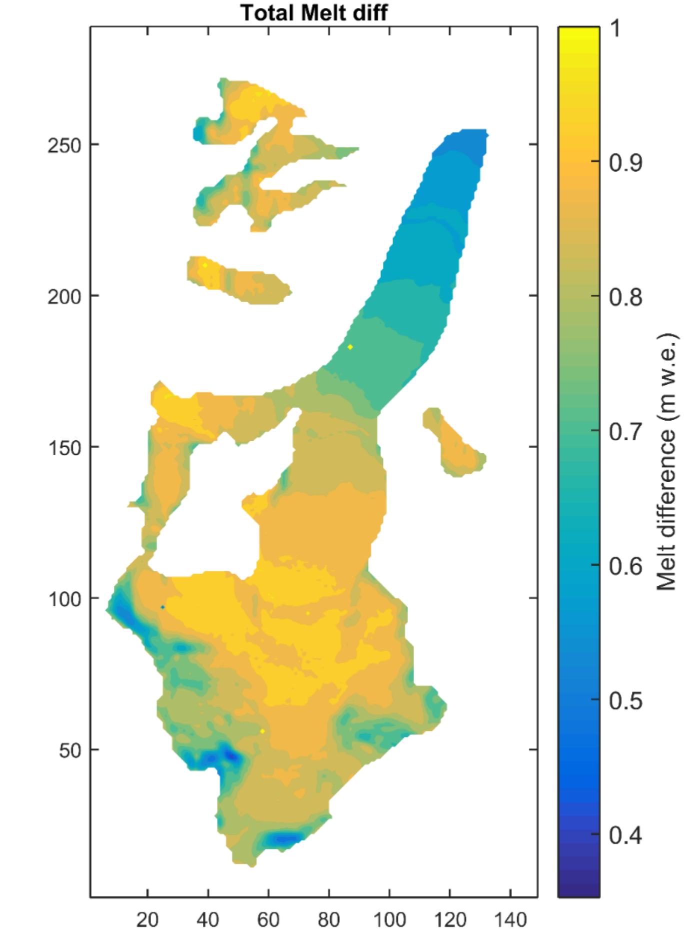
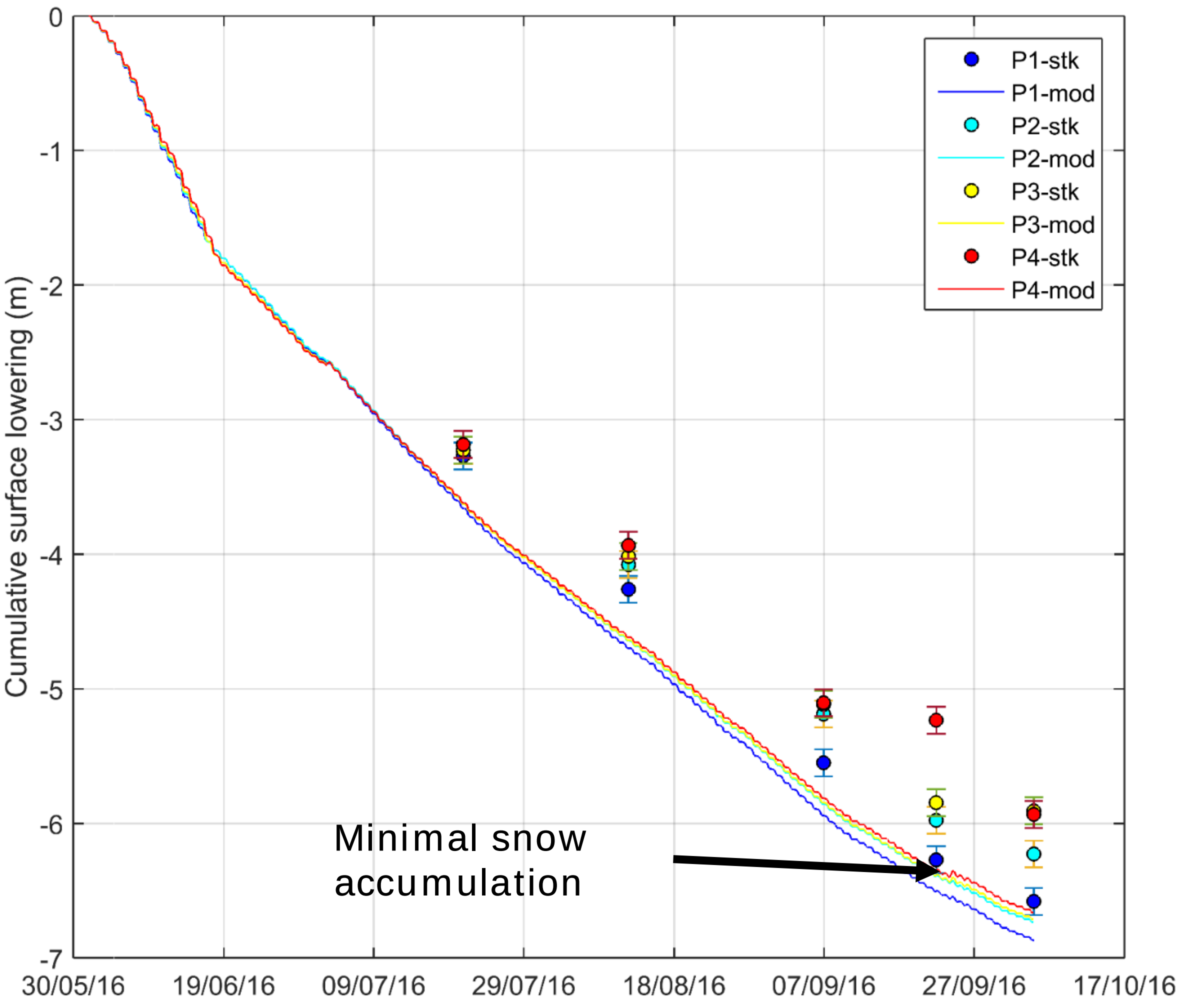


Difference between Run 1 and Reference run over the melt season

Strong melt increases at higher elevations: up to 0.95 m compared to the Reference Run (using on-glacier Ta)

