



Glacier melt contribution to summer streamflow during extremely dry summers

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HS2.1.7 Snow and ice accumulation, melt, and runoff generation in catchment hydrology: monitoring and modelling

Extreme dry and hot summers cause droughts and lead to

low flow conditions



In Europe, such extreme summers were observed in recent years:

e.g. 2003, 2015 and 2018



The European Alps - also known as Europe's water tower -
play an important role during such extreme summers by providing (extra)

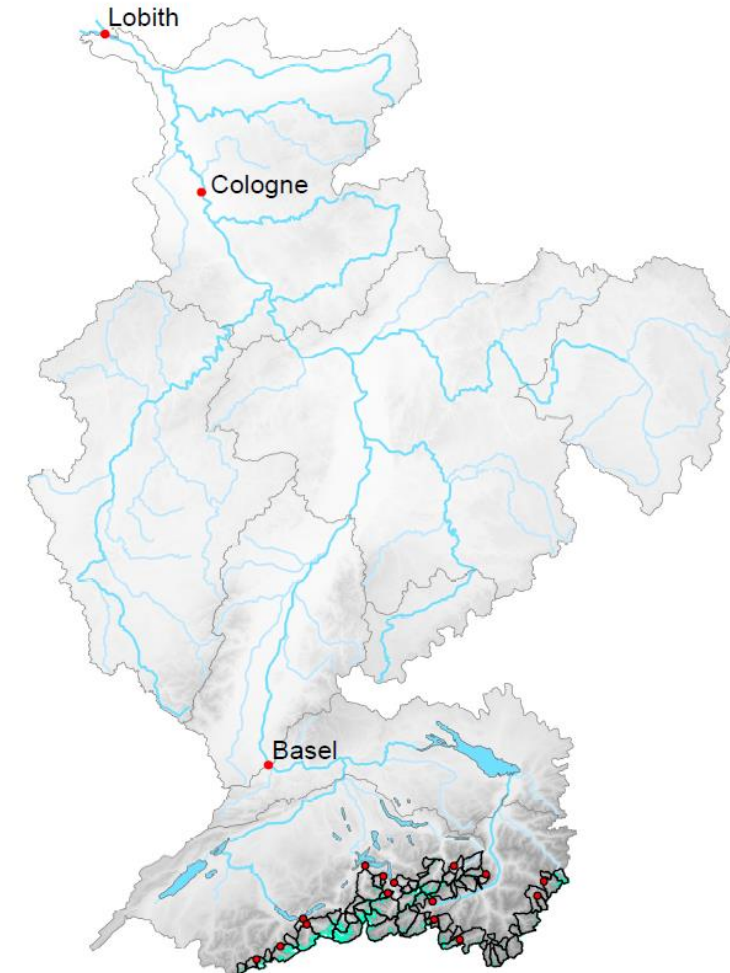
water from the melt of snow and ice



How much water do glaciers supply during such downstream low flow years?



We focus on the **Rhine river basin** and analyzed simulated and observed
streamflow from the glacierized headwaters and downstream

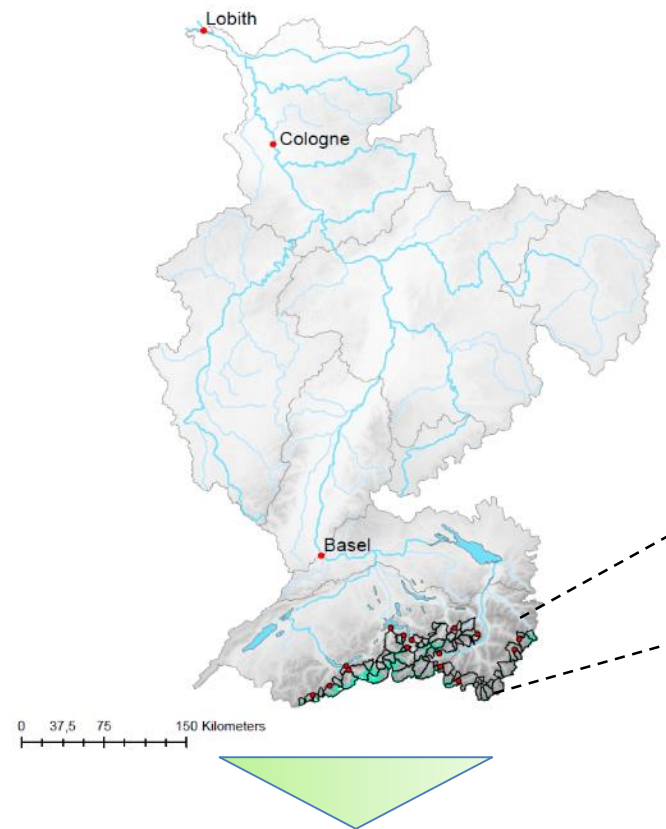


0 37,5 75 150 Kilometers

Elevation from SRTM

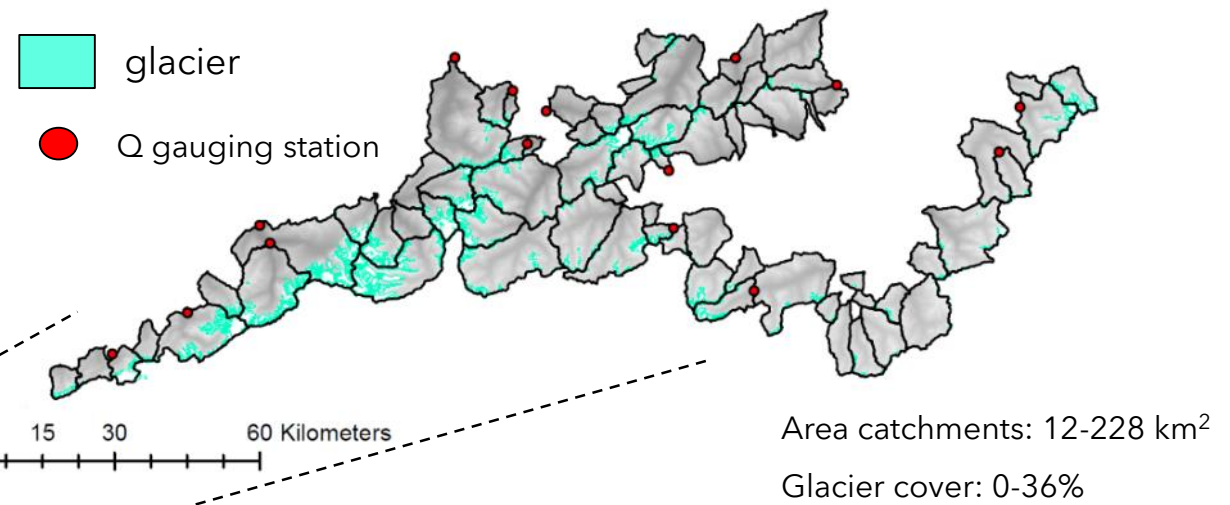
Overview of methods – upstream and downstream

