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Dominant flood generating mechanisms across the United States

Wouter R. Berghuijs[1*], Ross A. Woods[1], Christopher J. Hutton[1, 2], M. Sivapalan[3, 4]

1. Department of Civil Engineering, University of Bristol, United Kingdom
2. School of Geographical Sciences, University of Bristol, Bristol, United Kingdom
3. Department of Civil and Environmental Engineering, University of Illinois at Urbana-Champaign, USA
4. Department of Geography and Geographic Information Science, University of Illinois at Urbana-Champaign, USA

*Correspondence to: W. R. Berghuijs, Department of Civil Engineering, University of Bristol, University Walk, BS8 1TR, Bristol, UK. E-mail: wb14708@bristol.ac.uk

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Key Points

1. Regional differences in mechanisms that control US flood timing and magnitude are exposed
2. Disparity in timing and variability between floods and rainfall emphasizes the importance of hydrological processes
3. Classification of dominant flood-generating mechanisms provides guidance to flood studies

Keywords Flood; Hydro-climatology; Precipitation; Soil Moisture; Seasonality; Snow

Abstract

River flooding can have severe societal, economic and environmental consequences. However, limited understanding of the regional differences in flood-generating mechanisms results in poorly understood historical flood trends and uncertain predictions of future flood conditions. Through systematic data analyses of 420 catchments we expose the primary drivers of flooding across the contiguous United States. This is achieved by exploring which flood-generating processes control the seasonality and magnitude of maximum annual flows. The regional patterns of seasonality and interannual variability of maximum annual flows are, in general, poorly explained by rainfall characteristics alone. For most catchments soil-moisture dependent precipitation excess, snowmelt, and rain-on-snow events are found to be much better predictors of the flooding responses. The continental-scale classification of dominant flood-generating processes we generate here emphasizes the disparity in timing and variability between extreme rainfall and flooding, and can assist predictions of flooding and flood risk within the continental US.

1. Introduction

Every year river flooding leads to fatalities [Ashley & Ashley, 2008; Di Baldassarre et al., 2010] and multi-billion dollar damage [Jongman et al., 2012; Winsemius et al., 2015], but floods also enhance ecosystem health and replenish reservoirs [Thomaz et al., 2007; Richter & Thomas, 2007]. Although their significance for society is evident, reliable estimation of flood hazard remains a challenge [Kundzewicz et al., 2014]. With an increased likelihood of high-intensity rainfall under a warming climate [Trenberth et al., 2003; Allan & Soden, 2008; Min et al., 2011; Kendon et a., 2014], the magnitude and frequency of floods are projected to increase [Milly et al., 2002; Pall et al., 2011; Arnell & Gosling, 2014]. While increased precipitation extremes have already been observed [Trenberth et al., 2003; Groisman et al., 2005; Allan & Soden, 2008; Min et al., 2011; Westra et al., 2013], there is low confidence regarding even the sign of trend in the magnitude of annual maximum floods (let alone exact predictions), both globally [Kundzewicz et al., 2014] and in the US [Lins & Slack, 1999; Villarini et al., 2009, 2011; Hirsch & Ryberg, 2012].

Predictions of future floods and interpretation of historical flood trends are usually based on statistical approaches using runoff- and sometimes precipitation-data [e.g., Gumbel, 1941; Cunnane, 1988; Lins & Slack, 1999; Villarini et al., 2009, 2011; Villarini & Smith, 2010; Smith et al., 2015], or through the use of mechanistic models describing precipitation partitioning at the scale of a river basin [e.g., Milly et al., 2002; Te Linde et al., 2011; Arnell & Gosling, 2014]. The usefulness and reliability of both methods are constrained by the degree to which they can represent the relevant processes that control flood response. Hence, improved process understanding is a key element for improving the prediction and interpretation of flood trends [Merz and Blöschl, 2008a,b,c; Milly et al., 2008; Kundewicz et al., 2014; Merz et al., 2014], especially under environmental change.

The need for process-based approaches for flood estimation catalyzed a wealth of studies that acknowledge that factors other than rainfall may play an important role in controlling floods [e.g., Merz et al., 1999; Merz & Blöschl, 2003; Sivapalan et al., 2005; Bradshaw et al., 2007; McCabe et al., 2007; Parajka et al., 2010; Freudiger et al., 2014; Slater et al., 2015]. Although these and many other studies emphasize the importance of different flood controlling processes, understanding of the regional differences in process controls of flooding responses is rather limited. Hirschboeck [1991] hypothesize the meteorological mechanisms that cause floods, and discuss the role of antecedent moisture and snow conditions. Villarini [2016] discusses which meteorological patterns are important for flood seasonality. Yet, for the United States there is no robustly tested continental-scale classification of regional differences in the dominant flood- processes generating.

In this study, we assess the dominant flood-generating processes for 420 catchments spread across the contiguous United States. We first explore the seasonality of floods for all catchments and subsequently use that information to test hypotheses about the underlying process controls, since the dominant flood-generating processes at a given location can be strongly linked to the time of the year that major floods occur [Hirschboeck, 1991; Merz et al., 1999; Merz & Blöschl, 2003; Sivapalan et al., 2005; Parajka et al., 2010]. By comparing the seasonality of floods in the context of four hypothesized flood-generating mechanisms, we explore which dominant processes correspond to the observed seasonality of flooding in individual catchments. To further clarify the role of these local runoff-generating mechanisms, we subsequently explore which of the hypothesized flood-generating processes controls the observed interannual variability in flood magnitude. Both flood characteristics have been explored before for the United States [Hoyt & Langbein, 1955; Guo et al., 2014; Villarini, 2016], but the hydrological processes that control both flood signatures have not been uncovered. By combining understanding generated from examining the controls on both the timing and magnitude of floods, we present an overview of the regional differences in the inferred dominant flood-generating processes of all catchments.

