Accelerated glacier mass loss in the Southeast Tibetan Plateau is dominated by phase change of monsoon precipitation

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Structure of the presentation

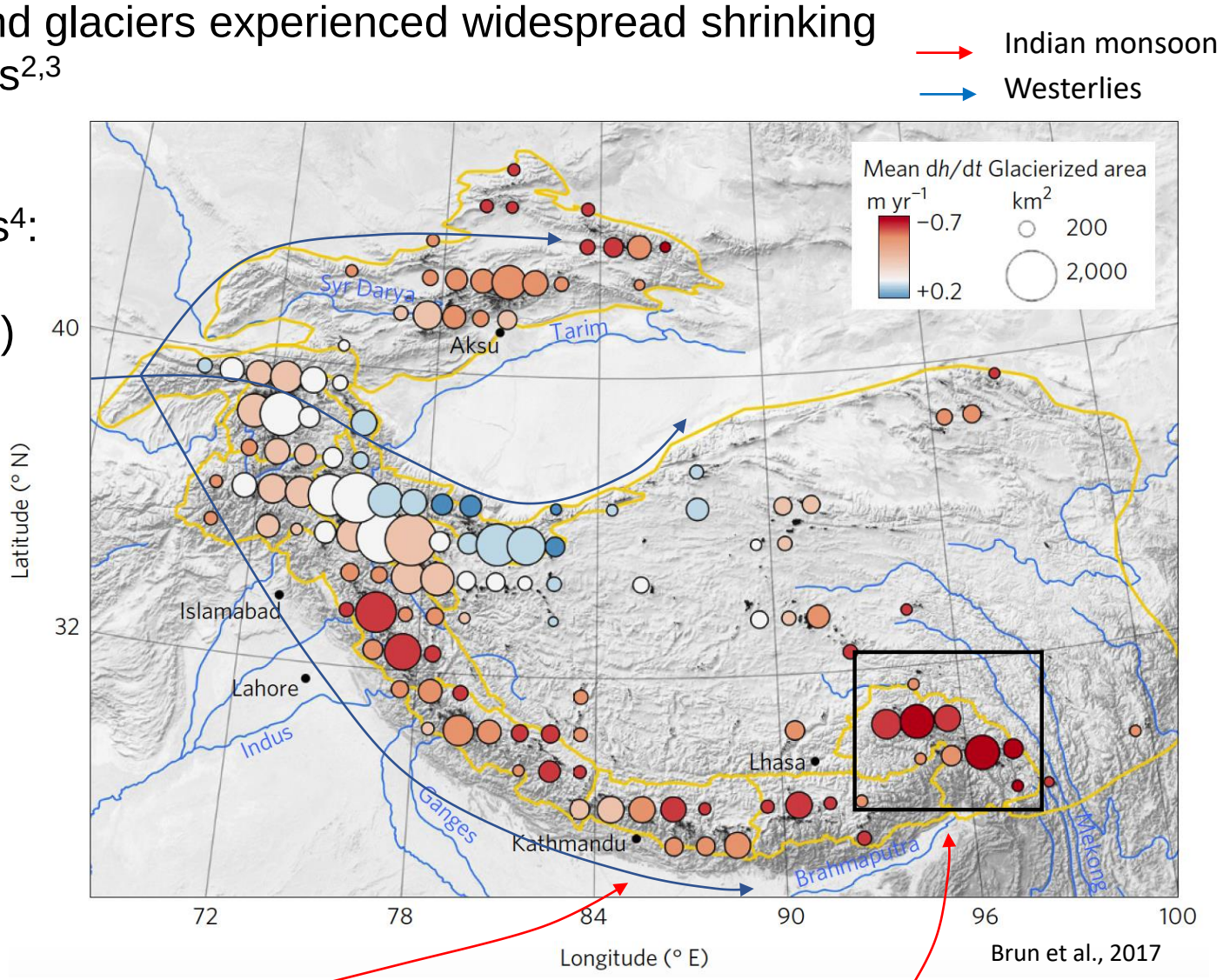
interactive

- Mountains are the water towers of Asia[1], and glaciers experienced widespread shrinking due to global warming over the last decades[2,3]

- Two global atmospheric circulation patterns[4]:
  - ➢ Westerlies (mostly in winter and spring)
  - ➢ Indian monsoon (in summer)

- Highest glacier mass losses observed in southeast Tibetan Plateau[2,4,5]

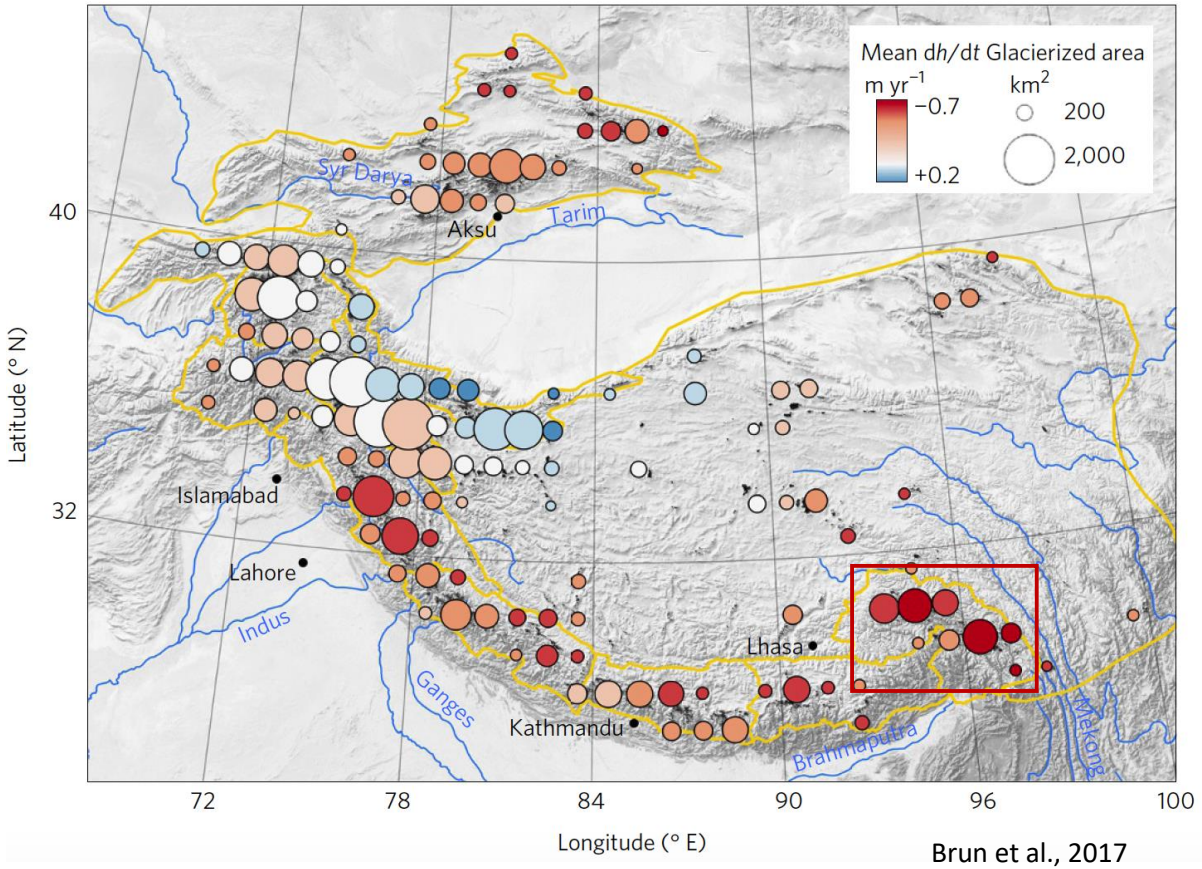
- Mass loss accelerated over the last 4 decades[6]



Brun et al., 2017

Research questions :

- What are the drivers and processes explaining this mass loss acceleration ?
- What are the implications for catchment runoff ?



Brun et al., 2017

Parlung No. 4 Glacier

Classification: maritime[7], spring-accumulation[8,9], debris-free, valley-type.

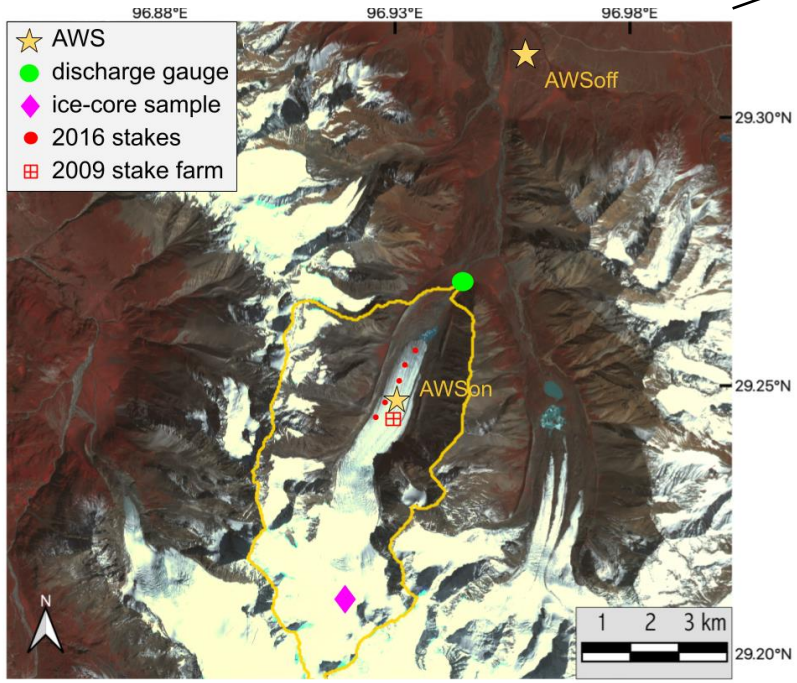
Elevation range: 4650 to 5964 m a.s.l.

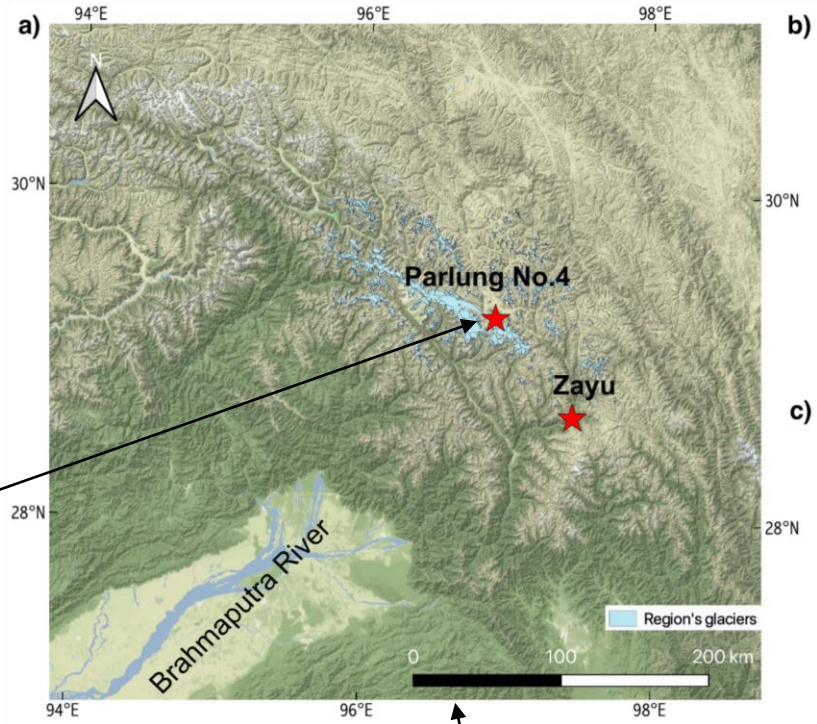
Glacier area and length: 11.7 km^2 and 8 km

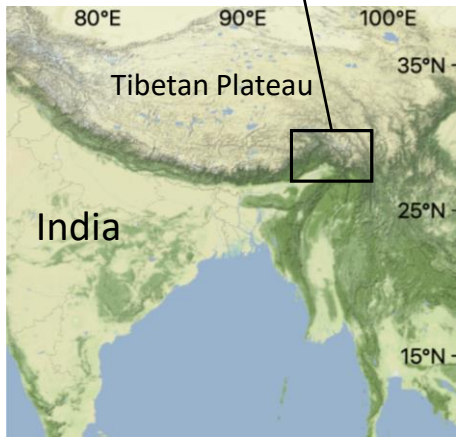
Coordinates: 29°14', 96°56'E

Catchment area: 24.4 km^2

- Considered as a benchmark glacier in this region, since its meteorology, surface energy fluxes and mass-balance have each been examined in recent years[10,11,12].



