NEW ENGLAND DROUGHT AND RELATIONS WITH LARGE-SCALE ATMOSPHERIC CIRCULATION PATTERNS

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ABSTRACT: To provide a basis for regional hydroclimatic forecasting, New England (NE) precipitation and streamflow are compared with indices for the El Nino/ Southern Oscillation, the Pacific-North American (PNA) pattern, and the North Atlantic Oscillation (NAO). Significant positive correlations are found between the NAO index and monthly streamflow at western inland locations, with the strongest seasonal correlations occurring in winter. Smoothed records for the winter NAO and winter streamflow are highly correlated at some sites, suggesting that interrelationships are most significant in the low frequency spectrum. However, correlations between the NAO and precipitation are not significant, so further examination of other factors is needed to explain the relationship between the NAO and streamflow. NAO-related regional air temperature, sea-surface temperature (SST), storm tracking, and snowfall variability are possible mechanisms for the observed teleconnection. Exceptionally cool regional air temperatures, and SSTs, and unique regional storm-track patterns characterized NE's climate during the famous 1960s drought, suggesting that concurrent (persistent) negative NAO conditions may have contributed to the severity of that event. Monthly and winter-averaged regional streamflow variability are also significantly correlated with the PNA index. This, along with results from previous studies, suggests that tropospheric wave character and associated North Pacific SST anomalies are also related to NE regional drought conditions.

(KEY TERMS: <u>hydroclimate;</u> New England; drought; North Atlantic Oscillation; Pacific/North American pattern.)

INTRODUCTION

Historical Drought and Prediction

Even in the northeastern United States, where water is generally abundant, recent drought conditions accompanied by increasing human demands on fresh-water resources require that we gain a better understanding of extremes in regional hydrologic variability. Hydrologic drought is of particular concern, since low streamflows often result in significant environmental damage including high surface-water temperatures, reduced levels of dissolved oxygen, higher concentrations of pollutants, and the landward migration of salt-water estuaries. The socioeconomic impacts of persistent hydrologic drought can last for months beyond the period of rainfall deficit. Furthermore, impacts of drought promise to be more severe in the future because of rapidly growing population, even with no change in the frequency or duration of events [American Meteorological Society (AMS), 1997]. Because of these issues, it is important to know not only when and where drought events are likely to occur, but for how long they may persist.

Empirical studies done over the past several decades have never shown that drought is the result of one factor exclusively (AMS, 1997). Research that focuses on multiple hydrologic variables (e.g.: Leathers et al., 2000) with consideration given to the interactions between remote climate conditions and local feedback mechanisms (e.g., Namias, 1966; Barlow et al., 2001) have offered important insights into possible causes for regionally extensive drought events in the northeastern United States. Still, due to the many factors that contribute to hydrologic variability and the inherent complexity of the hydrologic system, many questions remain regarding specific physical mechanisms responsible for the onset, persistence, and spatial extent of regional hydrologic drought.

The goal of this research is to identify how and to what extent large-scale atmospheric circulation patterns can be linked with drought and low streamflow in New England (NE). Using statistics to link variations in NE streamflow with well-known indices for atmospheric circulation patterns, our results, coupled with those from previous studies (Namias, 1966; Rogers and Van Loon, 1979; Hartley and Keebles, 1998; Leathers et al., 2000; Barlow et al., 2001), help to place NE in the context of the global climate system. Also, by providing evidence for physical associations between NE regional climate and dominant modes of Northern Hemisphere climate variability, the seasonal predictability of NE hydroclimate could improve to the extent that the occurrence and persistence of large-scale climatic disruptions can be predicted (e.g., Piechota and Dracup, 1999; Cordery and McCall, 2000).

Large-Scale Atmospheric Circulation Patterns and NE Climate; Previous Work

La Nina and El Nino mark extreme "events" in the El Nino/ Southern Oscillation (ENSO) cycle. The “signal” from an ENSO event usually reaches the extra-tropics during the "mature phase" of ENSO - the January immediately following an event year (Diaz and Markgraf, 1992). Hence, teleconnections between ENSO and mid-latitude climates are typically most apparent during winter. Based on storm-track data from 1951-1997, Kunkel and Angel (1999) found an increase in the frequency of Gulf-of-Mexico-generated cyclones and decreased frequency of Canadian Shield-generated cyclones during El Nino winters; the opposite is true during La Nina winters. Rogers (1984) noted similar sea-level pressure (SLP) patterns, with generally higher pressures over the Canadian Shield and relatively low pressures in the Gulf of Mexico/ Cape Hatteras region during El Nino winters. Also, Hirsch et al. (2001) noted a marked increase in East Coast winter storms during El Nino winters.

Despite the relevance of the above mentioned storm tracks to winter weather in NE (Ludlum, 1976), results from a number of studies indicate no clear link between ENSO and New England climate (e.g.: Ropelewski and Halpert, 1986; Kahya and Dracup, 1993; Dracup and Kahya, 1994; and Piechota and Dracup, 1996). Still, the evidence that ENSO influences extratropical atmospheric circulation is unequivocal and therefore warrants the inclusion of an ENSO index in this study. Furthermore, Ropelewski and Halpert (1986) pointed out that the regions without consistent ENSO-related signals might indirectly feel the effects of the ENSO cycle through the position of other ENSO-related phenomena such as the Pacific/ North American (PNA) pattern.

The PNA pattern describes the character of mid-tropospheric airflow across North America (Wallace and Gutzler, 1981). The PNA index is a function of the phase and intensity of quasi-stationary Rossby waves over North America and is said to be a good indicator of the mean location of the polar front jet during colder months (Leathers et al. 1991). Leathers et al. (1991) examined the relations between an index for the PNA and National Climate Data Center (NCDC) divisional temperature and precipitation data from 1947- 1982 but did not examine streamflow. While significant negative correlations between NE temperature and the PNA were evident ($r = -0.3$ to -0.5 in fall and winter), a PNA-precipitation signal was not as clear or consistent. An investigation of variations in the PNA pattern during warm ENSO events indicated that significant east-west shifting of the East Coast pressure trough can result in highly variable effects on NE climate, without any change in PNA index values (Keebles, 1992). Still, Barlow et al. (2001) concluded that 1962-1966 NE drought conditions were linked to a tropospheric wave anomaly over the Pacific/ North American region including a cyclonic center near NE that “oppos[ed] the climatological summertime inflow of moisture into the northeastern [U.S.]” (pp. 2122). Both Barlow et al. (2001) and Namias (1966) suggested that these conditions were related to persistent above-average North Pacific SSTs in a broad region centered around 40°N, 160°W. Not surprisingly, Leathers and Palecki (1992) noted a significant inverse relationship between SSTs in the same North Pacific region and the winter PNA index; above normal North Pacific SSTs are associated with a more zonal PNA pattern. Given the apparent connection between continental-scale tropospheric wave anomalies and NE drought conditions, a PNA index is included in the following analysis.

