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Coupled oceanic-atmospheric variability and U.S. streamflow

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[1] A study of the influence of interdecadal, decadal, and interannual oceanic-atmospheric influences on streamflow in the United States is presented. Unimpaired streamflow was identified for 639 stations in the United States for the period 1951–2002. The phases (cold/negative or warm/positive) of Pacific Ocean (El Niño–Southern Oscillation (ENSO) and Pacific Decadal Oscillation (PDO)) and Atlantic Ocean (Atlantic Multidecadal Oscillation (AMO) and North Atlantic Oscillation (NAO)) oceanic-atmospheric influences were identified for the year prior to the streamflow year (i.e., long lead time). Statistical significance testing of streamflow, based on the interdecadal, decadal, and interannual oceanic-atmospheric phase (warm/positive or cold/negative), was performed by applying the nonparametric rank-sum test. The results show that in addition to the well-established ENSO signal the PDO, AMO, and NAO influence streamflow variability in the United States. The warm phase of the PDO is associated with increased streamflow in the central and southwest United States, while the warm phase of the AMO is associated with reduced streamflow in these regions. The positive phase of the NAO and the cold phase of the AMO are associated with increased streamflow in the central United States. Additionally, the coupled effects of the oceanic-atmospheric influences were evaluated on the basis of the long-term phase (cold/negative or warm/positive) of the interdecadal (PDO and AMO) and decadal (NAO) influences and ENSO. Streamflow regions in the United States were identified that respond to these climatic couplings. The results show that the AMO may influence La Niña impacts in the Southeast, while the NAO may influence La Niña impacts in the Midwest. By utilizing the streamflow water year and the long lead time for the oceanic-atmospheric variables, useful information can be provided to streamflow forecasters and water managers.

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1. Introduction

[2] There is an increasing awareness that the oceanic-atmospheric variability occurs on interannual, decadal and interdecadal timescales. 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 continental U.S. streamflow response to the coupled influences of four oceanic-atmospheric modes of variability: El Niño–Southern Oscillation (ENSO), the Pacific Decadal Oscillation (PDO), the Atlantic Multidecadal Oscillation (AMO), and the North Atlantic Oscillation (NAO).

[3] 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 [*Philander*, 1990] with a periodicity of two (2) to seven (7) years. 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]. The Atlantic Multidecadal Oscillation (AMO) is defined as the leading mode of low-frequency, North Atlantic Ocean (0°–70°) sea surface temperature (SST) variability with a periodicity of 65–80 years [*Kerr*, 2000; *Gray et al.*, 2004]. The North Atlantic Oscillation (NAO) is associated with a meridional oscillation in atmospheric mass between Iceland and the

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Azores [*Hurrell and Van Loon*, 1995]. The NAO has displayed quasi-biennial and quasi-decadal behavior since the late 1800s [*Hurrell and Van Loon*, 1995] and its behavior is generally referred to as decadal. Similar to ENSO, the PDO, AMO and NAO have cold/negative and warm/positive phases.

[4] Recent research has focused on the coupling of the interannual ENSO phenomenon with PDO, AMO and NAO. *Gershunov and Barnett* [1998] evaluated the PDO's influence on ENSO for sea level pressures and heavy daily precipitation in the continental United States. El Niño (La Niña) signals were found to be strong and stable during the warm (cold) PDO phase. *Harshburger et al.* [2002] determined that the largest departures for Idaho spring streamflow occurred during the La Niña/PDO cold phase. This is consistent with the findings of *Gershunov and Barnett* [1998] that ENSO (El Niño or La Niña) is strongest during the similar PDO (warm or cold) phase. In forecasting Columbia River streamflow, *Hamlet and Lettenmaier* [1999] defined six climate categories for ENSO (warm, cold or neutral) and PDO (warm or cold). The utilization of the climate categories significantly improved long lead time forecasts. Also in the Pacific Northwest, *Beebee and Manga* [2004] found significant relationships between seasonal streamflow and, both ENSO and PDO. *Pizarro and Lall* [2002], when evaluating flood potential in the western United States using partial correlation, identified coupled PDO-ENSO regions in the Pacific Northwest, upper Colorado River basin and Southwest.

[5] *Rajagopalan et al.* [2000] examined the coupled effects of ENSO, PDO, and the NAO on summer season Palmer drought severity index (PDSI) values for the United States and determined that PDO (or NAO) does not enhance (or dampen) ENSO's effect on PDSI for the seasons (and period of record) evaluated. *Hidalgo and Dracup* [2001, 2003] evaluated spring-summer streamflow and rainfall in the upper Colorado River basin, considering the influence of ENSO and PDO and acknowledged a possible ENSO – PDO modulation of cold season precipitation in the northern Rocky Mountains and the upper Colorado River basin appears to be strongly influenced by the AMO. *McCabe et al.* [2004] attributed more than 50% of the United States spatial and temporal variance in multidecadal drought frequency to the PDO and AMO. The largest drought in the past 250 years (based on tree ring reconstructions) in the Yellowstone basin occurred during an AMO warm–PDO warm cycle [*Hidalgo*, 2004]. In evaluating the AMO's impact on rainfall, *Enfield et al.* [2001] determined that the majority of the United States has less than normal rainfall during the AMO warm phase. *Rogers and Coleman* [2003] evaluated interactions between the AMO, ENSO, the Pacific North American (PNA) teleconnection pattern and streamflow in the United States. The streamflow response to the shift in phase of the AMO was apparent in the upper Mississippi River basin, the northern Rocky Mountain region, and upper Colorado River basin [*Rogers and Coleman*, 2003].

[6] The goal of the research presented here was to improve the understanding of how large-scale interannual and interdecadal ocean-atmosphere phenomena (both individually and coupled) influence hydrologic variability in the continental United States. Much of the prior research has focused on specific regions of the United States and certain phenomenon; however, the comprehensive investigation of large regions (i.e., the entire continental United States) is important since it is expected that the large-scale ocean atmosphere phenomena (i.e., ENSO, PDO, AMO, and NAO) may influence hydrology at a large scale. Furthermore, an updated continental U.S. streamflow data set was developed. This is important since the study of interdecadal influences requires an extended period of record. To attain the research goal, nonparametric testing was utilized to evaluate the large-scale response of U.S. streamflow to the phase of PDO, AMO, NAO, and ENSO. Additionally, the coupled response of PDO, AMO, or NAO with ENSO was evaluated to determine if there was any influence of hydrologic variability in regions impacted by ENSO.

2. Data

[7] The major data sets used to develop the relationships between oceanic-atmospheric variability and streamflow variability are unimpaired streamflow data for the United States and oceanic-atmospheric data for the Pacific and Atlantic Oceans.

