Climatic Change (2016) 135:639–653
DOI 10.1007/s10584-015-1574-0

Changes in the low flow regime over the eastern United States (1962–2011): variability, trends, and attributions

Jonghun Kam[1,2] **· Justin Sheffield**[1]

Received: 6 November 2014 / Accepted: 29 November 2015 / Published online: 5 December 2015

Abstract We examine trends and variability in low flows over the eastern U.S. (S. Carolina to Maine) and their attribution in a changing climate. We select 149 out of 4878 USGS stations over the eastern U.S., taking into account data availability and minimal direct management. Annual 7-day low flows (Q7) are computed from the series of daily streamflow records for 1962–2011 and compared to an antecedent precipitation (AP) index calculated over the corresponding basin for each station. In general, a north–south (increasing-decreasing) dipole pattern in low flow trends is associated with trends in AP. The exception is in the southern part of the study area including Virginia and the Carolinas, where moderate increasing trends in AP may have been offset by water withdrawals and increasing potential evapotranspiration (PET) as driven by increasing temperature and vapor pressure deficit. A principal component analysis (PCA) of Q7 and AP indicates that the North Atlantic Oscillation (NAO) and Pacific North America (PNA) pattern show statistically significant correlations for Q7 at 1 and 2 month lead time, respectively, via large-scale pressure patterns. Our findings suggest that the inter-annual variability of low flows has increased due to significant anti-correlation between the NAO and PNA during recent decades, and the future risk of low flow extremes may be further enhanced with temperature driven increases in PET and persistence of the multi-decadal relationship between NAO and PNA.

Key findings

1. There is a north-south increasing-decreasing trend pattern in warm season low flows over the eastern U.S.
2. The trends are associated with increases in antecedent precipitation in the north and increasing PET trends and water management in the south that exceed precipitation increases.
3. Inter-annual variability in low flows is linked to the NAO and PNA, which may provide predictive skill at one to two month lead time.

Electronic supplementary material The online version of this article (doi:10.1007/s10584-015-1574-0) contains supplementary material, which is available to authorized users.

✉ Jonghun Kam
jkam@princeton.edu

[1] Department of Civil and Environmental Engineering, Princeton University, Princeton, NJ 08544, USA

[2] Present address: 201 Forrestal Campus, Princeton, NJ 08540, USA

1 Introduction

Streamflow is a hydrological response of the land surface at the catchment scale to precipitation and is a major water resource available for human use and ecological needs. During the drier part of the year, low precipitation (low supply) and/or high evapotranspiration (high demand) conspire to reduce streamflow and water availability. This natural seasonal hydrological phenomenon is known as the low flow period (Smakhtin 2001). Low flows may also occur in the cold season when water is stored in the snowpack and soils and/or rivers are frozen, causing a reduction in flow. With variations in climate, decreases in seasonal precipitation and increases in potential evapotranspiration can lead to reductions in low flows, with adverse effects on human activities and ecosystem function (Bradford and Heinonen 2008). These low flow season hydrological droughts can be exacerbated by water management (Wada et al. 2013) with a range of impacts from environmental (e.g., migration of wildlife) to economic (e.g., increased costs due to water scarcity). For example, since the 1950s, groundwater withdrawals in the U.S. have increased dramatically and can affect low flow generation at the regional scale (Castle et al. 2014; Hughes et al. 2012; Konikow 2013). Future projections of changes in hydrological droughts indicate that they will become more intense and longer (Hayhoe et al. 2007; Feyen and Dankers 2009) even with adaptation to mean changes in climate (Wanders et al. 2014). Given the impacts of low flow droughts and the potential for changes in the future, better understanding of the low flow regime and its generating mechanisms is necessary.

Drivers of low flow variability are complex, and include antecedent precipitation, atmospheric demand, surface water management (urbanization, dams, reservoirs, and irrigation), and groundwater withdrawals (Smakhtin 2001; Dingman 2008). Antecedent precipitation (AP) is one of the major drivers. During the low flow season, when the catchment is relatively dry, streamflow is an accumulated response and the impact of any precipitation events is delayed and muted. This impact depends on the geographical characteristics of the catchment (e.g., regional climate, terrain slope, soil type, basin size, groundwater dominance, hydrological connectivity, etc.) (Gupta 2008). For example, Fig. 1a shows the delayed response to AP for USGS station ID 01531500 (located at Towanda, PA), for which it takes up to 3 months from the last major streamflow peak to reach the annual minimum, and the impact of any precipitation events is small compared to the wet season. Better understanding of the variability of low flows and its driving mechanisms can provide invaluable information for improving seasonal forecasting of low flows, quantifying hydrological drought risk, and understanding the potential future changes in low flows under climate change and direct anthropogenic influences (Wang and Cai 2009).

Low flows are particularly important over the eastern U.S. and elsewhere, where the interaction of human activities (e.g., population growth and agricultural activity) with natural systems is relatively high (Hayhoe et al. 2007). The hydroclimatic regime over the eastern U.S. has changed over the past half century. During the 1950s–1990s, low and median flows (but not high flows) have increased (Lins and Slack 1999; Douglas et al. 2000) due to increasing fall precipitation (Small et al. 2006). McCabe and Wolock (2002) found that these increases were generally due to abrupt changes around the 1970s. More recent studies (e.g., Patterson et al. 2012; Sayemuzzaman and Jha 2014; Sadri et al. 2015) found that some regions of the eastern U.S., including the Mid-Atlantic (Mid-ATL) and Southeastern (SE) regions, have decreasing trends in annual and seasonal averaged flow and increasing trends in surface temperature. Coopersmith et al. (2014) found that temporal shifts in annual precipitation and