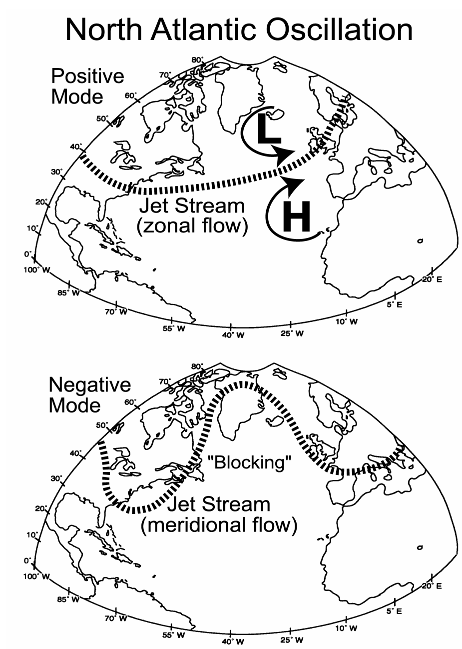


Figure 1. Schematic illustration of N. Atlantic Atmospheric conditions during positive (upper panel) and negative (lower panel) phases of the North Atlantic Oscillation (NAO). During positive NAO winters the atmospheric pressure gradient between Iceland and the Azores is at a maximum and the mid-latitude westerlies dominate air circulation throughout the region. During negative NAO winters the Icelandic low is weak and commonly acts as a blocking mechanism.

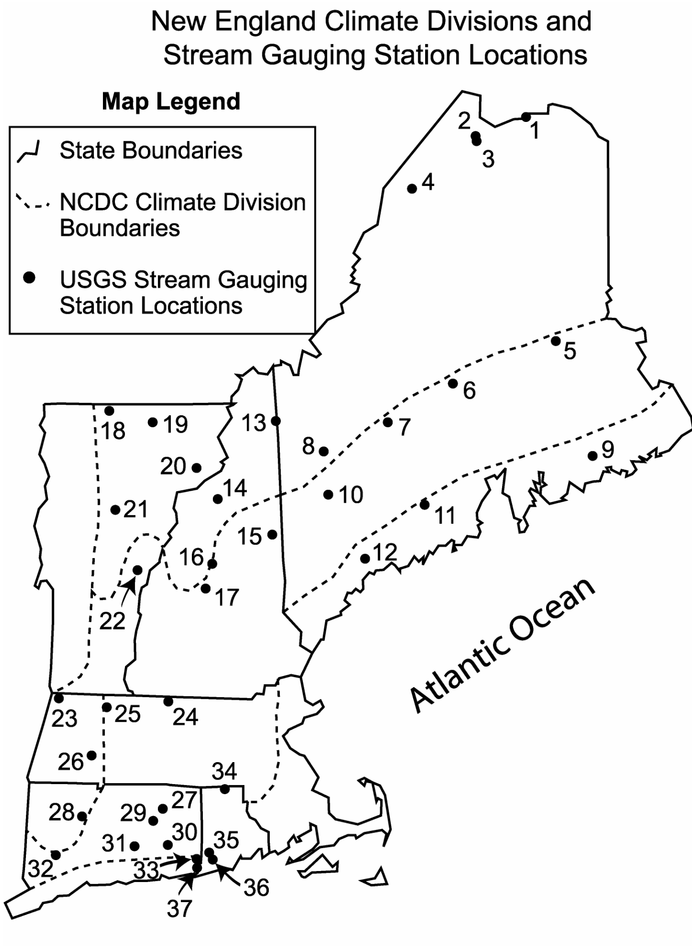
The North Atlantic Oscillation (NAO) is the dominant mode of SLP variability in the North Atlantic region (Hurrell, 1995). The NAO index, defined here as the SLP difference between the Azores high and the Icelandic low, describes the steepness of a north-south atmospheric pressure gradient across the North Atlantic Ocean (Figure 1). When the NAO shifts between its modes of variability, the North Atlantic Ocean experiences changes in wind speed and direction that affect heat and moisture transport to the surrounding continents and seas (Hurrell, 1995).

There is little evidence for an association between NE precipitation and NAO variability, however other NE regional climatic variables that may influence streamflow have been linked to the NAO. For example, significant associations have been observed between the NAO and NE regional tropospheric airflow (Yarnal and Leathers, 1988; Hurrell, 1996; Hartley and Keebles, 1998), surface air temperatures (Bradbury et al., *submitted* (a)), storm-track patterns (Rogers, 1990; Hartley and Keebles, 1998; Thompson and Wallace, 2001), snowfall variability (Hartley and Keebles, 1998), tree-ring chronologies (Cook et al., 1998), and coastal SSTs (Rogers and van Loon, 1979). Furthermore, of particular relevance with respect to drought, Rogers and van Loon (1979) and Rogers (1990) found that some SST and SLP anomalies related to the phase of the winter NAO persist into the following seasons, suggesting that spring and summer climatic conditions may also be linked to the phase of the winter NAO.

DATA AND METHODS

Regional Hydroclimate Indices

The NCDC monthly divisional precipitation and temperature data (NCDC, 1994) were used for the 15 climate divisions of NE from 1895 to 1999 (Figure 2). The climate divisions share similar climates, with consideration to topography, proximity to bodies of water, data availability, and political boundaries (Karl and Knight, 1986). Derived from a changing network of daily observations, NCDC precipitation data (Karl and Knight, 1986) represent the longest published monthly index for NE hydroclimate variability and were therefore compared with the atmospheric circulation indices over their entire length of record. Winter averages of the NCDC temperature data were used in multiple-linear regression analyses to examine the possible influence of regional temperature on winter streamflow variability.



