AGU PUBLICATIONS

Geophysical Research Letters

RESEARCH LETTER

10.1002/2014GL061980

Key Points:

- Temporal patterns in streamflow metrics indicate strong spatial coherence
- Streamflow metrics covary seasonally
- Streamflow is mostly unpredictable in terms of relations to climate indices

Supporting Information:

- Readme
- Figure S1
- Figure S2
- Figure S3
- Table S1

Correspondence to:
G. J. McCabe,
gmccabe@usgs.gov

Citation:
McCabe, G. J., and D. M. Wolock (2014), Spatial and temporal patterns in conterminous United States streamflow characteristics, *Geophys. Res. Lett.*, *41*, 6889–6897, doi:10.1002/2014GL061980.

Received 23 SEP 2014
Accepted 25 SEP 2014
Accepted article online 27 SEP 2014
Published online 13 OCT 2014

Spatial and temporal patterns in conterminous United States streamflow characteristics

Gregory J. McCabe[1] **and David M. Wolock**[2]

[1]U.S. Geological Survey, Denver, Colorado, USA, [2]U.S. Geological Survey, Lawrence, Kansas, USA

Abstract Spatial and temporal patterns in annual and seasonal minimum, mean, and maximum daily streamflow values were examined for a set of 516 reference stream gauges located throughout the conterminous United States for the period 1951–2009. Cluster analysis was used to classify the stream gauges into 14 groups based on similarity in their temporal patterns of streamflow. The results indicated that the temporal patterns in flow metrics (1) have strong spatial coherence within each region, (2) are similar among the three annual flow metrics and the four seasonal flow metrics within each region, (3) indicate some small magnitude trends over time, and (4) are only weakly associated with well-known climate indices. We conclude that most of the temporal variability in flow is unpredictable in terms of relations to climate indices and infer that, for the most part, future changes in flow characteristics cannot be predicted by these indices.

1. Introduction

Global warming is expected to result in substantial changes in streamflow (e.g., increases in extreme hydrologic events) and affect the management of water supplies [*Intergovernmental Panel on Climate Change*, 2014]. Increases in temperatures in the conterminous U.S. have been associated with increases in potential evaporation [*Intergovernmental Panel on Climate Change*, 2014; *McCabe and Wolock*, 2014; *Scheff and Frierson*, 2014], decreases in snowpack accumulations [*Hamlet et al*., 2005; *Knowles et al*., 2006; *Mote*, 2003; *McCabe and Wolock*, 2009], changes in the timing of runoff [*Hodgkins et al*., 2003; *Stewart et al*., 2004; *McCabe and Clark*, 2005; *Hodgkins and Dudley*, 2006], and decreases in the proportion of winter precipitation that falls as snow [*Huntington et al*., 2004; *Knowles et al*., 2006; *McCabe et al*., 2007; *McCabe and Wolock*, 2009].

Because of concern that global warming might alter the magnitude and timing of streamflow and water supplies, there have been numerous studies of historical patterns in streamflow in the conterminous U.S. [*Peterson et al*., 2013]. *Lettenmaier et al*. [1994] examined trends in annual and monthly streamflow across the conterminous U.S. and found positive trends for many of the streams analyzed. Similarly, *Lins and Slack* [1999] analyzed streamflow in the conterminous U.S. and found statistically significant positive trends for mostly low and moderate streamflows; they found positive trends only in high streamflows for a few sites. In another study, *Douglas et al*. [2000] also detected trends in low flows, but not in high flows (i.e., floods). In contrast, *Groisman et al*. [2001] reported increases in high streamflow in the conterminous U.S., particularly in the eastern U.S. The results of *Groisman et al*. [2001] apparently contradicted those from *Lins and Slack* [1999] and *Douglas et al*. [2000]. *Small et al*. [2006] suggest that precipitation in the conterminous U.S. increased for many locations during the fall season, but not during the spring season when high streamflows occur for many locations. Thus, the increase in precipitation during the fall season results in increases in low flows, whereas the absence of widespread increases in precipitation during the spring season likely explains the lack of trends in high flows.

In order to further explore historical patterns in streamflow, *McCabe and Wolock* [2002] examined variability in annual minimum, median, and maximum streamflows for 400 stream gauges in the conterminous U.S. *McCabe and Wolock* [2002] found noticeable increases in annual minimum and median daily streamflow for the period 1941–1999, and a less significant mixed pattern of increases and decreases in annual maximum daily streamflow. *McCabe and Wolock* [2002] also noted that most of the observed changes occurred in the eastern U.S. and that the changes in streamflow appeared to occur as a step change around 1970, rather than as a gradual trend, implying that a hydroclimatic regime shift had likely occurred.

Hirsch and Ryberg [2012] examined statistical relations between floods at 200 long-term (85–127 years of record) stream gauges in the conterminous U.S. and the global mean carbon dioxide concentration (GMCO2).