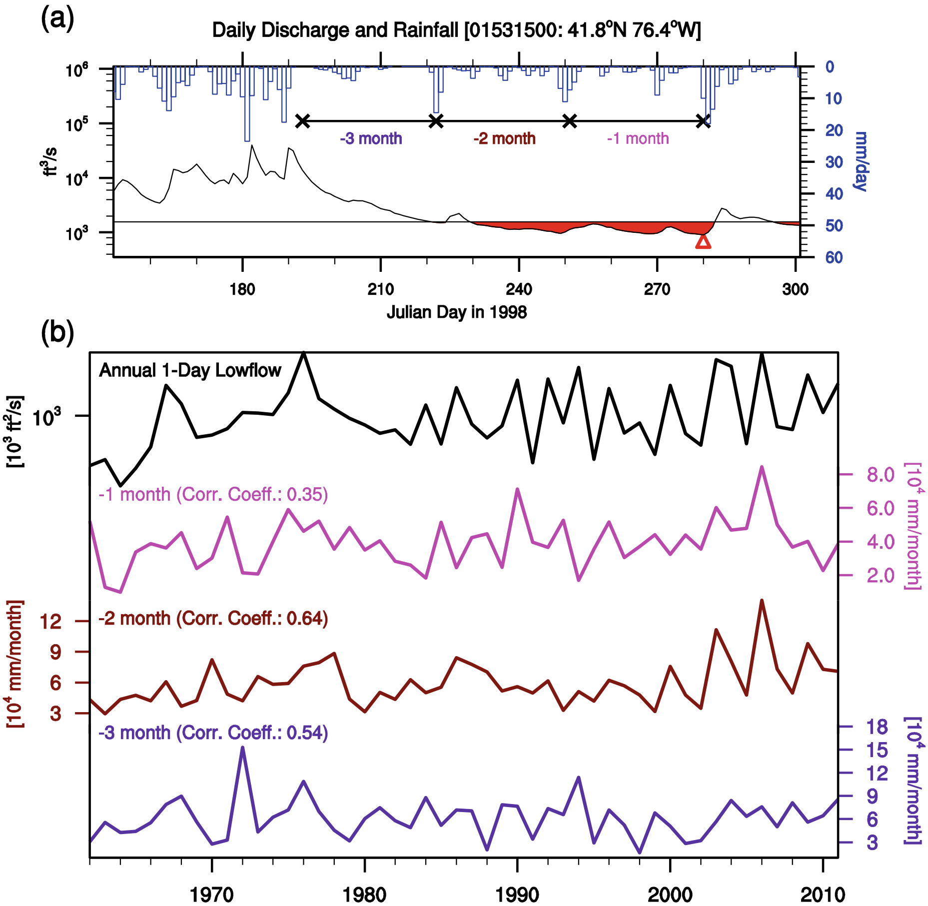


Fig. 1 **a** Time series of daily streamflow and precipitation at Susquehanna River in Towanda, PA, for 1998. **b** Time series of annual 7-day low flows and 30-day total antecedent precipitation at 1 to 3 month lead before the date of the annual low flow event (e.g., the antecedent precipitation accumulated during 0–29, 30–59, and 60–89 days, respectively) for 1962–2011

streamflow peaks have been observed after the 1970s and more significantly after 1980s over the northeastern (NE) U.S. region. Future scenarios from climate and hydrological models (Hayhoe et al. 2007) show decreasing trends in warm-season low flow statistics (e.g., low flow volumes) due to increasing surface temperature. The observed non-stationarity in the low flow regime and the projected changes suggest that the risk of hydrological drought over the eastern U.S. is increasing and may continue in the future.

In this paper we evaluate variability in the low flow regime over the eastern U.S. to 1) understand long-term changes and their attribution, and 2) to identify potential oceanic and atmospheric drivers of inter-annual variability. We use this information to understand the potential for seasonal prediction of low flow anomalies and to identify scenarios associated with elevated streamflow drought risk. We do this by examining long-term flow records from USGS stations and exploring the connections with large-scale climate drivers in the context of climate variability and change. In Section 2, the data and methods are described. Section 3 presents the results using different versions of the Mann-Kendall (MK) trend test and explores the connections between interannual variability of low flows and large-scale climate drivers, as well as other possible drivers. In Section 4 we summarize our findings.

2 Data and methods

2.1 Streamflow data

We download daily streamflow records for 4878 stations over the eastern U.S. from the United States Geological Survey (USGS) Water Data for the Nation database (USGS 2014, http://waterdata.usgs.gov/nwis). 2811 of these stations have remained active over the last decade. We calculate annual 7-day low flows (Q7) defined as the minimum low flow during February through November from the 7-day moving window time series of daily streamflows due to low quality of streamflow data during winter seasons. For comparison with antecedent precipitation, the original measurement unit from the USGS streamflow data, cfs (cubic feet per second), is converted to mm/day by dividing by the corresponding basin area (m^2) and multiplying by 3600*24 (s/day). Only data from February to November are considered because the quality of streamflow data during the winter season in northern rivers can be lower when they are subject to freezing, and our focus is on low flows generated in the warm season. Most stations have a fairly narrow season for Q7 during August-October (ASO), while some stations in North and South Carolina have a wider season (July-October).

Following Sadri et al. (2015). we evaluate the Q7 time series of the 2811 stations for evidence of management via statistical testing for step changes and examination of station notes. These step changes may originate from implementation of water management by a reservoir or withdrawal (Konikow 2013). or an indirect influence caused by, for example, land use change (Eng et al. 2013). They may be also driven by natural climatic shift (e.g. the 1976-77 climate shift in the Pacific (McCabe and Wolock 2002)), although an analysis of changes in antecedent precipitation (see Section 2.2) shows no evidence of step changes (not shown). We use the non-parametric Pettitt test (Pettitt 1979) to identify step changes. 740 stations have no step change in the record and 117 are common to the 743 HCDN-2009 stations (Lins 2012). which are judged to be minimally impacted based on GIS analysis and examination of site information. Finally, 149 stations have continuous records and show no step change over the period 1962–2011, including 46 HCDN-2009 stations (see Supplementary Material 1 (S.1)). This period is chosen as a trade-off between being long enough (50 years) and recent enough to identify long-term recent changes, and having good spatial coverage of the domain. These stations are located in the NE and Mid-ATL U.S. regions, and the northern part of the SE region (North and South Carolina). The USGS annual water-data reports indicate that 97 out of the 149 stations have been regulated before or after 1962 (dams, power plants, mills, reservoirs, etc.), although any impacts on the low flows are not large enough to be picked up by the Pettitt test. The rest of the selected stations have no record of regulation, and we therefore assume that the low flow data are unaffected by regulation (blue empty circles in S.2). This information enables us to qualitatively assess the human impact on the low flows regime over the study region. We note that the analysis of trends in low flows based only on the HCDN-2009 stations over the eastern US with data available for 1962–2011, shows very similar patterns to those using our selected stations (not shown).

2.2 Precipitation data

For precipitation, we use a recently published daily dataset from Livneh et al. (2013). ftp://ftp.hydro.washington.edu/pub/blivneh/CONUS/) to compute antecedent rainfall over the catchments upstream of the 149 stations. The data covers the continental U.S. (CONUS) at 1/16th degree (~6 km) spatial resolution for 1915–2011, and we use the latest version (version 1.2). Antecedent precipitation (AP) is calculated over the basin corresponding to each station for each low flow date, and for a range of window sizes (30, 60, …, 300, 330-day) to understand the lagged relationship with low flows. The catchment masks are derived from 30 arc sec digital elevation model data and scaled up to 1/16th degree (225 arc sec). Some of the stations share a few grid cells in their catchment masks (see S.1).

