
Earlier streamflow in a snow-dwindling world

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Impacts of climate change on water resources tend to be significant in regions where streamflow is substantially sourced as snowmelt from snowpacks[1,2]. In these areas, as the climate warms and the fraction of precipitation falling as snow (snow fraction, f_s) shrinks, streamflow is generally shifting toward earlier in the year by way of earlier snowmelt and increased proportional rainfall[1,3,4]. In a recent Article, Han et al.[5] call for revision of the '*less snow equals earlier streamflow*' paradigm, because their analysis indicates that while such paradigm upholds for average annual high-snow-fraction catchments ($\overline{f_s}>0.5$), lower-snow-fraction catchments ($0.1<\overline{f_s}<0.4$) experience later seasonal streamflow as snow fractions reduce. Here we use results generated by Han et al.[5] to show that trends towards earlier streamflow are instead dominant across the entire defined range of low to high snow-fraction catchments ($0.1<\overline{f_s}<1$), supporting the longstanding paradigm. In addition, we use catchment climatological data to demonstrate that comparing streamflow timing between low- and high-snow-fraction years, as used by Han et al.[5], is a misleading analogy to study effects of climate-warming-induced snow changes and subsequent streamflow seasonality.

Han et al.[5] used observations of snow-affected catchments over the Northern Hemisphere and quantified catchment-average streamflow center of mass (CTQ, Han et al. [5] Eq. 1), indicating the time of year when 50% of the annual streamflow has occurred. They use water years defined as Oct 1st through Sep 30th and cluster all catchments into six groups, binned by average annual snow fraction. Across water years 1950-2020, their comparison of CTQ for 10 years with high- versus low-snow-fractions suggests that, on average, catchments with $\overline{f_s}>0.5$ tend to have earlier CTQ in years with low snow fractions, whereas catchments with $\overline{f_s}<0.4$ tend to experience later CTQ in years with low-snow-fractions. The latter is their key result leveraged to revise the *'less snow equals earlier streamflow'* paradigm.

However, replotting the significant temporal CTQ trends by catchment, stratified by the same average annual snow fraction bins (Fig. 1e of Han et al.[5]), reveals that significantly earlier streamflow (as indicated by a negative CTQ trend, $n = 506$) is over four times more common than significantly later CTQ ($n = 119$). In catchments with $\overline{f_s}$ <0.4 alone, significantly earlier CTQ is still 3.7 times more common than later CTQ across the record period. A small fraction of individual catchments does trend towards significantly later CTQ, which is expected considering that any catchment will often undergo multiple changes at once (e.g., additional shifts in climate seasonality or landscape changes), potentially masking or counteracting the effects of temperature-driven dwindling snowpacks on streamflow seasonality. Yet, a dominant trend towards earlier streamflow is consistent in catchments within this dataset[5] across the entire range of snow fraction bins ($\overline{f_s}$ = 0.1-1) (Fig. 1).

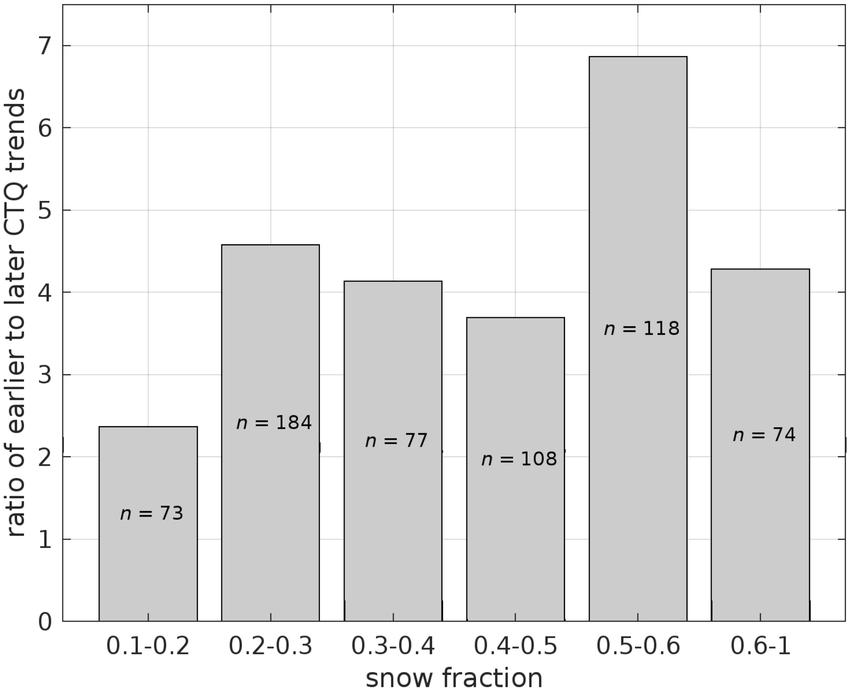

Fig. 1. The relative frequency of earlier to later streamflow. The ratio of catchments with significantly earlier CTQ to significantly later CTQ, stratified by catchment-average annual snow fraction. Data presented are CTQ trends from Han et al.[5] where n indicates the number of catchments per annual average snow fraction bin. These data indicate that catchment trends towards earlier CTQ are much more common than those toward later CTQ, which is consistent across the entire range of considered average annual snow fraction bins ($\overline{f_s}$ = 0.1-1).