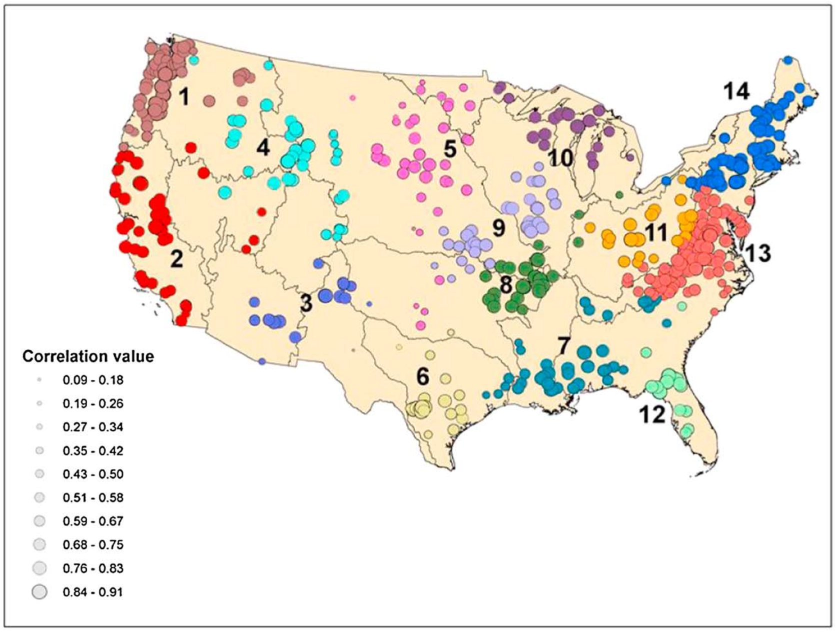

Figure 1. Clusters of United States Geological Survey stream gauges determined using the temporal variability of annual flow. The size of the symbols indicates the relative size of the correlations of annual flow at a site with the mean annual flow for the cluster. The lines indicate the boundaries of the 18 United States Geological Survey water resources boundaries in the conterminous United States.

The stream gauge locations were limited to those with drainage basins thought to contain minimal anthropogenic influences (e.g., dams, diversions, and urban development). Their results indicated that there was little evidence that flood magnitudes were increasing with increasing GMCO2. An unexpected result from the *Hirsch and Ryberg* [2012] study was that for the southwestern U.S., time series of flood magnitudes showed a statistically significant negative relation with GMCO2.

Recently, *Sagarika et al*. [2014] examined variability and trends in seasonal and water year (October through September) streamflow for 240 stream gauges considered to be minimally impaired by human influences in the conterminous U.S. for the years 1951–2010. *Sagarika et al*. [2014] reported positive trends in streamflow for many sites in the eastern U.S., and negative trends in streamflow for sites in the Pacific Northwest. The positive trends in streamflow for sites in the eastern U.S. are consistent with results reported by *McCabe and Wolock* [2002].

Even though there have been a number of previous studies of trends and variability in conterminous U.S. streamflow, there are still questions that remain unanswered including the following: Is the variability detected in streamflow records dependent on season or the streamflow statistic examined (e.g., minimum flows, mean flows, and maximum flows)? Has the apparent step change in runoff around 1970 for the eastern U.S. continued? Can the variability in streamflow in the U.S. be explained by atmospheric pressure/circulation or sea surface temperature (SST) variability? The objectives of this study are to answer these questions.

2. Data and Methods

Daily streamflow data from the U.S. Geological Survey National Water Information System (http://waterdata.usgs.gov/nwis/dv/?referred_module=sw) for 516 stream gauges in the conterminous U.S. were used in this study (Figure 1). The 516 sites were selected from a set of river basins that are expected to have minimal anthropogenic influences [*Falcone et al*., 2010]. To be selected, a stream gauge site needed to have complete daily flow data for at least 80% of the years for the period 1951–2009. These data were used to compute the minimum, mean, and maximum flow value for each site and for each meteorological season (i.e., December through February (DJF), March through May (MAM), June through August (JJA), and September through November (SON)). The number of sites that met the selection criteria was 358 sites (~70% of the 516 sites) in 1951. The number of sites meeting the selection criteria increased to 463 sites in 1961 (~90% of the 516 sites) and did not drop below 90% for the remainder of the years analyzed (1962–2009). These results indicate that there was good representation of streamflow sites across the U.S. for the period analyzed and that no regional biases would be expected.

Before analysis, the time series of seasonal minimum, mean, and maximum streamflow statistics were converted to Z scores so that differences in the absolute magnitudes of values across space would not influence the results and, thereby, places the focus of the analyses on temporal variability. The streamflow statistics for each site were converted to Z scores for each season separately. By converting the data to Z scores for each season separately, we also removed the effects of differences in the seasonality of streamflow.

The Z scores were computed using the equation

$$Z_i = \frac{\left(Q_i - \overline{Q}\right)}{Q_{\text{std}}} \tag{1}$$

where Z_i is the Z score for year i, Q_i is the streamflow for year i, $\overline{Q}$ is the long-term (1951–2009) mean Q, and Q_{std} is the long-term standard deviation of Q.