2. Methods

2.1. Data

We use daily streamflow and meteorological data for 420 MOPEX catchments for the period 1948-2001 [Duan et al., 2006]. We eliminated 18 of the 438 catchments of the original MOPEX dataset with less than 20 years of continuous data [Berghuijs et al., 2014a]. The catchments range in size from 67 to 10,329 km^2 and were originally characterized by limited human influence. Subsequent studies suggest that water balances in these catchments can be impacted by agricultural activities [Wang & Hejazi, 2011]. The seasonality of maximum annual flow (MAF) and of the hypothesized flood-generating processes are expressed by the mean date of occurrence ($\overline{\Phi}$) and the standard deviation of the mean date of occurrence (σ_{Φ}) using circular statistics [Burn, 1997; Young et al., 2000]. In the Supplementary Material we provide the computational details of $\overline{\Phi}$ and σ_{Φ}.

2.2 Hypothesized flood-generating mechanisms

Using a downward approach to hydrological prediction [Klemeš, 1983; Sivapalan et al., 2003] we investigate which of four hypothesized flood-generating processes can explain the timing and interannual variability of MAF. To assess the feasibility of hypothesized flood-generating processes, we compare the $\overline{\Phi}$-values of the MAF to those of the four hypothesized mechanisms. Subsequently we test how much of the interannual variability in MAF magnitude can be explained by the hypothesized mechanisms. Rather than using complex models for exact prediction, our aim is to test the first-order consistency of hypothesized processes and real-world observations.

Hypothesis 1: flooding is caused by the single largest precipitation event: streamflow is assumed to be independent of the pre-event antecedent soil moisture storage, which is controlled by seasonal rainfall, evaporation and drainage properties of the landscape. Runoff generating mechanisms associated with such floods can be infiltration excess overland flow [Horton, 1933]; preferential subsurface flow [Šimůnek et al., 2003]; saturation excess overland flow; and fill and spill flow for soils with storage capacities much smaller than total event precipitation [Dunne, 1978; Tromp-van Meerveld & McDonnell, 2006].

Hypothesis 2: flooding is caused by the single largest series of precipitation events: The MAF is caused by multiple precipitation events during a several day period. The period is set at 7 days, but analyses with periods ranging from 3 to 10 days yielded comparable results. This hypothesis suggests that flooding is still independent of evaporation controlled soil moisture conditions, but pre-event antecedent wetness conditions and water storage play an important role for streamflow generation. Runoff generating mechanisms associated with such floods can be saturation excess overland flow [Dunne, 1978], and fill and spill mechanisms [Tromp-van Meerveld & McDonnell, 2006].

Hypothesis 3: flooding is caused by the single largest precipitation excess event; the MAF is caused by the largest precipitation excess event of the year. Precipitation excess is defined as the rainfall excess compared to available soil moisture storage capacity:

$$P_e(t) = \max(0, P(t) - (S_{u,max} - S_u(t))$$

where P_e is precipitation excess, P is the daily observed precipitation, S_u is storage in the unsaturated zone, $S_{u,max}$ is the soil moisture storage capacity according to the bucket model of Milly [1994] at day t*:*

$$S_u(t) = S_u(t-1) + P(t) - P_e(t) - \min(0.75 \cdot E_p(t), S_u(t)).$$

Potential evaporation (E_p) is scaled to 75% of its daily value because not all E_P tends to be used for evaporation. $S_{u,max}$ is fixed at 125 mm as this on average corresponds to root zone storage capacity of MOPEX catchments [Gao et al., 2014] and, on average, simulates the long-term water balance within 1% of the observations (using this simple bucket model). Hypothesis 3 suggests that antecedent soil moisture storage, as controlled by seasonal rainfall and evaporation, is the primary control on runoff generation in flood events. Similar to Hypothesis 2, the runoff generating mechanisms associated with such floods can be saturation excess overland flow [Dunne, 1978] and the fill and spill mechanism [Tromp-van Meerveld & McDonnell, 2006], but storage is evaporation controlled.

Hypothesis 4: flooding is caused by the single largest snowmelt or rain-on-snow event: the MAF is generated by the largest snowmelt event or rain-on-snow event, where the snowmelt contribution is estimated according to a simple degree-day model [Hock, 2003]:

$$\mathrm{P_{snow}(t) = min\left(f_{dd} \cdot\ max(T - T_{crit}(t), 0)\,, S_{snow}(t)\right) + P(T(t) > T_{crit})}$$

where P_{snow} is the snowmelt rate, P is the precipitation rate for days when the daily average temperature T exceeds the temperature threshold T_{crit} set at 1 (^{o}C). f_{dd} is the melt rate set at 2.0 (mm/d/K) [Woods, 2009], and S_{snow} is the snow storage:

$$\mathrm{S_{snow}(t) = S_{snow}(t-1) + P(t(T(t) < 1) - P_{snow}(t)}$$

Since there is no data available on snowmelt, snow storage, and rain-on-snow events, the absolute value of P_{snow} is a rough approximation of snowmelt dynamics.

