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Snowfall Trends in the Central and Southern Appalachians 1963–1964 to 1992–1993

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ABSTRACT

Variations in seasonal (November-March) snowfall were examined over the central and southern Appalachians from West Virginia to Alabama. Over the thirty-year period 1963-1964 to 1992-1993, snowfall decreased significantly over much of the study region, a trend that can be attributed in part to a concurrent trend towards more positive values of the North Atlantic Oscillation teleconnection index. Spatial variations in trend magnitudes have led to changing snowfall differentials across the Appalachian mountains. In the south of the region, the west-east differential has decreased while farther north it has increased.

Keywords: snowfall, Appalachians, NAO index

INTRODUCTION

Until recently, investigations of changing snow climatologies emphasized variability of snow cover extent at hemispheric and continental scales (e.g. Walsh *et al.*, 1982; Heim and Dewey, 1984; Robinson and Hughes, 1991; Gutzler and Rosen, 1992; Karl *et al.*, 1993; Leathers and Robinson, 1993). This interest was prompted by the possibility that changes in snow cover extent may be a useful indicator of climate change, and has led to a more definitive search for a "fingerprint" of global climate change (Frei and Robinson, 1998). Despite the focus on snow cover, it has been recognized that variations in snowfall might also be useful diagnostics of climate variations at the continental and sub-continental scales (Wagner, 1979; Leathers *et al.*, 1993; Serreze *et al.*, 1998).

Studies of regional-scale snowfall variability, however, are often motivated by other considerations. In many parts of the United States, winter snowfall is an important component of the water supply, and may be an important recreational resource for the local tourist economy, while unusually large snowfalls can be disruptive to transportation and commerce. Some of the earliest descriptive accounts of snowfall climatologies and variations in the eastern United States were presented by Brooks (1915, 1917). Snowfall variations of the 1940s and 1950s in the northeastern United States were diagnosed by Namias (1960). More recently, investigations of regional snowfall variability in the eastern United States have focussed on New England (Suckling and Kimsey, 1988; Hartley, 1996; Hartley and Keables, 1998), and Pennsylvania (Acker and Soule, 1996). Suckling (1991) analyzed climatologies of snowstorms in the Deep South, but otherwise, snowfall variations south of the northeastern snowbelt have not been widely investigated.

The geographic complexity of the central and southern Appalachian region presents an interesting situation with regard to snowfall. First, elevations exceeding 600 m (2000 feet) extend as far south as northern Georgia, allowing snow to frequently fall farther south than in the adjacent coastal plain. Second, the region lies between the two major winter storm tracks of the eastern United States - the Ohio Valley/eastern Great Lakes storm track and the Atlantic coast storm track. Knappenberger and Michaels (1993) showed that the relative frequency of Ohio Valley cyclones and Atlantic coastal cyclones is significant to interannual variations of wintertime climate in the mid-Atlantic states. Third, there is the possibility that some lake-effect enhancement of snowfall may be felt on the

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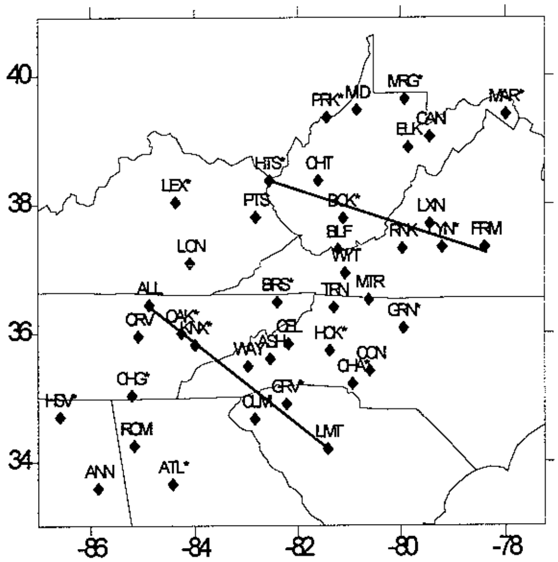


Figure 1. Distribution of snowfall stations. Lines indicate transects referred to in a later section.

western slopes of the Appalachians, for example in West Virginia (Schmidlin, 1992).