A data reduction technique was developed to group sites into clusters of similar temporal variability; this hierarchical clustering process enabled more straightforward depiction of spatial and temporal patterns during the period of analysis. The clustering process is based on Pearson correlations of time series of seasonal mean streamflow at each site. The process begins by correlating the time series at each site with time series at all the other sites. The site that is correlated with the most other sites, above a specified correlation coefficient value threshold ($r = 0.5$), then is removed from the original set of sites along with all of the sites that are correlated with the selected site above the specified correlation coefficient value threshold; this group comprises the first initial cluster. Subsequently, of the remaining sites, the site with a time series that is correlated above the specified threshold with time series for the most remaining sites is removed along with all of the sites that are correlated with it; this group is the second cluster. The analysis step is repeated until there are no correlated sites within the pool of remaining sites. If a site was not correlated with any other site with a correlation of 0.5 or larger, then the site was unassigned to a cluster. After assigning as many sites as possible to clusters, 14 clusters were identified with at least 10 sites in each cluster. This process resulted in a total of 403 (78%) of the 516 sites being assigned to 14 clusters.

During this type of hierarchical clustering process, a site can be clustered within a group when it actually fits better within another cluster. Therefore, to provide the most appropriate assignment of sites to each cluster, a second screening was performed. After identifying the sites that were assigned to each of the 14 clusters from the original clustering process, the time series of the sites in each cluster were averaged to produce an average time series of seasonal mean flow for each cluster. These cluster-average time series of seasonal mean flow then were correlated with the time series of seasonal mean flow for the original 516 sites, and each of the 516 sites was assigned to a cluster based on the highest correlation with the average time series for each of the 14 clusters. Only 25 sites assigned to a cluster in the initial clustering process were reassigned to a different cluster during the second clustering process. After this additional step, all 516 sites are assigned to one of the 14 clusters (even if a site was not initially assigned to a cluster). After the final clustering, cluster-average time series of seasonal mean flow were recomputed. For simplicity, the cluster assignments developed using the mean flow time series were subsequently used to compute cluster averages of minimum and maximum flows.

Figure 1 shows the cluster assignments for the 516 sites. The clusters are geographically coherent and indicate a correspondence to different climatic and physiographic regions across the conterminous U.S. The correlations between the time series of seasonal mean flow for each site with the respective average cluster time series typically ranged from 0.65 to 0.80 (i.e., the middle 50% of the distribution of all correlations) with a median value around 0.74. The median correlations for each cluster ranged from 0.59 (cluster 5) to 0.79 (cluster 12). The lowest single correlation value overall was for cluster 4 ($r = 0.10$), and the highest single correlation value overall was for cluster 6 ($r = 0.91$).

The clusters of sites with similar temporal variability provide a means to examine regional variability in streamflow. The geographic distributions of sites for each cluster (Figure 1) indicate that temporal variability in streamflow does not correspond well to drainage basin boundaries, such as the boundaries of the 18 water resources regions in the conterminous U.S. (Figure 1). Thus, watershed boundaries, such as water resources

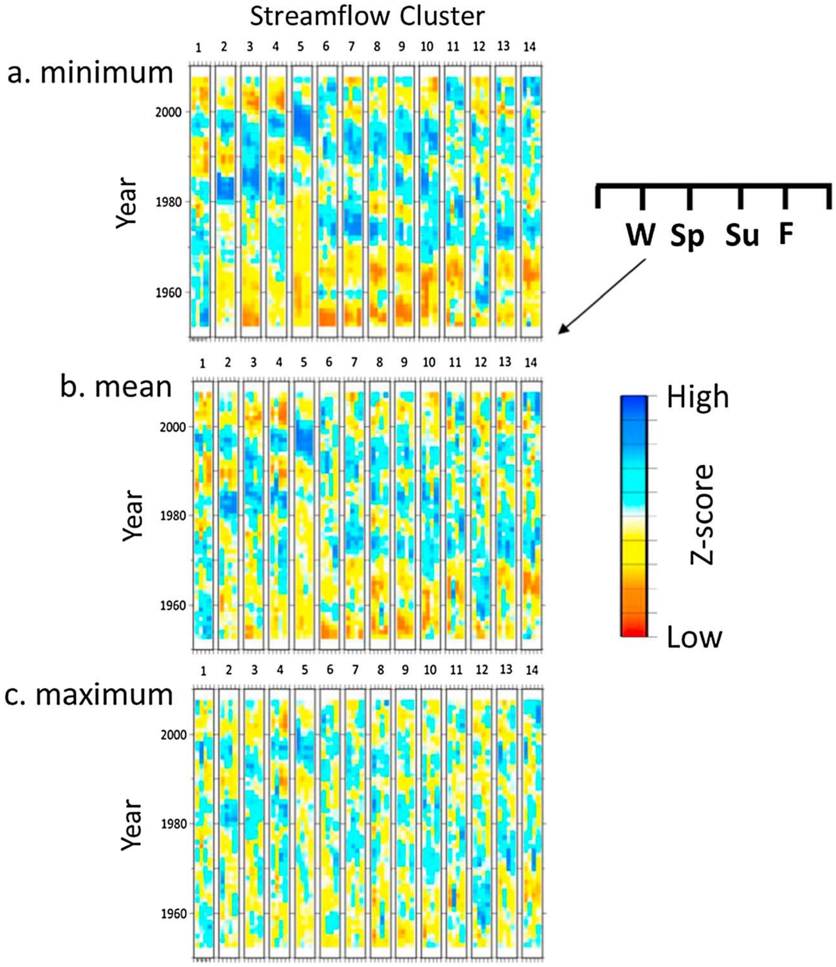

Figure 2. Departures of mean seasonal minimum, mean, and maximum streamflow for 14 clusters of stream gauges. For each cluster, the seasons from left to right are as follows: winter (W), spring (Sp), summer (Su), and fall (F).

regions, are not useful for segregating streamflow sites for an analysis of streamflow temporal variability. In contrast, the clusters of sites based on common temporal variability in streamflow are based on a data-driven method and provide a more robust classification of sites for analyses of regional streamflow variability.