Over-estimation of ablation for all stakes on lower-glacier



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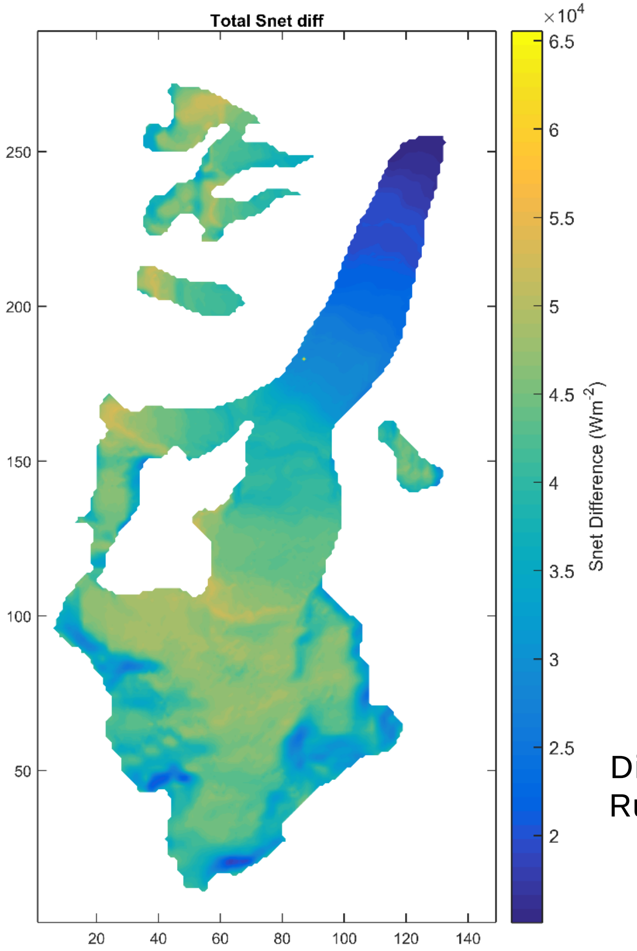


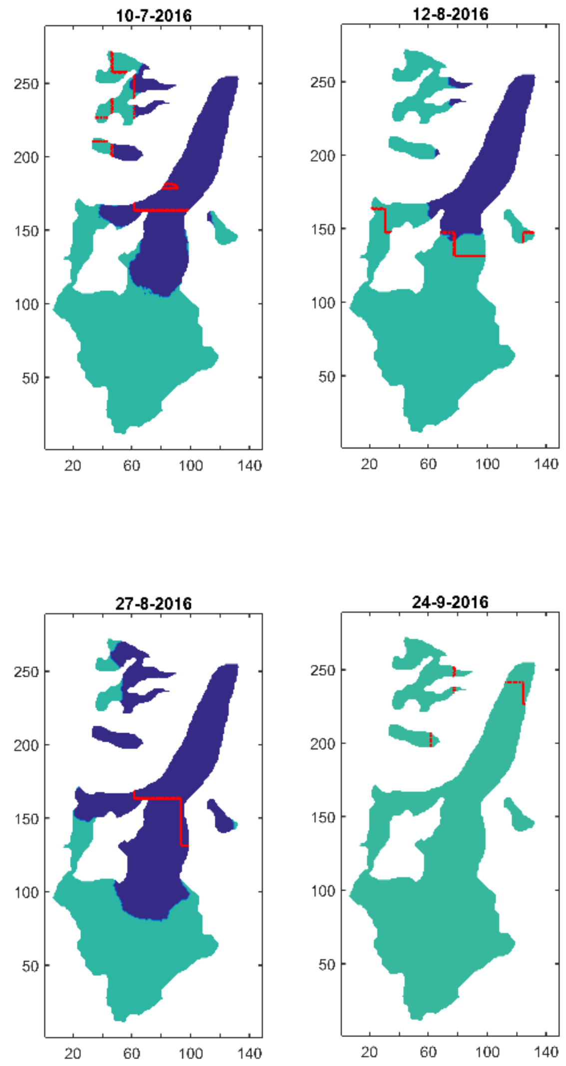
Strongest feedback: rapid depletion of snow cover and reduction of albedo

+

Reduced snow accumulation at mid-glacier due to threshold solid precipitation temperatures

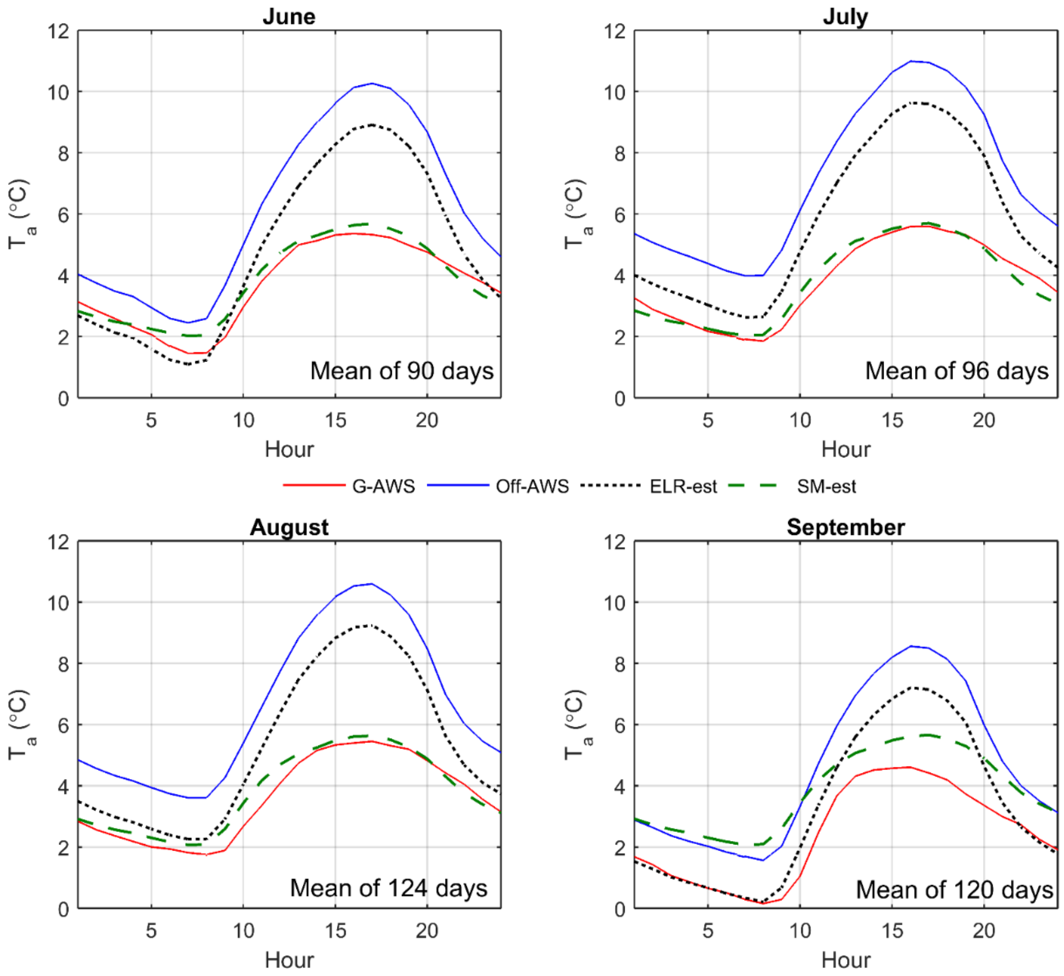
= Large increases of net shortwave radiation (season total up to +65,000Wm^2)

