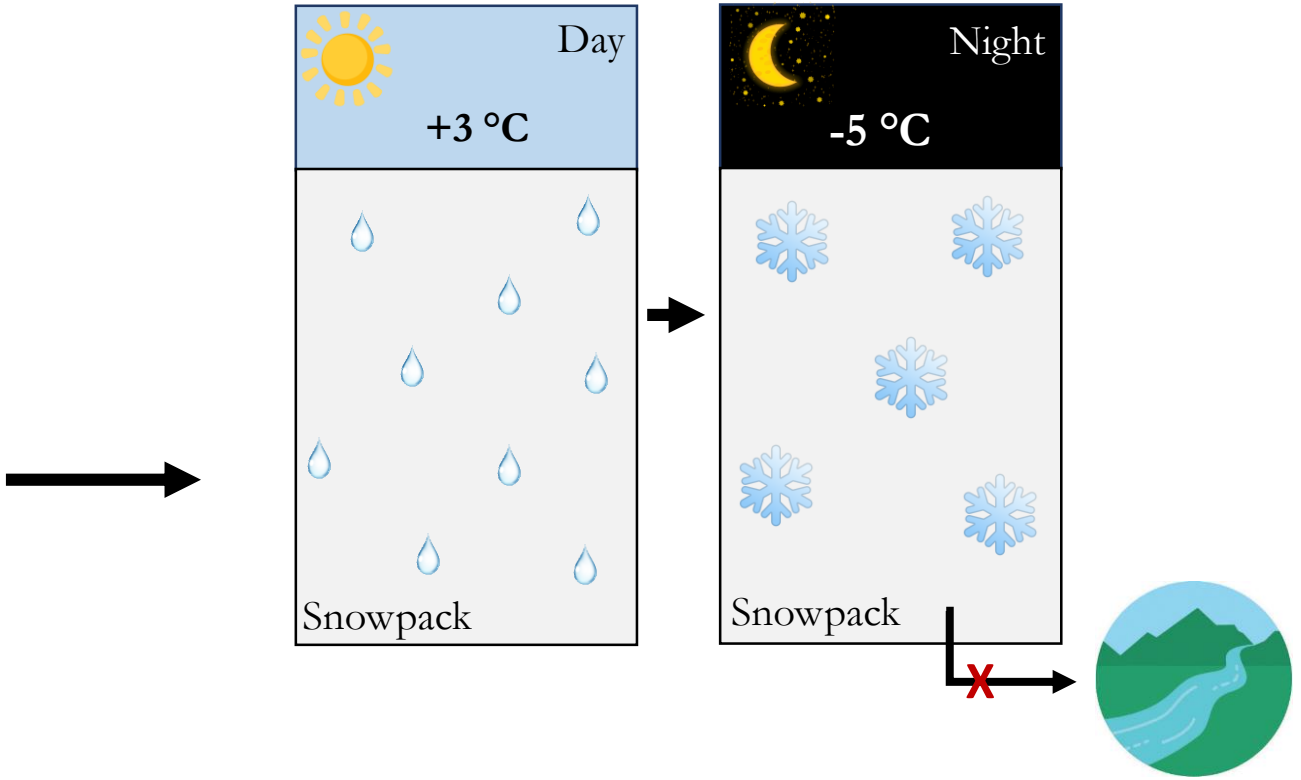
Spatial and temporal patterns of snowmelt refreezing in a Himalayan catchment

Sanne Veldhuijsen[1], R. J. de Kok[1], E. E. Stigter[1], J. F. Steiner[1], T. Saloranta[1] and W. W. Immerzeel[1] ([1]Utrecht University, [2]Norwegian Water Resources and Energy Directorate).

- Recent progress has been made in quantifing snowmelt in the Himalaya. However, translating snowmelt to snowmelt runoff is not as simple as often thought

Why not?

- The temperature fluctuates a lot around the freezing point, and therefore the snow melts during the day, and then refreezes during the night. This prevents melt to escape as runoff

