

From snowfall to streamflow: synthesizing the hydrology of high alpine catchments

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1) Context

- Alpine streamflow results from accumulation & melt processes (Fig. 1)
- Derive mean streamflow characteristics from **topography**, statistical properties of precipitation (P), temperature (T) alone?
- Assume **recession** time scales (geomorphology, geology) also depend on T , P and topography (co-evolution)
- Analyze CAMELS-CH data to link P , T , topography to streamflow, interannual water carry-over

Aim: **Key controls & climate sensitivity of alpine hydrology**

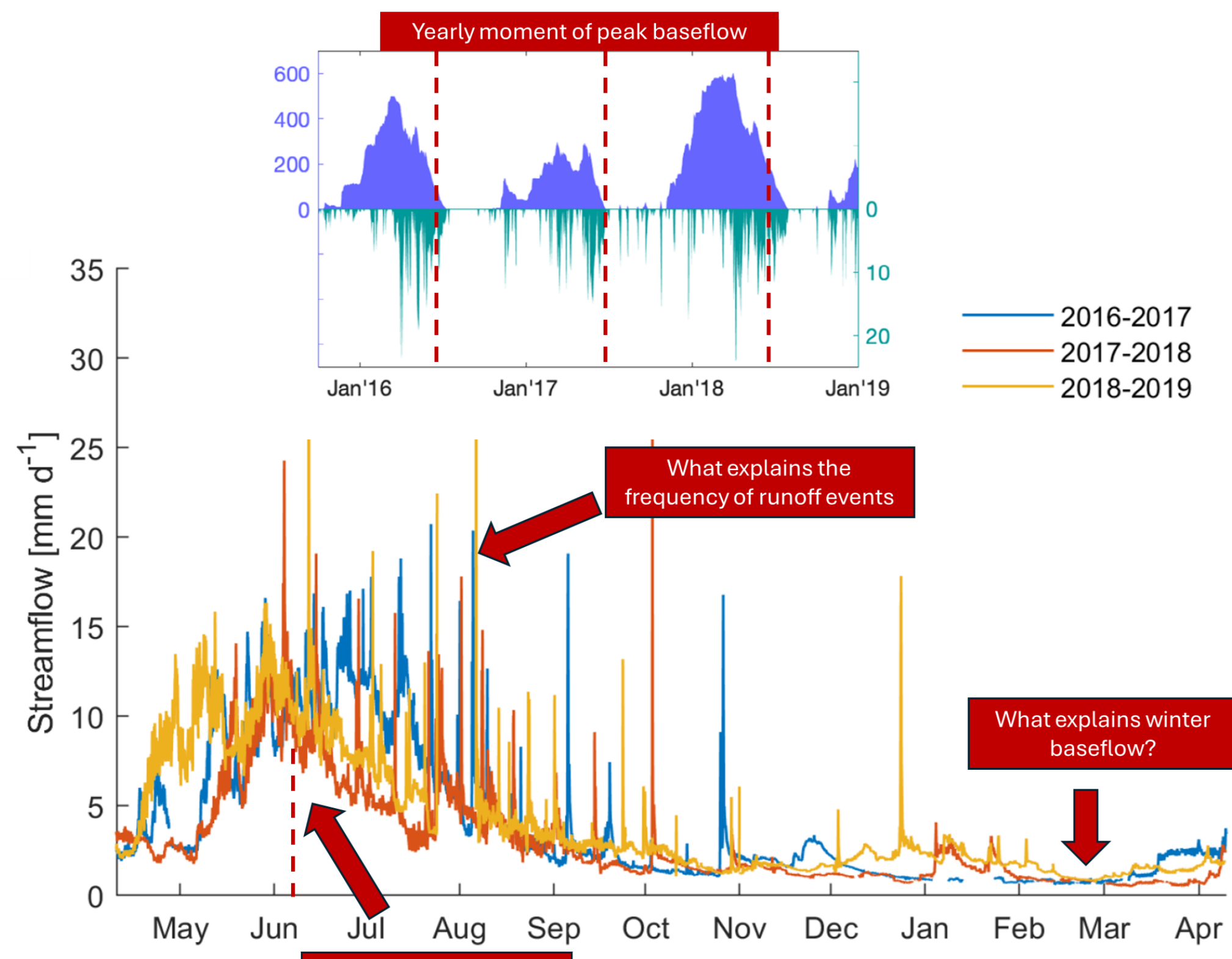


Fig. 1: Bottom: Example of typical snow-dominated streamflow from the Vallon de Nant catchment Switzerland: Observed streamflow over 3 very different snow years (Michelon et al. 2023); simulated snow cover & melt for the same years (Ceperley et al., 2020), Vallon de Nant (CH, see <https://zenodo.org/communities/vdn>)

