Northwest Flow Snowfall in the Southern Appalachians: Spatial and Synoptic Patterns

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ABSTRACT

Northwest flow (NWF) snowfall events are common occurrences in parts of the southern Appalachian Mountains and constitute a significant portion of annual snowfall totals on windward slopes due to orographic enhancement. The synoptic processes and spatial patterns of these events are dynamic and highly variable, which makes forecasting snow accumulations challenging. In this paper, we discuss the synoptic climatology and spatial patterns of NWF snowfall for the time period October 1980 to May 1990. In particular, we identify the synoptic patterns and associated topographic controls on the spatial patterns of NWF snowfall in the region. Snowfall events are defined using a combination of hourly observations from first-order stations and daily snowfall reports from cooperative stations. These events are manually classified into common synoptic groups using NOAA's Daily Weather Maps weekly series. Using National Center for Environmental Prediction (NCEP) Reanalysis Data, we develop and compare composites of synoptic fields associated with light and heavy snowfall events across northwestern North Carolina and southeastern West Virginia.

Keywords: northwest flow snowfall, spatial patterns, synoptic patterns, southern Appalachians

INTRODUCTION

Snowfall is highly variable across the southern Appalachian Mountains, with lower elevations in the south averaging less than 38 cm annually, and elevations above 1000-m elevation averaging 76 cm to over 254 cm (Perry 1999, Doesken and Judson 1997, Reifsnyder 1980). The synoptic-scale atmospheric processes responsible for different snowfall events also vary considerably, leading to very different spatial patterns of snowfall. Recent mega snowstorms have generated increased interest in the climatology and synoptic climatology of winter storms in the eastern United States (e.g., Zielinski 2002, Schwartz and Schmidlin 2002, Hirsch et al. 2001, Keeter et al. 1995, Davis et al. 1993, Kocin and Uccelini 1990). This literature has contributed immensely to an increased understanding of the synoptic processes associated with rapidly deepening extratropical cyclones and their spatial patterns across the eastern United States—including the southern Appalachians. Less has been said, however, on the synoptic climatology of other types of snowfall events, some of which are of even greater regional significance than explosive cyclones (e.g., Gaffin et al. 2003, Moyer 2001, Fishel and Businger 1993).

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Low-level northwesterly flow can produce light to moderate, and occasionally heavy, snowfall in portions of the southern Appalachian Mountains. Northwest flow (NWF) snowfall events are common occurrences on windward slopes and at higher elevations of the southern Appalachian Mountains, but comparatively rare on lower elevation leeward slopes. In addition, they represent a special challenge to operational weather forecasters due to limitations in the major forecast models and the high spatial variability of snowfall accumulations (Lee 2004). Other than Schmidlin (1992), we are aware of no studies that focus on the climatology of NWF snowfall in the central or southern Appalachians. Schmidlin (1992) focused on NWF snowfall at Snowshoe, West Virginia, but speculated on only the synoptic processes farther south in the Appalachians. He found that NWF snowfall at Snowshoe accounted for between 25 and 30 percent of the total annual snowfall. In addition, he concluded that moisture for these snowfall events was partly of Great Lakes origin due to the fact that the leeward shores of Lake Erie also received snowfall. Also, the Greenville–Spartanburg, South Carolina, National Weather Service Office has constructed maps of selected recent NWF snowfall case study events and in some instances provides a short text discussion (see http://www.erh.noaa.gov/gsp/localdat/lcldata.htm).

This paper analyzes the spatial and synoptic patterns of NWF snowfall in the southern Appalachian Mountains using a map compositing approach. We define the southern Appalachian Mountain region as extending from north Georgia to southeastern West Virginia, including extreme east Kentucky and extreme northwest South Carolina (Fig. 1). The highest mountains in eastern North America are found in this region, with over two hundred peaks exceeding 1,500 m and eight exceeding 2,000 m (Tagliapietra 1997). Maps, charts, and discussions of the percent contribution of NWF snowfall to annual snowfall totals for the ten-year snow season period October 1980 to May 1990 help to illustrate the spatial patterns across the study area. Through the compositing of 18 different synoptic fields, we also compare the synoptic patterns associated with light versus heavy NWF snowfall events in northwestern North Carolina (NW NC) and southeastern West Virginia (SE WV). The specific research objectives of this paper therefore are to 1) assess the spatial variability of NWF snowfall and 2) compare composites of different synoptic fields for light and heavy NWF snowfall events in NW NC and SE WV. The results presented in this paper are preliminary and are part of a larger ongoing research effort focusing on the synoptic climatology of snowfall in the southern Appalachian Mountains.

