Universiteit Utrecht

Faculty of Geosciences
Physical Geography

Climate change decisive for Asia's snow meltwater supply

P.D.A. Kraaijenbrink, E.E. Stigter, T. Yao, W.W. Immerzeel

Philip Kraaijenbrink
Assistant Professor
p.d.a.kraaijenbrink@uu.nl
www.philipkraaijenbrink.nl
www.mountainhydrology.org

Streamflow in the high mountains of Asia (HMA) is strongly influenced by meltwater. Past and future changes in seasonal snow are of particular interest, as its meltwater discharge is substantial, yet specifics are largely unknown.

Here we show that across the region snowmelt is a more important contributor to streamflow than glacier melt, that its magnitude and timing have changed considerably over the last four decades, and that snow meltwater supply may decrease drastically in the future.

Present state

Running the model for present-day climate provides a spatiotemporal characterization of snow water equivalent (SWE) and snowmelt. This allows for a basin-wide comparisons of meltwater contributions, which reveals that snowmelt is consistently more important for streamflow than glacier melt (Fig. 1).

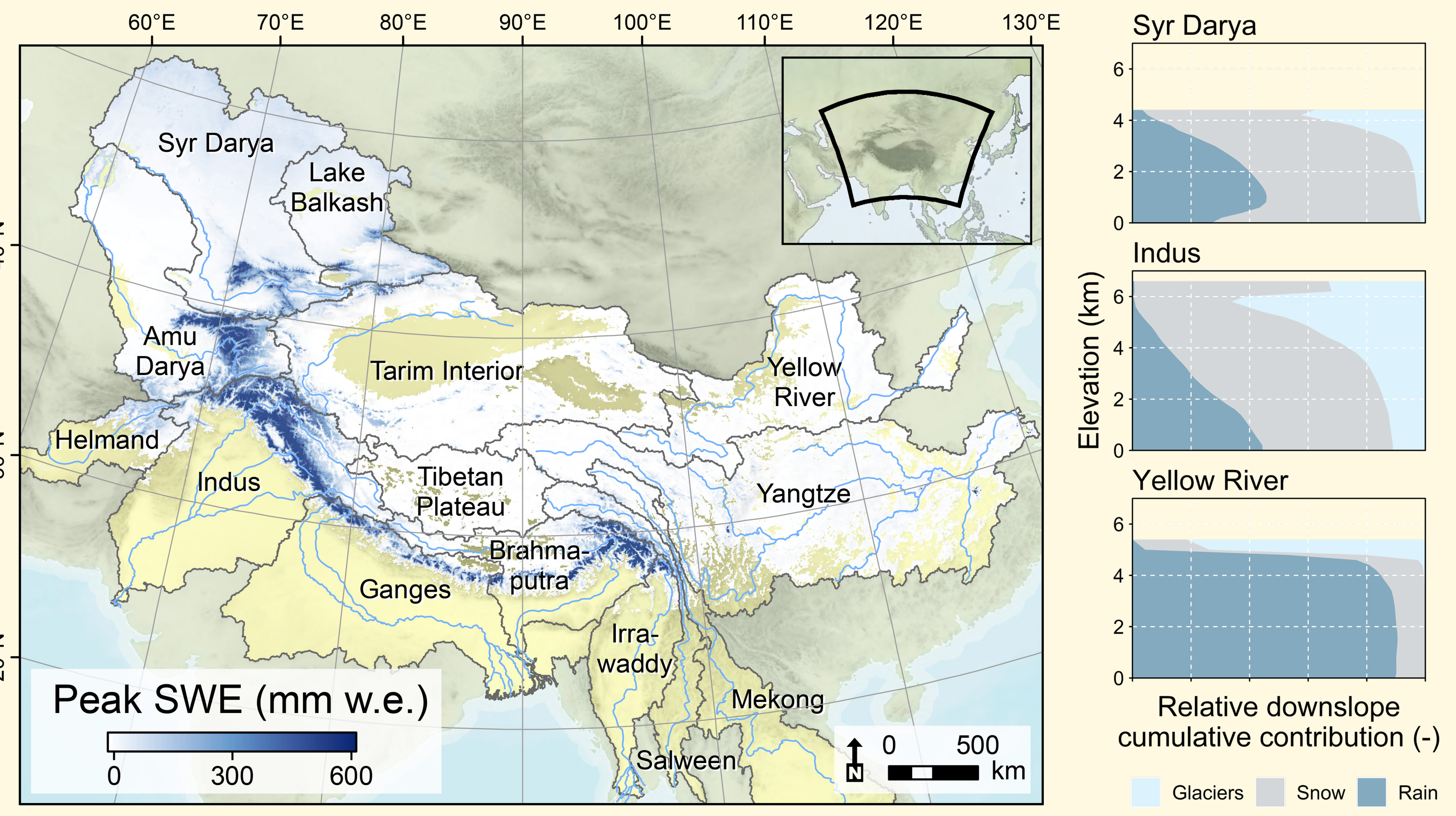

Figure 1. Snow water equivalent and relative streamflow contributions. Overview map of HMA and simulated annual peak SWE over the period 2000–2018 (left). Relative contribution of snowmelt, glacier melt (based on Kraaijenbrink, 2017) and rainfall runoff to river discharge for three selected basins over the same period (right). The contributions are cumulated from high to low elevation.

Validation

To validate the model performance, SWE output was compared with snow depths derived from Sentinel-1 radar measure-ments (Fig. 6; Lievens, 2019).

