The Influence of Regional Storm Tracking and Teleconnections on Winter Precipitation in the Northeastern United States

James A. Bradbury*,**, Barry D. Keim**,***, and Cameron P. Wake**,****

*Department of Geosciences, University of Massachusetts, Amherst

**Institute for the Study of Earth Oceans and Space, University of New Hampshire

***Southern Regional Climate Center, Louisiana State University

****Department of Earth Sciences, University of New Hampshire

Secular changes in regional storm tracking are examined as physical mechanisms for observed teleconnections between the New England hydroclimate and four predictor variables: the Southern Oscillation Index, the North Atlantic Oscillation, the Pacific Decadal Oscillation, and regional sea-surface temperatures. The main modes of New England winter precipitation, snowfall, and cyclone variability are resolved using varimax rotated principal component analysis. The first rotated principal component of regional cyclone variability defines an out-of-phase relationship between marine versus continental cyclone activity and is statistically linked with the Southern Oscillation, the Pacific Decadal Oscillation, and precipitation in northern New England. Also, El Niño winters generally accompany a slight increase in southern New England precipitation. The second cyclone rotated principal component, defining an inverse relationship between cyclone occurrences along the East Coast and cyclone occurrences along the northern boundary of the Gulf Stream, is well correlated with regional precipitation and snowfall, demonstrating the significance of marine storm tracking as a control on New England winter hydroclimatic variability.

Extreme North Atlantic Oscillation conditions are linked with distinct regional storm tracking patterns such that northwestern New England experiences fewer cyclones during negative North Atlantic Oscillation winter months. Statistical relationships between sea-surface temperatures and principal modes of regional cyclone occurrences are also noteworthy; however, more work is needed to assess the utility of sea-surface temperatures in the development of future seasonal forecasts. Also, confirming earlier findings, cool sea-surface temperature conditions are shown to accompany both drier conditions inland and greater winter snowfall totals in southern coastal regions.
Key Words: hydroclimate, New England, storm tracking, synoptic climatology, teleconnections.

Changes in the frequency of regional climatic events such as severe winter storms, cold-air outbreaks, and drought are often thought to be related to large-scale atmospheric circulation patterns and major modes of climatic variability, such as the El Niño/Southern Oscillation (ENSO), the North Atlantic Oscillation (NAO), and the Pacific Decadal Oscillation (PDO). With this in mind, a few recent studies (Hartley and Keables 1998; Bradbury, Dingman, and Keim 2002; Bradbury, Keim, and Wake 2002) have investigated New England (NE) climate in the context of global teleconnection patterns and their variability. Also, a number of related works focusing on large-scale teleconnections related to ENSO, the NAO, and the PDO have included NE in their larger study domains (e.g., Rogers 1984, 1990; Hurrell and van Loon 1997; Kunkel and Angel 1999; Trenberth and Caron 2000; Barlow, Nigam, and Berbery 2001; Thompson and Wallace 2001). Nevertheless, with only a few exceptions (e.g., Hartley and Keables 1998; Hirsch, DeGaetano, and Colucci 2001), these studies rarely explicitly consider the role of regional storm tracking when examining how changing large-scale patterns may influence NE regional climate variability.

As a result, it is difficult to conclusively determine the physical nature of observed associations, particularly when studies using differing datasets on differing spatial and temporal scales yield conflicting results. For example, Hurrell (1995), using a North Atlantic regional moisture-budget analysis (1981–1994), and Hurrell and van Loon (1997), examining northern hemisphere temperature anomalies (1864–1994), both found little evidence for a significant link between the NAO and NE climate. However, results from regional-scale analyses by Yarnal and Leathers (1988), Bradbury and colleagues (Bradbury, Dingman, and Keim 2002; Bradbury, Keim, and Wake 2002), and Hartley and Keables (1998) suggest that the

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NAO has important links with regional winter atmospheric circulation, temperature, snowfall, streamflow, and sea-surface temperatures (SST), particularly in the low-frequency (decadal-scale) spectrum.

Defining the main modes of NE climate variability, as observed in the instrumental record, is a necessary step toward making meaningful assessments of the accuracy of regional climate predictions made by general circulation models (IPCC 2001). Furthermore, a process-based understanding of the causes of low-frequency variability in past NE climate may improve future medium- to long-range regional forecasting capabilities. With this goal in mind, this study considers four potentially useful climatic predictor variables. The Southern Oscillation Index (SOI) has become a practical tool for predicting hydroclimate (e.g., Piechota and Dracup 1999) and cyclone variability (DeGaetano, Hirsch, and Colucci 2002) in several tropical and—to a lesser extent—extratropical regions around the world. Attention is also being focused on the predictive capabilities of the NAO (Mehta et al. 2000; Gamiz-Fortis et al. 2002), and the related Northern Hemisphere Annular Mode (NAM) (Thompson, Baldwin, and Wallace 2002), making this another potentially useful variable for regional forecasting (Hurrell, Kushnir, and Visbeck 2001). By virtue of its decadal-scale persistence alone, the PDO may also have predictive value for long-lead forecasting in some regions—for example, the U.S. Southwest (Schmidt and Web 2001). Finally, NE regional SSTs are also considered because of their strong month-to-month persistence as well as the fact that anomalies are significantly correlated with the NAO and that this association is known to improve when SSTs are compared with the previous winter's NAO index value (Hartley 1996; Rossby and Benway 2000).

Previous Studies of Regional Cyclone Activity

Winter cyclones traversing NE originate in a wide range of locations around the North American continent (Ludlum 1976). Important regions of cyclogenesis include a long band in the lee of the Rocky Mountains, extending almost continuously from the Northwest Territories to northern Texas (Zishka and Smith 1980). Two other active cyclogenesis areas include the Gulf of Mexico and the East Coast, particularly near Cape Hatteras, North Carolina (Zishka and Smith 1980; Whittaker and Horn 1981, 1984). In general, winter cyclones that reach NE either traverse the Great Lakes and the St. Lawrence River Valley or follow the Atlantic seaboard northward (Whittaker and Horn 1984). Regional storms typically avoid the Appalachian Mountains, although low-pressure centers that do track over this high terrain frequently deepen (Colucci 1976). Atlantic cyclones generally either travel parallel to the coastline toward NE or diverge from the coast and follow the northern boundary of the Gulf Stream eastward (Colucci 1976). The convergence of the St. Lawrence and coastal storm tracks in the vicinity of NE has long been thought to contribute to the complexity of this region's climate (Ludlum 1976).

Some studies have explicitly examined the spatial and temporal variability in East Coast cyclone activity (e.g., Hirsch, DeGaetano, and Colucci 2001). Hartley and Keables (1998) and Serreze and colleagues (1998) investigated the synoptic conditions associated with snowfall variability in the eastern United States. The larger spatial scale of Serreze and colleagues' (1998) study, however, did not allow for a detailed examination of NE's unique conditions. Kocin and Uccellini (1990) provided a thorough summary of synoptic conditions associated with major late twentieth-century snowstorms along the East Coast of the United States.

