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Atlantic Sea-Surface Temperatures and New England Snowfall

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ABSTRACT

This paper examines the possibility of an association between winter (December-March) snowfall in New England and sea-surface temperature anomalies (SSTAs) in the adjacent Atlantic Ocean. Regional snowfall indices for southern and northern New England were obtained by rotated principal components analysis (PCA). Composite maps of winter Atlantic SSTAs and 700-mb geopotential height anomalies were generated for cases of above- and below-average winter snowfall totals for southern and northern New England, respectively. A monthly index of SSTAs around the coast of New England was obtained from rotated PCA of SSTAs in the western Atlantic Ocean and compared for high-snow and low-snow cases.

In northern New England, no direct association between snowfall and SSTAs is indicated by either the composite maps or the monthly SSTA index -- high or low snowfall totals can be attributed primarily to anomalies in the 700-mb circulation. In southern New England, high (low) snowfall totals are associated with negative (positive) SSTAs off the Atlantic coast, and these anomalies are often already evident in December, suggesting Atlantic sea-surface temperatures may be of utility in long-range winter forecasts for coastal regions.

Key words: Snowfall, New England, Atlantic sea-surface temperatures

INTRODUCTION

Recent studies of hemispheric and continental-scale snow cover and snowfall variability (e.g., Leathers *et al.*, 1993; Leathers and Robinson, 1993; Karl *et al.*, 1993; Gutzler and Rosen, 1992) have been prompted by the possibility that such variability may be a useful indicator of climate change. Regional snowfall variability has been given less attention, despite the importance of snowfall to some regional water supplies and the capacity of heavy snowfalls to disrupt transportation, communications, public services, and commerce (Roony, 1967).

Although New England is somewhat less dependent than other regions (such as in the western United States) on winter snowfall as an annual water resource, snow is an important component of the winter hydrologic system. Runoff of groundmelt can significantly augment streamflows during prolonged cold, dry periods (Federer, 1965). Over much of the region, the intra-season distribution of runoff is influenced by the fraction of precipitation that falls as snow (Hartley and Dingman, 1993). An understanding of the variations in seasonal snowfall is thus relevant to winter streamflow hydrology and water resource management.

Since 1950, snowfall in the northeastern United States has shown variability on a decadal scale rather than a consistent trend. The late 1950s to early 1970s was a period of relatively high snowfalls 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. Snowfall totals in northern New England were exceptionally high from

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the mid-1960s through the 1970s (Suckling and Kimsey, 1988).

Namias (1960) attempted to relate the snow characteristics of winters in the northeastern United States to the prevailing large-scale upper-air circulation. Winters of high snowfall were found to be associated with (i) strong positive 700 mb anomalies over Canada and adjacent portions of the Atlantic Ocean; and, (ii) a stronger than normal trough over the eastern United States and a strong ridge over the far west. The relatively snowless winters were characterized by a pattern of strong ridges over the Atlantic and Pacific Oceans with an anomalous trough over the far west. However, anomalous southerly flow in the 1950s resulted in decreased snowfall to the east of the Appalachians, but increased snowfall to the west where the climate is more continental in nature.

Heavy snowfalls in the New England region require an upper-level trough to provide a source of vorticity, upper-level divergence and vertical ascent for the development of surface cyclones, as well as an anticyclone over the Great Lakes or southern Canada to promote advection of cold air into the region at the surface (Kocin and Uccellini, 1990). Thus, variations in the large-scale circulation which determines the preferred locations, frequencies and strengths of these synoptic features may be reflected in variations in seasonal snowfall. In addition, the relatively warm waters of the Atlantic Ocean and the Gulf Stream significantly influence the temperature structure of the lower troposphere through exchanges of sensible and latent heat at the atmosphere-ocean interface (Kocin and Uccellini, 1990). Atlantic sea-surface temperature anomalies (significant departures from the seasonal average) have been linked to shifts in storm tracks (Namias, 1966) and to winter precipitation anomalies along the east coast of the United States (Colucci, 1976), with wet (dry) conditions associated with positive (negative) sea-surface temperature anomalies. Ocean-atmosphere interactions can result in feedbacks between sea-surface temperature anomalies and anomalous atmospheric circulation patterns, allowing climatic anomalies (such as the northeastern United States drought of 1962-65) to persist once established (Namias, 1966). By influencing temperatures and precipitation, it is possible that variations in Atlantic sea-surface temperatures might also be a factor in snowfall variability.

This paper examines the possibility that snowfall in New England is influenced by Atlantic sea-surface temperature anomalies. The research presented here is part of a more comprehensive assessment (still in progress) of the various factors that contribute to New England winter climatic variability in general, and exceptional snowfall seasons in particular.