2.3 Potential evapotranspiration data

We also use monthly average potential evapotranspiration (PET) from the Climate Research Unit (CRU) TS v3.21 dataset (http://badc.nerc.ac.uk/browse/badc/cru/data/cru_ts/cru_ts_3.21/data/). The data have 0.5 degree (~50 km) spatial resolution for 1901 to 2012. PET is defined as the maximum possible evapotranspiration under no restrictions of available water at the land surface and is used as an indicator for atmospheric water demand. The PET data from the CRU dataset are calculated using the Food and Agricultural Organization (FAO) grass reference evapotranspiration equation (Ekstrom et al. 2007). which takes into account the radiative forcing and atmospheric demand based on several climate variables (e.g., temperature, water vapor pressure, and cloud cover).

2.4 Climate indices

To identify teleconnections, we use seven monthly climate indices from the National Oceanic and Atmospheric Administration (NOAA) Earth System Research Laboratory (http://www.esrl.noaa.gov/psd/data/climateindices/list/), including the Artic Oscillation (AO), North Atlantic Oscillation (NAO), Oceanic Niño Index (ONI), Pacific-North Atlantic (PNA) pattern, Tropical Northern and Southern Atlantic Indices (TNA and TSA), and Western Hemisphere Warm Pool (WHWP) index. We compute 3-month averages over 1962–2011 for different periods from February-April (FMA: −6 month lead to the peak season of low flow events (August-October (ASO)) to ASO (zero month lead). The analysis excludes decadal SST variations over the Pacific and Atlantic Oceans due to the relative short study period (50 years).

2.5 Trend test

To quantify trends in the Q7 time series and associated precipitation and PET, we use the non-parametric Mann-Kendall (MK) trend test. The MK trend test requires serially independent data because otherwise this will lead to overestimation (underestimation) of the significance of trends with positive (negative) serial correlation in the data, which often exist in long-term hydroclimate records. Therefore, we use three different versions of the MK test (Kumar et al. 2009). 1) MK test without autocorrelation (MK), 2) MK test with one-lag autocorrelation and trend-free pre-whitening (MK-1), and 3) MK test with complete autocorrelation structure (MK-2). The difference among the results from the different MK tests show the impact of autocorrelation structure in the hydrological data. Long-term persistence (LTP) is another source of uncertainty in the application of the classical MK trend test. We also applied the MK test with account for LTP following the method of Hamed (2008). but the results showed no difference from those using the MK-2 test (not shown). We compute the Theil-Sen (TS) slope of the local trends which is the median of all sub-trends in the series. We use a significance level of α=0.05. We also test the field significance of the local trends to account for spatial correlation among stations using the False Discovery Rate (FDR) approach (Wilks 2006). The local trend is defined as field significant when the local significance (α_i) is less than or equal to the global significance level (here, α=0.05) weighted by its rank over the total station number (i/N; i is the rank of the local station and N is the number of stations (here, N=149)).

2.6 Principal component analysis

We conduct a principal component analysis (PCA; Wilks 2006) for Q7 and AP-90 in order to extract the major modes of their inter-annual variability. The loadings of the PCs are computed from the eigenvectors and show the spatial pattern for the corresponding PC mode. The scores of the PCs are computed by projecting the data on to the loadings, and show the temporal variations of the PCs. The results of the PCA for Q7 and AP-90 are shown in Section 3.5.

3 Results

3.1 Correlation between Q7 Low flows and antecedent precipitation

To identify the time period of antecedent precipitation associated with Q7, we compute temporal correlations between Q7 and monthly (30-day) total antecedent precipitation at different lagged times from −1 month (−29 to 0 days from the date of occurrence of the low flow event) to −11 months (−329 to −300 days). For most of the stations the inter-annual variability of Q7 has a maximum correlation with monthly total antecedent precipitation at 1 to 3 months (Fig. 2). We therefore focus on the 90-day total antecedent precipitation (AP-90) when examining the attribution of trends in Q7.

3.2 Trends in Q7 low flows for 1962–2011

The MK trend test for Q7 indicates that 12 stations (out of 149) show significant increasing trends and 11 stations show significant decreasing trends for 1962–2011 (Fig. 3a and see S.1). Five and three stations in the NE region have significant increasing and decreasing trends, respectively. Over the northern part of the Mid-ATL region, seven stations show a significant increasing trend while there are no stations with significant decreasing trends. In the southern part of the domain, including North and South Carolina, there are no stations with an increasing trend and eight stations with a significant decreasing trend. The decreasing trends over the southern part of the domain are consistent with the results from the MK-1 and MK-2 tests. Among the stations with significant trends, the slope (expressed in mm/day by dividing by the basin area) is 0.08 mm/day/30 years and −0.16 mm/day/30 years, respectively, on a regional basis (see S.2). For comparison, the means of Q7 is 0.13 mm/day and 0.13 mm/day over the stations with significant increasing and decreasing trends, respectively. We also

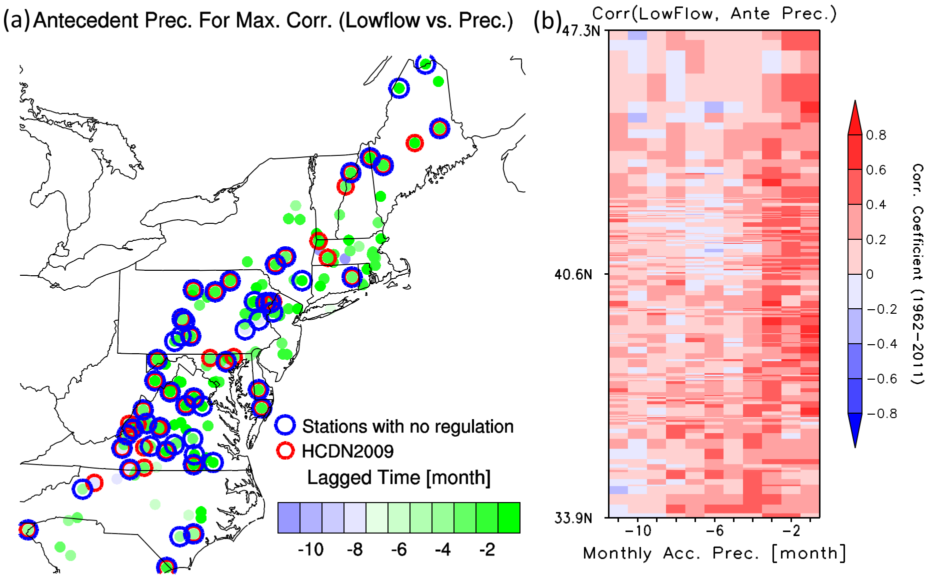


Fig. 2 **a** Spatial distribution of lead time with maximum correlation between Q7 and AP-30. **b** Correlation between Q7 and AP-30 at different lead time steps (x-axis; from −11 month lead time step through zero month lead time step) from the dates of Q7 occurrence for 1962–2011 over 149 stations (y-axis). *Blue* and *red* empty circles represent stations with no regulation and in the HCDN2009 station list, respectively

calculated the changes in the 10-year return value of Q7 (7Q10) over the stations with significant decreasing trends in order to highlight the significance of the trends. In general, 7Q10 is a standard design flow used by the US Environmental Protection Agency (EPA) for water quality standards. We found that those stations with significant decreasing trends showed a significant (>50 %) reduction in the design flow over the past 50 years. Based on the FDR approach, four stations are field significant among 11 stations with significant decreasing trends, and one out of 12 stations with an significant increasing trend is field significant. This indicates that the results from the MK tests are overestimated by the strong spatial correlation in hydro-climate variables over the study region (Andreadis and Lettenmaier 2006).