1 Downstream – whole Rhine basin



Observed streamflow from gauging stations
Lobith (NL), Cologne (DE) and Basel (CH)
from 1970-2019

2 Upstream – glacierized headwater catchments



Streamflow **simulations** of 65 glacierized catchments

- HBV-light model
- streamflow components: $Q_{ice} + Q_{snow} + Q_{rain}$
- Simulation period: 1973 - 2020
- 15 gauged and 50 ungauged catchments
- Model calibration based on Q , snow (SWE and area), glacier volume changes

Low flow years at downstream locations

Selection of downstream low flow years in period 1970-2019 based on a range of criteria:

- lowest total Q (1 Oct - 30 Sep)
- lowest total summer flow (1 Jun - 31 Aug)
- 7 day minimum flow
- fixed (mean annual 7-day min. flow) and varying threshold (20th percentile)

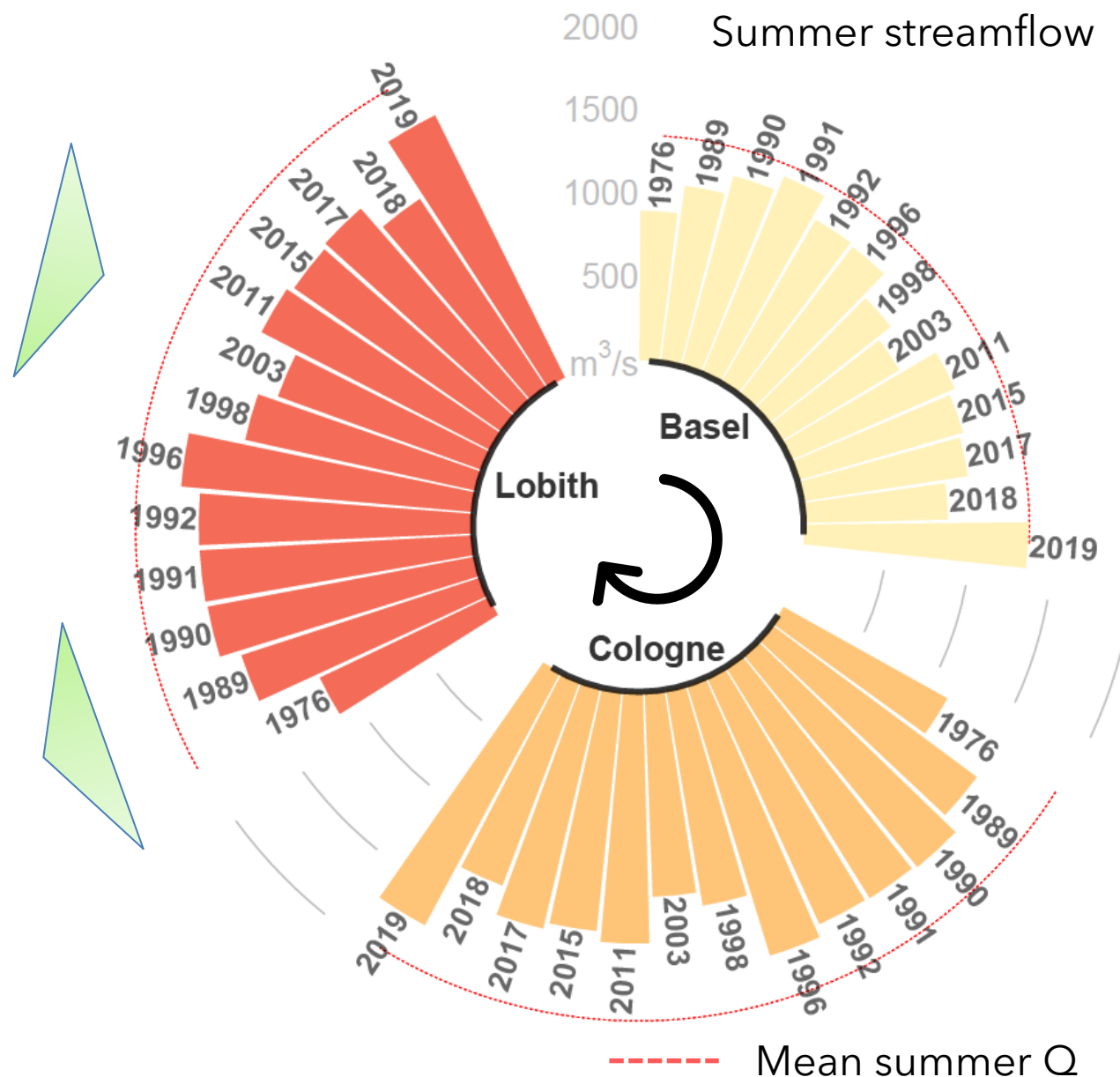


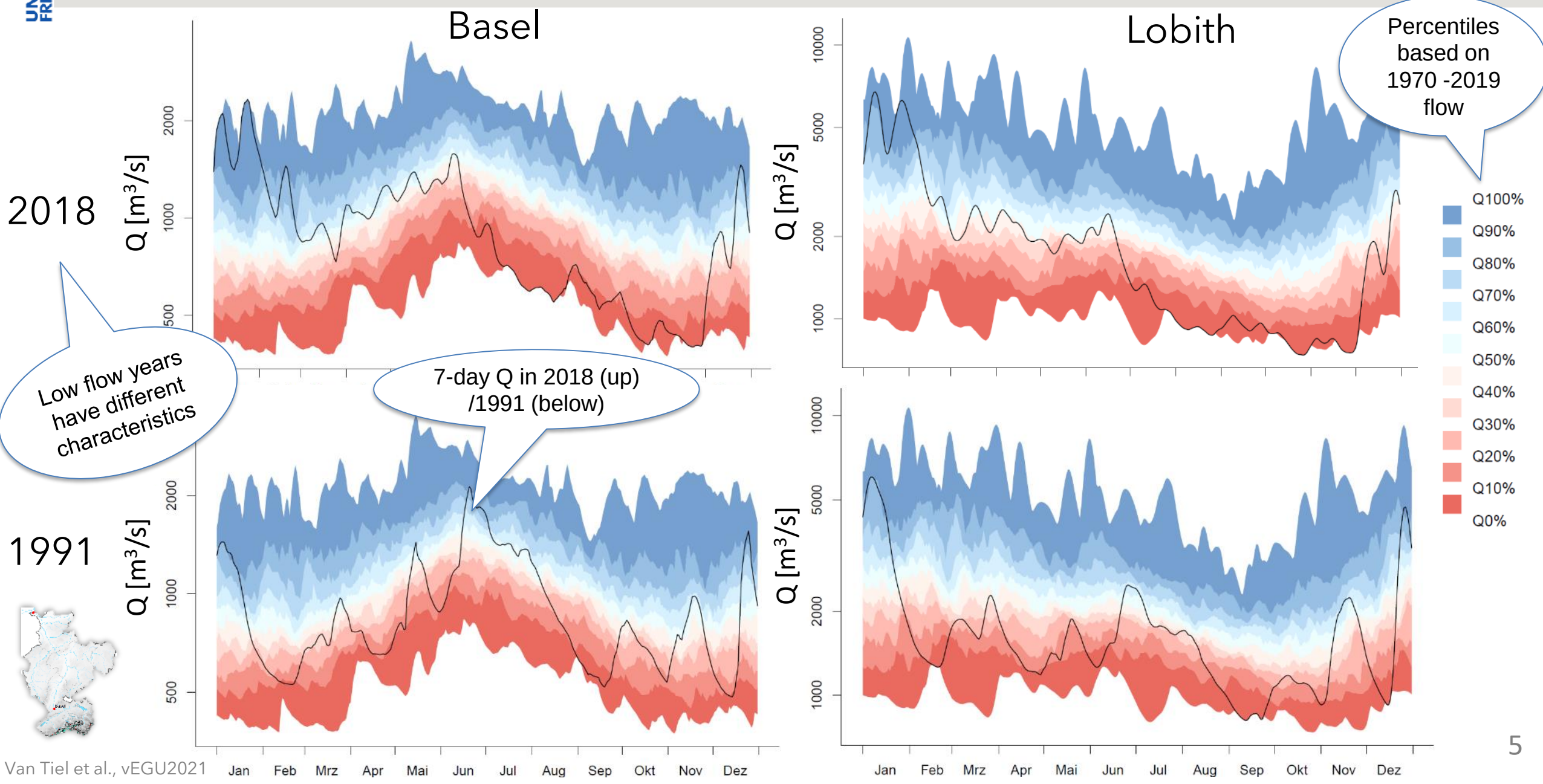
Lowest (low) flow years:

- 1976, 1998, 2003, 2018

Multiple low flow years:

- 1989 - 1992
- 2017 - 2019

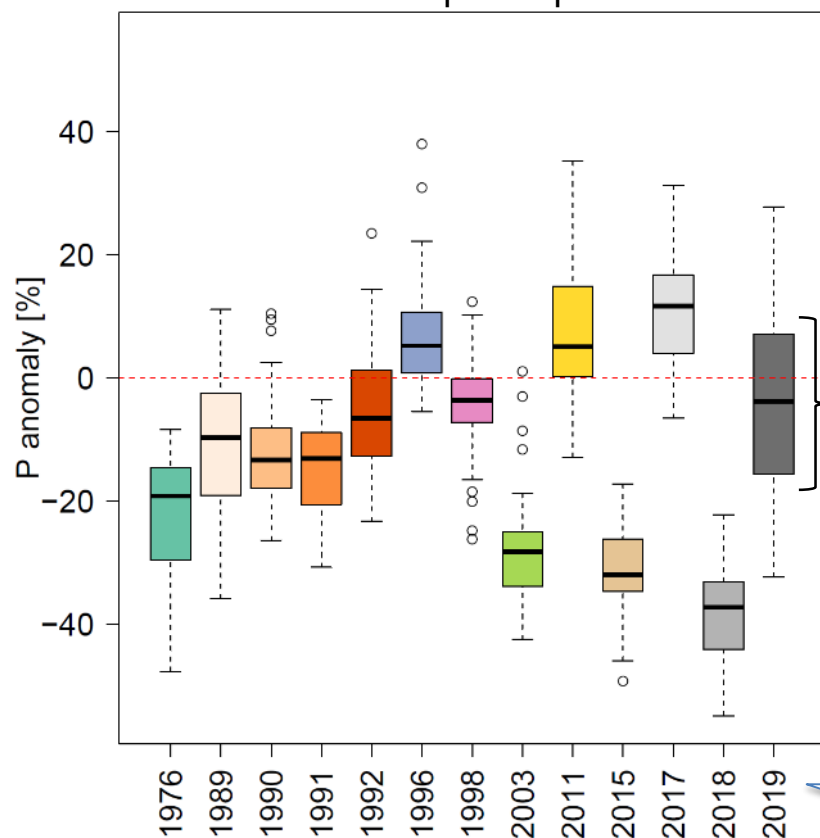




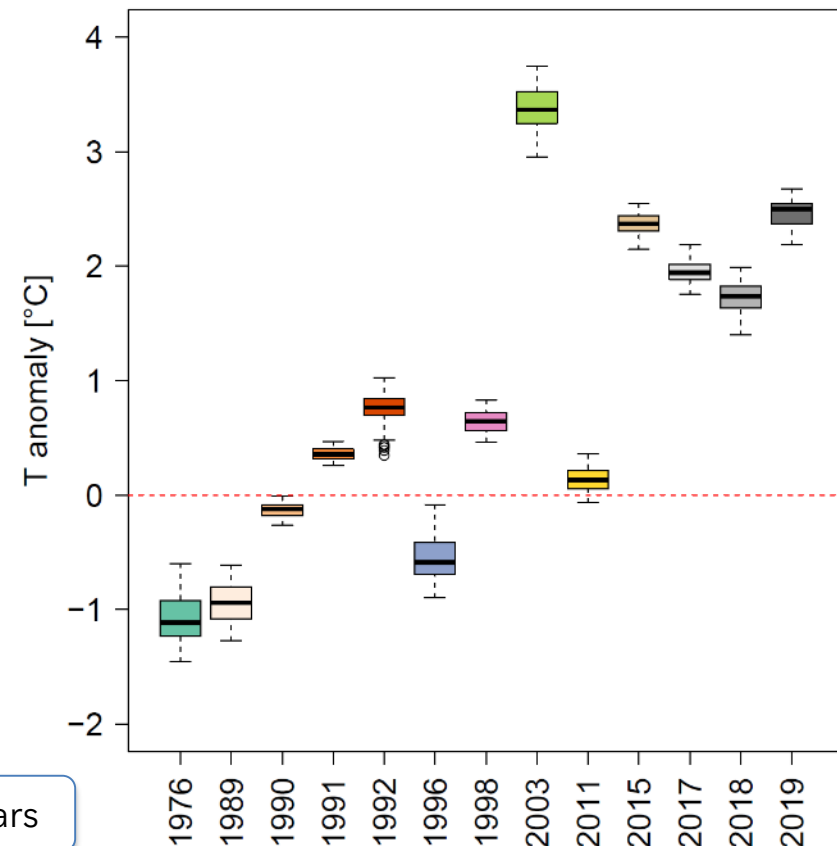
Observed P and T

wetter
↑
drier

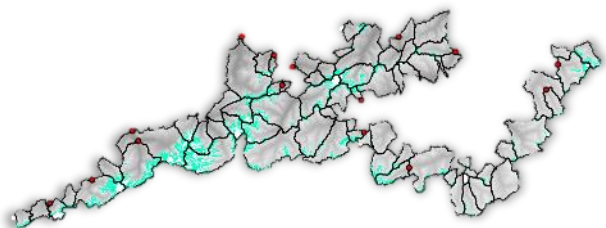
Summer precipitation



Summer temperature

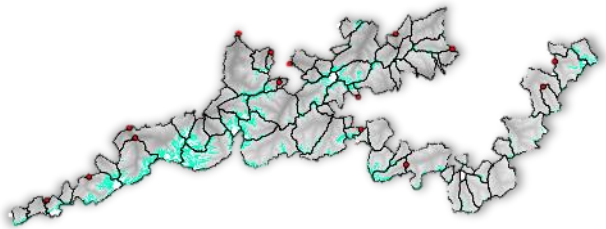
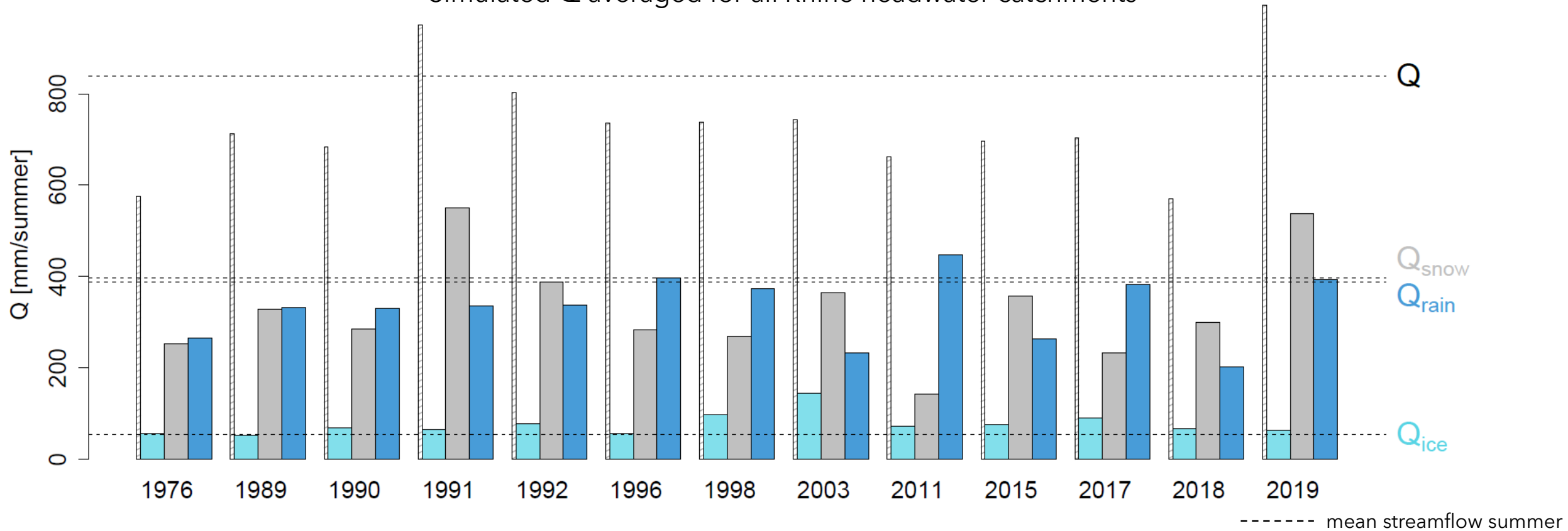