DATA AND METHODS

Data sets

Snowfall

Daily observations of snowfall were retrieved from EarthInfo's "NCDC Summary of the Day" CD-ROM database for a network of 27 stations, selected to provide adequate spatial coverage of the New England region while maximizing record length and minimizing the amount of missing observations. Seasonal (December-March) totals at each of these stations were computed for the winters 1949-50 through 1991-92 (e.g. Table 1). Occasional missing daily values were simply substituted from neighboring stations. Corresponding observations of temperature and precipitation, if available, were consulted to verify that the substitutions were reasonable. Some stations have month-long blocks of missing data, or months for which large numbers of daily values are missing, in which case the monthly totals were estimated from regression analysis against a neighboring station.

Sea-surface temperatures

Gridded monthly sea-surface temperature analyses for the period 1950-1992 were obtained from the Data Support Section of the National Center for Atmospheric Research (NCAR). This data set is a reconstructed analysis (Smith *et al.*, 1996) from the Climate Prediction Center (formerly Climate Analysis Center) of the National Center for Environmental Prediction (formerly National Meteorological Center) and is referenced to a 2 degree latitude by 2 degree longitude grid. Monthly and seasonal sea-surface temperature anomalies (SSTAs), as departures from the 1950-1992 monthly and seasonal averages in degrees Celsius, were computed on a grid cell basis for the western Atlantic Ocean from the North American coast (between Florida and Newfoundland) east to longitude 45°W.

Atmospheric circulation

Gridded monthly values of 700-mb geopotential heights, referenced to a 5 degree latitude by 5 degree longitude grid, were obtained from the Data Support Section of NCAR. These analyses were originally constructed by the National Meteorological Center.

Table 1. December-March snowfall totals (cm) for stations indicated in Figure 1a

	1. Boston, MA	*2. Hartford, CT*	*3. Concord, NH*	*4. Burlington, VT*	*5. Rumford, ME*
1950	78	103	125	147	223
1951	76	126	88	109	148
1952	83	152	222	173	252
1953	70	100	81	121	161
1954	55	86	90	209	204
1955	63	52	94	194	188
1956	127	172	192	195	192
1957	128	96	163	112	176
1958	108	123	167	234	247
1959	86	106	171	193	169
1960	102	112	144	167	181
1961	151	200	152	112	132
1962	111	93	154	171	163
1963	76	132	144	170	282
1964	160	142	193	116	185
1965	124	139	95	119	123
1966	112	134	150	229	223
1967	144	207	190	192	177
1968	108	96	114	190	150
1969	136	137	187	188	374
1970	124	152	136	219	209
1971	141	167	227	330	345
1972	113	121	182	205	201
1973	25	82	107	181	185
1974	86	71	90	194	117
1975	63	95	151	168	176
1976	118	118	184	212	237
1977	145	120	210	157	211
1978	214	206	209	207	259
1979	58	71	161	178	211
1980	32	37	65	95	81
1981	51	23	115	131	74
1982	123	107	190	187	213
1983	83	116	95	147	110
1984	109	110	192	151	192
1985	63	56	131	210	179
1986	38	57	107	207	177
1987	89	107	154	140	195
1988	111	129	151	139	153
1989	38	38	71	95	154
1990	87	92	148	175	218
1991	49	76	83	89	154
1992	53	52	75	174	123

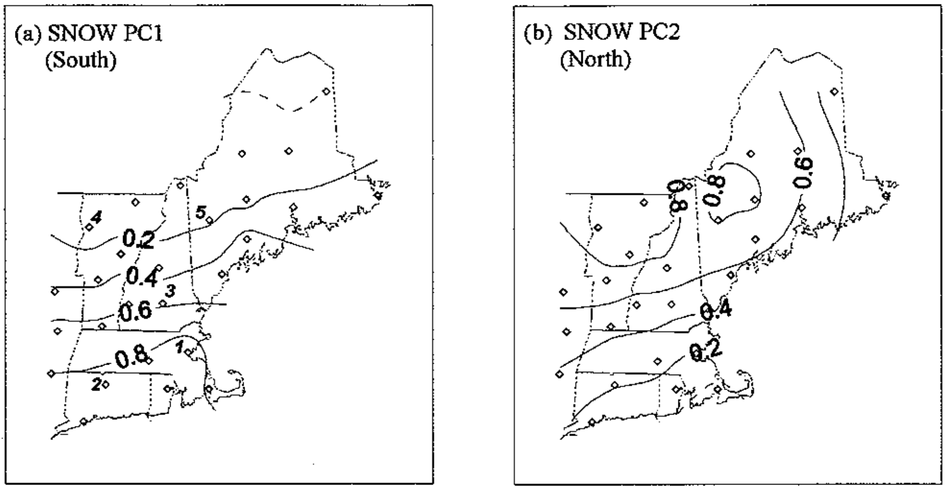

Figure 1. Component loading patterns for rotated PCs of seasonal snowfall (numbered stations in (a) are referenced in Table 1)

Monthly anomalies, as departures from the 1950-1992 average in geopotential meters, were computed for grid points within the regions bounded by 20-70°N and 30-150°W. The monthly anomalies were averaged for the overall winter anomaly.

