SCIENCE ADVANCES | RESEARCH ARTICLE

ENVIRONMENTAL STUDIES

Spatially coherent regional changes in seasonal extreme streamflow events in the United States and Canada since 1950

Evan N. Dethier[1]*, Shannon L. Sartain[1], Carl E. Renshaw[1], Francis J. Magilligan[2]

Complex hydroclimate in the United States and Canada has limited identification of possible ongoing changes in streamflow. We address this challenge by classifying 541 stations in the United States and Canada into 15 "hydro-regions," each with similar seasonal streamflow characteristics. Analysis of seasonal streamflow records at these stations from 1910 to present indicates regionally coherent changes in the frequency of extreme high- and low-flow events. Where changes are significant, these events have, on average, doubled in frequency relative to 1950 to 1969. In hydro-regions influenced by snowmelt runoff, extreme high-flow event frequency has increased despite snowpack depletion by warming winter temperatures. In drought-prone hydro-regions of the western United States and Southeast, extreme low-flow event frequency has increased, particularly during summer and fall. The magnitude and regional consistency of these hydrologic changes warrant attention by watershed stakeholders. The hydro-region framework facilitates quantification and further analyses of these changes to extreme streamflow.

INTRODUCTION

Ongoing changes in the hydrological cycle generated by climate change are expected to increase in the 21st century (*1*–*6*). Despite robust monitoring programs, however, complex and variable hydroclimatology in the United States and Canada poses substantial challenges for analysis of streamflow trends resulting from these changes (*1*, *7*–*10*). Numerous billion-dollar floods and droughts have occurred in the past decade in the United States and Canada, an increase in frequency relative to prior decades (*11*), prompting concerns that extreme flow events are increasing in frequency. These and less severe hydrologic events have revealed vulnerabilities in river management practices and aging infrastructure that threaten human life, infrastructure, and ecology in river corridors (*12*). However, the links between changing precipitation patterns and changing streamflow are not straightforward because streamflow across the United States and Canada responds to widely varying precipitation type and timing (*5*, *13*, *14*); daily and seasonal temperature fluctuations (*15*); patterns of vegetation, snowfall, and evapotranspiration (*16*–*18*); and drainage network and channel characteristics (*14*, *16*, *19*). Thus, to this point, there has been no consensus on whether extreme streamflows are increasing in frequency.

Prior studies have been limited by at least one of several challenges. With some important exceptions [e.g., (*9*, *20*)], previous analyses of streamflow records are mostly restricted to records of annual peak flows, which, in general, are longer than daily streamflow records. However, by focusing only on the annual peak flow, these studies miss entirely changes to extreme low events and may miss important changes occurring on a seasonal basis (*1*). In addition, studies have taken a range of approaches to aggregating or regionalizing data to improve statistical power, from individual river analysis to watershed boundaries and to political boundaries or subregions determined by latitude/longitude grids. Although some of these groupings may have government planning or enforcement relevance, they often do not reflect hydrologic boundaries and are not defined consistently across different studies. These approaches risk not detecting important, ongoing changes to river systems that have potential consequences for human life, infrastructure, and ecology.

To resolve these existing spatial and temporal hydrologic limitations, here, we develop an objective method for clustering 541 gaged rivers in the United States and Canada into hydrologically coherent groups, minimizing within-group hydroclimatological variability and allowing for sensitive detection of trends on both an annual and seasonal basis. Using this approach to increase the signal-to-noise ratio, we show that increases in the frequency of both high- and low-flow extreme streamflow events are, in fact, widespread. Significant changes in annual high flow have occurred particularly in regions affected by snowmelt. At the seasonal scale, additional coherent changes in the frequency of extreme streamflows have occurred within numerous hydro-regions over the past half-century. These include statistically significant trends toward more frequent extreme high-discharge events in the summer, fall, and winter in hydro-regions affected by snowmelt and a link between drought and increasing frequency of extreme low-flow discharge events on the Pacific coast and Southeast United States. In addition, the hydro-region framework provides the means for evaluating influential hydroclimatological parameters in each hydro-region that is not overly narrow (e.g., individual river analysis), broad (e.g., national-scale analysis), or arbitrary (e.g., analysis within political boundaries). This classification allows for more sensitive detection of ongoing trends by analyzing in aggregate changes to tens to hundreds of rivers likely responding to similar streamflow generating mechanisms, thus minimizing noise due to the inherent natural variability of river systems. The hydro-regions accommodate the diversity of hydrologic regimes in the United States and Canada and, due to their easy transferability to any dataset of daily streamflow records in those countries (e.g., including stations with shorter records), provide a framework for further analysis of flood mechanisms and future trends.

