

NOTES AND CORRESPONDENCE

U.S. East Coast Trough Indices at 500 hPa and New England Winter Climate Variability

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ABSTRACT

Using monthly gridded 500-hPa data, two synoptic indices are defined to better understand the principle mechanisms controlling intraseasonal to multiannual winter climate variability in New England (NE). The “trough axis index” (TAI) is created to quantify the mean longitudinal position of the common East Coast pressure trough, and the “trough intensity index” (TII) is calculated to estimate the relative amplitude of this trough at 42.5°N. The TAI and TII are then compared with records for NE regional winter precipitation, temperature, and snowfall with the goal of understanding physical mechanisms linking NE winter climate with regional sea surface temperatures (SST), the North Atlantic Oscillation (NAO), and the Pacific–North American (PNA) teleconnection pattern. The TAI correlates most significantly with winter precipitation at inland sites, such that a western (eastern) trough axis position is associated with greater (lower) average monthly precipitation. Also, significant correlations between the TAI and both NE regional SSTs and the NAO suggest that longitudinal shifting of the trough is one possible mechanism linking the North Atlantic with NE regional winter climate variability. The NE winter temperature is significantly correlated with the TII, regional SSTs, and the NAO. While the PNA also correlates with the TII, NE winter climate variables are apparently unrelated to the PNA index.

1. Introduction

Efforts to characterize and effectively explain the key remote and local controls on New England (NE) winter climate have been limited to a few recent reports (Hartley 1996; Hartley and Keables 1998; Bradbury et al. 2002). However, studies of winter teleconnections at larger spatial scales, including NE within their study’s domain, are far more abundant (e.g., Rogers and van Loon 1979; Ropelewski and Halpert 1986; Rogers 1990; Leathers et al. 1991; Hurrell 1995; Enfield et al. 2001). Most of these find relatively little or no relationship between NE winter climate and hemisphere-scale atmospheric circulation patterns [i.e., the North Atlantic Oscillation (NAO), the Pacific–North American (PNA)

pattern, the El Niño–Southern Oscillation, and the Atlantic Multidecadal Oscillation]. There is evidence for significant teleconnections between NE climate and the NAO and PNA indices (Hartley and Keables 1998; Leathers et al. 1991; Bradbury et al. 2002); however, New England’s proximity to the centers of action for the NAO and PNA make the mechanisms behind these links unclear. For example, the PNA serves as an effective index for the mean configuration of the polar front jet over much of North America, and thus temperature variability in much of the United States (Leathers et al. 1991), yet the present study finds NE temperature to be unrelated. Furthermore, despite the recognized climatic significance of lateral shifting in quasi-stationary long waves (Harman 1991), neither the NAO nor PNA teleconnection patterns are known to characterize this dynamical feature of tropospheric flow (Keables 1992). Hence, a new way of characterizing NE regional atmospheric flow is needed to identify and as-

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sess the dominant mechanisms driving winter climate variability more objectively.

In winter, the U.S. east coast marks the boundary between a cold (often snow covered) continent and the warmer Atlantic Ocean, as well as the dramatic meridional sea surface temperature (SST) shift at the northern edge of the Gulf Stream, where atmospheric circulation is characterized by strong eddy activity (Lau 1988), frequent baroclinicity (Harman 1991), and as a result, vigorous and widespread regional cyclogenesis (Colucci 1976; Zishka and Smith 1980). While these fixed geographical features largely determine the mean location of the East Coast trough, little is known about the principal controls on intraseasonal to interannual variability in the longitude and character of this trough. Therefore, two new indices are developed to examine the extent that regional SSTs and large-scale atmospheric circulation patterns relate with trough variability and with NE winter climate variability on intraseasonal to multiannual timescales. Using gridded monthly 500-hPa data, the trough axis index (TAI) describes the longitudinal position of the common East Coast trough, while the trough intensity index (TII) estimates the regional long-wave amplitude of the trough.

The three primary objectives are the following:

- 1) Determine the relevance of our regional indices (the TAI, TII) in terms of NE winter climate (temperature, precipitation, and snowfall).
- 2) Analyze statistical relationships between NE winter climate variables, regional SSTs, the NAO, and the PNA pattern.
- 3) Describe possible mechanisms responsible for apparent teleconnections between NE climate and large-scale atmospheric circulation patterns using the TAI, TII, and regional SSTs as indices for regional synoptic climatology.

