Synoptic Classification of Snowfall Events in theGreat Smoky Mountains, USA

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ABSTRACT

Mean annual snowfall in the Great Smoky Mountains National Park (GSMNP) exhibits considerable spatial variability, ranging from 30 cm in the valleys to 254 cm at higher elevations. Snowfall can be tied to a variety of synoptic classes (e.g. Miller A or B cyclones, 500 hPa cutoff lows), but the frequency and significance of different synoptic classes have not been fully understood, particularly at higher elevations. In this paper, we manually classify all snowfall events during the period 1991 to 2004 according to a synoptic classification scheme, calculate mean annual snowfall by 850 hPa wind direction and synoptic class, and develop composite plots of various synoptic fields. Hourly observations from nearby first-order stations and 24-hr snowfall totals from five sites within the GSMNP are used to define snowfall events. NCEP/NCAR reanalysis data are used to develop composite plots of various synoptic fields and to compare differences in synoptic field values between heavy and light snowfall events for Miller A cyclones. Results indicate that over 50% of the mean annual snowfall at higher elevations occurs in association with low-level northwest flow and that Miller A cyclones contribute the greatest amount to mean annual snowfall at all elevations. Heavy Miller A events are characterized by low-level northwest upslope flow, longer durations, lower 500 hPa heights, lower 850 hPa temperatures, and stronger mid- and upper-level dynamics.

Keywords: Synoptic classification, snowfall, Great Smoky Mountains

INTRODUCTION

The Great Smoky Mountains National Park (GSMNP) in the southern Appalachian Mountains of North Carolina and Tennessee (Fig. 1) exhibits the greatest topographic relief in eastern North America, with elevations ranging from 244 m to 2,025 m. As a result, snowfall patterns are complex and strongly related to elevation and exposure (e.g. Perry and Konrad 2006) and can create significant forecasting challenges (e.g. Gaffin et al. 2003). Mean annual snowfall ranges from only 31 cm in the valleys to as much as 254 cm at the highest elevations, where extremely heavy snowfall in excess of 150 cm can occur with major storms (e.g. April 1987 and March 1993). Consequently, the societal impacts to the most-visited National Park in the country (NPS 2007) can be substantial. U.S. Hwy 441, an important link between western NC and eastern TN, crosses the GSMNP and reaches a high point at Newfound Gap (1,539 m), where the 166-cm mean annual snowfall – nearly the same as Portland, ME (NCDC 2002) – results in frequent road closures and travel delays. Due to its southerly latitude and proximity to major metropolitan

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centers in the southern U.S. where snow is a rarity, visitors are often caught off guard by the frequent heavy snowfall at higher elevations.