Analysis

The seasonal snowfall totals at the 27 stations were first standardized by subtracting the station mean for the period of record and dividing by the standard deviation, and then subjected to an S-mode principal components analysis (PCA). PCA is an eigenvector-based technique that transforms a data set of p inter-correlated 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).

Using an eigenvalue greater than unity as the selection criterion, four principal components, explaining 82 percent of the total variance of the snowfall data set, were retained and subjected to an orthogonal Varimax rotation (Kaiser, 1958) to identify spatially coherent regions of variation (e.g., Leathers *et al.*, 1993). The rotation identified two such regions, as indicated by large component loadings across the south (Figure 1a) and across the north (Figure 1b) of New England. The scores on these components (Figure 2) indicate the relative temporal variations of snowfall for each of the regions. Note that these time series represent the spatially coherent variations in snowfall -- variations that are unique to individual stations are likely to have minimal or no effect on these indices. The 7-highest- and 7-lowest-scoring winters on each of these components defined HIGH-NORTH, LOW-NORTH, HIGH-SOUTH and LOW-SOUTH snowfall conditions (Table 2) and composite maps of Atlantic SSTAs and 700-mb geopotential height anomalies were generated for these groups of winters.

Table 2. Composite winter groupings defined by scores on snowfall components.

	SOUTH	*NORTH*
HIGH	56, 61, 64, 65, 67, 70, 78	58, 63, 69, 71, 76, 78, 86
LOW	54, 55, 73, 80, 86, 89, 92	51, 57, 61, 64, 65, 80, 81

The Atlantic monthly SSTAs were also subjected to a rotated principal components analysis which identified a single component with large loadings around the northeastern United States (Figure 3a). Scores on this component serve as a regional index of anomalies in this section of the ocean. The monthly scores were compared between the HIGH-NORTH and LOW-NORTH, and HIGH-SOUTH and LOW-SOUTH cases, respectively.

The statistical significance of individual grid-point anomalies was assessed by bootstrap analysis (e.g., Portman and Gutzler, 1996). At each grid-point, 7 seasonal anomalies from the period of record were randomly selected (replacement

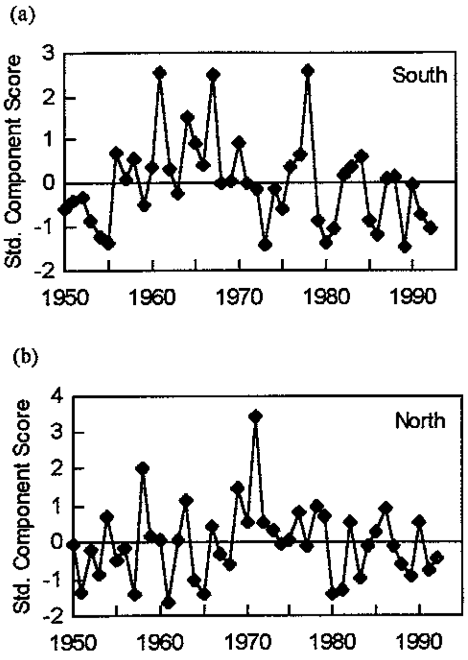

Figure 2. Scores on rotated snowfall PCs (a) South (b) North

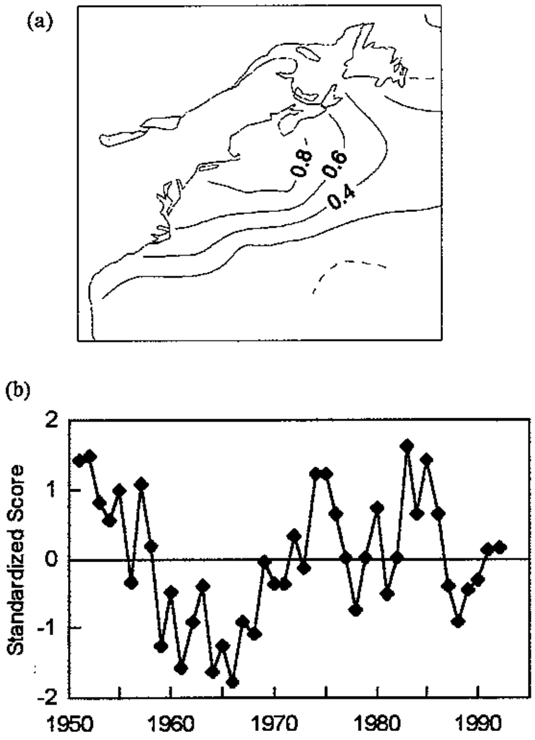

Figure 3. Rotated PC of SSTs used as index of regional anomaly (a) loading pattern (b) seasonal average of monthly scores

permitted) and averaged. This was repeated for a total of 500 random composite anomalies, from which the standard deviation was computed. Composite anomalies exceeding twice this value were deemed to be nominally significant at 95 percent probability.