Difference in net shortwave radiation between Run 1 and Reference run over the melt season



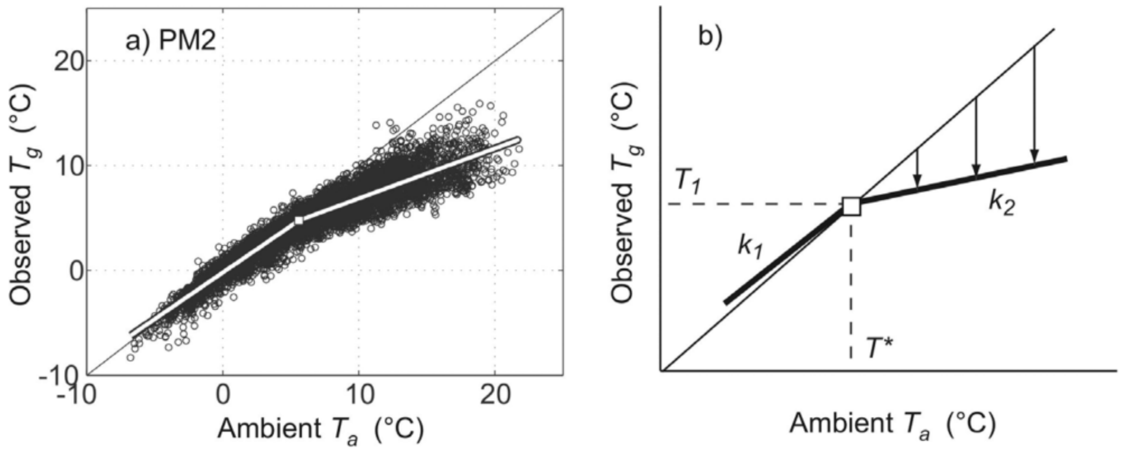
Simulated snowline position versus MODIS snowline (red line)

Run 2: Statistical air temperature estimation



Air temperature **modelled very well** in June-August using the statistical approach from Shea and Moore (2010) and their **original parameters**.

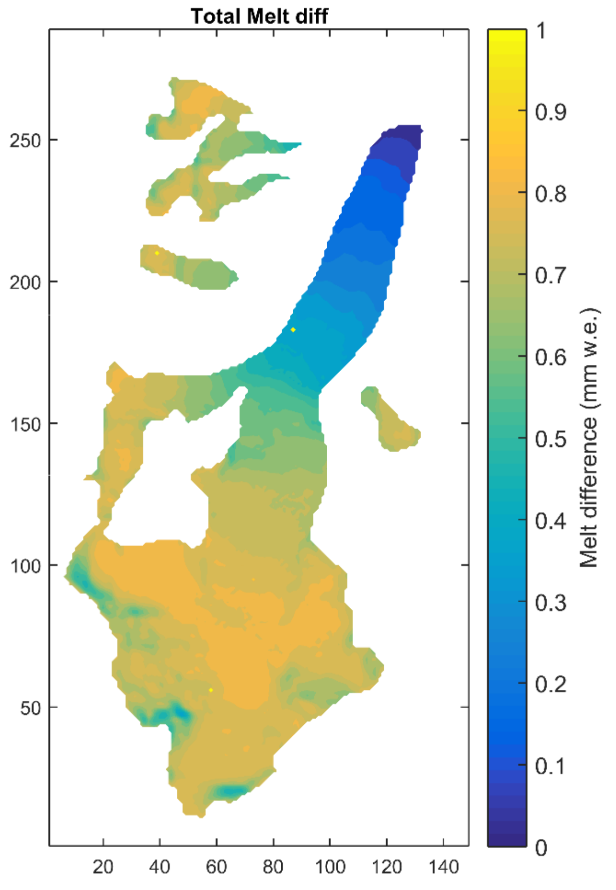
However too few observations to test appropriateness of model or alternatives at glacier tongue