2) Case study data

- Camels-CH data set (Höge et al., 2023): 298 river gauges (Fig. 2)
- Area: 0.6 km² - 36'404 km², elevation (catchment): 431 - 2929 m asl.)
- Only 88 gauges with flow not disturbed by management or large lakes

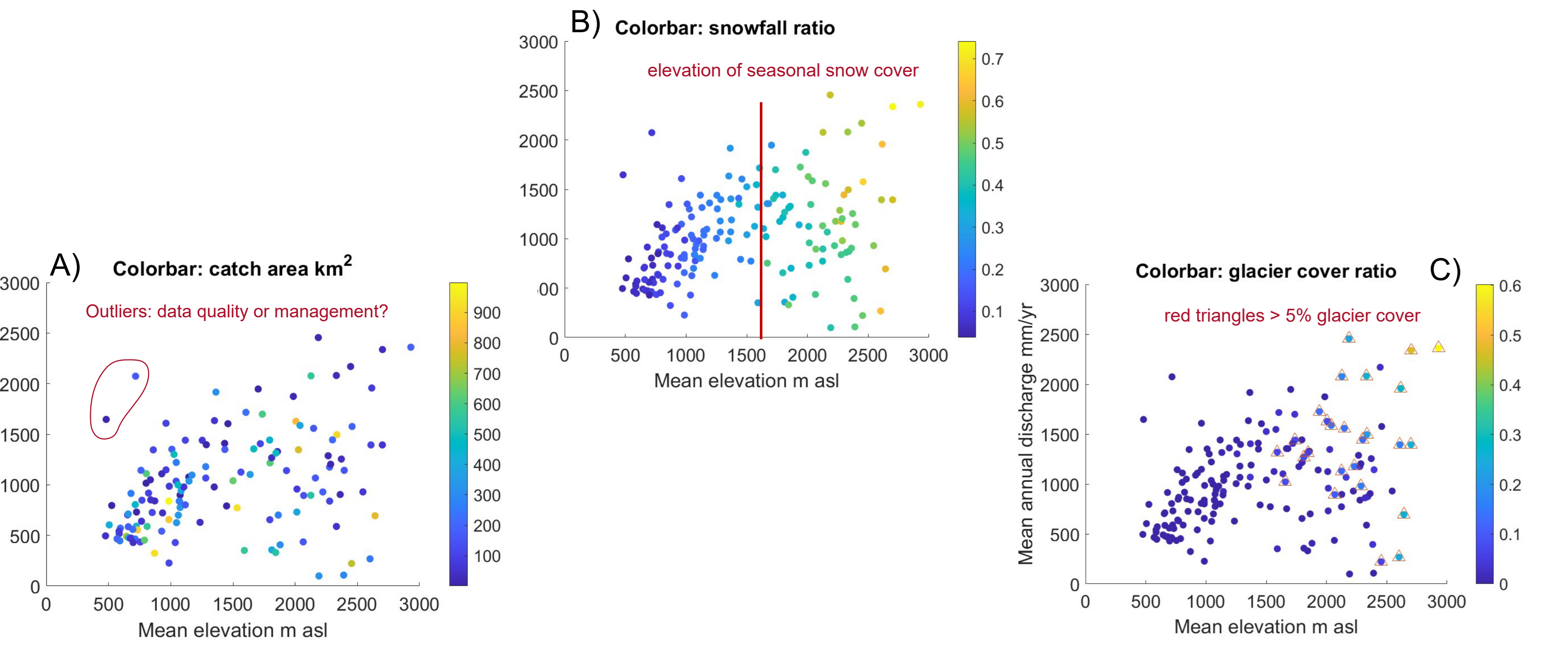


Fig.2: Mean annual discharge against mean elevation and A) catchment area (shown only area < 1000 km2), B) estimated snowfall ratio (transition between 0 & 2°C), C) glacier cover ratio