4. Results

4.1 Seasonality of floods and flood predictors

Results indicate the mean date ($\bar{\Phi}$) and variability of the date (σ_{Φ}) of MAF strongly vary among the study sites (Fig. 1a). Broadly speaking, $\bar{\Phi}$ ranges from winter period (western coastal states), to late winter and early spring (most eastern catchments, and parts of California), to late spring and early summer (Great Plains, Mid West, Rocky Mountains, Sierra Nevada, Northern Cascades), to late summer and autumn (New Mexico). The variability of the mean day of MAF also shows strong regional patterns. For catchments in the Rocky Mountains, and several coastal western catchments the timing of MAF is very predictable. The central and eastern part of the United States show regional differences in the degree of variability of the mean day of flood, with higher interannual variability in many of the coastal states and more southern catchments. We refer to other studies for a more extensive assessment of flood seasonality [Hoyt and Langbein 1955; Villarini, 2016] and its connection with the mean seasonal hydrologic conditions [Berghuijs et al., 2014b].

The $\overline{\Phi}$- and σ_{Φ}-values of the four hypothesized flow predictors (maximum daily precipitation, maximum weekly precipitation, precipitation excess, and snowmelt) all show regional patterns, which are not the same for all processes (see Fig. 1b-e). Maximum daily precipitation for the western coastal states generally falls during the winter period and these maximum daily precipitation events rarely happen during other times of the year. In the southeastern part of the US maximum daily precipitation, on average, occurs during winter and early spring, but this date is more variable. The other catchments have most maximum annual precipitation events during the summer period, during late summer (northeast) and Fall (e.g. Arizona), but regional differences exist in the temporal variability of this timing. Maximum weekly precipitation gives a very similar pattern, but with some regional differences (e.g. New Mexico and Florida). Precipitation excess is generally the highest during late winter and early spring. Exceptions are the west coast (winter dominated), the mid-west and some northeastern catchments. This date is not very variable between years for western and central catchments, but on the east coast this variability increases. Maximum snowmelt is only calculated for catchments with on average more than 10% of their precipitation falling as snow, which have maximum melt-rates at dates ranging from early spring to early summer. These snowmelt or rain-on-snow events are almost always during this part of the year.

Visual comparison of the $\overline{\Phi}$-values (Fig. 1) already indicates that some predictors are regionally highly unsuitable to describe when MAFs are occurring, and thus are not the dominant processes for flood generation. In other regions or for other predictors the correspondence is much better. Using scatter plots (Fig. 2) we highlight to what degree the $\overline{\Phi}$-values of flooding and predictors occur at the same time of the year. For daily precipitation only a small fraction of catchments have a predicted date with a reasonable correspondence to the observed flood date (Fig. 2a). The threshold is set at 35 days, but other time windows lead to comparable final results. For weekly precipitation a similar pattern is observed with few catchments having their flood timing well predicted by this mechanism. These results indicate that precipitation by itself is a good predictor of flood seasonality only for a small fraction of the catchments, suggesting that other processes play an important role. Many more catchments show a reasonable correspondence between precipitation excess and flood response. In general precipitation excess peaks slightly earlier in the year than observed flood, but differences are within a few weeks, suggesting that precipitation excess may be a more common control on flood generation. For most of the catchments with a significant amount of snowfall, the date of maximum snowmelt and rain-on-snow events is a good predictor for the timing of MAF.

4.2 Interannual variability of floods and flood predictors

The magnitude of MAF has differing degrees of interannual variability as the coefficient of variation (CV_Q = std. dev. (Q_{MAF}/mean(Q_{MAF}))) varies among catchments (Fig. 3a). The variability of annual flows is much larger for the central more arid catchments, as already indicated by Guo et al., [2014] and is in line with the finding of Farquharson et al. [1992] that the slope of the flood frequency curve increases with aridity. To test which hypotheses provide explanations of the interannual variability of flood magnitude, we quantify for individual catchments the Spearman rank correlation between annual values of flood magnitude, and annual values of hypothesized generating mechanisms. For catchments where multiple mechanisms are still feasible according to the seasonality approximations (Fig. 2), we examine which process is able to explain most of the variability in the runoff (Fig. 3b), and show the associated Spearman rank correlation (Fig. 3c). The mechanism that is within 35 days of flood seasonality and that best explains the interannual variability in flood magnitude is identified as the dominant flood-generating mechanism.

The patterns of dominant flood-generating mechanisms indicate that different regions have different hydrological processes of importance. Daily and multi-day precipitation is a control of floods for many catchments in the central arid part of the United States. For the vast majority of catchments precipitation excess is the mechanism that can best reproduce both the timing and magnitude of maximum annual flows. Snow controls the flood response in the Rockies, and also in some of the other northern or high altitude catchments; for most of the catchments with a significant amount of snowfall, the maximum snowmelt and rain-on-snow events are within the same period of the year as the timing of MAF (Rocky Mountains, Sierra Nevada, Northern Cascades, northern part of Appalachian and the most northern located catchments). For a limited number of the catchments no single mechanism considered here is capable of reproducing the flood seasonality and no dominant mechanism is identified. Some of these catchments are located in regions with a uniform flood timing distribution [Villarini, 2016].