2. Data and methods

The NE climate data used in this study include monthly totals of precipitation, snowfall, and monthly means of maximum (T_{\max}) and minimum (T_{\min}) temperature. These data have been through quality assurance and quality control checks by the National Climatic Data Center and were retrieved from EarthInfo's Summary of the Day CD-ROM database (EarthInfo, Inc. 2000). Whenever possible, data from first-order weather stations were used to minimize time of observation biases and ensure high quality data that are nearly continuous. To improve spatial coverage, data from three cooperative network stations were also included (Fig. 1 and Table 1). All months missing more than one daily observation were not given a total, or mean, value for that month. To remove right skewness, monthly totals of precipitation and snowfall were cube-root-transformed (hereafter referred to as PPT and snowfall, respectively). Seasonal means of raw monthly data were found to be

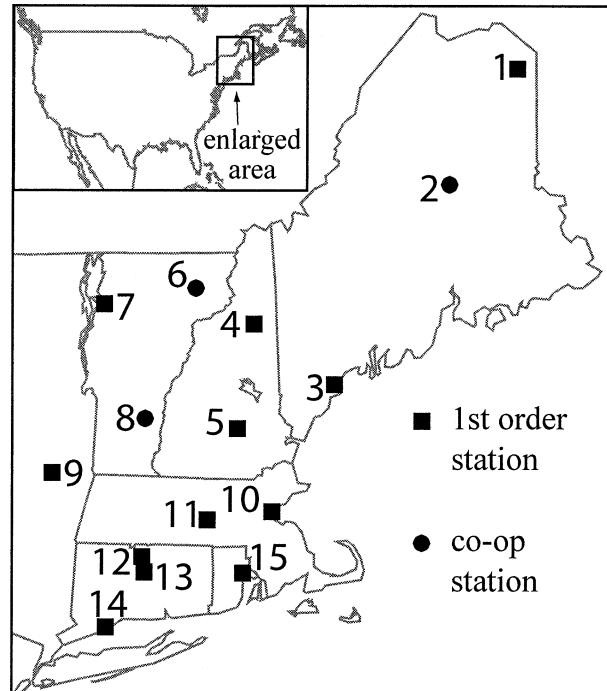


FIG. 1. Locations of weather stations selected for this study. Numbers (1–15) correspond with locations shown in Table 1 (note: snowfall data, unlike precipitation and temperature, are generally only available through Dec 1996).

significantly less skewed, therefore no transformations were made to these data. Because snowfall data from Hartford Brainard Field are sparse, data from Bradley International Airport were used in lieu of Brainard Field data for snowfall only. Winter is the only season examined in this analysis because atmospheric circulation and teleconnection patterns are known to be strongest at this time.

Atmospheric pressure data were provided by the National Centers for Environmental Prediction–National Center for Atmospheric Research (NCEP–NCAR) reanalysis CD-ROM database as calculated by NCEP–NCAR. Monthly 500-hPa pressure level data (from 1948 to 1998), on a $2.5^\circ \times 2.5^\circ$ resolution grid, were used to characterize general midtropospheric airflow and to derive the trough axis and trough intensity synoptic indices (described in section 3).

SST data were originally taken from NCEP–NCAR described in Smith et al. (1996) and at the Web site: <http://dss.ucar.edu/datasets/ds277.0/>. This study uses a subset of the monthly NCEP data as analyzed by season with rotated (varimax) principal component analyses (RPCA; Hartley 1996). Standardized monthly gridpoint values from January 1950 to November 1992 were averaged for several regions in the west Atlantic; each delineated according to loading patterns determined in the seasonal RPCA (available online at <http://people.moreheadst.edu/fs/s.hartley/atlantic/sstdata.htm>). In all four seasonal analyses, a significant loading pattern emerged in the

TABLE 1. Names of weather station locations shown in Fig. 1.

Station	State	Elevation (m)	Begin date	End date
1 Caribou Municipal Airport	ME	190	Jan 1948	Dec 1999
2 Millinocket Municipal Airport	ME	124	Jan 1949	Dec 1999
3 Portland International Airport	ME	14	Jan 1948	Dec 1999
4 Mount Washington	NH	1909	Jan 1949	Dec 1999
5 Concord Municipal Airport	NH	106	Jan 1948	Dec 1999
6 West Burke	VT	274	Jun 1948	Dec 1998
7 Burlington International Airport	VT	101	Jan 1948	Dec 1999
8 Cavendish	VT	244	Jun 1948	Dec 1999
9 Albany County Airport	NY	84	Jan 1948	Dec 1999
10 Boston Logan International Airport	MA	6	Jan 1948	Dec 1999
11 Worcester Regional Airport	MA	301	Jan 1949	Dec 1999
12 Hartford Bradley International Airport	CT	49	Jan 1955	Mar 1996
13 Hartford Brainard Field	CT	6	Jan 1948	Mar 1999
14 Bridgeport Sikorski Memorial Airport	CT	2	Jan 1949	Dec 1999
15 Providence T F Green State Airport	RI	16	Jan 1949	Dec 1999

region north of the Gulf Stream, south of Nova Scotia, and west of 60°W. Mean standardized SST values (December–March) from within this region were used in this study as an index for winter NE regional SSTs (hereafter referred to as “NE SST”). Original SST observations for all points in this region are available for at least 60 months in the 120-month period between 1950 and 1959 (90 months for the period between 1980 and 1989; Smith et al. 1996).

A winter [December–January–February–March (DJFM)] monthly NAO index was taken from the NCAR Web site, as defined by Hurrell (1995), using Stykkisholmur or Akureyri, Iceland, and Ponta Delgadas, Azores, as the sea level pressure (SLP) nodes. A mean winter NAO index, using SLP data from Lisbon, Portugal, for the southern station, was taken from the same source.