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[1] Department of Earth Sciences, Dartmouth College, 6105 Hinman, Hanover, NH 03755, USA. [2] Department of Geography, Dartmouth College, 6107 Hinman, Hanover, NH 03755, USA.
*Corresponding author. Email: evan.n.dethier.gr@dartmouth.edu

RESULTS

These analyses extend prior work on changes to annual peak flow by investigating both annual and subannual seasonal changes to high- and low-flow extreme events, following existing approaches for analyzing climate-driven changes in precipitation (*1*) and methods for analyzing nonlinear trends advanced by Mudelsee *et al.* (*21*) and Barichivich *et al.* (*22*). To do so, we leverage a large dataset of 541 stream gages in watersheds in the United States and Canada classified as minimally affected by human activity (*23*, *24*) and with temporally extensive records (≥60 yrs).

We use *k*-means clustering to systematically divide watersheds in the United States and Canada into objectively defined "hydro-regions" by minimizing within–hydro-region variance in flood timing and magnitude, location, and elevation (see Materials and Methods). Each hydro-region is defined using *k*-means clustering (*25*) based on high-flow seasonality, geographical location, and elevation (Table 1 and Fig. 1). Together, the resulting 15 hydrological zones provide an objective framework for regional-scale, aggregate analysis in the United States and Canada. Three cluster zones have an insufficient (<3) number of stations for analysis and are thus not considered here. The remaining 12 hydro-regions correspond closely to those of McCabe and Wolock (*9*), extending them from the coterminous United States to the entire United States and Canada. For periods beginning in 1910 to 1960 and extending to the present, we analyze the frequency of extreme high- and low-flow events on an annual and seasonal basis for each station individually and for all stations in each hydro-region in aggregate (e.g., fig. S1).

For each river in the analysis, we define extreme high-flow and low-flow events as daily average discharge events that respectively exceed and fall below the discharge threshold for a specified recurrence interval during the period of record (see Materials and Methods). To evaluate the sensitivity of our results to record length and event magnitude, we conducted the same analysis for six starting years (first year of each decade, 1910–1960) and five specified recurrence intervals (2, 3, 5, 10, and 25 years). For seasonal analyses, we considered events only from the months for a given season when determining the thresholds. For simplicity, and because >50% of stations in each hydro-region were operational by 1950 (fig. S7), here, unless specified otherwise, we describe changes from 1950 to present in the frequency of flows exceeding (high-flow) or falling below (low-flow) the record-averaged 5-year recurrence interval threshold. In general, the statistical significance of changes to event

Table 1. Seasonality of high- and low-flow events at hydro-regions considered in this study. We normalized high-flow events for each month by the annual peak mean daily discharge. For each hydro-region, we defined high-flow (green) and low-flow (brown) months as those with the maximum and minimum normalized high- and low-flow average, respectively (Fig. 1B and fig. S2). Months statistically indistinguishable from those maxima or minima were also defined as high- and low-flow months, respectively.

			High–/low-flow months												
Name	**High-flow type***	**Low-flow type†**	**O**	**N**	**D**	**J**	**F**	**M**	**A**	**M**	**J**	**J**	**A**	**S**	**Cluster no.**
Hawaii	iii	ii		🟩	🟩	🟩	🟩	🟩	🟩	🟫	🟫	🟫	🟫	🟫	1
Pacific Northwest	iii	i		🟩	🟩	🟩						🟫	🟫	🟫	2
Pacific Coast	i	ii				🟩					🟫	🟫	🟫	🟫	3
Appalachians	i	i						🟩				🟫	🟫	🟫	4
Mid-Atlantic lowlands	i	i						🟩				🟫			5
Northeast/Upper Midwest	i	iii	🟫		🟫	🟫	🟫		🟩			🟫	🟫	🟫	6
Rocky Mountain highlands	ii	ii	🟫	🟫	🟫	🟫			🟩	🟩		🟫	🟫	🟫	7
High Plains	i	ii	🟫	🟫	🟫	🟫	🟫			🟩				🟫	8
Rocky Mountains	ii	ii	🟫	🟫	🟫	🟫	🟫	🟫		🟩	🟩			🟫	9
Midwest	ii	i		🟫	🟫	🟫				🟩	🟩		🟫		10
Canadian Rockies	i	ii			🟫	🟫	🟫	🟫			🟩				11
Southeast	i	ii		🟫	🟫	🟫	🟫	🟫	🟫	🟫				🟩	12

*i: 1 month, ii: 2-month period, iii: > 2-month period; †i: <= 4-month period, unimodal; ii: > 4-month period, unimodal; iii: bimodal