5. Discussion

5.1 On exposing controls of flood response

The top-down hypothesis testing to explain the seasonality of floods provides a simple and repeatable (e.g. for other regions) method to decipher first order understanding of the diverse nature of flood-generating mechanisms. Good correspondence between the seasonality of MAF with only one process explanation suggests that the proposed flood-generating mechanism is the primary control of MAFs (Fig. 2). This is further substantiated by the Spearman rank correlation coefficient that indicates the ability of the mechanisms to explain the interannual variability in flood magnitude (Fig. 3c). Compared to other studies that use seasonality to learn about the process controls on floods [e.g., Hirschboek, 1991; Parajka et al., 2010; Villarini, 2016], our additional use of flood magnitude increases the robustness and reduces the equifinality in identifying dominant mechanisms.

The strong disparity between the dates of maximum precipitation events and the date of flooding is a simple but effective indicator that factors other than just precipitation control the magnitude of floods over the United States. Although the process explanations used here are extremely simplified, their first order differences in the analysis indicate strong regional patterns in the controls of flood seasonality. With no correspondence between maximum daily and weekly precipitation and flood response in all but some central states, it must clearly be that other processes, e.g., snowmelt and soil moisture, control the flood response across the majority of the United States.

In future work the flood-generating mechanisms can be refined further by expanding the downward approach to hydrological prediction through modeling studies, which can reflect the role of sub-daily flow dynamics, landscape properties, spatial variability in more detail. The understanding presented here of regional patterns of flood-generating mechanisms may also be expanded to more locations in the US, including more human impacted environments, and can be extended to other continents.

5.2 Implications for flood prediction and trend analysis

Although statistical approaches have played and will always play an important role in flood estimation, they have to be complemented by the search for the causal mechanisms and dominant processes in the atmosphere, catchment and river system that leave their fingerprints on flood characteristics [Merz & Blöschl, 2008a,b; Merz et al., 2014]. With the currently limited representation of process understanding in continental scale US river flood studies [e.g., Lins & Slack, 1999; Villarini et al., 2009; Hirsch & Ryberg, 2012], this study opens new pathways to better account for the correct process controls and thereby improve flood estimation. The increased likelihood of extreme rainfall under climate warming [Trenberth et al., 2003; Min et al., 2011; Kendon et a., 2014] is projected to also lead to increases in the magnitude and frequency of floods [Milly et al., 2002; Pall et al., 2011; Arnell & Gosling, 2014]. Although our results do not necessarily suggest that such predictions are not representative, they indicate that for the majority of the soil moisture controlled environments a more appropriate question is: how do changes in extreme precipitation interact with soil water dynamics to alter precipitation excess events? This is potentially one important reason why observed increases in precipitation extremes are not reflected in historical flooding data [Ivancic & Shaw, 2015; Kundzewicz et al., 2014; Lins & Slack, 1999; Villarini et al., 2009, 2011; Hirsch & Ryberg, 2012], but when one focuses on the time of the year that such floods occur, distinct increases in flood occurrence are observed [Mallakpour & Villarini, 2015]. Since the study only highlights the primary controls of flood response, and the nature of seasonality and process controls may change under changing climate and landscape condition, especially in snowy regions [Regonda et al., 2005; Köplin et al, 2014] and regions that urbanize [Ashley et al., 2005], the nature of flooding may strongly shift.

6. Conclusions

We highlight strong regional differences in the time of the year that MAFs have occurred across the contiguous United States. By combining this flood statistic with potential process explanations we highlight strong regional patterns in some of the mechanisms that may be controlling MAF. Flood seasonality is, in general, explained poorly by extreme rainfall seasonality; only for the central arid part of the USA is flood seasonality controlled by extreme precipitation events. Evaporation controlled soil moisture plays a dominant role for the majority of catchments, while for catchments with much snow the timing of MAF is primarily controlled by snow dynamics. This disparity between extreme flows and extreme rainfall is also reflected in the interannual variability of the magnitude of MAF; the interannual variability of MAF is poorly explained by precipitation variability; whereas the variability of evaporation and soil moisture-controlled precipitation excess explains more of the MAF variability. This suggests that across large parts of the USA including now readily available information on hydrological processes can strengthen the relationships between statistical characteristics of extreme precipitation and extreme floods.