Map #	USGS #	Station Name	Record length
1	1014000	St. John R.	1927-99
2	1010500	St. John R.	1947-99
3	1011000	Allagash R.	1932-99
4	1010000	St. John R.	1951-99
5	1030500	Mattawamkeag R.	1935-99
6	1031500	Piscataquis R.	1903-99
7	1047000	Carrabassett R.	1926-99
8	1055000	Swift R.	1930-99
9	1022500	Narraguagus R.	1949-99
10	1057000	L. Androscoggin R.	1932-99
11	1038000	Sheepscot R.	1939-99
12	1060000	Royal R.	1950-99
13	1052500	Diamond R.	1942-99
14	1137500	Ammonoosuc R.	1940-99
15	1064500	Saco R.	1930-99
16	1076500	Pemigewasset R.	1904-99
17	1078000	Smith R.	1919-99
18	4293500	Missisquoi R.	1934-99
19	4296000	Black R.	1952-99
20	1134500	Moose R.	1948-99
21	4287000	Dog R.	1936-99
22	1144000	White R.	1929-99
23	1333000	Green R.	1950-99
24	1162500	Priest R.	1953-99
25	1169000	North R.	1950-99
26	1180500	Mid. Br. Westfield R.	1911-64
27	1121000	Mt Hope R.	1941-99
28	1188000	Burlington Br.	1932-99
29	1119500	Willamantic R.	1935-99
30	1127500	Yantic R.	1931-99
31	1193500	Salmon R.	1929-99
32	1204000	Pomperaug R.	1933-99
33	1196500	Quinnipiac R.	1931-99
34	1111500	Branch R.	1957-99
35	1118000	Wood R.	1953-99
36	1117500	Pawcatuck R.	1942-99
37	1118500	Pawcatuck R.	1942-99

Figure 2. NCDC climate divisions and stream gauging station locations. Numbers on the map correspond to streams listed at right.

United States Geological Survey (USGS) daily streamflow data were averaged into monthly time series for this analysis. Hydro-Climatological Data Network (HCDN) (Slack and Landwehr, 1992) criteria were used to distinguish good quality records from those that are confounded by anthropogenic influences. Since streamflow is the shortest regional climate index used in this study, length of record was our first priority in selecting stations from the HCDN. We also tried to achieve adequate spatial coverage of the entire NE region. However, heavy human impacts on many streams in the more populated (i.e. coastal) regions limited the availability of suitable records from these areas. Figure 2 lists the 37 HCDN stream gauging stations that were used in this study and illustrates their locations.

Indices for large-Scale Atmospheric Circulation

The Southern Oscillation Index (SOI) data were taken from the National Centers for Environmental Prediction (NCEP). This index for ENSO is based on monthly SLP anomalies from Darwin, Australia, and Tahiti, normalized by the standard deviation of the monthly values from January 1951 to December 1980. The index was calculated by NCEP by dividing the difference between the normalized SLP at the two stations by the standard deviation of the monthly differences from 1951-1980 (Chelliah, 1990). The main reason for using this index is that we found ENSO indices based on SST data to have higher levels of autocorrelation, making them less suitable for correlation analyses, which is the primary statistical tool used in this study.

The index for the PNA was taken from the NCEP Climate Prediction Center's (CPC) Northern Hemisphere Teleconnection pattern analysis. This index is derived from a rotated principal-component analysis (RPCA) of Northern Hemisphere monthly mean 700-mb height anomalies (Barnston and Livezey, 1987), in which the PNA was identified as an important teleconnection pattern in all months except June and July (January 1964-July 1994). The CPC's RPCA analysis determined 10 principal patterns for each month based on the entire flow field, not just a few selected grid-points, thereby creating the most robust signature of the atmospheric circulation patterns during the period of record. When the index is positive, the airflow across the U.S. tends to be more meridional; negative index values represent more zonal (west to east) flow. The CPC's monthly PNA index is available from January 1950 to the present (excluding June and July); therefore all correlation analyses related to the PNA are from 1950 to 1999.

The monthly NAO index was taken from the National Center for Atmospheric Research (NCAR), as defined by Hurrell (1995), using Stykkisholmur or Akureyri, Iceland, and Ponta Delgadas, Azores, as the SLP stations. The monthly index is defined as the difference between normalized monthly SLP anomalies from each station. To achieve normalization, each monthly SLP anomaly was divided by the long-term (1865-1984) standard deviation from the respective stations. This version of the index was used because it more accurately captures the non-winter variability in the NAO (compared with indices that use SLP data from Portugal and Gibraltar), in seasons when the subtropical high-pressure system shifts away from the mainland (Rogers, 1990; Hurrell and Van Loon, 1997). Still, it should be noted that the correlation values between the two centers of action are significantly closer to zero during the warmer seasons, making the monthly index proportionately less meaningful for that time of year (see Table 1 in: Hurrell and Van Loon, 1997). The winter (DJFM) NAO index was also taken from NCAR, using the same statistical methods as the monthly index; however SLP anomaly data from Lisbon, Portugal, were used for the southern station. This is because, during the December- March season, the signal-to-noise ratio of the Iceland- Portugal index is higher than the index based on Iceland-Azores (see Table 1 in: Hurrell and van Loon, 1997).

Methods Overview

The focus of this research is a correlation analysis between hydroclimatic variables in NE and indices for large-scale atmospheric circulation. To conform to the assumptions of regression and Pearson statistics, the following section describes how monthly precipitation and streamflow data were "normalized" through a two-step process. First, each sample was transformed to reduce right skewness, and then standardized to reduce month-to-month autocorrelation and seasonality in the precipitation and streamflow records.

Simple "pairwise" regression analysis was used to identify the climate indices that show significant linear correlations with regional precipitation and streamflow. Here, each of the large-scale atmospheric indices, on monthly (all year) and seasonal (winter only) time scales, are correlated with precipitation from all 15 NCDC divisions and streamflow at 37 gauging stations in NE (Figure 2). For the remainder of the study, only winter-average (Dec. - March) data were used because it is during this season that the PNA and NAO indices are most highly correlated with regional streamflow. It is also during the winter that the climate indices are the most robust and significant characterizations for Northern Hemisphere atmospheric circulation. March data are included in our winter averages because: 1) the winter index for the NAO (Hurrell, 1995) includes SLP data from March; and 2) NE typically experiences winter weather (i.e.: the polar front is frequently to the south of NE) during March (Ludlum, 1976) and snowfall is abundant.

