ATLANTIC OCEAN-ATMOSPHERE INTERACTIONS AND SNOWFALL IN SOUTHERN NEW ENGLAND

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ABSTRACT

This paper examines in further detail a previously identified inverse association between seasonal snowfall totals in southern New England and sea surface temperature anomalies (SSTAs) in the adjacent Atlantic Ocean. Variations of western Atlantic SSTAs and of the mid-tropospheric circulation over North America and the adjacent Atlantic Ocean during the cold-season months of October-March are each examined by principal component analysis. Canonical correlation analysis identifies the dominant modes of joint variability (contemporaneous and lagged) between Atlantic SSTAs and the atmospheric circulation. Comparisons are made between HIGH-SNOW and LOW-SNOW winters. Results suggest that the mid-tropospheric circulation of December has a disproportionate influence on seasonal snowfall. Persistence of Atlantic SSTAs established partly through atmosphere-ocean coupling in the late fall/early winter is proposed as a possible linkage. The extent to which the SSTAs then influence precipitation form is still currently under investigation, but there are indications that SSTAs might influence the Atlantic Coast storm track, as well as air temperatures in southern and coastal New England.

INTRODUCTION

Snowfall in the northeastern United States has shown variability on a decadal scale since 1950. The late 1950s to early 1970s was a period of relatively high snowfall from the mid-Atlantic region to southern New England (Leathers *et al.*, 1993; Acker and Soule, 1995) while preceding and succeeding periods were characterized by lower snowfall amounts. Variations in seasonal snowfall in the eastern United States have been diagnosed in terms of mid-tropospheric circulation patterns over eastern North America (Namias, 1960; Wagner, 1979; Hartley and Keables, 1997).

Hartley (1996) identified an association between winter (December-March) snowfall in southern New England and sea surface temperature anomalies (SSTAs) in the adjacent Atlantic Ocean (this previous study is referred to hereafter as H96). Composite HIGH-SNOW and LOW-SNOW winter groupings were defined by the extreme values of an index of winter snowfall for southern New England (Figure 1). High (low) snowfall totals were found to be associated with negative (positive) SSTAs off the Atlantic coast (Figure 2), although it was not established whether the SSTAs were the cause of the snowfall anomalies (directly or indirectly) or were simply the product of the associated atmospheric circulation anomaly patterns. However, in most cases of exceptionally high or low seasonal snowfall totals, the corresponding SSTAs were evident as early as December, suggesting that the association with snowfall was not merely a coincidental effect of the anomalous winter climatic regime.

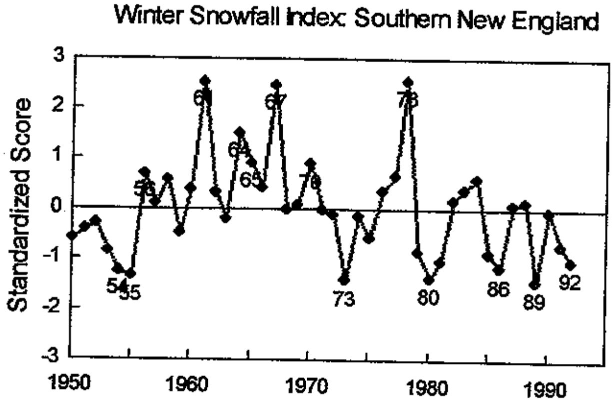

FIGURE 1. Winter snowfall index for southern New England (from H96)

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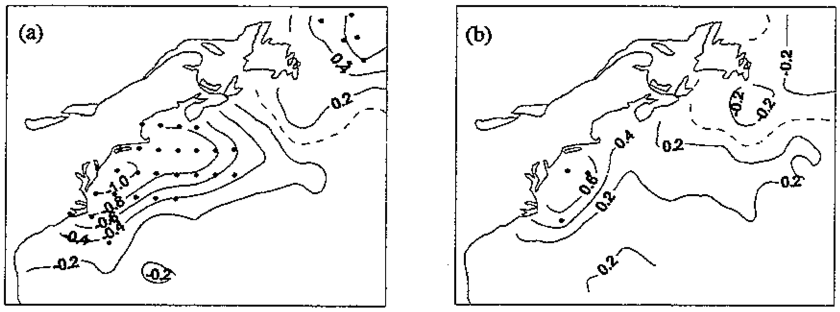


FIGURE 2. Composite SSTAs (deg. C) for (a) HIGH-SNOW and (b) LOW-SNOW winters. HIGH-SNOW and LOW-SNOW winters are indicated in Table 1. Dots indicate grid-points at which composite anomaly was judged by bootstrap procedure to be statistically significant at the 95 percent confidence level.