The present study is a preliminary investigation of snowfall variability of the region. Trends in seasonal snowfall are examined as are associations with atmospheric teleconnection patterns. Presentation of the results in a spatial framework also suggests that there have been changes in snowfall differentials across the region.

METHODS

Data

Daily snowfall data were obtained from the TD3200 Summary of the Day data set of the National Climatic Data Center. The spatial coverage of stations is shown in Figure 1. These stations represent the best compromise among record length, completeness of record, and areal coverage. Of the 40 stations, 17 (indicated by asterisks on Figure 1) have complete records for the winters (November-March) of 1963-64 through 1992-93. Missing month-long blocks of data at Paintsville, KY (PTS), Mt. Airy, NC (MTR) and Wytheville, VA (WYT) were estimated from proximal stations by regression analysis. At many stations, some months had occasional missing daily values. Where possible, substitutions were made from suitable neighbors. Where no suitable neighbor was available, no adjustment was made to the monthly total. At 18 stations, no more than 6 months in the 30-year record are affected. At 3 stations, 7-12 months are affected, while at 2 stations, more than 12 months are affected. The worst case is PTS for which 14 months were estimated by regression and 21 months have occasional missing daily values. However, this station was retained to partly fill the data void of eastern Kentucky. At other stations, missing or incomplete monthly values were randomly scattered among the 30-year record, such that exclusion of these monthly values would have made it almost impossible to obtain a concurrent record of a statistically useful sample size across the region. Hence it was determined that use of monthly estimates was justified for the purpose of completeness of record. Winter season totals were computed from the monthly totals.

Monthly indices of the Pacific-North American (PNA) and North Atlantic Oscillation (NAO) atmospheric circulation patterns (Wallace and Gutzler, 1982) were obtained from the Climate Prediction Center (formerly the Climate Analysis Center) of the National Center for Environmental Prediction (NCEP). Winter season indices were computed as an average of the November-March indices.

As a further diagnostic of mid-tropospheric circulation patterns, gridded monthly 700 mb fields from NCEP (formerly the National Meteorological Center) were obtained from the Data Support Section of the National Center for Atmospheric Research (NCAR).

Analysis

Possible associations between winter snowfall totals and winter indices of the PNA and NAO patterns were examined by correlation analyses (Johnston, 1992; Sprent, 1993). Where time-series graphs suggested long-term trends, the significance of the trend was assessed by computation of Kendall's tau as applied by Dettinger and Cayan (1995). The magnitude of the trend was estimated by linear regression analysis (Bowerman and O'Connell, 1990) of winter snowfall totals against calendar year. Spatial variations in teleconnection associations and temporal trends were displayed with contour plots of correlation coefficients, and further examined by taking transects across the Appalachians.

RESULTS AND DISCUSSION

Average winter (November-March) snowfall totals for the period 1964-1993 are shown in Figure 2. A bullseye maximum (represented by more than one station) is evident at the higher elevations of eastern West Virginia. Away from the bullseye, snowfall maxima are oriented along the spine of the Appalachian Mountains roughly as far as the border

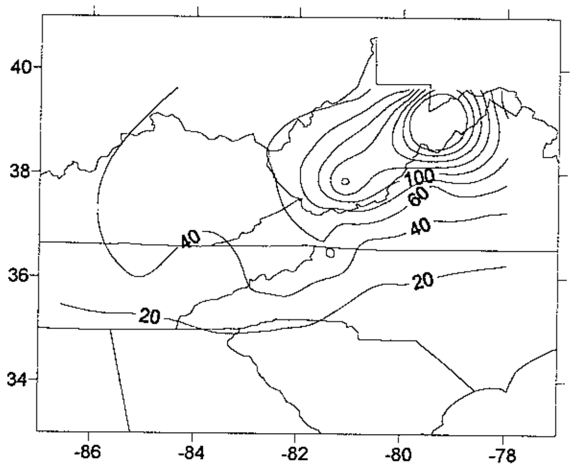


Figure 2. Average November-March snowfall totals (cm) for the winters 1964-1993. In the "bullseye", the values are around 180 cm at Elkins, WV and around 300 cm at Canaan Valley, WV.

between Kentucky and Tennessee, south of which the contour lines resume a more latitudinal orientation.