RESULTS AND DISCUSSION

HIGH-SOUTH vs. LOW-SOUTH

The HIGH-SOUTH case is associated with significantly negative 700-mb height anomalies over the eastern United States and adjacent Atlantic Ocean (Figure 4a), a pattern that favors more frequent incursions of cold air into the eastern United States from central Canada (Yarnal and Leathers, 1988). The anomalous trough also displaces the region of maximum positive vorticity advection to the south and east, so that east coast storms are more likely to pass to the southeast of New England rather than tracking inland, thus more frequently favoring snow rather than rain in the extreme south. An extensive region of significantly negative SSTAs is observed along the Atlantic coast from Cape Hatteras to Nova Scotia (Figure 4b).

A more zonal 700-mb circulation is observed for the LOW-SOUTH case (Figure 5a), with positive height anomalies over the United States and the Atlantic Ocean, and negative height departures over eastern Canada and Greenland. A strong zonal flow pattern tends to inhibit the southward advance of continental polar air masses as well as the troughing over the eastern United States that often leads to development of large surface cyclones. However, there is considerable variability among the LOW-SOUTH winters such that no feature of the anomaly pattern is statistically significant. A region of positive SSTAs is observed to the south of New England (Figure 5b).

Scores on the sea-surface temperature principal component (SSTPC) indicate negative SSTAs in all 4 months for 5 of the 7 HIGH-SOUTH winters (Figure 6a), and positive SSTAs in all 4 months for 4 of the 7 LOW-SOUTH winters (Figure 6b). In all 4 months, the differences in component scores between the HIGH and LOW cases were shown by the Mann-Whitney U-test (Sprent, 1993) to be significant at a level of 0.02 or better (Table 3). The null hypothesis that the composite means of the scores for the HIGH and LOW cases are not significantly different from zero was assessed by bootstrap analysis similar to that described in the

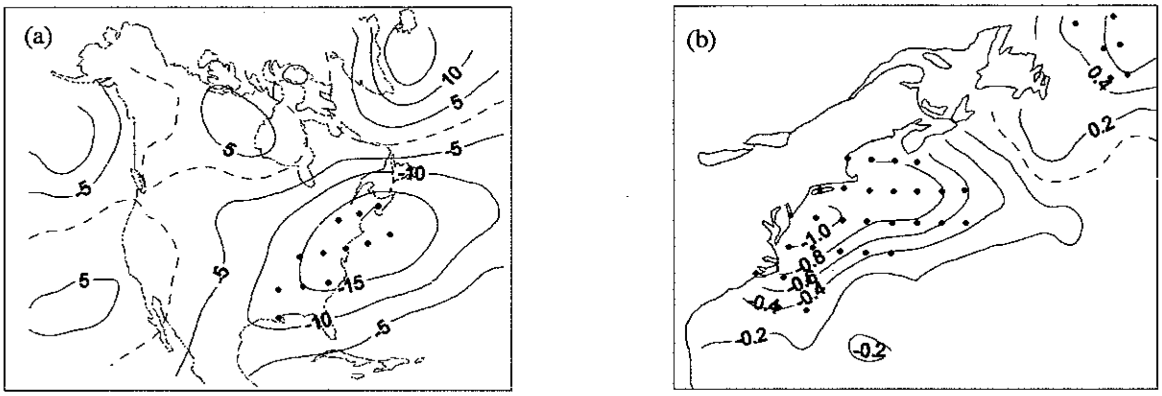

Figure 4. HIGH-SOUTH composites. (a) 700-mb geopotential heights - departures from average (gpm) (b) Sea-surface temperature anomalies (deg. C). Dots indicate gridpoint anomalies judged to be significant by bootstrap analysis.