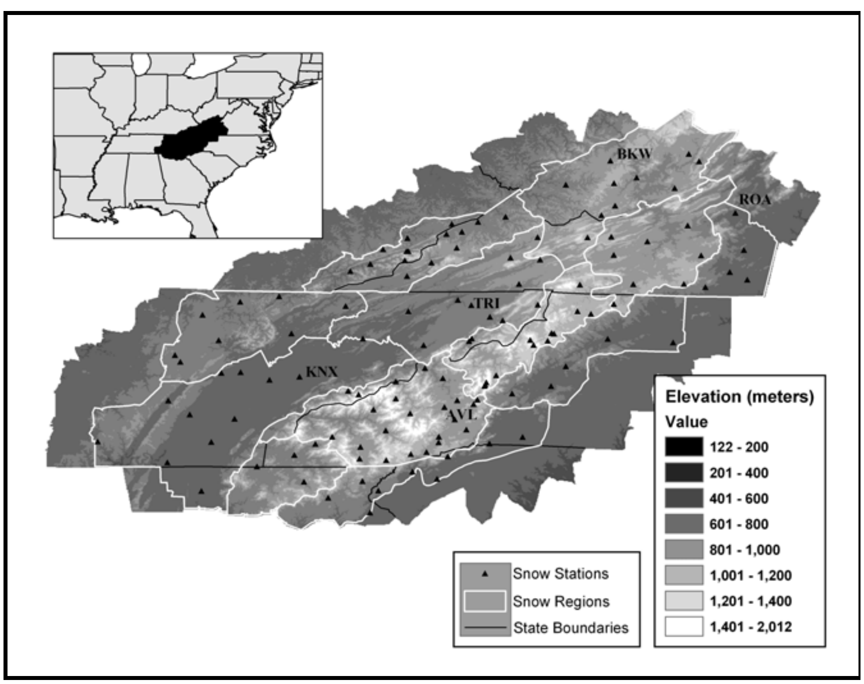

Figure 1. Co-op stations and snow regions in the southern Appalachians.

DATA AND METHODS

Daily snowfall records for the period 1948 to 2001 served as the source of the daily snowfall data. We extracted these data from the National Climatic Data Center's Cooperative Summary of the Day CD-Rom (NCDC 2002) for 112 co-op stations in the southern Appalachian Mountains (Fig. 1). For the purposes of this paper, we focused on the ten snow seasons (October to May) from 1980 to 1990.

We defined a snowfall event as having occurred if at least one co-op station in the region reported snow accumulation on a given date. In these cases, we then referenced hourly surface observation summaries from the first-order stations of Knoxville (KNX), Asheville (AVL), Tri-Cities (TRI), Beckley (BKW), and Roanoke (ROA) for considerably improved temporal resolution of temperature and precipitation. From interpretation of these data, we were able to approximate the onset, maturation, and ending time as well as the duration of reported snowfall across the region. Assessment of the maturation time involved determining the maximum spatial extent of snowfall reported at the first-order stations. An event remained active if precipitation was reported during a six-hour period. When precipitation was no longer reported at any of the first-order stations for more than six hours, we defined the event as having ended at the hour precipitation was last reported. In some cases, all of the first-order stations with the exception of Beckley (BKW) show two or three distinct periods of precipitation: one with isentropic lift and/or the main synoptic-scale surface cyclone and another with NWF snowfall. In the cases where the temporal resolution of the daily co-op data was adequate, we separated these different precipitation periods into separate events. In many instances, snowfall events spanned two or more days, which necessitated a manual approach in which we totaled the daily snowfall data for the inclusive periods to derive snowfall event totals. We defined all of the snowfall events during the ten-year snow season period in this manner and ended with the beginning, maturation, and ending dates/times and snowfall event totals for each co-op station for 332 events.