2.1. Streamflow Data

[8] Unimpaired streamflow stations for the United States were identified from *Wallis et al.* [1991]. This data set consists of average monthly streamflow for 1,009 unimpaired stations from 1948 to 1988. 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). The reduction of 370 (1009 minus 639) unimpaired streamflow stations was a result of the data not being updated on the USGS website and missing data. A review of the USGS NWISWeb resulted in 172 stations not having updated data, 184 stations missing a year (or multiple years) of data and 14 stations missing both updated and a year (or multiple years) of data. However, extending the period of record was important because it provided both recent data and, increased the number of years used when performing the analysis. The average monthly streamflow rates (in cubic feet per second (cfs)) were averaged for the water year (October of the previous year to September of the current year) and converted into streamflow volumes (km^3) with proper conversions. Water year streamflow data covering a period from 1951 to 2002 (52 years) were then used in the following analysis. Interdecadal and interannual climatic indices were evaluated 1 year prior (1950–2001) to streamflow and are described in the following sections.

2.2. Interdecadal and Decadal Oceanic Data (PDO, AMO, and NAO)

[9] Interdecadal and decadal oceanic-atmospheric indicators include the Pacific Decadal Oscillation (PDO), Atlantic Multidecadal Oscillation (AMO) and the North Atlantic Oscillation (NAO). PDO Index values are available from the Joint Institute for the Study of the Atmosphere and Ocean, University of Washington (http://tao.atmos.washington.edu/pdo/). For the period 1900 to present, the warm phase (1925–1945 and from 1977 to present) of the

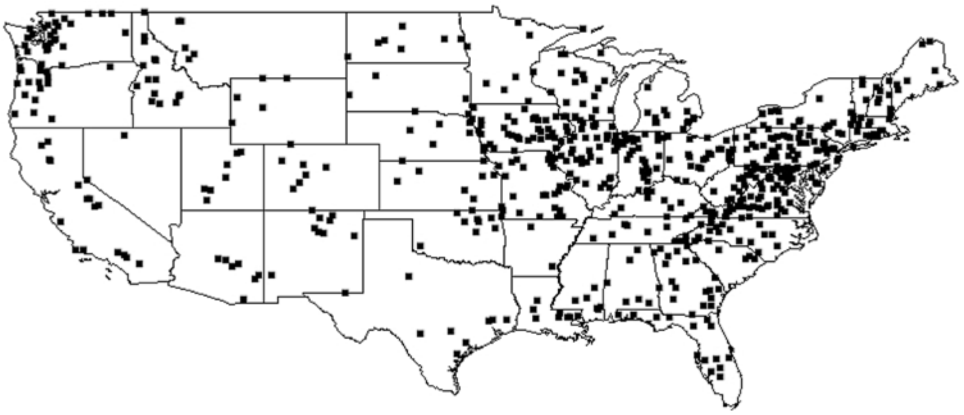

Figure 1. Locations of unimpaired U.S. Geological Survey streamflow stations in the continental United States.

PDO Index was a positive numerical index value while the cold phase (1900–1925 and 1945–1977) was a negative numerical value [*Mantua et al.*, 1997; *Hare and Mantua*, 2000]. A review of the PDO Index indicates a shift to the cold phase around 1999 or 2000.

[10] The AMO index consists of detrended SST anomalies for the previously defined Atlantic Ocean region. AMO index values are available from the National Oceanic and Atmospheric Administration (NOAA) Climate Diagnostics Center (CDC) (http://www.cdc.noaa.gov/ClimateIndices/). From 1856 to present, the AMO exhibited a 65 to 80 year cycle. The AMO is defined as being in a warm phase from 1860 to 1880 and 1930 to 1960 and cool phases from 1905 to 1925 and 1970 to 1990. Recent studies suggest that the AMO returned to a warm phase in 1995 [*Enfield et al.*, 2001; *McCabe et al.*, 2004; *Gray et al.*, 2004]. While *Rogers and Coleman* [2003] limited their evaluation of the AMO to the central core of the AMO warm (1936–1956) and the AMO cold (1968–1988), *McCabe et al.* [2004] evaluated coupled effects of PDO and AMO for four periods: PDO warm and AMO warm (1926–1943), PDO cold and AMO warm (1944–1963), PDO cold and AMO cold (1964–1976), and PDO warm and AMO cold (1977–1994). This analysis eliminates the two transitional periods (1961–1969 and 1991–1994) of the AMO. The periods for the PDO and AMO used in the *McCabe et al.* [2004] study were adopted for this study. In addition, the recent changes of the PDO to cold in 2000 and the AMO to warm in 1995 were used in this study (Table 1).

[11] The NAO Index is defined as the difference in normalized mean winter (December to March) sea level pressure (SLP) anomalies between Iceland and Portugal [*Hurrell*, 1995]. The SLP anomalies were standardized by subtracting the mean and dividing by the standard deviation. NAO index values were obtained from the National Center for Atmospheric Research (NCAR) Web site (http://www.cgd.ucar.edu/cas/jhurrell/indices.html). Since 1864, the NAO has displayed both interannual variability and long-term persistence in a particular phase [*Hurrell and Van Loon*, 1995]. *Hurrell and Van Loon* [1995] applied a low-pass filter to the yearly NAO Index values to remove fluctuations of less than four years. This resulted in a negative (low) phase during the early 1950s to 1970s, a positive/negative fluctuation during the 1970s to early 1980s, and a positive (high) phase from the early 1980s to mid-1990s. When applying the low-pass filter to current (1996 to 2004) NAO Index values obtained from the NCAR website, the NAO has maintained a positive phase into the

Table 1. Years Identified as Warm/Positive or Cold/Negative for the PDO, AMO, NAO, and ENSO (1950–2001)

	PDO	AMO	NAO	ENSO
Cold Negative	1950–1976, 2000–2001	1964–1994	1952–1972, 1977–1980	1950,[a] 1954, 1955,[a] 1956,[a] 1964,[a] 1970, 1971,[a] 1973, 1974,[a] 1975, 1981, 1988,[a] 1998, 1999[a]
Warm Positive	1977–1999	1950–1963, 1995–2001	1950–1951, 1973–1976, 1981–2001	1953, 1957, 1963, 1965,[a] 1969, 1972,[a] 1977, 1982,[a] 1987,[a] 1991,[a] 1993,[a] 1994,[a] 1997[a]

[a] Denotes core ENSO years per NOAA-CDC.

early 2000s. The NAO Index phases, as defined by *Hurrell and Van Loon* [1995] were used in this study with the NAO remaining in a positive phase from 1995 until the end of the period of record (Table 1).

2.3. Interannual Oceanic Data (ENSO)

[12] Currently there is no single data set that is universally accepted for the measurement of ENSO [*Beebee and Manga*, 2004]. Two data sets typically used to evaluate the magnitude of ENSO include the Niño 3.4 [*Trenberth*, 1997] sea surface temperature (SST) region and the Troup Southern Oscillation Index (SOI). The Niño 3.4 SST region is located along the equatorial Pacific Ocean (5°S–5°N, 170°–120°W) and monthly index data were obtained from the National Weather Service (NWS) Climate Prediction Center (CPC) (http://www.cpc.ncep.noaa.gov/data/indices/). The Troup SOI, used by the Australian Bureau of Meteorology (ABOM), is the standardized anomaly of the mean sea level pressure difference between Tahiti and Darwin. Monthly Troup SOI values were obtained from the ABOM (http://www.bom.gov.au).