Only one station, Elkins, WV, shows any significant association with the PNA teleconnection pattern, and this is only marginal. The lack of a PNA signal is not surprising considering that both temperature and precipitation are negatively correlated with the PNA index over the region in most of the winter months (Leathers *et al.*, 1991). Thus the positive phase of this pattern, characterized by an amplification of the eastern trough, will tend to result in colder, but also drier, conditions and not necessarily more snowfall.

This discussion will concentrate on associations with the NAO for which correlations are significant over much of the region (Figure 3). Associations are strongest from the mountains of western North Carolina up through south-central Kentucky. Example scatterplots of snowfall vs. NAO index are given for Asheville, NC and Bristol, TN (Figure 4). Correlations are non-significant south and east of the mountains and at a few of the West Virginia stations.

The snowfall-NAO association can be explained with reference to the mid-tropospheric circulation patterns at extreme values of the NAO index. Figure 5 shows seasonal 700-mb height anomalies composited over the 5 largest positive-index winters and the 5 largest negative-index winters. Positive NAO winters are characterized by positive height anomalies stretching from the east coast of the United States eastward over the Atlantic Ocean. This height anomaly pattern results in an

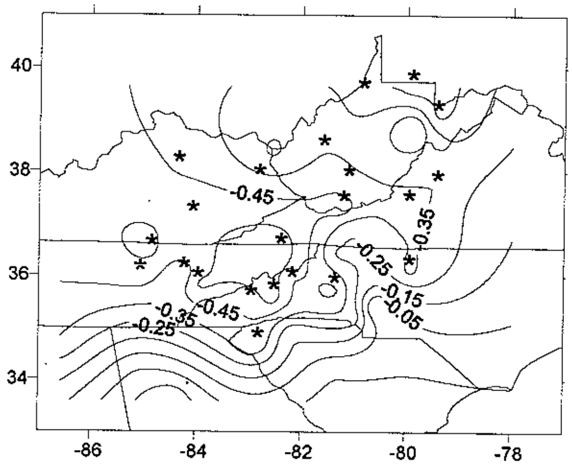


Figure 3. Computed correlation coefficients between seasonal snowfall and a seasonal index of the NAO teleconnection pattern. Shown are Pearson product-moment correlation coefficients. A map of Spearman Rank Correlations shows the same pattern. Asterisks indicate stations at which both correlation coefficients are significant at the 0.05 level.

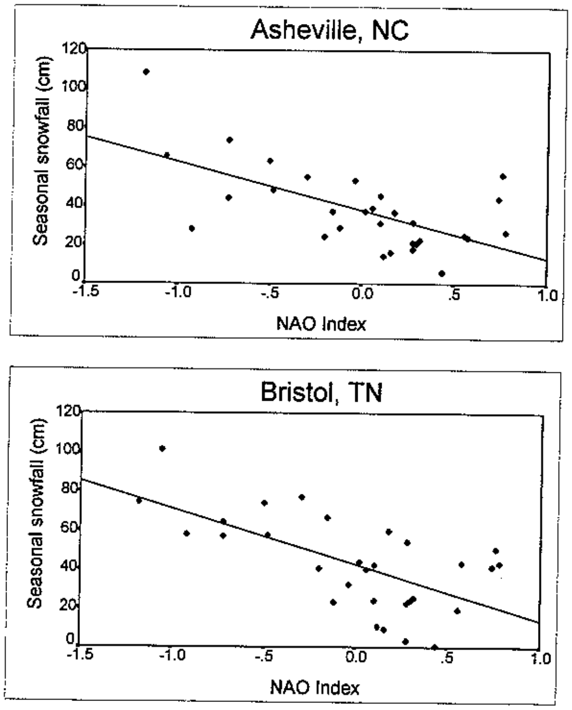
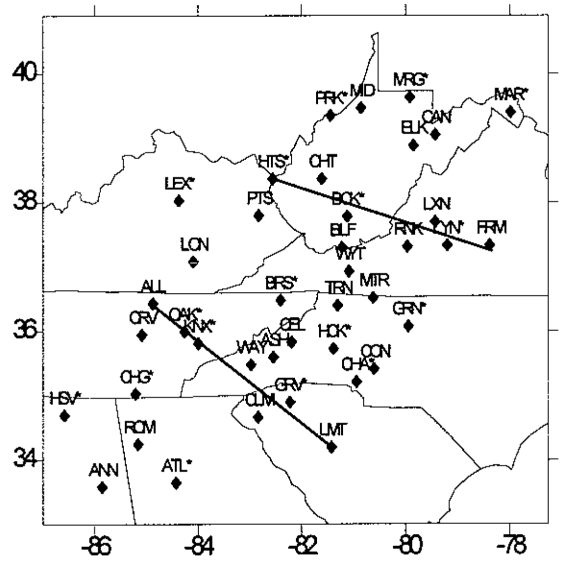