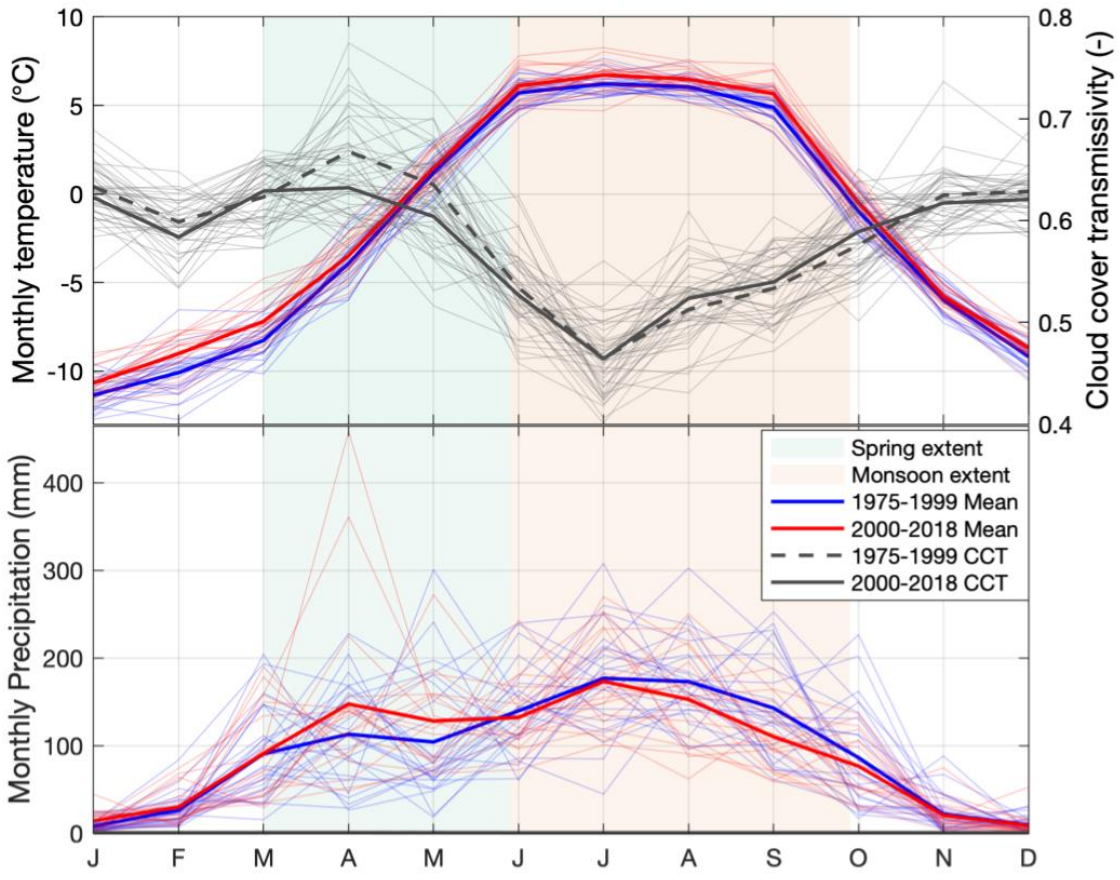




Parlung No. 4 Glacier

Climate of the region :

- Influenced by southern westerlies and the Bay of Bengal vortex during spring, and by the Indian monsoon in summer.
- One of the wettest places in the Tibetan Plateau, with annual sum amounting to 1000-3000 mm[7].
- Double-peak precipitation pattern, with around 30% and 44% of annual precipitation falling in spring (Mar-May) and summer (Jun-Aug) respectively.

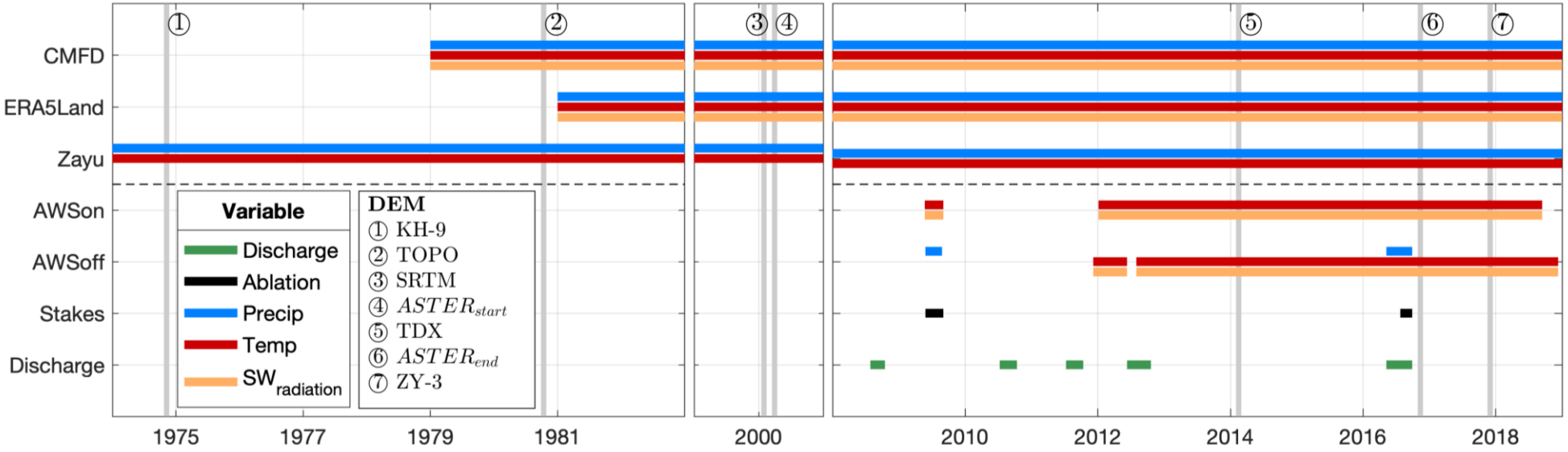


Data availability

- Meteorological forcing : off-glacier AWS, national weather station at Zayu, reanalysis datasets (CMFD[13] and ERA5-Land[14]).

- In-situ observation : discharge, ablation stakes, ice-core drill sample, surface energy fluxes.

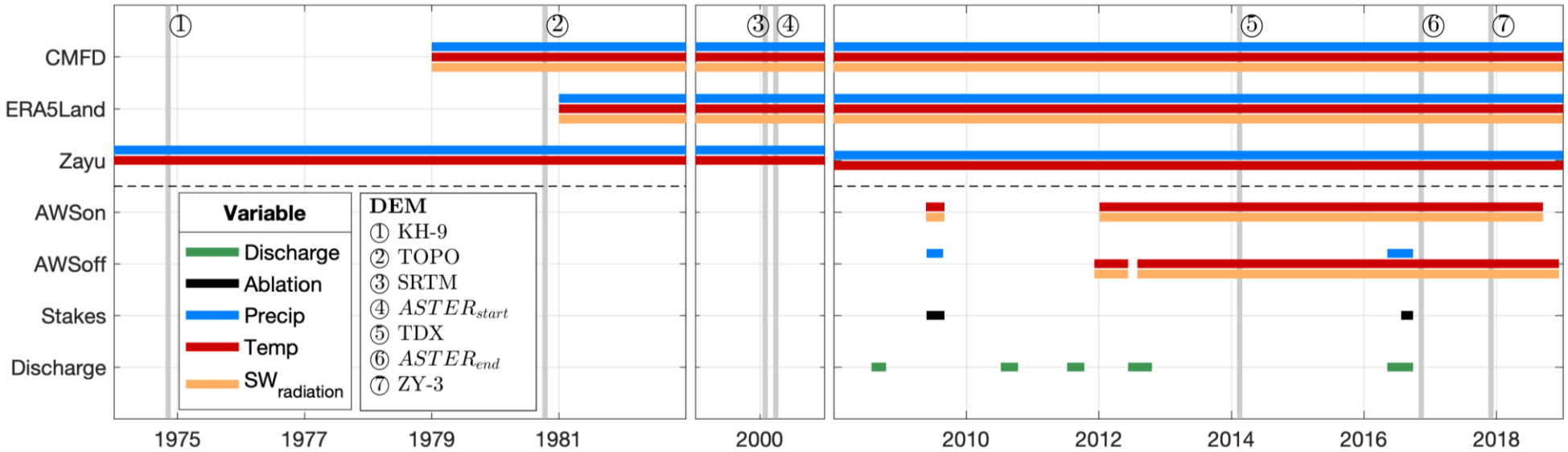
- Remote-sensing observation: Digital elevation models, elevation change maps for different periods, MODIS fractional snow cover.



Meteorological forcing reconstruction

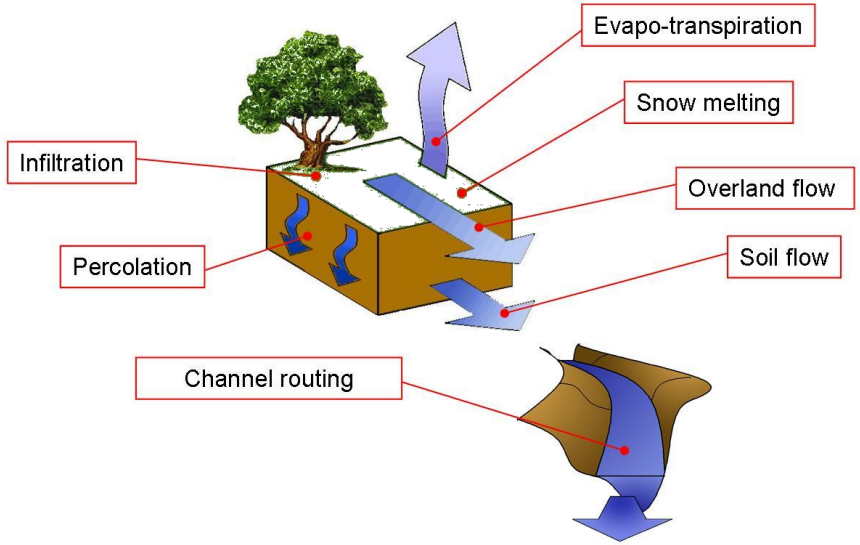
- Only few years of in-situ meteorological measurements, but need for 45 years of continuous forcing to run the model.

- Bias-correction of reanalysis datasets (CMFD and ERA5-Land) and Zayu's weather station data with AWS data, selection of the best performing dataset.