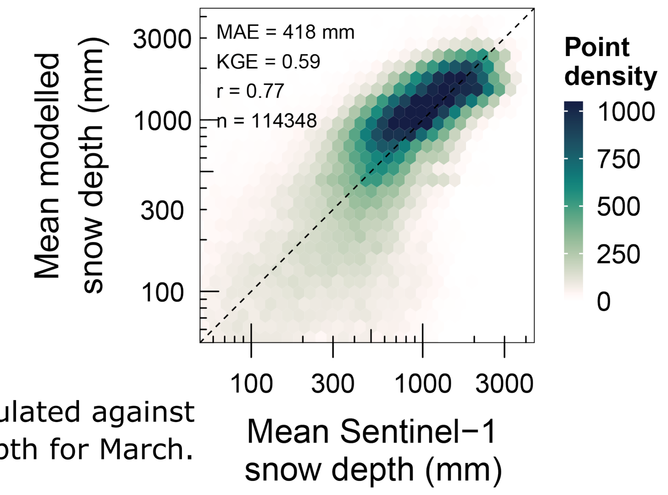

Figure 6. Simulated against observed snow depth for March.

References

Hock, R. 2003. "Temperature Index Melt Modelling in Mountain Areas." *Journal of Hydrology*, Mountain Hydrology and Water Resources, 282 (1): 104–15.

Kraaijenbrink, P.D.A., M.F.P. Bierkens, A. F. Lutz, and W.W. Immerzeel. 2017. "Impact of a Global Temperature Rise of 1.5 Degrees Celsius on Asia's Glaciers." *Nature* 549 (7671): 257–60.

Lievens, H., M. Demuzere, H.P. Marshall, R.H. Reichle et al. 2019. "Snow Depth Variability in the Northern Hemisphere Mountains Observed from Space." *Nature Communications* 10 (1): 1–12.

Approach and methods

Model. We implemented a temperature index model (Hock,2003) that runs at a 3-hourly time step on a 0.05° grid, includes a refreezing component and accounts for altitudinal variability using a subgrid model routine. Given the spatial and temporal scale of this study and the lack of spatially representative input data to calibrate and validate snow models in HMA, this provides the optimal approach.

Forcing. The model is forced climatologically by ECMWF ERA5 gridded reanalysis data (1979-2018; hourly; temperature (*T*) and precipitation *(P)).* Biases in the reanalysis data are removed by calibrating the model using the MODIS 500 m snow cover over the period 2000–2018.

Projection. To analyse future changes in seasonal snowpacks and snowmelt discharge we perform (i) a bottom-up elasticity approach where we superimpose combinations of *T* and *P,* and (ii) perform model runs with CMIP5 ensemble means for RCP2.6 (n=28), RCP4.5 (n=38), RCP6.0 (n=21), and RCP8.5 (n=35).