Figure 4. Example scatterplots of seasonal snowfall against a seasonal index of the NAO pattern. Linear best-fit lines are shown for reference only.



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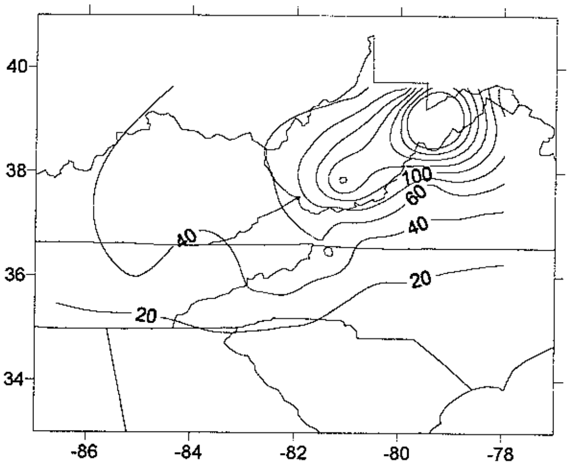

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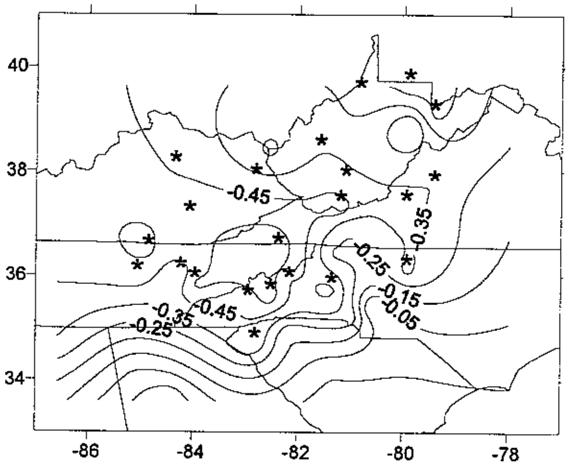

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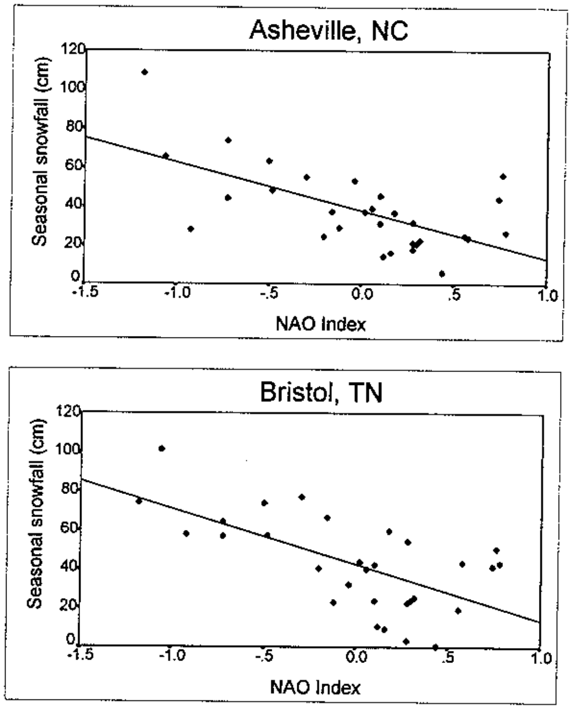