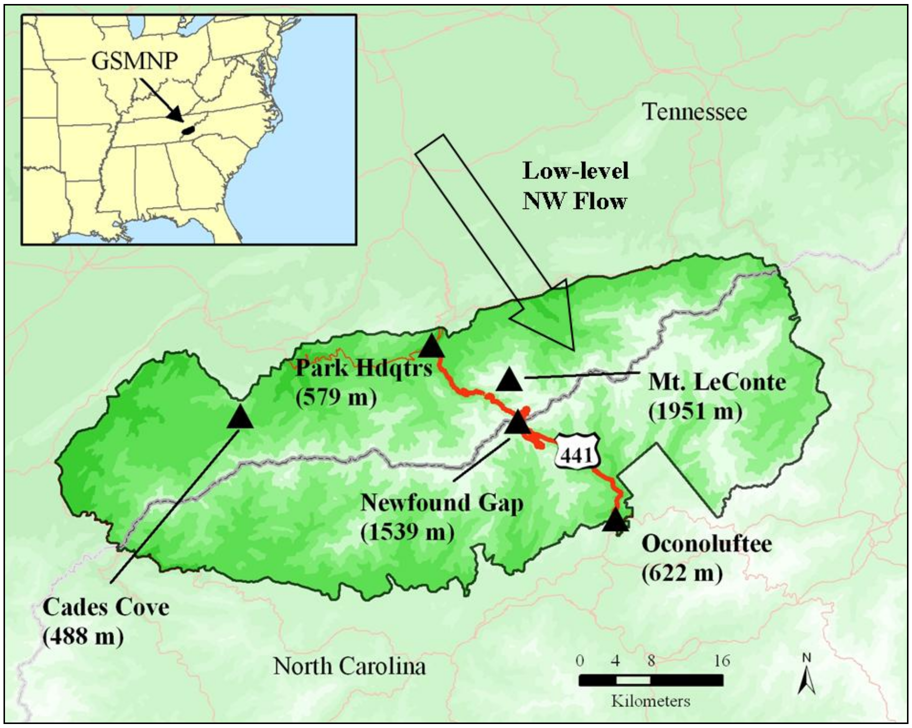

Figure 1. Location of Great Smoky Mountains National Park and snow stations.

This paper analyzes snowfall patterns in the GSMNP and is guided by four major research questions: 1) What is the snowfall climatology of the GSMNP? 2) What percentage of mean annual snowfall is tied to northwest low-level (850 hPa) flow and how does this vary by elevation? 3) What are the dominant synoptic classes responsible for snowfall and how does their significance vary by elevation? 4) How do values for various synoptic fields and composite plots vary between heavy and light Miller A cyclones for the high elevations?

DATA AND METHODS

Daily snowfall records for the period 1991 to 2004 served as the source of snowfall data used in this study. These data were collected by GSMNP observers and archived by the Morristown, TN, NWS Office for five locations (Fig. 1): Cades Cove (488 m), Park Headquarters (579 m), Oconoluftee (620 m), Newfound Gap (1,539 m), and Mt. LeConte (1,951 m). The daily snowfall data were coupled with hourly observations from Knoxville, TN (293 m), and Asheville, NC (662 m), to define snowfall events and approximate onset, maturation, and ending time. Assessment of the maturation time involved determining the hour in which the spatial extent and intensity of precipitation was greatest. An event remained active if precipitation was reported during a six-hour period. When precipitation was no longer reported at either TYS or AVL for more than six hours, we defined the event as having ended at the hour precipitation was last reported. Using this approach, we identified 332 snowfall events between 1991 and 2004.

We manually classified each snowfall event into one of 12 synoptic types (Table 1) according to the synoptic patterns identified from once-daily surface and 500-hPa analyses (e.g. NOAA 1991). The first synoptic class consists of northeastward-tracking cyclones (NE) that pass north of area. These cyclones typically result in light snowfall accumulations across the Appalachians (Knappenberger and Michaels 1993) as the region is initially in the warm sector. However, once the cold front passes, upslope snow commences in association with the cold and moist low-level northwest flow. Snow associated with a moist (e.g. Gulf origin) southwesterly low-level flow ahead of an eastward moving disturbance west or north of the area (NEb) constitutes a second synoptic class. The precipitation region is often along a relatively narrow NE-SW oriented axis that may extend from the Gulf to the Ohio Valley/Great Lakes region. A third class consists of southeastward-tracking clippers that pass north or across the region.

Table 1. Synoptic classification scheme used in this study.

Class	Description
NE	Northeastward tracking low passes to the north of area
NEb	Snow associated with a moist (e.g. Gulf origin) southwesterly low-level flow ahead of a northeastward moving disturbance
SE	Southeastward-tracking clipper that passes north or across the area
MBN	Miller B to the north -- Filling cyclone NW of region undergoes secondary cyclogenesis N of Cape Hatteras, NC)
MBS	Miller B to the south -- Filling cyclone SW to NW of region undergoes secondary cyclogenesis S of Cape Hatteras, NC
MAB	Miller A/B -- Cyclones that display both Miller A and Miller B characteristics
MA	Miller A -- Cyclone or series of small cyclones pass south and then east of area
GU	Gulf -- Surface wave or weak low moves along Gulf
CL	Cutoff Low -- A 500 hPa cutoff low moves across the region (often slow & sometimes quasi-stationary).
LC	Lee Cyclogenesis -- Surface lows develops to the lee of the Appalachain Mountains
SF	Stationary Front overhead or just south of area
U	Upslope -- NW upslope flow in the absence of synoptic-scale surface features
X	Unclassified