Next, physical causes for apparent teleconnections found through the pairwise regression analysis are investigated using multiple linear regression (MLR) techniques. This was done via 10 case studies, where MLR models were used to predict streamflow. By including more than one climate variable in a regression model for streamflow, the significant predictor variables could be examined in the context of other potentially influential variables. This involves examining interrelationships between predictor variables and developing a conceptual model of the important drought-related feedback mechanisms operating within the regional hydrologic system. Finally, multi-annual and decadal-scale climate variability were compared to examine low frequency associations between NE regional streamflow and the NAO and

PNA indices. To do this, winter streamflow and the climate indices were smoothed and then compared using correlation statistics.

Data Normalization

When non-normal data are used in correlation analyses there is a risk that confidence intervals will be invalid (Helsel and Hirsch, 1992). To work with approximately normal data, each sample of divisional precipitation data was "normalized" by a two-step process. First, all monthly data were transformed using a cube-root transformation. Second, they were standardized to account for seasonal variability, and to limit autocorrelations. The "standardization" of the precipitation values was accomplished as follows:

$$p_{m,y} = \frac{P^{1/3}{}_{m,y} - E(P^{1/3}{}_{m})}{S(P^{1/3}{}_{m})}$$

where $P^{1/3}{}_{m,y}$ is a cube-root-transformed divisional precipitation value for the month-*m* and year-*y*, $E(P^{1/3}{}_{m})$ is the mean of all cube-root-transformed month-*m* values, and $S(P^{1/3}{}_{m})$ is the standard deviation of all the cube-root-transformed month-*m* values. This standardization procedure produces monthly precipitation values ($p_{m,y}$) in terms of their standard deviation from the average for the month in which each value was recorded. "Normalized" monthly (January- December) precipitation data are hereafter referred to as PPTm, and winter averages (December – March) are called PPTw. Our criterion for achieving normalization was satisfied, using the Probability-Plot Correlation Coefficient test (Vogel, 1986, 1987), when more than half of the data samples from each population tested positive for normality with at least 95% confidence.

The same normalization procedure was performed on the streamflow data, except that a log-transformation was used prior to standardization:

$$q_{m,y} = \frac{\log_{10}(Q_{m,y}) - E[(\log_{10}(Q_m)]}{S[\log_{10}(Q_m)]}$$

where $\log_{10}(Q_{m,y})$ is a log-transformed streamflow value for month-*m* and year-*y*, $E[\log_{10}(Q_m)]$ is the mean of all log-transformed month-*m* values, and $S[\log_{10}(Q_m)]$ is the standard deviation of all the log-transformed month-m values. This standardization procedure produces monthly streamflow values ($q_{m,y}$) in terms of their standard deviation from the average for the month in which each value was recorded. "Normalized" monthly and winter-averaged streamflow data are hereafter referred to as Qm and Qw, respectively. Winter averages of NCDC temperature data (TEMP) were generally normally distributed and therefore not subjected to a normalization procedure.

Monte Carlo Simulations: Establishing Critical r-Values

The downfall of testing multiple hypotheses, or "multiplicity", is that each time an additional null hypothesis is tested, the probability of making a type-1 error (concluding that an association exists when one does not), increases geometrically (Brown and Katz, 1991). Further statistical problems arise because hydrologic and climatic data often show strong persistence, or autocorrelation. The use of Monte Carlo simulations to establish critical r-values eliminates statistical concerns related to multiplicity and autocorrelation.

Monte Carlo simulations were used to establish critical r-values for the Pearson correlation analyses between the climate indices (independent variables) and both PPT and Q (dependent variables).

Simulations imitate the multiple hypotheses that are tested between each individual climate index (X) and each group of *m* normally-distributed dependent variables [Y_i (i = 1,…, *n*)]. In each Monte Carlo simulation, Y_i's are replaced by a group of *m* "proxy" computer generated, normally distributed, white-noise series (Z_i). For each climate index, the simulation is run 2000 times, *m**2000 Pearson r-values are produced, and then ranked. Next, critical r-values (at the 0.05 significance level, for example) are set for each dependent variable by simply identifying the 95th percentile of the ranked r-values. Different Monte Carlo simulations are run to generate confidence levels for each "situation" [e.g.: corr(NAO,Qw); corr(PNA,Qw): etc.]. With this technique, any autocorrelation within a climate index's time series does not confound the statistical significance of the results because simulations are done to determine specific critical r-values with respect to each climate index.

To account for cases with significant autocorrelation in Y_i, the set of *m* white noise series Z_i are replaced by normally distributed red-noise series that contain the same levels of autocorrelation as the average Y_i, from their respective populations. The varying lengths of streamflow records (*n*) (Figure 2) requires that multiple Monte Carlo simulations are run to replicate the streamflow analysis at various time steps (i.e.: 1900-1999, 1910-1999, etc.) and critical r-values were used for records with comparable lengths.

Record Smoothing and Decadal-scale Comparisons

To investigate the possibility of decadal scale associations between Qw and both the NAO PNA indices, these records were smoothed. Robust splines were used as smoothing filters to remove less-than-decadal variability and the weights were chosen objectively with the aid of spectral analysis. The smoothed records had very high levels of first order autocorrelation (coefficients up to 0.90) so red-noise series with the same level of autocorrelation were used in the Monte Carlo simulations to determine the critical r-values at the 0.10, 0.05, and 0.01 significance levels. Next, regression analysis was used to estimate the amount of low-frequency variability shared by Qw and both the NAO and PNA indices.

RELATIONSHIP OF NE HYDROCLIMATE TO CIRCULATION INDICES

Correlation Analysis Results

No statistically significant linear associations were found between monthly, and winter-averaged SOI, and PPT or Q ($a < 0.05$). This is consistent with previous investigations into ESNO teleconnections and the NE region. One reason for the lack of correlation between our hydro-climatological data and the SOI may be due to the notable difference in structure between their respective time series. Given the high level of persistence in the SOI, a correlation analysis may be somewhat inappropriate. Therefore, event-specific coding of the SOI is done in the MLR analysis to get a different perspective on how ENSO could be related to NE hydroclimate.