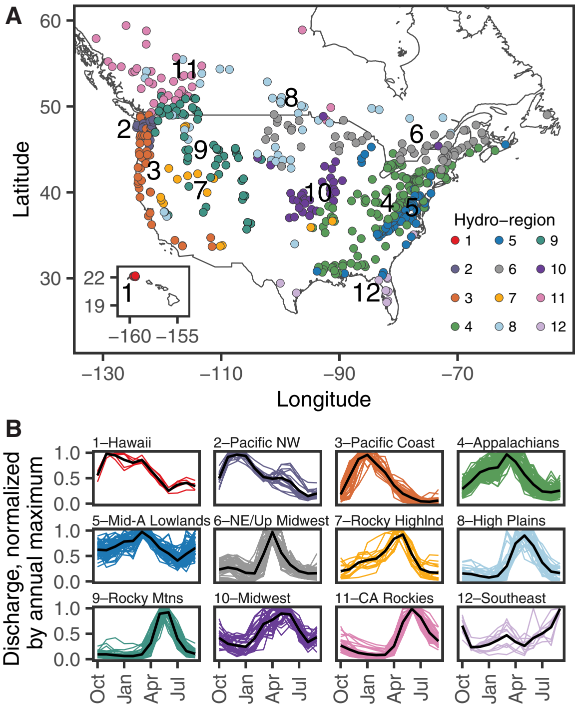

Fig. 1. Monitoring stations at rivers in the United States and Canada are assigned to 12 "hydro-regions" (indicated by color in both panels). (**A**) Location of each monitoring station. (**B**) The average annual flood seasonality for each station is shown in the hydro-region–associated color, with the hydro-region mean shown as a bold black line. Hydro-regions are determined by K-means analysis based on dominant high-flow seasonality, calculated as the average of the monthly peak discharge normalized by the annual peak of the mean daily discharge, as well as elevation, latitude, and longitude (not plotted).

frequency is not sensitive to either the analysis start year or the event magnitude (fig. S4).

Trends toward increasing high-flow events are widespread in the United States and Canada. High-flow events of >5-year recurrence interval magnitude are increasing in 6 of 12 hydro-regions (5 hydro-regions, $P < 0.01$; 1 hydro-region, $P < 0.05$; Fig. 2A), primarily in hydro-regions with at least some snowmelt influence (Fig. 3A). No hydro-region has experienced a statistically significant decrease in high-flow frequency. Hydro-region aggregate analysis is sensitive to changes that are not statistically significant at individual stations, likely because of the rarity of these events. Statistically significant change in the frequency of the 5-year annual high-flow event only occurred at 34 of 327 individual stations (10%; 9% more frequent, 2% less frequent; Fig. 2 and fig. S3).

Changes in extreme low-flow frequency are somewhat more variable. Low-flow events have become more frequent in the Pacific Northwest, Pacific Coast, Rocky Mountain highlands, and Southeast hydro-regions and less frequent in the Appalachians and Midwest hydro-regions. Significant changes occurred both toward increasing frequency of low-flow events within some hydro-regions at the annual scale (Fig. 2B, top) and at 120 individual stations (29%; 17% more frequent, 11% less frequent; fig. S3).

Seasonal analysis of the frequency of extreme high- and low-flow events reveals changes in extreme streamflow frequency not necessarily evident in the annual analysis. Significant changes in the frequency of extreme streamflows have occurred in the past 70 years at either the seasonal or annual scale for most hydro-regions in the United States and Canada (Figs. 2 and 3). In particular, in seasons other than the long-term dominant flood season for hydro-regions in the northern and eastern United States and Canada, seasonal extreme high-flow events have become more frequent and extreme low-flow events less frequent (Figs. 2 and 3). Along the Pacific Coast, where recent drought has been well documented (*26*), seasonal extreme low-flow events have increased in frequency in summer and fall, the dominantly low-flow seasons. In addition, drought in the Southeast United States has led to more frequent seasonal extreme low-flow events, particularly in the spring and summer.

We quantified the magnitude of changes in event frequency as the percent change in the number of events exceeding each recurrence interval threshold occurring in a reference period (1950–1969) and the present period (2007–2016). In instances of statistically significant trends ($P < 0.05$) in extreme event frequency, extreme event frequency of all recurrence interval thresholds increased on average 106% (± 0.4% SE; median = 75% increase; Fig. 4 and fig. S6). Hydro-regions with statistically significant changes for a given season across several event magnitudes had larger and more consistent changes in extreme event frequency (Fig. 4).

Across all event magnitudes and analysis periods, stations located in hydro-regions with significant ($P < 0.05$) changes in the frequency of extreme discharge events generally exhibit changes consistent with the hydro-region in aggregate (Fig. 3 and figs. S3 and S5). For changes in extreme high-flow event frequency, on average, 80% (±9% SE) of stations within a hydro-region were consistent with hydro-region behavior, with 21% (±6% SE) of those changes statistically significant ($P < 0.05$). Changes at stations in hydro-regions with significant changes in extreme low-flow frequency were similarly consistent, with 75% (±11% SE) changing in the same direction and 24% (±9% SE) statistically significant. Very few stations exhibited significant changes in frequency opposite to the hydro-region aggregate change, with only 3% (±% SE) and 1% (±1% SE) statistically significant at high-flow and low-flow hydro-regions, respectively.