Miller Type A and Miller Type B cyclones are responsible for most of the big snowstorms across the southern Appalachians, mid-Atlantic, and into the northeastern U.S. (Miller 1946, Kocin and Ucellini 1990, Keeter et al. 1995, Mote et al. 1997) and constitute the next four synoptic classes. All of the 20 major snowstorms in the northeastern U.S. analyzed by Kocin and Ucellini (1990) were of the Miller Type A or B variety. Miller A (MA) cyclones are characterized by the development of a surface cyclone along a frontal boundary in the Gulf of Mexico separating cold continental air from maritime tropical Gulf or Atlantic air. The surface low tracks northeastward out of the Gulf of Mexico, in some cases paralleling the Atlantic coastline and intensifying further. Miller Type B cyclones, however, initially track west of the Appalachians. As the primary low dissipates in the Ohio Valley, a secondary low develops along the Atlantic coast. In this paper, we differentiate between Miller B cyclones that undergo secondary cyclogenesis south (MBS) and north (MBN) of Cape Hatteras. We also identify a hybrid class (MAB) that display characteristics of both Miller A and Miller B cyclones.

The remaining synoptic classes include weak surface waves or lows in the Gulf of Mexico (GU), slowly moving or quasi-stationary 500 hPa cutoff lows (CL), cyclones that develop to the lee (east) of the Appalachian Mountains (LC), stationary fronts (SF), and northwest upslope flow (U). The 500 hPa cutoff lows are well known to produce heavy snowfall across the region, with Newfound Gap reporting 152 cm on 2-5 April 1987 (NWS 1987) and Mt. Pisgah (near Brevard, NC) reporting 102 cm on 6-9 May 1992 (Fishel and Businger 1993). Likewise, Perry et al. (2007) have shown that northwest upslope flow in the absence of surface expression or synoptic-scale support contributes substantially to mean annual snowfall totals across the southern Appalachians, particularly at higher elevations and along windward slopes. Events we were unable to classify were simply designated as unclassified (X).

We used gridded (2.5 by 2.5 degree latitude/longitude mesh), twice-daily synoptic fields that were extracted from CDs containing the National Centers for Environmental Prediction (NCEP) Reanalysis dataset (Kalnay et al. 1996) to determine the 850-hPa flow and analyze the synoptic patterns. These fields were spatially interpolated to the center of the GSMNP. Using the 0000 and 1200 UTC gridded synoptic fields, we undertook a temporal interpolation to estimate field values during the event maturation time. We employed an inverse distance technique to carry out all spatial and temporal interpolations. *Synoptic Climatology Suite* (Konrad and Meaux 2003) was used for compositing of synoptic fields and calculation of mean differences between heavy and light Miller A cyclones.

RESULTS AND DISCUSSION

Mean annual snowfall for the period 1991 to 2004 ranges from 31.5 cm at Park Headquarters (579 m) to 254.0 cm atop Mt. LeConte (1,951 m) (Fig. 2). The other low-elevation stations of Cades Cove (488 m) and Oconoluftee (622 m) exhibit mean annual snowfall totals very close to those measured at Park Headquarters, whereas the 166.0 cm total at Newfound Gap (1,539 m) is considerably higher. A significant amount of inter-annual variability of snowfall totals is noted in the low-elevation stations (as noted by the high coefficients of variation – Fig. 2), with less than 10 cm falling in some years and as much as 150 cm in others. At the higher elevations, however, the inter-annual variability is considerably less, and annual snowfall totals range from a minimum of 86.1 cm to a maximum of 424.8 cm. This lower inter-annual variability appears to be related to the greater diversity of synoptic classes that contribute to annual snowfall totals at the higher elevations (Fig. 4), so that snowfall does not depend on a few select synoptic classes (e.g. Miller A cyclones).