Previous studies have linked variability in ENSO and the NAO to spatial and temporal changes in major northern hemisphere storm tracks. For example, East Coast winter storms are known to increase during El Niño events (Hirsch, DeGaetano, and Colucci 2001), with lower atmospheric pressures (Trenberth and Caron 2000) and greater cyclone activity more common throughout the southern United States during these winters (Kunkel and Angel 1999). On the other hand, La Niña winters are characterized by lower atmospheric pressures over central and western Canada (Rogers 1984; Trenberth and Caron 2000), favoring more continental storm activity in the Midwest and St. Lawrence storm tracks (Kunkel and Angel 1999). Still, evidence for a consistent NE hydroclimatic response to ENSO remains elusive: regional precipitation is sensitive to many other factors that are unrelated to variability in ENSO, such as the mean location of the East Coast trough (Keables 1992; Bradbury, Keim, and Wake 2002). Other considerations may include the strength of individual El Niño and La Niña events and the indices chosen to define them (Noel and Changnon 1998).

Atmospheric circulation anomalies related to opposite modes of the PDO are similar to those associated with ENSO's extremes, at least for the North American continent. For example, positive PDO winters (similar to El Niño winters) generally accompany enhanced meridional circulation over North America, with drier conditions across most northern U.S. states and above-average precipitation in southwestern and southeastern regions (Mantua et al. 1997). Though less work has been done examining teleconnections related to this mode of North Pacific climate variability, it is widely thought that the phase of the PDO can effectively either dampen or enhance ENSO-related teleconnections in North America (Schmidt and Web 2001).

Rogers (1990) showed that during extreme negative NAO conditions (weak north-south sea-level pressure gradient in the North Atlantic), East Coast cyclones often diverge to the east (near 45° N), as opposed to following their more common northeastward trajectory (Serreze et al. 1997). Thompson and Wallace (2001) observed an increase in the frequency of "nor'easters" during low NAM index (negative NAO) conditions. Still, few studies have explicitly examined how large-scale changes in cyclone frequency or storm-track distribution relate to variability in surface climate, particularly in the northeastern United States. As a result, the underlying mechanisms for major past changes in NE regional hydroclimate remain poorly understood (e.g., Bradbury, Dingman, and Keim 2002).

Data and Methods

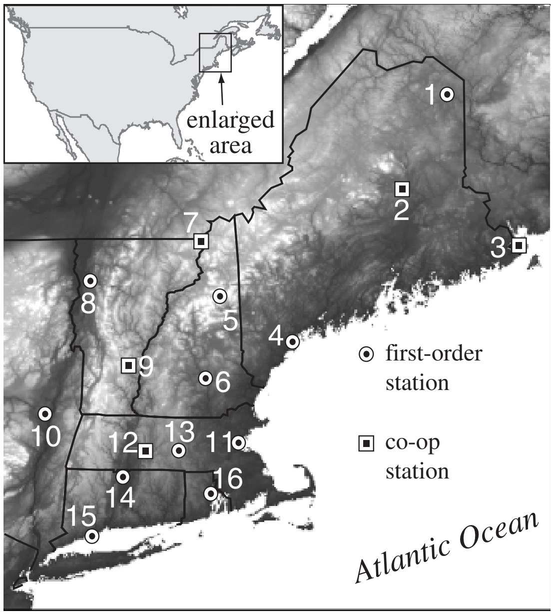
This study investigates possible mechanisms by which important modes of natural climate variability (e.g., ENSO and the NAO) relate to NE regional cyclone occurrences and surface hydroclimate. We conducted separate rotated principal component (RPC) analyses based on correlation matrices to resolve empirically the spatial loading patterns and time series ("scores") that explain the most variance in NE winter precipitation, snowfall, and cyclone occurrences. We based our truncation process for selecting significant principal components (PCs) on the level of spatial coherence observed in plots of loading patterns for the first five PCs. We removed all higher-order components showing poor regional continuity and then retained and orthogonally rotated the remaining PCs according to the varimax criterion.

Richman (1986) recommends the use of PC rotation for cases such as this, in which the scores from the PCs are to be used as indices representing physical modes of regional climatic variability. We also took care to assure that the conclusions drawn from all solutions were robust by conducting the same analyses using unrotated empirical orthogonal function (EOF) techniques (not shown), as suggested by Dommenget and Latif (2002). While some subtle differences occurred, the spatial details of the loading patterns from both rotated and unrotated methods were remarkably similar and the corresponding scores were very well correlated, as expected.

We used Pearson correlation statistics to compare the RPC scores with one another and with indices for ENSO, the NAO, the PDO, and regional SSTs. We also used two-tailed *t*-test statistics to determine whether the differences between monthly mean cyclone occurrences were significant when months from opposite phases of the NAO were compared. Finally, we considered results from this analysis along with results from several earlier studies in order to propose likely physical mechanisms responsible for observed statistical relationships described above. We examine winter here because that is when atmospheric circulation is strongest, the large-scale patterns that we are most interested in are best defined in the geopotential height field (Hurrell and van Loon 1997; Hoerling and Kumar 2000), and precipitation is generally more controlled by large-scale baroclinicity and cyclone activity than during other seasons.

Surface climate variability is represented by winter (December to March [DJFM]) totals of precipitation and snowfall from sixteen stations across the six NE states (Figure 1). Monthly data were initially retrieved from the National Climatic Data Center's online database of climate data. To assure better quality and continuity of record, first-order weather sites were chosen to represent the majority of the regional station data used. Missing monthly values were estimated from neighboring stations using multiple linear regression (MLR) analyses before compiling the winter totals used in this study. This was rarely necessary for precipitation data, except for the missing years of record before 1956 at Hartford, Connecticut, and after 1995 at Worcester, Massachusetts. Usually less than 5 percent of the monthly values from any given station were missing (slightly more for snowfall), and the MLR models always explained at least 70 percent of the variability in the predicted station's monthly data. March is included as part of NE's winter season because snowfall recorded at many sites during this month is often equal to or greater than December totals.