DISCUSSION

Our cluster approach provides meaningful categorization of sites with similar flood regimes, allowing for objective evaluation of aggregate trends in the frequency of extreme streamflow events. Several prior studies of changing flood hazard for the United States have found that trends are sporadic, often catchment specific, and thus difficult to generalize regionally (*2*, *9*, *10*, *27*); those trends that have been found are difficult to link to climate indices of changing climate (*8*–*10*). Although we do observe variability both within and among hydro-regions, our classification of rivers into hydrologically similar groups reveals hydro-region coherence, both in the direction of change and lack thereof.

Additional insight is gained by our seasonal approach, which indicates coherent seasonal trends both for several hydro-regions (*9*) and among hydro-regions similar in geography and flood-generating mechanism(s). It is important to note that high-flow and/or low-flow events during typically nonflood seasons may, in some cases, not have the same magnitude as the annual peak flow. In many cases, they, in fact, may be extreme for any season, particularly in hydro-regions with multimodal high-flow and/or low-flow seasonality. Regardless of whether these flows represent the annual peak or low

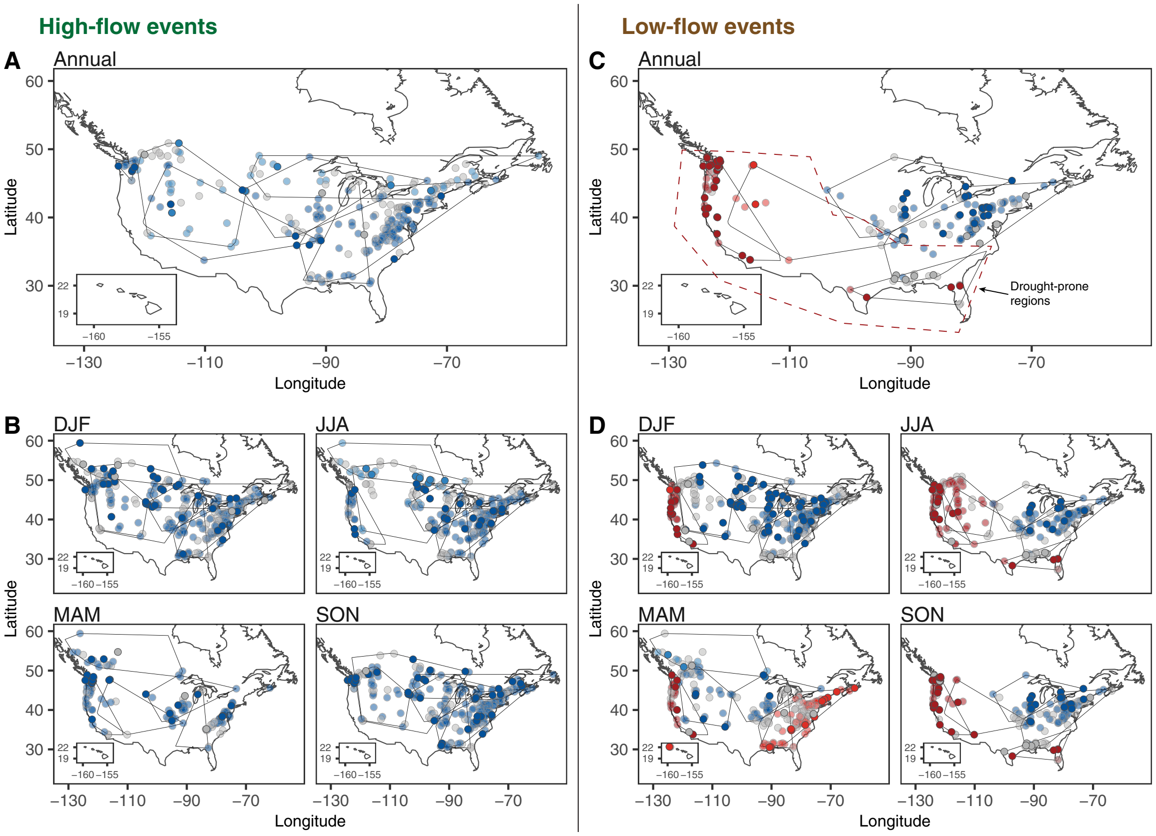

Fig. 2. Stations in hydro-regions with significant annual and/or seasonal trends in extreme high-flow and low-flow event frequency. Extreme flow events are ≥5-year recurrence interval events from 1950 to present. The upper panels (**A** and **C**) show changes to high- and low-flow events on an annual basis. The lower panels (**B** and **D**) show changes on a seasonal basis, as indicated by the season labels (DJF, December, January, and February; MAM, March, April, and May; JJA, June, July, and August; SON, September, October, and November). Blue (red) station icons indicate wetter (drier) conditions; i.e., increase (decrease) in frequency of high-flow events and decrease (increase) in frequency of low-flow events. Gray station icons indicate stations that do not conform to the hydro-region trend. Opaque colors indicate statistical significance ($P < 0.05$). The solid black lines delineate the geographic outer bounds of hydro-regions. The dashed red line in (C) indicates drought-prone regions.

point, however, they may be consequential for setting antecedent conditions that could lead to flood or drought (*28*, *29*) and/or have immediate consequences for important infrastructure, agriculture practices, and ecological sensitivity within each basin.