Our analysis revealed no significant ($a = 0.05$) associations between NE PPT and the PNA. There are, however significant correlations between the PNA and both Qm (n=499) and Qw (n=50) at a two stations in NH and ME (Figure 3a). These results suggest that a meridional circulation is

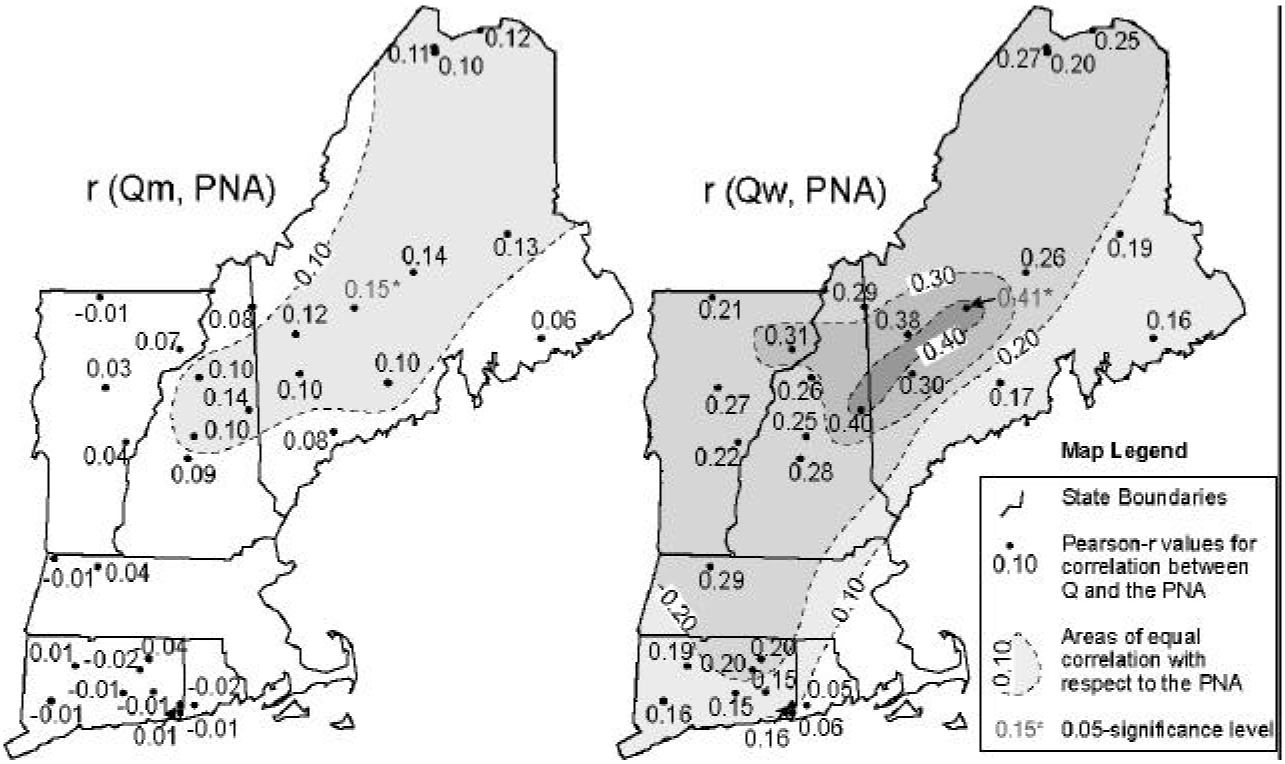


Fig. 3a: Results of the monthly and winter correlation analyses between the PNA and Q for the periods of record listed in Figure 2.

significantly related to higher streamflows (and zonal circulation associated with lower streamflow) in a region centered near the middle of New Hampshire and Maine. The spatial distribution of the winter correlations (Figure 3a, right panel) broadly resembles the January "New England pattern" identified by Lins (1997), suggesting a possible PNA link to that mode of regional streamflow variability. Unfortunately, the lack of previous research relating the PNA to NE climate limits our ability to explain the physical nature of the streamflow-PNA teleconnection. Possible remote forcing mechanisms for this relationship are discussed in the following section and in the conclusion of this paper.

There are no statistically significant correlations between NE PPT and the NAO. However, the NAO is significantly correlated with Qm at many locations (a = 0.05). The spatial distribution and strength of the correlations between both Qm and Qw and the NAO indices is illustrated in Figure 3b. While the winter r-values are not above the 0.05-Monte Carlo statistical significance level, some are close and there is spatial coherence between the regions that show the highest correlations with the monthly NAO indices and those that show the highest r-values during winter.