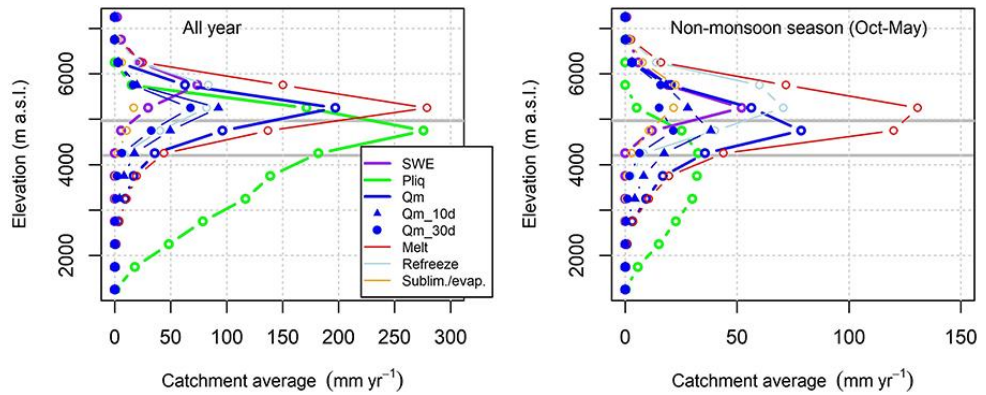


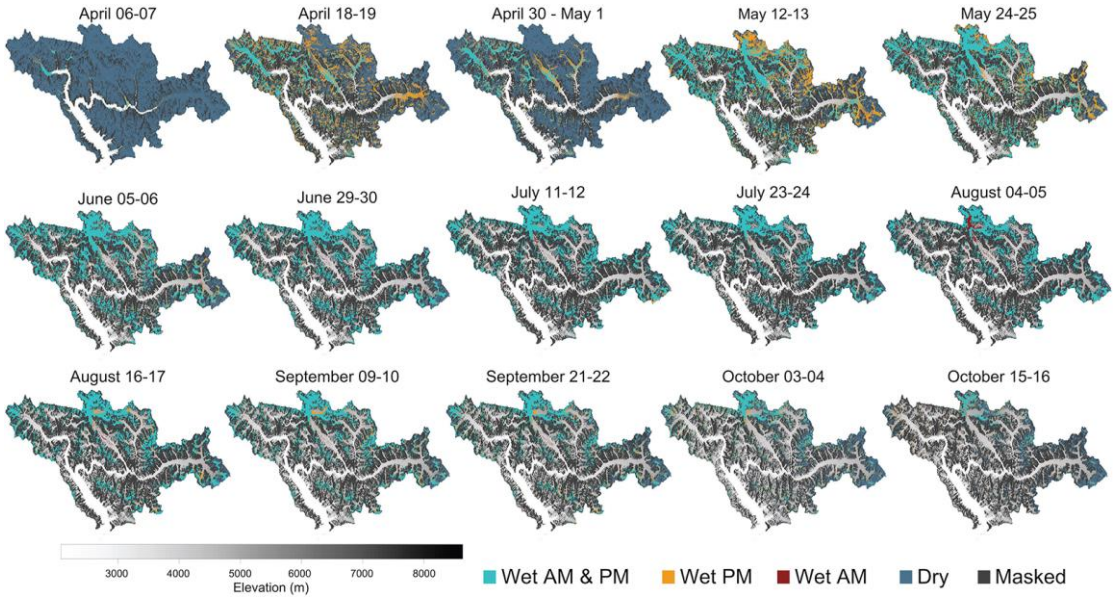
What do we know about snowmelt refreezing so far?

- Important in Antarctica, the Arctic, Sub-Arctic and in alpine areas (up to 100% of the melt)
- Importance depends on elevation and air temperature

And in the Himalaya?

- **Saloranta et al. (2019):** 36% of the melt in a catchment refreezes
  Elevation profiles of all year and non-monsoon season
- **Lund et al. (2020):** Remotely sensed diurnal melt-refreeze cycles





Saloranta, T., Thapa, A., Kirkham, J. D., Koch, I., Melvold, K., Stigter, E., (2019). A model setup for mapping snow conditions in High-Mountain Himalaya. *Frontiers in Earth Science*, *7*, 129.
Lund, J., Forster, R. R., Rupper, S. B., Deeb, E. J., Marshall, H. P., Hashmi, M. Z., & Burgess, E. (2020). Mapping snowmelt progression in the Upper Indus Basin with synthetic aperture radar. *Frontiers in Earth Science*, *7*, 318.

What do we aim to explore (in more detail) on a catchment scale?

- How does refreezing vary with **elevation** and **aspect**?
- How does refreezing vary between **seasons** and **years**?
- What are the **driving forces** of these patterns?

How to model this?

Degree day? – ignores important processes

Energy balance? – too much input uncertainty

Analytical method?

Minimizes input uncertainty:
Only temperature, precipitation (and incoming shortwave radiation)

Includes important processes:
- Release of latent heat
- Thermal insulation of the snowpack

Model

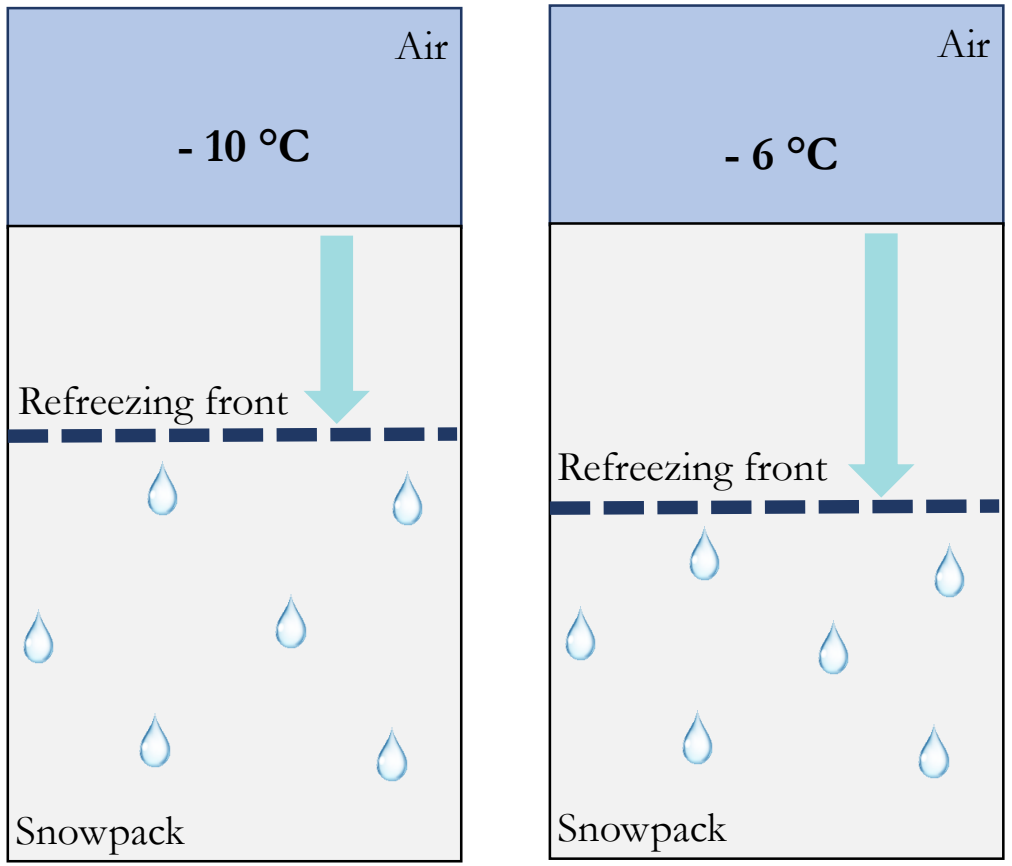
seNorge snow model (Saloranta et al. 2019)