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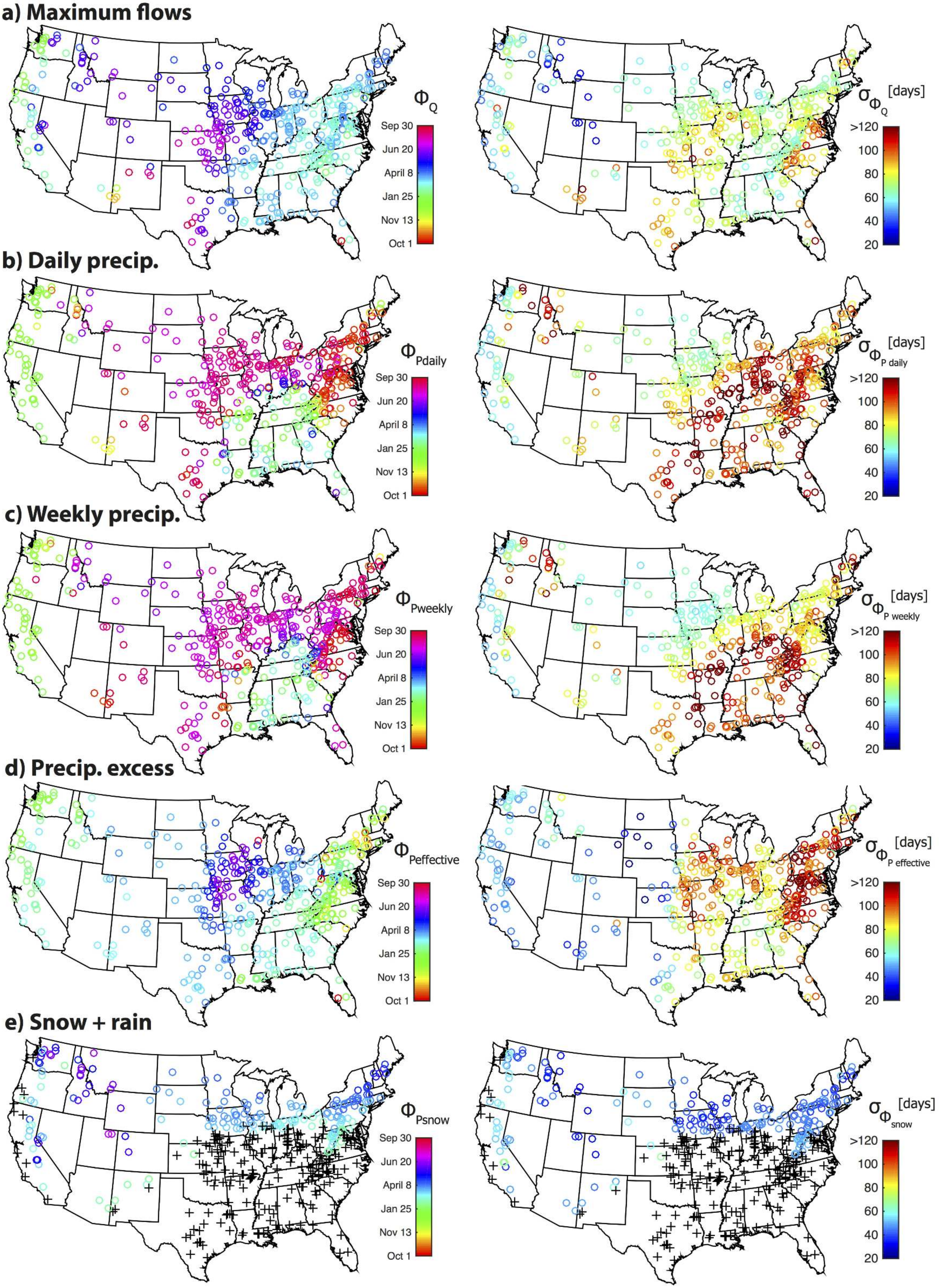
List of Figures

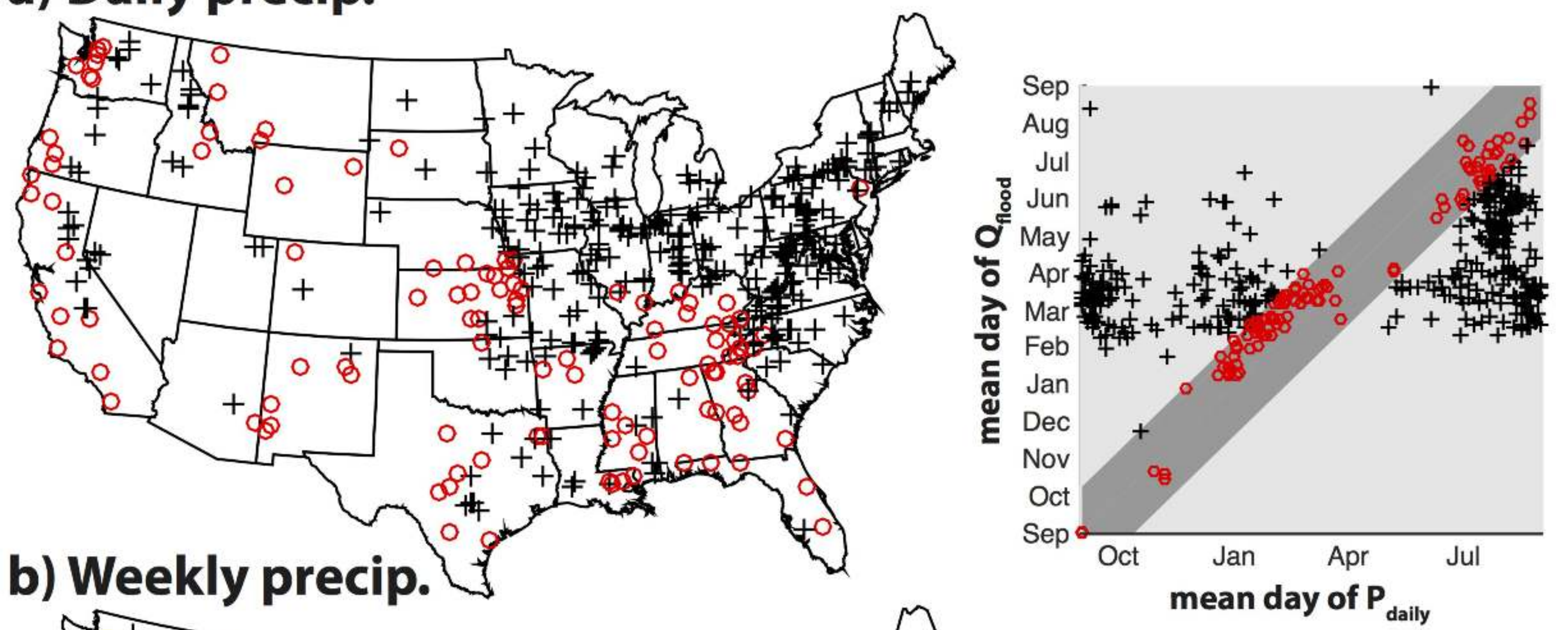
Figure 1: Mean day of (a) maximum annual daily flow, (b) maximum daily precipitation, (c) maximum weekly precipitation, (d) maximum precipitation excess, and (e) maximum snowmelt and associated standard deviations (right column). Black crosses indicate that the data were not calculated due to an absence of significant snow (<10% of total precipitation).