Glacio-hydrological model : TOPKAPI-ETH

- fully distributed
- process oriented



- 30m spatial resolution
- hourly time step
- run from 1975 to 2019

Ice and snow melt: Enhanced ETI model

$$M=\begin{cases} TF \cdot T_i + SRF \cdot (1-\alpha_i) \cdot I_{\downarrow i} & T_i > T_T \\ 0 & T_i \leq T_T \end{cases}$$

Pellicciotti et al. (2005)[22]

Albedo parameterization :

$$\alpha = \begin{cases} \alpha_{Snow_i} & Snow_{Depth} > 0 \\ \alpha_{Ground_i} & Snow_{Depth} = 0 \text{ and cell } i \text{ not glacierized} \\ \alpha_{Ice_i} & Snow_{Depth} = 0 \text{ and cell } i \text{ glacierized} \end{cases}$$

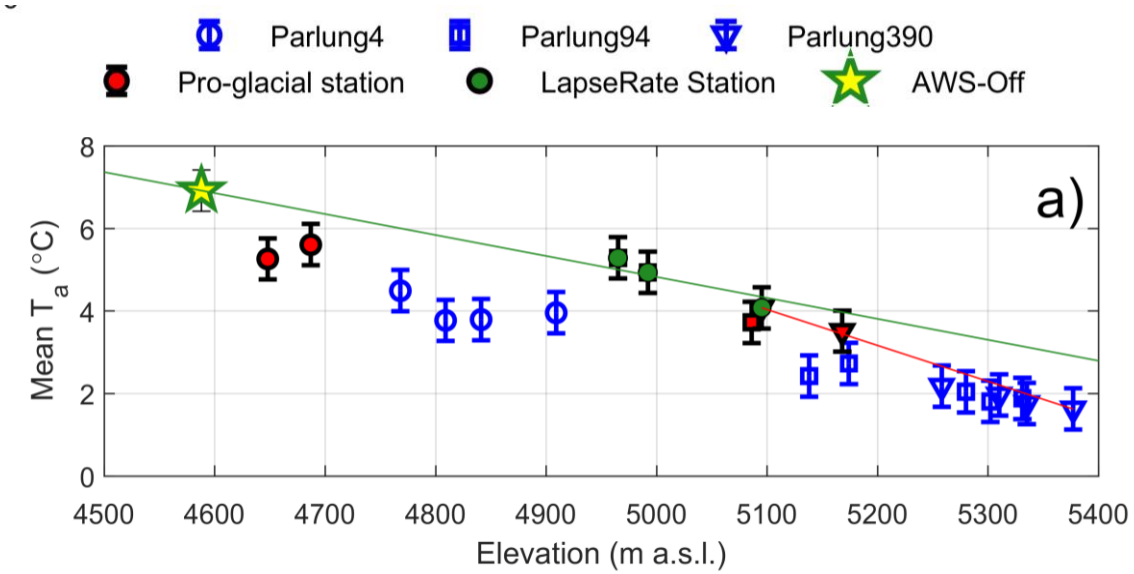
Brock et al. (2000)[23]

$$\alpha_{snow_i} = Albf_1 + Albf_2 \cdot log_{10}(T_{acc_i})$$

→ Calibrated using on-glacier AWS data

Meteorological forcing distribution

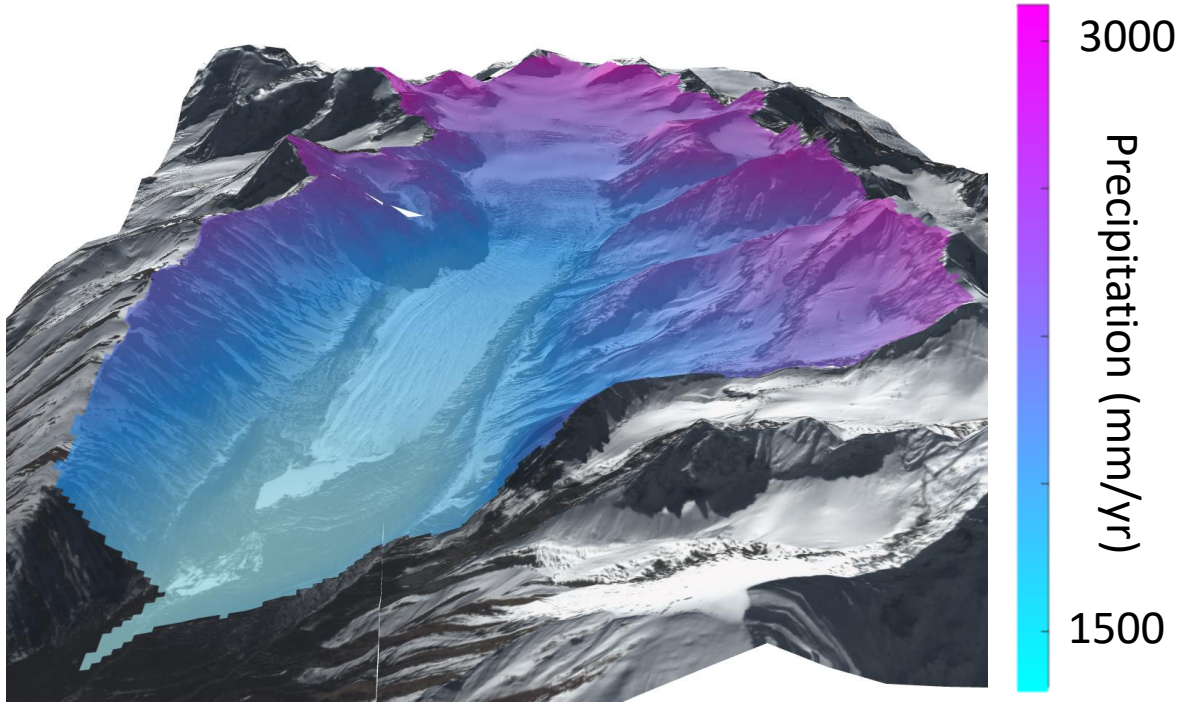
Temperature extrapolation



Shaw et al. (2021)[24]

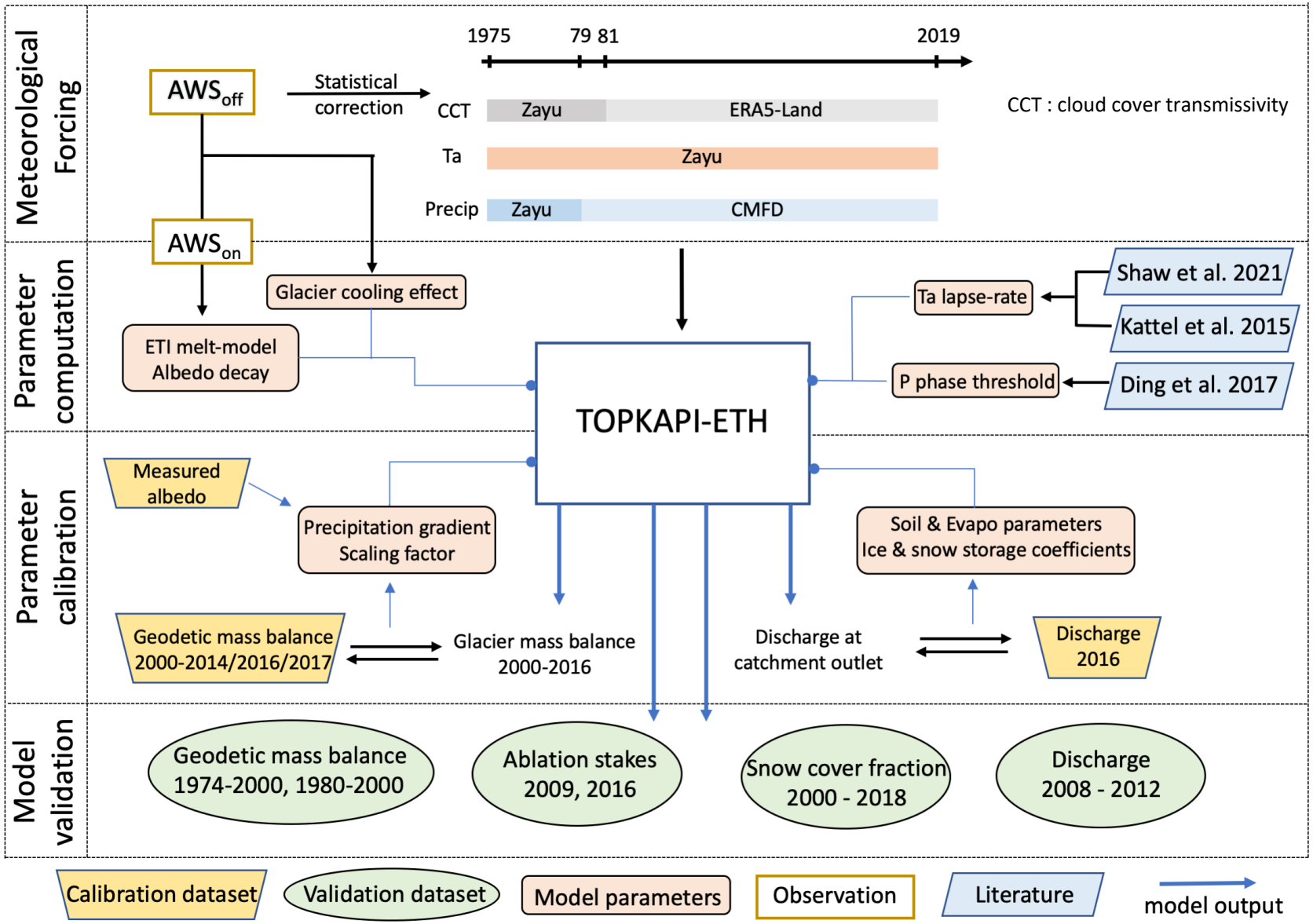
Mean lapse-rates and glacier cooling effect derived from T-loggers installed during a 2018-2019 campaign

Precipitation extrapolation



Precipitation gradient calibrated against geodetic mass balance and measured albedo

Model set-up procedure summary



Catchment solid water balance

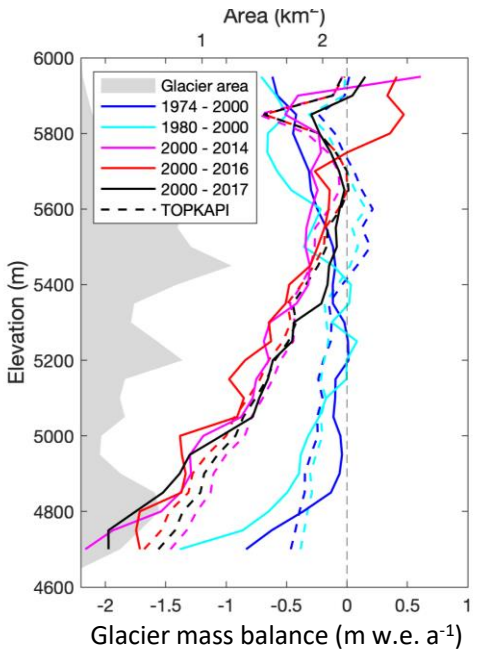
- Catchment solid water storage: water stored as ice or snow in the catchment.
- Catchment solid water balance :

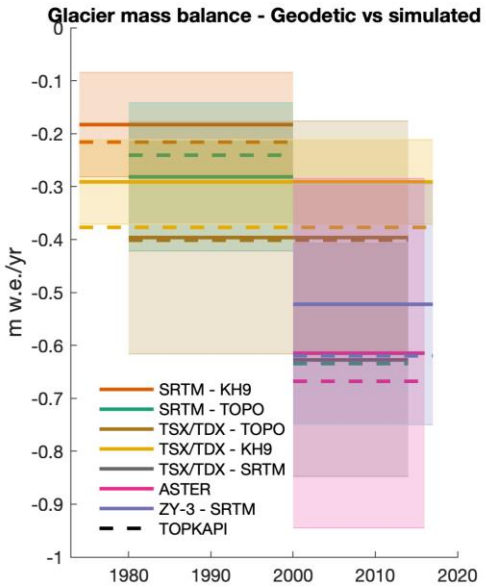
$\Delta_{storage}$ = Solid precipitation - Icemelt - Snowmelt