3) Methods

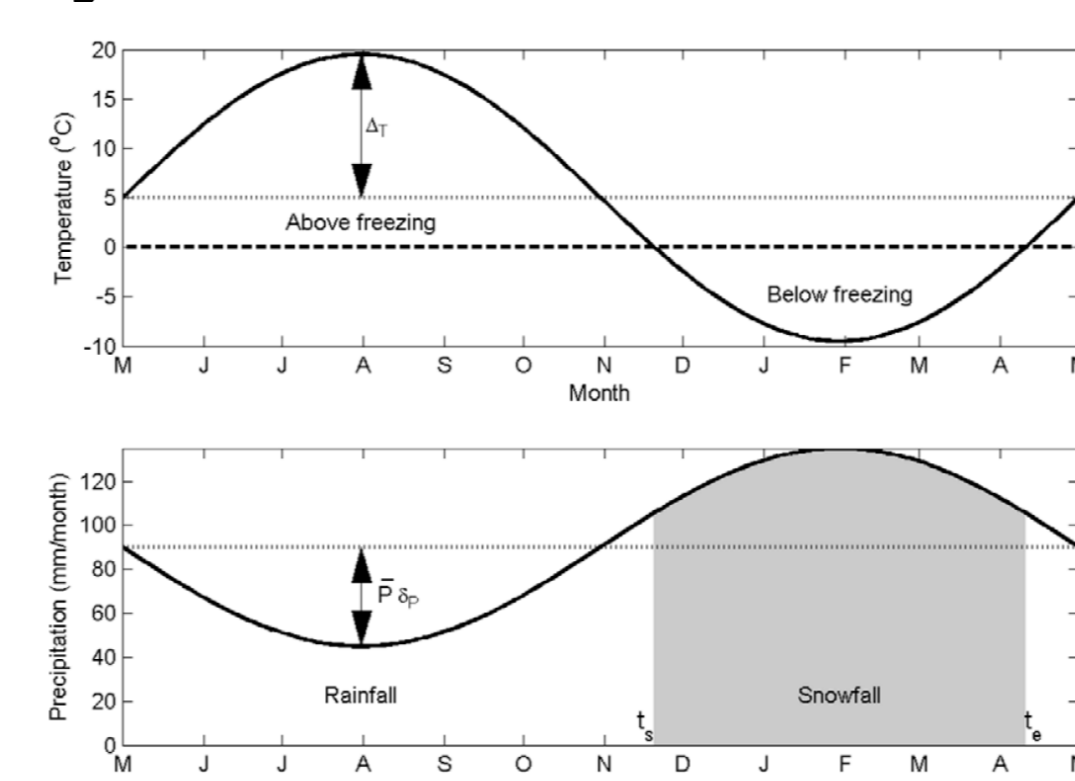
- Analytic streamflow distribution model approach (Botter et al., 2009, 2013, Schaepli et al., 2013, Santos et al., 2018)

$$p(Q, t \rightarrow \infty) = cQ^{\left(\frac{\lambda}{k}-1\right)} \exp\left(-\frac{Q}{\alpha k A}\right)$$

$$\lambda = \langle Q \rangle / \alpha$$

λ : Freq. of runoff generating input events (Poisson process)
 α : Mean precip. on days with precip > 0
 k : Linear recession coefficient
 A : Catchment area
 c : Normaliz. cst (Gamma distribution)

- Analytical snow model, Woods, 2009



Analytic description of snow onset & melt out based on describing P & T as sine curves:

$$P(t) = \bar{P} [1 + \delta_P \sin(2\pi(t - s_P)/\tau)],$$

$$T(t) = \bar{T} + \Delta_T \sin(2\pi(t - s_T)/\tau),$$

Snow climate summarized in 2 dim-less variables:

$$\bar{T} = \frac{\bar{T} - T_0}{|\Delta_T|}$$

$$\delta_P^* = \delta_P \text{sgn}(\Delta_T) \cos(2\pi(s_P - s_T)/\tau)$$

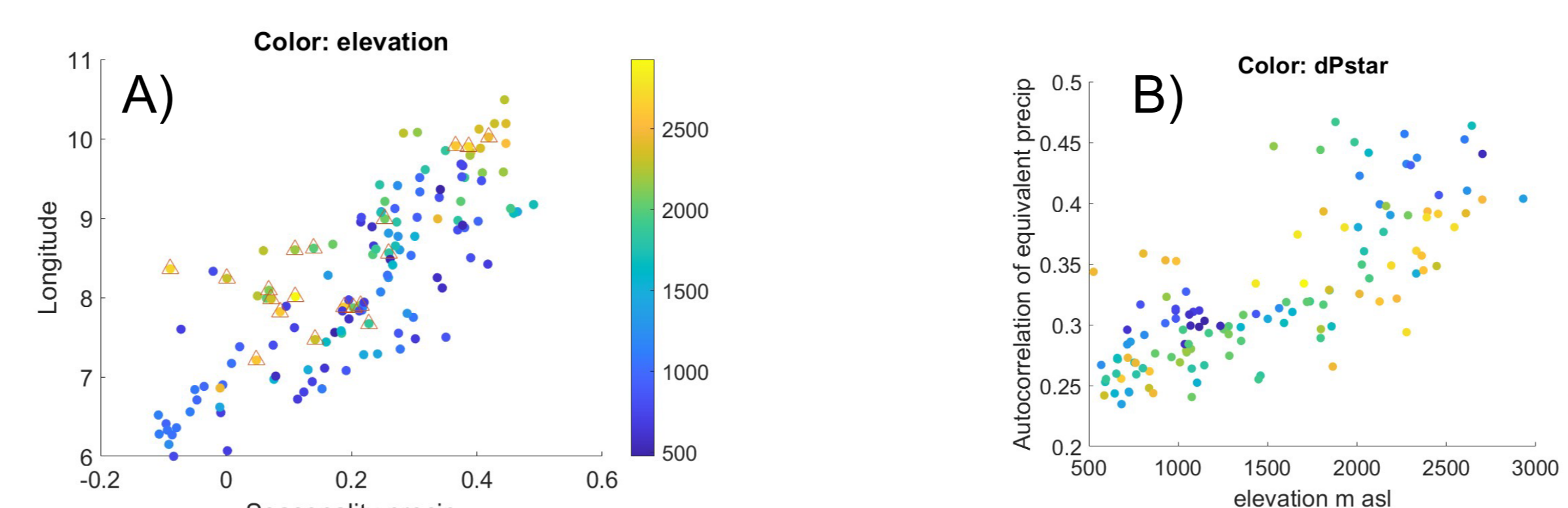


Fig. 3: A) Relationship between precip seasonality relative to temperature seasonality (deltaPstar, see Methods) and catchment longitude; (red: triangles: catchment with > 5% glacier cover, color scale: elevation); we see that the CAMELS-CH data set shows certain (limited) variation in seasonality from west to east; B) relationship between autocorrelation (lag-1) of equivalent precipitation (melt + rain) and elevation to appreciate Poisson-process hypothesis required for the analytic streamflow distribution model to hold (see Methods).

4) Results I

- Analysis of equivalent precip. input (peq): rainfall + melt (Fig. 3)