The present study examines variations of western North Atlantic Ocean SSTs and interactions with the mid-tropospheric circulation over the western Atlantic region in order to better understand the importance of Atlantic SSTAs to the seasonal snowfall regime of southern New England. Most recent research on North Atlantic Ocean SSTs emphasizes the use of global climate models and/or observations to diagnose patterns of atmosphere-ocean coupling (e.g., Peng and Fyfe, 1996; Kushnir, 1994; Wallace *et al.*, 1990), variability of SSTs (e.g., Battisti *et al.*, 1995; Deser and Blackmon, 1993) or the atmospheric response to SSTAs in the northwest Atlantic Ocean (e.g. Kushnir and Held, 1996). In general, however, there have been few attempts to link Atlantic SSTAs to regional climate anomalies in the eastern United States, although some associations have been indicated with precipitation anomalies (Namias, 1966; Colucci, 1976) and with anomalies of winter-season temperature, precipitation and snowfall in New England (Hartley and Keables, 1997).

The atmospheric circulation and SSTA patterns associated with HIGH-SNOW and LOW-SNOW winters are examined on a monthly basis. Contemporaneous and lagged coupled modes of variability, both contemporaneous and lagged, of the SST and 700-mb height fields are also investigated in order to better understand cause and effect with regard to the winter climate regime and seasonal snowfall anomalies in the New England region.

DATA AND ANALYSIS

Data

Monthly totals of precipitation and snowfall, and means of temperature at Providence, Rhode Island, were computed from daily observations retrieved from EarthInfo's "NCDC Summary of the Day" CD-ROM data base. Providence was selected as a reference station because seasonal snowfall at this location is highly correlated (R = 0.90) with the Southern New England snowfall index of H96. Providence is a first-order station with no missing data.

Sea surface temperature anomalies for the months October through March (as standardized departures from the monthly average for the period of record) for the years 1950-1992 were computed from a reconstructed analysis by the Climate Prediction Center of the National Center for Environmental Prediction (NCEP) (Smith *et al.*, 1996), referenced to a 2x2 degree latitude-longitude grid. Areal coverage includes the western Atlantic Ocean from the North American coast (between Florida and Newfoundland) east to longitude 45°W.

Standardized monthly anomalies of the 700-mb height field were computed from gridded monthly analyses originally constructed by the National Meteorological Center (now known as NCEP) and obtained from the Data Support Section of the National Center for Atmospheric Research (NCAR). The analyses are referenced to a 5x5 latitude-longitude grid and areal coverage corresponds roughly with the region bounded by 20-70°N and 30-150°W.

Analysis

Monthly precipitation, temperature and snowfall

The previous study (H96) only considered anomalies of seasonal snowfall totals. Monthly anomalies of precipitation, temperature and snowfall at Providence were examined to verify that the snowfall anomalies were indeed a seasonal phenomenon and not dominated by anomalies in any one winter month.

Month-to-month variations of SSTs and 700-mb circulation

Unrotated principal component analyses (PCA) of standardized anomalies for the months October to March were computed for each of the SST and 700-mb height fields. PCA is an eigenvector-based technique that transforms a data set of *p* intercorrelated variables into *p* uncorrelated components which are linear functions of the original variables (Haan, 1977). For a more detailed account of PCA and its application, the reader is referred to Yarnal (1993). Monthly scores on the leading PCs were compared between the HIGH-SNOW and LOW-SNOW winter groups of H96 (Table 1). HIGH-SNOW and LOW-SNOW composite anomaly patterns were also computed separately for each month. This analysis was performed for the SST field in H96, but only for the months December through March, and so is repeated here.

Table 1. Winters selected for composite analysis

	WINTER (of January)
HIGH-SNOW	56, 61, 64, 65, 67, 70, 78
LOW-SNOW	54, 55, 73, 80, 86, 89, 92

Ocean-atmosphere coupled modes

Coupled modes of variability of the 700-mb height and SST fields were investigated by canonical correlation analysis (CCA). CCA is a multivariate statistical technique that relates two data fields by identifying linear combinations of variables in one field that are most strongly correlated with linear combinations of variables in the other field (Bretherton *et al.*, 1992). The 700-mb height and SST fields were each subjected to an unrotated PCA in order to reduce the number of variables input to the CCA. This was done separately for each calendar month of October through March. The number of components retained for input to the CCA varied from month to month, but enough components were retained in each case to account for a combined variance explained of 70 percent, a threshold that represents a reasonable tradeoff between random errors due to sampling fluctuations (higher variance threshold) and systematic errors (lower variance threshold) (Bretherton *et al.*, 1992). Both contemporaneous associations (e.g. December SSTs vs. December 700-mb heights) and lagged associations (e.g. January SSTs vs. December 700-mb heights) were considered.