Past changes

Over the last four decades we find changes in seasonal snow storage in various regions in HMA (Fig. 2) and reveal that the timing and magnitude of snow meltwater supply to the rivers has changed considerably (Fig. 3).

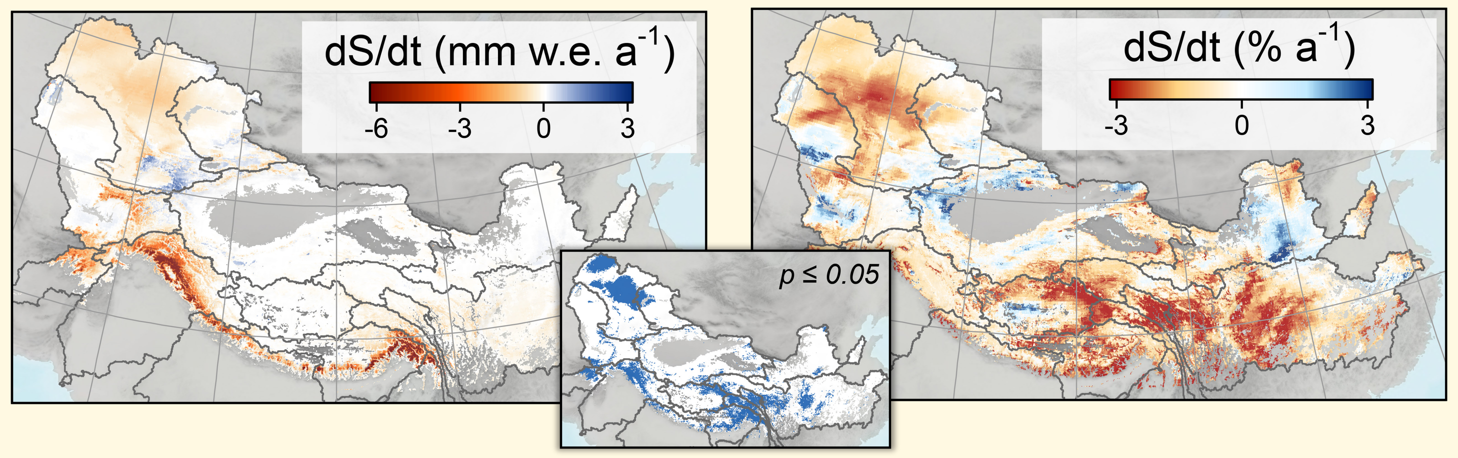

Figure 2. Historical absolute and relative trends in mean SWE. Absolute (left) and relative (right) trends in the annual peak SWE over 1979-2018. Statistically significant areas indicated in blue (center).