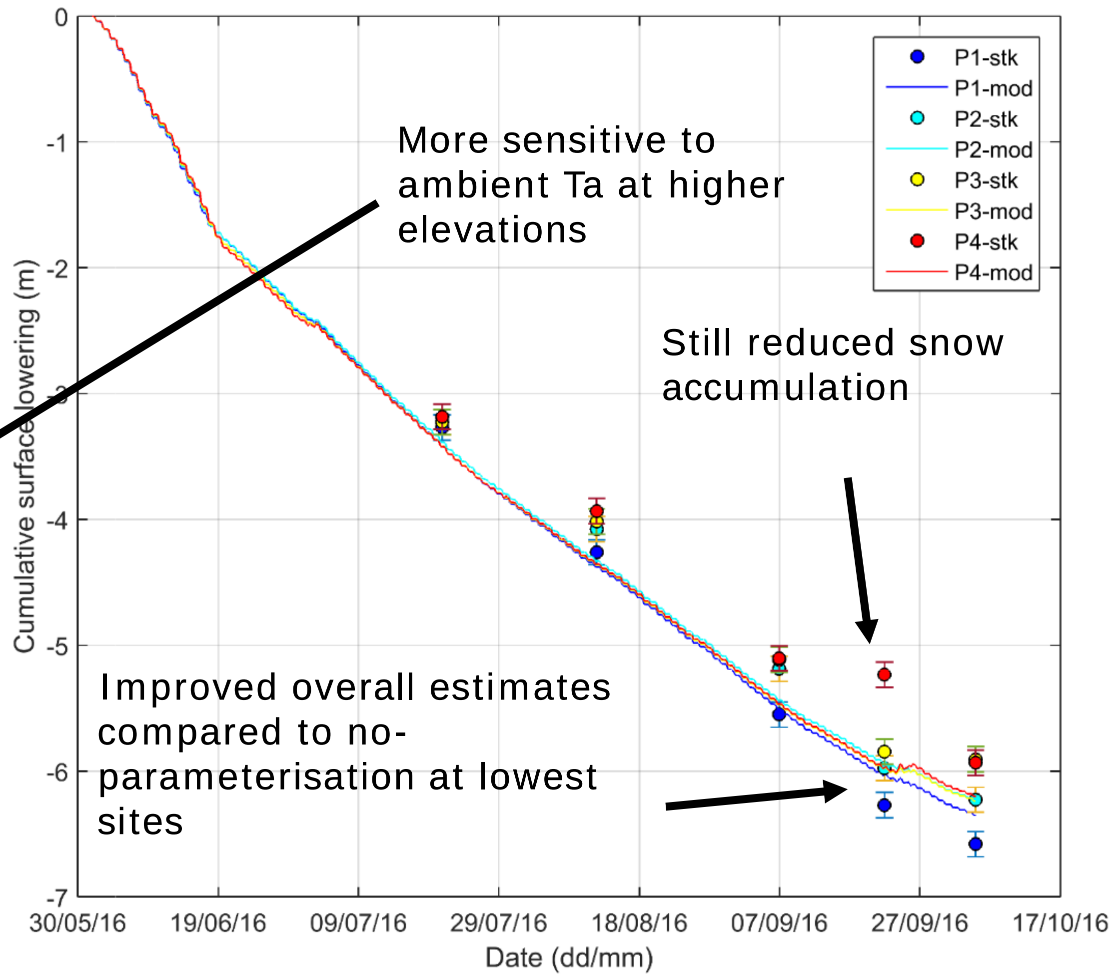


Source: Shea and Moore (2010)

Run 2: Statistical air temperature estimation (Shea and Moore, 2010)

Difference in melt and air temperature between Run 2 and Reference run
(total over the melt season for melt, average for air temperature)



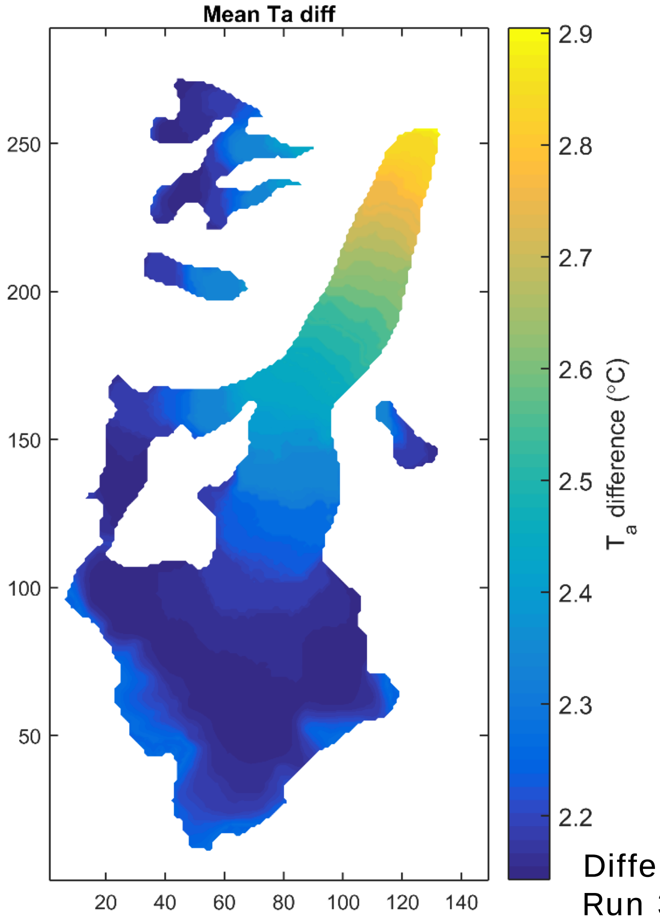


More sensitive to ambient Ta at higher elevations

Still reduced snow accumulation

Improved overall estimates compared to no-parameterisation at lowest sites

Run 3: Physically-based modelling of air temperature (Ayala et al., 2015 model)



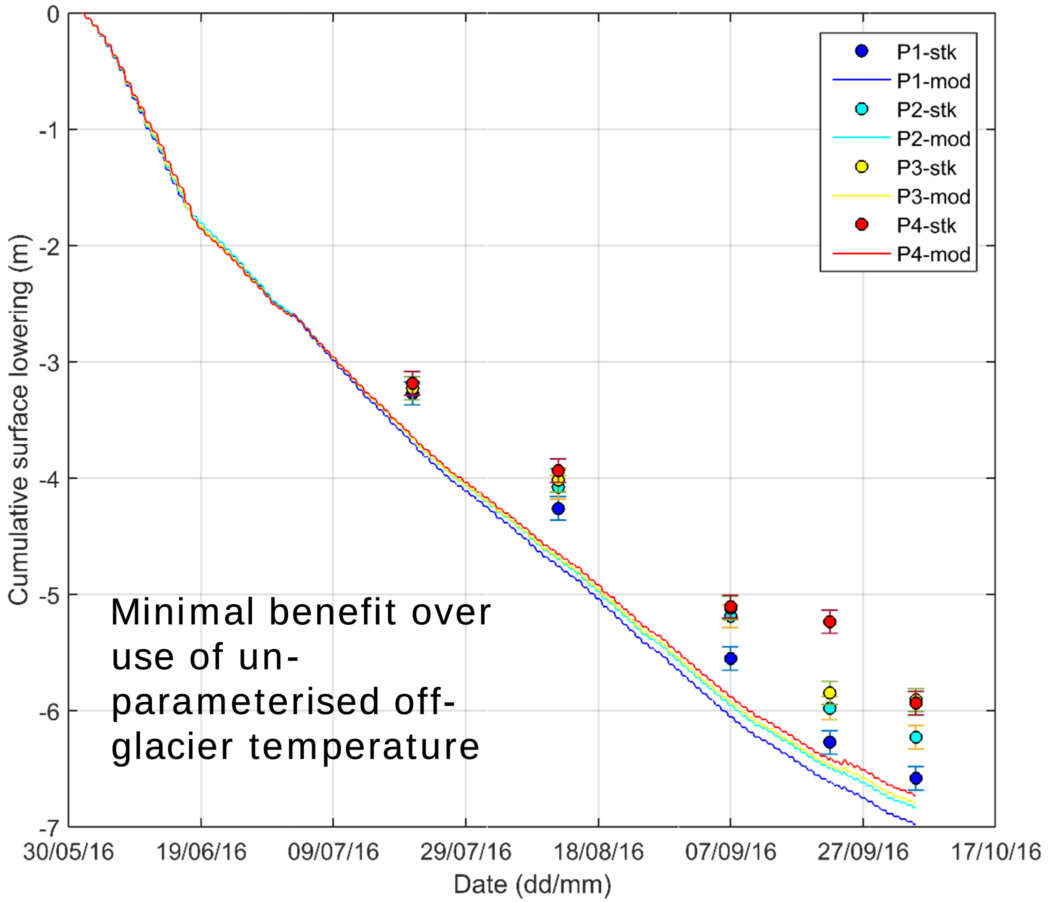
Difference in temperature between Run 3 and Reference run