[13] 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 occurs prior to the beginning of the streamflow water year and ENSO (e.g., an interannual oceanic-atmospheric phenomena) was better represented by a season. Various techniques were available to define the occurrence of a summer season ENSO event. In identifying winter (December to February) ENSO events, *Gershunov* [1998] defined a winter El Niño (La Niña) as when the anomaly in the Niño 3.4 SST region is greater (lesser) than 1.1 standard deviations of the long-term mean. When evaluating ENSO and PDO, *Gershunov and Barnett* [1998] reduced the value to 0.8 times the standard deviation. 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]. *Hamlet and Lettenmaier* [1999] reduced this value to 0.5 standard deviations. *Harshburger et al.* [2002] identified an ENSO event when the seasonal mean Niño 3.4 SST anomalies are greater (less) than +0.5°C (−0.5°C). *Rogers and Coleman* [2003] identified extreme warm (El Niño) and cold (La Niña) events when the Niño 3.4 SST anomaly exceeded absolute 0.75°C.

[14] For this study, the approach of *Gershunov and Barnett* [1998] was applied to the Niño 3.4 index and Troup SOI index 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, AMO and NAO while excluding questionable ENSO events [*Gershunov and Barnett*, 1998]. Table 1 summarizes the ENSO events used in this study.

3. Methodology

[15] First, the individual impacts of the interdecadal or decadal (PDO, AMO or NAO) oceanic-atmospheric influence on continental U.S. streamflow (639 stations) was evaluated. Next, the individual impact of the interannual ENSO on continental U.S. streamflow was evaluated. Finally, an evaluation of the impacts of the coupling of the interdecadal (PDO, AMO or NAO) influence with the interannual ENSO on continental U.S. streamflow was performed.

[16] The nonparametric rank-sum test [*Maidment*, 1993] was performed on the response of streamflow medians to changes in oceanic- atmospheric phase, including coupling. The method compares two independent data sets and determines if one data set has significantly larger values than the other data set. The rank-sum test assumes the two data sets are identically distributed and there is no assumption of normality. Typically, streamflow is not normally distributed. Additionally, this approach does not assume any form of linear relationship as is inherent in correlation analysis. A limitation of nonparametric analysis is that the inherent extremes in hydrologic data are not well represented. For the analysis presented in this paper, the general shift in streamflow data is of interest and not necessarily the occurrence of extreme hydrologic events. Additionally, the assumption of identical distributions between the two data sets can sometimes be difficult to verify due to the limited number of years in each data set.

3.1. Nonparametric Testing of Interdecadal (PDO, AMO, or NAO) Phases (Cold or Warm) on Streamflow

[17] The phases (cold/negative or warm/positive) were evaluated for the PDO, AMO or NAO such that significant (greater than 95%) differences in streamflow medians were reported. For each of the interdecadal influences, significant continental U.S. streamflow regions (i.e., Pacific Northwest) were identified. For each region, the individual stations were identified and the yearly (water year) streamflow volume (standardized anomaly) was determined. Finally, the yearly values for all stations in the region were averaged to produce a composite time series of yearly streamflow.

3.2. Nonparametric Testing of Interannual ENSO Phases (Cold, La Niña, or Warm, El Niño) on Streamflow

[18] The phases (cold, La Niña, and warm, El Niño) were evaluated for ENSO such that significant (greater than 95%) differences in streamflow medians were reported. Similar to the interdecadal evaluation in 3.1, significant continental U.S. streamflow regions (i.e., Pacific Northwest) were identified. For each region, the individual stations were identified and the yearly (water year) streamflow volume (standardized anomaly) was determined. Finally, the yearly values for all stations in the region were averaged to produce a composite time series of yearly streamflow.

3.3. Nonparametric Testing of Coupling of Interdecadal (PDO, AMO, or NAO) and Interannual ENSO on Streamflow

[19] The impacts of the coupling of the interdecadal or decadal (PDO, AMO or NAO) influence with the interannual ENSO on continental U.S. streamflow were performed. An evaluation was performed of the impact of the interdecadal phase (e.g., PDO, cold, and PDO, warm) on a specific phase (e.g., cold, La Niña) of ENSO. This analysis identifies continental U.S. streamflow regions in which the interdecadal phase influences La Niña (or El Niño). Each