The index used for the PNA teleconnection pattern was calculated by NCEP, as identified using RPCA on monthly mean 700-mb height anomalies (after Barnston and Livezey 1987). These data (with a complete description of the techniques used to derive them) are available from 1950 to the present at the NCEP Web site.

This study synthesizes a variety of datasets to gain a better understanding of New England’s complex historical winter climatology. The analysis uses two newly developed synoptic-scale climate indices, regional meteorological and SST data, and indices for large-scale atmospheric circulation. Monte Carlo simulation analyses (described in detail by Bradbury et al. 2002) were used to set conservative significance levels for the correlation statistics. This was done to account for the autocorrelation in each time series, which was particularly an issue with regard to NE SSTs, and the multiplicity of hypotheses tested (Brown and Katz 1991). Since monthly snowfall totals at many NE locations are higher in March than December, March is included in this winter (DJFM) climate analysis. All analyses of winter seasonal means therefore include all four winter months and are referenced by the calendar year of January.

3. Development of regional synoptic indices

a. 500-hPa trough axis index (TAI)

The monthly TAI quantifies the mean longitudinal position of the quasi-stationary midtropospheric East Coast trough and provides a way of assessing low-frequency variability in regions experiencing upper-level divergence and convergence (Fig. 2), baroclinic instability (Harman 1991), and cyclone activity. The East Coast trough is most commonly located near 75°W longitude (Harman 1991), and the TAI domain extends 45° east and west of this line (from 120° to 30°W) to allow for extreme trough configurations and positions. The northern and southern boundaries were set to include grid points from latitudes within, or closest to, NE (Fig. 3). The TAI index was calculated by averaging the longitudinal positions (Lon) of the minimum 500-hPa heights (H_{\min}) observed at each of the four latitudinal steps ($j = 40^\circ, 42.5^\circ, 45^\circ, \text{ and } 47.5^\circ\text{N}$) within the index range, to produce a practical index in longitudinal units (relative to the prime meridian):

$$\text{TAI} = \text{average} [\text{Lon}(H_{\min})_j].$$

Some months were not assigned TAI values based on the following two concerns. First, if $\text{Lon}(H_{\min})_j$ was greater than 40° east or west of the minimum height observed at a neighboring latitude [$\text{Lon}(H_{\min})_{j\pm 1}$] then the 500-hPa pressure field for that month was plotted and visually inspected for the existence of a “double trough” within the index domain. In only a few rare instances (months), where the TAI represented an average of two troughs (i.e., a ridge), TAI values were not assigned. Second, if minimum pressure level values from any of the four latitudinal steps (Fig. 3) were at the lateral boundary of the index range [i.e., $\text{Lon}(H_{\min})_j = 30^\circ$ or 120°W], no TAI value was assigned to that month. These data were discarded because they may provide inaccurate representations (biases) of the actual trough axis location. This screening procedure only re-

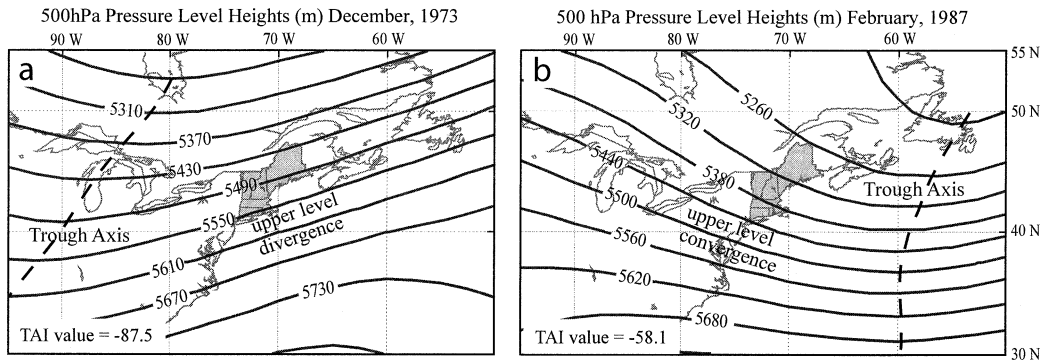


FIG. 2. Example months where the trough axis is displaced (a) west (increased upper-level divergence over NE) and (b) east (increased upper-level convergence) of the long-term mean position (average TAI = -75°).

moved 14 winter months, leaving a nearly continuous 190-month time series for analysis (Fig. 4).

b. 500-hPa trough intensity index (TII)

The TII, an estimate of wave amplitude at 42.5°N , is the mean height change at the 500-hPa surface from equal distances east and west of the East Coast trough axis. Initially, a random sample of plotted winter monthly 500-hPa fields were inspected to establish that 30° of longitude is the shortest half wavelength (distance between any neighboring ridge and trough) and therefore the best distance over which the relative trough amplitude should be calculated. Using a longer distance introduces the possibility that the slope inclination could change sign between grid points, creating a bias toward lower trough intensity. The TII has subsequently been calculated over several different longitudinal ranges, yielding similar results and conclusions.