Only those canonical variates passing a Chi-Square test at a significance level of 0.05 were retained for further examination. As applied by Knappenberger and Michaels (1993), the canonical vectors were mapped back onto the original data space by premultiplying the canonical loading matrix by the PC loading matrix. The result of each CCA is then a pair of loading patterns - one for the SST field and one for the 700-mb height field - and a pair of canonical score time series. Canonical scores were compared between the HIGH-SNOW and LOW-SNOW composite winter groups.

Persistence

Persistence in the SST and 700-mb height fields was assessed by computation of month-to-month correlation coefficients of component scores on the leading PCs of each of the fields. Month-to-month correlations of anomalies at individual grid points were also computed.

RESULTS AND DISCUSSION

Monthly precipitation, temperature and snowfall at Providence

Figure 3 compares precipitation, temperature and snowfall by month for HIGH-SNOW and LOW-SNOW winters. Results of Mann-Whitney U-test comparisons are given in Table 2. Comparing HIGH-SNOW and LOW-SNOW winters, precipitation does not differ significantly in any one month, while significant differences in temperature are indicated for December and March. Snowfall differs significantly in December, January and March, with marginal significance in February. It appears that anomalous snowfall seasons are not dominated by one particular month, and are more likely the result of anomalies in temperature rather than precipitation.

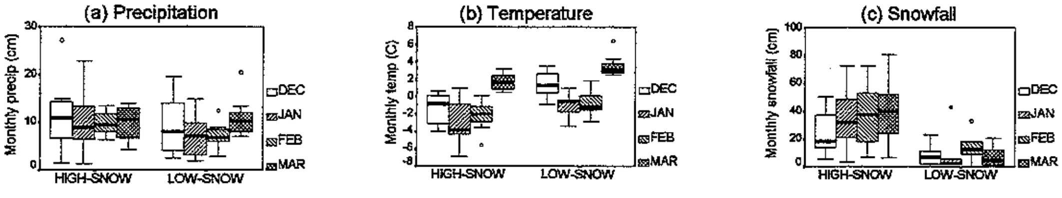


FIGURE 3. Comparison between HIGH-SNOW and LOW-SNOW winters of monthly precipitation, temperature and snowfall at Providence, RI

Table 2. HIGH-SNOW vs. LOW-SNOW: significance of Mann-Whitney U-tests

	PRECIP	TEMP	SNOW
December	0.65	0.02	0.05
January	0.34	0.11	0.02
February	0.14	0.14	0.07
March	0.95	0.01	0.01

Monthly SSTAs

The SSTA PCs were subjected to a Varimax rotation in order to obtain a component focused on the region immediately around New England (Figure 4a), with the scores on this component taken as monthly indices of SST variability in this region. Figures 4b and 4c show the monthly scores on this component for the HIGH-SNOW and LOW-SNOW winters, respectively. The HIGH-SNOW winters are characterized by negative scores in the months December through March, with establishment as early as November in some cases. More positive scores characterize the LOW-SNOW winters although there is considerably more spread within each month than for the HIGH-SNOW winters. Table 3 shows results of a Mann-Whitney U-test comparison of the HIGH-SNOW scores against the LOW-SNOW scores, and t-tests of the HIGH-SNOW and LOW-SNOW composite scores.

Table 3. Scores on rotated SST PC - significance of HIGH-SNOW vs. LOW-SNOW comparisons

	OCT	NOV	DEC	JAN	FEB	MAR
HIGH-SNOW vs. LOW-SNOW (Mann-Whitney U-test)	.09	.14	.006	.003	.004	.002
HIGH-SNOW composite (t-test)	.19	.11	.01	.003	0.01	.000
LOW-SNOW composite (t-test)	0.18	0.36	0.04	0.08	0.14	0.19