The model ('ModGB') uses parameters from Juncal Norte Glacier (Chile): a strong assumption (even if with similar size and orientation)

Likely not suitable for modelling temperature on Parlung Number 4 Glacier.

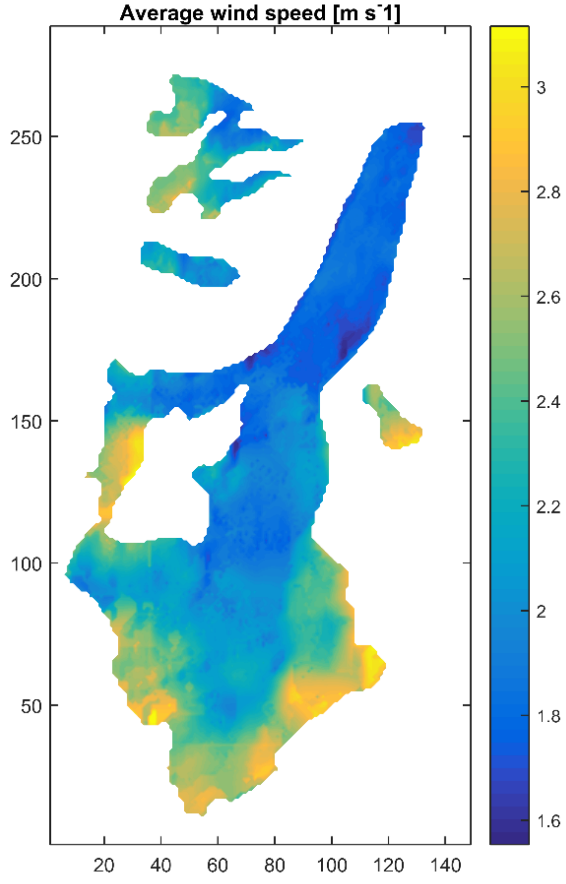
Ablation zone temperatures high – over-estimated melt ->

Difficult to constrain using only one AWS data point.



Run 4: Distributed wind speed

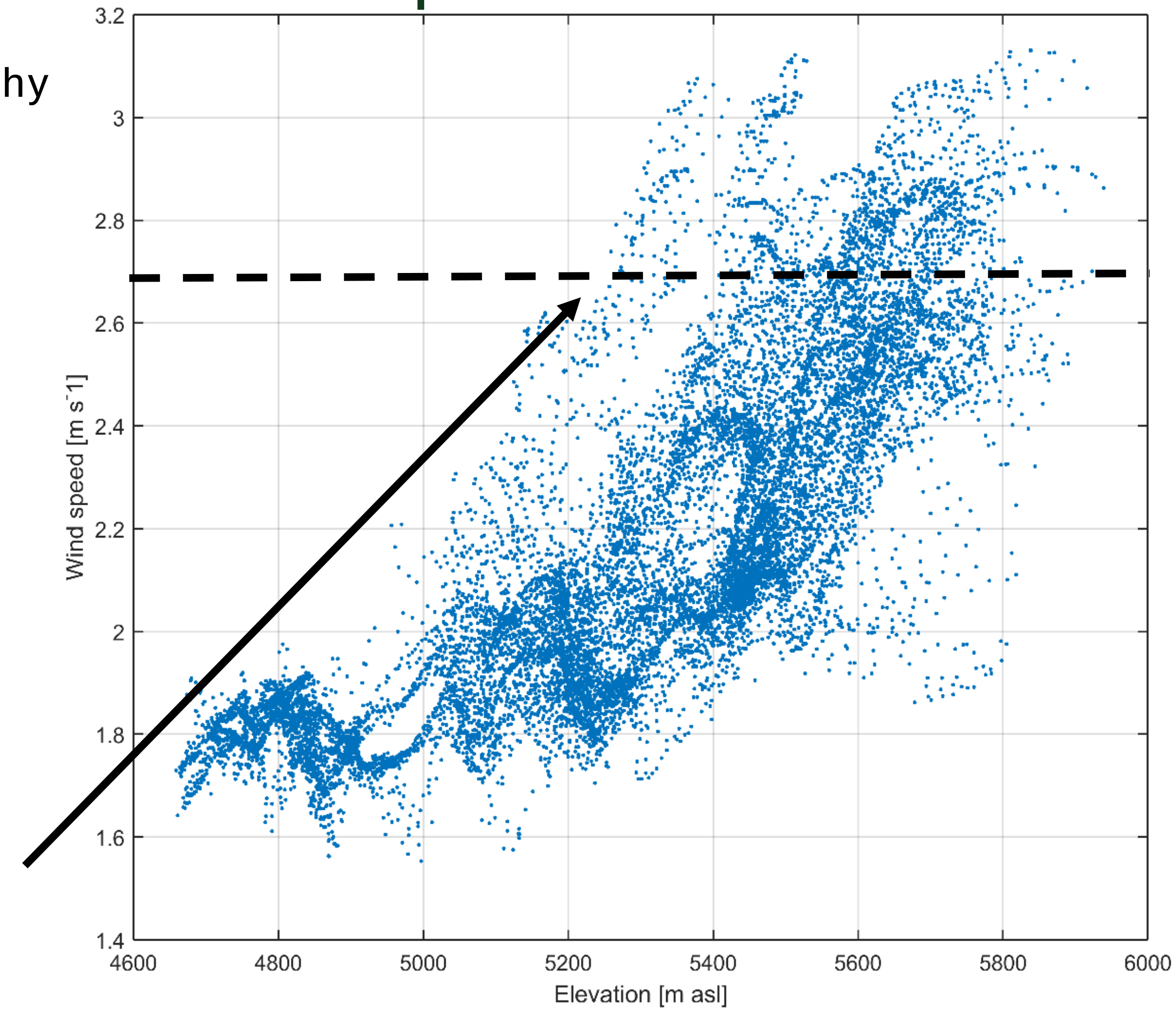
Method of Peleg et al. (2017): it accounts for topography