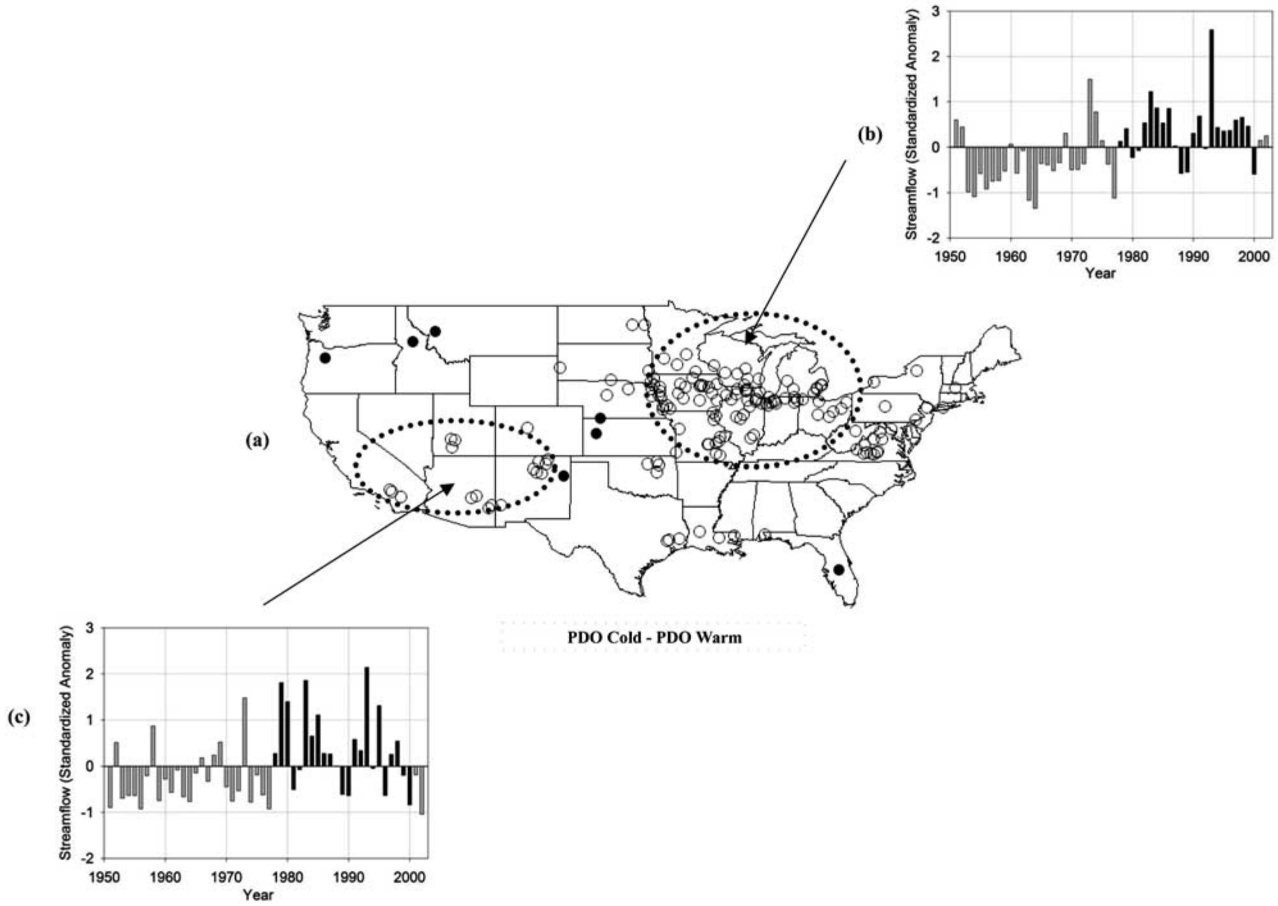

Figure 2. (a) Significant (95%) difference in streamflow medians for PDO cold – PDO warm. Positive (negative) significance is represented by solid (open) circles. Yearly streamflow (standardized anomaly) averaged for all stations in regions (b) Midwest and (c) Southwest. Gray (black) bars represent PDO cold (warm) years.

data set tested consists of only La Niña (or El Niño) years. If testing was performed and a significant region (or regions) was identified, it was concluded that the interdecadal phase does impact La Niña (or El Niño). However, if a significant region (or regions) was not identified, it was concluded that the interdecadal phase does not impact La Niña (or El Niño).

4. Results

[20] The results of the nonparametric testing are presented in Figures 2–7. For the continental U.S. streamflow maps, a solid (open) circle represents a positive (negative) test result at the 95% confidence level. Additionally, plots (vertical bar charts) are provided representing the average yearly streamflow (standardized anomaly) for all stations in a defined region. The black bars represent warm/positive years, and the gray bars represent cold/negative years.

4.1. Interdecadal (PDO and AMO) and Decadal (NAO) Testing

4.1.1. PDO

[21] Figure 2 presents the results of nonparametric testing of the PDO cold and warm phases. Two distinct regions (upper to middle Mississippi River basin and Southwest) were identified in which a difference in streamflow, between a PDO cold phase and a PDO warm phase, were significant (Figure 2a). The upper to 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 difference in streamflow was also apparent in the streamflow regional time series (Figures 2b and 2c). For the upper to middle Mississippi River (Southwest) basin, 69% (79%) of the years were below normal streamflow during the PDO cold phase while 74% (65%) of the years were above normal streamflow during the PDO warm phase. *Nigam et al.* [1999] linked PDO to the upper to middle Mississippi River basin while *Hamlet and Lettenmaier* [1999], *Harshburger et al.* [2002], and *Beebee and Manga* [2004] established the PDO signal in Pacific Northwest streamflow. The current research identified only three statistically significant streamflow stations in the Pacific Northwest, and thus the results differ from the previous studies cited. This could be attributed to the period of record, season or lagged approached used in the current research.

[22] The physical mechanisms related to climate influences of the PDO are similar to way that ENSO impacts on

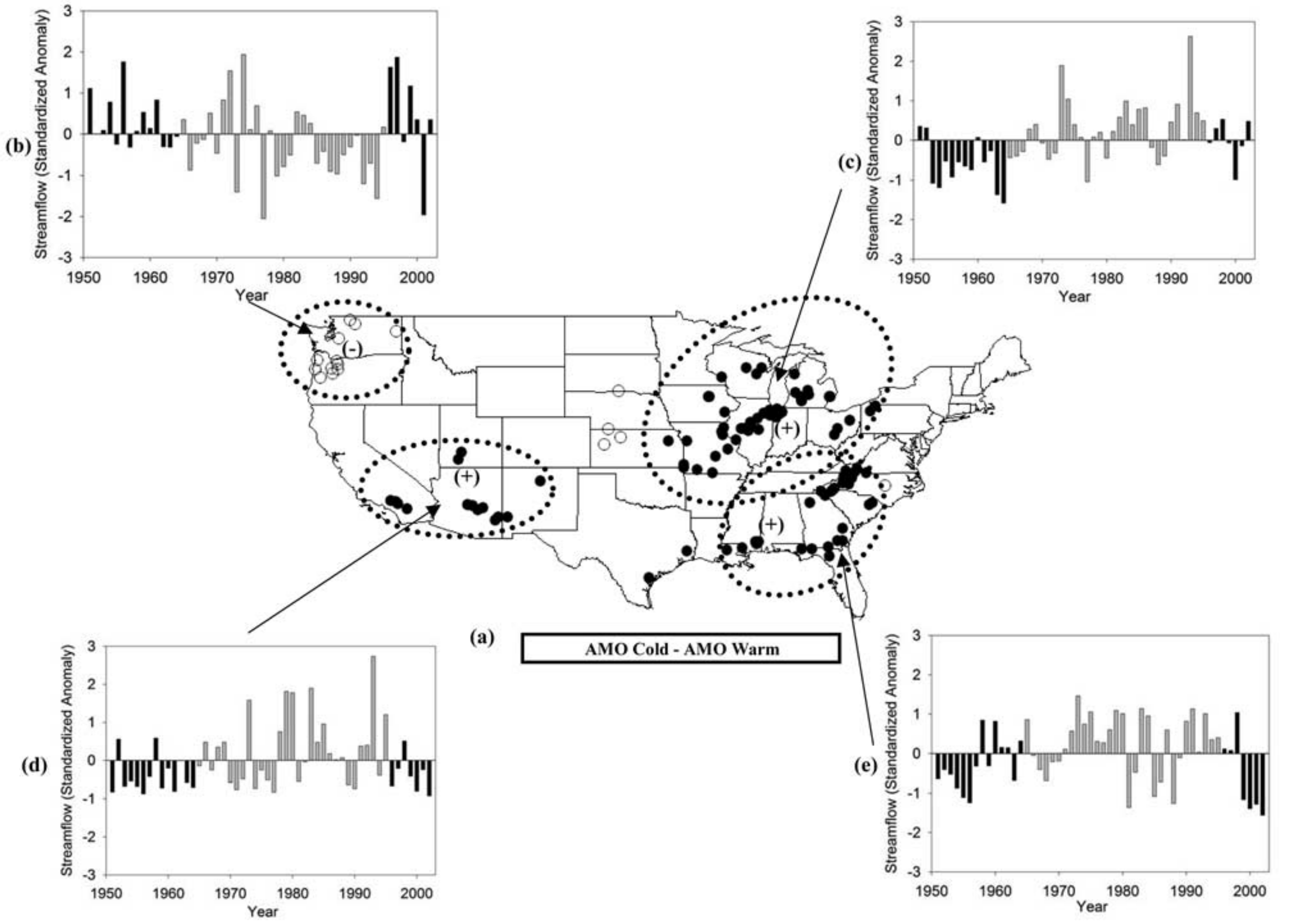

Figure 3. (a) Significant (95%) difference in streamflow medians for AMO cold – AMO warm. Positive (negative) significance is represented by solid (open) circles. Yearly streamflow (standardized anomaly) averaged for all stations in regions (b) Northwest, (c) Midwest, (d) Southwest, and (e) Southeast. Gray (black) bars represent AMO cold (warm) years.

large-scale circulation patterns. During the PDO warm phase, there is an intensification of the Aleutian Low in the North Pacific and higher sea level pressures in the western United States. This results in a southerly shift in the jet stream and intensification of the subtropical jet stream that influences the southern United States [*Mantua and Hare*, 2002].