warmer
↑
colder



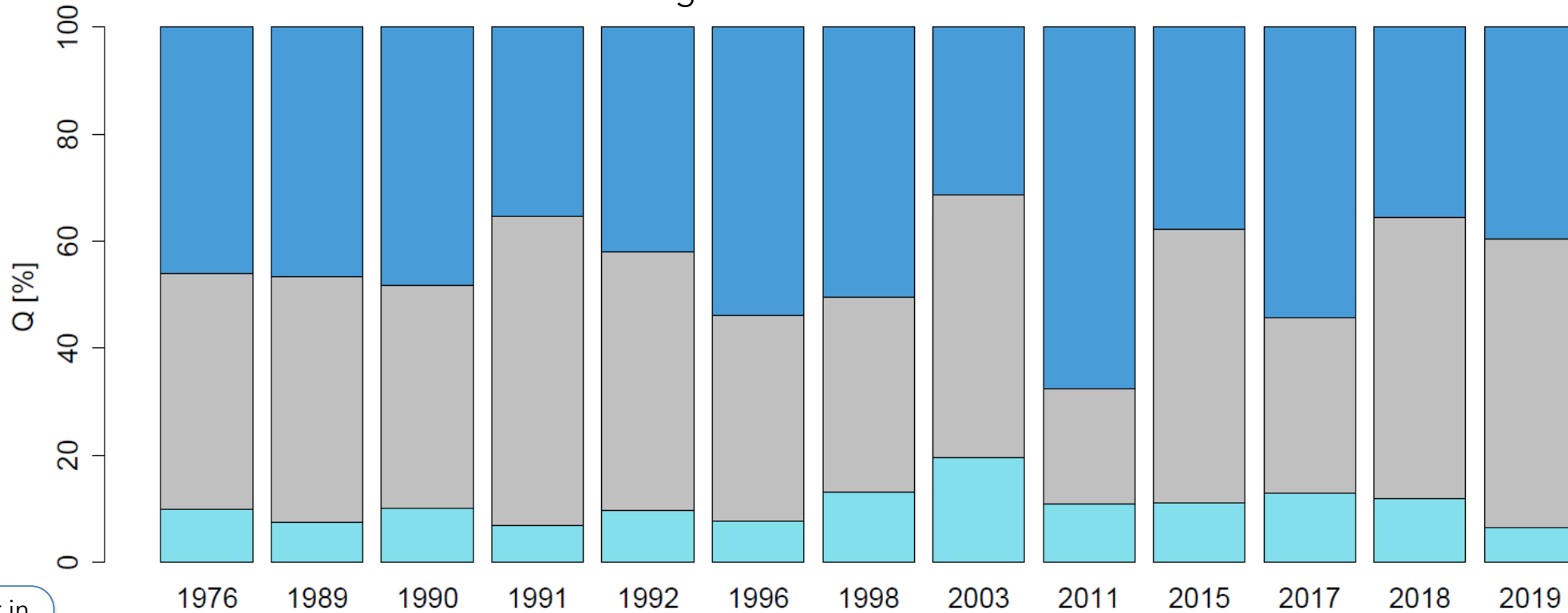
- During downstream low flow years, **upstream** summers are in general also drier and warmer, especially in 2003, 2015 and 2018

Simulated Q averaged for all Rhine headwater catchments

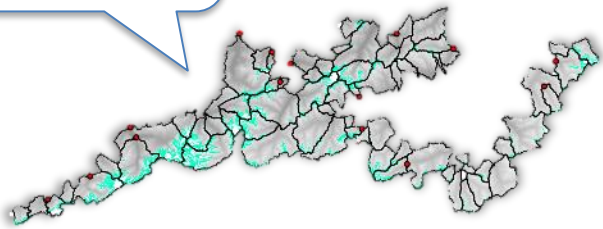


- Streamflow in summer is in most low flow years lower than normal, also upstream - but not in 1991 and 2019
- Q_{snow} also shows a negative anomaly in most years
- Q_{rain} is lower than normal in most years, but not in 1996, 2011 and 2019