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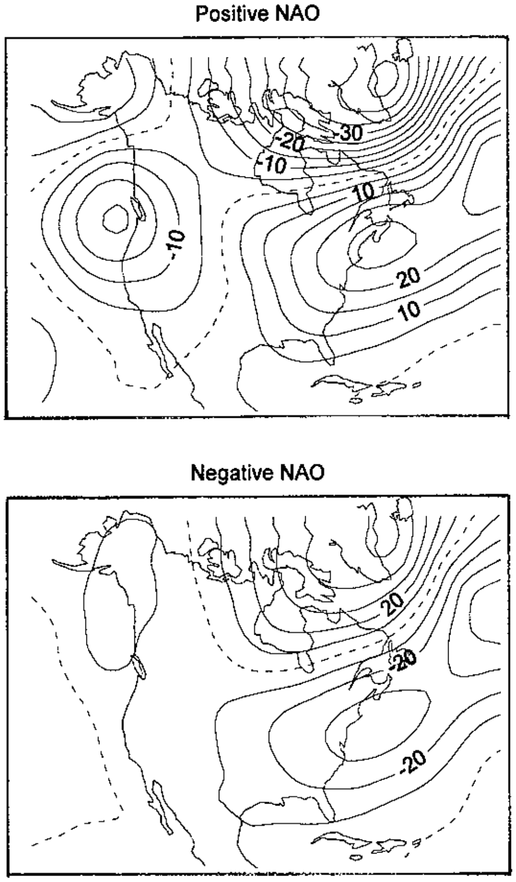

Figure 5. Composited 700-mb height anomalies (m) for positive and negative NAO winters.

anomalous southeasterly flow of mild maritime air from the Atlantic Ocean, and warmer-than-average winter temperatures. Negative NAO winters are characterized by negative height anomalies over the eastern United States and Atlantic Ocean, and anomalous flow from the north to northeast, resulting in colder-than-average temperatures. The positive height anomalies over Greenland suggest more frequent blocking, a situation that tends to favor a southward and eastward shift of the zone of maximum storm frequency over the eastern United States (Resio and Hayden, 1975). In this case, the Atlantic storm track is perhaps more active, and cold-air advection during winter storms results in snow as opposed to rain. These patterns are thus consistent with the negative correlations between snowfall and the NAO index. South and east of the mountains, correlations are non-significant, suggesting that the coldest winters are perhaps still warm enough to favor rain over snow most of the time. The non-significant correlations at a few stations in West Virginia are harder to explain, especially as correlation is non-significant at Elkins (ELK) but significant at nearby Canaan Valley (CAN). If indeed lake-effect enhancement is felt at the higher elevations of West Virginia then an increased frequency of synoptic conditions favorable to lake-effect snowfalls from 1951-1982 (Leathers and Ellis, 1996) may mask an NAO signal.

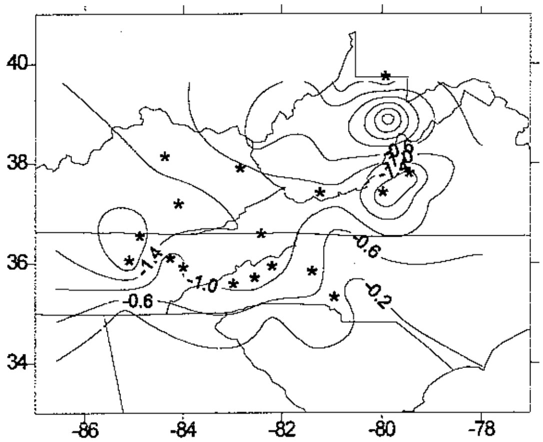

Figure 6. Estimated trend in seasonal snowfall in cm/year. Asterisks indicate stations for which Kendall's tau indicates a trend significant at the 0.05 level.