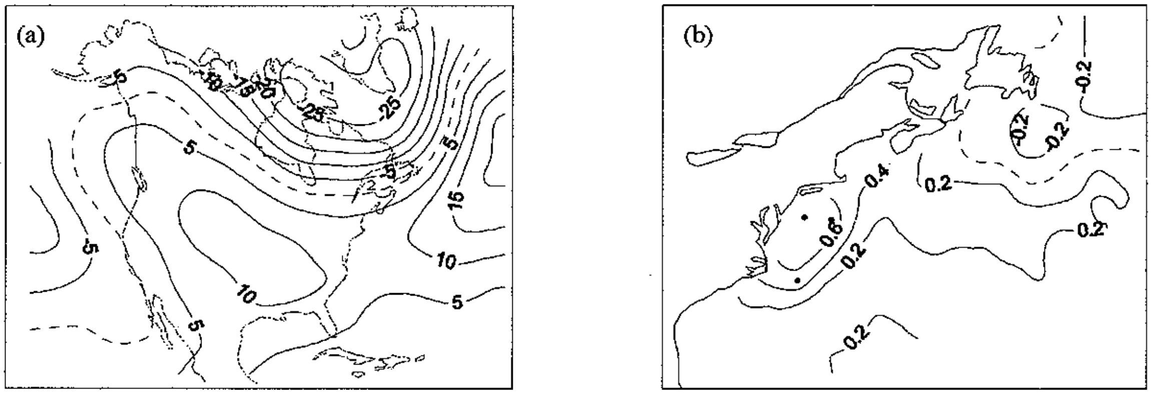

Figure 5. Same as Figure 4, but for LOW-SOUTH composite.

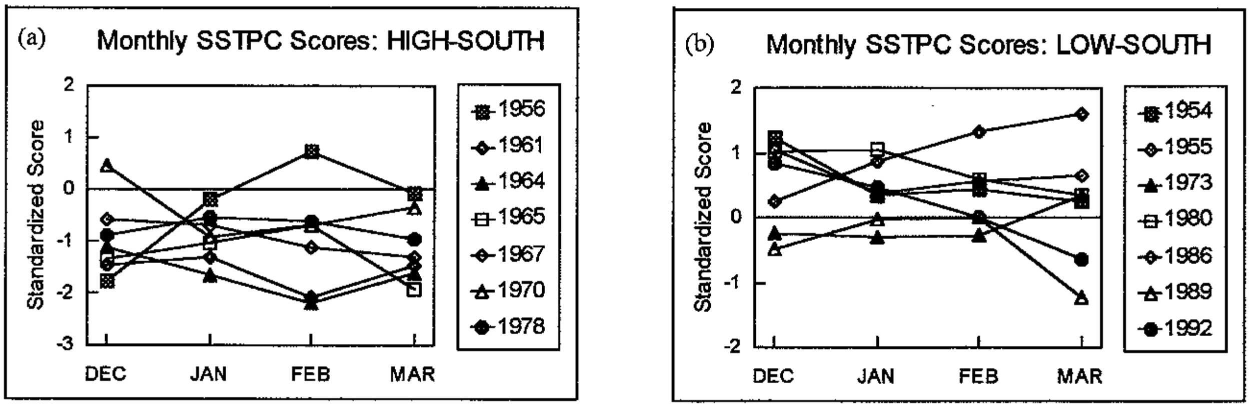

Figure 6. Monthly SST component scores (relative SST anomalies) for (a) HIGH-SOUTH and (b) LOW-SOUTH winters

Table 3. Composite SSTPC scores for HIGH-SOUTH and LOW-SOUTH cases and significance tests of composite anomalies

	HIGH-SOUTH composite mean	*LOW-SOUTH composite mean*	*HIGH vs. LOW significance*	*HIGH-SOUTH anom. sig.*	*LOW-SOUTH anom. sig.*
DEC	-0.95	0.53	p = .006	p = .016	p = .134
JAN	-0.89	0.40	p = .003	p = .002	p = .110
FEB	-0.94	0.38	p = .018	p = .012	p = .160
MAR	-1.09	0.19	p = .012	p = .004	p = .316

previous section. The p-values in the two rightmost columns of Table 3 indicate the fraction of the 500 random composite means exceeding in magnitude the HIGH-SOUTH and LOW-SOUTH means, respectively (i.e. two-tailed significance). The HIGH-SOUTH composite mean anomalies are shown to be highly significant, while the LOW-SOUTH composite anomalies are at best only marginally significant. However, the area of anomaly significance is less extensive in the LOW-SOUTH case (Figure 6b), and the anomalies thus contribute relatively less information to the regional SSTPC score.

In 5 of the LOW winters and 6 of the HIGH winters, the SSTAs already have the appropriate sign in December. If the anomalies were absent in December and developed with the progression of winter, then one might conclude that the seasonal SSTAs are simply the result of the anomalous snowfall conditions (through increased or decreased exchanges of sensible and latent heat with unusually cold or mild air masses). However, this is clearly not the case.

HIGH-NORTH vs. LOW-NORTH

The HIGH-NORTH case is also associated with a significantly deeper-than-normal 700-mb trough over the eastern United States (Figure 7a). In the LOW-NORTH case the anomalous trough is displaced eastward over the Atlantic Ocean (Figure 8a). Anomalous troughing off the Atlantic seaboard has been shown to result in cool, dry conditions in the northeastern United States (Namias, 1966; Yarnal and Leathers, 1988), due to more frequent northwesterly winds and the influence of continental polar air masses. Cool and dry conditions are most usually associated with low snowfalls in the north of New England (Brooks, 1917). However, as in the LOW-SOUTH case, there is considerable variability among the LOW-NORTH winters so that none of the anomaly centers are statistically significant.
Along the northeast coast, no coherent pattern of SSTAs is evident for either the HIGH or LOW case (Figures 7b and 8b).