Figure 2 shows means and standard deviations of winter totals of precipitation and snowfall. Coastal and southern regions typically receive significantly greater amounts of precipitation than do inland sites. It is also clearly noticeable that northern inland NE normally receives greater amounts of snowfall than do most southern locations. In general, higher means are accompanied by correspondingly elevated standard deviations, except in the case of coastal snowfall, which is highly variable. One remarkable feature depicted in Figure 2 is that mean winter snowfall and precipitation totals recorded at the Mt. Washington Observatory are more than double the amounts observed at all other weather stations in the region. While data recorded atop Mt. Washington is clearly unusual in the context of the other sites, it was included to represent the orographic effects caused by the



	Station	State	Elevation (m)	Begin Date	End Date
1	Caribou Municipal Airport	ME	190	1952	2002
2	Millinocket Municipal Airport	ME	124	1951	2002
3	Eastport	ME	26	1951	2002
4	Portland International Jetport	ME	14	1951	2002
5	Mount Washington	NH	1909	1951	2002
6	Concord Municipal Airport	NH	106	1951	2002
7	Cannan	VT	311	1951	2002
8	Burlington International Airport	VT	274	1951	2002
9	Cavendish	VT	101	1951	2002
10	Albany County Airport	NY	84	1951	2002
11	Boston Logan Int'l Airport	MA	6	1951	2002
12	Belchertown	MA	107	1951	2002
13	Worcester Regional Airport	MA	301	1949	1995
14	Hartford Bradley Int'l Airport	CT	50	1956	2002
15	Bridgeport Sikorski Memorial	CT	2	1951	2002
16	Providence T F Green State Airport	RI	16	1951	2002

Figure 1. Locations and names of weather stations selected for this study. Numbers 1–16 correspond to labeled locations shown on map. Shading illustrates topography; lighter land areas represent higher elevations. Global 30-arc-second elevation data (GTOPO30) were provided by the U.S. Geological Survey's Earth Resources Observation Systems Data Center.

significant topographic relief of the Appalachian Mountains (Figure 1), which undoubtedly contributes to NE's complex and variable hydroclimate.

Cyclone-occurrence data were taken from the National Oceanographic and Atmospheric Administration's

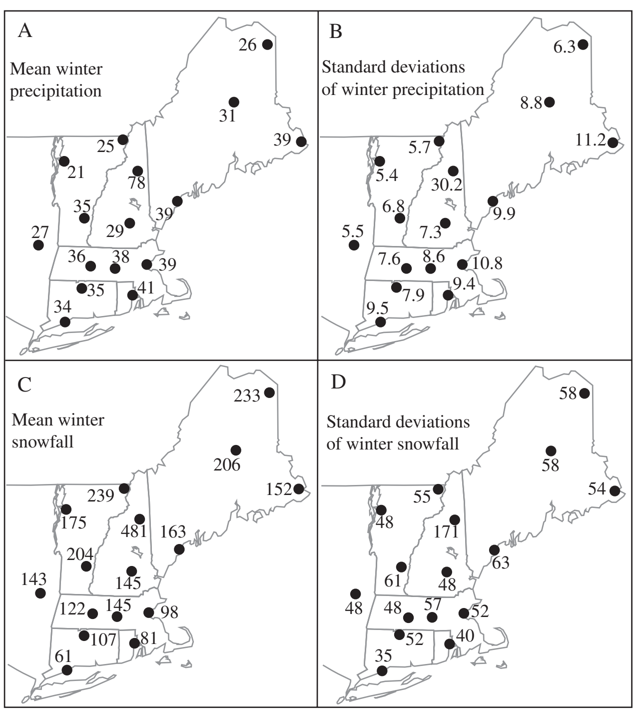


Figure 2. Means and standard deviations for winter (DJFM) precipitation (A, B) and snowfall (C, D). Units = cm.

(NOAA) Climate Diagnostics Center (CDC) web site, as calculated from an algorithm developed by Serreze and Lo (Serreze 1995; Serreze et al. 1997; NOAA/CIRES 2003). The algorithm detects and tracks cyclone centers from an equal area (250 × 250 km) northern hemisphere grid of six-hour sea-level pressure (SLP) (Armstrong and Brodzik 1995) by identifying grid-points with SLP values below a local minimum threshold. Results from Blender and Schubert (2000) suggest that similar algorithms used on T42-resolution gridded datasets at six-hour time steps have a 0.85 probability of accurately mapping cyclones and cyclone tracks.

Our definition of "cyclone occurrence" includes every time the Serreze algorithm detects a cyclone at a grid-point. Figure 3A shows a compilation of every regional winter (DJFM) cyclone occurrence from 1958 and 2000. Cyclone-occurrence maxima in the Great Lakes and St. Lawrence Valley represent an active regional winter-storm track. A relatively broad cyclone-occurrence maximum leading northeast from Cape Hatteras represents a very active and variable marine and coastal storm track, corroborated by Colucci (1976), Zishka and Smith (1980), and Whittaker and Horn (1984). Also clearly noticeable are cyclone-occurrence minima over the Appalachian Mountains and marine regions south of the Gulf Stream.

The Serreze algorithm also notes the location of the first and last times each cyclone is identified, providing a useful tool for mapping the main regions of cyclogenesis

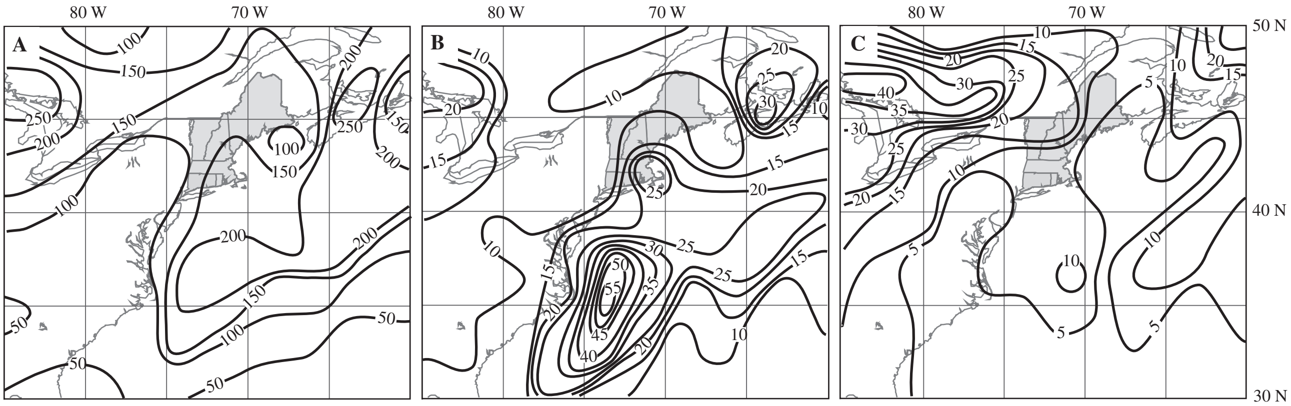


Figure 3. (A) Total cyclone occurrences, (B) cyclogenesis, and (C) cyclolysis events for all winter months (DJFM) between 1958 and 2000.

and cyclolysis, respectively. For this study, cyclogenesis (cyclolysis) is defined as the first (last) time the algorithm detects any cyclone that was persistent for at least two six-hour time-steps. Within our study region, cyclogenesis is most common east of Cape Hatteras, the Great Lakes, Cape Cod, and Nova Scotia (Figure 3B). Cyclogenesis minima are apparent over the Appalachian Mountain range and over northern NE and the northern Gulf of Maine. Figure 3C shows that cyclolysis is most common in continental areas north of 40° N, particularly in the Great Lakes region (also found by Zishka and Smith 1980) and is extremely rare in southern marine areas. This suggests that cyclolysis is a more important mechanism in limiting the frequency of regional continental storm activity, compared with coastal storms, changes in which are more likely to be governed by variability in cyclogenesis and storm tracking.