Magnitudes of snowfall trends over the three decades were estimated by linear regression and are shown in Figure 6. Significance of trends was assessed by computing Kendall's tau. Significant downward trends are indicated to the north and west of the mountains in the south-central part of the region, and on the eastern slope of the mountains in Virginia. The pattern bears resemblance to the map of snowfall-NAO correlations in Figure 3.

Figure 7 shows a marked positive trend in the NAO index over the three decades. Thus, it would

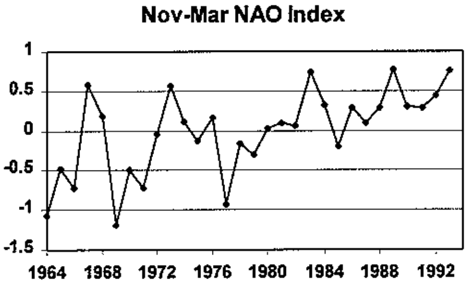

Figure 7. Seasonal NAO index from 1963-64 to 1992-93.

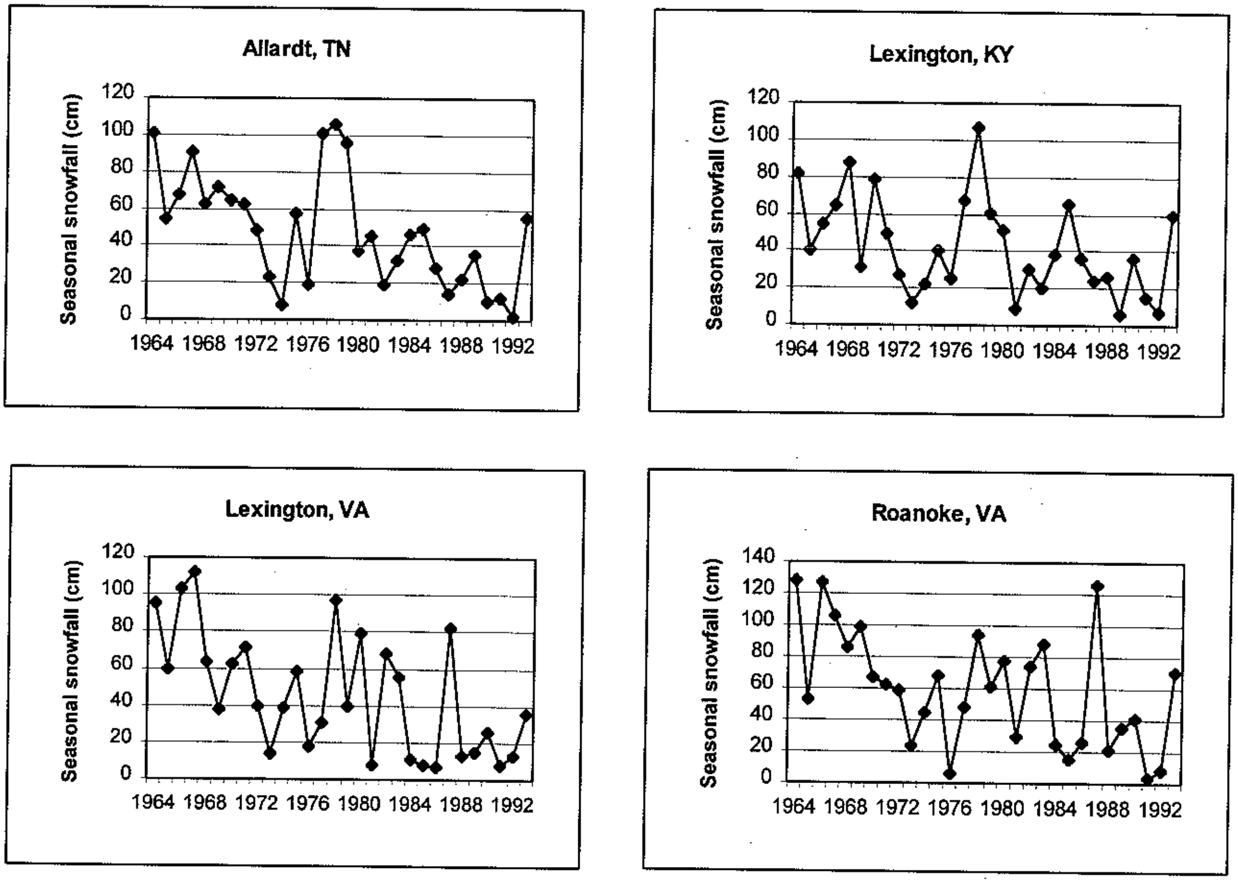

Figure 8. Example time series of seasonal snowfall.

be reasonable to infer that the downward trends in snowfall over much of the region can be explained in part by the trend to more positive values of the NAO index.