- Q_{ice} is above or at average in all years, 2003 had the highest ice melt component

Simulated Q averaged for all Rhine headwater catchments



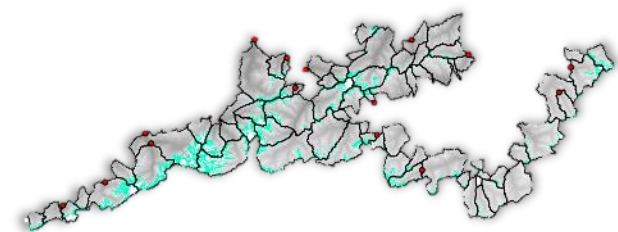
Glacier cover in all headwater catchments is 6% in total



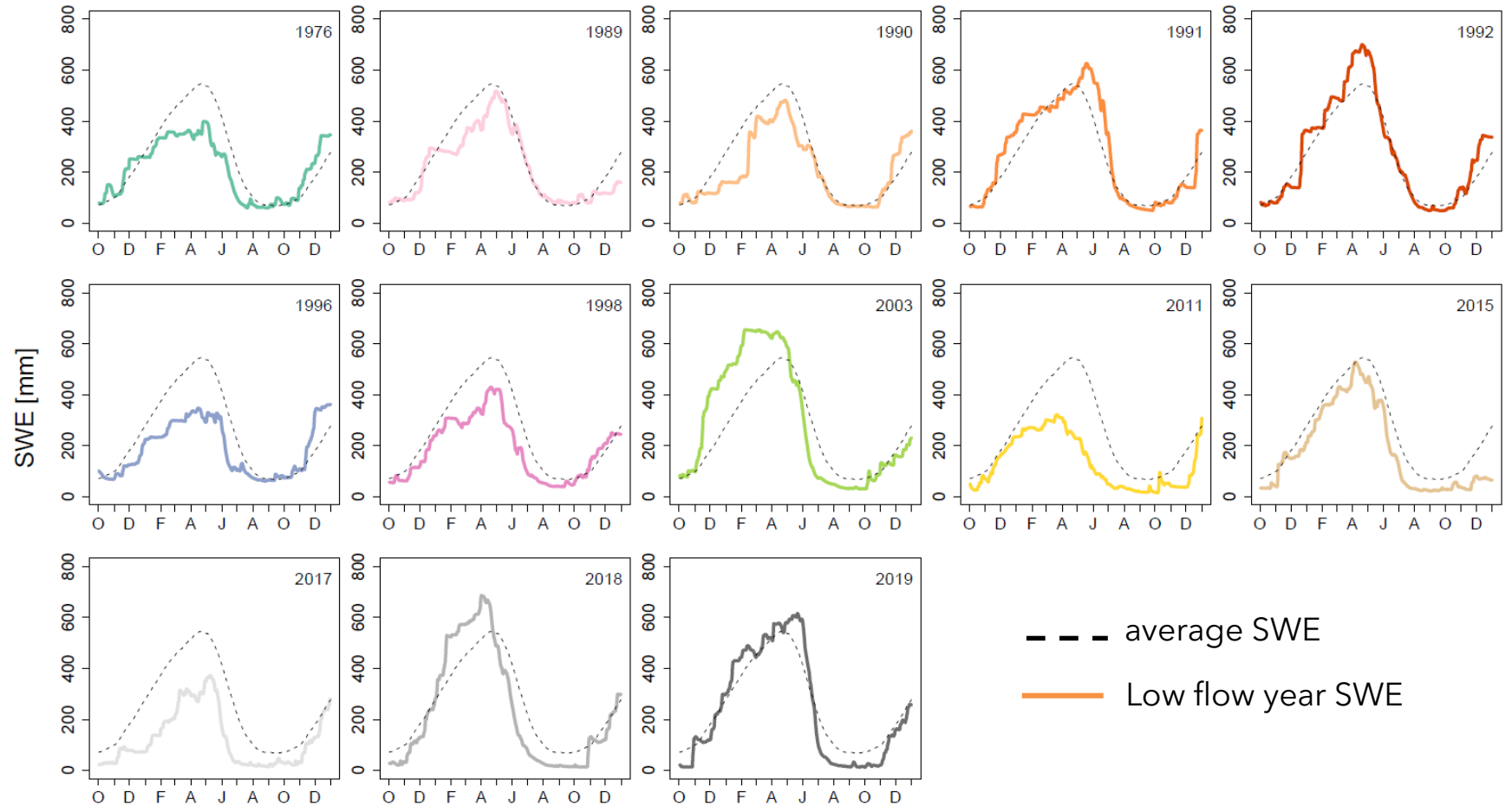
- Streamflow in summer from the headwater catchments comes often for more than 50% from the melt of snow and ice in downstream low flow years
- in 2003, 20% of the headwater runoff came from the melt of ice