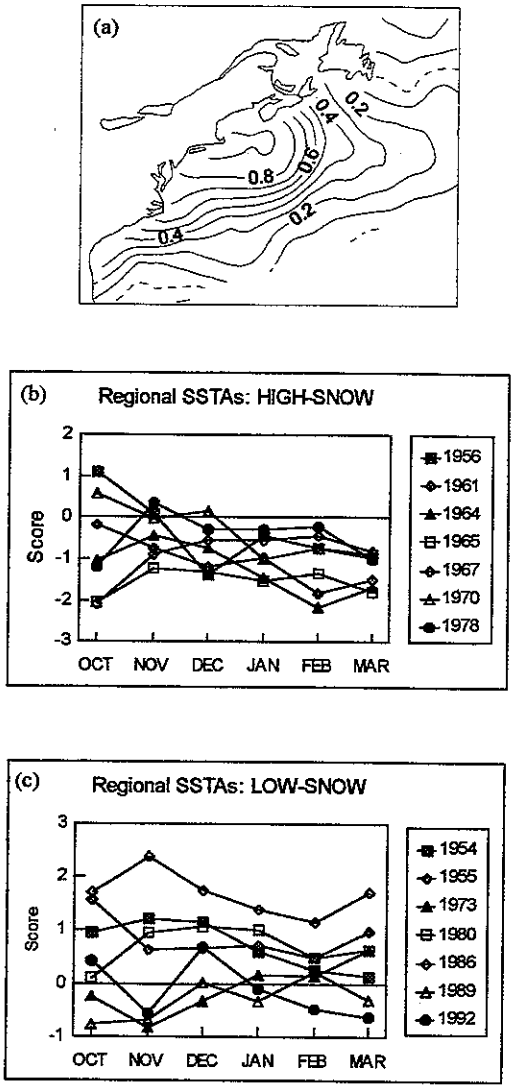


FIGURE 4. Rotated PC of SST field (17 percent variance explained) (a) Loading pattern (b) Monthly scores for HIGH-SNOW winters (c) Monthly scores for LOW-SNOW winters

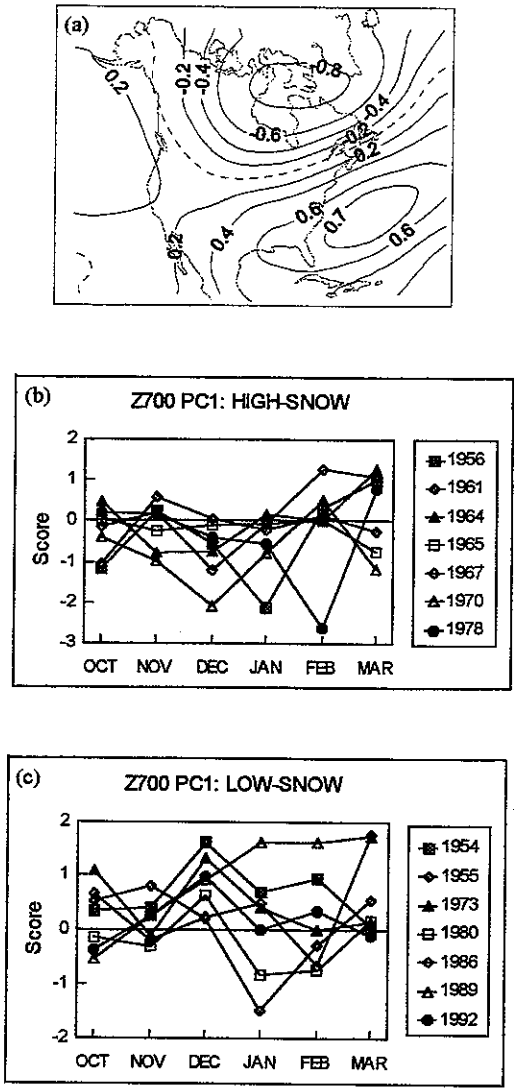


FIGURE 5. First unrotated PC of 700 mb height field (24 percent variance explained) (a) Loading pattern (b) Monthly scores for HIGH-SNOW winters (c) Monthly scores for LOW-SNOW winters

Composite monthly standardized anomaly maps for HIGH-SNOW and LOW-SNOW winters were examined but are not shown. In the HIGH-SNOW case, negative anomalies around New England are evident in December, become firmly established in January and then persist for the remainder of the winter. In the LOW-SNOW case, positive anomalies are observed in all four months, and are in fact strongest and most significant in December.

Monthly 700-mb height anomalies

Figure 5a shows the loading pattern of the first unrotated component (the leading component of the rotated solution is almost identical). This component is convenient as the positive (negative) phase of this pattern qualitatively resembles the LOW-SNOW (HIGH-SNOW) 700-mb composite identified in H69. Figures 5b and 5c show the monthly scores on this component for the HIGH-SNOW and LOW-SNOW winters. Table 4 shows results of a Mann-Whitney U-test comparison of the HIGH-SNOW scores against the LOW-SNOW scores, and t-tests of the HIGH-SNOW and LOW-SNOW composite scores.