4.1.2. AMO

[23] Figure 3 presents the results of nonparametric testing of the AMO cold and warm phases. Significant positive (i.e., AMO cold phase results in increased streamflow when compared to AMO warm phase) regions were identified in the upper to middle Mississippi River basin, lower Appalachians/Gulf of Mexico, and Southwest (Figure 3a). A significant negative region was identified in the Pacific Northwest. The streamflow regional time series (Figures 3b, 3c, 3d, and 3e) show the distinct difference in streamflow response between the regions. During the initial (1950 to 1963) AMO warm phase, the upper to middle Mississippi River basin, the lower Appalachians/Gulf of Mexico and Southwest experience below normal yearly streamflow for 79%, 86% and 64% of the 14 year period of record, respectively, while the Pacific Northwest was above normal for 64% for the same period. It is noteworthy that a large number of extreme (i.e., yearly streamflow anomaly greater than one) years occur in the Southwest (Figure 3d) and the Appalachians/Gulf of Mexico (Figure 3e) during the AMO cold phase. Each region experiences a significant (i.e., greater than one) number of "flood" years during the AMO cold. While some of this variation can be attributed to ENSO, several extreme years were not influenced by ENSO or, in the Southeast, hurricane activity. *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 water year. *Enfield et al.* [2001], when correlating the AMO with rainfall, identified a large pattern of significantly negative correlations throughout the United States, except for positive correlations in the Pacific Northwest, thus demonstrating the opposite response to the AMO. *Enfield et al.* [2001] also discussed the physical mechanisms associated with the AMO phases and found that there was an opposite response in winter cyclonic activity in the

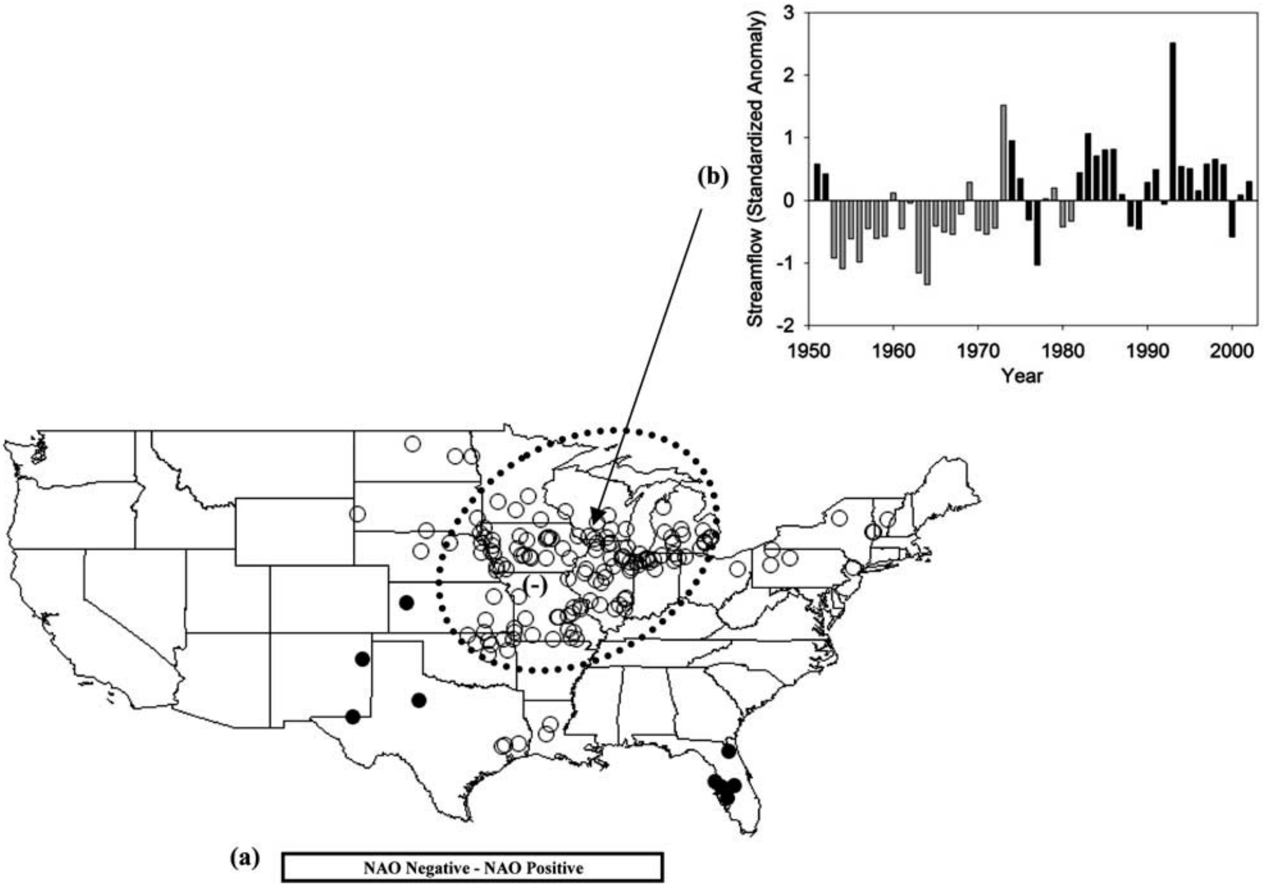

Figure 4. (a) Significant (95%) difference in streamflow medians for NAO cold – NAO warm. Positive (negative) significance is represented by solid (open) circles. (b) Yearly streamflow (standardized anomaly) averaged for all stations in the region Midwest. Gray (black) bars represent NAO negative (positive) years.

Pacific Northwest and the Southwest as represented in the 500 hPa geopotential heights.

4.1.3. NAO

[24] Figure 4 presents the results of nonparametric testing of the NAO negative and positive phases. A distinct region (upper to middle Mississippi River basin) was identified in which a difference in streamflow, between a NAO negative (low) phase and a NAO positive (high) phase, was significant (Figure 4a). The NAO positive phase results in increased streamflow when compared to the NAO negative phase in the upper to middle Mississippi River basin (Figure 4b). *Visbeck et al.* [2001] observed that during a positive NAO, conditions are warmer and wetter than average in the eastern United States. These climate impacts may be due to the northern shift of the jet stream during the NAO positive phase [*Visbeck et al.*, 2001]. The results of the current research did not identify statistically significant streamflow stations in the eastern United States.