The TII was calculated at constant latitude ($j = 42.5^\circ\text{N}$) for every month assigned a TAI value. The index is the mean difference between 500-hPa heights (H_i) at the center of the trough [$(H_{\min})_i$] and the 500-hPa heights from 12 grid points (30° longitude) east (H_{i+30°) and west (H_{i-30°) of the trough center ($120^\circ\text{W} > i > 30^\circ\text{W}$):

$$\text{TII} = \{[(H_{\min})_i - H_{i+30^\circ}] + [(H_{\min})_i - H_{i-30^\circ}]\}/2.$$

To accommodate cases where $(H_{\min})_i$ was less than 12 grid points away from the lateral boundaries of the TAI domain (e.g., $i = 115^\circ\text{W}$) the TII was calculated by

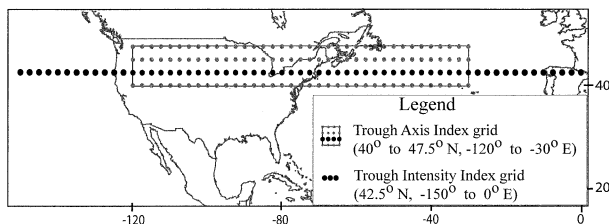


FIG. 3. Location of grid points used to derive the regional synoptic indices (TAI and TII).

adding 24 more grid points along 42.5°N latitude (see Fig. 3). Theoretically, a high TII value corresponds to winter months where the regional pressure trough has more amplitude and therefore a greater meridional component to flow. Visual inspection of the 500-hPa surface during months with the highest and lowest TII values (e.g., Fig. 5) confirms the validity of this interpretation.

4. Results and discussion

a. Characteristics of the TAI and TII

Both the TAI and TII clearly indicate that the East Coast trough made a gradual shift toward an eastward and more meridional configuration throughout the 1950s and into the early 1960s (Fig. 4). Leathers and Palecki (1992) confirm that there was a significant change in character of the midtropospheric flow across North America during this time period. Other studies found evidence for a significant expansion of the circumpolar vortex throughout the late 1950s and early 1960s (Burnett 1993; Davis and Benkovic 1994).

Comparing 95% confidence intervals for the true mean of monthly TAI and TII values (Fig. 6) reveal significant intraseasonality in these records from December to March. It is apparent that the East Coast trough axis typically shifts significantly eastward over the course of the average winter (possible causes for this are discussed in section 4c). Winter intraseasonality of the monthly TII is also apparent (Fig. 6); trough intensity is strongest in January and February, and significantly weaker during March. The TII peak in January is coincident with the coldest month of the year for most locations along the East Coast. In addition, this month also has the steepest N-S temperature gradient in the Northern Hemisphere, which serves to induce strong meridional circulation and high TII values.

b. Relations between the TAI, TII, and NE winter climate

Associations between the TAI and TII and monthly PPT, T_{\max} , T_{\min} , and snowfall were determined using

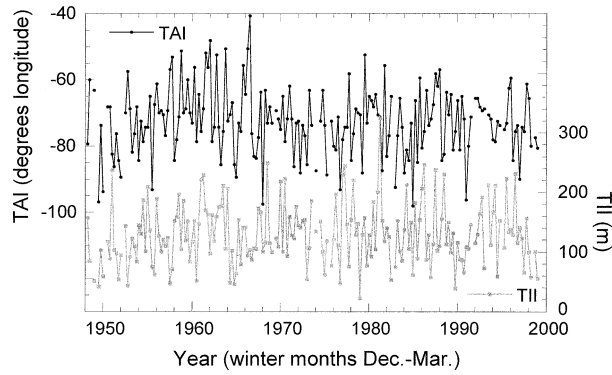


FIG. 4. Time series plots of the TAI and TII. Out of 204 winter months between 1948 and 1998, 190 months were assigned index values. See text for details.

pairwise correlation analysis. The TAI is significantly correlated with monthly and winter mean PPT, particularly at inland and northern locations (Figs. 7a,b). This relationship indicates that an eastward (westward) displaced trough is linked with below (above) average NE regional precipitation. This result was expected given that the most active midlatitude storm tracks occur immediately downstream of pressure troughs (Lau 1988; Cai and Van den Dool 1991), while regions just upstream of troughs are associated with anticyclonic flow at the surface and are generally considerably drier (Klein 1948; Harman 1991). The inland PPT sensitivity to TAI variability is likely caused by the remote proximity of these sites to the baroclinic zone associated with the winter trough position. For example, when the trough shifts eastward the coastal regions are more likely to remain at the western edge of the coastal storm track, while inland sites are closer to a region of relative high pressure and upper-level convergence (Fig. 2).