Table 4. Scores on unrotated PC1 of 700 mb heights - significance of HIGH-SNOW vs. LOW-SNOW comparisons

	OCT	NOV	DEC	JAN	FEB	MAR
HIGH-SNOW vs. LOW-SNOW (Mann-Whitney U-test)	.23	.34	.002	.14	.95	.57
HIGH-SNOW composite (t-test)	.24	.61	.04	.13	.91	.48
LOW-SNOW composite (t-test)	.35	.31	.005	.74	.60	.09

Significant differences were found for the month of December only, and the separation of scores between the HIGH-SNOW and LOW-SNOW winters is quite obvious in Figures 5b-c. (No significant differences were found for any month on the second and third leading PCs.) These results suggest that the 700 mb circulation regime of December has a greater influence on seasonal snowfall than the circulation of any other month. The possibility that the December circulation sets the scene for the remainder of the winter, with Atlantic SSTs as the link, is examined next.

Contemporaneous atmosphere-ocean coupled modes

Significant canonical variable (CV) pairs were found for all months except October. Two significant CV pairs were found for December -- the canonical loading pattern of the first CV is shown in Figure 6. The 700 mb loading pattern strongly resembles that of the first unrotated PC of the cold-season 700 mb height field (presented in the previous section). The corresponding SST loading pattern is dipolar with negative anomalies northward from New England and positive anomalies to the south. This CV contains 39 percent overlapping variance and explains 13 percent of the input SST field and 8 percent of the input 700 mb height field.

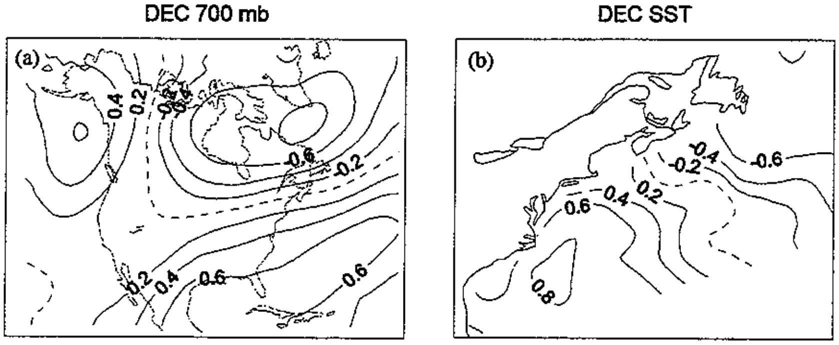


FIGURE 6. Loading patterns for first CV of December contemporaneous association

The CV pairs for the months November, January, February and March are qualitatively similar to the first CV pair of December. Zonally oriented, dipolar patterns tend to characterize interannual fluctuations in winter SSTs (Kushnir, 1994; Deser and Blackmon, 1993) and are generally associated with dipolar patterns in atmospheric fields that resemble the 700 mb pattern in Figure 6. For example, the strong zonal flow indicated by the anomaly pattern of Figure 4a is associated with anomalous warming in the anticyclonic belt due to increased Ekman downwelling, and with anomalous cooling in the belt of the westerlies due to increased wind speeds and ocean-air turbulent energy transfer (Wallace *et al.*, 1990). The results of the contemporaneous CCA are summarized in Table 5.

Table 5. Summary of contemporaneous CCA

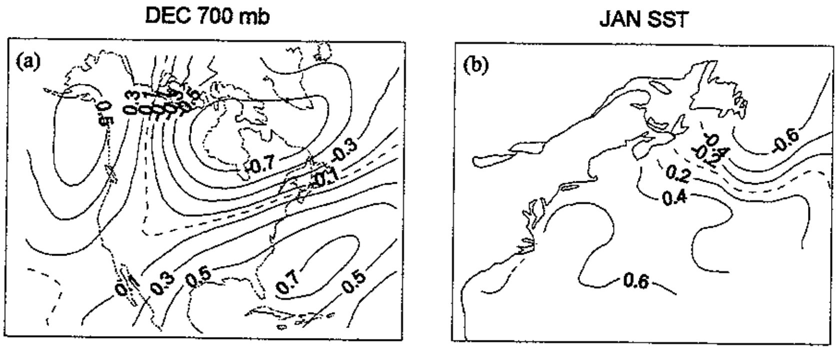
	Canonical	Coeff. of Determination (%)		CV-score comparison[1]	
Month	Correlation	700 mb	SST	700 mb	SST
October	none sig.				
November CV1	0.64	7	14	no	no
December CV1	0.63	8	13	yes	yes
CV2	0.49	5	8	no	yes
January CV1	0.67	11	15	no	yes
February CV1	0.64	8	14	no	no
March CV1	0.65	8	14	no	no

1. Comparison = results of Mann-Whitney U-test comparison of CV scores between HIGH-SNOW and LOW-SNOW winters in southern New England (level of significance = 0.05)

The above results suggest that coupling between the 700 mb circulation and SSTAs is strongest in December for which there are two significant CV pairs accounting for around 21 percent of the variance in the SST field. The CV score comparisons also agree with results presented earlier that the atmospheric circulation of December is disproportionately important to the winter as a whole.