3. Results and Discussion

Comparisons of the time series of seasonal Z scores for minimum, mean, and maximum streamflow for the 14 clusters indicate that all three of the flow statistics have similar temporal variability (Figure 2). Most (68%) of the correlations between seasonal mean flows and seasonal minimum flows are greater than 0.7 (84% of the correlations were greater than or equal to 0.6), and all of the correlations between seasonal mean flows and seasonal maximum flows are all greater than 0.7. Thus, when mean flows are lower (higher) than average, the minimum and maximum flows also, in general, are lower (higher) than average. Additionally, the flow anomalies (Z scores) for each season within each cluster were highly correlated with annual mean flow. When annual mean flow is lower (higher) than average, winter (DJF), spring (MAM), summer (JJA), and fall (SON) flows also tend to be lower (higher) than average (Figure 2). The correlation coefficient values between the annual mean flow and seasonal mean flows ranged from 0.16 to 0.99, with a median value of 0.67 (with all, but one, correlation being statistically significant at a 95% confidence level ($p < 0.05$)). Because of the mostly high correlations among flow statistics and between annual mean flow and seasonal flow, the remainder of the study is based on the temporal variability of annual mean flows for each cluster.

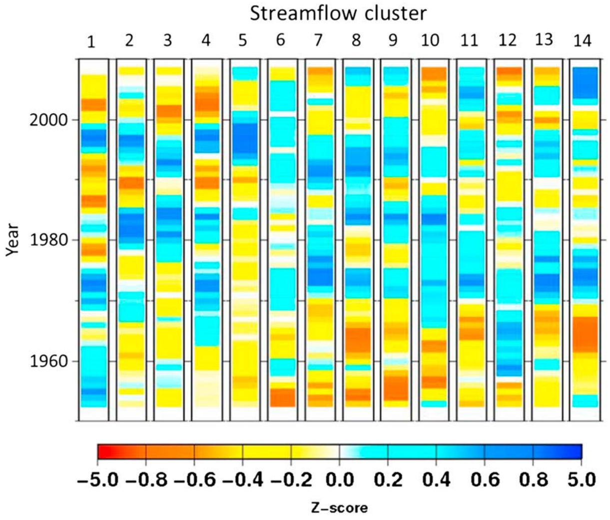

Figure 3. Five year moving average mean annual flow for 14 stream gauge clusters in the conterminous United States.

The time series of Z scores for the cluster annual mean streamflow were smoothed with a 5 year moving average to remove some of the high-frequency noise in each time series (Figure 3). Notable features in these time series are a number of extended wet and dry periods (Figure 3). Some clusters (e.g., clusters 6 through 11, 13, and 14) show a general increase in streamflow during the analysis period but do not show clear long-term monotonic trends. Nevertheless, Kendall's tau values (nonparametric trend statistics [*Press et al.*, 1986]) were computed for each cluster time series (the unsmoothed time series), and the results indicated two clusters (8 and 9) with statistically significant tau values at $p < 0.05$ and three clusters (1, 5, and 11) with statistically significant tau values at $p < 0.10$. The Kendall's tau value at one of the clusters (cluster 1) was negative, while the remaining tau values (clusters 5, 8, 9, and 11) were positive. All of the clusters indicating increases in mean annual streamflow are in the Mississippi River basin, whereas the cluster with a negative Kendall's tau is in the northwestern U.S. A similar geographic pattern also was reported by *Sagarika et al*. [2014]. It should be noted that a statistically significant tau value does not necessarily indicate a monotonic trend in the tested variable. A step change in a time series also can result in a statistically significant trend.

A number of clusters indicate an abrupt increase in streamflow about 1970 (clusters 6, 7, 8, 9, 11, 13, and 14). Additionally, these seven clusters are all located in the eastern U.S. These results are consistent with the findings presented by *Sagarika et al*. [2014] and with *McCabe and Wolock* [2002] who reported a step-like increase in annual minimum and median streamflow for sites in the eastern U.S. during the 1941–1999 period. However, the longer streamflow time series used in the current analyses indicate that the step increase to higher flow about 1970 in the eastern U.S. may have shifted to a regime of lower streamflow after about 2000 (see time series for clusters 7, 8, 9, and 13 in Figure 3).

The variability of streamflow for cluster 5 shows a prolonged period of mostly negative departures, except for a very wet period during the 1990s. This period of high positive departures is related to anomalously high precipitation in the north central U.S. This precipitation change resulted in a dramatic rise in levels of Devils Lake in North Dakota [*Hoerling et al*., 2010].

Overall, the time series of flow values indicate nearly random variability with periods of persistence. The flows vary within a range for a number of years and then shift to a different regime for a period of time before shifting again.

