A precipitation shift from snow towards rain leads to a decrease in streamflow

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In a warming climate, precipitation is less likely to occur as snowfall (Solomon 2007, Krasting 2013). A shift from a snow- towards a rain-dominated regime is currently assumed not to influence the mean streamflow significantly (Barnett 2005, Regonda 2005, Stewart 2005, Solomon 2007, Gentine 2012, Godsey 2013). Contradicting the current paradigm, we argue that mean streamflow is likely to reduce for catchments that have significant reductions in the fraction of precipitation falling as snowfall. With more than one-sixth of the Earth's population depending on meltwater for their water supply (Barnett 2005) and ecosystems that can be sensitive to streamflow alterations (Bunn 2002), the consequences of a reduction in streamflow can be substantial. By applying the Budyko water balance framework (Budyko 1974) to catchments located throughout the contiguous United States we demonstrate that a higher fraction of precipitation falling as snow is associated with higher mean streamflow, compared to catchments with marginal or no snowfall. Additionally, we show that the fraction of each year's precipitation falling as snowfall has a significant influence on the annual streamflow within individual catchments. This study is limited to introducing these observations; process-based understanding at the catchment scale is not yet available. Given the importance of streamflow for society, new studies are required to respond to the consequences of a temperature-induced precipitation shift from snow to rain.

Natural and anthropogenic influences such as climate and land-cover change or long-term fluctuations of the system undermine the assumption that the hydrological cycle can be considered stationary (Milly 2008: Koutsoyiannis 2010). One of the most profound and widely-anticipated changes in the hydrological cycle is the temperature-induced shift of winter precipitation from snow towards rain and earlier melt of the winter snowpack (Laternser 2003, Hamlet 2005, Mote 2005, Solomon 2007, Pierce 2008, Barnett 2008). A shift from a snow towards a rain regime leads to changes in the within-year distribution of streamflow (Regonda 2005, Stewart 2005, Solomon 2007, Molini 2011, Godsey 2013), which are associated with a significant impact on human freshwater resources (Barnett 2005, Solomon 2007) and disruptions of ecosystem functioning (Vaganov 1999, Cayan 2001, Westerling 2006, Solomon 2007). The projected global temperature increase (Solomon 2007) is expected to affect future snowfall (Solomon 2007, Krasting 2013) and consequently the temporal distribution of river water availability will continue to change. Though these impacts of warming on temporal streamflow distribution are acknowledged, the influence of the change in form of precipitation on the long-term mean streamflow is generally either assumed to be negligible (Barnett 2005, Regonda 2005, Stewart 2005, Solomon 2007, Gentine 2012, Godsey 2013), or found to be insignificant using FLUXNET data (Williams 2012), or not included in simulations (e.g. Milly 2005). However, this assumption that the long-term water balance is not significantly affected by a precipitation shift from snow towards rain is not yet substantiated by empirical findings at the catchment scale.

Here, we study the role of snowfall for the mean-annual and inter-annual streamflow using data from 420 catchments located across the contiguous United States. The mean-annual streamflow of catchments is studied by a between-catchment comparison of the long-term (16-54 year, mean 47 year) partitioning of incoming precipitation into evaporation or streamflow. These observations are put in context of the Budyko hypothesis (Budyko 1974). This hypothesis assumes that the long-term water balance is primarily a function of the atmospheric supply and demand of water, expressed as the ratio of mean potential evaporation ($\overline{E_p}$) to the mean precipitation ($\bar{P}$). The Budyko hypothesis is a widely used tool to normalize observations among a wide range of climatic settings; it enables the effects of secondary controls on a catchment's water balance to be identified (Dooge 1992, Zhang 2004). We examine the influence of the mean fraction of precipitation that falls as snow ($\overline{f_s}$) on the mean streamflow ($\bar{Q}$). Since between-catchment differences in the water balance can be caused by many factors which are correlated with the long-term average snow fraction, we also analyze the inter-annual streamflow of catchments to estimate the annual streamflow variation due to variations in the snow fraction. To conclude, we quantify the sensitivity of streamflow to potential changes in $\overline{f_s}$ that may result from temperature rise.

Figure 1a displays the long-term streamflow measurements of the 420 study catchments in the context of the Budyko hypothesis, and stratified by long-term mean snow fraction ($\overline{f_s}$). Overall, the pattern of observations is consistent with the Budyko curve, with a mean overestimation of the normalized streamflow ($\bar{Q}/\bar{P}$) by just 0.02. Figure 1a also shows that, in general, larger values of $\overline{f_s}$ are associated with lower normalized evaporation ($\bar{E}/\bar{P}$) and higher normalized mean streamflow ($\bar{Q}/\bar{P}$). Figure 1b clarifies this effect by displaying the observed streamflow anomaly from the Budyko curve as a function of snow fraction, ($\overline{f_s}$). A linear regression ($p < 0.01$) indicates an average increase in normalized streamflow ($\bar{Q}/\bar{P}$) of 0.37 per unit increase in snow fraction, ($\overline{f_s}$).