Some downstream low flow years are characterized by high snow water equivalent (SWE): 1992, 2003 and 2018.....

....while other low flow years had very little snow: 1976, 2011 and 2017



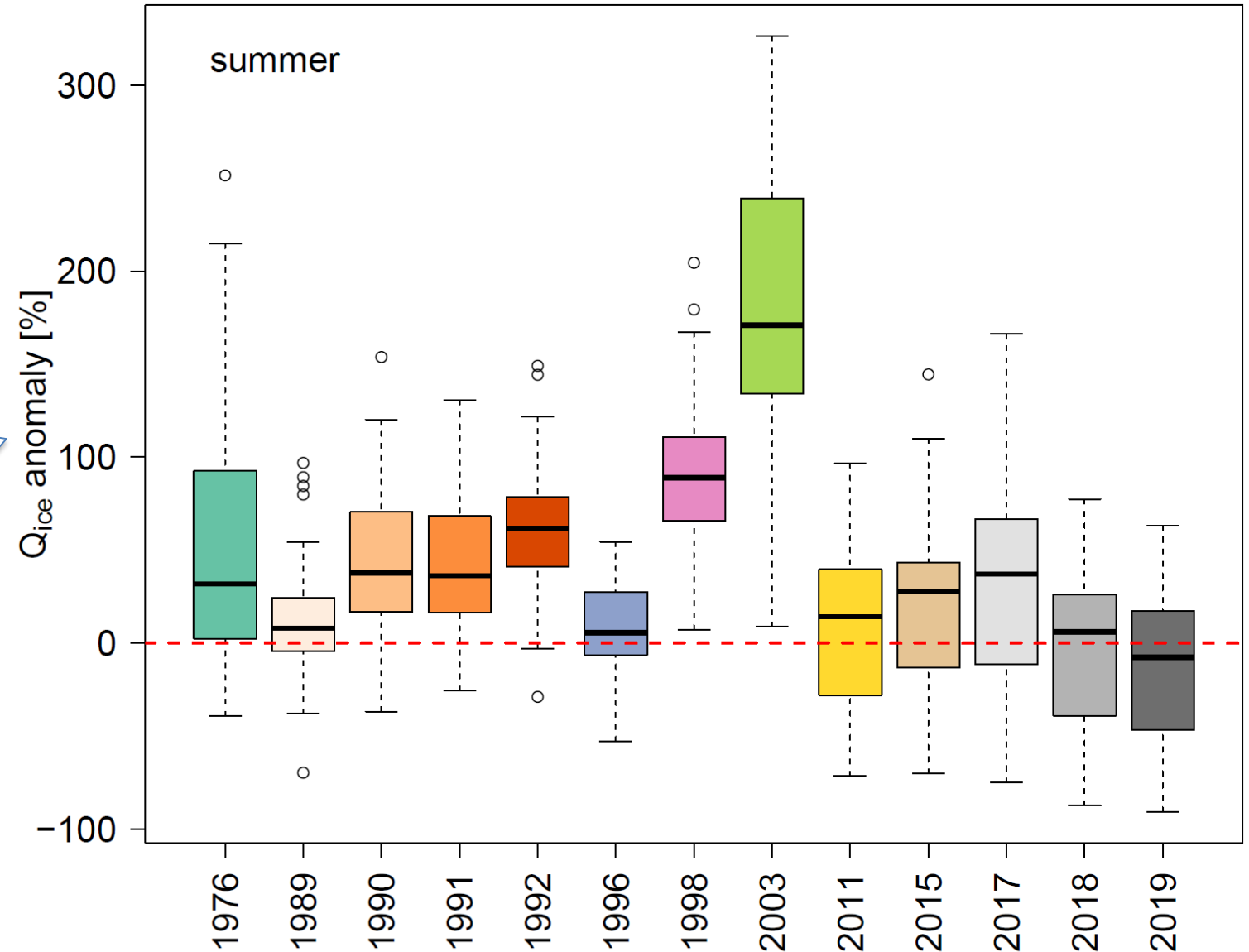
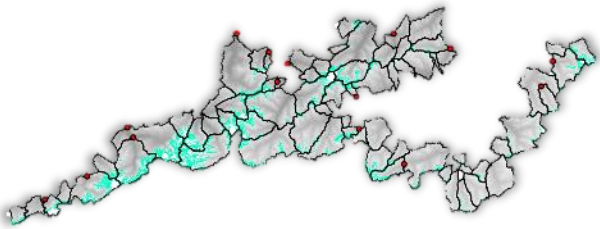
Simulated SWE averaged for all Rhine headwater catchments



- Q_{ice} shows in most years positive anomalies
- 2003 shows the highest anomaly
- In recent years the anomalies are smaller and in some catchments negative