<- Assumes sheltered conditions at lower glacier

Does not account for topographic funnelling or katabatic effects (ignores the glacier boundary layer)

Mean wind speed at AWS = 2.69 m s^{-1}



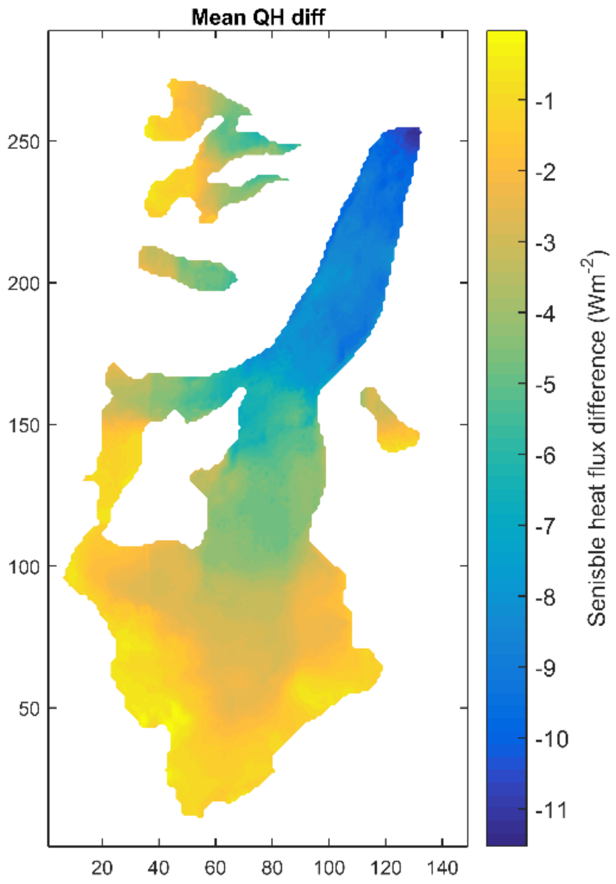
Run 4: Distributed wind speed

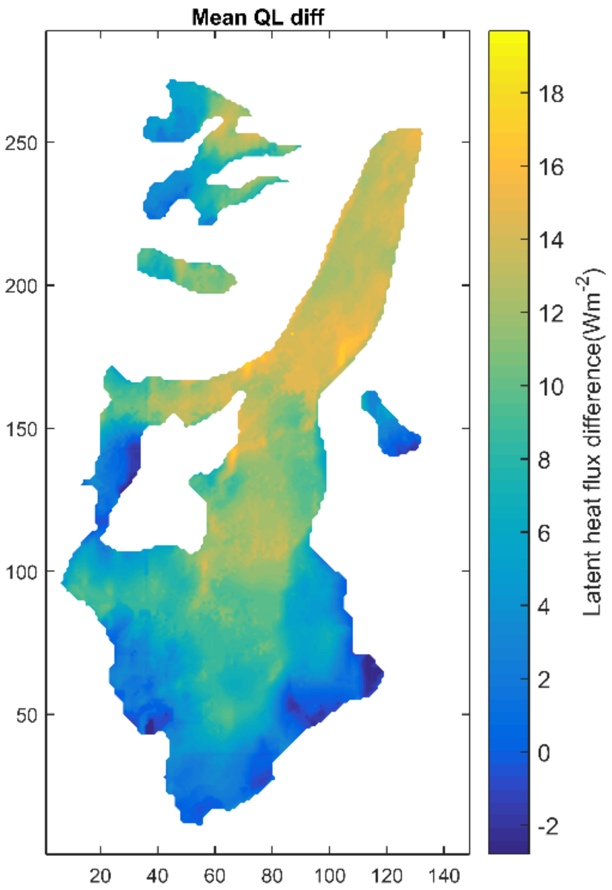
Differences in turbulent sensible and latent heat fluxes between Run 4 and Reference run (with constant wind speed)

Reduction of mean sensible heat flux (QH) by up to 11 Wm^2 on the lower tongue

Increase in mean sensible latent heat flux

Difference in mean QH/QL at AWS = -8Wm^2/+13Wm^2





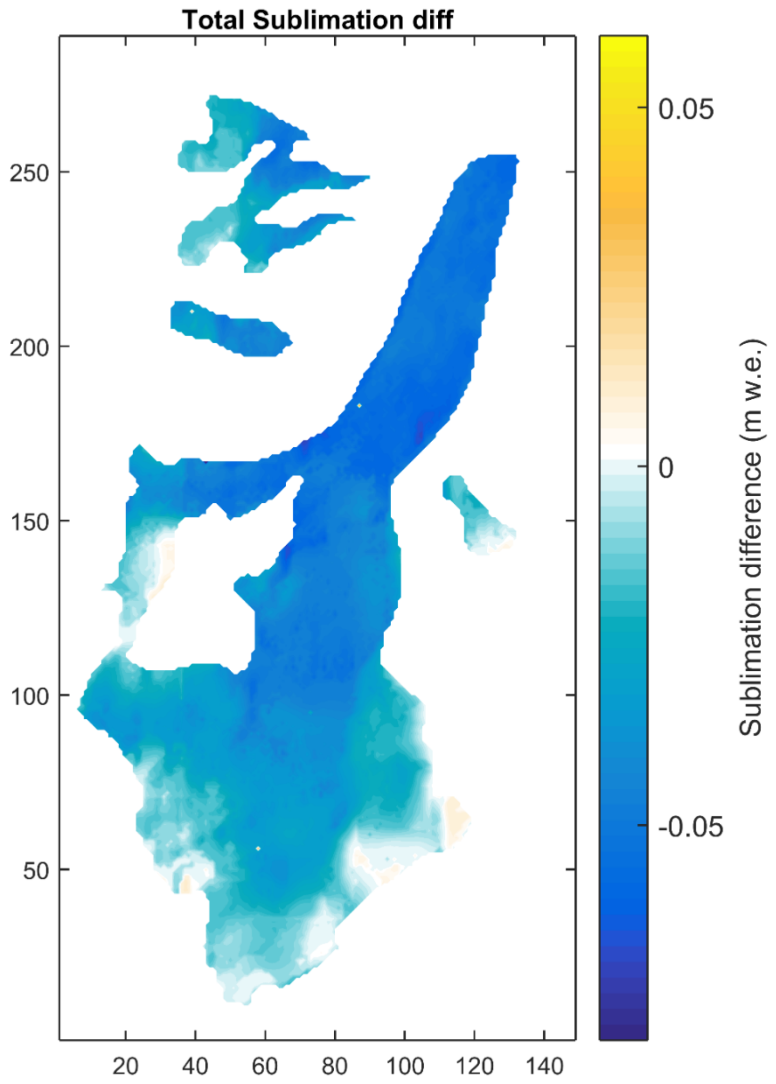
Run 4: Distributed wind speed

Difference in sublimation between Run 4 and Reference run (with constant wind speed)