Once the events had been defined, we manually classified each event by the presence or absence of isentropic lift (i.e., warm air advection) in the lower troposphere. Isentropic lift typically occurs in the vicinity of fronts, particularly warm fronts, and is often responsible for light to moderate precipitation. For this study, we were only interested in those snowfall events in which there was no isentropic lift, as this synoptic pattern is tied to southerly or southwesterly flow rather than NWF. We then defined twelve snow regions within the study area based on similarities in elevation and exposure (Fig. 1) Using the co-op data for the stations in each snow region, we calculated summary statistics (e.g., mean, maximum, and minimum snow totals).

From the original 332 events, we identified 75 NWF snowfall events in NW NC and 104 NWF snowfall events in SE WV. These events met the following criteria: 1) absence of isentropic lift, 2) measurable snowfall recorded in at least one station in the respective snow region, 3) 850 hPa northwesterly wind (270 to 360 degrees), and 4) subsidence at 700 hPa. Using the regional snowfall means for NW NC and SE WV as derived from co-op stations in those respective snow regions (Fig. 2), we further stratified these samples into a "heavy" group, defined as the top quartile, and a "light" group, defined as the bottom three quartiles. For NW NC, the actual stratification value associated with the 75th percentile is 2.8 cm; the mean for the light events is 1.1 cm and 5.3 cm for the heavy events. In SE WV, the stratification value associated with the 75th percentile is 2.4 cm, and the mean for the light events is 0.8 cm and 5.0 cm for the heavy events.

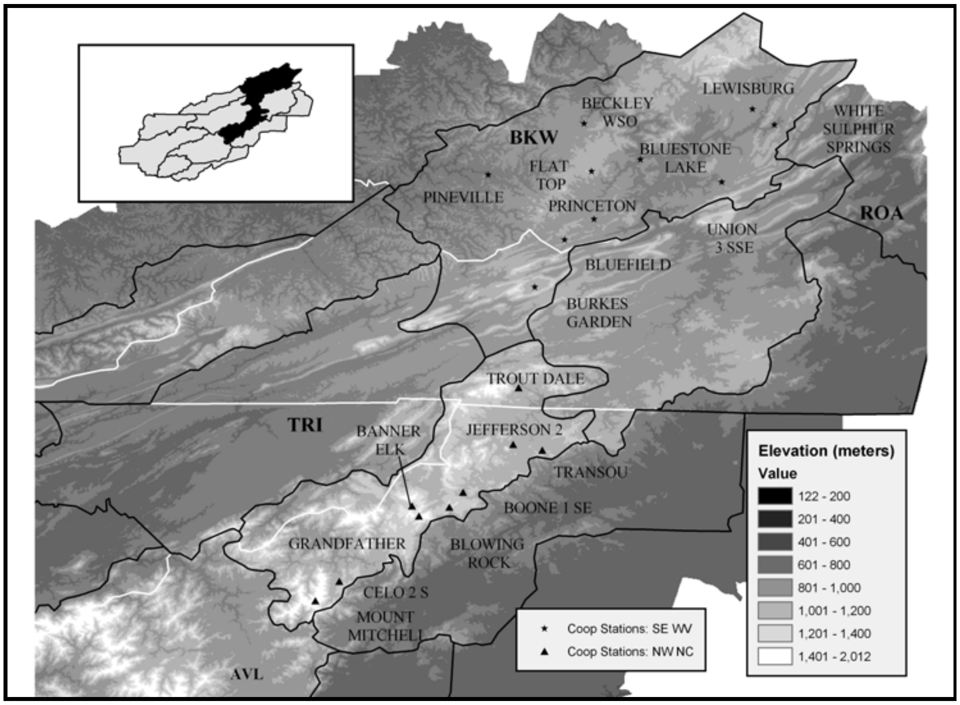

Figure 2. Co-op stations and snow regions in NW NC and SE WV.

To identify synoptic features associated with NWF snowfall, we used gridded (2.5 by 2.5 degree latitude/longitude mesh), twice-daily synoptic fields that were extracted from CDs containing the National Center for Environmental Prediction (NCEP) Reanalysis dataset. These fields were spatially interpolated onto a 1,332 by 1,332 km grid at a 222-km interval centered over NW NC. Using the 0000 and 1200 UTC gridded synoptic fields, a temporal interpolation was undertaken to estimate field values during the event maturation time. An inverse distance technique was used to carry out all spatial and temporal interpolations. We used the Synoptic Suite software package (Konrad and Meaux 2003) to carry out these analyses and map the synoptic fields.