- Single layer
- Enhanced temperature-index
- Albedo decay
- Compaction
- Refreezing

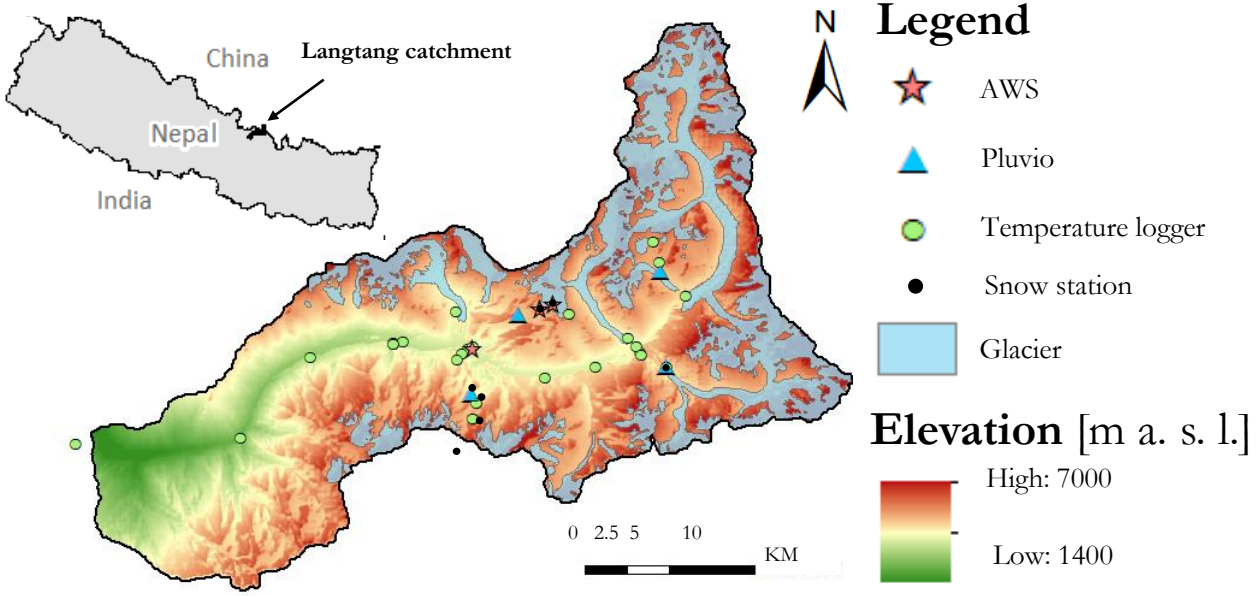
Refreezing: based on Stefan's Law

The snowpack is cooled from the snow-atmosphere interface in downward direction. During this cooling, all liquid water is assumed to refreeze, thereby forming a refreezing front that penetrates downwards, during which latent heat is released. The growth of the refreezing front is calculated as:

$$\text{Growth refreezing front} = \sqrt{\frac{2\kappa_s}{\rho_{lw} L}(-T_a)\Delta t_s}$$



Study area



Settings:

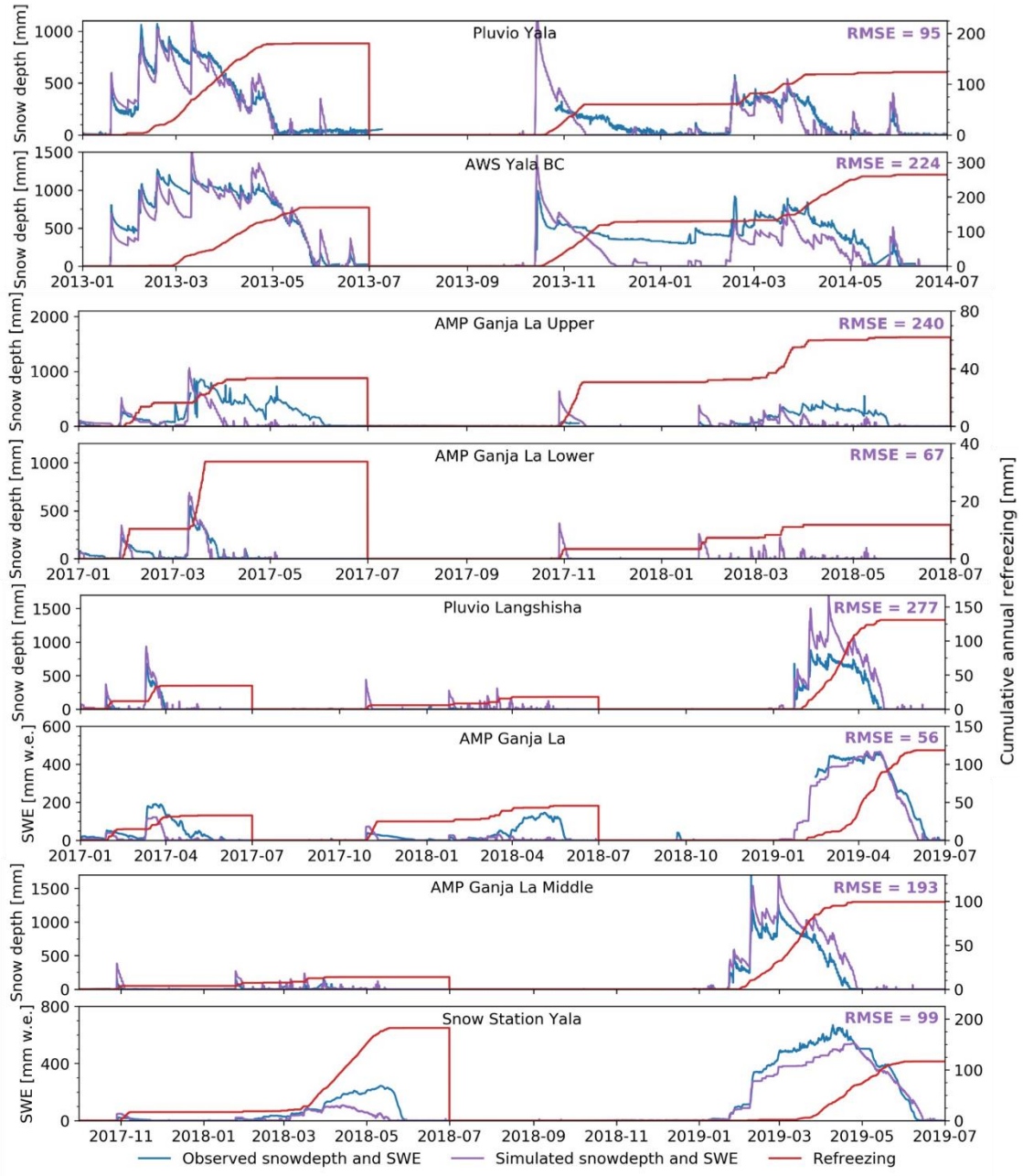
- **100 m resolution**
- **Hourly timestep**