In the HIGH-NORTH case, both positive and negative SSTAs are indicated in all months (Figure 9a). It appears that SSTAs are not a critical factor in high snowfall seasons in northern New England as long as the atmospheric circulation pattern is favorable to precipitation. In the LOW-NORTH case, however, the winters are clustered into two distinct groups, with either strong positive, or strong negative SSTAs. The 4 winters with strong negative SSTAs are all associated with a strong anomalous 700-mb trough over the Atlantic, as previously discussed. The low snowfall totals for these winters can thus be attributed to the atmospheric circulation anomalies, although the negative SSTAs may have a role in sustaining this circulation pattern once established (Namias, 1966). Of the 3 LOW-NORTH winters with positive SSTAs, one also features the anomalous offshore trough. In the two remaining winters, however, this trough is absent and the low snowfall might be partly explained by Atlantic SSTAs.

SOUTH vs. NORTH

High snowfall seasons in the south and the north are associated with very similar atmospheric circulation anomaly patterns. However, high snowfall in the south appears to be conditional on negative SSTAs while in the north, no such condition is apparent. This suggests a possible thermal response to the SSTAs in the south where snowfall is generally limited by temperature rather than by precipitation (Brooks 1917). A scatterplot of the southern snowfall index against the seasonally averaged SSTPC score (Figure 10a) suggests a possible thermal threshold, below which snowfall is

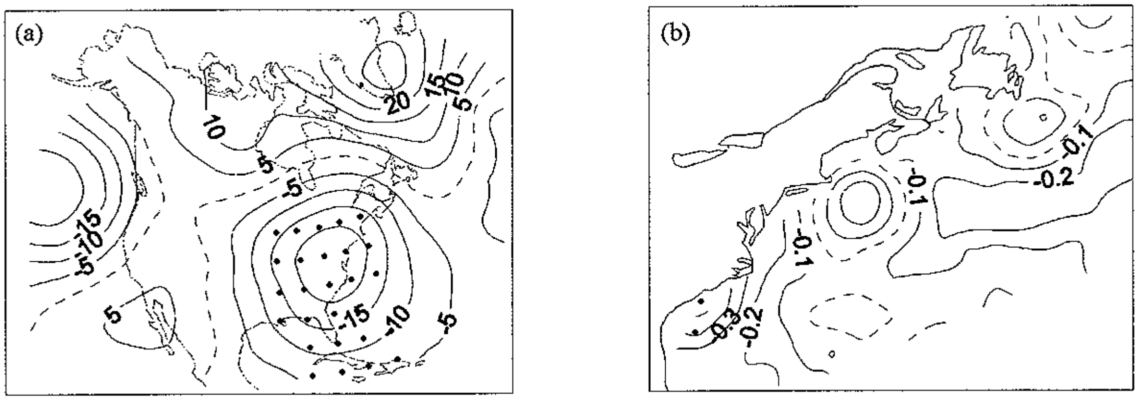

Figure 7. HIGH-NORTH composites. (a) 700-mb geopotential heights - departures from average (gpm) (b) Sea-surface temperature anomalies (deg. C). Dots indicate gridpoint anomalies judged to be significant by bootstrap analysis.