This updated result raises a question around why the CTQ trends in Figure 1 exhibit such different behavior than the comparison of CTQ between low- and high-snow-fraction years, per average snow fraction bin, by Han et al[5] (Fig. 3a of ref. 5). Similar to Han et al.[5], we target the impacts of precipitation and temperature on annual snow fraction and CTQ timing. First, data from 671 diverse catchments[6] illustrate that annual variability in snow fractions is primarily controlled by precipitation timing, but trends over time are controlled by temperature. Namely, rank correlations between annual snow fractions and annual freezing-season precipitation fractions (i.e., portion of annual precipitation from days of the year where daily mean temperature < 0°C for at least 25% of the historic record) are stronger (median ρ=0.34) than the correlations between annual snow fractions and annual freezing days (median ρ = 0.14) (Fig. 2a). In contrast, temporal trends in annual snow fractions are more strongly correlated to trends in freezing days (ρ = 0.50) than to trends in freezing-season precipitation (ρ = 0.30). Thus, annual snow fractions tend to decline over time because of reduced freezing days caused by rising temperatures, but largely vary between years because of annual variations in precipitation timing.

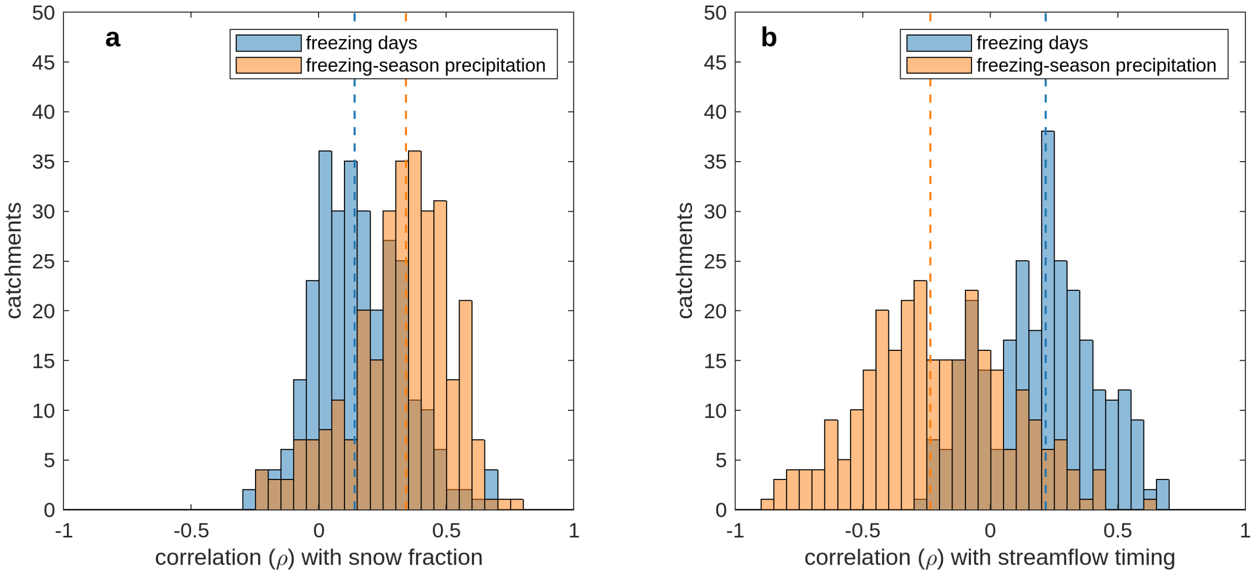

Fig. 2. Effects of freezing days and freezing-season precipitation on annual snow fraction and streamflow timing. Spearman rank correlation coefficients ρ of annual snow fractions versus annual freezing days and annual freezing-season precipitation fractions (a). Spearman rank correlation coefficients ρ of annual streamflow timing (CTQ) versus annual freezing days and annual freezing-season precipitation fractions (b). Together, these correlations show that annual variability of snow fractions is largely controlled by freezing-season precipitation and less by the number of freezing days. Yet, although both freezing days and freezing-season precipitation positively correlate with snow fraction (Fig. 2a), their effects on streamflow timing differ in sign (Fig. 2b).

