Interdecadal and Interannual Oceanic / Atmospheric Variability and United States Seasonal Streamflow

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Abstract
A study of the influence of interdecadal and interannual oceanic / atmospheric influences on seasonal streamflow in the U.S. is presented. Unimpaired streamflow was identified for 639 stations in the U.S. for the period 1951 – 2002. Pacific Ocean [El Niño-Southern Oscillation (ENSO) and Pacific Decadal Oscillation (PDO)] and Atlantic Ocean [Atlantic Multidecadal Oscillation (AMO)] oceanic / atmospheric phases (e.g., warm or cold) were identified for the year (or season) prior to the year of the winter-spring season streamflow (i.e., long lead-time). Statistical significance testing of the difference in means (and medians) of streamflow, based on the interdecadal and interannual oceanic / atmospheric phase (warm or cold), was performed applying the two-sample \(t\)-test and the rank-sum test. Additionally, the coupled effects of the oceanic / atmospheric influences were evaluated, based on the long-term phase (warm or cold) of the interdecadal variables (PDO and AMO) and ENSO, and streamflow regions in the U.S. were identified that respond to these climatic couplings. The results show that, in addition to the well-established ENSO signal, the PDO and AMO influence streamflow variability in the United States. Additionally, the phase (warm or cold) of the PDO and AMO enhance (or dampen) the ENSO signal in several streamflow regions in the United States. By utilizing the winter-spring streamflow season (e.g., typical period of peak runoff) and the long lead-time for the oceanic / atmospheric variables, useful information can be provided to streamflow forecasters and water managers.

Introduction
Furthermore, recent studies have shown the influence of coupled oceanic / atmospheric variability on climate of regions around the world. Information gathered from such studies could be utilized in long lead-time forecasts of streamflow. The study presented here investigates seasonal streamflow response to the coupled influences of the three of the most well understood oceanic / atmospheric modes of
variability: El Niño-Southern Oscillation (ENSO); the Pacific Decadal Oscillation (PDO); and the Atlantic Multidecadal Oscillation (AMO).

ENSO refers to the interaction of the periodic large-scale warming or cooling of the central-eastern equatorial Pacific Ocean with the Southern Oscillation, a large-scale atmospheric pressure pattern across the tropical Pacific. The warm phase of ENSO is referred to as El Niño and the cool phase is referred to as La Niña. ENSO displays a periodicity of two (2) to seven (7) years [Philander 1990]. The PDO is a oceanic / atmospheric phenomena associated with persistent, bimodal climate patterns in the northern Pacific Ocean (poleward of 20° north) that oscillate with a characteristic period on the order of 50 years (a particular phase of the PDO will typically persist for about 25 years) [Mantua, et al., 1997; Mantua and Hare, 2002]. A similar pattern to the PDO, but occurring in the Atlantic Ocean, is the Atlantic Multidecadal Oscillation (AMO). The AMO is defined as the leading mode of low-frequency, north Atlantic Ocean (0 to 70°) sea surface temperature (SST) variability with a periodicity of 65 to 80 years [Kerr, 2000; Gray et al., 2004]. Similar to ENSO, both the PDO and AMO have cold and warm phases.

The review of recent studies, focusing on the PDO, AMO and ENSO, reveal a clear “teleconnection” between these atmospheric / oceanic phenomena and U.S. hydrologic variability [e.g., Gershunov and Barnett, 1998; Hamlet and Lettenmaier, 1999; Rajagopalan et al., 2000; Hidalgo and Dracup, 2001 and 2003; Enfield et al., 2001; Harshburger et al., 2002; Rogers and Coleman, 2003; McCabe et al., 2004; Hidalgo, 2004]. The goal of the research presented here was to evaluate continental U.S. seasonal streamflow response to the coupling of atmospheric / oceanic variability (ENSO, PDO, AMO). In determining streamflow regions influenced by atmospheric / oceanic variability, verification was accomplished by comparing the results of two statistical methods.