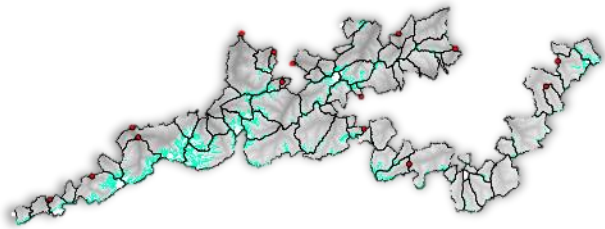
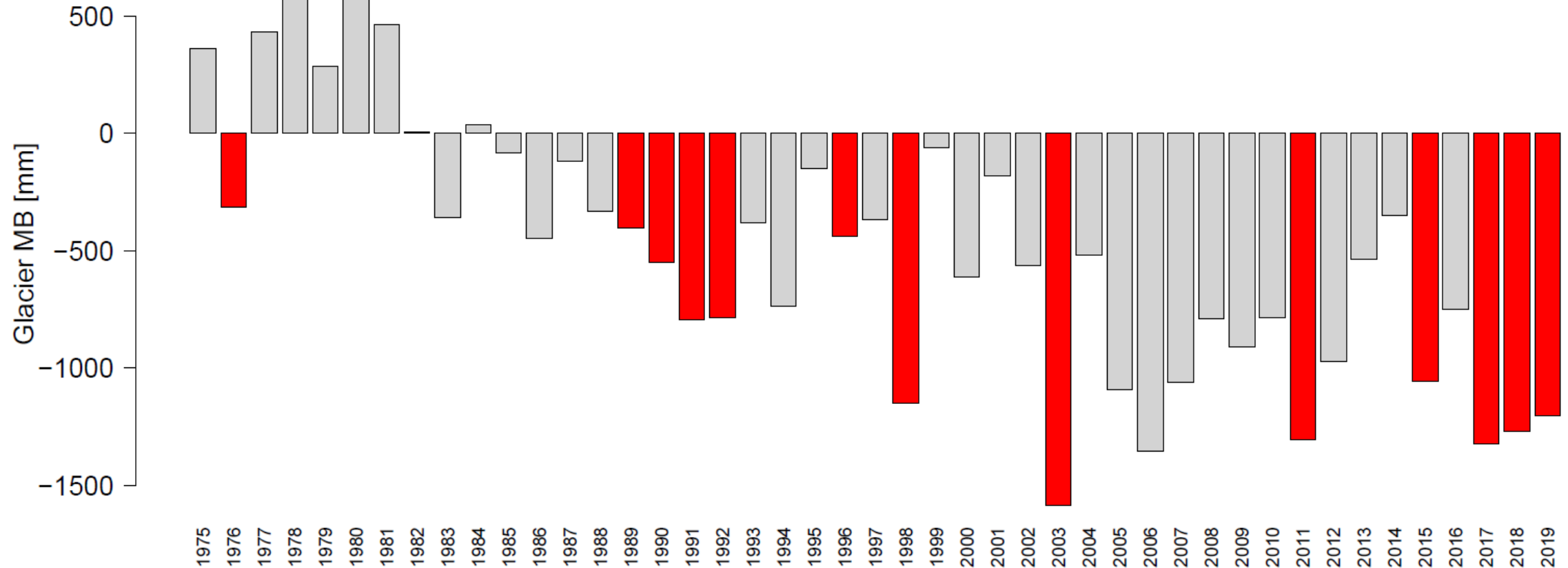
$$A = \frac{Q_{ice}(y) - \overline{Q_{ice}}}{\overline{Q_{ice}}}$$

60/65 glacierized catchments were selected that have glacier cover >0.1% in 2010



Simulated annual glacier mass balances averaged for all Rhine headwater catchments

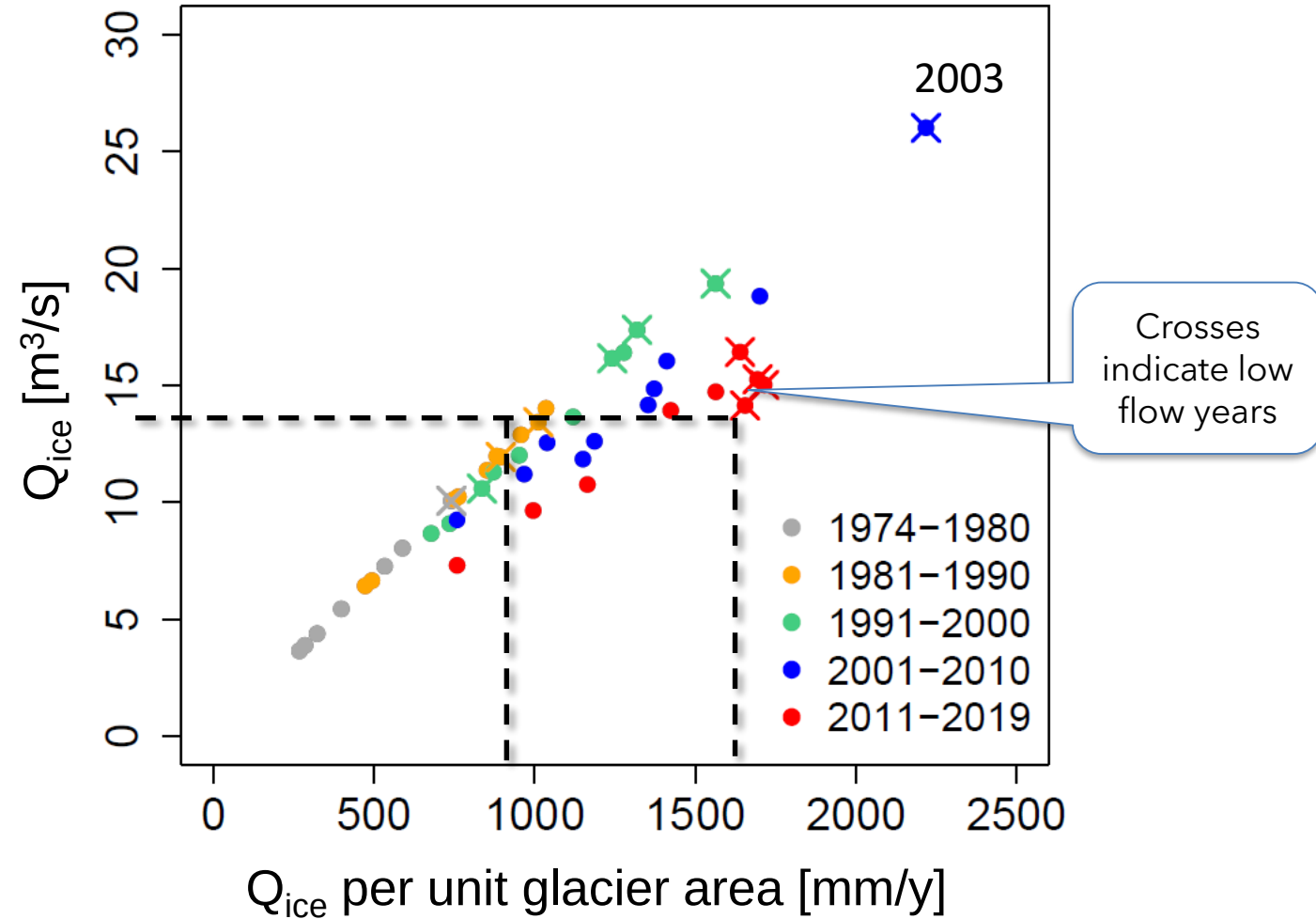
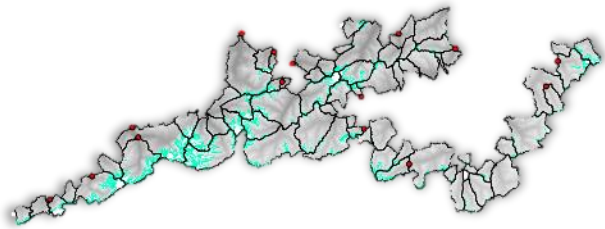
■ Downstream low flow years