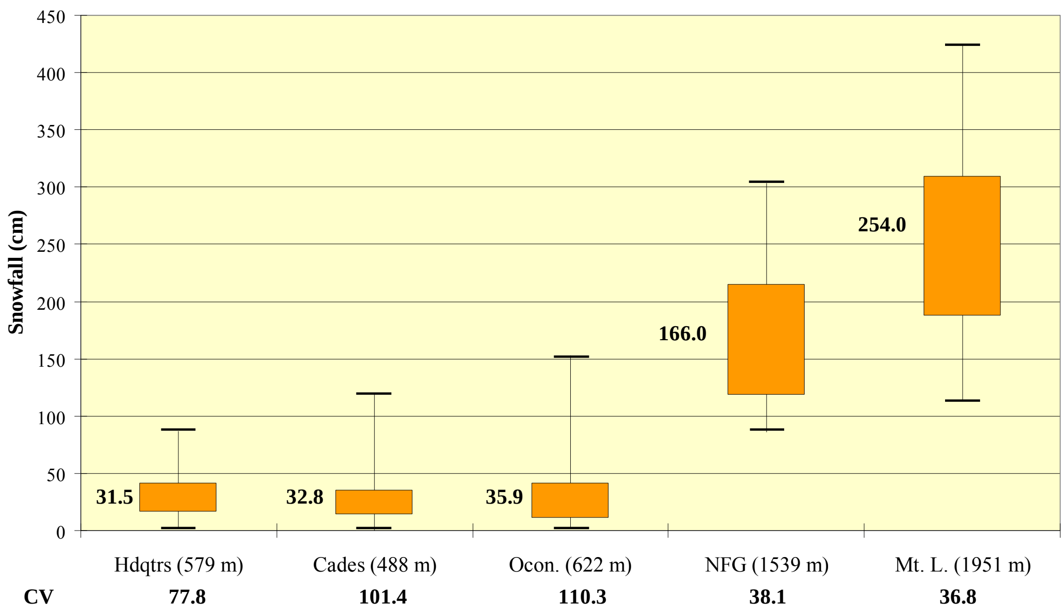

Figure 2. Box and whisker plots showing minimum/maximum annual snowfall (whiskers), 25th to 75th percentile ranges (orange box), mean annual snowfall (text), and coefficient of variation (bottom) for the period 1991-2004.

A high percentage of the mean annual snowfall across the GSMNP occurs in association with low-level northwest flow, ranging from 48% at the lower elevations to 57% at the higher elevations (Fig. 3). The Great Smoky Mountains are ideally positioned for orographic enhancement of snowfall in periods of low-level northwest flow as their SW-NE orientation is approximately perpendicular to the wind direction. The 1,500-m relief from the Tennessee Valley to the crest of the GSMNP also results in sustained upslope flow, further enhancing snowfall. Conversely, the GSMNP is heavily shadowed in periods of low-level southeast flow due to the high terrain of the Balsam Mountains and Blue Ridge to the south and east. As a result, southeast flow contributes 5% or less to mean annual snowfall totals. Nearly a quarter (24%) of annual snowfall at both low and high elevations is tied to southwest flow. Although not particularly conducive to orographic enhancement given the orientation of the topography, southwest flow occurs frequently throughout the cool season. Since southwest flow does not produce downslope conditions across GSMNP, southwest winds is a greater contributor to mean annual snowfall. The difference is most evident when comparing southwest vs. southeast flow snowfall contribution at the lower elevations. Likewise, northeast flow does not favor orographic enhancement, but can result from strong synoptic-scale coastal cyclogenesis and contributes 27% to mean annual snowfall at lower elevations and 14% at higher elevations.