The magnitude of the downward trend exceeds 1 cm/year over most of the area for which the trend is significant. Example time series of some downward trends are shown in Figure 8.

However, interannual variations in snowfall (residual of the long-term trend) may be less well explained by the NAO index. For example, the winter 1967 had a positive value (0.6), yet snowfall totals were well above average over part of Virginia (stations FRM, LYN, LXN, and RNK). Hartley and Keables (1998) found the snowfall-NAO association in New England to be non-significant at the interannual time scale and suggested that an apparent lag association between the NAO and sea surface temperature anomalies off the east coast of the USA might be a factor. Snowfall in southern New England has been linked with Atlantic sea surface temperature anomalies (Hartley, 1996) and it is possible that this association exists elsewhere along the Atlantic seaboard. The importance of Atlantic sea surface temperature anomalies to eastern USA climate is currently under investigation.

The spatial variations in snowfall trends can be illustrated by contour plots of snowfall across a transect through time. Two transects were considered - one across the northern part of the region, and one farther south (see Figure 1). The exact orientation of the transects was limited by the spatial distribution of stations. Several other transects were examined, but add nothing to the results presented here. Figure 9 shows that in the north of the region, the downward trend is confined to the eastern slope of the mountains, while in the south, the downward trend is seen on the western slope. Figure 10 shows that in the north of the region, the snowfall differential across the mountains increased from the 1960s to the 1980s, while in the south the reverse happened.