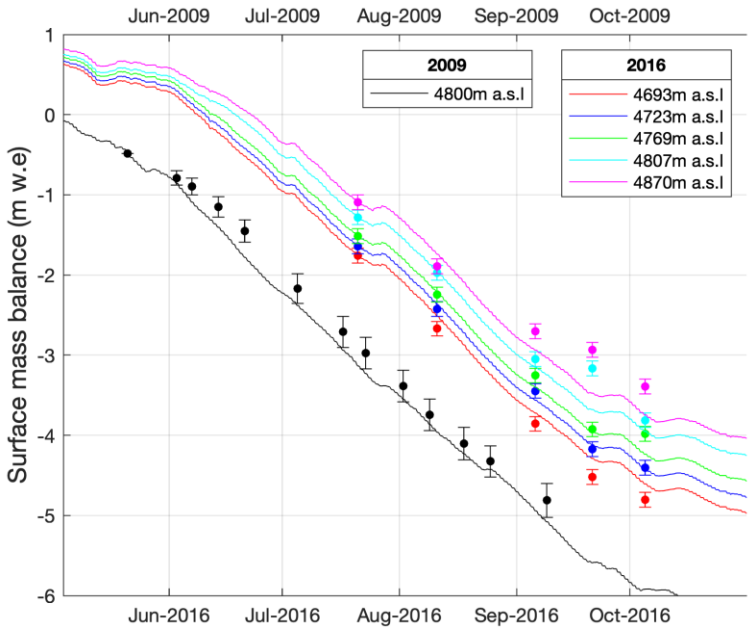
- We quantify the relative contribution of each component to cause the additional glacier mass loss of the recent period (2000-2018).
- A change in solid precipitation can be due to :
  - a change in precipitation amount
  - a change in the rain-snowfall ratio

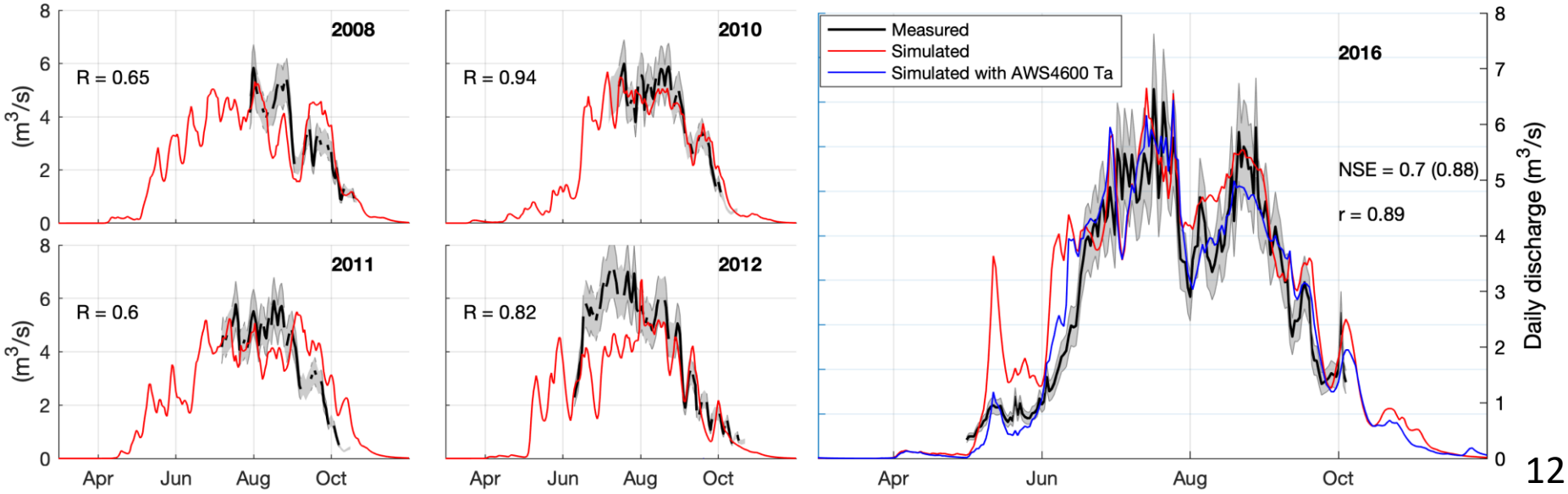
Model performance

- Good match with ablation stakes and measured discharge.
- Reproduces well the geodetic mass balance of the different sub-periods.



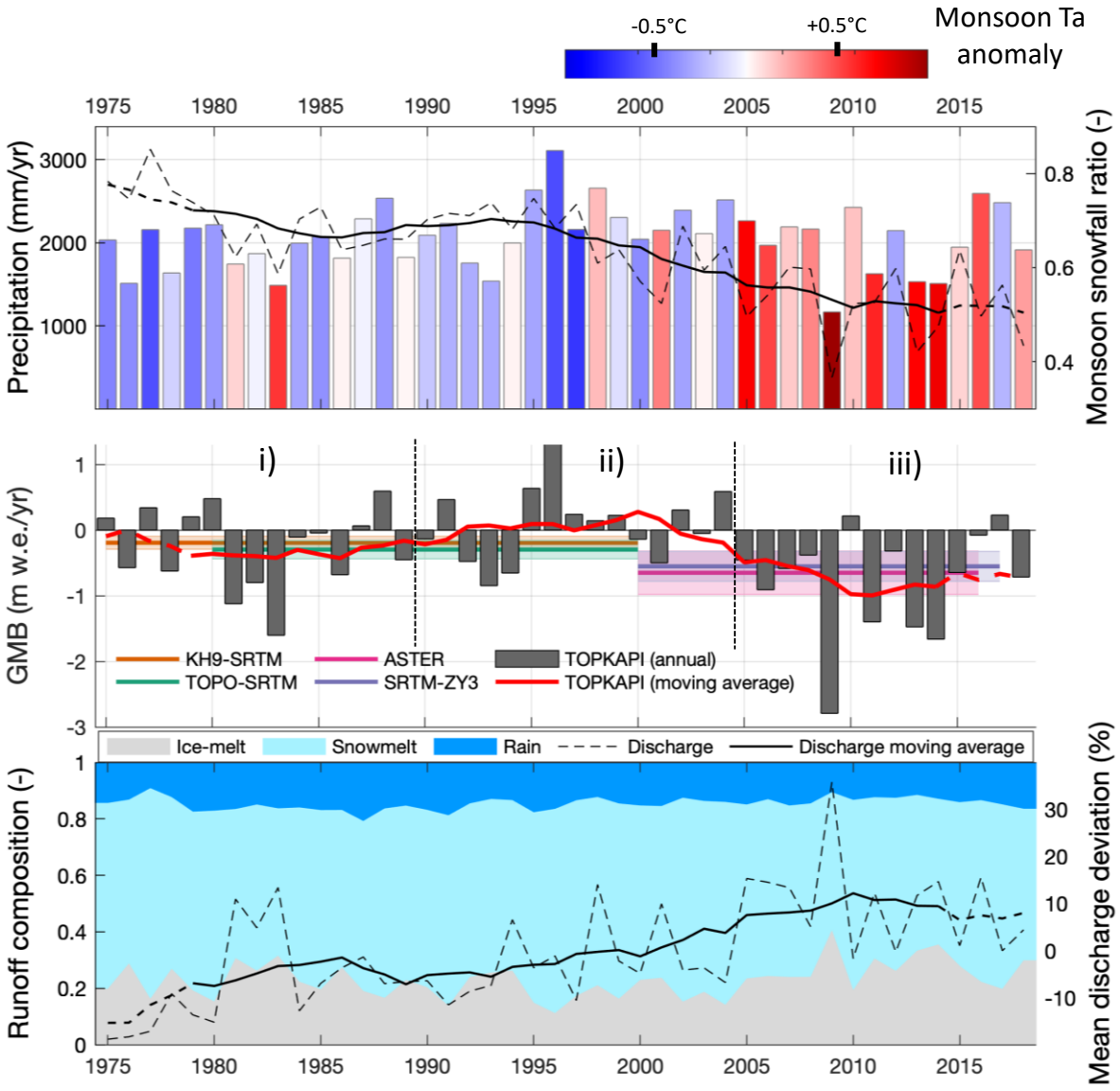






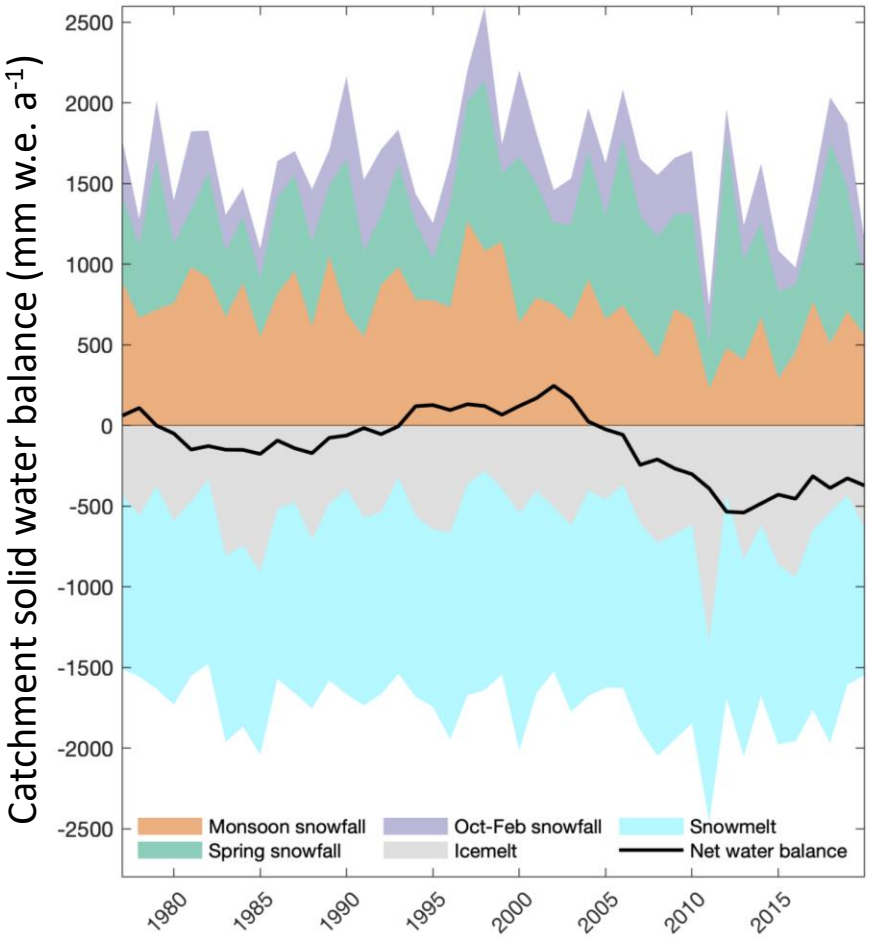
Reconstruction of climatic forcing and catchment hydrology since 1975

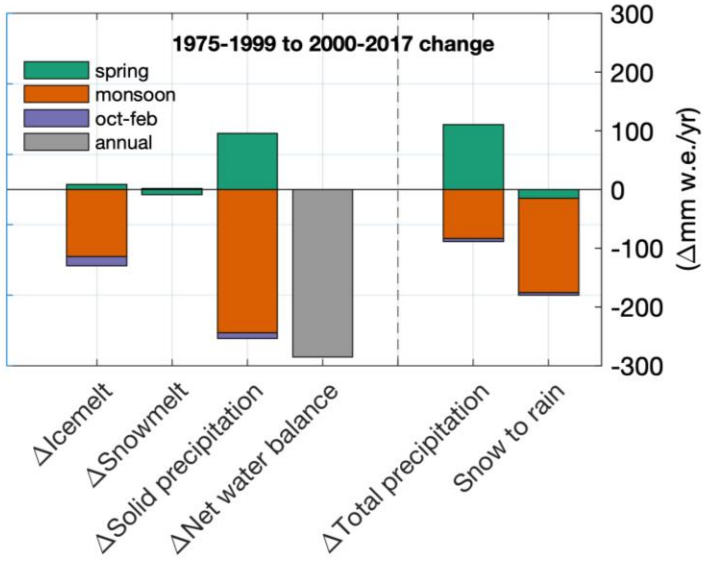
- Three distinct periods of glacier-mass balance :
  - i) - 0.28 m w.e. a^{-1} in 1975-1989
  - ii) + 0.07 m w.e. a^{-1} in 1990-2004
  - iii) - 0.78 m w.e. a^{-1} in 2005-2018
- Significant warming of 0.39°C $.dec^{-1}$ since the 1990s.
- Increase in catchment runoff of 13% between the two geodetic observation periods (1975-1999 and 2000-2018), mostly driven by a 23% increase in ice-melt.