3.1. Climate Indices

It is important to understand the climatic driving forces of water supply variability to improve water management and seasonal water supply forecasts. Previous research includes numerous analyses that show relations between the variability of the hydroclimate of the conterminous U.S. (e.g., precipitation and streamflow) and indices of sea surface temperature (SST) variability and indices of atmospheric pressure variability [*Namias and Cayan*, 1984; *Ropelewski and Halpert*, 1986; *Redmond and Koch*, 1991; *Cayan et al*., 1999; *Sutton and Hodson*, 2003; *Leathers and Palecki*, 1992; *Hurrell*, 1995; *Tootle and Piechota*, 2006].

Sea surface temperature (SST) and atmospheric pressure indices used in this study include NINO3.4 SSTs (SSTs averaged for the region 5° (S) south latitude to 5° (N) north latitude and 170° (W) west longitude to 120° (W) west longitude; these SSTs are an index of the variability of the El Niño–Southern Oscillation (ENSO) [*Trenberth*, 1997]), the Pacific Decadal Oscillation (PDO), the Atlantic Multidecadal Oscillation (AMO), the Pacific North

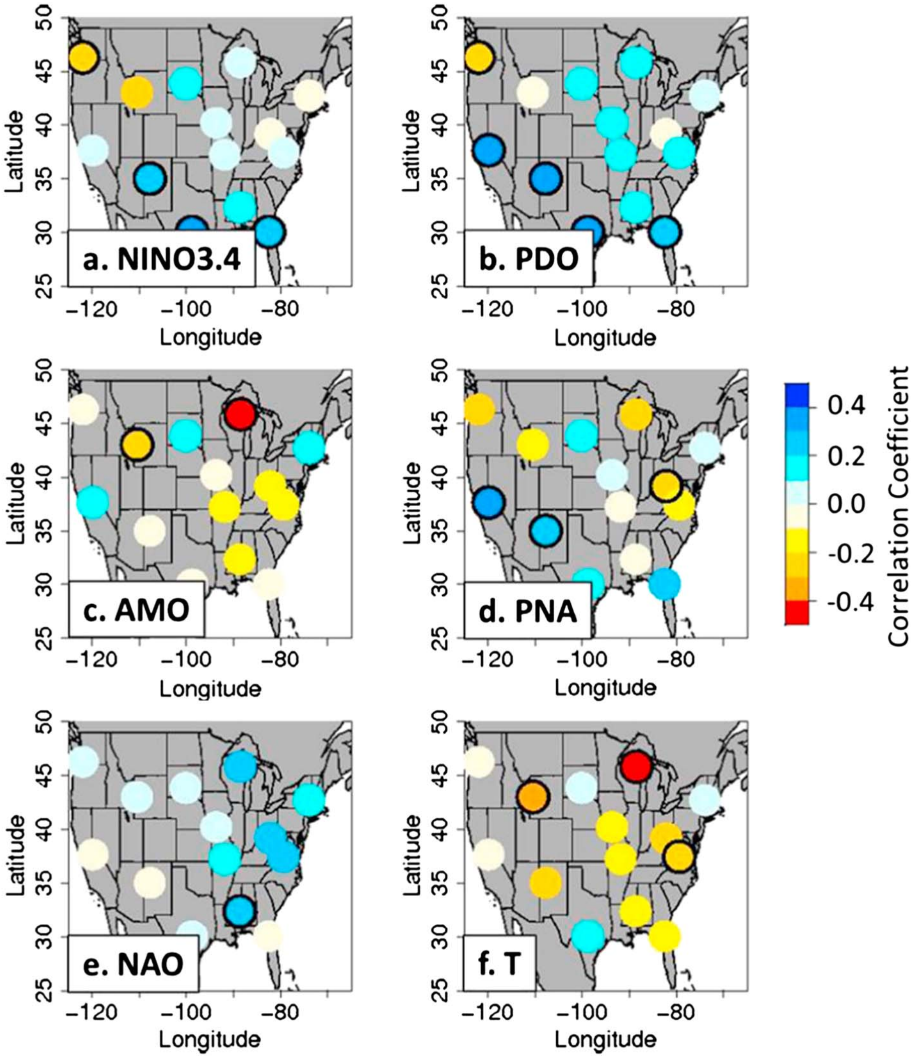

Figure 4. Correlations between mean cluster annual streamflow and annual climate indices. The color of the circle indicates the relative magnitude of the correlation, and the circles outlined in black are statistically significant at a 95% confidence level. (NINO3.4: NINO3.4 sea surface temperatures, PDO: Pacific Decadal Oscillation, AMO: Atlantic Multidecadal Oscillation, PNA: Pacific North American Index, NAO: North Atlantic Oscillation, and *T*: mean conterminous United States temperature.)

American (PNA) Index, and the North Atlantic Oscillation (NAO). Because of widespread scientific interest in global warming, we also included mean annual U.S. temperature (*T*) as one of the climate indices used in the analyses.