Lagged atmosphere-ocean coupled modes

No significant variates were found corresponding to SSTAs leading the 700 mb circulation. Therefore, this discussion focuses on associations with SSTAs lagging the atmosphere. Significant lag associations were found for all paired months, and the loading patterns of the leading CV pairs (e.g. Figure 7) are extremely similar to the patterns presented previously for the contemporaneous associations. Thus, the positive SSTAs observed in December in association with the zonal 700 mb pattern of Figure 6a have a tendency to persist into January and advance northeastward along the coast (Figure 7b). The results of the lagged CCA are presented in Table 6.


DEC 700 mb

JAN SST

FIGURE 7. Loading patterns of first CV of December-January lag association

Table 6. Summary of lagged CCA (CV-score comparison as in Table 5)

700 mb => SST Association	Canonical Correlation	Coeff. of Det. (%) 700 mb	SST	CV-score comparison 700 mb	SST
OCT-NOV CV1	0.80	11	21	no	yes
NOV-DEC CV1	0.81	11	22	yes	no
CV2	0.56	5	10	no	yes
CV3	0.47	4	7	no	no
DEC-JAN CV1	0.70	10	16	yes	yes
JAN-FEB CV1	0.81	16	22	no	no
FEB-MAR CV1	0.71	10	17	no	no
CV2	0.56	6	11	no	no

The results of the Mann-Whitney U-test comparisons (two rightmost columns of Table 6) again confirm the relative importance of the December circulation to the winter as a whole. It is apparent that atmosphere-ocean coupling in the fall and early winter is also important. The three NOV-DEC CV pairs account for a just under 40 percent of the variance of the December SST input field. In both Tables 5 and 6, February and March are not significantly distinguishable between HIGH-SNOW and LOW-SNOW winters, suggesting that the snowfall regime is established earlier in the season and then persists somehow.

Persistence of SSTAs and 700 mb height anomalies

SSTAs in the western Atlantic are strongly persistent from month-to-month (for example, Table 7), especially in the second half of the winter when the ocean mixed layer reaches its greatest depth. Persistence is especially high at grid points around New England where month-to-month correlation coefficients exceed 0.8 from December onwards. On the other hand, 700 mb height anomalies show much less persistence (Table 7). Significant month-to-month correlations for grid-point anomalies are observed only at latitudes below the continental United States, i.e. beyond the reach of the winter storm tracks, and in interior portions of Canada later in the winter, presumably reflecting the effects of snow cover (not shown).

Table 7. Comparison of SSTA and 700-mb height anomaly persistence (month-to-month correlations)

	SST PC	700-mb PC1
OCT-NOV	0.47	0.25
NOV-DEC	0.73	0.31
DEC-JAN	0.79	0.22
JAN-FEB	0.87	0.45
FEB-MAR	0.86	0.43

Thus, although coupled atmosphere-ocean patterns, including lag associations, can be identified in all winter months, SSTAs in the late winter may be as much a reflection of the early winter circulation as that of the late winter. Persistence of SSTAs may be what links the circulation of December to anomalous seasonal snowfalls, and this is discussed briefly in the sections that follow.

SST gradients

Atlantic coast storms tend to track along two zones of local maximum baroclinicity (Carlson, 1991). One of these is the region of high SST gradients along the northern edge of the Gulf Stream. The other is the land-ocean boundary itself. Positive SSTAs along the Atlantic seaboard enhance the latter while decreasing the former -

conversely for negative SSTAs. Thus, the presence of SSTAs along the east coast, by displacing the zone of baroclinicity, may affect the tracks taken preferentially by coastal storms. This has important implications for snowfall, because the location of the rain-snow line during winter storm events depends so strongly on the track taken by the storm.

As a precursory examination of this problem, SST "gradients" (temperature differences) were computed along a number of transects oriented roughly perpendicular to the coastline (Figure 8). Standardized gradient anomalies were computed for all transects within this region and averaged for a regional anomaly. The correlation between seasonal snowfall and this regional anomaly is highly significant ($R = 0.62$; $p = .000$) and in fact, the December regional SST gradient anomaly is a better predictor of seasonal snowfall (25 percent variance explained) than the December regional SSTA itself (16 percent variance explained).