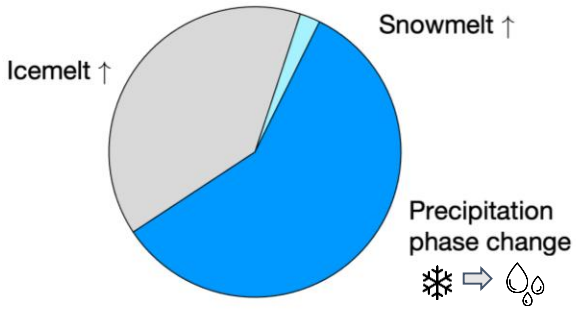


Drivers of recent glacio-hydrological changes

- From 1975-1999 to 2000-2018, the recent additional mass loss was due to less annual snowfall (-158 mm) and more snow- and ice-melt (+7 and +121 mm).
- Seasonal changes are more contrasted: solid precipitation increased in spring (+ 96 mm) but decreased sharply in monsoon months (- 244 mm).
- Monsoon snowfall decrease mostly caused by precipitation phase change, as well as a decrease in precipitation amounts.







Implications

- The role of precipitation phase change in explaining those glaciers' sensitivity to temperature change was suggested in previous studies[15,16] through sensitivity analyses. Here we attribute the recent mass loss to this change in precipitation phase during the monsoon months (Jun-Sep), and to the concurrent ice-melt intensification.

- Spring precipitation phase is still largely unaffected by the warming, thus spring accumulation became increasingly important in providing mass to the glacier.

- Decadal changes in precipitation can compensate for or accentuate the warming-induced losses, but even the observed slight increase in spring precipitation was unable to slow the rapid decline of glaciers in the southeast TP.

- The catchment discharge increase due to enhanced ice-melt could raise the risk of glacier lake outburst flood occurrence in a region which is already classified as high hazard zone[17].

Future work

- This model set-up could be used for future projection to estimate when the maximum contribution of glacier melt to catchment runoff is likely to occur (peak water).

- The understanding of the complex interactions between spring and monsoon precipitation and their decadal changes could be improved by using a new suite of high resolution atmospheric models that reduce uncertainty in spatially-resolved, convective precipitation and meteorological forcing[18,19].

- Future predictions could be improved by more utilizing physically-based, land-surface models which incorporate detailed parameterizations of phase change thresholds[11] and account for meltwater refreezing[20] as well as sublimation[21] and snow redistribution.

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Air temperature reconstruction

Precipitation reconstruction

Forcing annual trends

Surface elevation change

Catchment hypsometry

DEM and ice-thickness

Spatial snowfall changes

Discharge seasonality changes

Model performance sensitivity

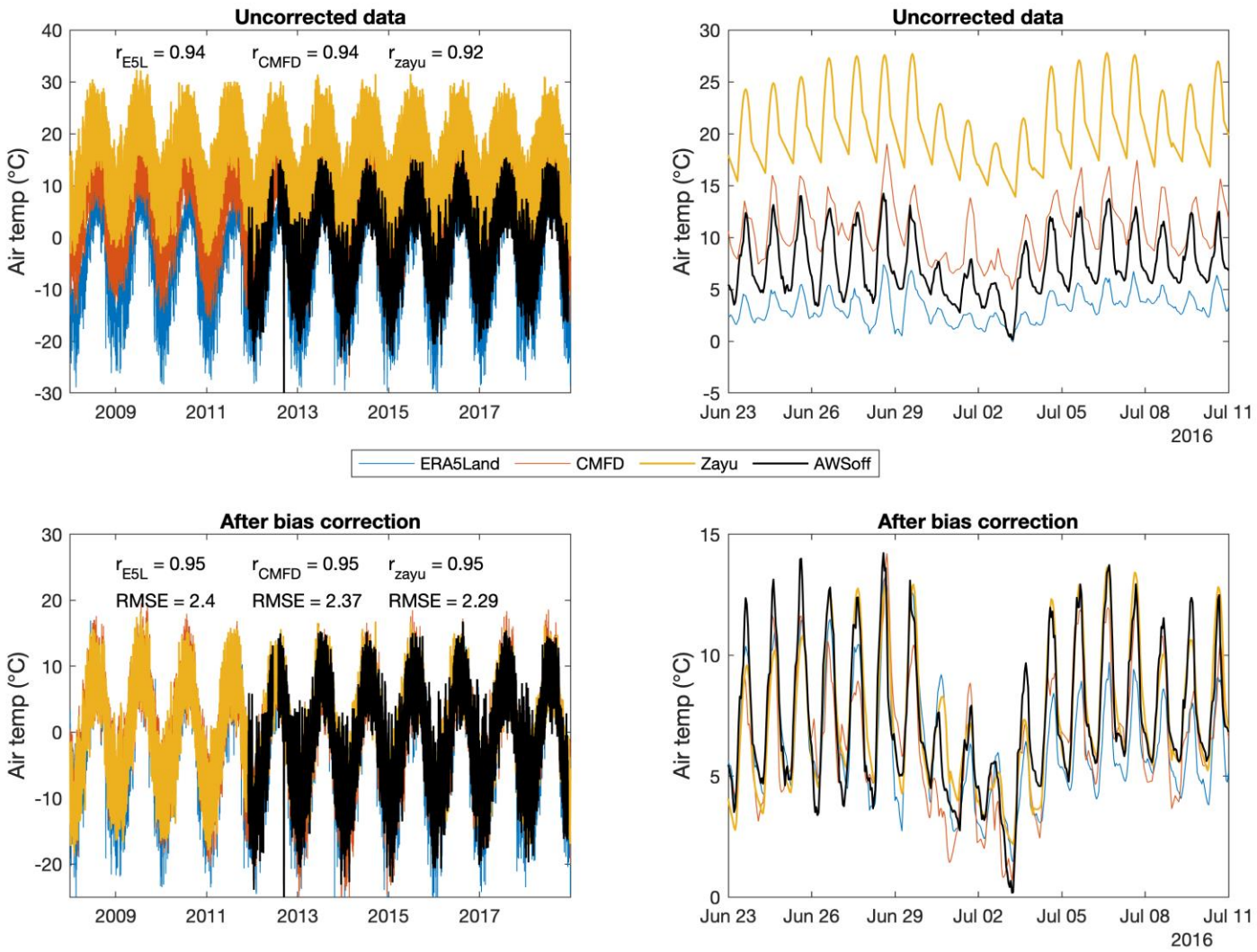
Results sensitivity

Forcing experiment

interactive

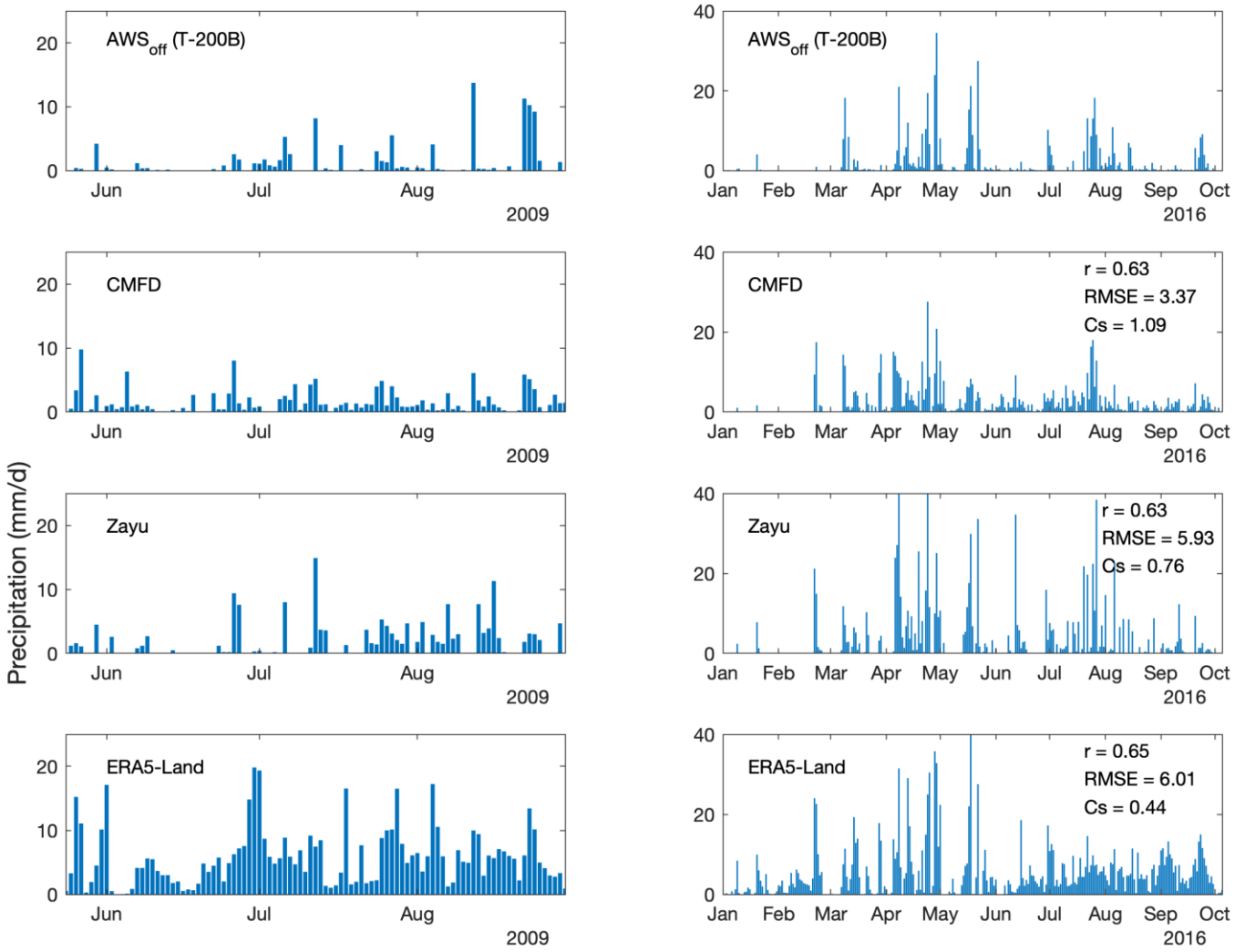
Air temperature reconstruction

Air temperature comparison between the different data sources, before and after applying a monthly-hourly shift to statistically bias-correct (extrapolate) the reanalysis product (national station data) at the AWS_{off} location.