3.3 Attribution of trends in Q7 low flows

The MK-0 test for AP-90 shows that 42 stations have significant increasing trends over the NE and Mid-ATL regions and two stations have significant decreasing trends over the SE region (Fig. 3d; see S.2). There are more stations with significant trends in AP-90 than those in Q7 partly because of the stronger spatial correlations in AP-90 than those in Q7 among adjacent stations over the NE region. AP-90 is driven by mesoscale meteorological processes (e.g., squall lines, mesoscale convective systems, etc.), which can cover several catchments while Q7 is also controlled by the geographical characteristics (drainage area, slope, soil type, etc.) of a catchment. The results from the MK-1 and MK-2 tests are very similar due to the weak serial correlation structure in AP-90. A field significance test shows that 14 stations and one station with increasing trend and decreasing trend, respectively, are field significant. The increasing

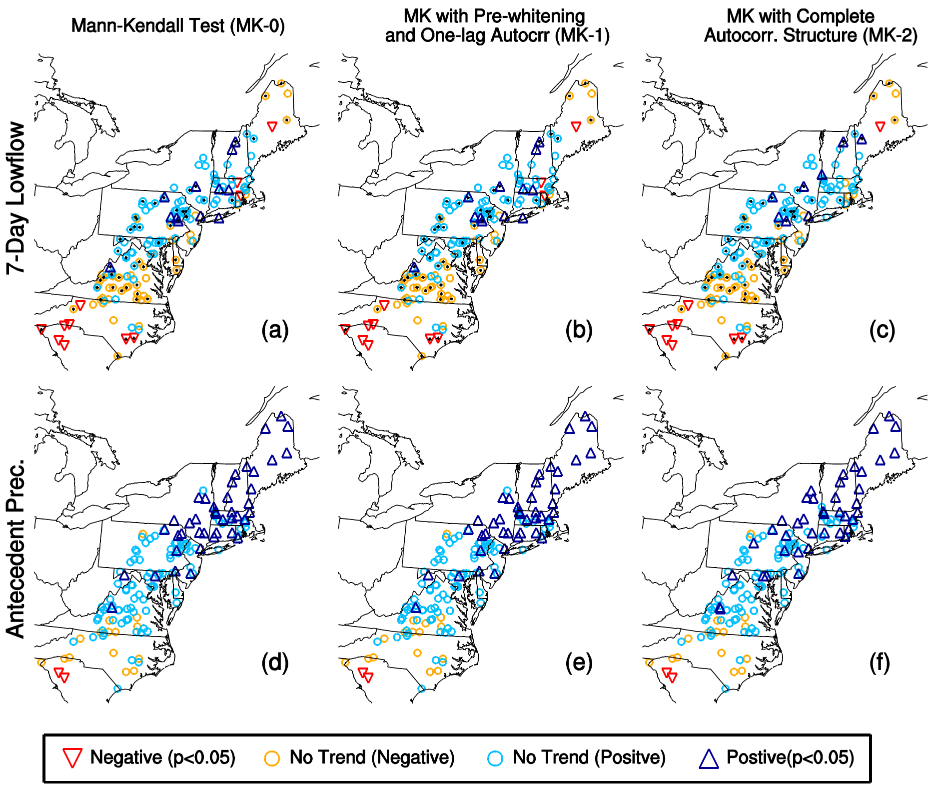


Fig. 3 Spatial distribution of the trends in annual 7-day low flows (Q7) and 90-day accumulated antecedent precipitation (AP-90) from three versions of Mann Kendall test over 1962–2011. *Dots* represent stations with no regulation

and decreasing trends in Q7 over the NE region and South Carolina are consistent with the corresponding trends in AP-90, suggesting that changes in antecedent precipitation are driving the changes in low flows.

We apply the MK test for Q7 and AP-90 over 1962–1991 and 1982–2011 because the results from the two other MK tests are consistent with those from the MK test due to weak autocorrelation structure in the data. Interestingly, the Mid-ATL region shows weak consensus of the trends in Q7 and AP-90, with the consensus weaker during 1982–2011 than during 1962–1991 (Fig. 4). Five out of 11 stations over this region show significant decreasing trends in Q7. These five stations are flagged in the USGS notes as having experienced some form of regulation, indicating that regulation may have overwhelmed any increases in low flows from increasing precipitation.

Changes in PET may have also contributed to changes in low flows. Figure 5 shows the results from the MK test for PET over three periods (1962–2011, 1962–1991, and 1982–2011). Here, we present the results for averaged PET over the 6-month warm season (May-October). These results are consistent with the results from using a 3-month moving window of the warm seasons (May-July through August-October; not shown). Parts of the NE and Mid-ATL regions along the Atlantic coast