SPATIAL PATTERNS OF NWF SNOWFALL

NWF snowfall totals are highly variable, as orographic enhancement leads to higher totals on windward slopes and little, if any, snow on leeward slopes at lower elevations (Fig. 3). In the snow regions in the eastern foothills of the southern Appalachians, NWF snowfall contributes only 0.4 to 0.5 percent of annual snowfall totals. These regions are on the leeward side of the southern Appalachians where northwesterly winds are tied to downsloping. At higher elevations and in the regions with greater westerly or northwesterly exposure, the percent contribution of NWF snowfall increases substantially. In extreme southwest North Carolina and northern Georgia, for example, NWF snowfall contributes 7.9 percent of the average annual snowfall. NWF snowfall makes the greatest contribution to average annual snowfall in the mountain regions farther north, ranging from 16.6 percent in NW NC to 20.8 percent in SE WV. These higher percent contributions are particularly noteworthy, because it is in these regions that average annual snowfall totals are greatest.

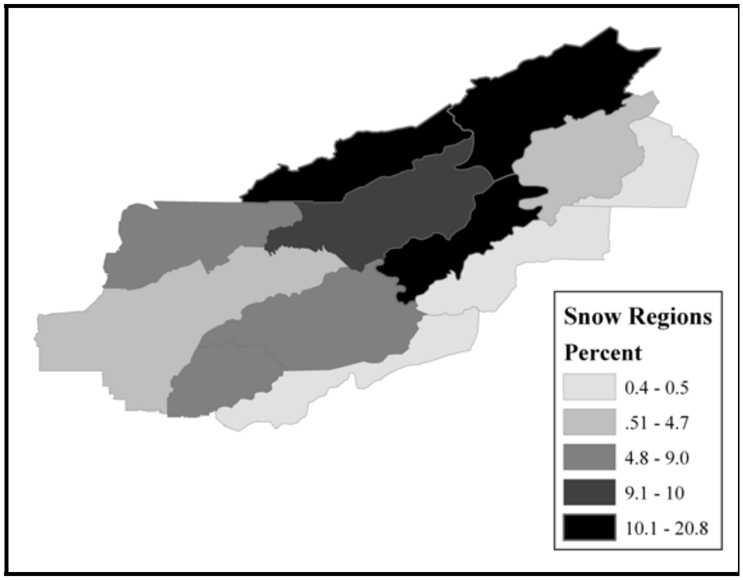

Figure 3. Percent northwest flow (NWF) snowfall by snow regions in the 1980s.