Meteorological forcing

Combining a network of 32 meteorological stations with high-resolution simulations

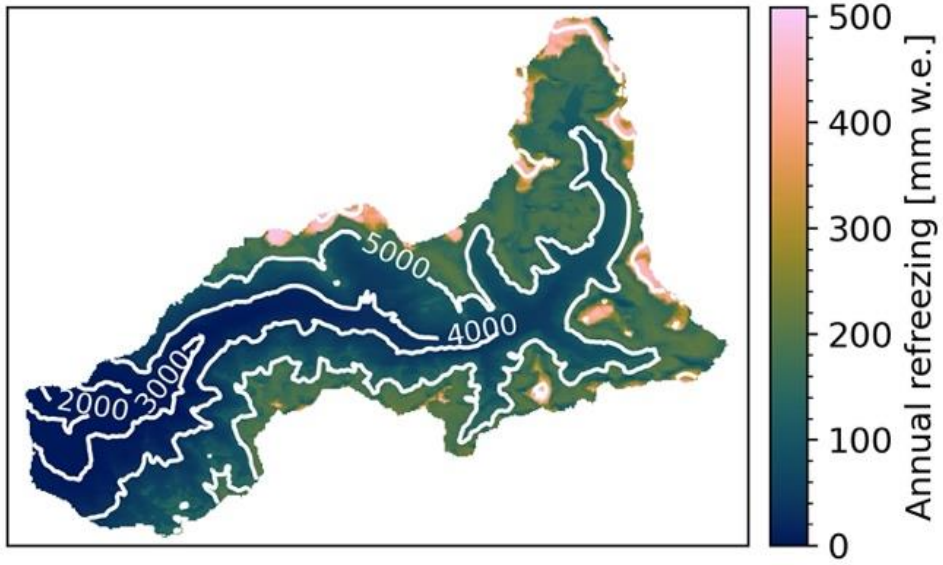
- **Temperature:** Extrapolated observed temperature with calculated lapse rates
- **Precipitation:** WRF precipitation scaled with observations
- **ISWR:** Calculated clear-sky radiation corrected with WRF transmissivity.

Snowdepth validation



Results & discussion

Elevation:



Refreezing generally increases with elevation

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Colder + more snowfall

- **21%** of the snowmelt refreezes (hourly timestep) → **122 mm/year**
- **Only 5%** of the snowmelt refreezes **(19 mm/year)** when a **daily** timestep is used

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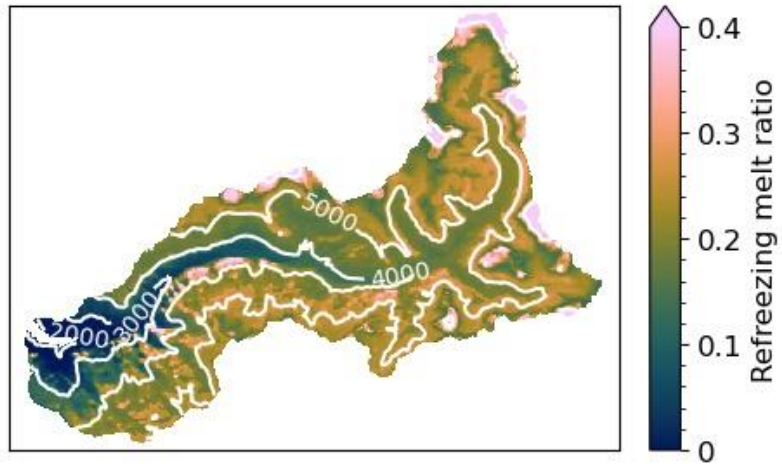
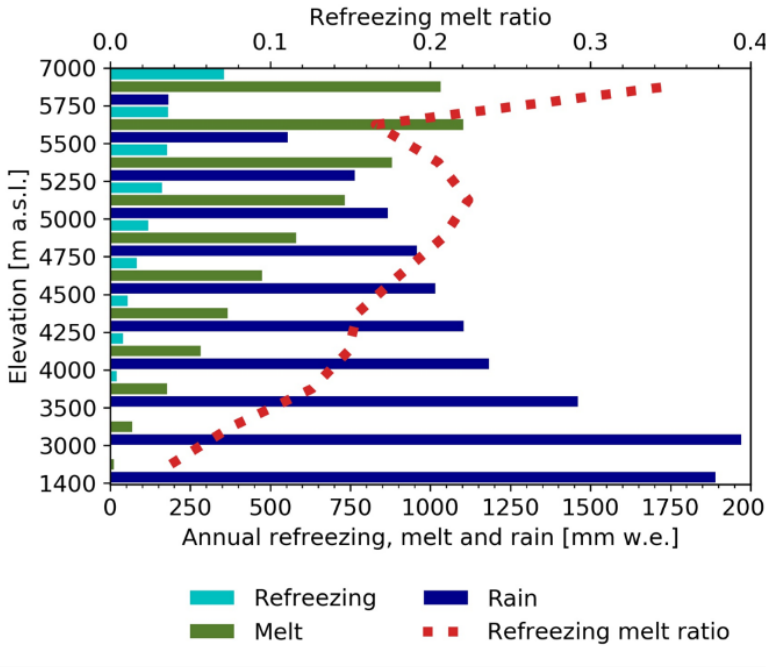
Important to use sub-daily timesteps to capture diurnal melt-refreeze cycles