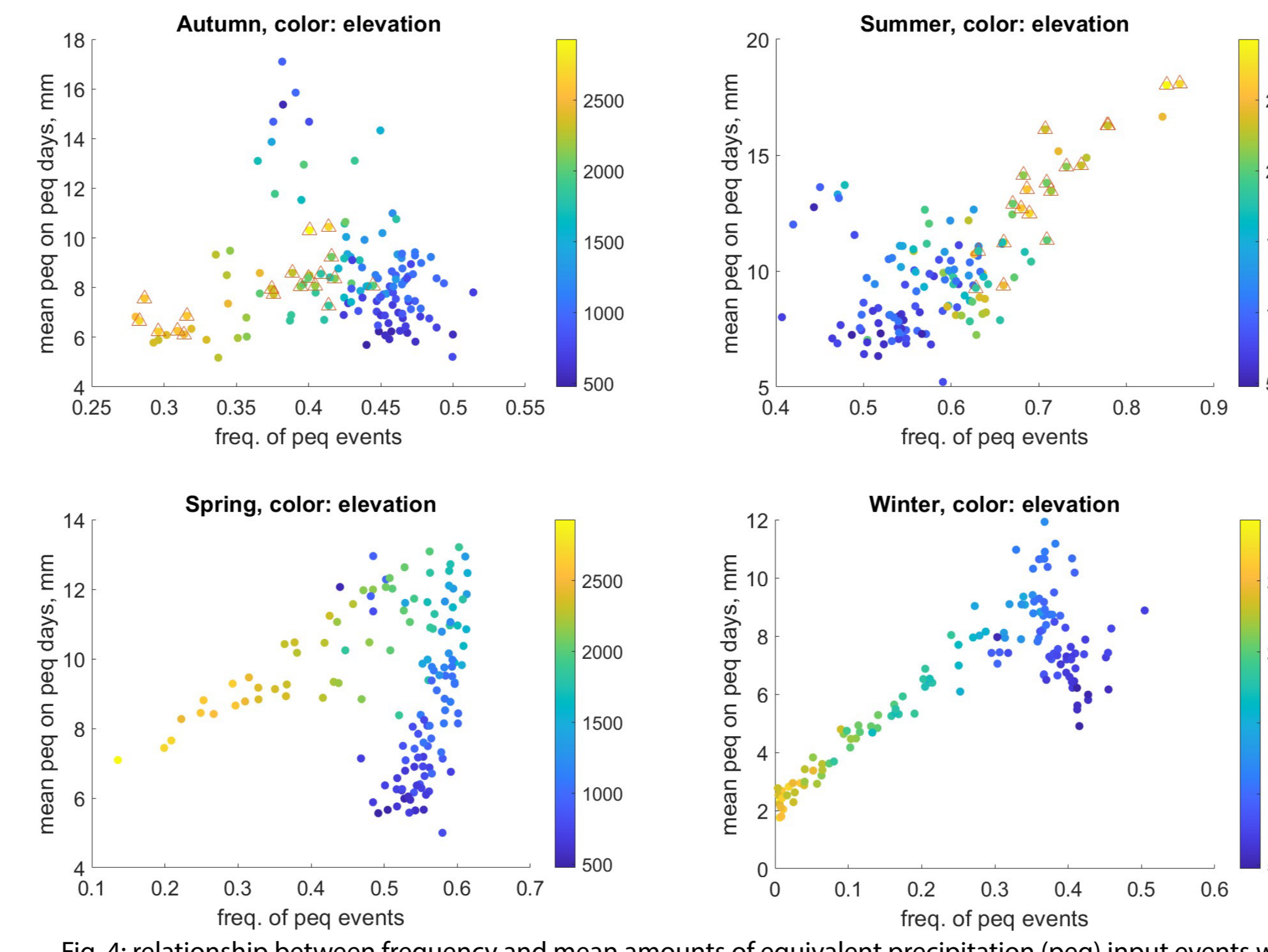


Fig. 4: relationship between frequency and mean amounts of equivalent precipitation (peq) input events where equivalent precipitation is estimated using a simple degree-day snow melt model with a melt factor 2.5 mm/°C/d)

5) Results II: Snow carry-over effects

- Input events und runoff generation frequency in summer (Fig. 5)