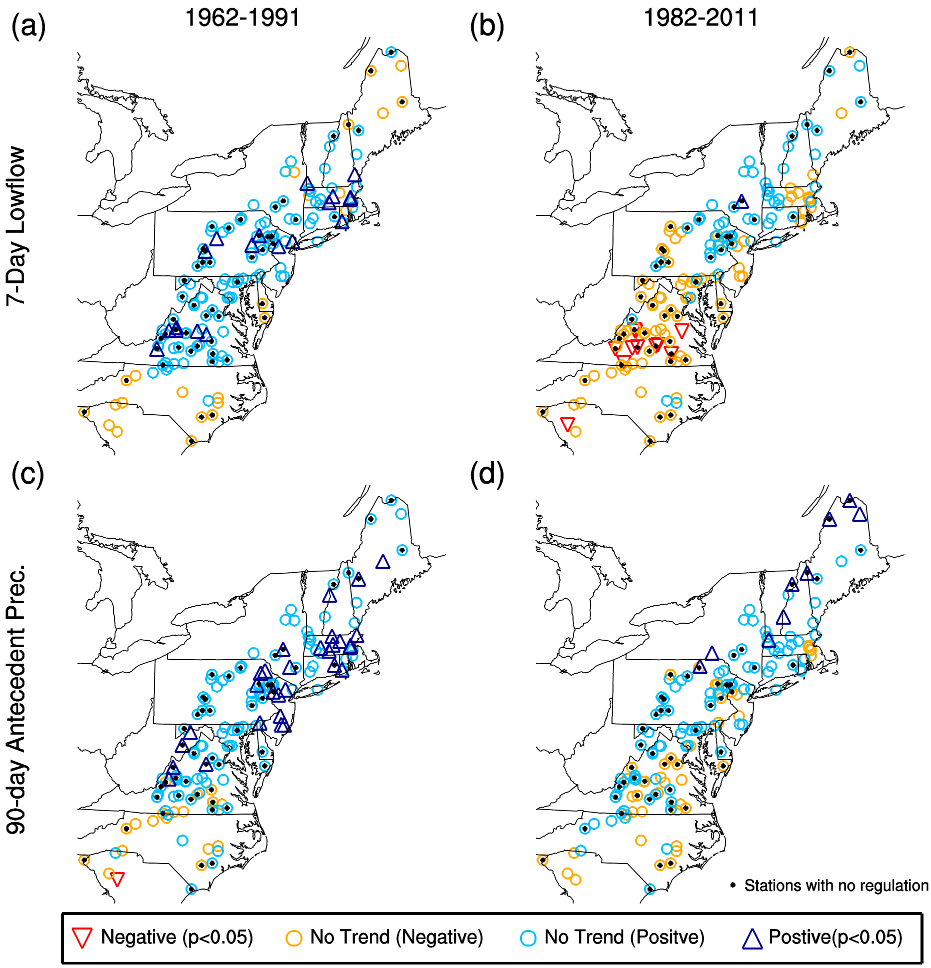


Fig. 4 Spatial distribution of the trends in annual 7-day low flows (Q7) and 90-day accumulated antecedent precipitation (AP-90) from the classical Mann Kendall test for the period **a** and **c**: 1962–1991 and **b** and **d**: 1982–2011)

show significant increasing trends with a slope of 0.17 and 0.26 mm/day/30 years for 1962–2011 and 1982–2011, respectively, on a regional basis (Fig. 5). Due to the coarse resolution of the PET data, the field significance of the PET trends are not tested. Even though the significance of these PET trends might be overestimated, their magnitude is comparable to those of antecedent precipitation, which suggests that the regional climate regime over the Carolinas has become drier.

Over South and North Carolina, a combination of decreasing trends in AP-90 (less water supply) and increasing trends in PET (higher water demand), has resulted in stronger decreasing trends in Q7 than any other states in the region. The trends are stronger in recent decades indicating that this region is becoming more vulnerable to drought, possibly as a result of surface warming, and likely exacerbated by regulation.

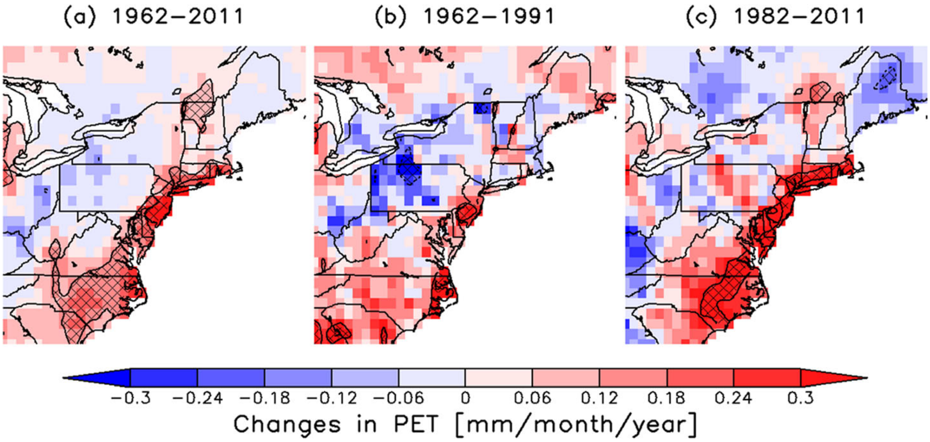


Fig. 5 Spatial distribution of the trends in potential evapotranspiration (PET) from the classical Mann Kendall test for **a** 1962–2011, **b** 1962–1991, and **c** 1982–2011

3.4 Longer term trends for selected stations

The climate of the eastern U.S. is subject to decadal variations, which may impact the robustness of the trends. In other words, a trend may be a part of natural decadal variation. We examine the trends in Q7 and AP-90 over 14 stations for 1932–2011, as limited by stations with no regulation and available data (see S.3). The spatial distributions of the trends in Q7 and AP-90 for 1932–2011 is similar to that for 1962–1991 rather than 1982–2011. This suggests that the low flow regime over the eastern U.S. has changed more significantly since the 1980s, with weak consensus of the trends in antecedent precipitation since other drivers have played a role in more recent decades.

3.5 PCA analysis for Q7 low flows and AP-90

The first PCA mode (PC1) represents a north–south (increasing-decreasing) trend in Q7 and AP-90, which explains 22 and 19 % of the total variability, respectively. This is consistent with the spatial patterns of trends from the MK test, and so we only show the results for the second PCA mode (PC2) from here on. The scores of the PC2 mode for Q7 and AP-90 are normalized by the standard deviation (Fig. 6a) and show an inter-decadal variability, which is correlated positively (negatively) with the station low flow time series in the Mid-ATL (NE) region (Fig. 6). They explain 7 and 9 % of the total variability, respectively. The contributions of the other PCA modes (not shown) are generally small, ranging from 3 to 5 %, due to the high variability (low signal-to-noise ratio) of Q7 and AP-90 over the many stations that have a small catchment area (the number of stations with drainage area below 100 km^2 is 103).