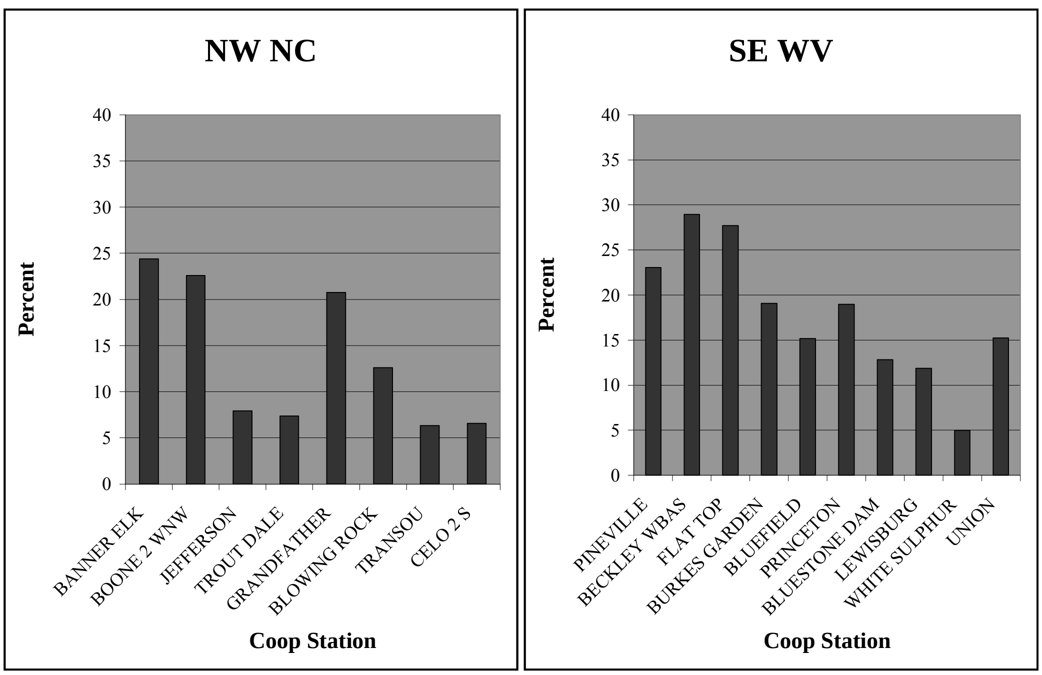

Figure 4. Percent NWF snowfall by co-op stations in (a) NW NC and (b) SE WV for the 1980s.

Even more noteworthy perhaps than the variations in percent contribution of NWF snowfall at the regional level is the variability within NW NC and SE WV (Fig. 4). In NW NC, for example, the percent contribution of NWF snowfall ranges from 6.6 percent in Celo to 24.4 percent of the annual average in Banner Elk. Celo is southeast of the Unaka Mountains and immediately east of the Black Mountains—the highest mountains in eastern North America, so they are on a leeward slope within NW NC. Banner Elk, however, is situated in the Elk River basin, which drains northwest towards northeast Tennessee. Low-level northwest flow funnels up the northwestern slopes, maximizing NWF snowfall totals in Banner Elk and in locations near the border of North Carolina and Tennessee. In SE WV, the percent contribution of NWF snowfall ranges from 5.0

percent in White Sulphur Springs to 28.9 percent in Beckley. Again, White Sulphur Springs is near the Virginia border, well east of the higher terrain. Beckley, however, is at a comparatively higher elevation on a northwestern slope. It is important to note that the NWF snowfall estimates presented above are conservative, as this framework does not include events in which a period of isentropic lift or synoptic-scale rising motions at 700 hPa were evident.

SYNOPTIC PATTERNS OF NWF SNOWFALL

NWF snowfall in the southern Appalachians typically occurs in conjunction with a surface cyclone (i.e., lower 1000 hPa heights) to the east–northeast and a 500 hPa trough to the northeast (Fig. 5). Higher surface pressures and 500 hPa ridging are also typically noted to the west. The southern Appalachians lie within the pressure gradient that results, producing low-level northwest winds that are generally perpendicular to the southwest-to-northeast-oriented topography. Low and mid-level moisture can be wrapped around from an intensifying surface cyclone to the northeast with this synoptic pattern, and the Great Lakes may also contribute some low-level moisture under ideal wind trajectories. Low-level cold air is also advected southward by the low-level northwesterly flow, but temperatures aloft warm in association with anticyclonic vorticity advection with the approaching upstream ridge. Synoptic-scale rising motions are typically observed well east–northeast of the southern Appalachians; therefore, the topography appears to provide the necessary lift to extract the remaining low-level moisture.

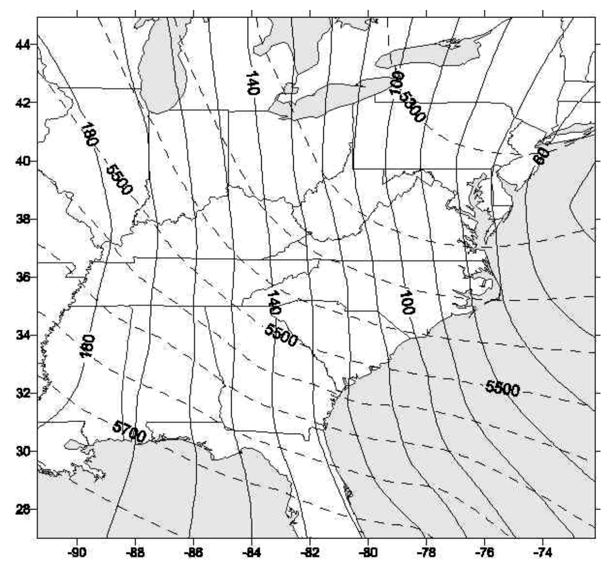

Figure 5. Composites of 1000 hPa heights (solid) and 500 hPa heights (dashed) for NWF snowfall.