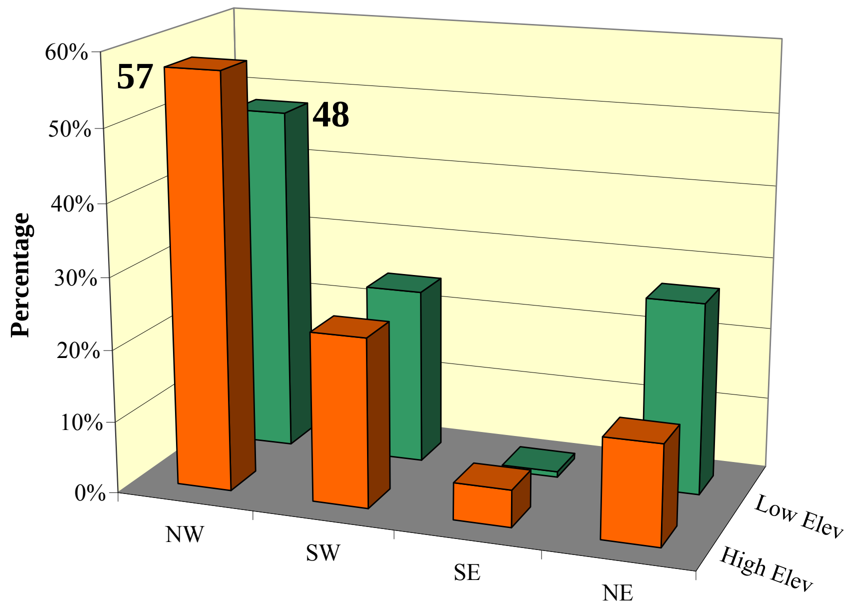

Figure 3. Percent mean annual snowfall by 850 hPa wind direction.

Miller A cyclones constitute the synoptic class that contributes the most to mean annual snowfall totals (Fig. 4), ranging from 26% at high elevations to 43% at low elevations. Miller B South cyclones, northeastward-tracking cyclones that pass north of the area, 500 hPa cutoff lows, and northwest Upslope in the absence of surface expression also contribute substantially to mean annual snowfall. Interestingly, the Miller A/B and Miller B North cyclones are of minor importance at both low and high elevations. Miller A cyclones are also tied to the highest mean event snowfall totals (Fig. 5), averaging 18.0 cm at the high elevations and 10.7 cm at the low elevations. 500 hPa cutoff lows and Miller A/B cyclones rank highly as well, particularly at high elevations, whereas the lowest mean event snowfall totals are associated with Miller B North cyclones, Upslope, and unclassified events. For all synoptic classes, mean event snowfall ranges from 5.1 cm at low elevations to 10.1 cm at high elevations, reflecting the importance of orographic lifting and lower temperatures in producing higher snowfall totals.

In order to better understand the synoptic climatology of Miller A cyclones, we compared composite plots and composite field values between heavy (top quartile of snowfall) and light (bottom three quartiles) events for the high elevations. Although important characteristics of individual events (i.e. cold air damming) may be masked due to the resolution of the NCEP reanalysis data and the compositing process, this analysis highlights certain synoptic-scale features and event variables that are common to heavy Miller A cyclones. The heavy events are tied to a much deeper surface cyclone (Fig. 6), which continues to strengthen as it tracks northeastward along the mid-Atlantic coast. This is in contrast to the light events, in which the weaker cyclone tracks east-northeast into the open Atlantic, further away from the area. Additionally, the surface high in the heavy events is much stronger and appears to be centered over the upper Midwest, as opposed to the weaker high that ridges into the mid-Atlantic in the 1000 hPa height composite plots for the light events. The end result is a much stronger cyclonic flow across the eastern United States and air trajectories more conducive to heavy northwest flow snowfall (Perry et al. 2007).