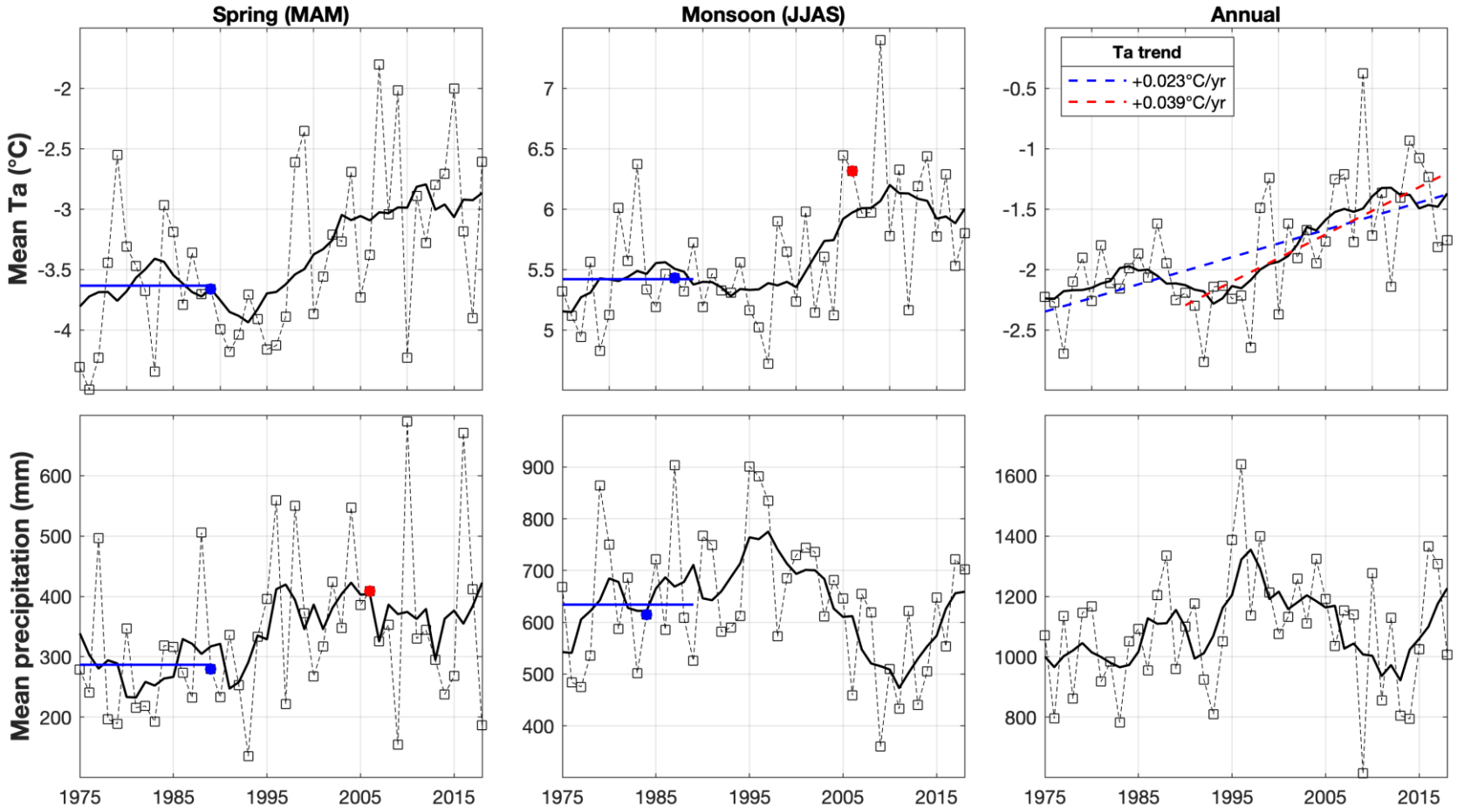
Precipitation reconstruction

Daily precipitation comparison between the different data sources. The pearson correlation coefficient (r) and root-mean-square error (RMSE) are computed between the precipitation measured at AWS_{off} (T-200B) and the precipitation from the source (CMFD, Zayu or ERA5-Land) mentioned in the corresponding subplot. The precipitation scaling factor (Cs) is computed as the ratio of total precipitation amounts measured at AWS_{off} and total precipitation amounts obtained for the corresponding source.



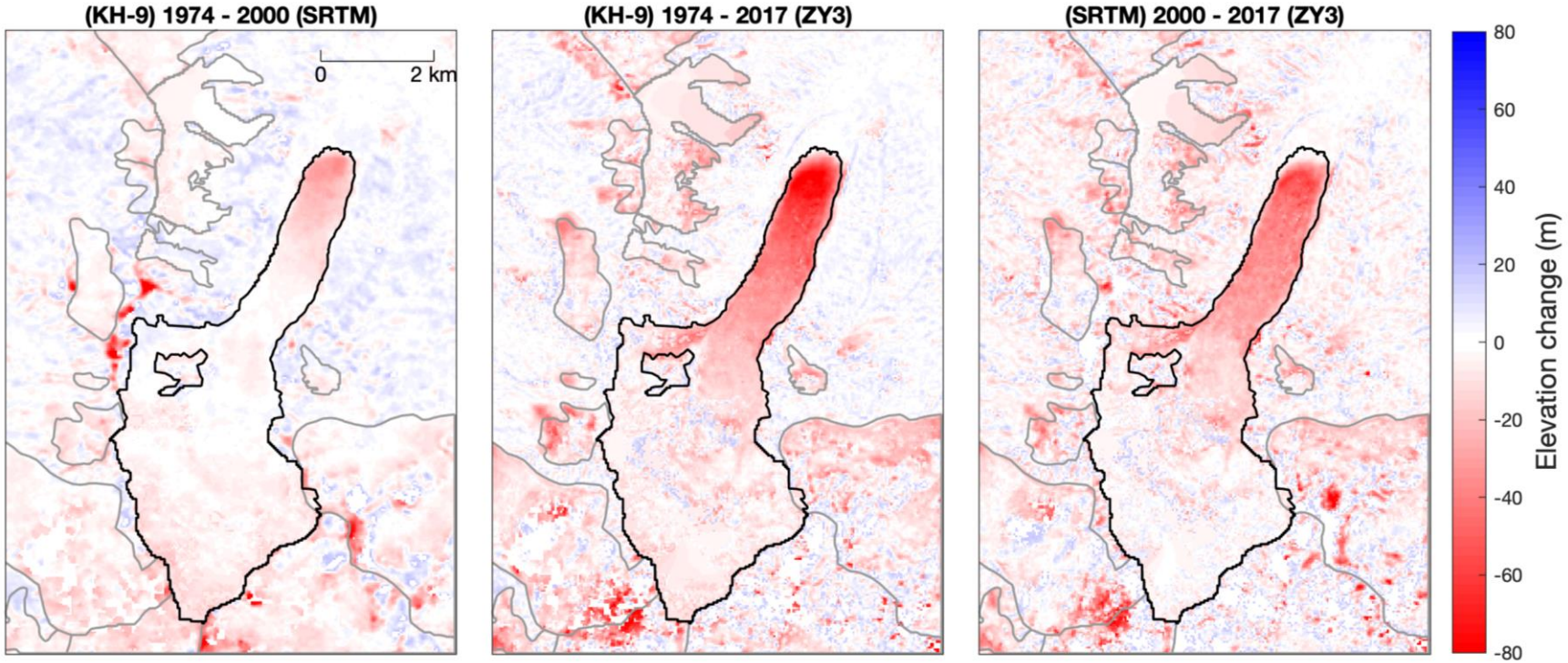
Forcing annual trends

Mean temperature and precipitation averaged over spring, monsoon and year-around at AWS_{off} location. The black-solid line is a 10-year moving average. The year repeated in the forcing experiment for each variable is shown in blue, selected as being the closest to the 1975-1989 average (blue line). The mean annual temperature trends computed over the period 1975-2018 (+0.22°C.dec^{-1}) and 1990-2018 (0.39°C.dec^{-1}) are shown in dashed lines blue and red respectively.



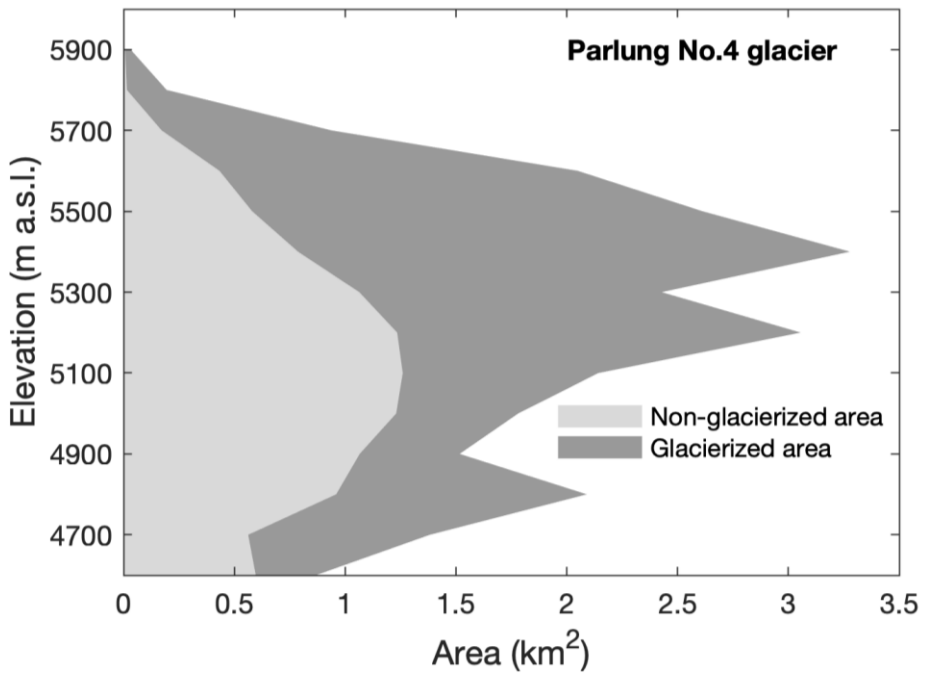
The red dots correspond to the year 2006, used as a detailed example of the experiment result (slide 30).

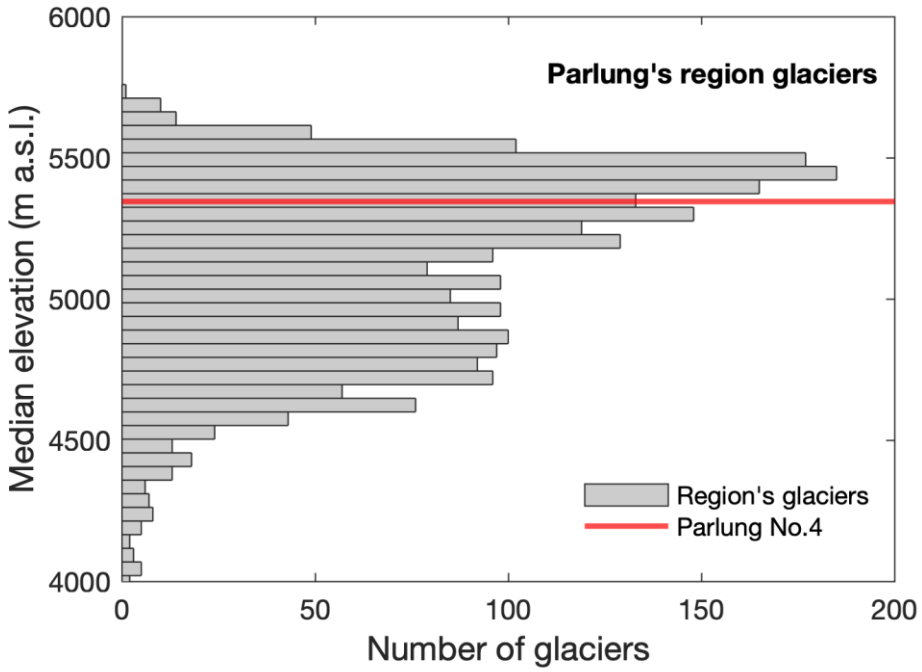
Remotely sensed surface elevation change



Elevation change maps derived from DEM differencing after the removing of outliers and gap-filling. No-data pixels are colored in black. The outlines of Parlung No.4 glacier are shown in black, and the outlines of the surrounding glaciers are shown in grey. The DEM of 1974 was derived from Hexagon KH-9 images by Dehecq et al. (2020)[25]