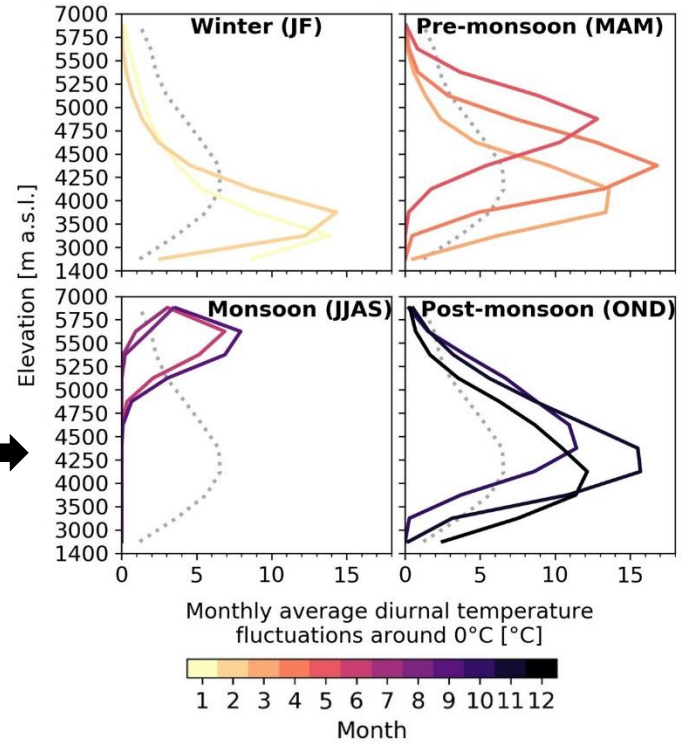




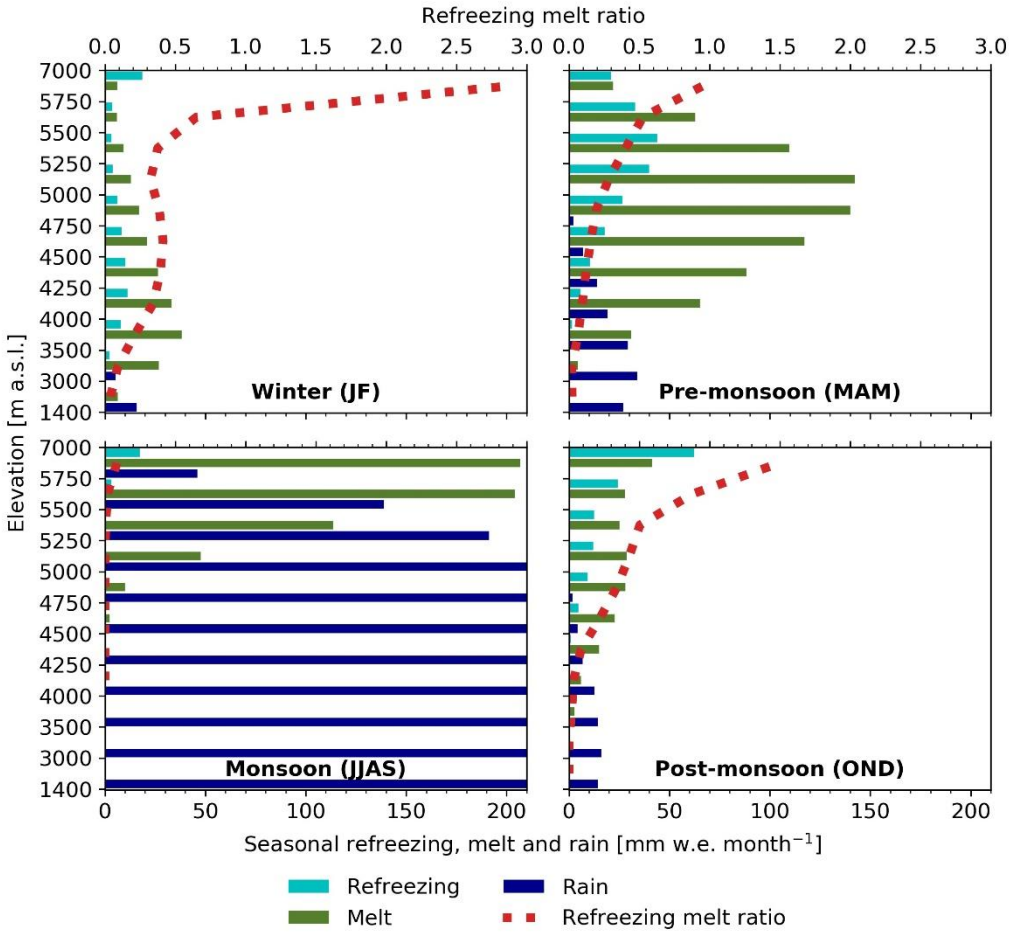
Refreezing melt ratio:

minimum around 5,250 – 5,750 m a.s.l.