We have assessed the uncertainties in these data and their interpretation. Precipitation measurements are sensitive to undercatch, especially for solid precipitation (Groisman 1994) and so have been corrected here according to Groisman (1994). Changes in soil and groundwater storage are orders of magnitude smaller than the other fluxes and thus considered negligible over a multi-annual period. Inter-annual changes of snow storage are minimal due to absence of large areas with perennial snow cover in any of the 420 catchments. Streamflow measurement errors and exchanges with aquifers can bias results of individual catchments, but are unlikely to be strongly correlated to the snow fraction. The above uncertainties are thus unlikely to result in a misinterpretation of the observed patterns in context of the Budyko hypothesis.

Given that the mean partitioning of precipitation into streamflow and evaporation is partly governed by physiographic controls that may be spatially correlated with the long-term snow fraction (e.g. topography, soil, landcover, etc.), and since the Budyko framework does not examine between-year variations in streamflow, we extend the analysis with a study of the inter-annual streamflow. We selected catchments with a significant amount of snowfall, while maintaining a large number of catchments (97 catchments with $\overline{f_s} > 0.15$). For each catchment, we use linear regressions to investigate whether year-to-year variations in normalized annual streamflow ($Q/\bar{P}$) can be linked to the corresponding variations in snow fraction between years.

Figure 2 displays the sensitivity of normalized annual streamflow to annual snow fraction for the 97 catchments. Sensitivity is defined as the change in normalized annual streamflow ($Q/\bar{P}$) per change in the annual fraction of precipitation falling as snowfall (f_s) (see Methods). The mean increase of $Q/\bar{P}$ per unit of f_s is 0.29 (standard deviation 0.21) and 94 of the 97 catchments display a positive value of this sensitivity. This indicates that an increase in the annual f_s is almost always associated with an increase in the annual streamflow, but sensitivities differ per catchment. The results are not significantly influenced by changes in soil-water and groundwater storage variation between years; we established this by repeating the analysis using 5-year averages in place of annual averages; the conclusions were unaffected.

Variations in f_s between years are caused both by fluctuations of the mean winter temperature and the fraction of precipitation falling during the winter period. An identical sensitivity analysis using temperature instead of f_s indicates that, on average, the annual streamflow decreases when the mean winter temperature (1 Nov. – 1 Apr.) increases. This holds solely for the set of catchments with high $\overline{f_s}$ values, and is not applicable for summer temperatures (1 May. – 1 Oct.) or catchments with marginal snowfall ($\overline{f_s} \leq 0.15$). The results therefore suggest that mean stream flow is not merely related to the timing of precipitation or the associated temperature, but that the form of precipitation also is a determining factor.

To provide a context for the streamflow sensitivity to annual snow fraction, we consider the effect of temperature warming, under the assumption that the observed historical climate series are representative for future scenarios. The historical climate series for the 97 snow-affected MOPEX catchments indicate that a large fraction of precipitation that now falls under the temperature threshold will in future fall at temperatures above that threshold. A 2°C temperature rise for the 97 studied catchments leads to an average 35% decrease in $\overline{f_s}$ (standard deviation 11%). For a 4°C temperature increase, $\overline{f_s}$ reduces by 60% (standard deviation 15%). As shown above, the average change in normalized streamflow is 0.29 per unit of f_s, but varies by catchment. Under the simplifying assumption of a system otherwise at steady-state, this implies that a 2°C temperature rise, on average, could potentially lead to a decrease of normalized streamflow ($Q/\bar{P}$) in the order of 0.1 times the historical f_s. Given that mean streamflow is in general significantly lower than the mean precipitation the proportional change in actual mean streamflow can be much higher. Although other factors, such as changes in precipitation patterns (Groisman 2004, Dore 2005), can locally compensate for changes in the annual streamflow, clearly temperature rise will alter the hydrological cycle. This will require an understanding of catchment function that goes beyond the assumption that systems fluctuate within an unchanging envelope of variability (Milly 2008), including the need to more comprehensively acknowledge the role of snow for the long-term streamflow patterns.