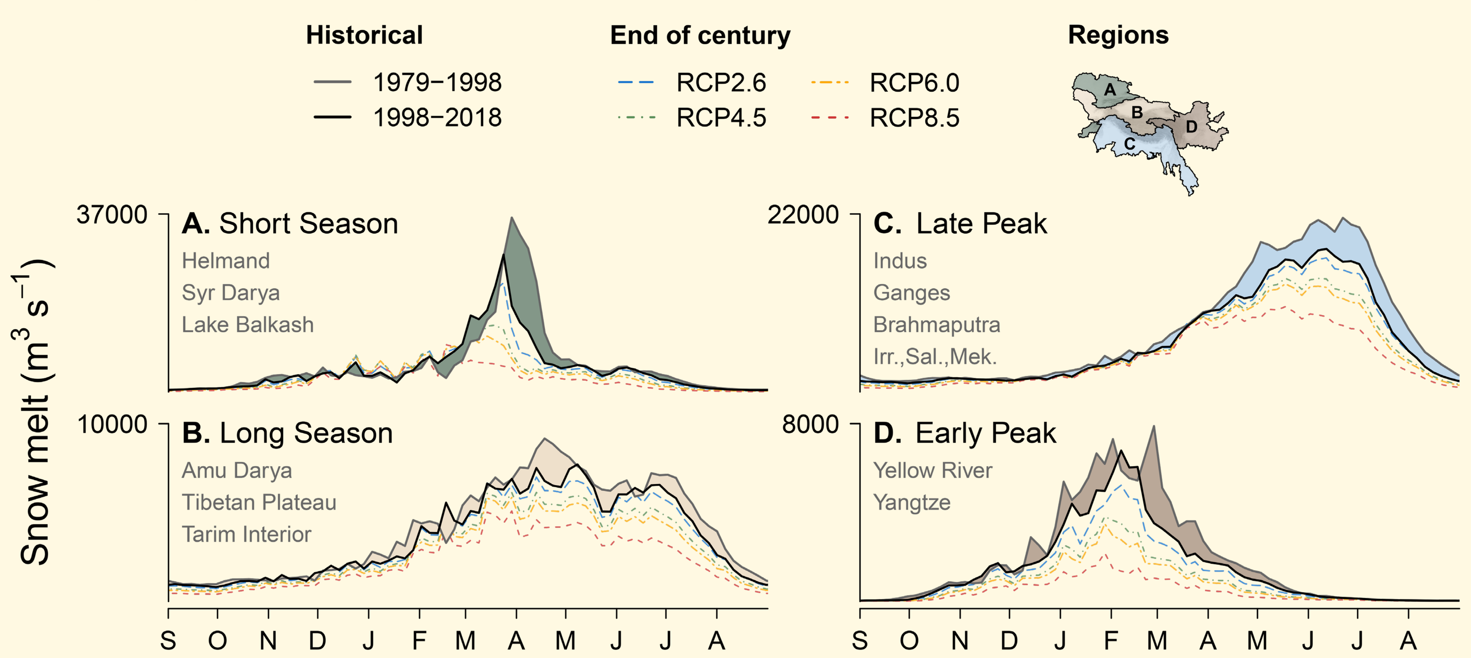

Figure 3. Snowmelt hydrographs for four melt regimes. Climatological snowmelt hydrographs for four melt regimes (A-D) present in HMA for 1979–1998 and 1998–2018. Differences between the two periods are shaded. The dashed lines represent end of century (2071-2100) hydrographs for each of the four CMIP5 RCPs.

Future projections

The bottom-up elasticity analysis shows that there are large spatial differences in sensitivity of snowmelt to changes in temperature and precipitation (Fig. 4). Although glacier mass loss is considerable, their end-of-century streamflow contribution is shown to be much less sensitive to climate change than that of snow (Fig. 5).

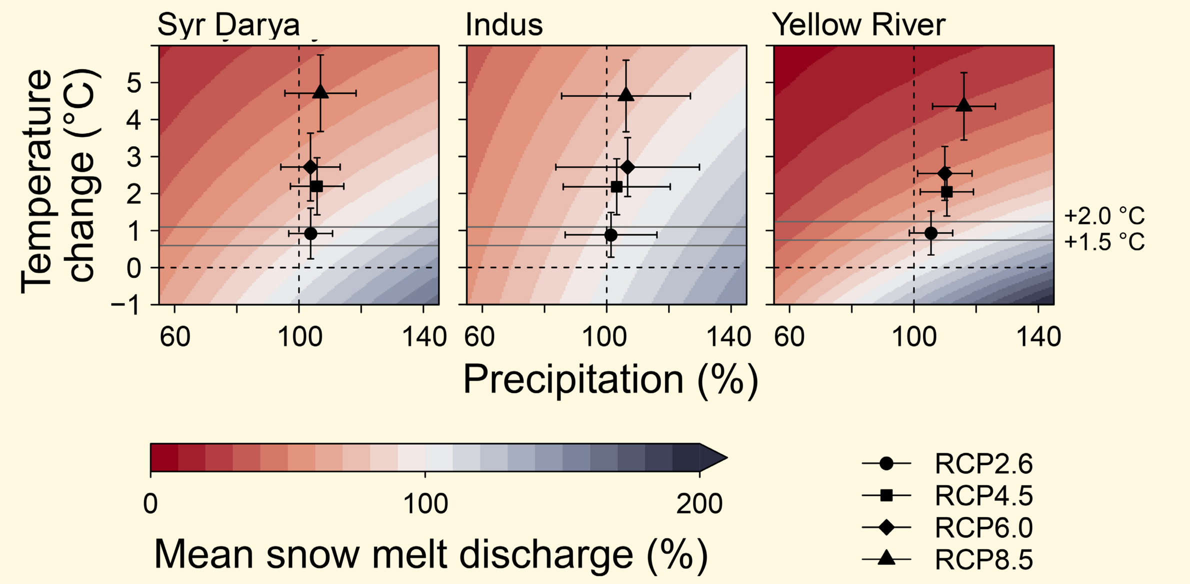

Figure 4. Sensitivity of snow melt discharge. Relative difference for selected basins in climatological annual snowmelt between reference period 2000–2018 and the same period with superimposed changes in *P* and *T*.