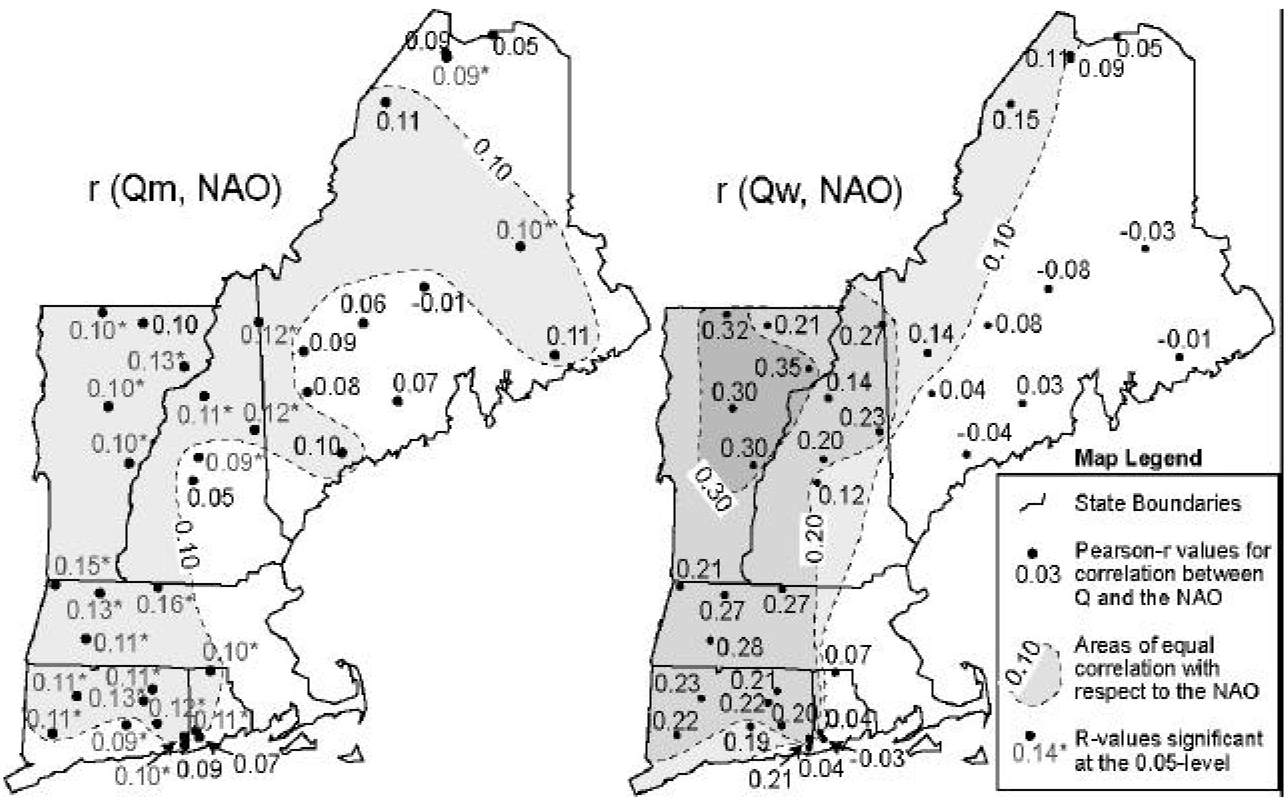


Figure 3b. Same as Figure 3a but for NAO and Q. None of the r-values from the winter correlation analysis were significant above the 0.05-level however several were close.

Also, results from a two-way ANOVA model indicate that the phase of the NAO is a significant (a = 0.05) predictor of mean Qw, especially in VT and western MA. The obvious problem is to explain why NE streamflows are significantly correlated with the NAO, yet there appears to be no association between the NAO and PPT. Certainly, precipitation is not the only climatic variable that controls the distribution and variability of runoff, particularly in winter; therefore an in-depth analysis of 10 “case-study” streams was conducted to address this issue.

Multiple Linear Regression and Qw Prediction; Results from 10 Case Studies

As shown, Qw in some regions is significantly correlated with the NAO and the PNA indices, while PPTw in the same regions appears uninfluenced by these atmospheric circulation patterns. To provide a better understanding of the physical controls on NE winter streamflow variability, stepwise multiple linear regression (MLR) is used to relate 10 inland streams in Connecticut, Vermont, New Hampshire, Massachusetts, and Maine with possible predictors for Qw. The predictors that were considered include: PPTw, TEMP, the SOI, the PNA, and the NAO. Because the PNA was included in each stepwise regression analysis, only winters from 1950-1999 were considered in this section of the study. Finally, since our correlation analyses already determined that significant associations exist between both the PNA and the NAO and Qw, each MLR model is considered to be statistically independent of the others (i.e.: multiplicity was not accounted for when determining the significance levels discussed in this section).

The best models for Qw at most streams included significant terms (in order of significance) for: PPTw, TEMP, and the PNA and/ or the NAO. These results indicate that variability in the NAO and PNA indices accounts for winter streamflow variability in some way that is independent of PPTw and TEMP. Hence, other mechanisms, besides precipitation or temperature-driven snowmelt, must explain at least part of the NAO and PNA signals that were found in NE Qw.

Coded values for the NAO and SOI were also considered, such that the top and bottom 25th percentile of NAO and SOI winters were designated as positive and negative events, respectively, and all others were designated as "non-events". Interestingly, when the coded indices were included in our stepwise regression procedure, significant PNA terms were replaced by a (more significant) coded SOI term in several models of Qw from CT, MA and southern VT. Regardless of which term is used (the coded SOI or PNA index) these results suggest that a Pacific signal is detectible in Qw, such that La Niña events (or negative PNA patterns) are dryer than non-ENSO or El Niño winters (or positive PNA patterns) at these sites. This is not surprising considering the fact that the winter PNA is highly correlated with the SOI ($r = -0.61$, p-value = 0.001); this teleconnection has been noted in other studies as well (e.g., Leathers and Palecki, 1992).

In contrast to the PNA, the NAO has been linked to several indices for NE regional climate, providing us with the opportunity to speculate about some possible physical explanations for the observed NAO-Qw relationship. Since the temporal distribution of winter streamflow in NE is significantly affected by the proportion of precipitation that falls as snow (Hartley and Dingman, 1993), the role of NAO-related snowfall variability (Hartley and Keebles, 1998) was considered as one possible mechanism for the NAO-Qw link. However, NAO-related snowfall cannot account for a regionally coherent NAO-Qw signal, since Qw at northern sites shows a significant negative correlation with snowfall, while in CT, where spring melt occurs earlier, positive correlations are observed between Qw and snowfall (not shown). Another possible explanation involves the observed positive correlation between the NAO and regional temperatures (Bradbury et al., *submitted* (a)). Regional TEMP indices are generally positively correlated with Qw and PPTw; in some cases TEMP alone explains up to 30% of Qw variability. Apparently, winters characterized by more frequent cold-air advection into the region also tend to be drier than normal.

Furthermore, positive correlations between regional SSTs and the NAO may be involved in a positive feedback loop between regional surface air temperatures, SSTs, and the NAO (Bradbury et al., *submitted* (a)). It seems likely that other factors, including low-frequency changes in NAO-related storm-tracking patterns (Rogers, 1990; Hartley and Keebles, 1998; Bradbury et al., *submitted* (b)) or variability in regional cloudiness and evapotranspiration may also play a role in the observed NAO-Qw signal.