Snowmelt-dominated regions

Changes in the frequency of extreme streamflows are most common in the Canadian and northern U.S. hydro-regions where the annual peak flow is consistently associated with spring snowmelt runoff (Figs. 2 and 3). Of the six hydro-regions with statistically significant increases in annual high-flow frequency (Pacific Northwest, Appalachians, Mid-Atlantic lowlands, Northeast/Upper Midwest, Rocky Mountain highlands, Rocky Mountains, and Midwest), all but the Mid-Atlantic lowlands have snowmelt influence. However, a statistically significant increase in extreme high-flow frequency in the annual peak flood season has only occurred for three of eight snowmelt-affected hydro-regions: the Pacific Northwest, the Rocky Mountain highlands, and the Midwest. In many instances, the lack of an increase in the annual snowmelt peak flood is consistent with the evidence that we find for coherent early snowpack depletion within hydro-regions in the form of the following: (i) an increase in the frequency of seasonal extreme high-flow events in the season prior to the peak flood season (Canadian Rockies, Pacific Northwest, High Plains, Midwest, Northeast/Upper Midwest, and Appalachians: all but the Rocky Mountain hydro-regions) and/or (ii) a decrease in the frequency of extreme low-flow events in the flood season and/or the season prior (Rocky Mountain lowlands, Canadian Rockies, Northeast/Upper Midwest, and High Plains).

Studies linking changes in the timing of high flows to changing snowmelt and precipitation patterns in the United States provide mechanistic evidence for early snowpack depletion. In the western United States and Canada, various streamflow metrics have shifted earlier by 1 to 4 weeks (*30*, *31*), likely because of warmer alpine temperatures increasing winter-season melt and the percent of precipitation falling as rain (*18*). In the Northeast United States, Collins (*20*) found minimal evidence for shifts in the timing of annual peak flows, but Hodgkins and Dudley (*32*) showed that the centroid of winter-spring streamflow has shifted at 32 to 64% of snowmelt-affected sites in the eastern North America. In the western United States, drought has and is projected to limit snowpack generation and groundwater recharge (*33*–*35*), a pattern reflected in increased frequency of extreme low flows in the Pacific Coast and Pacific Northwest hydro-regions during summer and fall (fig. S3). In each of these distinct hydro-regions, changes to regional hydro-climate in the season before or during the flood season reduce the likelihood of high-magnitude snowmelt streamflows.

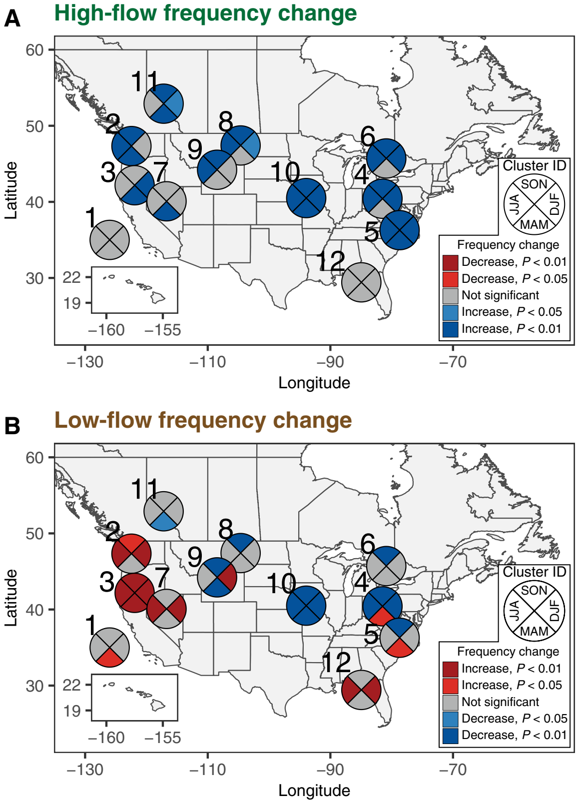

Fig. 3. Aggregate seasonal trends in extreme high-flow and low-flow event frequency for each hydro-region. Trends for high-flow (**A**) and low-flow (**B**) events are determined using the Cox-Lewis statistic. Extreme flow events are ≥5-year recurrence interval events from 1950 to present. Each season occupies a quadrant position. Quadrants colored blue have experienced increasing frequency of high-flow events or decreasing frequency of low-flow events; quadrants colored red have experienced decreasing frequency of high-flow events or increasing frequency of low-flow events (dark red/blue: $P < 0.01$; light red/blue: $P < 0.05$). Quadrants are placed approximately at the hydro-region geographic centroid, although some have been shifted slightly to avoid overlap.