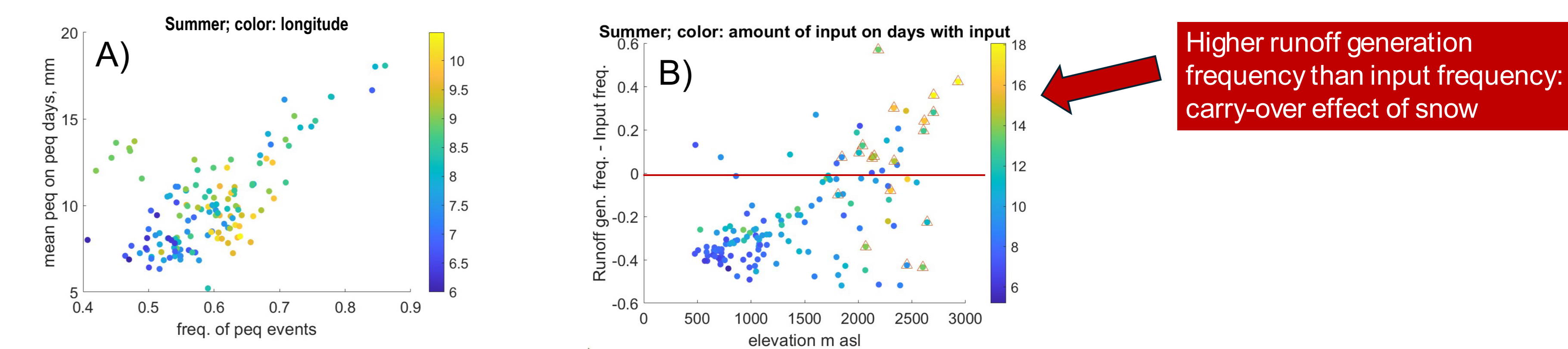


Fig. 5: A) Relationship between frequency of input events (rainfall + melt) and amount of input as a function of longitude (as a proxy of seasonality, Fig. 3, and of mountain ranges within Switzerland (map not shown: low longitude: Valais area, high longitude: Grisons area); B) y-axis: difference between runoff generation frequency (computed from mean summer streamflow, based on the relationship between runoff generation frequency and mean streamflow, see Methods) and input frequency (input = rain + melt); x-axis: elevation; color: amount of input on days with input (red: triangles: catchment with > 5% glacier cover);

- Effect of input frequency on baseflow generation (Fig. 6)

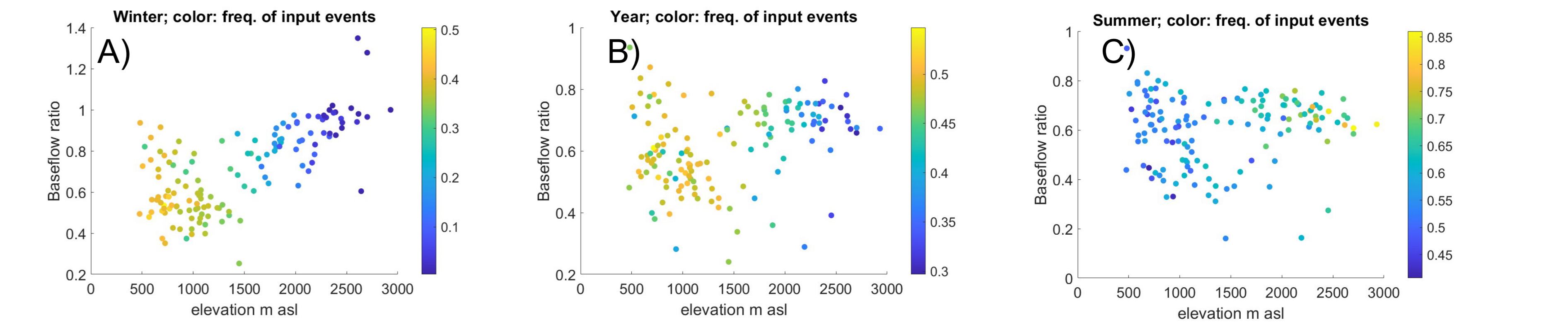


Fig. 6: A) Relationship between baseflow ratio and elevation for winter (A), entire year (B), summer (C); color: frequency of input events (rainfall + melt); previous Figures show that we can understand streamflow generation from elevation and precip seasonality but for the full picture, we need to understand the ratio of baseflow, which captures the role of subsurface storage; here we estimated baseflow by connecting all local low streamflow points (see inset); the results show that baseflow ratio (baseflow divided by total streamflow during selected seasons) has an unclear relationship to elevation across all seasons; what is the missing element here?

Conclusion:

- Can predict (too!) many streamflow features from topography & precipitation alone, but not baseflow ratio
- Challenge: Precip properties (frequency!) at (large) catchment scale

Outlook:

- Link of recession time scales to dominant geomorphological units ?
- Role of summer snowfall events / winter rainfall events ?
- Role of vegetation ? -> tree limit around current seasonal snow cover limit
- Should snow cover be inferable from streamflow ? (Wiersma et al., 2026)