The observation that a lower f_s is associated with lower streamflow on the annual and mean-annual timescales is restricted here to empirical evidence, and does not reveal the physical processes behind these observations. The processes underlying the sensitivity of mean streamflow to snowfall may be related to differences in: the infiltration capacity of soils, the duration of infiltration periods, the timing of infiltration periods, the evaporation from snow-covered and snow-free soils, the growing season length, the soil moisture regime, the potential evaporation, amongst other factors. Given the diversity of catchments in our sample, each with its own internal heterogeneity, the mechanisms connecting snow to mean streamflow are likely to result from combinations of factors and may vary from site to site. Further work is needed to clarify which hydrological processes are the main contributors to the sensitivity we have presented.

In summary, this study uses historical data from a wide range of catchments to investigate the role of the fraction of precipitation falling as snow for the long-term and the inter-annual mean streamflow of catchments. There is evidence that, in context of the Budyko hypothesis (Budyko 1974), catchments with a high fraction of long-term precipitation falling as snowfall are characterized by significantly higher long-term mean streamflow than catchments with little or no snowfall. In addition, analysis of inter-annual variability indicates that the annual fraction of precipitation falling as snow has a significant influence on the mean annual streamflow, independent of precipitation amount. Both results indicate that a change in phase of precipitation from snow towards rain significantly decreases the mean streamflow. Although the study catchments are restricted to the contiguous United States, the diversity of physiographic and climatic settings, and the number of catchments used, suggest that snowfall may affect the mean streamflow in other regions as well. This finding has significant implications for water resource planning, as the projected global temperature rise is expected to lead to significant reductions in f_s in many regions around the world, and our results indicate that this would decrease mean streamflow in these regions, unless other factors compensate (Groisman 2004, Dore 2005). It is particularly relevant to “water towers” (Viviroli 2007) where societally important functions, such ecosystem stability, hydropower, irrigation, and industrial or domestic supply are derived from snowmelt. Associated process explanations are not yet available and need to be understood if society is to respond adequately to the consequences of a temperature-induced precipitation shift from snow to rain.

Methods

Data

Data are from 420 catchments belonging to the Model Parameter Estimation Experiment (MOPEX) (Schaake 2006). Catchments are located throughout the contiguous United States and span four of the five main climate types of the Köppen-Geiger climate classification. Drainage areas of the catchments vary between 67 and 10,329 km^2. Daily time series of precipitation, temperature, potential evaporation and streamflow are all available for up to 54 years (1948-2001). Potential evaporation is calculated based on the NOAA Pan Evaporation Atlas (Farnsworth 1983), using the Penman method (Penman 1948). The PRISM method (Daly 2008) was applied for interpolation of the temperature and precipitation values to account for topographic effects when estimating catchment mean precipitation and temperature. Streamflow values were sourced from the United States Geological Survey. The catchments were selected to have a limited anthropogenic influence, and their decadal water balance is not significantly influenced by changes in glacier storage: the perennial snow-covered area does not exceed 3% for individual catchments and is for most catchments non-existent. Annual values used in the analysis are from 1 Sep. to 31 Aug. to minimize effects of carry over storage of snowfall. The dataset is available online: www.nws.noaa.gov/oh/mopex/mo_datasets.htm

Snowfall estimation

The fraction of precipitation falling as snow (f_s) is approximated using a simple temperature threshold on each day of recorded data (e.g., Hock 2003). Precipitation on days with an average temperature below 1ºC is considered to be entirely snowfall, while on days with temperature above 1ºC, precipitation is considered to be entirely rainfall. The conclusions of the paper are robust to changes in the method of snowfall estimation within reasonable bounds (e.g. other temperature thresholds, or more complex schemes that linearly partition precipitation between snow and rain for temperatures between two thresholds).

Undercatch correction

In the context of the Budyko framework, the precipitation measurements are corrected for mean monthly undercatch. Corrections for undercatch are made according to Groisman (1994).

Budyko framework

The Budyko curve used for the normalization of the long-term water balances of catchments is as follows:

$$\frac{1-\bar{Q}/\bar{P}}{\bar{P}} = \sqrt{\frac{\overline{E_p}}{\bar{P}}\tanh\left(\frac{\bar{P}}{\overline{E_p}}\right)\left(1-\exp\left(-\frac{\overline{E_p}}{\bar{P}}\right)\right)}$$

where $\bar{Q}$, $\bar{P}$ and $\overline{E_p}$ are the long-term mean values for the streamflow [L/T], precipitation [L/T] and potential evaporation [L/T]. Similar equations proposed by others (e.g. Pike, 1964) will slightly alter the water balance anomalies for individual catchments but yield similar conclusions regarding the influence of snowfall.