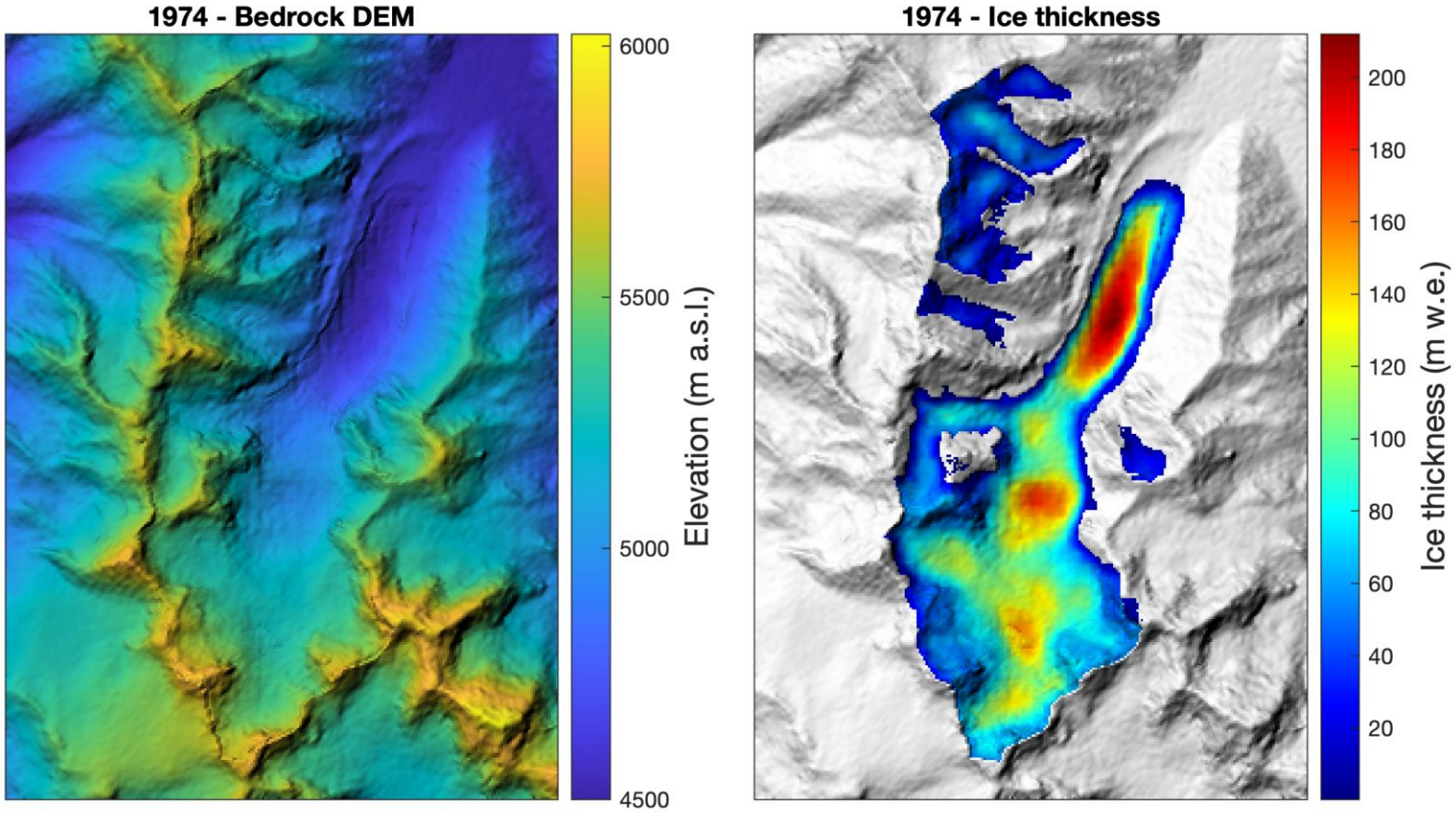
Parlung No.4 hypsometry and representativeness





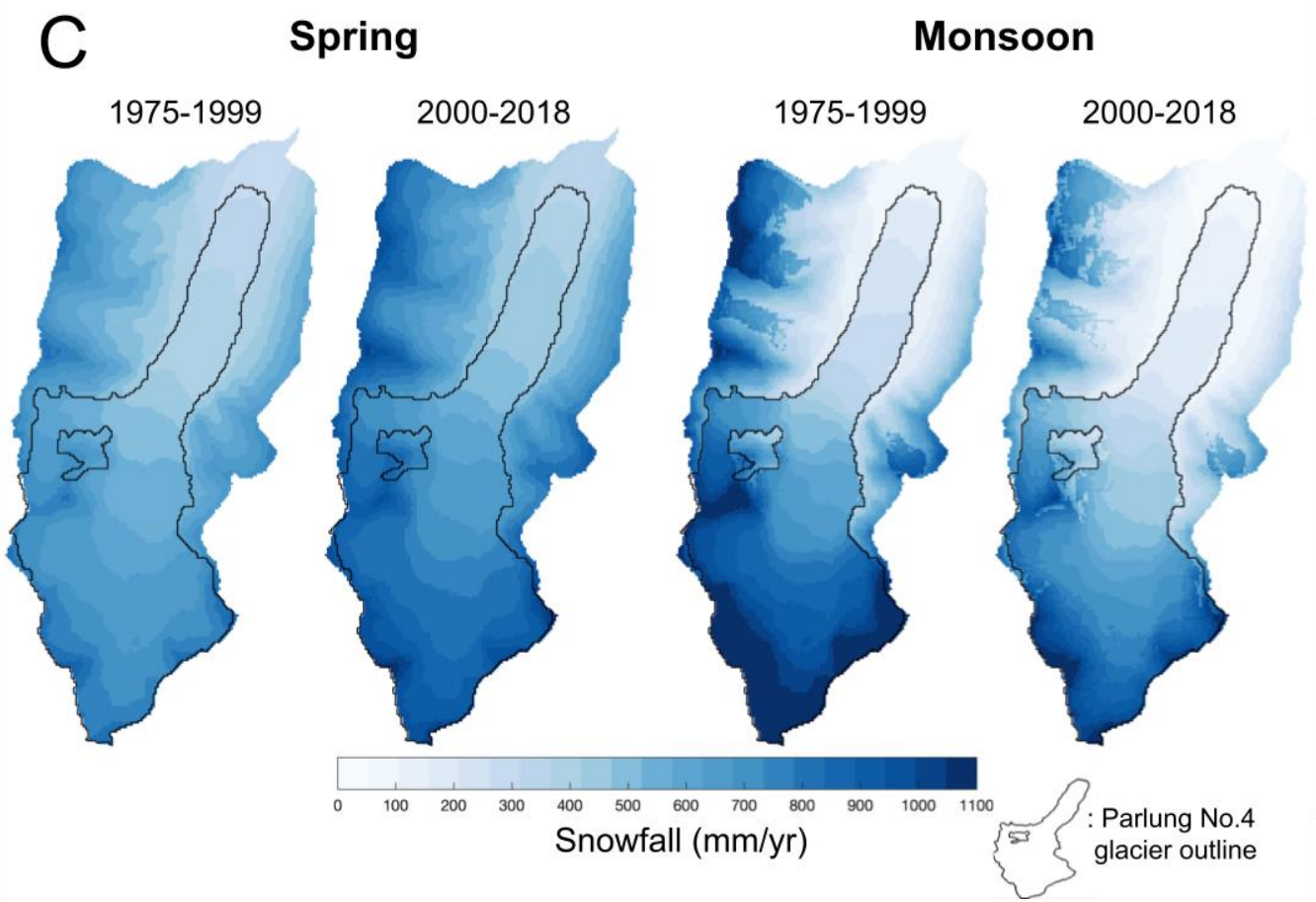
Median elevation distribution of glaciers in the proximity of Parlung No.4, the latter is highlighted in red

Parlung No.4 bedrock DEM and initial ice-thickness



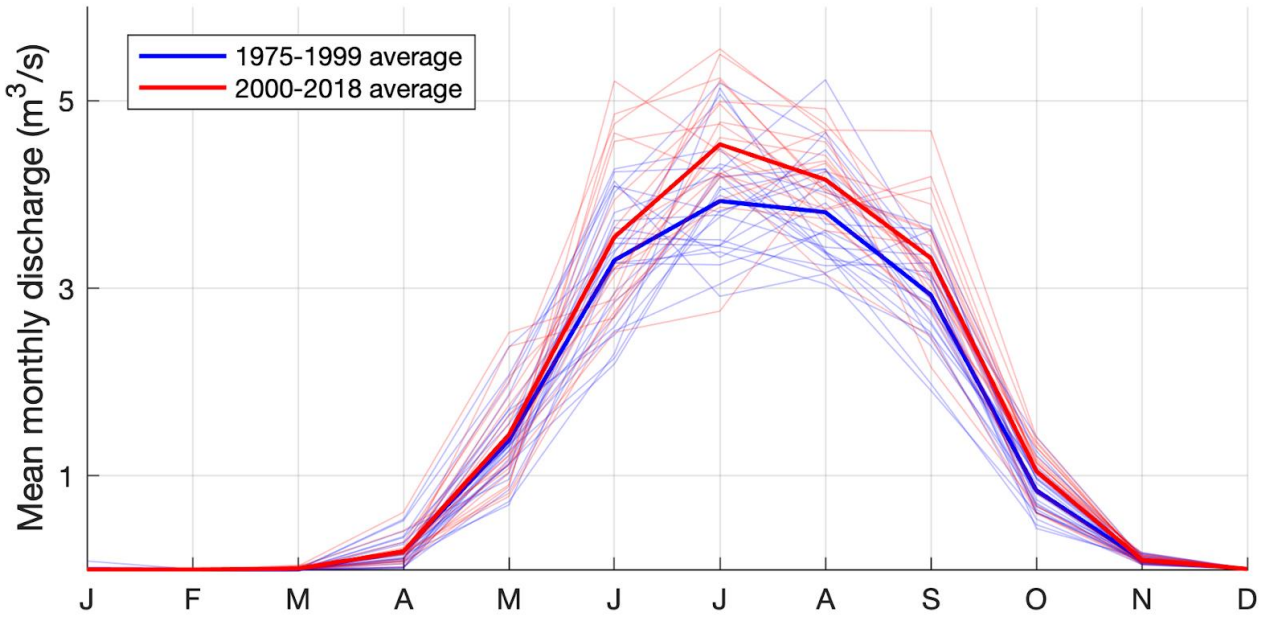
Spatial representation of spring and monsoon snowfall recent changes

- Increase in spring snowfall at all elevation
- Decrease in monsoon snowfall, especially pronounced in the high elevation areas
- Strong elevation gradient in monsoon snowfall due to both vertical precipitation and temperature gradient
- Less strong gradient in spring, since most of the catchment is below freezing temperature