Up to 25% of monthly and winter mean temperature variability is explained by the TII, which suggests that this index may be a meaningful indicator of the mean location of the polar front (Fig. 8). When the amplitude of the East Coast trough is greater (Fig. 5b) the polar

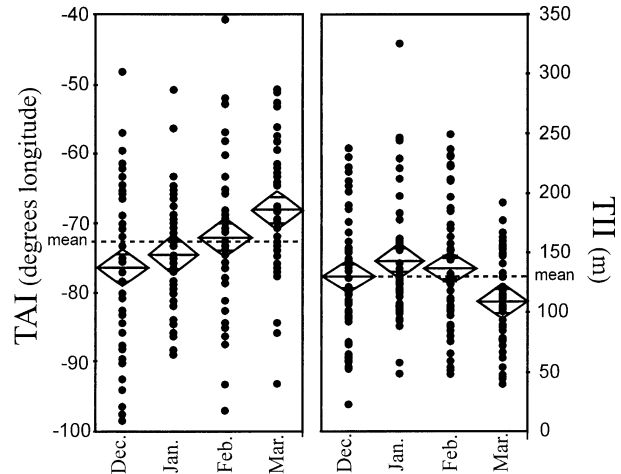


FIG. 6. All (left) TAI and (right) TII values plotted by month with “means diamonds.” The vertical endpoints of the diamonds form the 95% confidence intervals for the true mean of the TAI and TII during each month, respectively.

jet front is typically displaced south, allowing for more frequent polar airmass advection into NE. Caribou and Millinocket, Maine, are less sensitive to winter TII variability since they are apt to remain north of the polar front for most of this season, regardless of the position of the front.

c. Relations between regional SST and NE winter climate

Confirming earlier work by Hartley and Keables (1998), we found NE SSTs correlate significantly with regional surface air temperature (Figs. 9a,b and 10a,b), precipitation (Figs. 9c and 10c; mostly inland and north) and snowfall (Figs. 9d and 10d; in the south). Hartley (1996) provides a more detailed discussion and analysis of the SST–snowfall relationships. Results from a simple 1-month lag correlation analysis between monthly SSTs and NE regional air temperatures (not shown) suggest that SST anomalies typically follow the air tem-

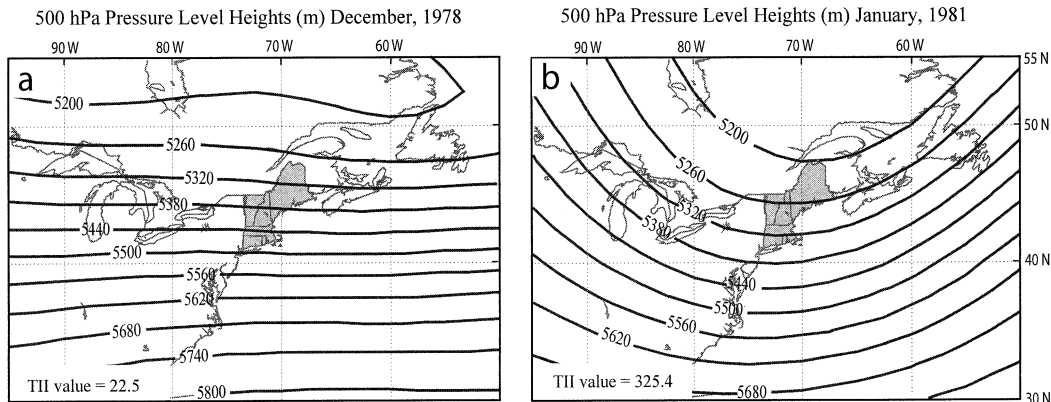


FIG. 5. Example months where the East Coast trough has (a) low and (b) high intensity.

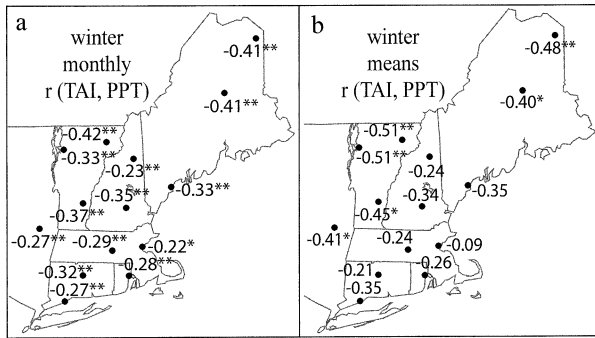


FIG. 7. Correlation statistics comparing New England winter PPT with the TAI. Analysis includes winter (DJFM) months and seasonal means with Monte Carlo significance levels marked ** and * for the 0.01 and 0.05 α level, respectively.

perature anomalies. In multiple linear regression models of NE regional temperature, the TII and NE SST combined explain more than 25% of the winter monthly (50% of the winter season interannual) temperature variability at most locations, except for northern Maine. The matter of identifying key mechanisms driving NE winter temperature variability will be revisited in the following section (4d).