Significant differences between the mean values directly overhead NW NC for light and heavy NWF snowfall events exist for seven of the 18 synoptic fields analyzed in this study (Table 1). Heavy NWF snowfall events are tied to significantly higher relative humidity values both in the column from 1000 to 500 hPa and at 850 hPa. An axis of higher (1000 to 500) mean relative humidity is evident from West Virginia northeast to New England, with the greatest mean difference of 9.0 percent over the southern Appalachians (Fig. 6). In the heavy NWF snowfall events, 700 hPa troughing is evident to the northeast and the greatest mean difference in 700 hPa heights is found over the southeastern United States, almost 38 m lower (Fig. 7). A tight gradient in the 850 hPa thermal advection exists from north to south over the southern Appalachians in the heavy NWF snowfall events, and once again, the greatest mean differences, with values of 2.1° C/12 hrs are found over the region (Fig. 8). Therefore, cold air advection at 850 hPa is still present with the heavy NWF snowfall events, but at a more moderate level compared to the light events.

Table 1. Summary of synoptic fields in northwestern North Carolina (NW NC).

Field	Light n = 57	Heavy n = 18	Mean Difference	Relative Difference	T-score	
1000–500 hPa Mean Relative Humidity	53.4	62.4	9.0	0.99	4.29	*
700 hPa Height	2924.8	2887.0	–37.8	–0.7	–2.3	*
850 hPa Relative Humidity	72.7	81.3	8.6	0.67	3.54	*
500 hPa Height	5438.6	5383.6	–54.9	–0.65	–2.25	*
850 hPa Height	1423.5	1396.9	–26.6	–0.63	–1.99	*
200 hPa Divergence	2.0	2.8	0.8	0.6	2.13	*
850 hPa Thermal Advection	–5.7	–3.6	2.1	0.51	2.39	*
1000 hPa Height	139.8	115.7	–24.1	–0.5	–1.64	
1000–500 hPa Thickness	5298.8	5268.0	–30.9	–0.37	–1.26	
500 hPa Relative Humidity	27.4	31.0	3.6	0.31	0.96	
850 hPa Wind Speed	13.9	15.0	1.1	0.31	1.15	
850 hPa Temperature	266.1	264.8	–1.3	–0.27	–0.91	
Vertical Velocity	21.6	18.5	–3.1	–0.26	–1.25	
Precipitable Water	0.66	0.74	0.08	0.24	0.85	
850 hPa Wind Direction	304.4	308.4	4.1	0.24	0.89	
500 hPa Vorticity Advection	0.6	–0.2	–0.8	–0.2	–0.64	
850 hPa Mixing Ratio	2.03	2.13	0.1	0.14	0.49	
850–500 hPa Temperature Change	18.40	18.29	–0.11	–0.03	–0.11	

* Significant at p = 0.05

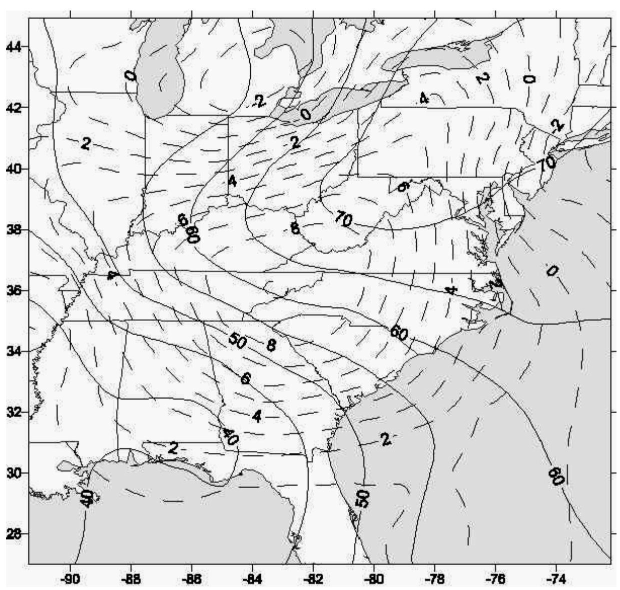

Figure 6. 1000 to 500 hPa mean relative humidity for heavy NWF snowfall (solid) and mean difference of heavy events minus light events (dashed).