- Thicker snowpack → more insulation
- Melts during monsoon → less temperature fluctuations due to **clouds**

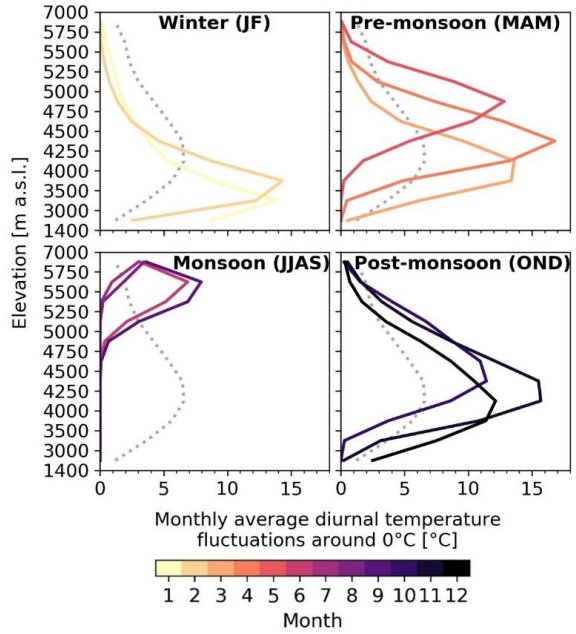


Seasonal variability:



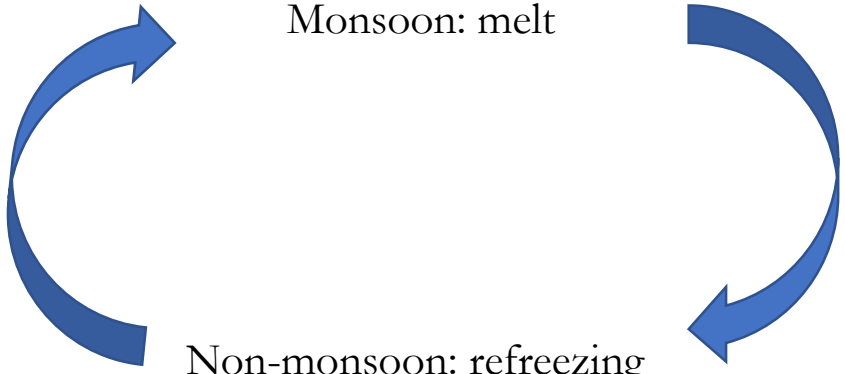
< 5,750 m a.s.l.

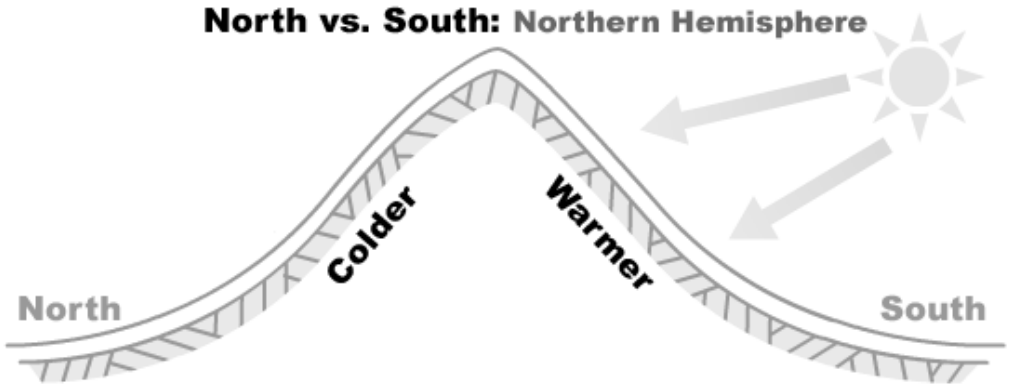
- Dominant forcing: SWE and diurnal temperature fluctuations

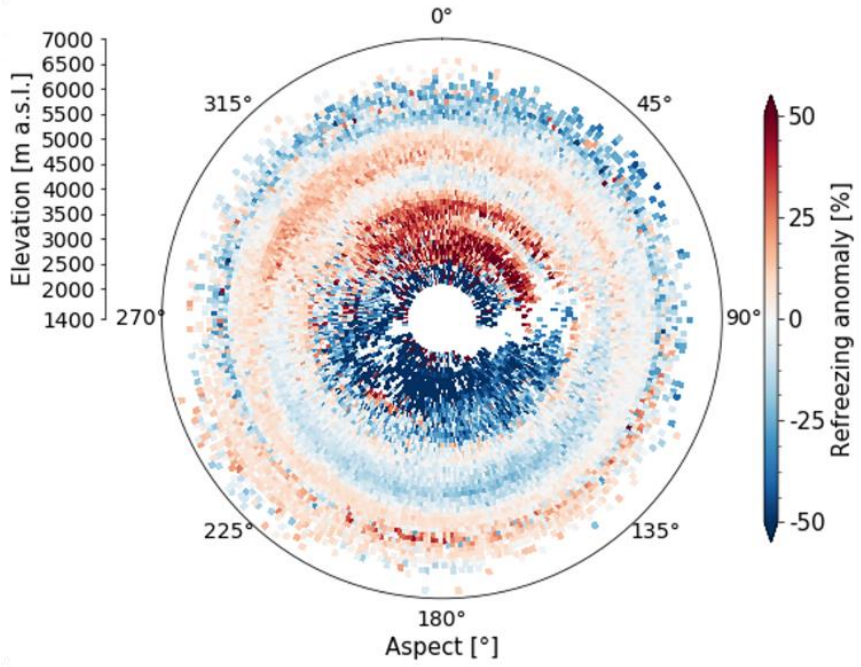


> 5,750 m a.s.l.