We next demonstrate that reduced freezing days and freezing-season precipitation have opposing effects on CTQ timing (Fig. 2b). Years with less freezing-season precipitation or fewer freezing days both have lower snow fractions (i.e., typically positive correlation coefficients; Fig. 2a). However, correlated to annual CTQ, lower annual freezing-season precipitation fractions tends to lead to later annual CTQ (i.e., negative correlation coefficient; median ρ=-0.23; Fig 2b), whereas fewer annual freezing days tends to lead to earlier CTQ (i.e., positive correlation coefficient; median ρ=0.22; Fig 2b). Thus, years with lower snow fractions, which to occur due to precipitation timing (Fig. 2a), will often experience later CTQ, whereas reductions in freezing days lead to earlier CTQ (Fig. 2b). Together, our results indicate that temporal CTQ trends (Fig. 1), which are predominantly controlled by temperature, often exhibit opposite behavior from the comparison of CTQ between low- and high-snow-fraction years presented by Han et al[5], which are trends in interannual variability predominantly controlled by precipitation timing. Thus, in studying the effects of climate warming on streamflow timing trends, using low- and high-snow-fraction years by Han et al[5] is a misleading analogy.

Streamflow derived from snowmelt in snow-affected regions is a major water resource to society and ecosystems[2], and climate warming continues to drive hydrologic changes in these regions[7-9]. Resolving the full nature of streamflow regime shifts in all catchments studied by Han et al.[5] is beyond the scope of this response. Yet the analysis presented here reveals that CTQ timing shifts are overall consistent with the '*less snow equals earlier streamflow*' paradigm. We also emphasize that focusing on interannual variability in annual snow fraction can be a biased analogy to study effects of climate-warming-induced streamflow seasonality changes.

Methods

We use the data from Fig. 1e of Han et al.[5] where the center of mass of streamflow (CTQ) is calculated by:

$$\mathrm{CTQ} = \sum_{i=1}^{12} (i \cdot q_i) \,/\, \sum_{i=1}^{12} (q_i)$$

where i is the time in months from the beginning of the water year and q_i is monthly streamflow (mm month^{-1}) for water-year month i. Water years are defined as Oct 1st through Sep 30th. Han et al.[5] calculated temporal CTQ trends using yearly CTQ values. We also use snow fraction values presented in Fig. 1a of ref. 5.

We quantify the extent to which trends and interannual variability of annual snow fraction are controlled by precipitation timing versus temperature using 25 years of daily data from 671 catchments[6]. We use these data because timeseries datasets presented in Han et al.[5] are not made available and rely on reanalysis (ERA5-Land) precipitation data, which contain increased uncertainty compared to in-situ observations[10]. Daily snowfall is estimated using a 0°C temperature threshold, and repeating the analysis behind Fig. 2 for other phase partitioning temperature thresholds (i.e., 1-2°C) yields similar overall results and conclusions. We use linear regression to quantify trends in time for snow fractions, freezing days, and freezing season precipitation fractions. For each water year (Oct 1st through Sep 30th) in snowy catchments ($\overline{f_s}$ >0.1), we calculate the fraction of annual precipitation that falls during the freezing period (called *freezing-season precipitation fraction*). The freezing period is defined as the days of the year where, over the historic record, at least 25% of days had a daily mean temperature below 0°C. In addition, per water year and catchment, we quantify the number of days with a daily mean temperature below 0°C. We calculate water year specific CTQ using daily streamflow timeseries and annual snow fractions based on daily timeseries of mean precipitation and temperature. Subsequently, for each catchment, we quantify spearman rank correlations between annual variations in snow fraction and freezing days and freezing-season precipitation fractions

(Fig. 2a). Finally, we quantify spearman rank correlations between annual streamflow timing (CTQ) and annual freezing days and freezing-season precipitation fractions (Fig. 2b). The code to reproduce all presented figures and statistics is made available (see code availability statement).

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Competing interests

The authors declare no competing interests.

Contributions

Both authors contributed equally to this work.

Data availability

Data from Fig. 1 is available at from Han et al.[5] and can be downloaded at https://www.nature.com/articles/s41586-024-07299-y. Data used in Fig. 2 is available at https://ral.ucar.edu/solutions/products/camels.

Code availability

All code to produce the presented results is available via https://surfdrive.surf.nl/files/index.php/s/Pf3pZ33t7Z2oD62 and will be uploaded to a Zenodo repository when the manuscript gets accepted.

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