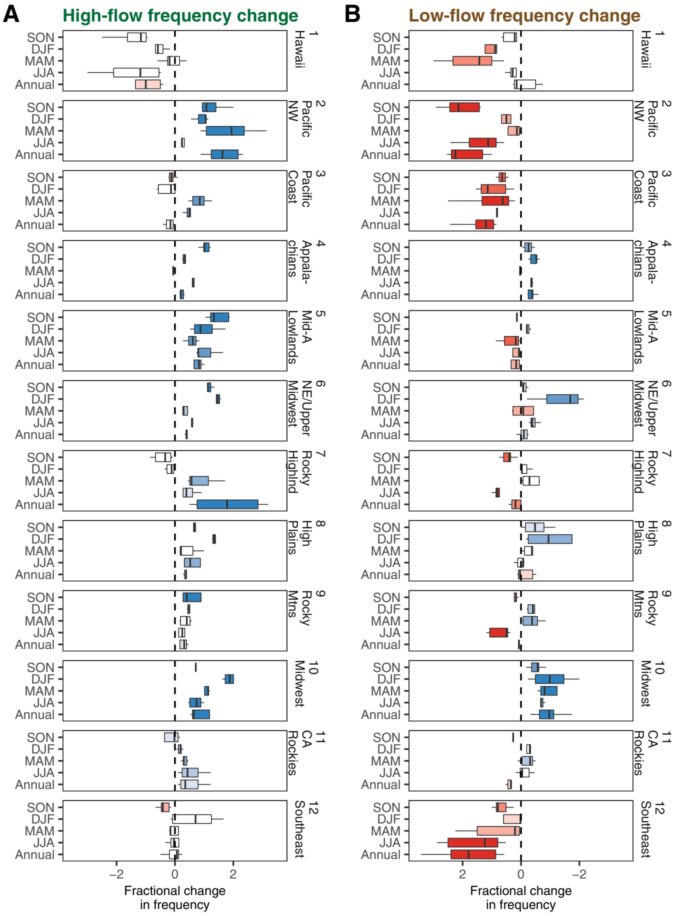

Fig. 4. Fractional changes in the occurrence of high-flow and low-flow events, computed by comparing the past two decades (2007–2016) to a reference period (1950–1969). Boxes indicate the interquartile range of observed frequency changes for that season for different magnitude events [high-flow events (**A**); low-flow events (**B**); recurrence intervals: 2, 3, 5, 10, and 25 years]. Whiskers extend to the range of the observed data excluding outliers. Boxes are colored according to the direction of change (blue, wetter; red, drier) and shaded by the number of recurrence interval categories with statistically significant changes for each season, with dark colors indicating statistical significance across all categories, and white indicating no statistically significant change for any category. CA, Canadian.

This changing hydrology of snowmelt-dominated systems, particularly the depletion of snowpack required for generating high flows, has likely dampened snowmelt contribution to spring flows in snowmelt regions. We nonetheless do not observe any coherent hydro-region decrease in annual high-flow frequency in these regions. Documented increases in extreme precipitation events during the high-flow season (*3*, *36*–*38*) may balance the reduction in snowpack storage (*18*). For regions with observed increase in high-flow events in peak-flow seasons, precipitation increase has likely exceeded snowpack depletion.

In addition, increased extreme high-flow frequency during nonflood seasons has thus contributed to increases in annual-scale high-flow events for several hydro-regions without flood-season increases (Northeast/Upper Midwest, Appalachians, and Rocky Mountains). Pronounced increases in summer and fall precipitation in the Midwestern U.S., Northeast U.S., and Canadian border (*3*, *36*) have coincided with increasing frequency of extreme high-flow streamflow for those seasons in the Northeast/Upper Midwest, Midwest, and Appalachian hydro-regions. When extreme precipitation events occur during typically nonflood seasons, prevailing low soil moisture and high evapotranspiration generally reduces the magnitude of these events relative to their precipitation intensity. However, increases in both average and extreme precipitation during those seasons (*1*, *3*, *36*), coincident with our observations of decreasing frequency of low-flow events, may prime drainage systems for extreme flooding by mimicking antecedent conditions common during the spring snowmelt period (*39*).

Nonsnowmelt-dominated regions

Hydro-regions with limited or no snowmelt influence show more bidirectional changes, with increases in frequency of both high-flow and low-flow events. Increased occurrence of extreme low-flow events is widespread on the U.S. West Coast for all seasons, with >50% increase in the frequency of low-flow events for all seasons and event magnitudes in the Pacific Coast hydro-region. High-flow events have also increased in frequency during the dry seasons on the Pacific Coast of the United States, consistent with forecasts of hydrologic shifts in that region toward more extreme precipitation events and more extended droughts (*5*). Different mechanisms dictate flood generation and timing along a north-south and elevation gradient for the U.S. West Coast. However, coherent behavior among the three west-coast hydro-regions (Pacific Northwest, Pacific Coast, and Rocky Mountain highlands) indicate that larger-scale climatic forcings associated with climate change may be overprinted on these regional differences (*5*, *6*).