- High amounts of refreezing
- Dominant forcing: seasonal temperature fluctuations → seasonal melt-refreeze cycles







Aspect:

- < 5,250 m a.s. l. refreezing is higher on north-facing slopes:
  - → Snowpacks are too shallow to store the additional meltwater
  - → This accelerates the depletion of the snowpack
  - → This decreases the potential for refreezing

- > 5,250 m a.s.l. refreezing is higher on south-facing slopes:
  - → Deeper snowpacks can store the additional meltwater
  - → This increases melt-refreeze cycles

Intra-annual variability

- Intra-annual variability:
- Pre-monsoon (2013, 2019)
- Post-monsoon (2013)

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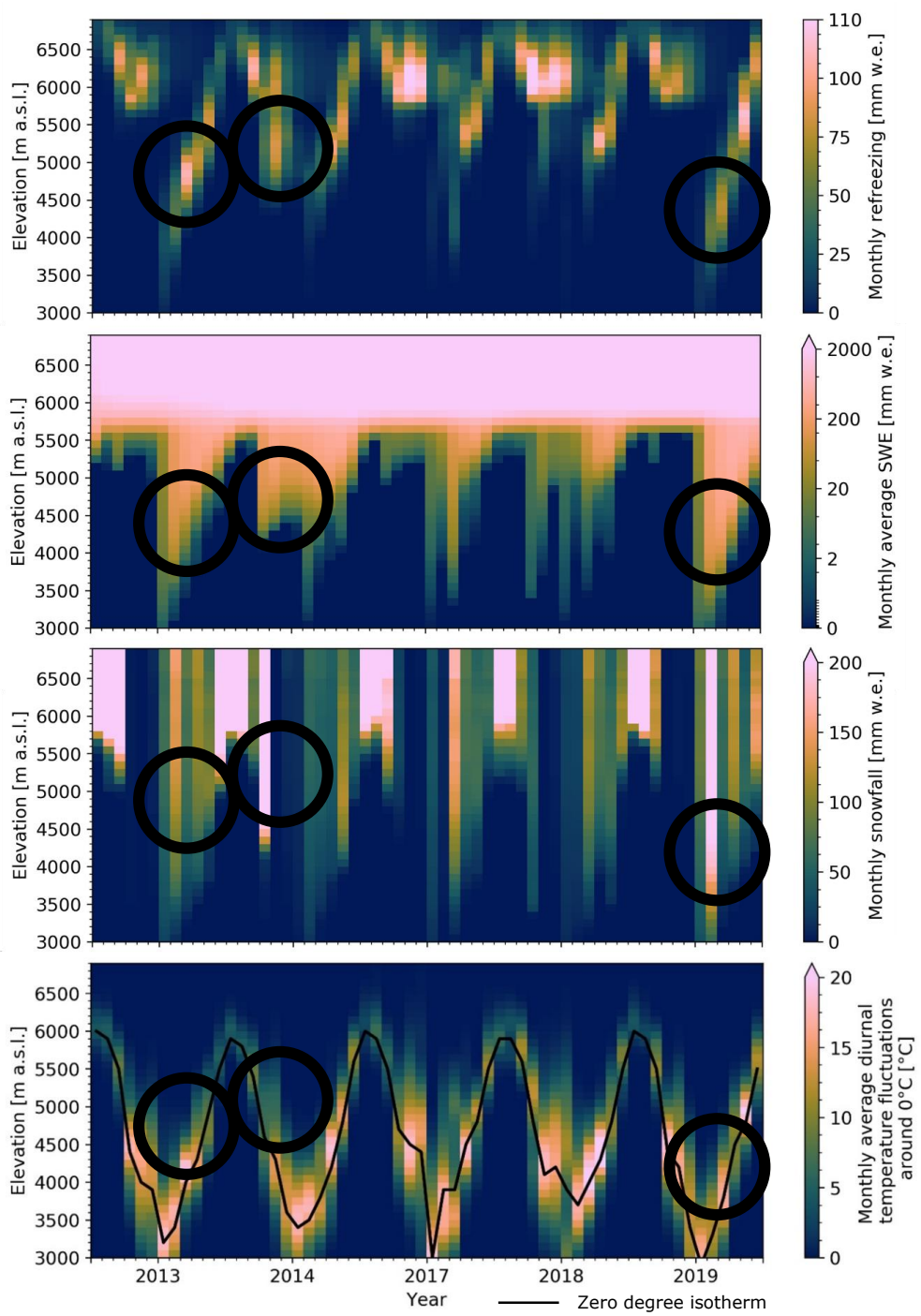
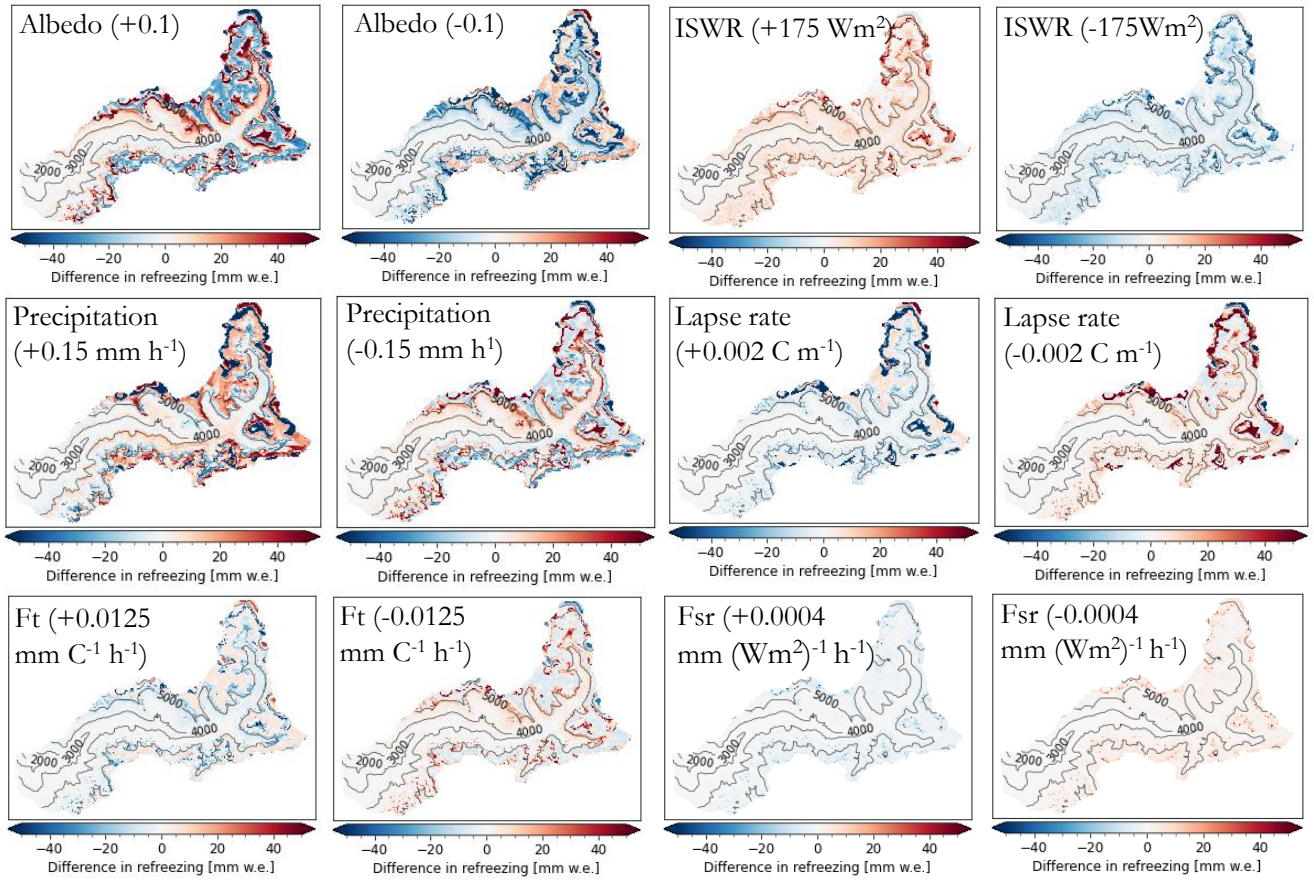
Related to fluctuations in snowfall