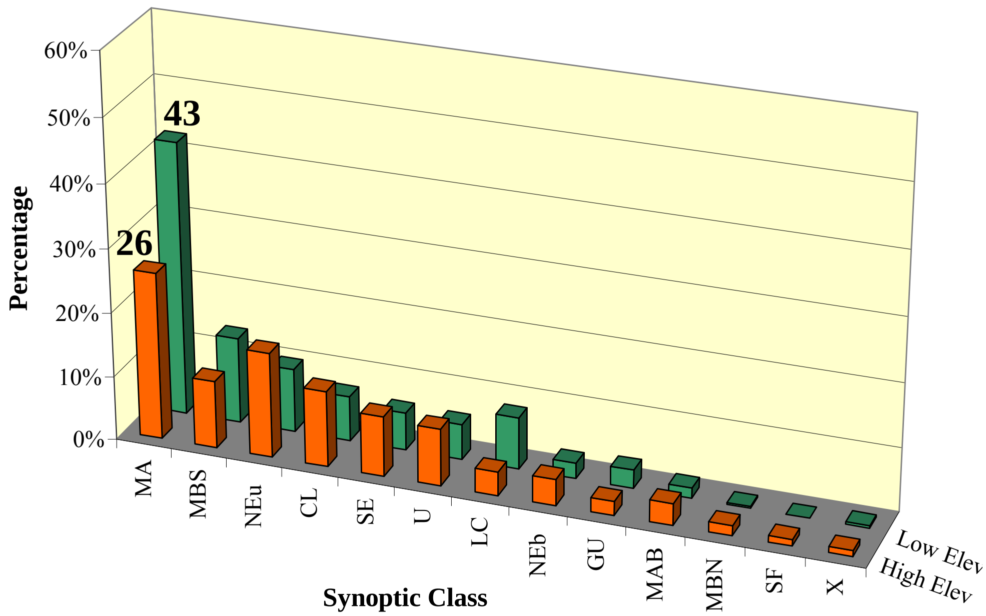

Figure 4. Percent mean annual snowfall by synoptic class.

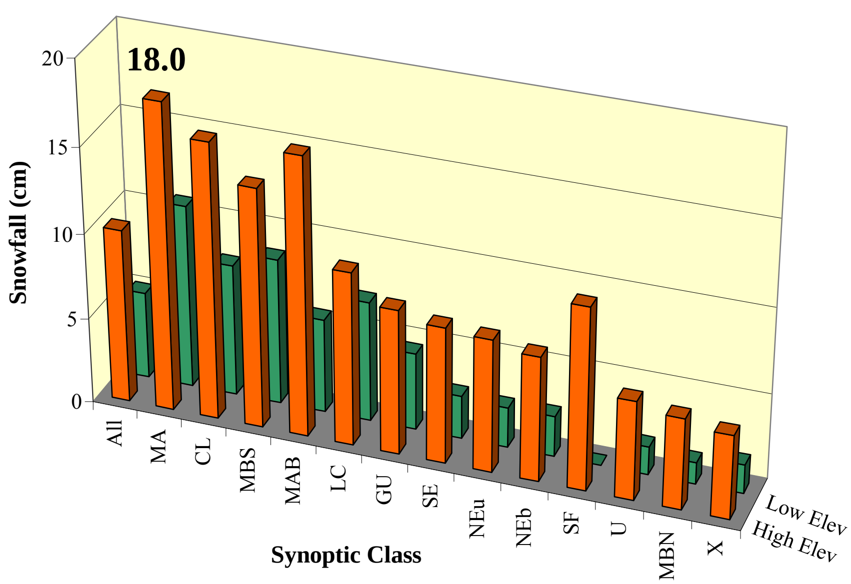

Figure 5. Mean event snowfall by synoptic class.