Relationships between NE regional SSTs and East Coast cyclone activity (Colucci 1976; Hartley and Keables 1998) suggest that anomalously cool SSTs in the region east of NE, and north of the Gulf Stream, are generally associated with fewer coastal storms tracking up the East Coast, and more following the Gulf Stream

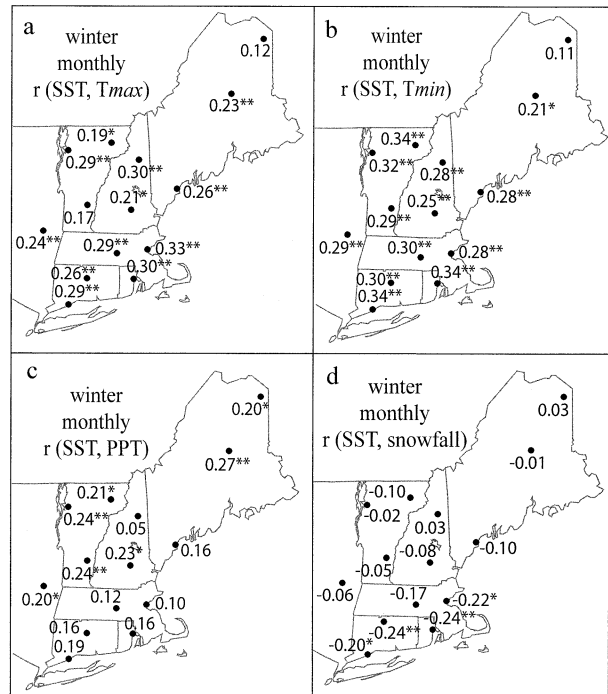


FIG. 9. Same as Fig. 7 but for mean winter NE climate variables with NE SST.

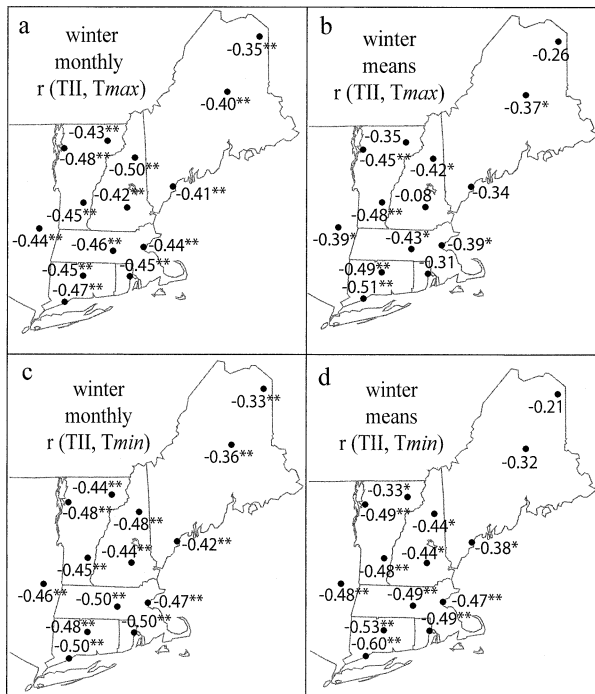


FIG. 8. Same as Fig. 7 but for NE temperatures and the TII.

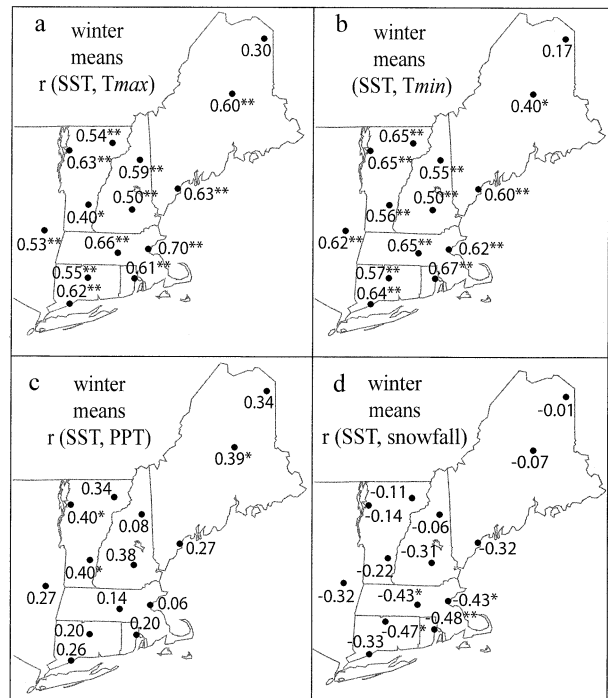


FIG. 10. Same as Fig. 7 but for mean monthly NE climate variables with NE SST.

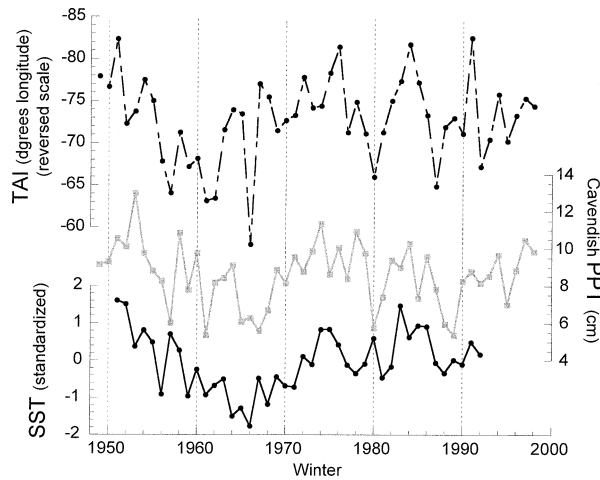


FIG. 11. Time series plots of mean winter TAI, PPT in Cavendish, VT, and NE SST.