4.2. ENSO Testing

[25] Figure 5 presents the results of nonparametric testing of ENSO cold (La Niña) and warm (El Niño) phases. The well-established ENSO signal was displayed in Florida, the Southwest and the Pacific Northwest (Figure 5a). Strong negative (i.e., El Niño resulted in increased streamflow when compared to La Niña) differences in streamflow for Florida, Arizona and Southern California while the opposite occurs for the Pacific Northwest. These results were also apparent in the streamflow time series (Figures 5b, 5c, and 5d). *Kahya and Dracup* [1993a, 1993b, 1994a, 1994b] established a lag between ENSO and streamflow response in these regions. *Zorn and Waylen* [1997] and *Schmidt et al.* [2001] reported the ENSO signal in Florida while the previously cited studies of *Hamlet and Lettenmaier* [1999], *Harshburger et al.* [2002], and *Beebee and Manga* [2004] focused on 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. As noted earlier, the ENSO impacts can be explained by the southerly shift in the jet stream during the warm (El Niño) phase.

4.3. Coupling of Interdecadal (PDO, AMO, or NAO) and ENSO Testing

4.3.1. PDO and ENSO

[26] The coupling of PDO and ENSO was evaluated by examining streamflow relationships for PDO cold/El Niño – PDO warm/El Niño and PDO cold/La Niña – PDO warm/La Niña. The results of the nonparametric rank-sum testing provided minimal to no stations, and therefore the

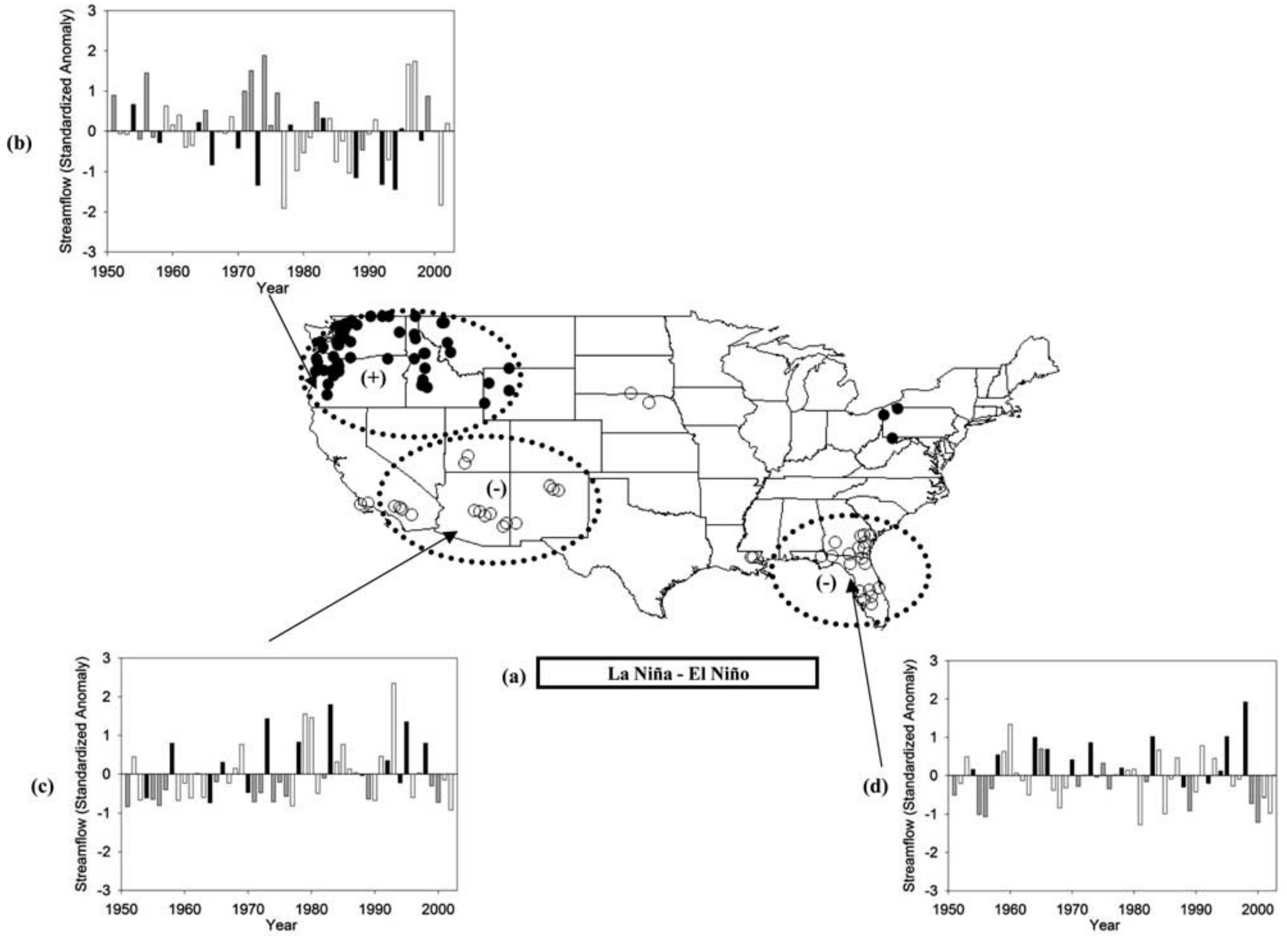

Figure 5. (a) Significant (95%) difference in streamflow medians for La Niña – El Niño. Positive (negative) significance is represented by solid (open) circles. Yearly streamflow (standardized anomaly) averaged for all stations in regions (b) Northwest, (c) Southwest, and (d) Southeast. Gray (black) bars represent ENSO cold (warm) years while white bars represent neutral years.

impact of the PDO phase on El Niño (or La Niña) was not reported. *Rajagopalan et al.* [2000] determined that PDO does not enhance (or dampen) ENSO's effect on summer season PDSI in the continental United States. The results of *Rajagopalan et al.* [2000] differed from the winter precipitation results of *Gershunov et al.* [1999]. At the 95% significance level, the current research did not identify a PDO impact of ENSO, however, if the significance level was reduced to 90% (results not provided), a region was identified in the upper to middle Mississippi River basin in which the PDO influences El Niño.

4.3.2. AMO and ENSO

[27] The coupling of AMO and ENSO was evaluated by examining streamflow relationships for AMO cold/El Niño – AMO warm/El Niño and AMO cold/La Niña – AMO warm/La Niña. For AMO cold/La Niña – AMO warm/La Niña, a large, positive spatial region of significant streamflow stations was identified in the Southeast United States (Figure 6a). A La Niña (El Niño) event generally results in decreased (increased) streamflow in the Southeast (Figures 5a), while the AMO cold (warm) phase results in increased (decreased) streamflow in this region (Figures 3a and 3e). In the Southeast, La Niña events occurring in an AMO cold (warm) phase result in significantly greater (lesser) streamflow than those occurring in an AMO warm phase. Thus a La Niña during the AMO warm phase results in more severe droughts.