The Southeast United States has also experienced variable changes in precipitation, with a >15% increase in fall precipitation and 0 to 15% decrease in summer precipitation (*1*), although the mechanism(s) for changing precipitation patterns remains unclear (*37*). These changes span several hydro-regions on the U.S. East Coast, and other investigators have found that changes in high-flow frequency vary spatially and temporally for that region (*40*).

Varying flood mechanisms and timing have resulted in different responses to changing precipitation along a south-north gradient on the U.S. East Coast (e.g., Fig. 2). Increasing low-flow frequency corresponding to the decrease in spring and summer precipitation has occurred in the Southeast hydro-region but, to a lesser extent, at higher latitudes. Farther north and upslope, increases in annual and seasonal high-flow frequency have occurred in the Mid-Atlantic lowlands and Appalachian hydro-regions, which more closely resemble the Northeast/Upper Midwest hydro-region change toward increasing streamflow.

Differences in high- and low-flow trends

In aggregate, we find that more individual stations have experienced an increase in low-flow frequency than have experienced an increase in high-flow frequency (*9*, *27*). High-streamflow events are generally less spatially coherent on an annual basis; particularly in small catchments, floods may be local to that catchment. However, droughts are generally reflective of large-scale climatic forcing and thus are more likely to be regional and coherent within a hydro-region (e.g., fig. S1). Because of this spatial variability, changes in extreme high-flow frequency may be more difficult to detect using time series from individual stations.

Benefits of the hydro-region approach

The spatially coherent hydro-regions begin to address the analytical challenge presented by river-to-river variability in extreme event timing. Because the extreme events that we describe occur on average only once every 2 to 25 years at a given river, analysis of individual rivers inevitably suffers from lack of statistical power in these short records (<100 years), particularly for the most extreme events. However, when we consider numerous similar rivers in aggregate using the hydro-region approach, we minimize the inherent variability of natural systems and, in many cases, detect a hydro-region–wide signal. In cases of statistically significant change in frequency for a given hydro-region, we do not argue that every river in a region has experienced increasing flood frequency in the past 70 years; natural variability precludes that outcome under almost any realistic scenario. The changes that we show nonetheless indicate an increase in the likelihood of extreme events, consequential for human life, infrastructure, and ecology, for many hydro-regions and in many seasons.

The hydro-region framework is readily transferrable to other studies and provides the basis for urgently needed mechanistic studies of individual stations and of hydro-regions in aggregate. For example, an analysis of stations in the New England region of the United States [U.S. Geological Survey (USGS) Hydrologic Unit Code 1] would suffer because coastal sites are responsive to different runoff-generating mechanisms than those in the interior (*36*). Our clustering approach provides an objective means for separating these rivers into two categories and includes, in the interior category, additional rivers to the north (in eastern Canada) and west (in the Great Lakes and Upper Midwest regions). The resulting analysis indicates that the interior stations, assigned to the Northeast/Upper Midwest hydro-region, are prone to increased extreme winter flooding, while those along the coast (assigned to the Appalachian hydro-region) are less so (Fig. 4). Analysis of just New England stations would not record this hazard as clearly, if at all, with potential management implications. Similarly, the Midwest hydro-region has experienced several multibillion-dollar floods in the past decade (*11*). The hydroclimatological basis for some of these floods has been investigated (*41*), but further attention should be directed toward the comparative sparing of hydro-regions to the north and east, and the possibility that thresholds recently exceeded in the Midwest may be of future concern in the High Plains or the Appalachians hydro-regions. Further detailed inquiry of varying flood mechanisms can be defensibly targeted on the basis of hydro-region distinctions.

Decisions regarding extreme river high- and low-flow events have billion-dollar consequences. To better plan for mitigation and/or adaptation to a changing hydroclimate (*1*), it is important to improve our incomplete understanding of river flood and drought generation. Our approach identifies systems currently undergoing change and the magnitude of that change. Developed to address challenges due to the complexity of these systems and changes, the hydro-region framework provides the means for sensible, aggregate analysis and seasonal consideration needed to accurately project future flood and drought risk in the United States and Canada.

MATERIALS AND METHODS

All source code used to access discharge data and conduct the described analyses can be accessed at https://github.com/evandethier/hydrology-trends. We analyzed all stations in the United States (USGS) and Canada [Water Survey of Canada (WSC)] with continuous records of daily discharge measurements from 1960 to present and minimally affected by anthropogenic activity as established by the USGS Hydro-climatic Data Network (HCDN) or the designation of "unregulated" by the WSC. We eliminated stations with more than 1 year of consecutive missing observations. The resulting dataset included 389 stations in the United States and 125 in Canada (USGS/HCDN and WSC) (*24*). Because the records most consistently report mean daily discharge, we use that metric in this analysis, referring to it simply as "discharge."