3.2. Streamflow Correlations With Climate Indices

Correlations between cluster average flow and NINO3.4 SSTs and PDO indicate negative correlations in the northwestern U.S. and positive correlations across the southern U.S. (Figures 4a and 4b). This pattern of correlations reflects the dipole effects of ENSO (and PDO) on precipitation (and streamflow) in the western U.S. [*Redmond and Koch*, 1991]. During El Niño conditions (also positive PDO), precipitation and streamflow are generally below average in the northwestern U.S. (e.g., cluster 1) and above average in the southwestern U.S. (e.g., cluster 3). During La Niña conditions (and negative PDO), the opposite precipitation and streamflow departures generally occur. The correlations appear to be slightly stronger and more significant for PDO than for NINO3.4 SSTs (Figure 4b).

The correlations for AMO indicate weak and mostly negative correlations for the majority of the 14 clusters (Figure 4c). The most negative and most significant correlations are for the Great Lakes region and the central

Rocky Mountains. The negative correlations between AMO and flow for most clusters indicate that when the AMO is positive (warm North Atlantic Ocean) streamflow for most of the U.S. is below average. This result is consistent with previous research [*McCabe et al.*, 2004; *Sutton and Hodson*, 2003].

PNA correlations with flow for the 14 clusters generally indicate negative correlations across the northern U.S. and positive correlations across the southern U.S. (Figure 4d). The pattern of correlations of PNA with flow for the 14 clusters has some similarities with the pattern of correlations for NINO3.4. The similarity in correlation patterns for PNA and NINO3.4 occurs because when NINO3.4 SSTs are warmer (cooler) than average, PNA is generally in a positive (negative) phase. The correlation between annual NINO3.4 SSTs and annual PNA is 0.45 ($p < 0.01$).

Correlations between NAO and annual average flow are strongest in the eastern U.S. and comprise the only statistically significant correlation in the southeastern U.S. (Figure 4e). When the NAO is positive, there is an increased frequency of storms and attendant precipitation across the eastern U.S., thus resulting in increased runoff [*Hurrell*, 1995; *Greatbatch*, 2000].

The spatial pattern of correlations between temperature and flow (Figure 4f) is similar to the pattern of correlations between AMO and flow (Figure 4c). The correlations with temperature suggest that when temperature is above average, flow generally is below average. The negative correlations between temperature and flow likely result, in part, because of the positive correlation between temperature and AMO ($r = 0.59$, $p < 0.01$). When AMO is positive, temperature is generally above average and precipitation is generally below average across much of the conterminous U.S., resulting in below average flow [*Sutton and Hodson*, 2003; *McCabe et al.*, 2004].

Because previous research has indicated potential lagged relations between climate indices and the hydroclimate of the conterminous U.S. [*Redmond and Koch*, 1991; *McCabe and Dettinger*, 2002; *Ge and Gong*, 2009], an analysis of 1 year and 2 year lagged correlations between flow and the climate indices was performed. For most of the climate indices the 1 year lagged correlations with flow were less statistically significant than the nonlagged correlations, except for AMO and NAO. For AMO and NAO, the 1 year lagged correlations appear to be more statistically significant than the respective nonlagged correlations. These results suggest that there may be modest ability to predict flows for some regions of the country using AMO and NAO. Overall, however, the results for both lagged and nonlagged correlations indicate only weak relations between the climate indices and flow variability (see supporting information for more details). Similarly, *McCabe and Wolock* [2014], in a study of the covariability between global SSTs and annual runoff for the conterminous U.S., found that the amount of variability in runoff explained by SSTs was small.

To quantify the amount of variability in streamflow explained by the climate indices, we regressed streamflow for each cluster (the dependent variable) against the climate indices (the independent variables). The explained variance in streamflow from these regressions ranged from 7% to 31%, with a median value of 16%. These results indicate that only a small fraction of the total variability in streamflow is explained by the climate indices. To investigate whether variability in streamflow for individual sites (rather than cluster averages) would be better explained by the climate indices, we performed the regressions for each of the 516 sites. The explained variance in streamflow for all 516 sites ranged from 2% to 47% with a median value of 15%. These results are comparable to the analyses performed using the cluster-averaged streamflow time series. Analyses using 1 year and 2 year lagged climate indices also did not result in an overall increase in the explained variance of streamflow (see supporting information for more details).

Since the well-known climate indices we used in our analyses did not explain much of the variability in streamflow, we performed additional analyses to determine if other regions of SSTs or atmospheric pressures were more strongly related to streamflow variability than the climate indices that we used. Correlations were computed between time series of cluster-averaged streamflow with (1) global gridded annual mean SSTs (obtained from the Kaplan SST V2 data provided by the NOAA/Oceanic and Atmospheric Research/Earth System Research Laboratory Physical Sciences Division, Boulder, Colorado, USA, from their Web site at http://www.esrl.noaa.gov/psd/ Kaplan data set) and (2) global gridded annual mean 500 hPa atmospheric pressure heights (obtained from the Twentieth Century Reanalysis data provided by the National and Oceanic Administration at http://www.esrl.noaa.gov/psd/data/gridded/data.20thC_ReanV2.html). The results (see supporting information) did not indicate any regions of SSTs or 500 hPa heights that were substantially better correlated to the cluster-averaged streamflow variability than were the climate indices that we used.