[28] The significant difference in La Niña streamflow in the Southeast region (Figure 6a) is displayed in Figure 6b. For the 14 La Niñas in the period of record, eight occurred during an AMO cold phase while six occurred during an AMO warm phase. For the Southeast region, during the AMO cold phase, seven of eight La Niñas resulted in above normal streamflow while during the AMO warm phase, all six La Niñas resulted in below normal streamflow. For this region, the average streamflow (i.e., standardized anomaly) for the AMO cold La Niñas was +0.40 while the average streamflow for the AMO warm La Niñas was −0.89 (almost one standard deviation below normal). For all La Niñas the average streamflow was −0.16. Given the current AMO warm phase, the development of a La Niña could severely impact (i.e., drought) the southeastern United States.

[29] A physical explanation of the AMO-ENSO coupling is challenging. The southeastern United States was influenced by both the AMO (section 4.1.2) and ENSO (section 4.2). The AMO cold phase appears to dominate La Niña such that streamflow was above normal when typically La Niña results in below normal streamflow. This

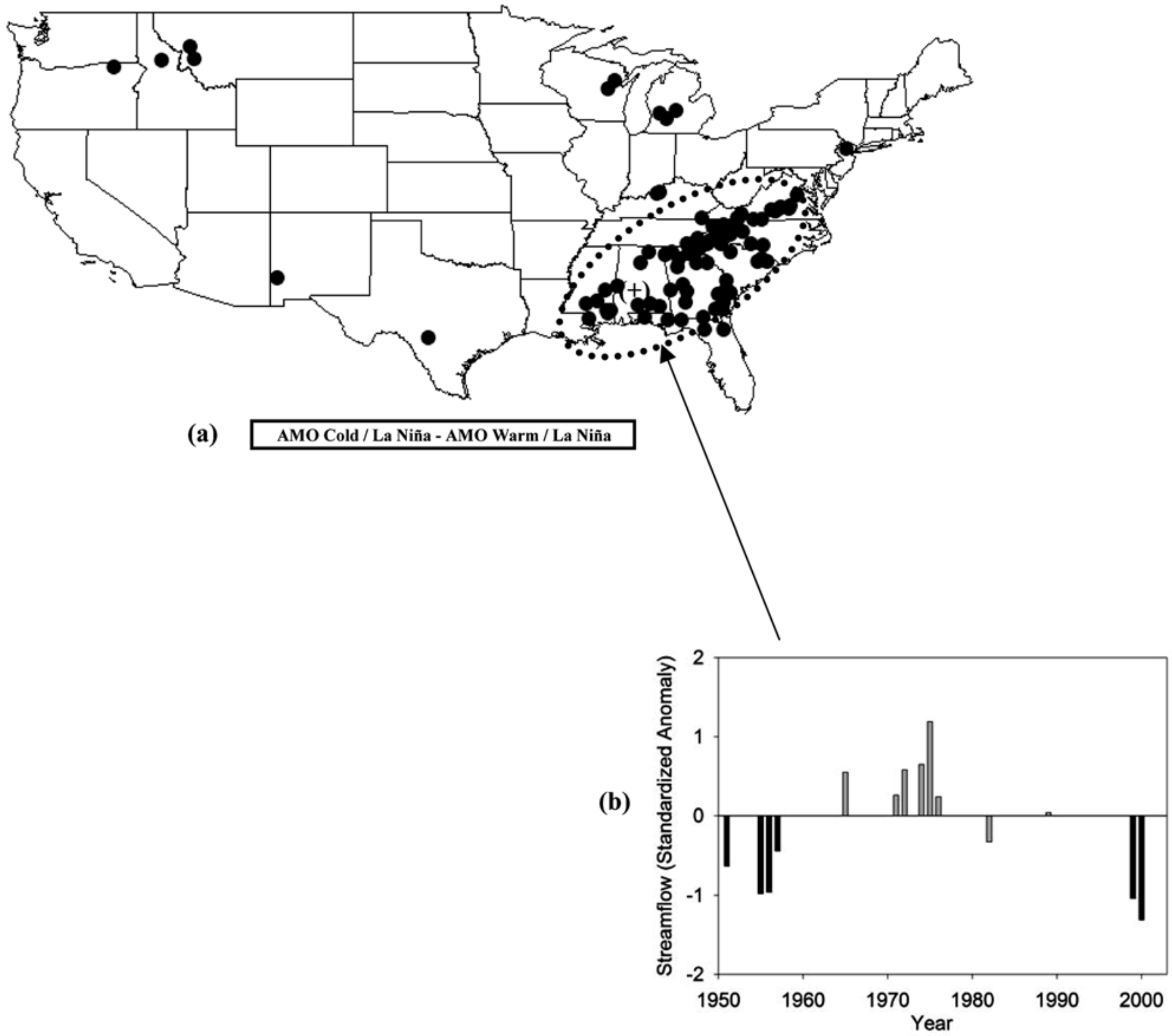

Figure 6. (a) Significant (95%) difference in streamflow medians for AMO cold/La Niña – AMO warm/La Niña. Positive (negative) significance is represented by solid (open) circles. (b) La Niña year streamflow (standardized anomaly) averaged for all stations in the region Southeast. Gray (black) bars represent La Niñas during AMO cold (warm) years.

may be due to the spatial location of the southeastern United States, being adjacent to the Atlantic Ocean and thus impacted more by Atlantic Ocean SST variability. The results of the nonparametric rank-sum testing of AMO cold/El Niño – AMO warm/El Niño provided minimal stations and therefore was not reported.

4.3.3. NAO and ENSO

[30] The coupling of NAO and ENSO was evaluated by examining streamflow relationships for NAO negative/El Niño – NAO positive/El Niño and NAO negative/La Niña – NAO positive/La Niña. For NAO negative/La Niña – NAO positive/La Niña, a large, negative spatial region of significant streamflow stations was identified in the midwestern United States (Figure 7a). The negative result indicates that a La Niña during an NAO positive phase results in significantly more streamflow than a La Niña during an NAO negative phase (Figure 7b). For the 14 La Niñas in the period of record, six occurred during an NAO negative phase while eight occurred during an NAO positive phase. All six La Niñas during the NAO negative phase resulted in below normal streamflow (i.e., standardized anomaly) with an average of -0.65. During the NAO positive phase, six (of eight) La Niñas were above normal with an average streamflow of $+0.45$. The average of all 14 La Niñas in this region was -0.02.