Data
The major datasets used to develop the relationships between oceanic / atmospheric variability and streamflow variability were unimpaired streamflow data for the U.S. and oceanic / atmospheric data for the Pacific and Atlantic Oceans.

Unimpaired streamflow stations for the U.S. were identified from Wallis et al. [1991]. This data set was updated by obtaining current streamflow data from the U.S. Geological Survey (USGS) NWISWeb Data retrieval (http://waterdata.usgs.gov/nwis/). The revised data set consists of average monthly streamflow for 639 unimpaired stations from 1951 to 2002 (Figure 1). In evaluating streamflow runoff volume for six-month continuous periods during the water year (i.e., October to March, January to June and April to September), almost 80% of the stations identified produced the greatest runoff volume during the January to June period. The average monthly streamflow rates (in cubic feet per second – cfs) were averaged for the winter-spring season (January thru June) and converted into streamflow volumes (km³) with proper conversions.
Figure 1: Locations of unimpaired U.S. Geological Survey streamflow stations in the continental United States.

Interdecadal oceanic / atmospheric influences include the Pacific Decadal Oscillation (PDO) and the Atlantic Multidecadal Oscillation (AMO), each displaying warm and cold phases. McCabe et al. [2004] evaluated coupled effects of PDO and AMO for four periods: PDO warm / AMO warm (1926 to 1943), PDO cold and AMO warm (1944 to 1963), PDO cold and AMO cold (1964 to 1976), and PDO warm and AMO cold (1977 to 1994). The periods used in the McCabe et al. [2004] study were adopted for this study with the assumption that the PDO remains in the warm phase until the end of the study period (2001) and the AMO shifts to warm in 1995 and remains until the end of the study period.

The NOAA-CDC (http://www.cdc.noaa.gov/ENSO/Compare/) defined the ENSO summer season as May to September and identified core El Niño and La Niña years for the summer season. The summer season was selected for ENSO since it was better represented by a season (e.g., an interannual oceanic / atmospheric phenomena). Various techniques were available to define the occurrence of a seasonal ENSO event [e.g., Gershunov, 1998; Hamlet and Lettenmaier, 1999; Harshburger et al., 2002; Rogers and Coleman, 2003]. When evaluating ENSO and PDO, Gershunov and Barnett [1998] defined a seasonal El Niño (La Niña) as when the anomaly in the Niño 3.4 sea surface temperature region [Trenberth 1997] is greater (lesser) than 0.8 standard deviations of the long-term mean. They concluded that this value was high enough to exclude questionable ENSO events and would allow for an adequate number of ENSO events when combining the PDO [Gershunov and Barnett, 1998]. For this study, the approach of Gershunov and Barnett [1998] was applied to the Niño 3.4 index and the Troup Southern Oscillation Index (www.bom.gov.au) for the summer (May to September) season and the results (summer season ENSO years identified) were used to compliment the NOAA-CDC core summer season ENSO year data set (i.e., recognize and incorporate additional ENSO years). This provides an adequate number of ENSO events to evaluate the impacts of the PDO and the AMO while excluding questionable ENSO events [Gershunov and Barnett, 1998].
Methodology
The impacts of the various interdecadal (PDO and AMO) and interannual (ENSO) oceanic / atmospheric influences on U.S. streamflow (639 stations) were evaluated by testing of streamflow means (and medians) for the individual and coupled oceanic / atmospheric influences. The current winter-spring (January thru June) season was the period selected for streamflow. The previous year (or season) was selected to define the phase (e.g., warm or cold) of the PDO, the AMO and ENSO. This analysis evaluated the current year winter-spring season streamflow response (e.g., positive or negative shifts in means or medians) to the previous year (or season) of the oceanic / atmospheric (PDO, AMO, ENSO) phase. The testing performed here was for both the individual and coupled oceanic / atmospheric indices with streamflow.