The SOI, which serves as an index for ENSO, was provided by the Climate Prediction Center (CPC), Camp Springs, MD. It is the difference between standardized monthly SLP anomalies from Darwin, Australia, and Tahiti; low (high) SOI values correspond with El Niño (La Niña) events (Chelliah 1990). A mean monthly NAO index, as defined by Hurrell (1995), using Stykkisholmur or Akureyri, Iceland, and the Azores station as the sea-level pressure (SLP) nodes, was taken from the National Center for Atmospheric Research (NCAR) Website. A monthly PDO index, as calculated by Mantua and colleagues (1997), was taken from the University of Washington's Joint Institute for the Study of the Atmosphere and Ocean Website (University of Washington/NOAA). This index is based on the first PC of monthly North Pacific SST anomalies poleward of 20° N. Time series of winter SOI, NAO, and PDO averages (DJFM) are considered as predictors in correlation analyses while individual monthly NAO values are used to spatially map and compare cyclone occurrence patterns during opposite NAO phases.

The extended reconstructed SST dataset (Smith and Reynolds 2003), available at 2° × 2° resolution from 1856 to 2002, was taken from the CDC Website (NOAA/CIRES 2003). Initially, an EOF analysis performed on winter (DJFM) averaged anomalies from seventy-five grid-points within a West Atlantic region (from the U.S. East Coast to 60° W and 30° N to 46° N) indicated that winter SSTs in this region generally vary in phase (the first EOF explains more than 80 percent of total variance). Given these results, we decided to simplify the SST component of this study by focusing on the relatively small domain that we selected for our cyclone RPC analysis (see below). Hence, SST anomalies from twenty-five grid-points within this region were reduced, via EOF analysis, into one index of NE regional SST variability that explains 94 percent of the total regional variance (1950–2002; Figure 4).

Analysis and Results

Primary Modes of NE Precipitation and Snowfall Variability

RPC analyses were conducted on winter totals of precipitation and snowfall from all stations (Figure 1) for the period between 1951 and 2002. Figure 5 shows the spatial distribution of the loadings for the first two rotated modes, which explain 74.6 percent and 71.3 percent, respectively, of regional precipitation and snowfall variance. The first RPC of precipitation (PPT-RPC_1) explains 41.6 percent of the overall regional variance and is generally considered to be a good index for southern and coastal NE winter precipitation. The loading patterns from the second RPC (PPT-RPC_2) indicate that this mode

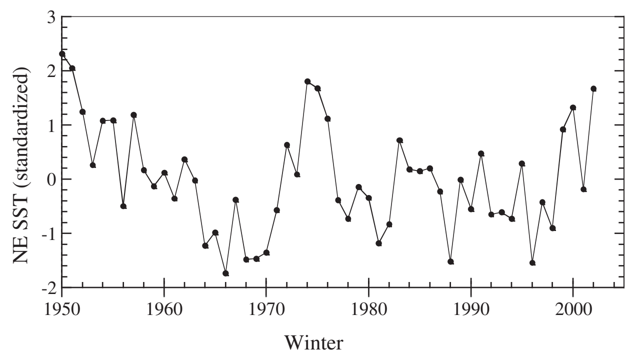


Figure 4. Time series for the scores of the first EOF of NE regional SST (NE SST).

is most representative of precipitation in northern inland NE. The first RPC of regional snowfall (SNW-RPC$_1$) explains 46.7 percent of total regional variance and, like PPT-RPC$_1$, is most heavily loaded at southern coastal sites. The second snowfall RPC (SNW-RPC$_2$) explains 24 percent of the variance and is most heavily loaded at northern inland stations.

The loading patterns for the first two RPCs of regional snowfall obviously share spatial similarities with the corresponding PPT-RPCs (Figure 5). When Figures 5A–B are compared with Figures 5C–5D, however, one noticeable

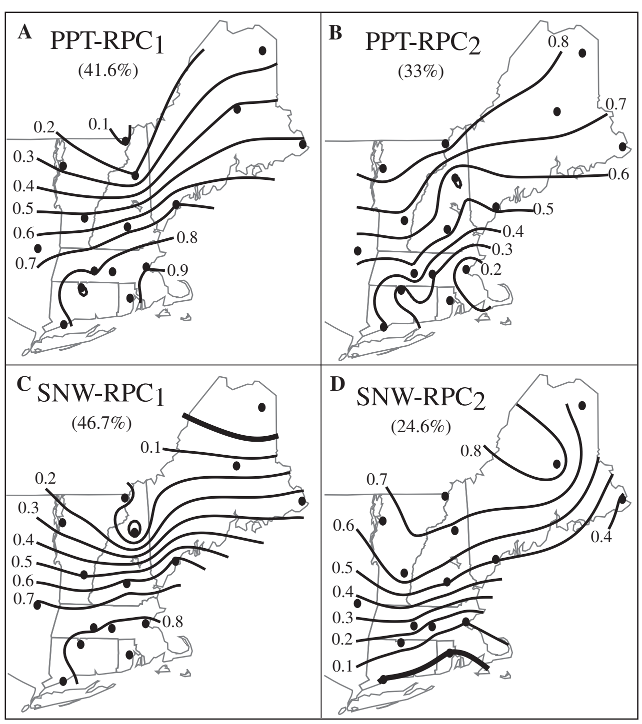


Figure 5. Loading patterns for the first two precipitation and snowfall RPC modes, based on winter (DJFM) totals from 1951 to 2002. Percent of overall variance explained by each mode is shown in parentheses. Solid isolines delineate correlation values between individual station data and RPC scores. The zero isoline is solid bold.

difference is the relative spacing of the isolines. This illustrates the existence of a steep north-to-south continuity gradient in regional snowfall variability relative to precipitation. For example, records for interannual snowfall variability from Caribou, Maine, are uncorrelated with those from Bridgeport, Connecticut ($r = 0.007$; $p < 0.96$); on the other hand, precipitation variability is far more coherent when comparing these same distal stations ($r = 0.52$; $p < 0.001$). The simplest explanation for this is related to the more temperature-dependent nature of snowfall in NE's southern coastal regions relative to the northern mountains, where snowfall is more precipitation-dependent (Hartley 1996; Serreze et al. 1998).