Figure 2: Correspondence of predictors of maximum annual flow and the mean day of maximum annual daily flow as indicated by scatterplots with the 35 days hypothesis rejection limit and the spatial occurrence of rejected (black symbols) and plausible (colored symbols) hypotheses. The number of catchments that fall within the rejection limit varies per mechanism: maximum daily precipitation (109/420), maximum weekly precipitation (122/420), precipitation excess (249/420), and snowmelt (155/420).

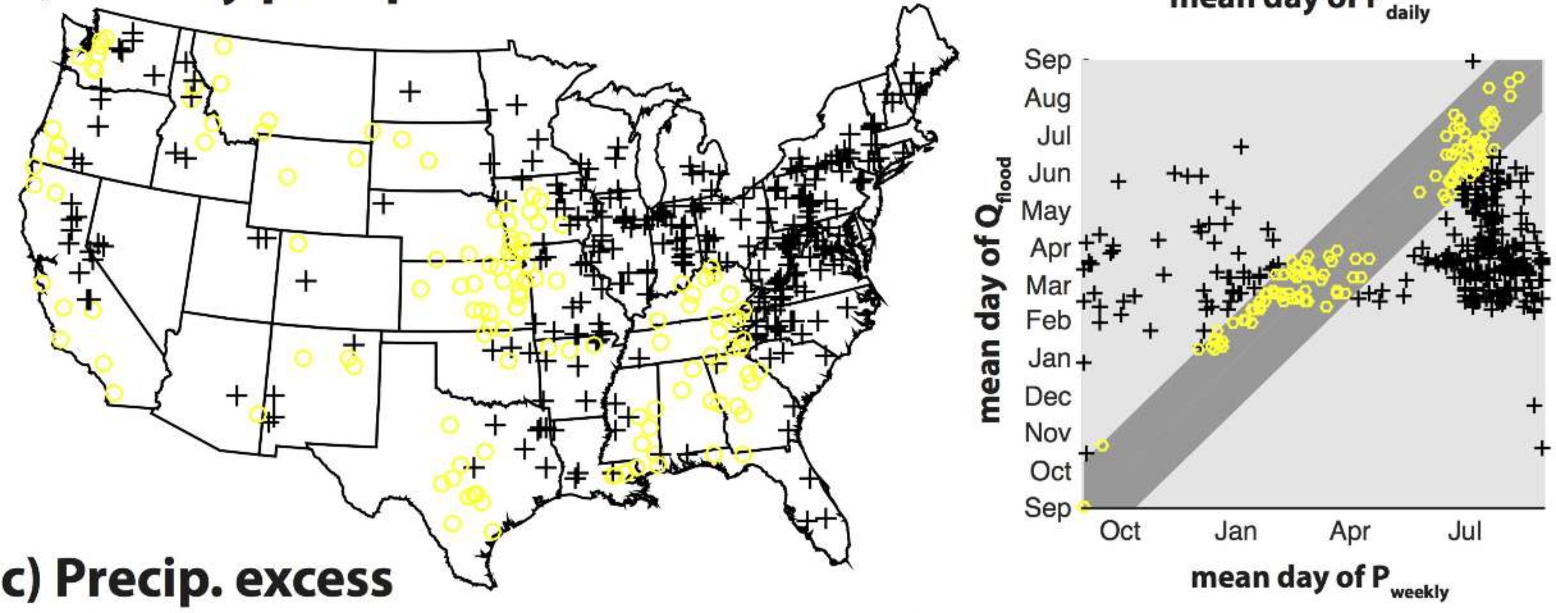
Figure 3: (a) Coefficient of variability of annual maximum flow (CV_Q), (b) the mechanism that explains most variability in the runoff magnitude (based on highest Spearman rank correlation coefficient), and (c) the associated interannual variability explained as expressed by the Spearman rank correlation coefficient. Black crosses indicate that all mechanisms were already rejected in the seasonality analysis.


a) Maximum flows
Φ_Q
Sep 30
Jun 20
April 8
Jan 25
Nov 13
Oct 1
σ_{Φ_Q} [days]
>120
100
80
60
40
20
b) Daily precip.
Φ_{Pdaily}
Sep 30
Jun 20
April 8
Jan 25
Nov 13
Oct 1
$\sigma_{\Phi_{P\ daily}}$ [days]
>120
100
80
60
40
20
c) Weekly precip.
$\Phi_{Pweekly}$
Sep 30
Jun 20
April 8
Jan 25
Nov 13
Oct 1
$\sigma_{\Phi_{P\ weekly}}$ [days]
>120
100
80
60
40
20
d) Precip. excess
$\Phi_{Peffective}$
Sep 30
Jun 20
April 8
Jan 25
Nov 13
Oct 1
$\sigma_{\Phi_{P\ effective}}$ [days]
>120
100
80
60
40
20
e) Snow + rain
Φ_{Psnow}
Sep 30
Jun 20
April 8
Jan 25
Nov 13
Oct 1
$\sigma_{\Phi_{snow}}$ [days]
>120
100
80
60
40
20