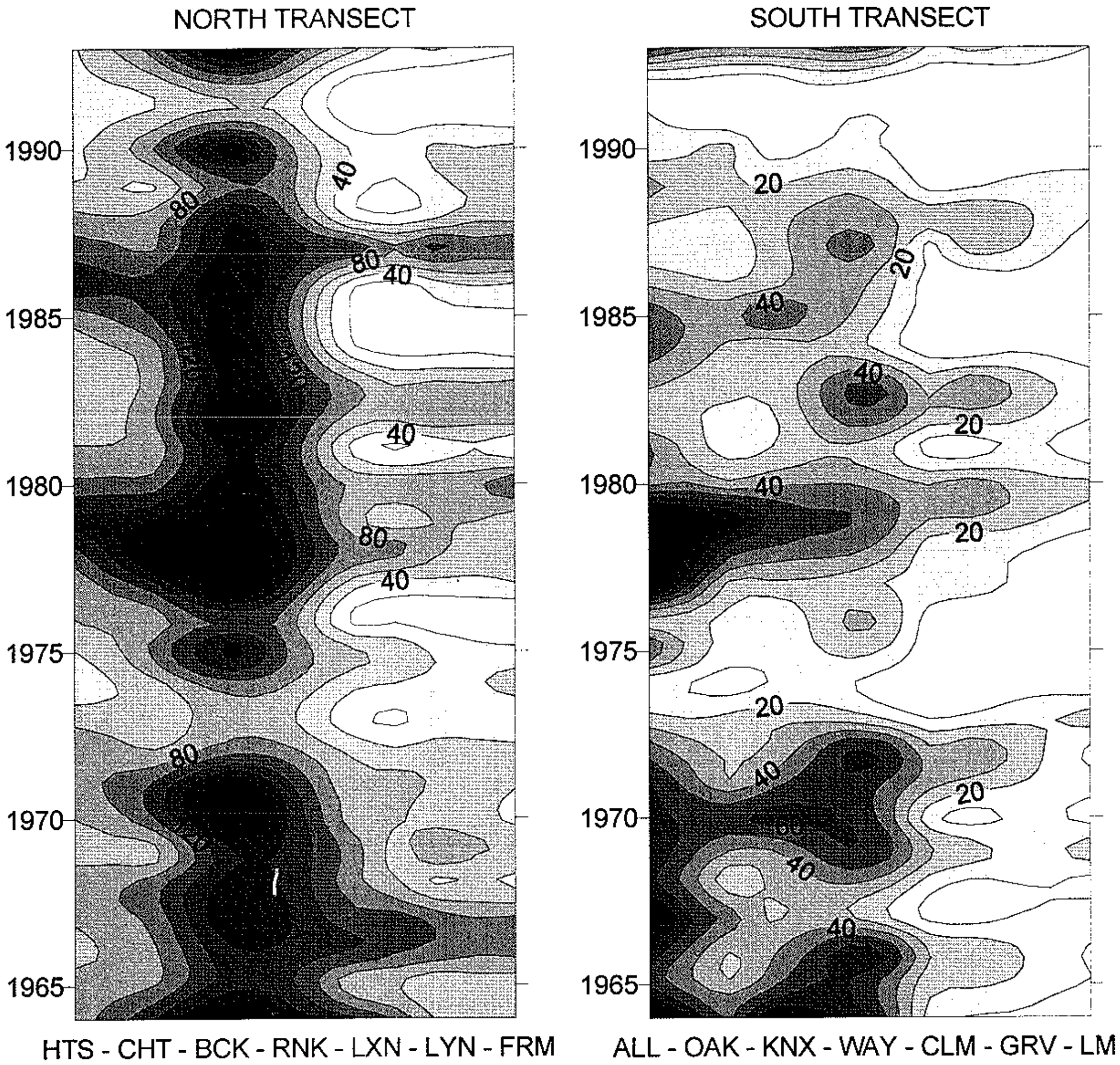

Figure 9. Temporal variations in snowfall (cm) along two transects across the Appalachians. See Figure 2 for transect locations. Note that contour shading is not the same for both transects.

CONCLUSIONS

Seasonal snowfall decreased significantly from 1963-64 though 1992-93 over a large area of the southern and central Appalachians. The decreasing trend can be attributed in part to a long-term trend towards more positive values of the NAO index over this period, with the largest trend magnitudes corresponding with the largest snowfall-NAO correlation coefficients. The spatial variations in trend magnitudes have led to changing snowfall differentials across the Appalachian mountains. In the south of the region, the west-east differential has decreased while farther north it has increased.

Ongoing and future work will examine monthly snowfall variations and consider other variables such as temperature, precipitation, Atlantic sea surface temperature anomalies, and variations in storm tracks.

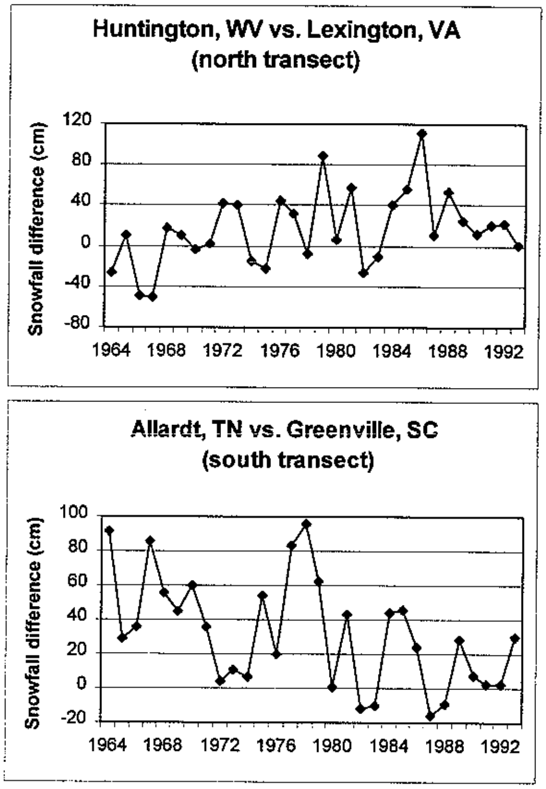

Figure 10. Trends of snowfall differentials across the Appalachians.

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