Contribution of 50% less sublimation at AWS compared to reference run (with AWS wind speed)

Melt total actually slightly higher (0.1 m w.e.) due to greater increase in QL than decrease in QH = energy gain to surface.

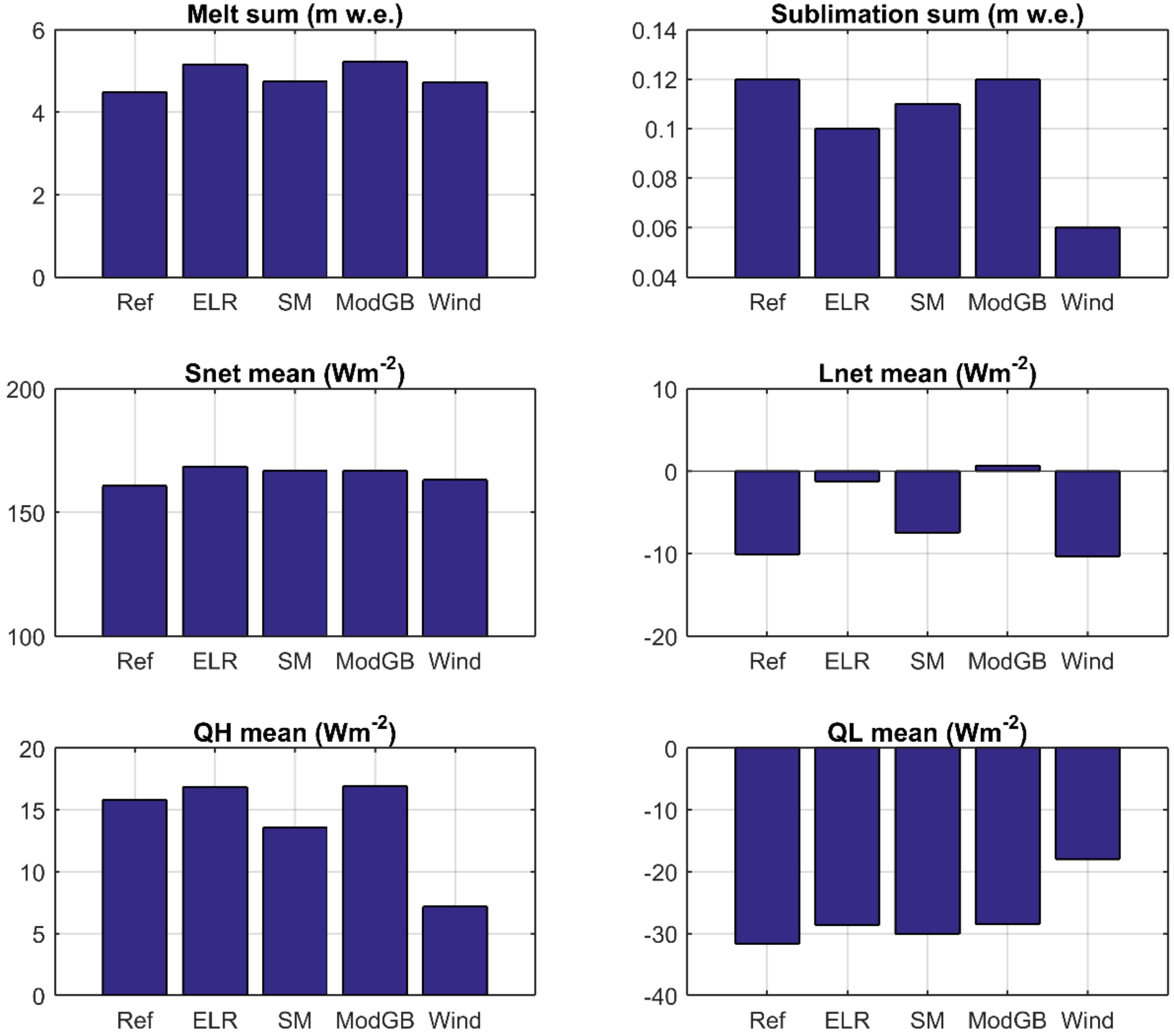
Differences are greatest at lower tongue



Comparison of model runs

Total of mass balance components and averages of energy fluxes at AWS for the different runs

- Clear influence of the air temperature distribution methods.
- Not enough measurements for validation of the two approaches accounting for the glacier boundary layer (Shea and Moore, 2010; Ayala et al., 2015): cooling down-glacier or warming?
- Influences of increased Snet for the off-glacier ('ELR') model run which emphasises a very important role for accumulation and albedo in accurate estimations of melt.



Conclusions: Overview

- A distributed model that performs generally well at distributed scale (ablation zone), validated at the AWS, stakes and with (conventional) satellite data:
    - A need for high elevation and spatially distributed data for validation

- Surface energy balance dominated by net shortwave radiation

- Strong sensitivity to Ta forcing due to effects on accumulation and albedo on mid- and upper-glacier regions:
    - We know from other regions in the world that accounting for glacier cooling effects is very important for glacier tongue
    - We do not really know which is the real distribution of air temperature over the glacier

- Very scarce knowledge also about wind speed variability: alternative methods to distribute wind speed need to account for **glacier katabatic wind layer**.