- Annual glacier mass balances are (very) negative during downstream low flow years → glaciers supply extra water but also reduce in volume...

.... This means that more melt is needed per unit area (higher melt rate) to provide the same volume of ice melt to downstream

From 1974 to 2019 - melt rates have increased



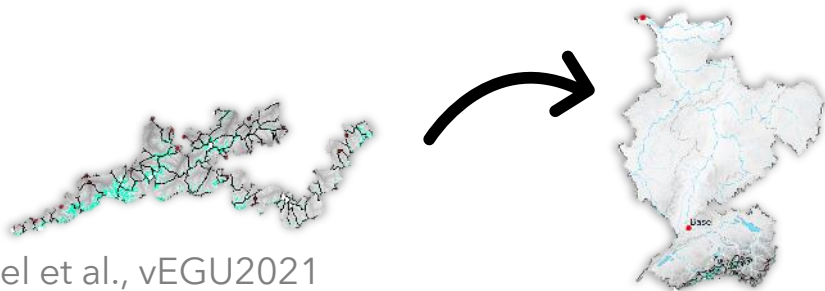
Importance of ice melt downstream

- How important is ice melt for downstream streamflow in low flow years?
- We compared the volume of Q_{ice} with the volume of water at Lobith
- For the daily time scale - the maximum absolute Q_{ice} volume in each low flow year was compared with the streamflow volume 13 days later in Lobith (travel time estimation from Huss & Hock, 2018)
- Ice melt contribution varies between 2-7% for the summer, but is much higher on the daily timescale (up to 22%). If there would not have been glaciers, streamflow would have been significantly lower on summer days in these already critically low flow years

low flow year	Q_{ice} summer [%]	Q_{ice} daily maximum [%]
1976	3.1	(30-7) 8.5
1989	2.1	(29-8) 7.5
1990	2.5	(18-8) 10.7
1991	2.4	(5-9) 13.1
1992	2.9	(10-9) 9.8
1996	1.9	(23-8) 5.2
1998	4.1	(25-8) 16.1
2003	6.7	(26-8) 21.8
2011	2.8	(5-9) 11.8
2015	3.1	(21-8) 10.4
2017	3.6	(17-8) 7.2
2018	3.0	(18-8) 11.9
2019	2.2	(8-8) 7.7

day with
max Q_{ice}

Dates indicate day in
Lobith with max Q_{ice}
in headwaters



- Downstream low flow years have different characteristics; in the headwaters they are most, but not all, drier and warmer
- Often >50% of the summer headwater runoff comes from the melt of snow and ice (most from snow), during downstream low flow years
- Glacier melt is important during low flow years in the Rhine and is partly compensating for precipitation deficits → this compensation is declining over time





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References:

- Huss, M., & Hock, R. (2018). Global-scale hydrological response to future glacier mass loss. *Nature Climate Change*, 8(2), 135-140.

Related research:

- Freudiger, D., Vis, M., and Seibert, J. 2020. Quantifying the contributions to discharge of snow and glacier melt. Hydro-CH2018 project. Commissioned by the Federal Office for the Environment (FOEN), Bern, Switzerland, 49 pp.
- Stahl, K., Weiler, M., Kohn, I., Freudiger, D., Seibert, J., Vis, M., Gerlinger, K., & Bohm, M. (2016). The snow and glacier melt components of streamflow of the river Rhine and its tributaries considering the influence of climate change. *Synthesis Report I-25, International Commission for the Hydrology of the Rhine Basin, Lelystad, Netherlands*.
- Van Tiel, M., Van Loon, A. F., Seibert, J., Stahl, K. (2021). Hydrological response to warm and dry weather: do glaciers compensate? *Hydrology and Earth System Sciences Discussions*, (in review)
- Van Tiel, M., Kohn, I., Van Loon, A. F., & Stahl, K. (2020). The compensating effect of glaciers: Characterizing the relation between interannual streamflow variability and glacier cover. *Hydrological Processes*, 34(3), 553-568.
- Weiler, M., Seibert, J., & Stahl, K. (2018). Magic components—Why quantifying rain, snowmelt, and icemelt in river discharge is not easy. *Hydrological processes*, 32(1), 160-166.

Questions? Please get in touch or join me in the text based chat

Thursday **29th April 09:45 - 10:30 CEST**

Session HS2.1.7 Snow and ice accumulation, melt, and runoff generation in catchment hydrology: monitoring and modelling

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