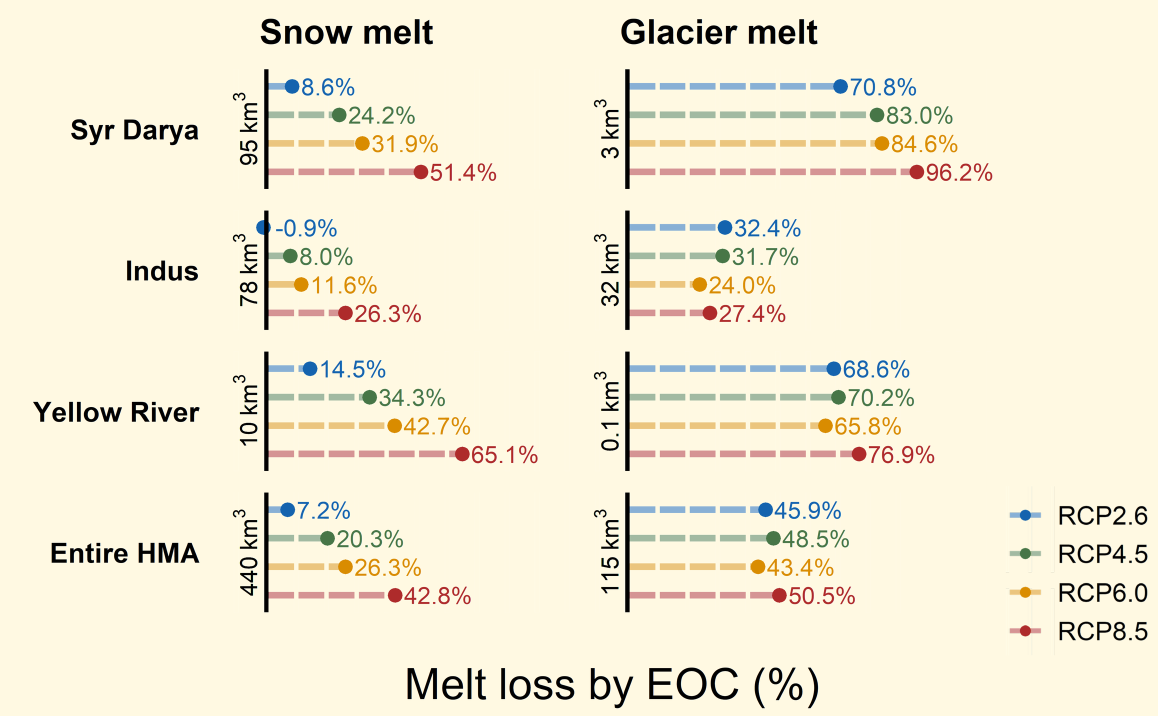

Figure 5. Projected losses in snow and glacier meltwater discharge. Simulated loss of annual snow (this study) and glacier (Kraaijenbrink, 2017) meltwater discharge by the end of century (2071–2100) for four RCP model ensembles and three selected basins.

Conclusions

- Snowmelt contribution to streamflow is considerable in many parts of HMA and hydrologically more important than glacier melt
- Timing and magnitude of snow melt has changed over 1979-2018
- Large future changes projected, but decrease in snowmelt strongly related to degree of climate change
- Considerable spatial heterogeneity in the sensitivity of snow and melt to changes in *P* and *T*
- Snow crucial to consider in future hydrological assessments

Published as: Kraaijenbrink, P. D. A., Stigter, E. E., Yao, T., and Immerzeel, W. W. (2021). Climate change decisive for Asia's snow meltwater supply. *Nat. Clim. Chang.* 11, 591–597. doi:10.1038/s41558-021-01074-x.