Sensitivity of inter-annual streamflow

Sensitivity is defined below as the change in normalized annual streamflow ($Q/\bar{P}$) per change in the annual fraction of precipitation falling as snowfall (f_s). It is well known that annual streamflow often depends strongly on annual precipitation; if precipitation were correlated with snow fraction then a naive approach would result in a spurious sensitivity of streamflow to snow fraction. In the equation below we make the required correction for the effects of correlation between *P* and f_s. Therefore, sensitivity is approximated by:

$$\frac{\partial(Q/\bar{P})}{\partial f_s} = \frac{\mathrm{d}F}{\mathrm{d}f_s} - \frac{\partial F}{\partial(P/\bar{P})}\frac{\mathrm{d}G}{\mathrm{d}f_s}$$

where

$$Q/\bar{P} = F(f_s, P/\bar{P}) \text{ and } P/\bar{P} = G(f_s)$$

and where *Q* is the annual streamflow [L/T], $\bar{P}$ is the mean annual precipitation [L/T], f_s is the annual fraction of precipitation falling as snowfall [-], and G(f_s) and $F(f_s, P/\bar{P})$ are approximated as functions linearly dependent on their variables. The derivatives are approximated by the slope terms of least squares estimators.

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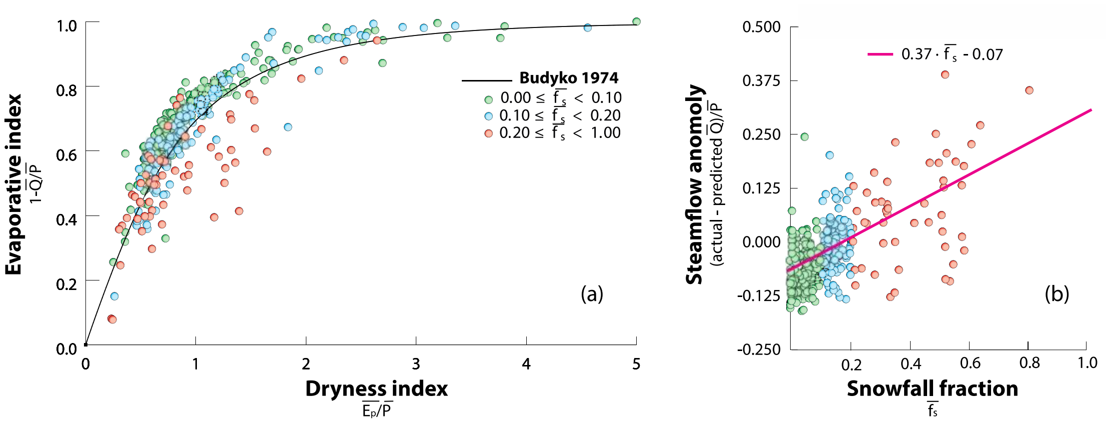

Figure 1: Mean annual streamflow and streamflow anomaly in the context of the Budyko hypothesis, stratified by snow fraction. The observed long-term streamflow and precipitation measurements are placed in context of the Budyko hypothesis. The Budyko hypothesis states the mean streamflow is primarily a function of the catchment's annual precipitation and potential evaporation. Departures below the Budyko curve for catchments with a significant fraction of the precipitation falling as snow indicate that an increased fraction of precipitation as snowfall is associated with higher streamflow.

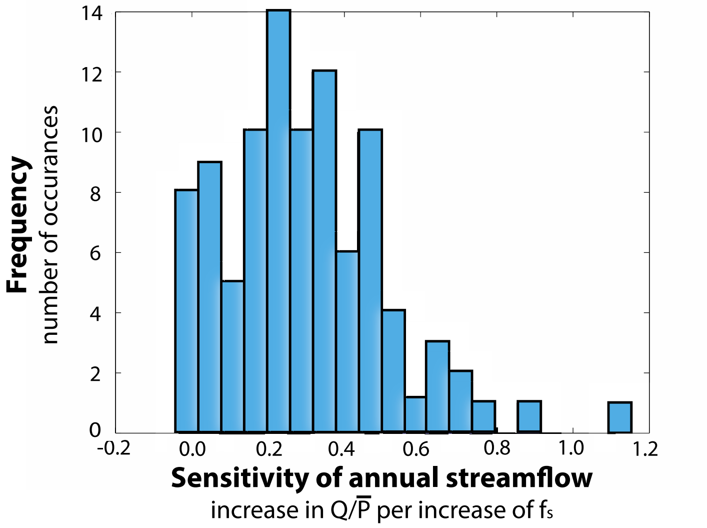

Figure 2: Sensitivity of annual streamflow to the fraction of annual precipitation falling as snowfall. The histogram displays the change in normalized streamflow ($Q/\bar{P}$) per unit of change of the annual snow fraction (f_s) for 97 snow-affected catchments ($\bar{f_s} > 0.15$). Positive values of sensitivity indicate that the annual streamflow of catchments varies (between years) directly with the annual f_s. Years with higher snow fraction, f_s, tend to have higher values of annual streamflow.