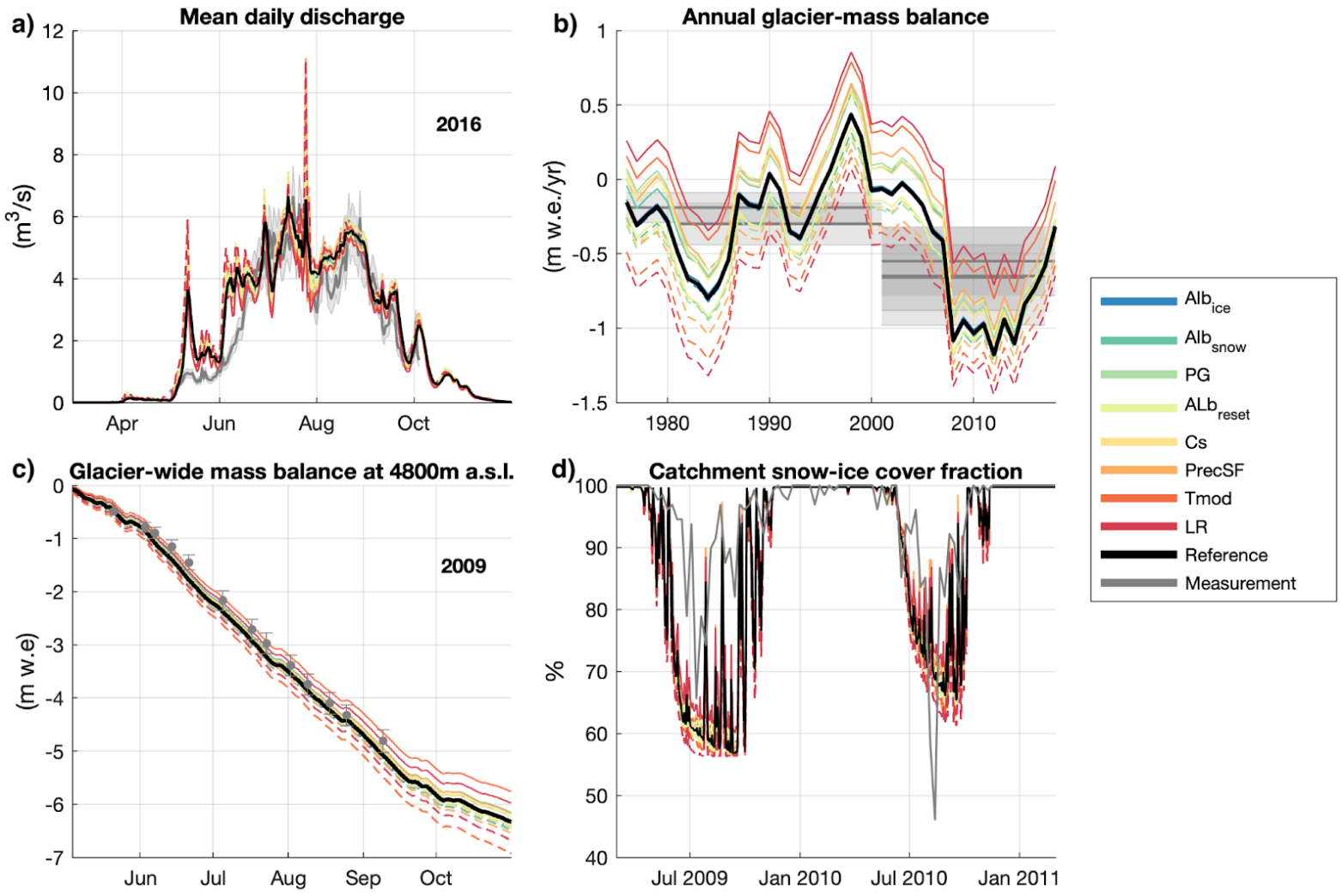
Monthly changes in catchment discharge

- No clear changes in catchment discharge before June
- Largest change are visible in June-July-August, and to a lesser extent in September
- No visible change in catchment discharge seasonality



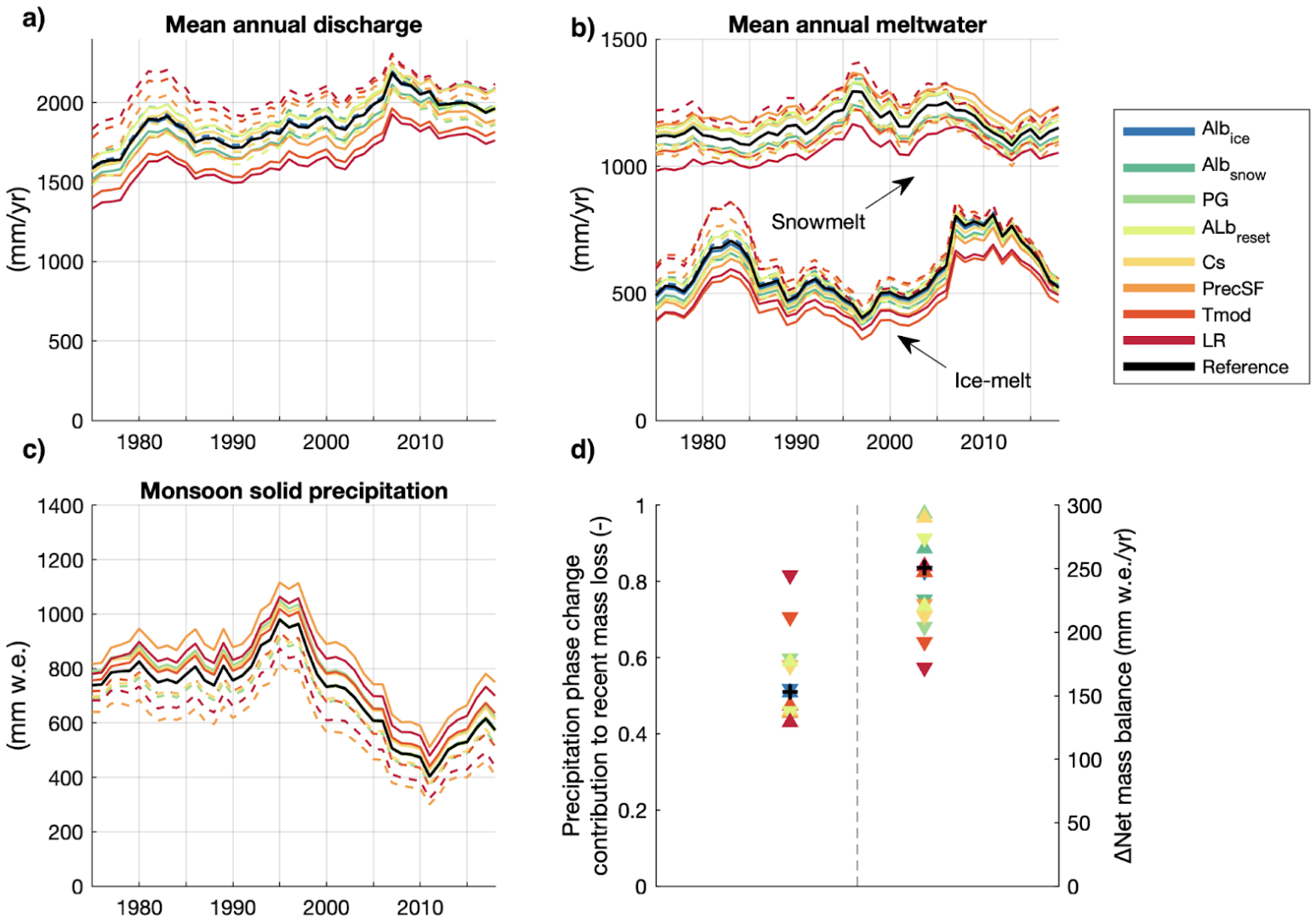
Model performance sensitivity to parameters uncertainty

Sensitivity of the model performance against validation datasets to changes in the key model parameters. Each parameter was varied once at a time, within a plausible range. Dashed lines indicate a lower parameter value, while solid lines indicate a high parameter value. The results from the reference run and the values derived from observation are also show shown as a basis for comparison.



Results sensitivity to parameters uncertainty

Sensitivity of our main results to changes in the key model parameters. Each parameter was varied once at a time, within a plausible range. Dashed lines indicate a lower parameter value, while solid lines indicate a high parameter value. The results from the reference run (black line or black cross) are also shown as a basis for comparison. The Δnet mass balance corresponds to the change in mean annual solid water balance between the early (1975-1999) and the recent (2000-2018) period.



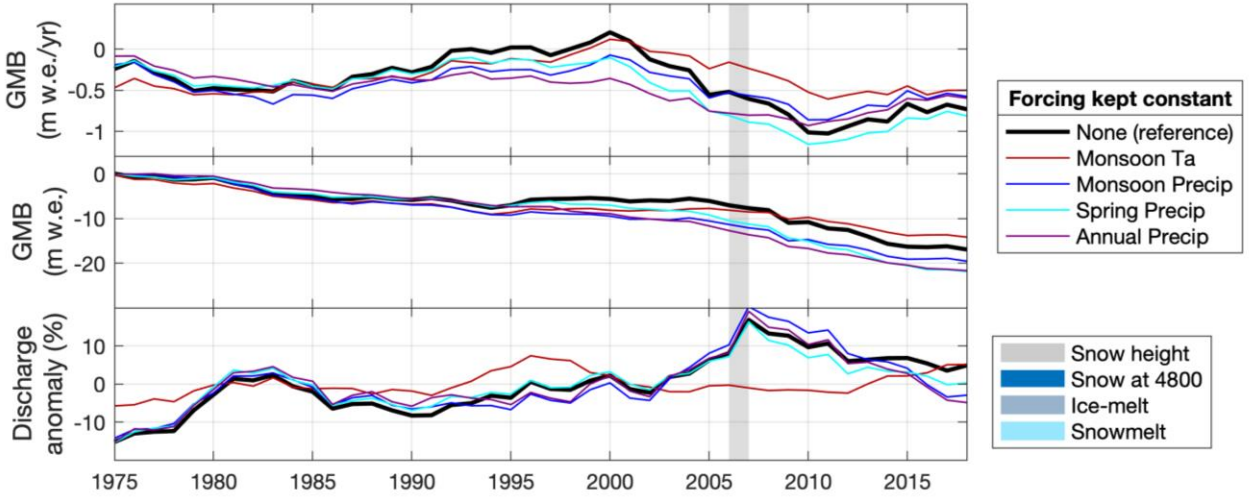
Our main results are not affected by the uncertainty in the parameters

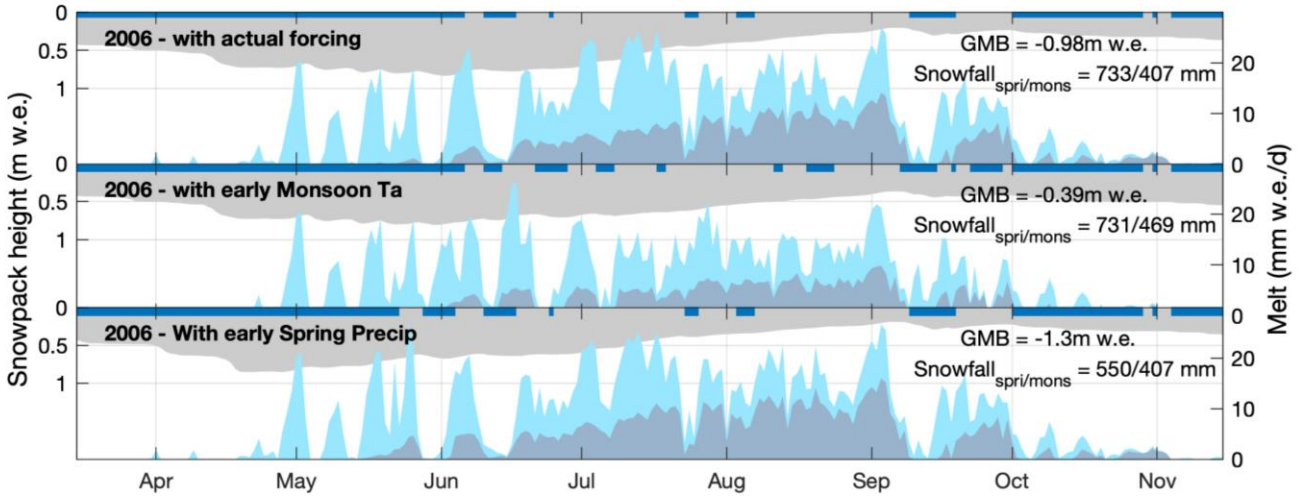
Forcing experiment

- Aim : investigate the role of each meteorological variable in explaining the recent mass loss acceleration

- Variables of interest :
  - spring temperature
  - spring precipitation
  - monsoon temperature
  - monsoon precipitation

- Each variable was turn by turn artificially set to remain at its mean 1975-1985 level during the whole simulation period





Forcing experiment

- When the monsoon temperature is set to the mean 1975-1985 conditions, the resulting annual GMB and catchment discharge during the recent period remained stable
- Similarly, higher spring and monsoon precipitation in 1995-2002 were responsible for the near-neutral GMB period
- Since 2005, increased spring precipitation and decreased monsoon precipitation have respectively mitigated and enhanced the mass loss primarily caused by monsoon warming