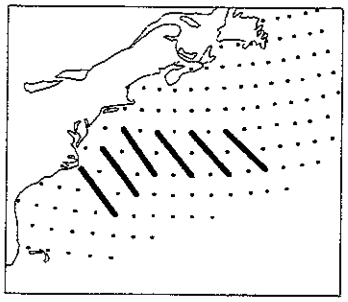


FIGURE 8. Transects for computation of SST gradient anomaly

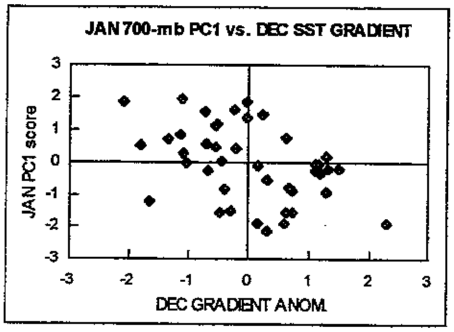


FIGURE 9. Scatterplot of January scores on 700 mb PC (loading pattern of Figure 3a) versus December SST gradient anomaly

Anomalously high SST gradients may result in greater frequency of coastal storms, greater development of coastal storms, and offshore displacement of the preferred storm track, or a combination of these. This is a problem that has yet to be investigated by analysis of storm data. However, the following result indicates that anomalous SST gradients in this sector of the Atlantic Ocean can exert an influence on the overlying atmospheric circulation. Figure 9 shows the January scores on the first unrotated PC of the 700 mb height field (loading pattern of Figure 5a) plotted against the December SST gradient anomaly. It is clear that an anomalously strong SST gradient in December tends to result in a negative phase of the 700 mb PC in January. A southeastward displacement of the Atlantic coast storm track, associated with the anomalously high SST gradient, has been shown to result in reduced cyclonic activity in the Iceland-Greenland area and then development of a high-pressure anomaly cell over Greenland. Blocking associated with this feature may help to sustain the anomalous circulation pattern (Dickson and Namias, 1976).

The canonical correlation analysis presented previously uncovered no lag associations in which the ocean leads the atmosphere. However, this result suggests that the effects of SSTA patterns on the overlying atmospheric circulation, although subtle, may not be insignificant. (This result was found for no other pair of months).

SSTA forcing of air temperature anomalies

Figure 10a shows Spearman Rank Correlation Coefficients of January-March average temperatures versus regional SSTs for the month of December. Correlations are highest in southern New England and decrease towards the interior and north of the region. Figure 10b shows the scatterplot for Providence, RI. Although the association is not strong, there is clearly a tendency for lower SSTs in December to be succeeded by lower temperatures over the remainder of the winter, which might in turn be reflected in a higher fraction of precipitation as snow. In a study of monthly mean air temperatures in the Netherlands, van den Dool (1984) found that the atmosphere seems to respond to a SSTA in the North Sea with an air temperature anomaly of the same sign, with a time lag of 15 days. But because of the abrupt change in lower boundary forcing near the coastline, the observed response was localized in nature, as appears to be the case for New England also.

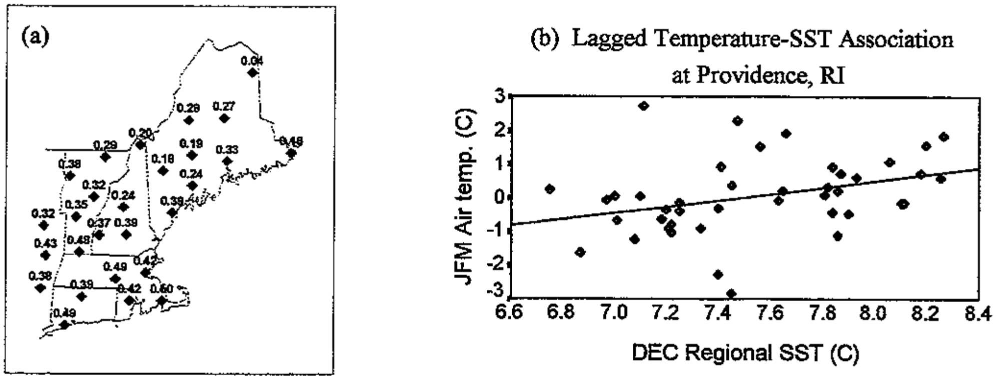


FIGURE 10. SSTA forcing of air temperature anomalies: (a) Spearman Rank Correlations of January-March air temperatures versus December regional SSTs (b) Scatterplot for Providence, RI