out to sea (Colucci 1976). Results shown in Table 2, which indicate that below-normal SSTs are typically associated with an eastward-displaced trough, generally support these findings. Also, the spatial distribution of the NE SST–PPT correlation statistics is nearly identical to that of the TAI–PPT (cf. Fig. 10c with Fig. 7b); the most significant relationships are found at inland and northern locations. These results suggest that regional SSTs are more influential on the winter trough axis position (and thus inland precipitation) than convection and low-level baroclinicity on a local (coastal) scale. Also, the tendency for coastal cyclone activity to follow a more offshore track during cool SST winters (Colucci 1976) may result in a greater number of storms merely glancing off the NE coast, leaving inland regions relatively dry, and, therefore, more sensitive to SST variability. Additionally, time series plots of winter mean NE SST, PPT (at Cavendish, Vermont), and the TAI (Fig. 11) hint that their association is also important on multiannual to decadal timescales.

Associations between NE SSTs and the monthly TAI suggests that TAI intraseasonality (Fig. 6) may be partially attributed to the progressive cooling of regional SSTs, over the course of the average winter season, and a resulting increase in the north–south SST gradient

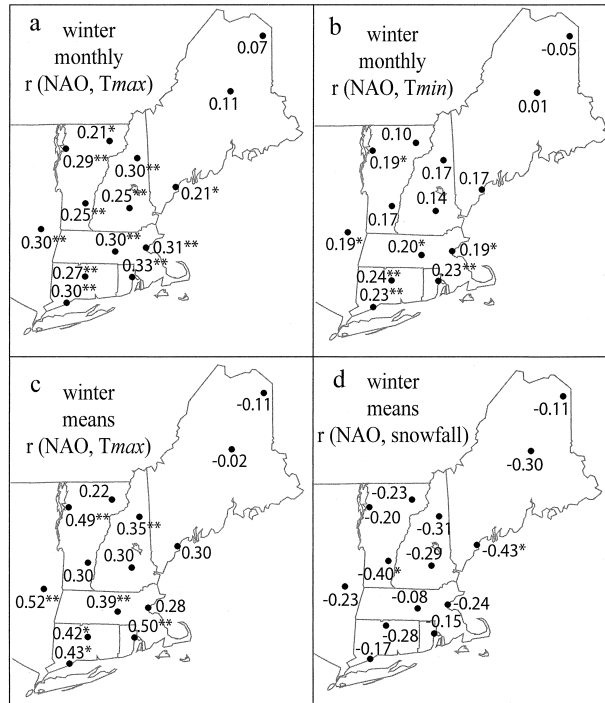


FIG. 12. Same as Fig. 7 but for NE temperatures and snowfall with the NAO index.

between the NE and Gulf Stream regions. In fact, results from Kushnir et al. (2002) confirm that a late winter peak in the SST gradient at the northern boundary of the Gulf Stream is likely to be associated with an increase in regional storm tracking and baroclinic activity.

d. Relations between the NAO, PNA, and NE regional winter climate

Figures 12a–c all indicate that the NAO is significantly related to regional winter temperatures (except for northern Maine). Also, in multiple linear regression models of T_{max} at several southern NE stations the NAO improves the model by 10% after accounting for variability explained by TII and NE SST. All three predictors combined explain roughly 35% of total winter monthly temperature variability at several sites. Yarnal and

TABLE 2. Correlation coefficients comparing winter (DJFM) monthly (M) and winter season averages (W) of the six climate indices used in this study. Bold entries are for $\alpha = 0.05$, and italic entries are for $\alpha = 0.01$.

	TII		NE SST		NAO		PNA		North Atlantic blocking*	
	M	W	M	W	M	W	M	W	M	W
TAI	0.02	0.14	-0.26	-0.48	-0.22	-0.15	0.04	0.13	0.11	-0.05
TII			-0.14	-0.22	0.03	-0.09	<i>0.39</i>	<i>0.41</i>	0.15	-0.24
NE SST					<i>0.25</i>	<i>0.39</i>	0.07	0.11	-0.11	-0.21
NAO							0.03	0.31	-0.61	-0.70
PNA									-0.09	-0.31

* (Shabbar et al. 2001; 1958–95).

Leathers (1988) explained a mechanism for the NAO–NE temperature relationship: negative NAO conditions are associated with a meridional flow regime [and increased blocking (Shabbar et al. 2001)], which causes more frequent deepening of the regional trough and colder East Coast temperatures. Resio and Hayden (1975) also noted a direct link between the frequency of North Atlantic blocking activity and enhanced East Coast trough intensity. It is therefore somewhat surprising that the TII is not significantly correlated with the NAO or an index for North Atlantic blocking (Table 2), however this inconsistency is likely the result of our definition of trough intensity. Manual inspection of the 500-hPa pressure field over the west Atlantic region for several months with high blocking frequency often revealed the existence of a conspicuous meridional flow regime. However, these pressure fields also generally had weak *north–south* pressure gradients and, as a result, near-average TII values.