During initial exploratory PC analyses of NE precipitation and snowfall, the loading patterns from the third and fourth EOFs were almost exclusively loaded at the Mt. Washington, Caribou, and Eastport sites (not shown). This is likely to be indicative of the complexity of this region's climate. Due to NE's geographical setting, including the presence of mountain ranges juxtaposed against a fairly long coastline (Figure 1), there appear to be many sharp climatic gradients across the NE region (Zielinski and Keim 2003). A more thorough examination of NE's mountain and maritime microclimates would undoubtedly contribute to our understanding of the regional climate as a whole; an explicit assessment of this topic, however, is beyond the scope of this study.

The time-series of the RPCs' respective scores represent indices for interannual variability in regional surface hydroclimate (1951–2002; Figure 6). While the first

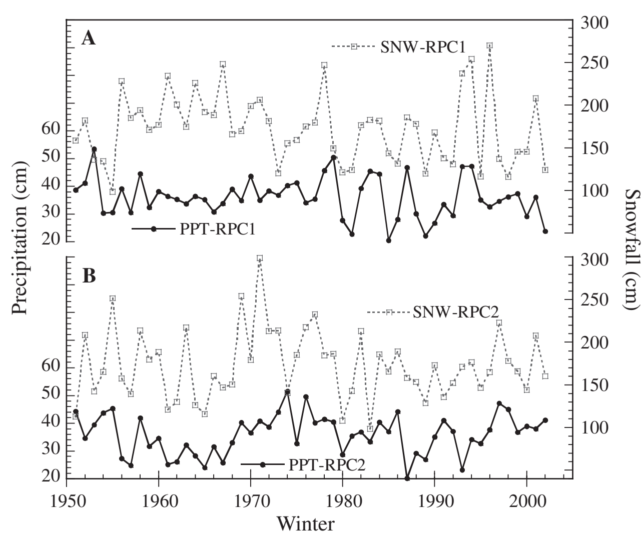


Figure 6. Time series for the (A) first and (B) second RPC scores of winter (DJFM) precipitation and snowfall. For plotting purposes, the scores are standardized and then scaled to the mean and standard deviation of average winter precipitation and snowfall for all stations.

Table 1. Correlation Coefficients Comparing Indices of New England Regional Cyclone Occurrence (CYN-RPC$_{1\text{-}3}$), Precipitation (PPT-RPC$_{1\text{-}2}$), and Snowfall (SNW-RPC$_{1\text{-}2}$)

	PPT-RPC$_1$	PPT-RPC$_2$	SNW-RPC$_1$	SNW-RPC$_2$
CYN-RPC$_1$	0.04	*** − 0.38	0.12	− 0.21
CYN-RPC$_2$	***0.44	0.13	***0.54	***0.44
CYN-RPC$_3$	− 0.05	0.13	− 0.15	0.23
PPT-RPC$_1$	—	—	***0.39	0.08
PPT-RPC$_2$	—	—	*** − 0.40	***0.46

* $\alpha \leq 0.10$
** $\alpha \leq 0.05$
*** $\alpha \leq 0.01$

two corresponding precipitation and snowfall modes are significantly correlated with one another, PPT-RPC$_2$ and SNW-RPC$_2$ are better matched (Table 1). The weaker correlation between PPT-RPC$_1$ and SNW-RPC$_1$ was expected, given (as previous explained) that snowfall is more temperature-dependent in southern coastal regions. In contrast, SNW-RPC$_2$ is poorly correlated with regional temperatures (not shown) and better explained by PPT-RPC$_2$ and cyclone variability (Table 1).

None of the RPC scores are characterized by significant upward or downward trends; however, some temporal features are noteworthy (Figure 6). PPT-RPC$_1$ is marked by periods with relatively low (1960–1977) and high (1978–1995) variance (also noted by Hartley and Keables 1998), with no apparent low-frequency changes in its mean. In contrast, PPT-RPC$_2$ demonstrates more consistent interannual variance, with a decadal-scale component of change, including the conspicuous transition from the dry 1960s to the wet 1970s. The raw station data (not shown) also make clear that precipitation shortfalls associated with the 1960s drought were generally less prevalent in southeastern NE, at least in winter. The scores from SNW-RPC$_1$ suggest that a slight decrease in southern NE snowfall began in the early 1970s; however, more recent high snowfall years, including 1993, 1994, 1996, and 2001 (2003 data not included), suggest an end to this trend. SNW-RPC$_2$ distinguishes the early 1970s from the rest of the record, indicating a snowfall peak in northern NE during this time period.

Primary Modes of Cyclone-Occurrence Variability

Cyclone occurrences from each grid-point within the domain shown in Figure 7 (note smaller domain than Figure 3) were tallied into winter totals, providing a field of twenty-nine continuous time-series for this RPC analysis (1959–2000). Principal storm tracks identified in previous studies (e.g., Klein 1957; Colucci 1976; Zishka and Smith 1980; Hayden 1981; Whittaker and Horn 1984), as well as those apparent in Figure 3, were carefully taken into account when delineating the domain for this regional analysis. We also considered our interest in resolving relatively subtle differences in synoptic-scale storm-tracking patterns that are most likely to influence NE winter hydroclimate.

Figure 7 shows the loadings of the first three RPC modes, which explain a total of 32 percent of the variance in regional cyclone occurrences. However, since, the spatial distribution of cyclone activity is highly uneven (Figure 3A), this figure offers a somewhat biased representation of actual storm tracks associated with each RPC mode. Therefore, another way of looking at these loading patterns in terms of associated storm tracks is to plot the

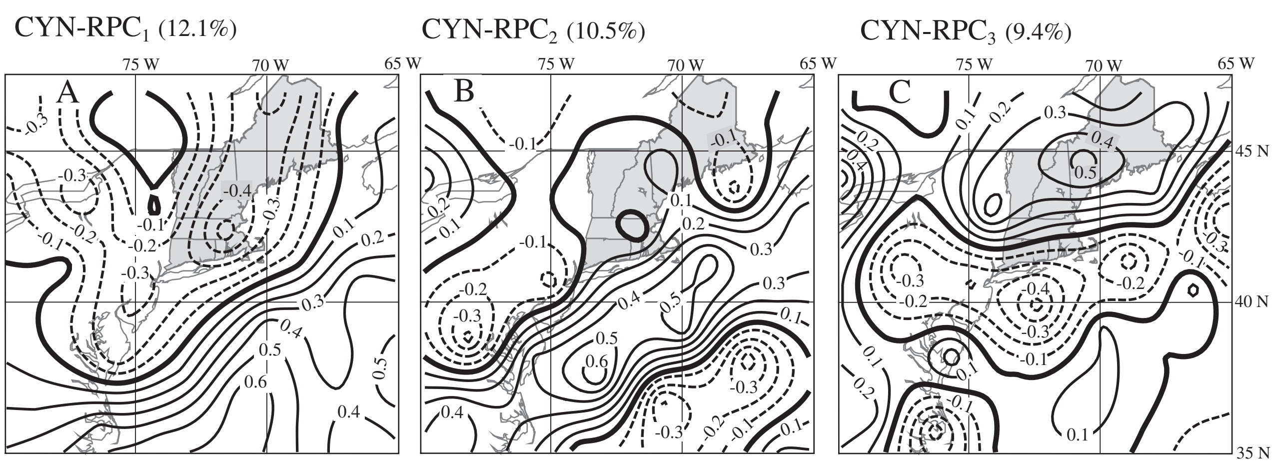


Figure 7. Loading patterns for the first three RPC modes of cyclone occurrences, based on winter (DJFM) totals from 1959 to 2000. Percent of overall variance explained by each mode is shown in parentheses. See Figure 8 for associated storm tracks, interpreted as the top and bottom fifteenth percentiles of each RPC mode. Positive isolines are solid, negative isolines are dashed, and zero isolines are solid bold.