To explore the potential driving mechanisms of variability in low flows, we compute temporal correlation coefficients between the PC2 scores and 3 month averages of seven climate indices at different lead times (FMA (−6 month lead) through ASO (zero month lead); Fig. 7a and b), where the peak season for Q7, ASO, is defined as the zero month lead time. The North Atlantic Oscillation (NAO) and Arctic Oscillation (AO) are correlated positively and significantly with Q7 and AP-90 at 2-month lead time (June-August), which has previously

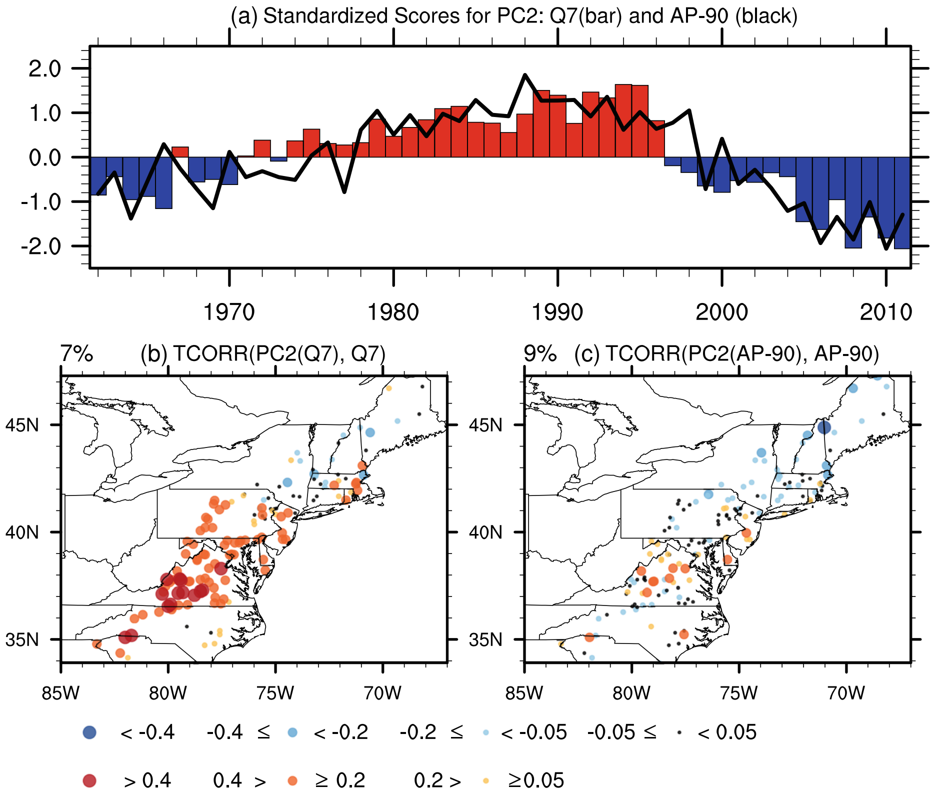


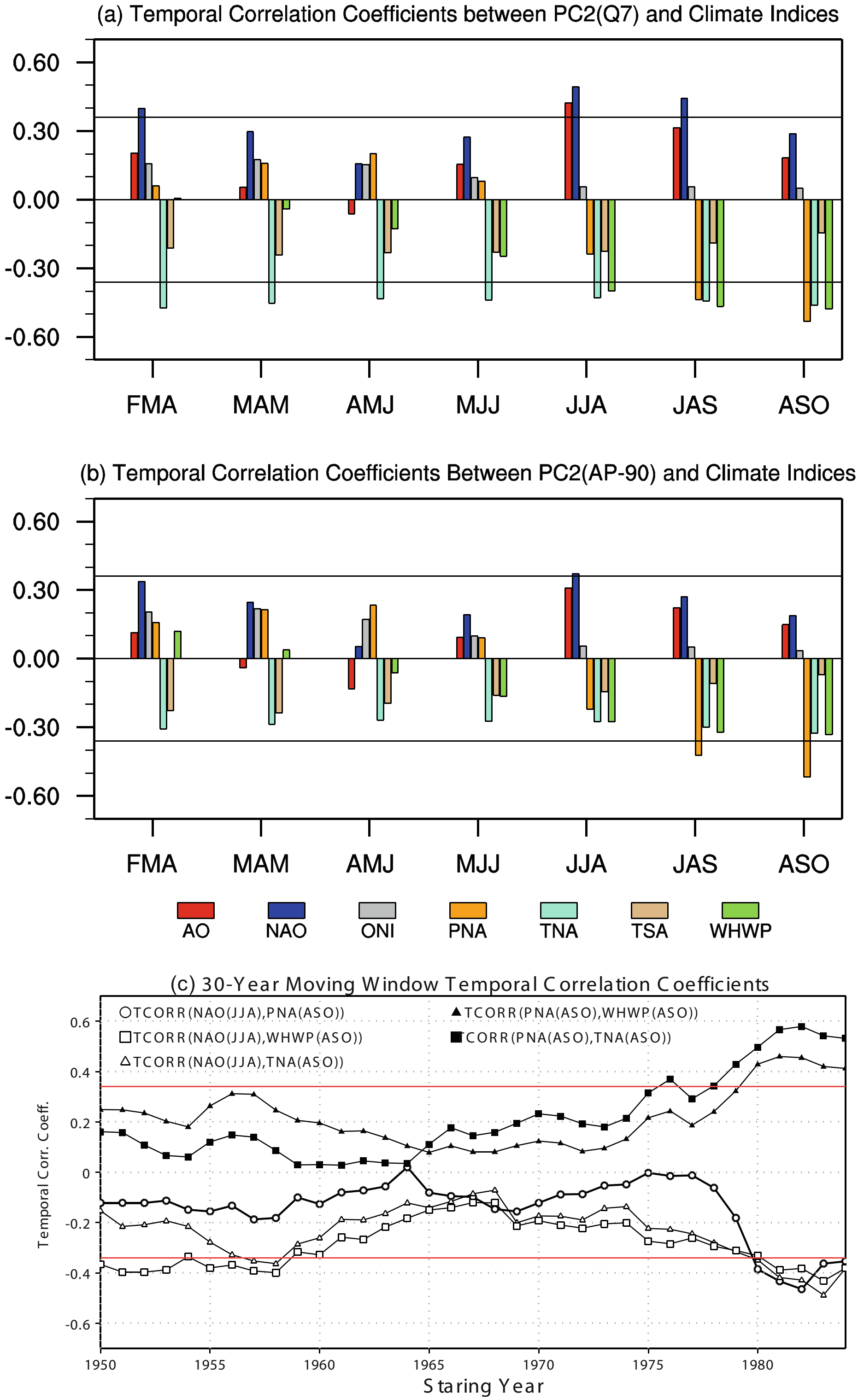
Fig. 6 **a** Standardized scores for the 2nd mode of the principal component (PC2) from Q7 (bar) and AP-90 (*green solid line*). **b** and **c**: Spatial distributions of temporal correlation coefficients of the data from the stations and the PC2 from Q7 and AP-90, respectively

been found to be a favorable condition for summer droughts over the eastern U.S. (Kingston et al. 2007; Kam et al. 2014).