4. Conclusion

Time series of seasonal minimum, mean, and maximum streamflow values for 516 reference stream gauges in the conterminous U.S. measured for the period 1951–2009 are analyzed to understand the variability of streamflow in the U.S. Results indicate that for the most part, seasonal values of streamflow are highly covariant. Additionally, streamflow statistics (i.e., minimum, mean, and maximum streamflow values) covary. Analyses of the annual mean streamflow time series for the 14 streamflow clusters indicated periods of extended wet and dry periods but did not indicate any strong monotonic trends. Thus, the mean cluster streamflow time series indicate nearly random variability with some periods of persistence. Also, the circa 1970 increase in streamflow reported by *McCabe and Wolock* [2002] for the eastern U.S. did not continue beyond about 2000. Comparing time series of climate indices (i.e., ENSO, PDO, PNA, AMO, NAO, and temperature) with the time series of mean flow for the 14 clusters indicates weak correlations that are statistically significant for only a few clusters. These results indicate that most of the temporal variability in streamflow in the conterminous U.S. is unpredictable in terms of relations to well-known climate indices.

Acknowledgments
The streamflow data were obtained from the U.S. Geological Survey National Water Information System at http://waterdata.usgs.gov/nwis/dv/?referred_module=sw. The NINO3.4 SSTs and AMO were computed from the Kaplan extended data set of monthly SSTs [*Kaplan et al.*, 1998] (http://www.esrl.noaa.gov/psd/data/gridded/data.kaplan_sst.html). NINO3.4 SSTs were computed as the average of SSTs for the region 5°S to 5°N latitude and from 170°W longitude to 120°W longitude and AMO was computed as the average of SSTs for the region 0°N to 70°N latitude and from 60°W to 10°W longitude. Monthly PDO data were downloaded from http://jisao.washington.edu/pdo/PDO.latest, and monthly PNA data were downloaded from http://www.cpc.ncep.noaa.gov/products/precip/CWlink/pna/norm.pna.monthly.b5001.current.ascii. Monthly NAO data were obtained from ftp://ftp.cpc.ncep.noaa.gov/wd52dg/data/indices/nao_index.tim. The monthly NINO3.4, AMO, PDO, PNA, and NAO data were used to compute annual averages of these data time series. Annual temperature anomalies for the conterminous U.S. were obtained from http://data.giss.nasa.gov/gistemp/graphs_v3/Fig.D.txt.

M. Bayani Cardenas thanks William Asquith and one anonymous reviewer for their assistance in evaluating this paper.

References

Cayan, D. R., K. T. Redmond, and L. G. Riddle (1999), ENSO and hydrologic extremes in the western United States, *J. Clim.*, *12*, 2881–2893.

Douglas, E. M., R. M. Vogel, and C. N. Kroll (2000), Trends in floods in the United States: Impact of spatial correlation, *J. Hydrol.*, *240*, 90–105.

Falcone, J. A., D. M. Carlisle, D. M. Wolock, and M. R. Meador (2010), GAGES: A stream gage database for evaluating natural and altered flow conditions in the conterminous United States, *Ecology*, *91*, 621.

Ge, Y., and G. Gong (2009), North American snow depth and climate teleconnection patterns, *J. Clim.*, *22*, 217–233, doi:10.1175/2008JCLI2124.1.

Greatbatch, R. J. (2000), The North Atlantic Oscillation, *Stoch. Environ. Res. Risk Assess.*, *14*, 213–242.

Groisman, P. Y., R. W. Knight, and T. R. Karl (2001), Heavy precipitation and high streamflow in the contiguous United States: Trends in the 20th century, *Bull. Am. Meteorol. Soc.*, *82*, 219–246.

Hamlet, A. F., P. W. Mote, M. P. Clark, and D. P. Lettenmaier (2005), Effects of temperature and precipitation variability on snowpack trends in the western United States, *J. Clim.*, *18*, 4545–4561.

Hirsch, R. M., and K. R. Ryberg (2012), Has the magnitude of floods across the USA changed with global CO_2 levels?, *Hydrol. Sci. J.*, *57*, 1–9.

Hodgkins, G. A., and R. W. Dudley (2006), Changes in the timing of winter-spring streamflows in eastern North America, 1913–2002, *Geophys. Res. Lett.*, *33*, L06402, doi:10.1029/2005GL025593.

Hodgkins, G. A., R. W. Dudley, and T. G. Huntington (2003), Changes in the timing of high river flows in New England over the 20th century, *J. Hydrol.*, *278*, 244–252.

Hoerling, M., J. Eischeid, T. Peterson, and R. Webb (2010), Understanding and explaining hydro-climate variations at Devils Lake, NOAA Climate Assessment, National Oceanic and Atmospheric Administration, July 2010, 21 p.

Huntington, T. G., G. A. Hodgkins, B. D. Keim, and R. W. Dudley (2004), Changes in the proportion of precipitation occurring as snow in New England (1949 to 2000), *J. Clim.*, *17*, 2626–2636.

Hurrell, J. W. (1995), Decadal trends in the North Atlantic Oscillation: Regional temperatures and precipitation, *Science*, *269*, 676–679.

Intergovernmental Panel on Climate Change (2014), Summary for policymakers, in *Climate Change 2014: Impacts, Adaptation, and Vulnerability. Part A: Global and Sectoral Aspects. Contribution of Working Group II to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change*, edited by C. B. Field et al., pp. 1–32, Cambridge Univ. Press, Cambridge, U. K., and New York.