[31] Figure 7a is similar to Figure 4a (i.e., NAO negative – NAO positive) except far fewer stations were identified. Physically, the NAO impacts the jet stream such that it shifts north during the positive phase and shifts south during the negative phase (NOAA, Climate factors helping to shape winter 2004–2005, NOAA News, http://www.noaanews.noaa.gov/stories2004/s2326b.htm). La Niña influenced events track easterly from the Pacific Ocean and thus are impacted by such a shift in the jet stream. *Kahya and Dracup* [1993a, 1994b] identified a Midwest region (similar to Figures 4a and 7a) in which La Niña results in reduced

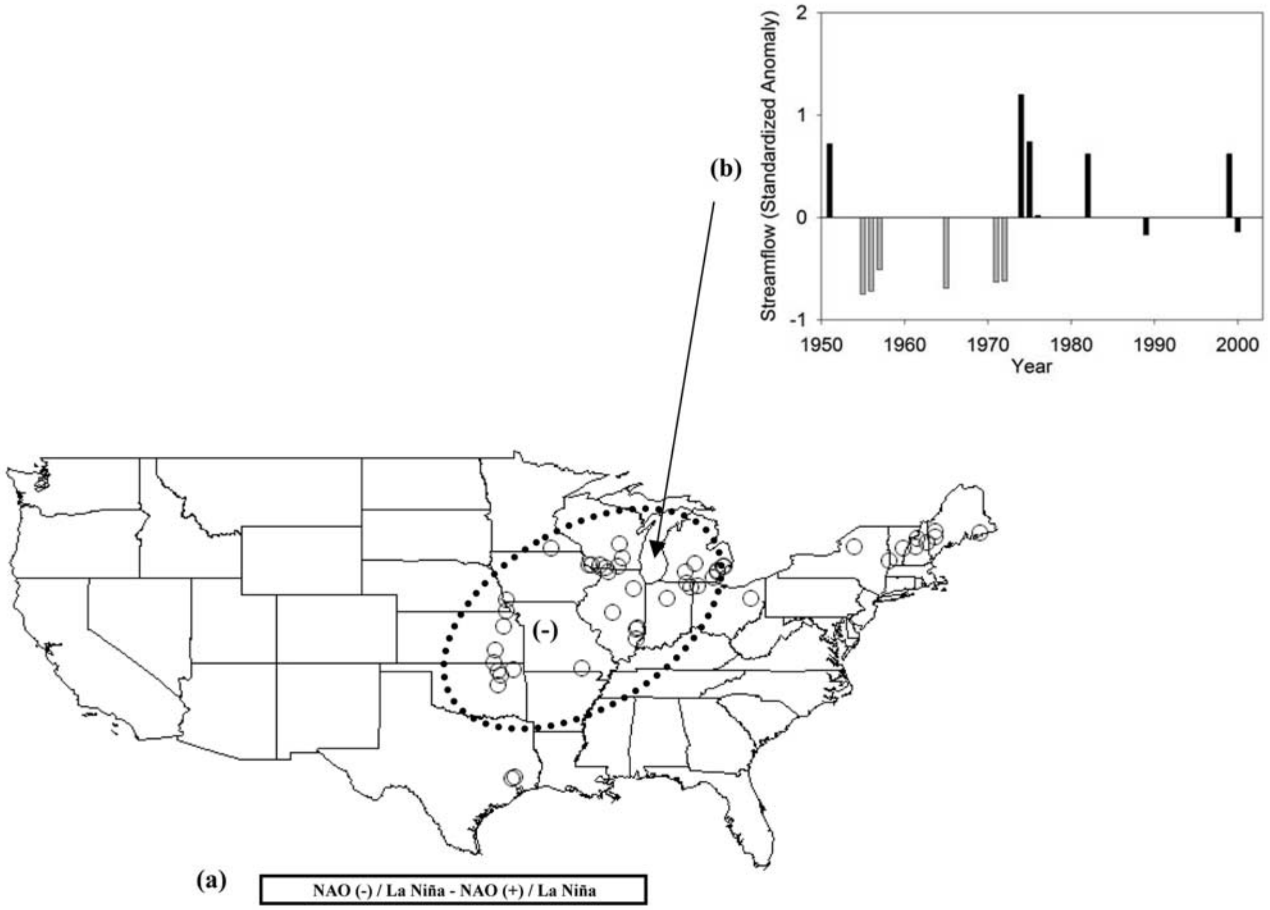

Figure 7. (a) Significant (95%) difference in streamflow medians for NAO negative/La Niña – NAO positive/La Niña. Positive (negative) significance is represented by solid (open) circles. (b) La Niña year streamflow (standardized anomaly) averaged for all stations in the region Midwest. Gray (black) bars represent La Niñas during NAO negative (positive) years.

streamflow. The NAO influenced shift in the jet stream may be influencing La Niña in this region. During the positive phase of the NAO, the jet stream shifts north and the Midwest region is impacted by La Niña (i.e., reduced streamflow). This results in NAO positive years, during La Niñas, being closer in streamflow volume to NAO negative years and thus fewer stations being significantly different.

[32] The results of the nonparametric rank-sum testing of NAO negative/El Niño – NAO positive/El Niño were similar to the AMO results and provided minimal stations and was not reported.

5. Conclusions

[33] The current research resulted in several new contributions in the understanding of the relationships between large-scale interannual and interdecadal ocean-atmosphere phenomena and continental U.S. streamflow. First, hydrologic variability of the entire continental United States was evaluated and the period of record was extended for such evaluation. It was important to evaluate the continental United States as a whole and not limit the evaluation to regional areas. Also, the behavior of interdecadal phenomena (i.e., cold or warm phase for ±25 years) required an extended period of record to fully evaluate the resulting hydrologic variability. Next, streamflow was selected as the hydrologic response variable and a lead time approach was adopted. Streamflow represents an integrator of the hydrologic cycle and is a vital socioeconomic and environmental parameter. The lead time approach adopted for the current research provided water managers important predictive information about streamflow variability in response to interannual and interdecadal phenomena. While the water year was adopted for the current research, applying the same methodology to winter-spring season (January to June) streamflow resulted in similar conclusions [*Tootle and Piechota*, 2005].

[34] The coupled impacts of AMO and NAO with ENSO on U.S. streamflow resulted in two interesting observations. First, the development of a La Niña during an AMO warm phase could influence (i.e., drought) the southeastern United States. The AMO, possibly due to the proximity of the Atlantic Ocean to the southeastern United States, is associated with La Niña in this region. Second, the phase of the NAO influences La Niña in the midwestern United States and is associated with significantly less streamflow during a NAO negative phase. This may be physically explained by the northern shift of the jet stream during the NAO positive phase. Interestingly, *Kahya and Dracup* [1993a, 1994b] established the midwestern United States as a nonlagged

ENSO influenced streamflow region, which responds to ENSO in a similar manner as the Southwest and Southeast (e.g., El Niño, increased streamflow, and La Niña, decreased streamflow).

[35] The individual impacts of the PDO, AMO and NAO resulted in several new observations. The phase of the AMO may indicate streamflow trends in the Pacific Northwest, Southwest, Midwest and Southeast while the NAO influences the Midwest streamflow. Unlike previous studies, the Pacific Northwest was (was not) identified as an AMO (PDO) influenced region and the NAO was (was not) identified in the midwestern (eastern) United States. This could be a result of the lead times and season (water year) selected.

[36] The results indicate that the phase of the PDO may prove to be a strong indicator of upper to middle Mississippi River and southwest U.S. streamflow. At the 95% confidence level established for the current research, PDO-ENSO coupling provided similar results (no significant regions) as the previous drought study of *Rajagopalan et al.* [2000]. However, at the 90% confidence level, the PDO influences El Niño in the upper to middle Mississippi River basin.

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