- Important to use multi-year timeseries in refreezing assesments





Temperature melt factor

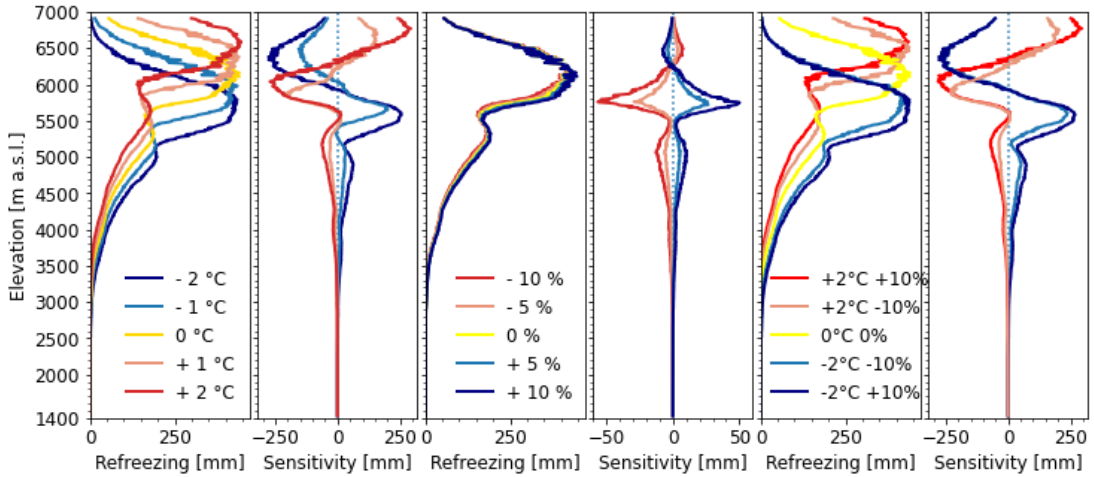
Shortwave radiative melt factor

Sensitivity analysis

- Most sensitivity to albedo uncertainty
- 200 MC runs → resulting standard deviations:
  refreezing: 10 mm (8.5% of the reference)
  refreezing melt ratio 0.019 (9.2% of the reference)
- Work in progress

Climate sensitivity analysis

- Most sensitivity to temperature changes via snowfall



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Future model improvements?

- Meltwater infiltration
- Cold content

Conclusions

- **21%** of the snowmelt refreezes (hourly timestep)
- **Only 5%** when a **daily** timestep is used
- Strong **altitudinal seasonal** variability (most refreezing in pre- and post-monsoon)
- **Aspect** is important
- Very high elevation: **seasonal** melt-refreeze cycle
- **Intra-annual** variablity in the pre- and post-monsoon seasons related to snowfall

Any questions or thoughts?

Feel free to send my an email:

s.b.m.veldhuijsen@uu.nl