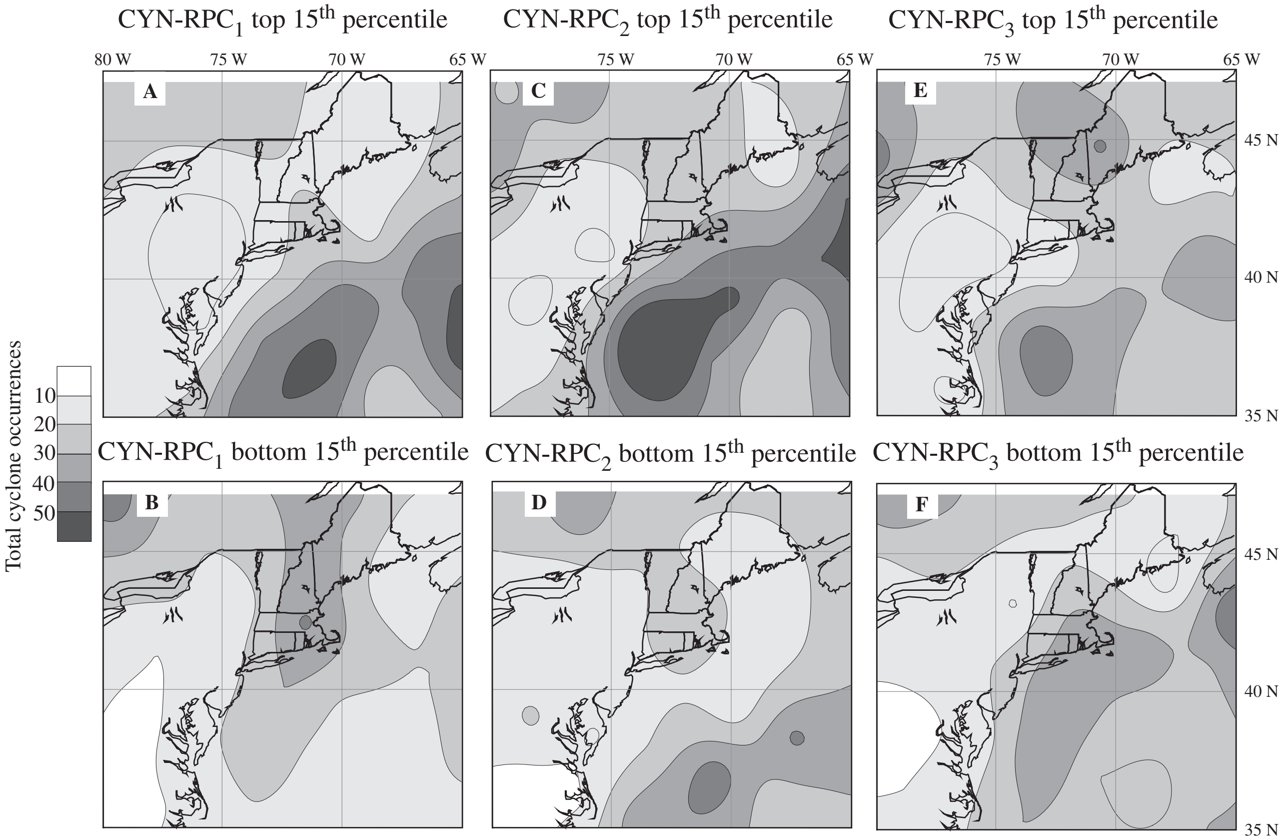


Figure 8. Total cyclone occurrences during winters in the top and bottom fifteenth percentiles of CYN-RPC$_{1-3}$ ($n = 7$ winters in each case). Darker areas represent the most active storm tracks associated with extremes of each mode.

total cyclone occurrences from the top and bottom fifteenth percentiles of each mode (Figure 8), as demonstrated by Bardin (2000).

The first rotated mode of cyclone occurrences (CYN-RPC$_1$) describes the most common regional tendency for Atlantic- and Cape Hatteras-region cyclone activity to be out of phase with activity over the continent, particularly NE. Hayden (1981) found similar results and concluded that this suggests the existence of a negative teleconnection pattern between West Atlantic and Colorado cyclone activity. The second mode (CYN-RPC$_2$) shows an apparent inverse relationship between marine cyclone occurrences along the East Coast and cyclone occurrences along the northern boundary of the Gulf Stream. The loading patterns from the third RPC (CYN-RPC$_3$) also resolve a dipole-like pattern, with loadings focused on two horizontal bands: one through the Great Lakes, upstate New York, and central NE, the other centered on the ocean region south of NE and Nova Scotia (Figures 7C and 8E, F).

The scores of each of the three principal modes of winter cyclone occurrences represent their respective interannual variability (Figures 9A–C). The time series for CYN-RPC$_1$ shows no significant trend (1959–2000), yet there appears to have been a step-like increase in the mean value of CYN-RPC$_1$ in the late 1970s, suggesting an increase in the frequency of marine cyclone activity relative to continental at this time. CYN-RPC$_2$ also has no apparent trend; however, there are a few particular winters worth mentioning, such as the peak in 1971 (corresponding with a peak in northern NE snowfall; Figure 6B) and the low in 1980 (also a low point for regional precipitation; Figure 6). Another noteworthy feature is the prominent increase in CYN-RPC$_3$ in the late 1960s, coincident with the end of the 1960s NE drought.