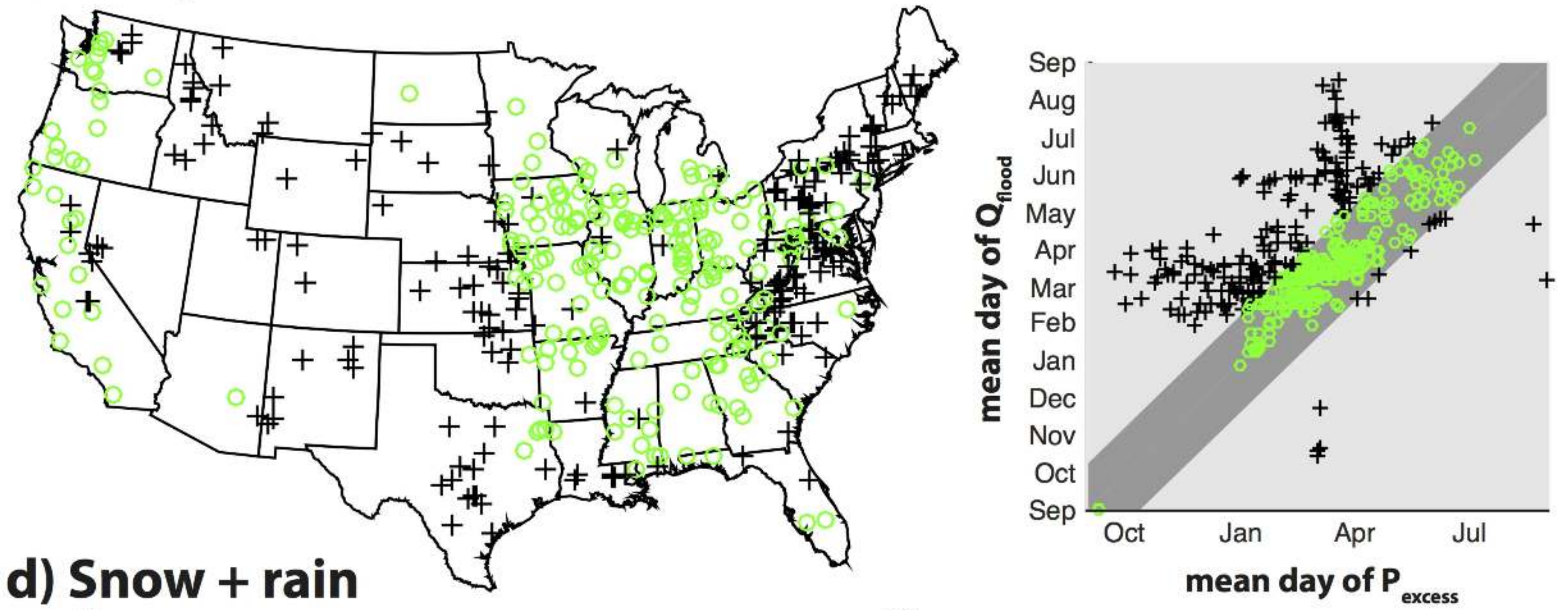
a) Daily precip.



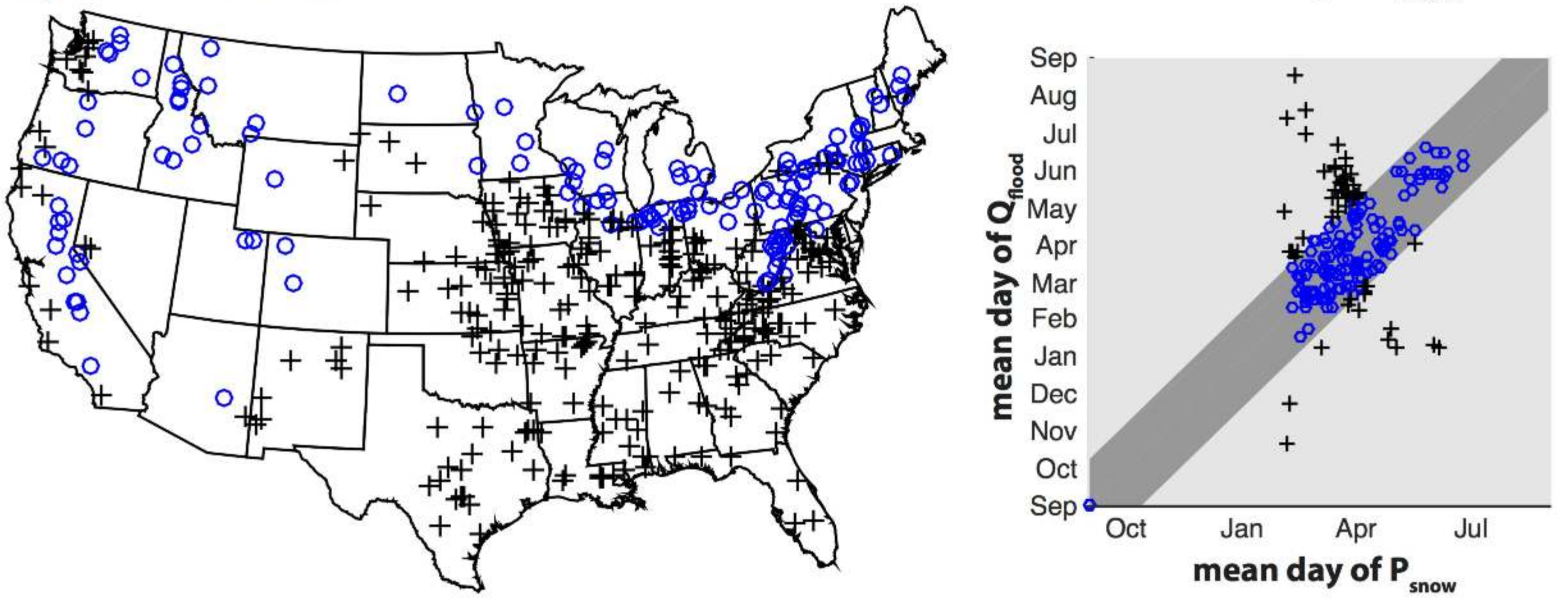
b) Weekly precip.