Along with the previously mentioned PNA/ SOI teleconnection, it is worth noting that the winter PNA and NAO indices are linked (r = 0.30, a = 0.05). While an association would be expected, the sign (positive) of the correlation is counterintuitive based on our conceptual understanding of what each index means in terms of regional atmospheric circulation. A negative PNA index is known to indicate zonal conditions while this flow regime in the North Atlantic region is typically associated with a positive NAO index. This apparent discrepancy highlights the need for different indices to better characterize NE regional atmospheric circulation (Bradbury et al., *submitted* (a)).

Decadal-Scale Associations between the NAO and Winter Streamflow

Comparisons between smoothed records for Qw and the winter NAO index reveal an important low-frequency component to this teleconnection (Table 1). Similar results were observed with respect to the NE snowfall-NAO association (Hartley and Keebles, 1998). The same procedure was used to compare the winter PNA with Qw; however no evidence for a multi-annual association was found. Time series plots of 12 regionally representative streams (Figure 4) show

TABLE 1. Smoothed Qw correlated with a smoothed record of the Winter NAO. Vermont and New Hampshire Qws show the strongest signs of correlation with the winter NAO on decadal-time-scales. Massachusetts and Connecticut also have high r-values however no Qw values from these states were significant at the 0.10-level.

Station	N	Qw smoothed Pearson-r
MAINE		
Allagash	67	0.62
Carrabassett	73	0.56
Little Androscoggin	67	0.46
Mattawamkeag	64	0.56
Narraguagus	50	0.50
Piscataquis	96	0.22
Royal	49	0.50
Sheep	60	0.58
St. John at Dickey	52	0.60
St. John below Fish R.	72	0.58
St. John at Ninemile	48	0.56
Swift	69	0.68
New Hampshire		
Ammonoosuc	59	0.73
Diamond	57	0.83**
Pemigewasset	95	0.59
Saco	69	0.73*
Smith	80	0.54
Vermont		
Black	47	0.78
Dog	63	0.79*
Missisquoi	65	0.76**
Moose	51	0.75
White	70	0.79**
Massachusetts		
Green	49	0.60
Westfield and North	49	0.63
Priest	46	0.75
Connecticut		
Burlington	67	0.57
Mt. Hope	58	0.56
Pomperaug	66	0.62
Quinnipiac	68	0.57
Salmon	70	0.48
Willamantic	67	0.58
Yantic	68	0.53
Rhode Island		
Branch	42	0.61
Pawcatuck at Westerly	57	0.37
Pawcatuck at Wood R.	57	0.09
Wood	46	0.57

** = r-value significant at the 0.05-level

* = r-value significant at the 0.10-level

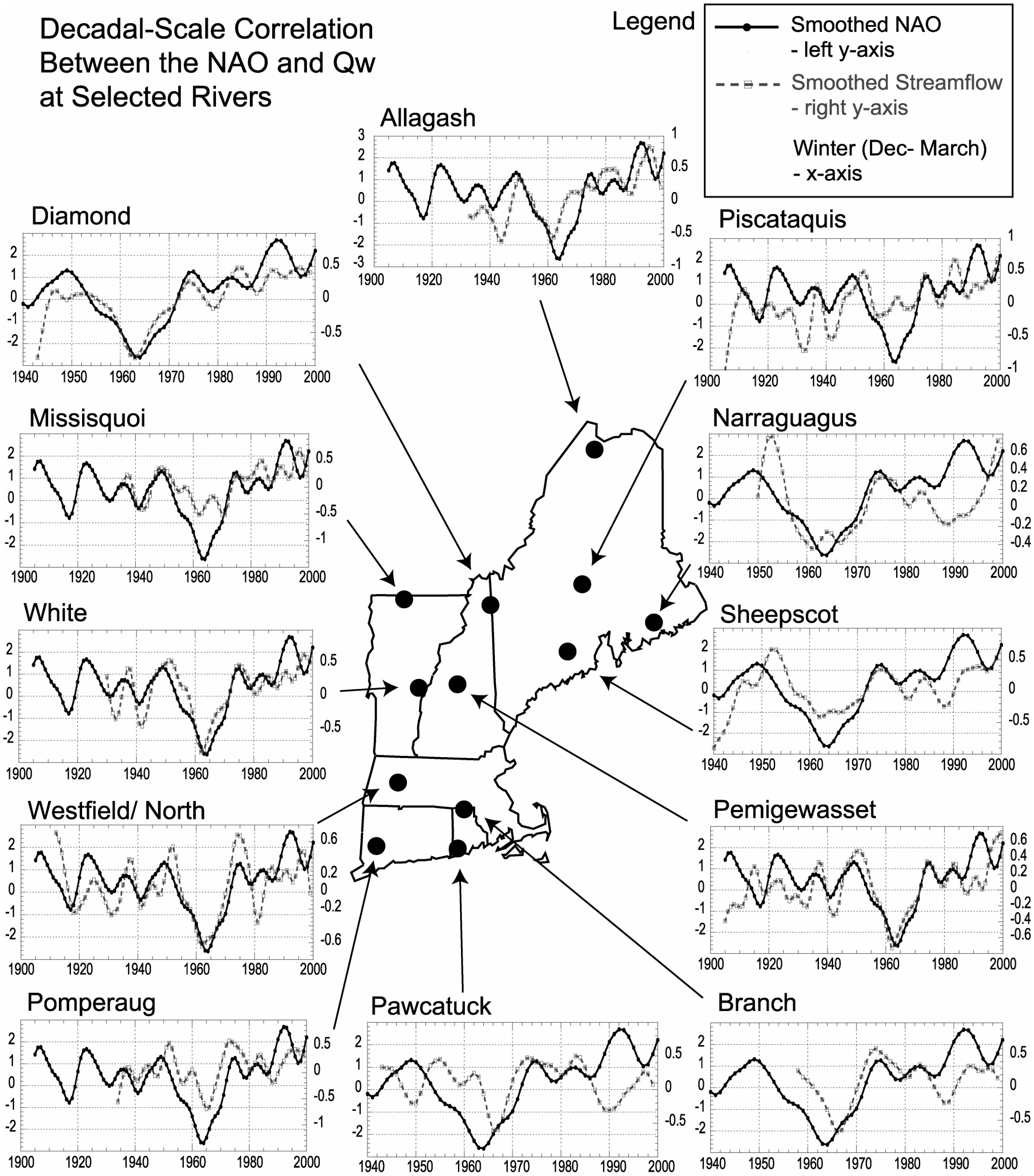


Figure 4. Time series plots of the smoothed Qw and winter NAO for 12 locations in NE. Notice there are two different scales on the x-axis due to the varying lengths of Qw. Also, normalized Westfield River data (Jan. 1912- Dec. 1949) are prefaced to normalized North R. data - to create one continuous record for streamflow variability in western Massachusetts from 1912-1999 - and labeled the "Westfield/ North" river.