The Pacific North Atlantic (PNA) pattern shows a significant negative correlation with the PC2 for Q7 and AP-90 at 1-month lead time (July-September) and a slightly stronger correlation at zero lead time. In general, a positive value of the PNA induces a high-pressure pattern over the tropical north Atlantic (close to Florida) (Pinto et al. 2011). This high pressure system appears to be related to variability in the tropical Atlantic in general, because of the significant correlations of the same sign with the Tropical North Atlantic (TNA) and Western Hemisphere Warm Pool (WHWP) indices. Variations of these indices are at a decadal time scale (Wang and Enfield 2001).

3.6 Potential mechanisms of Q7 low flow variability: linkage between the NAO and PNA

This PCA analysis indicates that the NAO and PNA play a dominant role in driving variability in warm-season low flows across the region. Previous studies have shown, however, that the relationship between the NAO and PNA varies over time. For example, Pinto et al. (2011)


(a) Temporal Correlation Coefficients between PC2(Q7) and Climate Indices
0.60
0.30
0.00
-0.30
-0.60
FMA
MAM
AMJ
MJJ
JJA
JAS
ASO
(b) Temporal Correlation Coefficients Between PC2(AP-90) and Climate Indices
0.60
0.30
0.00
-0.30
-0.60
FMA
MAM
AMJ
MJJ
JJA
JAS
ASO
AO
NAO
ONI
PNA
TNA
TSA
WHWP
(c) 30-Year Moving Window Temporal Correlation Coefficients
TCORR(NAO(JJA),PNA(ASO))
TCORR(NAO(JJA),WHWP(ASO))
TCORR(NAO(JJA),TNA(ASO))
TCORR(PNA(ASO),WHWP(ASO))
TCORR(PNA(ASO),TNA(ASO))
Temporal Corr. Coeff.
0.6
0.4
0.2
0
-0.2
-0.4
-0.6
1950
1955
1960
1965
1970
1975
1980
Staring Year

◀ **Fig. 7 a** and **b**: Temporal correlation coefficients between seven climate indices and the principal component (PC2) from Q7 (bar) and AP-90 (*green solid line*) at different lead time steps (x-axis; from February-April (−6 month lead time step) through August-October (zero month lead time step). **c**: The 30-year window temporal correlation coefficients among NAO, PNA, TNA, and WHWP. For each climate index, the 3-month average period are shown in the parentheses. X-axis show a starting year of the 30-year window. The *red lines* represents the temporal correlation coefficient at p-value=0.05

found that interactions between the NAO and PNA and their impact on storm tracks over eastern North America during the winter (DJF) follow a multi-decadal relationship, with stronger and statistically significant anti-correlation in the 1970s–1990s, which is coincident with the climatic shift in NAO/AO (Ulbrich and Christoph 1999). The origins of this anti-correlation between the PNA and NAO remains unclear, however.

To see whether this also applies to low flows during the warm season, we computed 30-year moving window temporal correlation coefficients between the NAO (JJA) and the PNA (ASO) using extended times series of the indices (1950–2013) (Fig. 7c). Anti-correlation between the NAO and PNA became statistically significant around 1980, consistent with the wintertime results of Pinto et al. (2011) although this is for a slightly different time period. These results suggest that interactions between the NAO and PNA might occur at the multi-decadal scale, and this may have enhanced their associations with Q7 and AP-90.

Based on the findings from this study and previous studies, we propose a potential driving mechanism of variability of Q7 over the eastern U.S. via interactions between the NAO and PNA. When the NAO falls into a negative phase during the summer, an anomalous north–south (low-high) dipole pressure pattern is placed between Greenland and the eastern U.S. These patterns lead to more precipitation and lower temperature between Greenland and Northern Europe, and less precipitation, higher temperature, and thus low streamflow over the eastern U.S., most strongly for the Mid-ATL U.S. (between 30 and 40°N) and weakly over the NE U.S. (north of 40°N) (Ulbrich and Christoph 1999; Raible 2007; Kingston et al. 2007). When the PNA is in a positive phase during the late summer, a high pressure pattern over Florida blocks moisture transport to the Mid-ATL and SE U.S., resulting in less precipitation over those regions (Knippertz and Wernli 2010).

Our results show a strong anti-correlation between the NAO and PNA in recent decades, when a stronger negative NAO might be expected during the positive phase of the PNA and vice versa. This has introduced preferential conditions for more extreme low flow events over the eastern U.S. The reason for the multi-decadal relationship between the NAO and PNA is not known, but the correlations with TNA and WHWP (Fig. 7c) suggest that there might be an association with tropical Atlantic variability (Wang 2002).

4 Conclusions

Our findings can be summarized as follows: 1) A dipole pattern of increasing and decreasing trends in Q7 low flows exists in the northern and southern part of the domain, respectively; 2) The increasing trends in the northern part are associated with increasing antecedent precipitation. The Mid-ATL region and the southern part of the SE region (North and South Carolina and Virginia) have significant decreasing trends in Q7 values that have increased the risk of hydrological droughts, and are possibly linked to increasing trends in PET driven by warming temperature; 3) the NAO and PNA are potential predictors for the occurrence of extreme low flow events, such that a negative NAO and positive PNA form a favorable condition for drought, and vice versa.

These findings suggest that the risk of low flow droughts over the eastern U.S. is higher during persistent negative NAO and positive PNA conditions, with elevated evaporative demand, and when impacted negatively by human impacts. This suggests that a continuation of the anti-correlation between the PNA and NAO, increasing near-surface air temperature, and increasing human pressures on water resources may exacerbate low flow droughts in the future. The direct anthropogenic impacts on low flows, however, remain uncertain and are highly dependent on local hydrological connectivity, although several studies (Bosch et al. 2003; Brutsaert 2010) have identified linkages between groundwater abstractions and low flows across the eastern coastal plain aquifer. Inter-annual variability in low flows appears to be linked to the PNA and NAO, and recent improvements in the predictability of the NAO (Scaife et al. 2014). at least for the wintertime, provide prospects for low flow prediction. Further work is needed to understand the interplay with large scale Rossby waves and decadal variations in climate (e.g., the relationship between the NAO and PNA), which may modulate the teleconnections shown here (e.g., Hanna et al. 2014).

Acknowledgments This work was supported by the USGS (G11AP20215) and NOAA (NA11OAR4310097). The authors would like to thank Dr. Sara Sadri and Dr. Joshua Roundy for conducting the Pettit test and extracting the corresponding basin masks to the 149 stations. The authors acknowledge the TIGRESS high performance computer center at Princeton University.