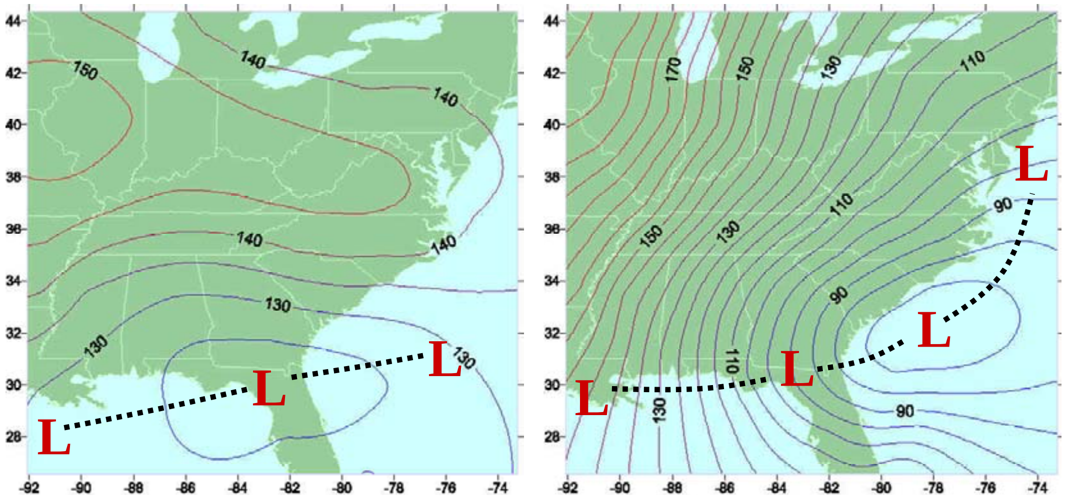

Figure 6. 1000 hPa height pattern at event maturation and 12-hourly storm track positions for light (left) and heavy (right) Miller Type A events.

As evident in the composite 1000 hPa height plots (Fig. 6) and also highlighted in Table 2, a defining characteristic of the heavy events is the existence of low-level northwest upslope flow during the second half of the storm, during which time heavy snow in association with synoptic-scale lift is further enhanced by orographic ascent. The heavy events are tied to considerably longer durations of all segments of the storm. Additionally, heavy events are tied to a much colder lower troposphere, as indicated by lower 500 hPa heights (Fig. 7), lower 1000-500 hPa thicknesses, and lower 850 hPa temperatures. An axis of higher 1000-500 hPa mean relative humidity is evident over the Ohio Valley in the heavy events, suggesting a more favorable environment for low-level northwest upslope flow in the latter stages of the event. Interestingly, 850 hPa moisture levels are significantly lower in the heavy events, suggesting that deep column saturation is more important than high values of precipitable water. Together, the composite plots and composite field values indicate that large-scale circulation patterns are the primary controls on snowfall totals in Miller A cyclones. In the heavy events there is a deeper 500 hPa trough that allows the cyclone to make the left turn up the coast and thereby provide a longer duration of snow—with a much greater northwest upslope component in its wake. The interested reader can refer to Kocin and Uccellini (2004a,b) for a detailed discussion of mesoscale and synoptic-scale processes related to East Coast cyclogenesis.