Comparing Cyclone-Occurrence Patterns with NE Climate

To identify the principal controls on New England regional precipitation and snowfall, the role of cyclone-occurrence variability is considered through Pearson correlation statistics (Table 1). CYN-RPC$_2$, or variability in Atlantic coastal versus Gulf Stream storm tracking, is most important in terms of explaining NE's winter

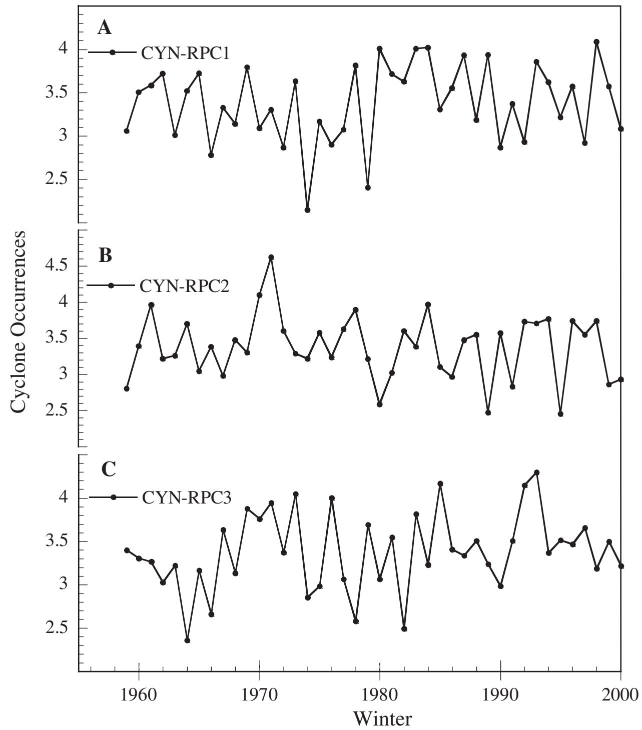


Figure 9. Time series for the first three RPC scores of winter (DJFM) cyclone occurrences. For plotting purposes, the scores are standardized and then scaled to the mean and standard deviation of the average winter cyclone occurrences for all grid points.

hydroclimatic variability. This is because storms with a marine coastal trajectory have the potential to produce large volumes of precipitation in the region, with maximum potential generally declining inland from the coast. Region-wide snowfall is also strongly associated with CYN-RPC$_2$ (Table 1), because this tracking pattern is conducive to low temperatures all across NE, with a steep southeast-northwest gradient. Hence, in this instance, most if not all precipitation would likely fall as snow in the north and west of the region, while some concurrent precipitation in southeastern NE could fall as rain.

The significant correlation between CYN-RPC$_1$ and PPT-RPC$_2$ (Table 1) illustrates the sensitivity of inland precipitation to continental cyclone activity versus marine cyclone activity. This is because more precipitation is expected to accompany enhanced regional cyclone activity through western and central NE (negative CYN-RPC$_1$; Figure 7A). Inland snowfall (SNW-RPC$_2$), on the other hand, is not sensitive to this mode of cyclone variability (Table 1), because inland convergence will generally increase warm air advection from the south and could promote liquid, as opposed to frozen, precipitation in the north and mountains. Finally, despite the fact that CYN-RPC$_3$ is not significantly correlated with any of the precipitation or snowfall modes (Table 1), it is plausible that a return to more frequent St. Lawrence storm-track activity (increasing CYN-RPC$_3$) in the late 1960s played a role in regional drought relief at this time, particularly for northern inland NE (compare Figure 6A with Figure 9C).

Comparing NE Climate with Predictor Variables

To provide a basis for future regional winter climatic forecasting, Table 2 shows the extent to which NE hydroclimatic indices are correlated with the SOI, the NAO, the PDO, and NE SSTs. Significant correlations are found between the SOI and CYN-RPC$_1$, confirming that coastal and marine cyclone activity generally increases during El Niño events, while continental cyclones become relatively more frequent during La Niña winters (corroborated by Kunkel and Angel 1999; Hirsch, DeGaetano, and Colucci 2001). In addition, Table 2 shows that the SOI is also slightly correlated with PPT-RPC$_1$, reflecting occasional precipitation increases in southern NE during El Niño winters (1958, 1983, 1987, and 1993); the opposite is true for some La Niña events (1976, 1989, 2000). Though this correlation value ($r = -0.24$; $p < 0.10$) shows that ENSO explains little overall variance in PPT-RPC$_1$, it is worth mentioning that when other indices were used to define ENSO (e.g., Niño 3 or Niño 3.4) similar or improved statistically significant results were found (not shown).

Similar results were also observed between the PDO and CYN-RPC$_1$, suggesting that circulation patterns associated with positive PDO events (resembling El Niño conditions) are conducive to East Coast marine-storm development, while a negative PDO favors more continental storm tracking. Another noteworthy point is that the apparent stepwise increase in CYN-RPC$_1$ that occurs at the end of the 1970s coincides with a comparable increase in the PDO index. Indeed, with few exceptions, major low-frequency variations in the PDO from 1959 to 2000 generally occur in phase with or lead similar secular changes in CYN-RPC$_1$.

Table 2. Correlation Coefficients Comparing Principal Component Scores in Table 1 with Possible Climatic Predictor Variables: The SOI, NAO, PDO, and NE SSTs

	SOI	NAO	PDO	NE SST
CYN-RPC$_1$	*** −0.38	0.08	***0.40	−0.22
CYN-RPC$_2$	−0.16	−0.20	0.22	** −0.34
CYN-RPC$_3$	−0.09	0.16	0.04	0.07
PPT-RPC$_1$	* −0.23	−0.05	0.10	0.00
PPT-RPC$_2$	0.13	−0.01	−0.07	**0.32
SNW-RPC$_1$	0.02	−0.19	0.05	*** −0.37

The NAO index does not correlate significantly with the primary modes of NE regional cyclone occurrences or precipitation (Table 2). However, results from a composite analysis comparing cyclone occurrences during extreme (top and bottom twenty-fifth percentiles) NAO conditions (Figure 10) indicates that negative NAO months are associated with an eastward displacement of the typical East Coast storm track (particularly from 40 to 45° N). This is consistent with results from the research of Rogers (1990) and DeGaetano, Hirsch, and Colucci (2002), who found that negative NAO conditions accompanied more frequent zonal, as opposed to meridional, movement of regional storms at this latitude. The statistically significant inverse relationship between the NAO and SNW-RPC$_2$ (Table 2) is consistent with results from the research of Hartley and Keables (1998), who found that typical negative NAO conditions are very similar to the large-scale circulation patterns most conducive to above-average regional snowfall. We also found below-average NE SSTs to be associated with more frequent coastal cyclone occurrences (positive correlation with CYN-RPC$_2$) and less inland precipitation (inverse relationship with PPT-RPC$_2$; Table 2). Confirming previous results of Bradbury, Keim, and Wake (2002) and Hartley and Keables (1998), NE SSTs are also inversely related with southern coastal NE snowfall (SNW-RPC$_1$; Table 2).