We grouped rivers with similar hydrologic and geographic characteristics using automated *k*-means clustering to define 15 clusters using 15 input variables: 12 normalized monthly high flows, latitude and longitude, and mean watershed elevation. *k*-Means clustering iteratively minimizes within-group variance for a predetermined number of categories. Although the number of cluster groups is chosen by the user, and the resulting groups are sensitive to outliers, *k*-means has the advantage of a straightforward premise and easy application to individuals not included in the initial clustering, which allows other researchers to use these methods and additional watersheds not included in this analysis to be analyzed using this hydro-region framework. To compare across watersheds of different areas and with differing total precipitation, we normalized monthly high flow for each month in the dataset using the ratio of the average monthly peak discharge to the average annual peak discharge. For each hydro-region, we used a Tukey honest significant difference (*42*) mean comparison for all the normalized monthly high flows to determine statistically distinct high- and low-flow months, referred to as high-flow months and low-flow months, respectively ($P < 0.05$; fig. S2). In some cases, a single month was statistically distinct from all other months, reflecting consistency in high- or low-flow timing. In other cases, statistically indistinguishable high flows occurred in multiple months. In this case, all months with statistically indistinguishable high flow were considered high-flow months. To generalize this timing, we categorized hydro-regions as one of three types based on the number of high-flow months: (i) for a single month peak, (ii) for a two-month peak, and (iii) for a greater than two-month period. Similarly, hydro-regions were categorized on the basis of the characteristics of the low-flow period: (i) for unimodal low-flow periods less than 5 months, (ii) for unimodal low-flow periods of 5 months or more, and (iii) for a bimodal low-flow periods.

Watershed extent was computed for each gaging station using elevation data from the Shuttle Radar Topography Mission digital elevation dataset, and mean watershed elevation was computed (*43*). We removed 27 stations from the initial dataset of 541 stations (5.0%) that did not have good agreement with their assigned hydro-region, defined as a K-means normalized Euclidean distance from the centroid of >8, and did not analyze the three clusters with two or fewer stations.

For each station and each hydro-region in aggregate, we used the Cox-Lewis statistic (*21*, *22*) to test for significant changes in the occurrence rate of high- and low-flow events. The Cox-Lewis statistic calculates a Z-score for selected events in a time series, defined as

$$Z = \frac{\frac{1}{n}\Sigma_i^n t - t_\mathrm{m}}{\frac{t_\mathrm{l}}{\sqrt{12n}}}$$

where event years, t, are defined as years with discharge greater (high flow) or less than (low flow) the 25-, 10-, 5-, 3-, and 2-year recurrence interval events for either the entire record (annual analysis) or a given season for the entire record (seasonal analysis); n is the number of events in the analysis; t_m is the midpoint year of the time series (e.g., 1989 for a start year of 1960), and t_l is the length of the discharge record in years.

We evaluated the sensitivity of our results to the analysis period, calculating the Cox-Lewis statistic for six periods at each station (start years: 1910, 1920, 1930, 1940, 1950, and 1960; end years: 2018 for hydro-regions with only USG stations and 2016 for hydro-regions with USGS and WSC stations or only WSC stations). To mitigate the effects of system memory, we calculated recurrence interval thresholds and selected the n extreme high-flow events exceeding those thresholds from discharge time series including only observations from the period of record, modified to remove all but the maximum discharge in a 7-day centered moving window (*36*). We define this set of events as the extreme high-flow events. Similarly, we defined the recurrence interval thresholds and the n extreme low-flow events as the flow events falling below those thresholds from a list of the lowest-discharge events for each water year in the analysis record. For seasonal analyses, events were selected from discharge time series only including events from the season in question and thus are the peak and lowest n events from each season for high- and low-flow analyses, respectively. Only stations with records beginning before the selected start year were included in that analysis. Some hydro-regions did not have any stations operational in 1910 or 1920. For each recurrence interval threshold, the Cox-Lewis statistic was analyzed with a null hypothesis of constant event occurrence rate during the analysis period and an alternative hypothesis of a monotonic trend toward increasing or decreasing occurrence (two-tailed Z test).

To identify the changing frequency of events of a given magnitude, we compared event occurrence at each hydro-region during a reference period (1950–1969), by which time most discharge stations were operational (fig. S7), and the current period (2007–2016). In addition, we estimated time-varying occurrence rates using a nonparametric Gaussian kernel methodology (*21*). We used 2000 bootstrap simulations to develop 90% confidence intervals (*22*).

SUPPLEMENTARY MATERIALS

Supplementary material for this article is available at http://advances.sciencemag.org/cgi/content/full/6/49/eaba5939/DC1

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