Given that the NAO is positively correlated with regional temperatures, it is not surprising to find a significant inverse relationship between the NAO and regional snowfall (winter averaged) at some sites (Fig. 12d). This relationship was not significant in the monthly analysis and is more apparent on longer timescales (Hartley and Keables 1998). Rogers and van Loon (1979) were the first to note a significant positive correlation between the NAO and NE regional SSTs. Recent studies also found considerable associations between the NAO and the latitude of the Gulf Stream (Taylor and Stephens 1998; Rossby and Benway 2000). Apparently, a southward displacement of the Gulf Stream, east of Cape Hatteras, often occurs following negative NAO events (mean lag time between 1 and 2 yr). Rossby and Benway (2000) attributed this relationship to NAO-related thermohaline conditions in the Labrador Sea and resulting changes in the Labrador Current. An inverse relationship between the NAO and the strength of the Labrador Current (Rossby and Benway 2000) helps explain the significant positive correlation between the NAO and NE SST (Table 2), which is strongest on multiannual to decadal timescales (Hartley and Keables 1998).

We find significant correlations between winter monthly variability in the NAO and the TAI (Table 2), such that negative NAO conditions accompany an eastward-displaced trough axis (and *visa versa*). These results are consistent with Rogers (1990) findings that negative NAO winters are linked to unique East Coast storm tracking patterns, where coastal storms often diverge from the continent near 45°N and follow a track almost directly east, as opposed to continuing on a more typical northeastward trajectory.

The TII and PNA index are significantly correlated (Table 2); both attempt to quantify the intensity of Rossby waves over North America. Despite the relationships between the TII with NE regional temperature and the TII with the PNA, the PNA is not significantly correlated with any NE climate variable (winter mean or

monthly) tested in this study, confirming the results of Hartley and Keables (1998).

5. Conclusions

Trough axis and trough intensity indices (TAI and TII) are shown to represent important features in regional midtropospheric flow that prove to be significantly interconnected with NE winter precipitation and temperature, respectively. Also, correlation statistics comparing the TAI and TII with regional and hemisphere-scale climate indices allow for the development of more meaningful conceptual models to explain the main controls on NE winter climate variability.

An eastward-displaced East Coast trough is associated with below-average NE regional precipitation, particularly at inland locations. Both NE SSTs and the NAO are related to longitudinal shifting of the trough axis, such that cool regional SSTs and negative NAO index months frequently accompany an eastern trough axis position. Hence, given the established relationships between the NAO and both NE SSTs (Hartley 1996) and NE regional hydroclimate (Bradbury et al. 2002) it is clear that the NAO has important, though complex, physical links with NE regional climate. Therefore, the synoptic conditions associated with the 1960s drought, which included persistent below-normal SSTs and an eastward-displaced trough (Namias 1966), were likely linked to the concurrent negative NAO conditions.

The NE winter temperature variability is associated with variability in the TII, the NAO, and regional SSTs. Clearly increased North Atlantic blocking activity (Resio and Hayden 1975) and positive TII values are associated with high Rossby wave amplitudes and an increase in frequency of polar airmass advection into NE. The exact nature of the relationship between NE air temperature and regional SST requires further attention.

Despite the important affects of snowfall on regional transportation and commerce (Hartley 1996), no good predictor for snowfall in the northern NE states has been found. This problem is made more difficult by the fact that snowfall is governed by a combination of highly variable parameters including storm tracking and regional temperature. While the NAO index has subtle statistical associations with seasonal snowfall totals (Hartley and Keables 1998), our results show weak spatial continuity in this relationship, highlighting the need for more research into possible causes for extreme snowfall seasons (like the recent winter of 2001). On the other hand, our results confirm earlier work that found snowfall in southern coastal NE to be significantly associated with regional SSTs. As noted by Hartley (1996), the typical persistence of SSTs makes this association potentially useful for the purpose of winter climate forecasting.

While the TAI and TII used for this study are regionally specific, the theory behind their development and their gridded data foundation makes them easily applicable to similar synoptic-scale climate investiga-

tions in other midlatitude regions around the world. In fact, any detailed study with the goal of examining specific regional signatures of global teleconnection patterns may benefit from the use of similar trough (or ridge) axis position and intensity indices. Few regional climate studies have applied such an approach, yet more work in this area may lead to better understanding of complex spatial and temporal relationships between upper-air patterns and regional surface climate variability. The simple and generic format of these indices could also make them useful for evaluating the skill with which general circulation models (GCMs) adequately replicate important upper-air patterns, with respect to surface climate variability, both spatial and temporal. Furthermore, as the resolution and quality of GCMs improve, axis position and intensity indices could be helpful tools for reaching a better mechanisms-based understanding of how rapidly changing atmospheric boundary conditions could affect the spatial and temporal variability of important upper-air patterns and related surface climate conditions.

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