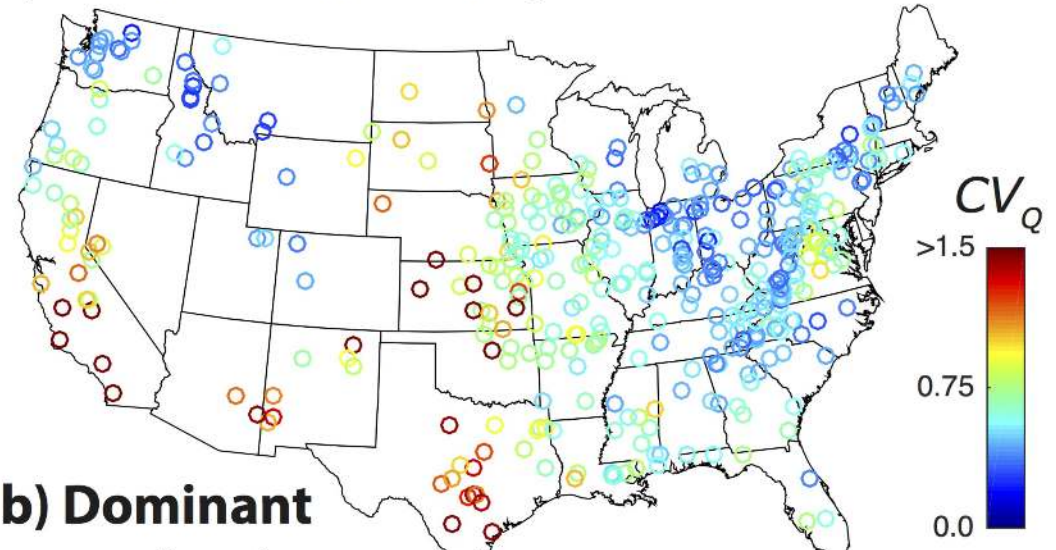
c) Precip. excess



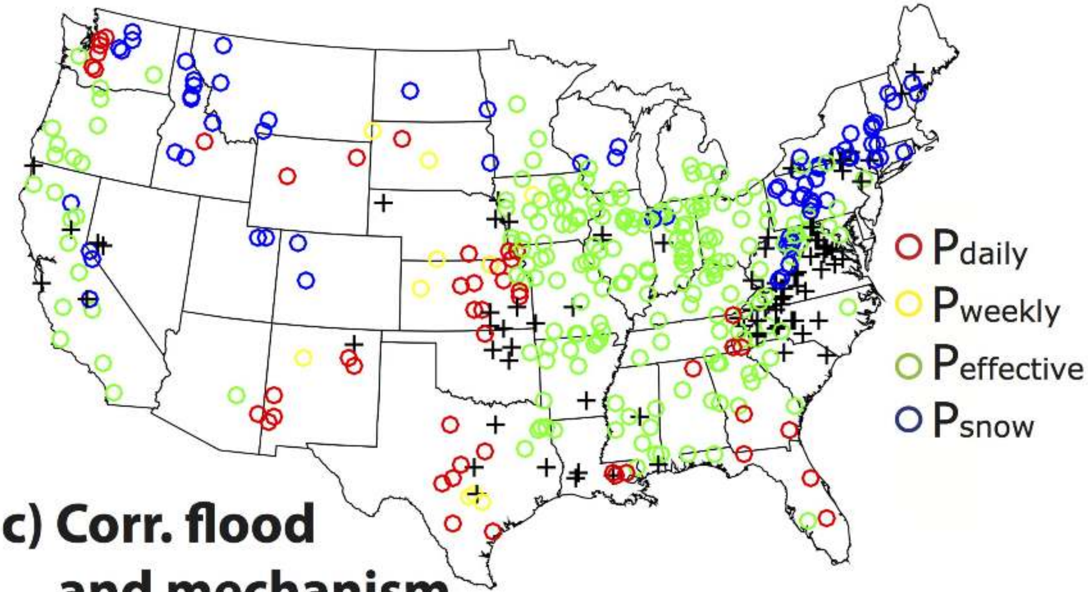
d) Snow + rain



a) Coeff. of variation Q



b) Dominant mechanism



c) Corr. flood and mechanism