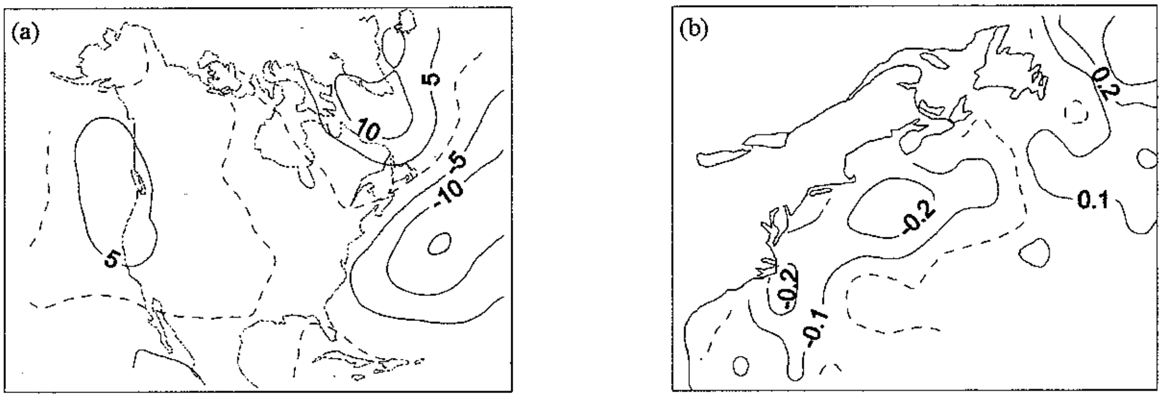

Figure 8. Same as Figure 7, but for LOW-NORTH composite

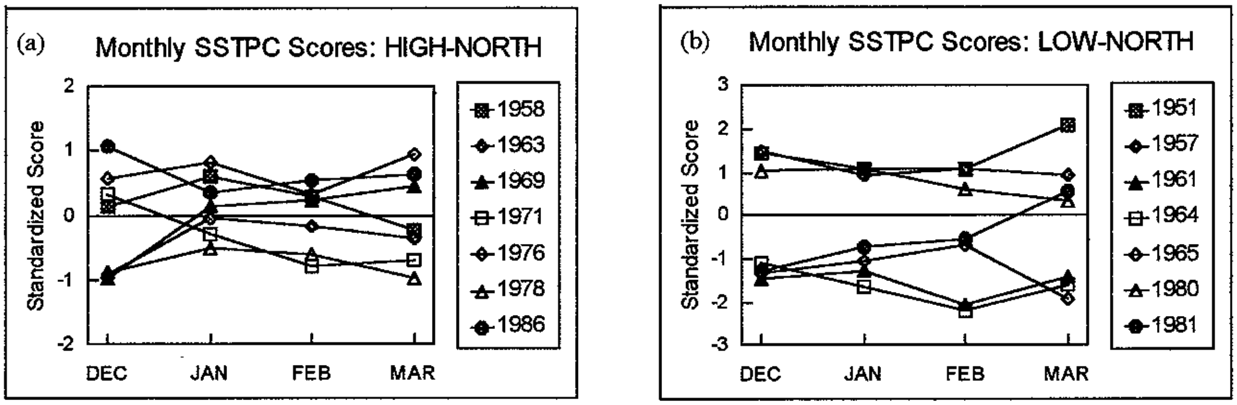

Figure 9. Monthly SST component scores (relative SST anomalies) for (a) HIGH-NORTH and (b) LOW-NORTH winters

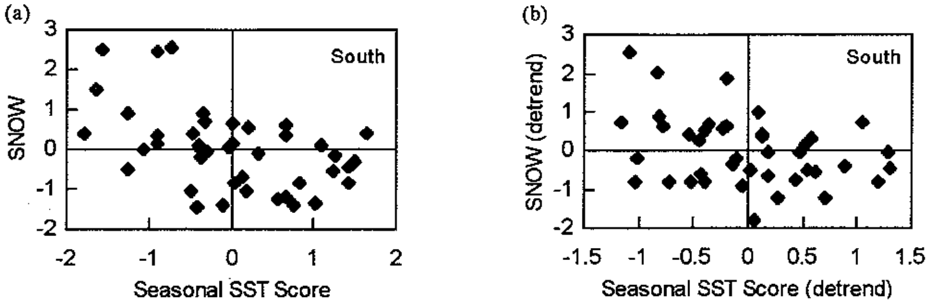

Figure 10. Scatterplots of southern snowfall index vs. seasonally averaged SSTPC scores (a) raw data (b) decadal-scale variations removed from time series

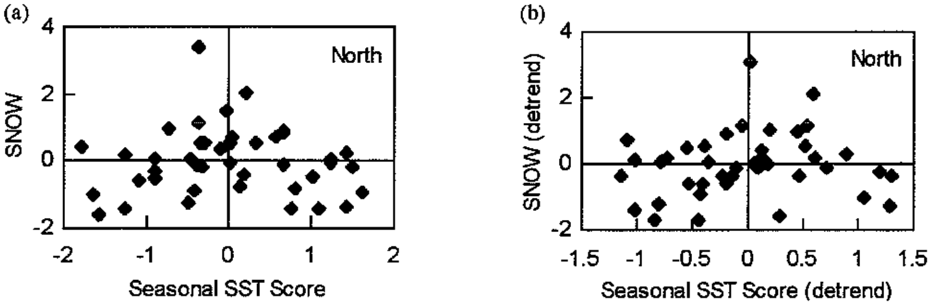

Figure 11. Scatterplots of northern snowfall index vs. seasonally averaged SSTPC scores (a) raw data (b) decadal-scale variations removed from time series

markedly increased, and above which no direct association is apparent. Negative SSTAs off the New England coast may directly influence snowfall totals by reducing sea-to-air transfers of sensible and latent heat as air is advected across coastal waters such that temperatures in the lower troposphere are cold enough to support snow. The effect of SSTs on precipitation form is evident in the intra-seasonal variations of snowfall along the coast, where snow is more likely in the latter half of the winter (Brooks 1917). In the early winter, when the ocean is still relatively warm, onshore winds can cause substantial warming at lower levels so that precipitation reaches the ground as rain, even if the 1000-500-mb thicknesses are apparently low enough to result in snow (Wagner 1957). However, the March-December SST difference is typically around -5°C, while the seasonal anomalies presented here are only around 1-2 degrees in magnitude.