The parametric Two-sample \( t \)-test [Maidment, 1993] and the nonparametric Rank-sum test [Maidment, 1993] were performed on the response of streamflow means (and medians) to changes in oceanic / atmospheric phase, including coupling. The use of the two different statistical tests allow for the comparison of a parametric (Two-sample \( t \)-test of the difference in mean streamflow) and a nonparametric (Rank-sum test of the difference in median streamflow) method. These methods compare two independent data sets and determine if one data set has significantly larger values than the other data set [Maidment, 1993]. The \( t \)-test assumes that the two data sets are normal with equal variances while the Rank-sum test assumes the two data sets are identically distributed [Maidment, 1993]. Typically, streamflow is not normally distributed, which would result in a decrease in the power of the \( t \)-test [Maidment, 1993].

Results
Initially, the phases (cold and warm) were evaluated for the PDO, AMO and ENSO such that significant (greater than 90%, 95% or 99%) differences in streamflow means (medians) were reported. Next, the coupled impacts of the interdecadal PDO (and AMO) phases on La Niña (and El Niño) on streamflow means (medians) were evaluated. Triangles represent a negative difference while circles represent a positive difference. The size of the symbol (triangle or circle) represents the magnitude of the significance level (i.e., the larger the size, the larger the significance). The shade (or color) of the symbol represents which test (or tests) was significant. A “hollow” or “open” symbol signifies that only the \( t \)-test provided a significant result. A “grey” symbol signifies that only the rank-sum test provided a significant result. Finally, a “black” or “filled” symbol signifies that both tests provided a significant result. In the case that both tests provided a significant result, if the significance levels were different (i.e., \( t \)-test of +95% and rank-sum test of +99%), the smaller of the two tests were reported (i.e. symbol size).

PDO, AMO, and ENSO Phases
Three distinct regions (Upper / Middle Mississippi River basin, Pacific Northwest and Southwest) were identified in which a difference in mean and median streamflow, between a PDO cold phase and a PDO warm phase, were significant (Figure 2a). The Upper / Middle Mississippi River basin and Southwest display a strong, negative difference (i.e., PDO warm phase results in greater streamflow than
PDO cold phase). The opposite (positive difference) was displayed for the Pacific Northwest. For the majority of the stations, both the \( t \)-test and rank-sum test provided similar results. Hamlet and Lettenmaier [1999]; Harshburger et al. [2002] and Beebee and Manga [2004] established the PDO signal in Pacific Northwest streamflow while Nigam et al. [1999] linked PDO to the Upper / Middle Mississippi River basin.

![Figure 2](image1)

(a)

![Figure 2](image2)

(b)

![Figure 2](image3)

(c)

**Figure 2:** Significant (90\%, 95\% and 99\%) difference in winter-spring streamflow means (medians) for (a) PDO Cold – PDO Warm, (b) AMO Cold – AMO Warm, (c) La Niña – El Niño.

Significant positive (i.e., AMO cold phase results in increased streamflow when compared to AMO warm phase) regions (Figure 2b) were identified in the Middle Mississippi River basin, Gulf of Mexico and Southwest. A significant negative region was identified in the Pacific Northwest and the Florida peninsula. Rogers and Coleman [2003] identified a positive region in the Upper Mississippi River basin for
core years of the AMO cold and warm phases. However, the Pacific Northwest (negative region) was not identified. This may be attributed to several factors including using only the core years of the AMO and using the winter season streamflow (i.e., no snowmelt) in lieu of the winter-spring season. Enfield et al. [2001] also identified the trend that AMO warm phase results in increased streamflow when compared to AMO cold phase in south Florida.

The well-established ENSO signal was displayed in Florida / Southern Georgia, the Southwest, the Upper Ohio River basin and the Pacific Northwest (Figure 2c). A strong negative (i.e. El Niño resulted in increased streamflow when compared to La Niña) differences in mean (median) streamflow is displayed for Florida / Southern Georgia and the Southwest, while the opposite occurs for the Upper Ohio River basin and the Pacific Northwest. Kahya and Dracup [1993a, 1993b, 1994a and 1994b] established a connection between ENSO occurrence and streamflow response in these regions. Hamlet and Lettenmaier [1999]; Harshburger et al. [2002]; and Beebee and Manga, [2004] identified the ENSO signal in the Pacific Northwest. Clark et al. [2001] investigated streamflow in the Lower Colorado River Basin and found that in El Niño years there is above-normal streamflow.