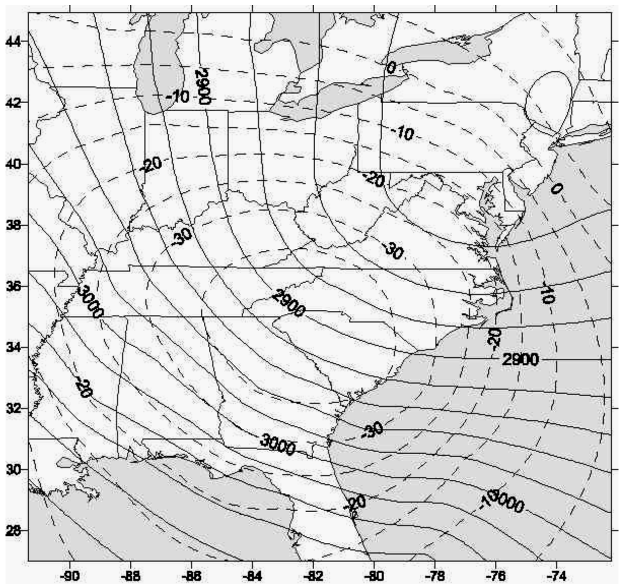

Figure 7. 700 hPa height for heavy NWF snowfall (solid) and mean difference of heavy minus light (dashed).

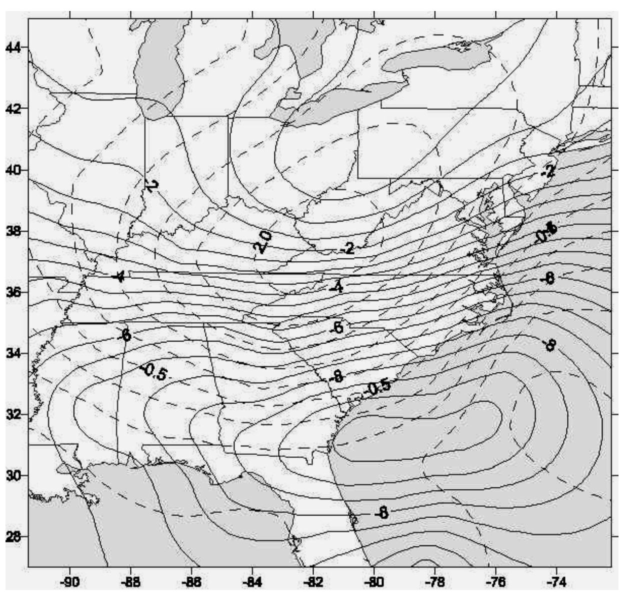

Figure 8. 850 hPa thermal advection for heavy NWF snowfall (solid)
and mean difference of heavy minus light (dashed).

The synoptic patterns of NWF snowfall in NW NC compare very favorably overall with those in SE WV, as the relative differences between the light and the heavy events for many of the same synoptic fields are significant (Table 2). The mean values for both 1000 to 500 hPa mean relative humidity and 850 hPa relative humidity vary significantly between the light and the heavy events in NW NC and SE WV, as well as 850 hPa, 700 hPa, and 500 hPa heights. Several dissimilarities between NW NC and SE WV are also apparent, however. In NW NC, the relative difference for 850 hPa thermal advection is much greater than in SE WV, where it is essentially unchanged between the light and the heavy events. In addition, the relative difference for 200 hPa divergence for NW NC is almost double that for SE WV. In SE WV, the relative difference for 500 hPa relative humidity is almost three times that for NW NC, whereas 850 hPa wind speed is more than twice the value for NW NC.