If the SSTAs do not directly force the snowfall anomalies, they may play a role in sustaining the atmospheric circulation anomalies associated with these conditions. Substantial cooling of the lower troposphere may favor an eastward extension of the region of negative 700-mb height anomalies over the eastern United States, so that the axis of the eastern trough is less likely to be displaced westward to a configuration which tends to pull warm, moist air up into New England - favorable to precipitation, but as rain rather than snow.

We can also not rule out the possibility that the SSTAs are simply the result of the corresponding atmospheric circulation anomalies and that the snowfall-SSTA association is purely coincidental. Interannual variability in wintertime SSTs is mainly due to local anomalies in the air-sea flux of sensible and latent heat, although oceanic advection may also be important along the east coast of North America (Battisti *et al.* 1995). Interdecadal SST variability, on the other hand shows no apparent correspondence with atmospheric circulation anomalies (Kushnir 1994). The decadal-scale variability in snowfall in the south (Figure 2a) is roughly in step with the decadal-scale variability in sea-surface temperatures (Figure 3b), with the period of relatively high snowfall (late 1950s to early 1970s) corresponding to a period of relatively lower sea-surface temperatures. The decadal variations were removed by fitting third-order polynomials to each of the time series. The snowfall-SSTA association for the detrended data (Figure 10b) is visually less evident than in Figure 10a (comparisons of correlation coefficients may not be meaningful here, owing to the non-linearity suggested in Figure 10a and strong autocorrelation in the raw SST time series), suggesting more of a decadal-scale phenomenon, in which case an atmospheric-SSTA association may not be involved. However, timescales of ocean-atmosphere interactions along the east coast of North America have not been examined in detail. In any case, drawing conclusions about decadal-scale associations from this relatively short record should be approached cautiously.

Finally, interannual variations in air temperature have not been discussed in this paper. The downward trend in snowfall in the south is accompanied by an upward trend in temperature. However, over much of the region, temperature and precipitation often explain less than half the total variance in snowfall, in agreement with the findings of Namias (1960). This is probably because the occurrence of snowfall depends only on air temperatures coincident with precipitation events. Atlantic SSTAs may be one of the factors that complicate the relationship between seasonal snowfall, temperature and precipitation in the south.

The snowfall-SSTA association is very different in northern New England (Figure 11a). As shown previously, low-snow winters in the north can be associated with either strongly negative or strongly positive SSTAs, while high-snow winters are associated with a range of SSTAs in between. Strongly negative SSTAs do not result in high seasonal snowfalls because of an apparent association with atmospheric circulation anomalies that result in reduced precipitation. There is the hint of a maximum in the snow-SSTA relationship and this is even more pronounced in the scatterplot of the detrended data, suggesting an annual-scale response, which is consistent with a regime where snowfall is generally limited by precipitation, and atmospheric circulation anomalies are the dominant factor in snowfall variability. At the decadal scale, seasonal snowfall appears to be independent of sea-surface temperature variability. In contrast with the south, the high-snowfall decade in the north was the 1970s (Figure 2b), a period of relatively wet conditions in the northeastern United States, due to a westward shift of the mean position of the eastern 700-mb trough (Yarnal and Leathers, 1988).

CONCLUSIONS

Atlantic sea-surface temperature anomalies do not appear to have a direct association with snowfall in the north of New England, where precipitation rather than temperature is generally the limiting factor. Exceptional snowfall seasons are largely explained by anomalous atmospheric circulation, although an apparent maximum in the snowfall-SSTA relationship, especially at the annual timescale, probably warrants further investigation.

In the south, however, there is a strong association between sea-surface temperature anomalies and seasonal snowfalls, with negative (positive) anomalies associated with above-average (below-average) snowfall totals. The anomalies may not be sufficient conditions for exceptional snowfall totals -- the large-scale atmospheric circulation patterns and atmosphere-ocean interactions have also to be considered (and are currently under investigation). It is important to emphasize that the exact nature of this association, strong as it is, can not necessarily be inferred from this study. As the association is not evident in northern New England, it is more probable that a temperature response (apparently non-linear), rather than a precipitation response, is involved, but whether the observed SSTAs are primarily cause or effect has not been established. However, in 5 out of the 7 low-snow winters, and 6 out of the 7 high-snow winters, the associated sea-surface temperature anomalies are already evident in December, suggesting that Atlantic sea-surface temperatures may be of utility in long-range winter forecasts for coastal regions.

Future work will examine further the role of Atlantic sea-surface temperatures in winter climate variability, with more particular attention to cyclonic activity, storm tracks, precipitation and air temperatures. The apparent decadal-scale association between sea-surface temperatures and snowfall in southern New England should also be re-examined for a longer period of record.

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