that the low-frequency link between Qw and the NAO is not always in phase or equal for all NE streams. It should also be noted that the smoothing splines apparently have a tendency to exaggerate trends in these records near the beginning and end of each original time series (Figure 4). Notwithstanding these problems, it is evident that decadal-scale streamflow variability, particularly from western inland sites, is generally well correlated with equivalent trends in the NAO index. While slow-to-change elements of the hydroclimatic system such as regional SSTs and the hydrologic storage effect are likely to play a mechanistic roll in this low frequency association, more research is needed to fully explain the physical nature of this phenomenon.

SUMMARY AND CONCLUSIONS

The influence of large-scale atmospheric circulation on interannual to decadal-scale New England hydroclimatic variability is investigated is this multi-step investigation. Winter and monthly averaged NE streamflow shows subtle yet significant links with the NAO and PNA teleconnection patterns. However, regional precipitation variability is uncorrelated with these patterns, suggesting that a combination of other factors including temperature, cloudiness, evapotranspiration, and storm tracking may play a role in explaining the observed statistical relationships. Building on this discussion, and our conceptual models described herein, possible physical mechanisms for the observed teleconnections have been subsequently investigated by the authors through the development of regional indices for winter atmospheric circulation (Bradbury et al., *submitted* (a)) and regional cyclone variability (Bradbury et al., *submitted* (b)). Further research, with a broader geographical range, may yield similar results since neighboring U.S. states apparently share a common low-frequency hydroclimatic behavior with NE (Lins, 1997).

Despite the lack of significant correlations between the PNA and NE precipitation, our results are consistent with previous work, which indicates that lower streamflows in central NE are linked to a zonal (negative) Pacific/ North American pattern. Barlow et al. (2001) concluded that a more zonal summertime North American atmospheric flow regime is associated with a dry northeastern U.S. Similar North American tropospheric flow is also associated with positive SOI (La Nina) winters and high SSTs in the North Pacific Ocean (centered at 40°N, 160°W). It is worth noting that the PNA-North Pacific SST teleconnection may also be linked to variability in the SOI. Indeed, along with the PNA-SOI link described earlier, there is also evidence for a significant inverse relationship between North Pacific SSTs and equatorial Pacific SSTs (ENSO) (Allan, 2000), although the details of this relationship remain somewhat controversial (Barlow et al., 2001). While the teleconnections that we observed are subtle, and explain little of the overall variance in NE winter streamflow, their statistical significance warrants further investigation, particularly given the potential that ENSO has shown with regard to hydroclimatic forecasting in other extratropical regions (Piechota and Dracup, 1999).

A mechanism explaining how negative NAO winter conditions could translate into lower streamflows in NE involves the position of the polar front jet. When the NAO is negative, the Icelandic Low is abnormally high and farther to the southwest of Iceland. This weakened low is associated with frequent blocking over Greenland (Shabbar et al., 2001) and meridional flow in the North Atlantic region. Atlantic blocking conditions enhance the East Coast trough and shift the polar front jet to a position farther south than normal (see Figure 1, lower panel). Under these conditions, NE temperatures are generally lower and coastal storms (including Nor'easters) tend to increase in frequency (Jones and Davis, 1995).

Thompson and Wallace (2001) also noted more frequent Nor'easters in the NE region associated with negative NAO conditions. In light of these observations, our results are somewhat counterintuitive; Nor'easters are known to bring significant moisture to the NE region, therefore above-average precipitation and streamflows might be expected. However, given that an enhanced regional trough favors coastal storm activity, an important consideration in terms of NE hydroclimate becomes the mean orientation of this storm track. For example, if the mean axis of the coastal storm track (associated with the enhanced trough) is shifted seaward, storms are less likely to deliver precipitation to the mainland (Namias, 1966; Yarnal and Leathers 1988). Furthermore, if an eastward-displaced coastal storm track persists into the spring and summer, following a series of negative-NAO winters, this would promote below-average annual streamflow, particularly inland. Bradbury et al. (*submitted* (a)) illustrate the importance of east-west shifting in the East Coast trough in terms of NE regional precipitation, particularly inland, and show that a negative NAO index is commonly associated with eastward displacement of this trough. An explanation for why our correlation analyses did not detect a relationship between the NAO and PPT could be that precipitation is more sensitive to transient atmospheric variability (e.g., big Nor'easters), whereas streamflow integrates other factors including the hydrologic storage effect and regional evapotranspiration, and is therefore more representative of low-frequency anomalies in regional hydroclimate, such as drought.

A discussion of the climatic conditions associated with the record 1960s NE drought expands on our conceptual model of the link between low streamflow and a negative NAO index. Persistent negative NAO conditions, cool surface air and below-average SSTs, and regional positive feedback mechanisms (below average water tables and soil moisture) were responsible for 1960s regional drought persistence (Namias, 1966). Namias also noted an eastward-displaced trough (at roughly 60°W) during every year of this drought event, which he attributed in part to anomalously cold regional SSTs. Our results also indicate that the NAO-NE hydroclimate link is most apparent in the low-frequency spectrum, again suggesting that a negative NAO trend could contribute to the persistence of regional hydrologic drought. Also, evidence that the winter NAO index is highly correlated with in-phase, and one-year-lagged, regional SST anomalies suggests that the ocean's "memory" for previous conditions adds to the multi-annual association between the NAO and NE climate (Hartley and Keables, 1998). Furthermore, this low-frequency link may be of particular relevance for future regional winter hydroclimatic forecasting, considering that modeling studies of North Atlantic climate (driven by SSTs) have been most successful at predicting multi-annual trends in the NAO (Rodwell et al., 1999; Mehta et al., 2000). Therefore, to the extent that NAO predictability improves, it may become a useful forecasting tool for important trends in NE winter hydroclimate, particularly in the low streamflow regime.

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