Kaplan, A., M. A. Cane, Y. Kushnir, A. C. Clement, M. B. Blumenthal, and B. Rajagopalan (1998), Analyses of global sea surface temperature 1856–1991 *J. Geophys. Res.*, *103*(C9), 18,567–18,589, doi:10.1029/97JC01736.

Knowles, N., M. D. Dettinger, and D. R. Cayan (2006), Trends in snowfall versus rainfall in the western United States, *J. Clim.*, *19*, 4545–4559.

Leathers, D. J., and M. A. Palecki (1992), The Pacific/North American teleconnection pattern and United States climate, Part II: Temporal characteristics and index specification, *J. Clim.*, *5*, 707–716.

Lettenmaier, D. P., E. F. Wood, and J. R. Wallis (1994), Hydro-climatological trends in the continental United States, 1948–1988, *J. Clim.*, *7*, 586–607.

Lins, H. F., and J. R. Slack (1999), Streamflow trends in the United States, *Geophys. Res. Lett.*, *26*, 227–230.

McCabe, G. J., and M. P. Clark (2005), Trends and variability in snowmelt runoff in the western United States, *J. Hydrometeorol.*, *6*, 476–482.

McCabe, G. J., and M. D. Dettinger (2002), Primary modes and predictability of year-to-year snowpack variations in the western United States from teleconnections with Pacific Ocean climate, *J. Hydrometeorol.*, *3*, 13–25.

McCabe, G. J., and D. M. Wolock (2002), A step increase in streamflow in the conterminous United States, *Geophys. Res. Lett.*, *29*(24), 2185, doi:10.1029/2002GL015999.

McCabe, G. J., and D. M. Wolock (2009), Recent declines in western U. S. snowpack in the context of 20th century climate variability, *Earth Interact.*, 13, 12 p.

McCabe, G. J., and D. M. Wolock (2014), Variability common to global sea-surface temperatures and runoff in the conterminous United States, *J. Hydrometeorol.*, *15*, 714–725, doi:10.1175/JHM-D-13-097.1.

McCabe, G. J., M. A. Palecki, and J. L. Betancourt (2004), Pacific and Atlantic Ocean influences on multidecadal drought frequency in the United States, *Proc. Natl. Acad. Sci. U.S.A.*, *101*, 4137–4141.

McCabe, G. J., L. E. Hay, and M. P. Clark (2007), Rain-on-snow events in the western United States, *Bull. Am. Meteorol. Soc.*, *88*, 319–328.

Mote, P. W. (2003), Trends in snow water equivalent in the Pacific Northwest and their climatic causes, *Geophys. Res. Lett.*, *30*(12), 1601, doi:10.1029/2003GL017258.

Namias, J., and D. R. Cayan (1984), El Niño: Implications for forecasting, *Oceanus*, *27*, 41–47.

Peterson, T. C., et al. (2013), Monitoring and understanding changes in heat waves, cold waves, floods, and droughts in the United States: State of knowledge, *Bull. Am. Meteorol. Soc.*, *6*, 821–834.

Press, W. H., B. P. Flannery, S. A. Teukolsky, and W. T. Vetterling (1986), *Numerical Recipes*, Cambridge Univ. Press, Cambridge, U. K.

Redmond, K. T., and R. W. Koch (1991), Surface climate and streamflow variability in the western United States and their relationship to large scale circulation indices, *Water Resour. Res.*, *27*, 2381–2399.

Ropelewski, C. F., and M. S. Halpert (1986), North American precipitation and temperature patterns associated with El Niño/Southern Oscillation (ENSO), *Mon. Weather Rev.*, *114*, 2352–2362.

Sagarika, S., A. Kalrab, and S. Ahmada (2014), Evaluating the effect of persistence on long-term trends and analyzing step changes in streamflows of the continental United States, *J. Hydrol.*, *517*, 36–53.

Scheff, J., and D. Frierson (2014), Scaling potential evapotranspiration with greenhouse warming, *J. Clim.*, *27*, 1539–1558, doi:10.1175/JCLI-D-13-00233.1.

Small, D., S. Islam, and R. M. Vogel (2006), Trends in precipitation and streamflow in the eastern U. S.: Paradox or perception?, *Geophys. Res. Lett.*, *33*, L03403, doi:10.1029/2005GL024995.

Stewart, I. T., D. R. Cayan, and M. D. Dettinger (2004), Changes in snowmelt runoff timing in western North America under a "business as usual" climate scenario, *Clim. Change*, *62*, 217–232.

Sutton, R. T., and D. L. R. Hodson (2003), Influence of the ocean on North Atlantic climate variability 1871–1999, *J. Clim.*, *16*, 3296–3313.

Tootle, G. A., and T. C. Piechota (2006), Relationships between Pacific and Atlantic Ocean sea surface temperatures and U.S. streamflow variability, *Water Resour. Res.*, *42*, W07411, doi:10.1029/2005WR004184.

Trenberth, K. E. (1997), The definition of El Niño, *Bull. Am. Meteorol. Soc.*, *78*, 2771–2777.