Table 2. Summary of major differences in synoptic fields between NW NC and SE WV

	NW	**NC**		**SE**	**WV**	
Field	**Relative Difference**	**T-score**		**Relative Difference**	**T-score**	
1000 hPa Height	–0.5	–1.64		–0.73	–3.55	*
1000–500 hPa Thickness	–0.37	–1.26		–0.52	–2.41	*
1000–500 hPa Mean Relative Humidity	0.99	4.29	*	0.94	4.92	*
200 hPa Divergence	0.60	2.13	*	0.32	1.42	
500 hPa Height	–0.65	–2.25	*	–0.99	–4.53	*
500 hPa Relative Humidity	0.31	0.96		0.84	4.31	*
500 hPa Vorticity Advection	–0.20	–0.64		–0.21	–0.9	
700 hPa Height	–0.7	–2.3	*	–1.02	–4.48	*
850 hPa Height	–0.63	–1.99	*	–0.94	–4.22	*
850 hPa Mixing Ratio	0.14	0.49		–0.06	–0.3	
850 hPa Relative Humidity	0.67	3.54	*	0.61	3.54	*
850 hPa Temperature	–0.27	–0.91		–0.36	–1.63	
850 hPa Thermal Advection	0.51	2.39	*	0.02	0.07	
850 hPa Wind Direction	0.24	0.89		0.19	0.86	
850 hPa Wind Speed	0.31	1.15		0.71	3.26	*
850–500 hPa Temperature Change	–0.03	–0.11		0.21	0.93	
Precipitable Water	0.24	0.85		0	0	
Vertical Velocity	–0.26	–1.25		–0.04	–0.15	

*Significant at $p = .05$

SUMMARY AND CONCLUSIONS

In this paper, we have analyzed the spatial and synoptic patterns associated with NWF snowfall in the southern Appalachian Mountains during the ten-year snow season period from October 1980 to May 1990. The percent contribution of NWF snowfall to annual snowfall totals is highly variable across the study area, with the highest values found in the mountain regions of NW NC and SE WV. NWF snowfall makes the lowest contribution to average annual snowfall totals in the southern Appalachian foothills in the southeast and east of the study area. Percent contribution of NWF snowfall to annual totals also shows significant variability within NW NC and SE WV, with higher elevations and northwesterly slopes seeing higher values in each. NWF snowfall contributes between 25 and 30 percent to average annual snowfall totals in locations on the western and northwestern slopes in the southern Appalachians. This estimate may even be quite conservative due to our inability to readily distinguish shorter-duration NWF snowfall that is common near the end of most types of snowfall events. In addition, we have discriminated out low-level northwesterly flow in conjunction with synoptic-scale lift (rising motions) at 700 hPa, when in fact these events could be classified as NWF snowfall as well.

Analyses of the synoptic patterns associated with NWF snowfall demonstrate the importance of 1000- to 500-hPa mean relative humidity, 850-hPa relative humidity, and 850-hPa, 700-hPa, and 500-hPa heights in differentiating the light events from the heavy events across both NW NC and SE WV. Heavy NWF snowfall events are associated with higher relative humidity and lower heights at these levels. In NW NC, the heavy events also exhibit higher values of 200-hPa divergence and lower values 850-hPa cold air advection. The heavy NWF snowfall events in SE WV are further associated with significantly higher 500-hPa relative humidity and 850-hPa wind speed. In both NW NC and SE WV, the amount of water vapor in the lower troposphere—as measured by precipitable water and 850-hPa mixing ratio—is not significantly different between the light and heavy events. Cyclonic vorticity advection at 500 hPa also exhibits very little difference, but we should note that the relatively coarse spatial and temporal resolution of the NCEP reanalysis data may not be adequately resolving mesoscale cyclonic vorticity maxima.

We should caution that the results presented in this paper are based on only ten years of snowfall data during the decade of the 1980s and therefore should not be taken to represent the entire record of NWF snowfall events in the southern Appalachians. The robustness of the results should improve as we develop a larger sample of events by extending the analysis back and forward in time. This project has also made us keenly aware of the missing and misreported cooperative observer snowfall data, and this limitation will need greater scrutiny in future work. We also plan to analyze synoptic fields at different stages of an event and incorporate regional-scale synoptic variables as opposed to focusing on mean differences in synoptic fields directly above NW NC or SE WV. Lastly, we intend to incorporate air trajectory analyses and radiosonde variables that may provide more information on moisture source regions and capping inversions associated with NWF snowfall.

ACKNOWLEDGMENTS

The authors would like to thank Chris Durham for his assistance extracting the hourly precipitation and temperature data, Laurence Lee for insightful comments on preliminary output, and Greg Dobson for helpful feedback on the cooperative observer snowfall data.

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