References

Andreadis KM, Lettenmaier DP (2006) Trends in 20th century drought over the continental United States. Geophys Res Lett 33:L10403

Bosch DD, Lowrance RR, Sheridan JM, Williams RG (2003) Ground water storage effect on streamflow for a southeastern coastal plain watershed. Ground Water 41:903–912. doi:10.1111/j.1745-6584.2003.tb02433.x

Bradford MJ, Heinonen JS (2008) Low flows, instream flow needs and fish ecology in small streams. Can Water Resour J 33:165–180

Brutsaert W (2010) Annual drought flow and groundwater storage trends in the eastern half of the United States during the past two-third century. Theor Appl Climatol 100:93–103

Castle SL, Thomas BF, Reager JT, Rodell M, Swenson SC, Famiglietti JS (2014) Groundwater depletion during drought threatens future water security of the Colorado River Basin. Geophys Res Lett 41:5904–5911. doi:10.1002/2014GL061055

Coopersmith EJ, Minsker BS, Sivapalan M (2014) Patterns of regional hydroclimatic shifts: an analysis of changing hydrologic regimes. Water Resour Res 50:1960–1983. doi:10.1002/2012WR013320

Dingman SL (2008) Physical hydrology, 2nd edn. Prentice Hall, Old Tappan, NJ

Douglas EM, Vogel RM, Kroll CN (2000) Trends in floods and low flows in the United States: impact of spatial correlation. J Hydrol 240:90–105

Ekstrom M, Jones PD, Lenderink HJ et al (2007) Regional climate model data used within the SWURVE projects. 1: projected changes in seasonal patterns and estimation of PET. Hydol Earth Syst Sci 11:1069–1083

Eng K, Wolock DM, Carlisle DM (2013) River flow changes related to land and water management practices across the conterminous United States. Sci Total Environ 463–464:414–422

Feyen L, Dankers R (2009) Impact of global warming on streamflow drought in Europe. J Geophys Res 114: D17116. doi:10.1029/2008JD011438

Gupta RS (2008) Hydrology and hydraulic systems, 3rd edn. Prentice Hall, Upper Saddle River, NJ

Hamed KH (2008) Trend detection in hydrologic data: the Mann–Kendall trend test under the scaling hypothesis. J Hydrol 349:350–363

Hanna E, Cropper TE, Jones PD, Scaife AA, Allan R (2014) Recent seasonal asymmetric changes in the NAO (a marked summer decline and increased winter variability) and associated changes in the AO and Greenland blocking index. Int J Climatol. doi:10.1002/joc.4157

Hayhoe K, Wake C, Huntington TG, Luo L, Schwartz MD, Sheffield J, Wood EF, Anderson B, Bradbury J, DeGaetano TT, Wolfe D (2007) Past and future changes in climate and hydrological indicators in the US Northeast. Clim Dyn 28:381–407

Hughes AG, van Wonderen JJ, Rees JG et al (2012) How to get your model results used: a guide to stakeholder engagement. In: Shepley MG, Whiteman MI, Hulme PJ, Grout MW (eds) Groundwater resources modelling: a case study from the UK. Geological Society, London, Special Publications, 364, pp 39–48

Kam J, Sheffield J, Wood EF (2014) A multi-scale analysis of drought and pluvial mechanisms for the southeastern United States. J Geophys Res Atmos 119:7348–7367

Kingston DG, McGregor GR, Hannah DM, Lawler DM (2007) Large-scale climatic controls on New England river flow. J Hydrometeorol 8:367–379

Knippertz P, Wernli H (2010) A lagrangian climatology of tropical moisture exports to the Northern Hemispheric extratropics. J Clim 23:987–1003

Konikow L (2013) Groundwater depletion in the United States (1900–2008). U.S. Geological Survey Scientific Investigations Report 2013–5079

Kumar S, Merwade V, Kam J, Thurner K (2009) Streamflow trends in Indiana: effects of long term persistence, precipitation and subsurface drains. J Hydrol 374:171–183

Lins HF (2012) USGS hydro-climatic data network 2009 (HCDN–2009): U.S. Geological Survey Fact Sheet, 2012–3047, 4 p., available only at http://pubs.usgs.gov/fs/2012/3047/

Lins HF, Slack JR (1999) Streamflow trends in the United States. Geophys Res Lett 26:227–230

Livneh B et al (2013) A long-term hydrologically based dataset of land surface fluxes and states for the conterminous United States: update and extensions. J Clim 26:9384–9392

McCabe GJ, Wolock DM (2002) A step increase in streamflow in the conterminous United States. Geophys Res Lett 29. doi: 10.1029/2002GL015999

Patterson LA, Lutz B, Doyle MW (2012) Streamflow changes in the south Atlantic, United States during the mid- and late 20th century. J Am Water Resour Assoc 48:1126–1138

Pettitt AN (1979) A non-parametric approach to the change-point problem. Appl Stat 28:126–135

Pinto JG, Reyers M, Ulbrich U (2011) The variable link between PNA and NAO in observations and in multi-century CGCM simulations. Clim Dyn 36:337–354

Raible CC (2007) On the relation between extremes of midlatitude cyclones and the atmospheric circulation using ERA40. Geophys Res Lett 34:L07703

Sadri S, Kam J, Sheffield J (2015) Non-stationarity of low flows and their timing in the eastern United States. Hydrol Earth Syst Sci Discuss 12:2761–2798. doi:10.5194/hessd-12-2761-2015

Sayemuzzaman M, Jha MK (2014) Seasonal and annual precipitation time series trend analysis in North Carlina, United States. Atmos Res 137:183–194. doi:10.1016/j.atmosres.2013.10.012

Scaife AA et al (2014) Skillful long-range prediction of European and North American winters. Geophys Res Lett 41:2514–2519

Smakhtin VU (2001) Low flow hydrology: a review. J Hydrol 240:147–186

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

U.S. Geological Survey (2014) National water information system data available on the World Wide Web (Water Data for the Nation), accessed [last accessed, August 2014], at URL (http://waterdata.usgs.gov/nwis/)

Ulbrich U, Christoph M (1999) A shift of the NAO and increasing storm track activity over Europe due to anthropogenic greenhouse gas forcing. Clim Dyn 15:551–559

Wada YL, van Beek PH, Wanders N, Bierkens MFP (2013) Human water consumption intensifies hydrological drought worldwide. Environ Res Lett 8:034036. doi:10.1088/1748-9326/8/3/034036

Wanders N, Wada Y, van Lanen HAJ (2014) Global hydrological droughts in the 21st century under a changing hydrological regime. Earth Syst Dyn 6:1–15. doi:10.5194/esd-6-1-2015

Wang CZ (2002) Atlantic climate variability and its associated atmospheric circulation cells. J Clim 15:1516–1536

Wang D, Cai X (2009) Detecting human interferences to low flows through base flow recession analysis. Water Resour Res 45:W07426

Wang CZ, Enfield DB (2001) The tropical western hemisphere warm pool. Geophys Res Lett 28:1635–1638

Wilks DS (2006) Statistical methods in the atmospheric sciences: an introduction. Academic Press, 467 pp