CONCLUSIONS

Anomalous snowfall seasons in southern New England are not dominated by anomalies of one particular month – the anomalous snowfall regime appears to be a seasonal phenomenon that is dependent on temperature rather than precipitation. Comparison of HIGH-SNOW winters with LOW-SNOW winters reveals significant differences in snowfall and SSTAs throughout the winter, but the mid-tropospheric circulation regime of December appears to have a disproportionate influence on seasonal snowfall. Persistence of Atlantic SSTAs established in part through atmosphere-ocean coupling in the late fall/early winter is a possible linkage between the December circulation and the seasonal snowfall regime. Based on these results, one may not discount the possibility of a direct association between seasonal snowfall and Atlantic SSTAs. The extent to which SSTAs might directly influence precipitation form is currently under investigation, but preliminary results suggest that SSTAs might influence the Atlantic Coast storm track, as well as air temperatures in southern and coastal New England.

REFERENCES

Acker, J.C. and P.T. Soule, 1995: Temporal characteristics of Pennsylvania snowfall, 1950-51 through 1989-1990. *Physical Geography*, 16, 188-204

Battisti, D.S., U.S. Bhatt, and M.A. Alexander, 1995: A modeling study of the interannual variability in the wintertime North Atlantic Ocean. *J. Climate*, 8, 3067-3083

Bretherton, C.S., C. Smith, and J.M. Wallace, 1992: An intercomparison of methods for finding coupled patters in climate data. *J. Climate*, 5, 541-560

Carlson, T.N., 1991: *Mid-latitude Weather Systems.* HarperCollins*Academic*, New York

Colucci, S.J., 1976: Winter cyclone frequencies over the eastern United States and adjacent western Atlantic. *Bull. Amer. Met. Soc.*, 57, 548-553

Deser, C. and M. Blackmon, 1993: Surface climate variations over the North Atlantic Ocean during winter, 1900-1989. *J. Climate.*, 6, 1743-1753

Dickson, R.R. and J. Namias, 1976: North American influences on the circulation and climate of the North Atlantic sector. *Monthly Weather Review*, 104, 1255-1264

Haan, C.T., 1977: *Statistical Methods in Hydrology*. The Iowa State University Press, Ames, IA

Hartley, S., 1996: Atlantic sea-surface temperatures and New England snowfall. *Hydrological Processes*, 10, 1553-1563

Hartley, S. and M.J. Keables, 1997: Synoptic associations of winter climate and snowfall variability in New England, USA. Submitted to *Int. J. Climatology*

Knappenberger, P.C. and P.J. Michaels, 1993: Cyclone tracks and wintertime climate in the mid-Atlantic region of the USA. *Int. J. Climatology.*, 13, 509-531

Kushnir, Y., 1994: Interdecadal variations in North Atlantic sea surface temperature and associated atmospheric conditions. *J. Climate*, 7, 141-157

Kushnir, Y. and I.M. Held, 1996: Equilibrium atmospheric response to North Atlantic SST anomalies. *J. Climate*, 9, 1208-1220

Leathers, D.J., T.L. Mote, K.C. Kuivinen, S. McFeeters, and D.R. Kluck, 1993: Temporal characteristics of USA snowfall 1945-1946 through to 1984-1985. *Int. J. Climatology*, 13, 65-76

Namias, J., 1960: Snowfall over the eastern United States: factors leading to its monthly and seasonal variations. *Weatherwise*, 238-247

Namias, J., 1966: Nature and possible causes of the northeastern United States drought during 1962-65. *Monthly Weather Review*, 94, 543-554

Peng, S. and J. Fyfe, 1996: The coupled patterns between sea level pressure and sea surface temperature in the midlatitude North Atlantic. *J. Climate*, 9, 1824-1839

Smith, T.M., R.W. Reynolds, R.E. Livezey, and D.C. Stokes, 1996: Reconstruction of historical sea-surface temperature using empirical orthogonal functions. *J. Climate*, 9, 1403-1420

van den Dool, H.M., 1984: Long-lived air temperature anomalies in the midlatitudes forced by the surface. *Monthly Weather Review*, 112, 555-562

Wagner, A.J., 1979: Mean 700 mb circulation patterns associated with snowiest and least snowy winter months over the eastern United States. *Proceedings of 36th Eastern Snow Conference*, 75-94

Wallace, J.M., C. Smith and Q. Jiango, 1990: Spatial patterns of atmosphere-ocean interaction in the northern winter. *J. Climate*, 3, 990-998

Yarnal, B., 1993: *Synoptic Climatology in Environmental Analysis: A Primer*. Belhaven Press, Boca Raton, FL