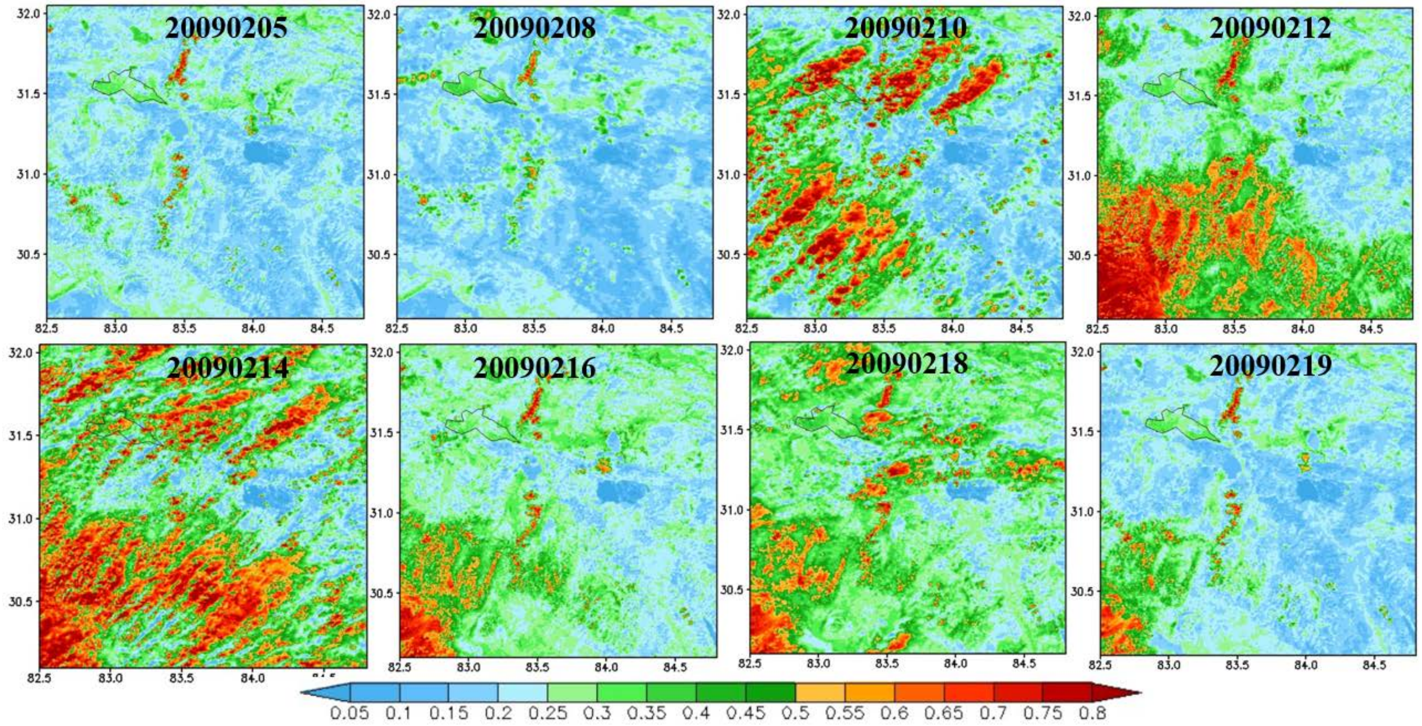
Conclusions: next steps

- **Albedo parameterisations** and **snow accumulation** require improvements and further testing: potential to exploit satellite data
  - Unknown precipitation gradients for this region
  - Improve albedo parameterisations exploiting the satellite products
  - Minimal satellite data currently employed to validate model at distributed glacier-scale.
- Necessary to account for **surface roughness** (z_0) **spatial variability** and **temporal evolution** which is a likely cause of under-estimation of ablation on the glacier tongue (stake P1).
- Develop **wind speed distribution methods** to combine topographic and glacier influences. Distributed on-glacier meteorological datasets are lacking – difficult to constrain.

We need to understand the **meteorological forcing** over glaciers and account for glacier-specific processes (cooling of air temperature, generation of katabatic winds, etc):
Different methods resulted in differences in simulated mass balance components

Conclusions: next steps

We need to understand the **meteorological forcing and surface variable dynamics** over glaciers



A **mismatch of scales** that can be overcome thanks to ground data: it is really the **combination** of **physically-based modelling** with **satellite data** and **ground observations** that will allow filling this knowledge gap

Conclusions: future project work

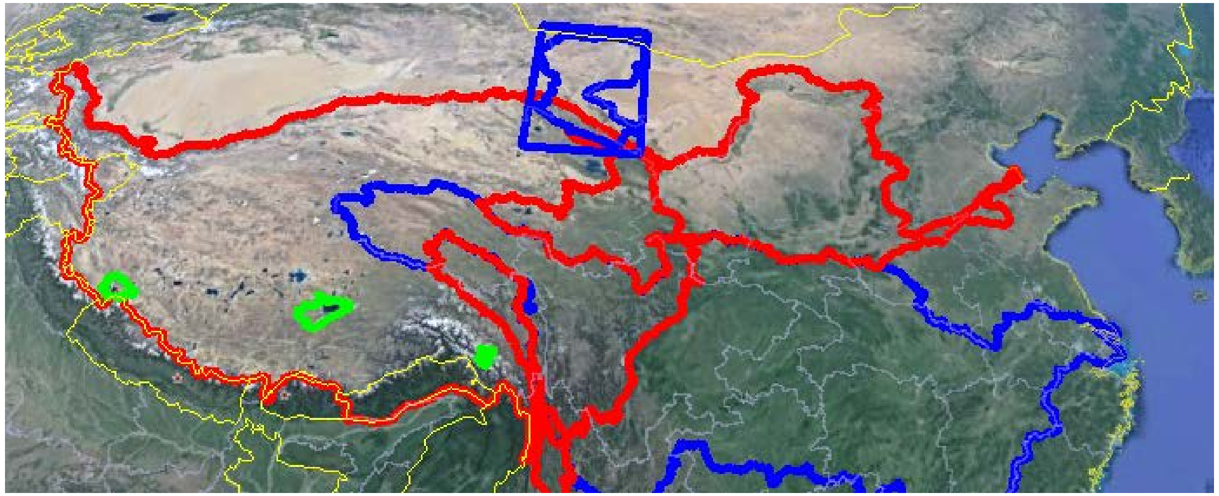
1. Long term simulations on this glacier to study consistency of patterns

2. Repeat the modelling for other **selected glaciers** across **different climates** on the Tibetan Plateau

3. Upscale to the catchment (and possibly regional) **scale**

4. Glacio-hydrological modelling to understand the **glacier** and **snow contribution** to river **runoff**

For all these, **integration** of the **modelling** with new, high resolution **satellite data** is crucial



Thank you very much for your attention