**Coupled ENSO – PDO and AMO Phases**

Negative differences in mean and median streamflow occur in the Upper / Middle Mississippi River basin region for El Niño / PDO cold phase – El Niño / PDO warm phase (Figure 3a). This indicates that, given the occurrence of an El Niño, the PDO warm (cold) phase enhances (dampens) the El Niño impacts to streamflow in this region.

In the Pacific Northwest, a La Niña event typically results in increased streamflow. Positive differences in mean and median streamflow occur in the Pacific Northwest region for La Niña / PDO cold phase – La Niña / PDO warm phase (Figure 3b). Given the occurrence of a La Niña, the PDO cold (warm) phase enhances (dampens) the La Niña impacts to streamflow in this region. Gershunov and Barnett [1998] found similar results when evaluating rainfall and noted that, when ENSO (El Niño – warm or La Niña – cold) are in phase with the PDO (warm or cold), the signals are strong and stable. The Lower Appalachian region also displays a positive difference, although generally not recognized as an ENSO influenced region.
Figure 3: Significant (90%, 95% and 99%) difference in winter-spring streamflow means (medians) for (a) El Niño / PDO Cold – El Niño / PDO Warm, (b) La Niña / PDO Cold – La Niña / PDO Warm.

Given the occurrence of an El Niño, two distinct regions (Upper / Middle Mississippi River basin and Pacific Northwest) were identified in which the AMO phase impacts streamflow (Figure 4a). El Niño increases streamflow in the Upper / Middle Mississippi River and the AMO cold phase also increases streamflow in this region. Given the occurrence of an El Niño, coupled with the AMO cold phase, streamflow is significantly less in the Pacific Northwest when compared to the coupling of El Niño and AMO warm phase (Figure 4a).

A La Niña event generally results in lower streamflow in the Southeast. The AMO cold (warm) phase dampens (enhances) La Niña in this region (Figure 4b). La Niña events occurring in an AMO cold phase result in significantly greater streamflow than those occurring in an AMO warm phase (Figure 4b).
Figure 4: Significant (90%, 95% and 99%) difference in winter-spring streamflow means (medians) for (a) El Niño / AMO Cold – El Niño / AMO Warm, (b) La Niña / AMO Cold – La Niña / AMO Warm.

Conclusions

The individual and coupled impacts of ENSO, PDO, and AMO on U.S. streamflow were presented in this study. The phase of the PDO (and AMO) displays enhancement (and dampening) of El Niño and La Niña in several regions. PDO cold (warm) phase dampens (enhances) El Niño in the Upper Mississippi River basin while PDO cold (warm) phase enhances (dampens) La Niña in the Pacific Northwest. AMO cold (warm) phase enhances (dampens) El Niño in the Upper Mississippi River basin and the Pacific Northwest. AMO cold (warm) phase dampens (enhances) La Niña in the Southeast.

It is noteworthy, that as of January 2005, there is an established PDO cold phase and AMO warm phase. These phases should persist for the next 10 to 20 years. The results of this study show that, when evaluated individually, the PDO cold phase (when compared to the PDO warm phase) results in decreased streamflow in the Midwest and Southwest, and increased streamflow in the Pacific Northwest. The results are identical for the AMO warm phase in each of these regions. This could result in long-term decreased streamflow in the Midwest and Southwest and increased streamflow in the Pacific Northwest.
Acknowledgments
This research is supported by the U.S. Geological Survey State Water Resources Research Program, the National Science Foundation award CMS-0239334, and the National Science Foundation, State of Nevada EPSCOR Fellowship.

References