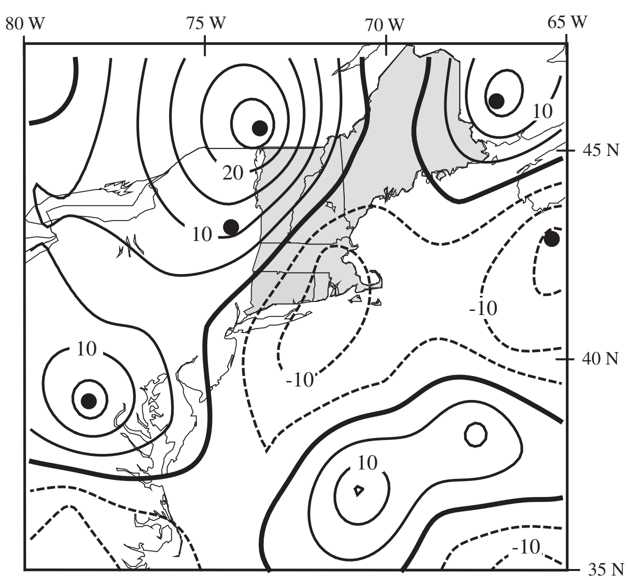


Figure 10. Composite of cyclone occurrences during winter months (DJFM) with high positive NAO index values (top twenty-fifth percentile; $n = 41$) minus cyclone occurrences during winter months with low negative NAO index values (bottom twenty-fifth percentile; $n = 41$) (January 1958–March 2000). Significant t-test results (< 0.05) are indicated by black dots at their respective grid-points. Isolines are equivalent to those in Figure 7.

Summary and Conclusions

In this study, the principal modes of NE regional winter precipitation, snowfall, and cyclone variability were resolved through rotated principal component analyses and shown to be interrelated with regional SSTs and three main modes of global-scale natural climate variability: ENSO, the NAO, and the PDO. Our results yield a better conceptual, process-based understanding of NE winter climate variability and may provide a basis for future development of winter-season empirical climate-prediction modeling.

Previous reports suggested that ENSO has no physical link with NE hydroclimate (e.g., Ropelewski and Halpert 1986; Kahya and Dracup 1993). This study yielded results to the contrary. We found the SOI to be correlated with PPT-RPC$_1$, indicating that southern coastal regions may receive greater winter precipitation during El Niño and less during La Niña events. One reason for the small amount of explained variance could be that an increase in the frequency of coastal storms during El Niño events is sometimes "cancelled out" by a concurrent decrease in the frequency of continental low-pressure systems (the opposite would be true during La Niña winters), resulting in the faint ENSO signal we observed. This hypothesis is supported by the more robust statistical relationship between CYN-RCP$_1$ and the SOI. We also found a similar—and possibly related—teleconnection between the PDO and the first mode of regional cyclone occurrences. One possible reason for the PDO's lack of association with regional precipitation and snowfall could be similar to the explanation given above for ENSO. However, our understanding remains somewhat speculative pending further research.

Extreme NAO conditions are shown to be associated with distinct regional storm-tracking patterns. During negative NAO conditions, a high-pressure system often builds over Greenland, resulting in frequent and prolonged North Atlantic blocking episodes (Shabbar, Huang, and Higuchi 2001). Blocking conditions favor the more frequent advection of polar air into the region (Thompson and Wallace 2001) and typically inhibit the normal flow of U.S. coastal storms, redirecting them eastward, away from the mainland (Resio and Hayden 1975; Rogers 1990). Thus, negative NAO conditions are generally associated with increased North Atlantic blocking, greater snowfall totals in northern NE, and—most critically in terms of regional hydroclimate—less frequent tracking of coastal storms directly through the NE region. This explains one possible mechanism for previously observed relationships between the NAO and inland NE streamflow (Bradbury, Dingman, and Keim 2002).

Thus, it is apparent that a physical link between NE climate and the NAO exists. Yet the signal is strongest in the low-frequency spectrum (Bradbury, Dingman, and Keim 2002). While the NAO index itself displays low-frequency behavior (Hurrell and van Loon 1997), it is possible that NAO-related regional SST variability also plays a mechanistic role in the NAO-NE teleconnection pattern by modulating long-term variability in regional winter storm tracking, temperatures, precipitation, and snowfall. This hypothesis has been of considerable interest, given that the unprecedented 1960s NE drought occurred within a well-documented set of persistent boundary conditions, including a strongly negative NAO, above-average North Pacific SSTs (negative PDO), and exceptionally cold regional SSTs (Namias 1966; Barlow, Nigam, and Berbery 2001). Yet precipitation shortfalls associated with the recent East Coast drought, which began in the late 1990s, occurred in the context of somewhat dissimilar conditions: while the NAO and PDO were both trending toward more negative values, as in the 1960s, NE SSTs were on the rise. This suggests that NE SSTs may not have had a dynamic connection with the persistence of the 1960s NE drought after all. However, given the observed statistical association between regional SSTs and inland precipitation (Table 2; Bradbury, Keim, and Wake 2002) it may be too early to discount any physical link between these variables. Still, we conclude that future attempts to make regional drought forecasts should at least consider the phase and tendency of the NAO and the PDO.

We found an inverse relationship between regional SST anomalies and snowfall totals in southern NE. Hartley and Keables (1998), who found similar results, explain that anomalously cool regional SSTs promote colder low-level atmospheric conditions in coastal regions and thus increase the likelihood of snowfall, as opposed to rain. If snowfall variability in southern NE is in fact responding to SST anomalies, the implication of these findings is that data from ongoing SST monitoring (e.g., National Data Buoy Center) could be used to improve future long-lead regional snowfall forecasting.

We also observed an inverse relationship between regional SSTs and variability in marine storm tracking patterns (CYN-RPC$_2$), such that more frequent coastal (as opposed to offshore) storms are associated with colder regional SSTs. This result may be an indication of the ocean surface responding to changes in storm tracking: high winds that accompany increased storminess would cause greater evaporative cooling at the ocean surface, enhanced ocean mixing, and more Ekman-driven upwelling. DeGaetano, Hirsch, and Colucci (2002) presented somewhat different results, finding that warm SSTs anomalies off the southeast U.S. coast sometimes precede winters with high East Coast storm activity, however, the driving force behind observed relationships between SSTs and atmospheric variability in midlatitude regions, particularly in the North Atlantic, remains somewhat controversial (Kushnir et al. 2002). While large-scale patterns in North Atlantic winter SST anomalies are thought to be largely driven by atmospheric pressure and surface-wind anomalies, the strength and positioning of storm tracks may, in turn, respond thermodynamically to changes in regional SST gradients—for example, at the northern boundary of the Gulf Stream (Kushnir et al. 2002).

It is important to note that results presented here were derived empirically and cannot explicitly address this question of causality. Nevertheless our findings shed light on some very interesting synoptic-scale patterns and relationships that are statistically significant and warrant further research and discussion.

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Correspondence: Climate System Research Center, Department of Geosciences, University of Massachusetts, Amherst, MA 01003, e-mail: bradbury@geo.umass.edu (Bradbury); Southern Regional Climate Center, Louisiana State University, Baton Rouge, LA 70803, e-mail: keim@lsu.edu (Keim); Climate Change Research Center, Institute for the Study of Earth, Oceans, and Space, University of New Hampshire, Durham, NH 03824, e-mail: cameron.wake@unh.edu (Wake).