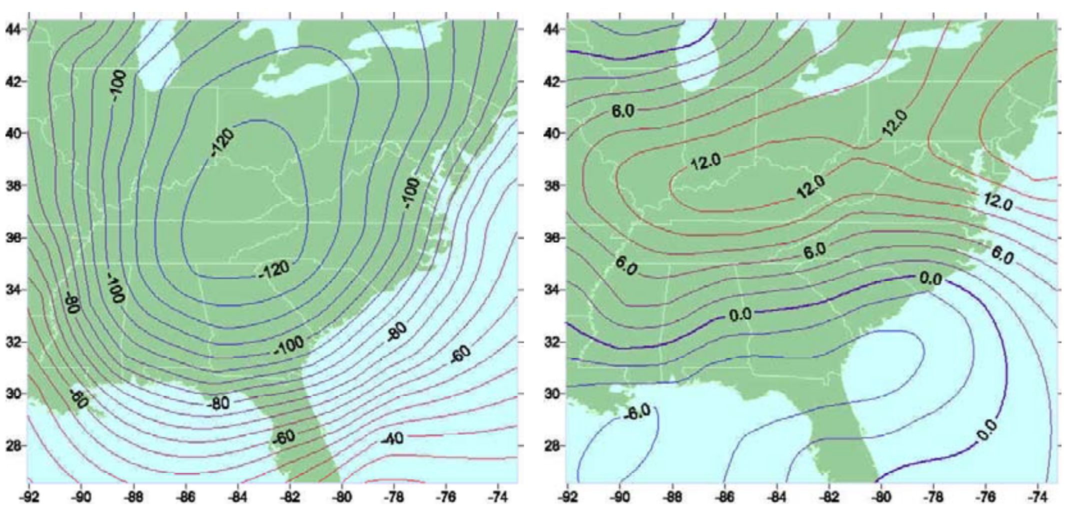

Figure 7. Composite plots of mean difference between heavy and light Miller Type A events for 500 hPa height (left) and 1000-500 hPa mean relative humidity (right).

Table 2. Composite synoptic field values and event variables for light vs. heavy Miller A cyclones for the high elevations.

MA High Elevation	Light (37)	Heavy (12)	Abs_Dif	Rel_Dif	T-Score
Snowfall (cm)	*6.7*	*42.6*			
NW Upslope Flow	54%	100%	46%	1.0	5.61
Beginning-Ending Hours	15.6	33.2	17.6	1.5	5.39
500 hPa Height	5551	5427	–124	–1.2	–3.88
Beginning-Maturation Hours	6.0	15.7	9.7	1.4	3.86
1000-500 hPa Thickness	5411	5314	–97	–1.2	–3.57
850 hPa Temperature	–0.7	–5.8	–5.2	–1.1	–3.48
Maturation-Ending Hours	9.6	17.5	7.9	0.9	2.45
500 hPa Vorticity	1.94	3.86	1.92	0.8	2.22
850 hPa Mixing Ratio	3.3	2.6	–0.7	–0.7	–2.00
850 hPa Wind Speed	8.4	10.7	2.3	0.6	1.87
200 hPa Divergence	2.50	3.58	1.08	0.5	1.85
1000-500 hPa Relative Humidity	69.8	77.5	7.7	0.6	1.68
850 hPa Thermal Advection	–0.3	–2.8	–2.5	–0.6	–1.52
500 hPa Relative Humidity	48.3	56.3	8.0	0.5	1.44
1000 hPa Height	140	114	–27	–0.5	–1.27
850 hPa Relative Humidity	74.0	80.2	6.2	0.4	1.11
500 hPa Vorticity Advection	2.27	3.56	1.29	0.4	1.02
700 hPa Vertical Velocity	–11.3	–21.6	–10.4	–0.4	–0.96
NW Flow at Maturation	46%	58%	12%	0.3	0.75
850 hPa Divergence	–0.52	–0.21	0.31	0.3	0.72
850 hPa Wind Direction	236	247	11	0.1	0.32
500 hPa Mixing Ratio	0.8	0.8	0.0	–0.1	–0.29

CONCLUSIONS

The topographic diversity of the GSMNP produces complex snowfall patterns, with mean annual snowfall during the period 1991 to 2004 ranging from 31 to 254 cm. Lower inter-annual variability is evident at higher elevations due to the greater diversity of synoptic classes contributing to annual snowfall totals. Additionally, a substantial amount of mean annual snowfall occurs in association with low-level northwest flow, whereas low-level southeast flow contributed the least amount. Due to the topographic orientation, northwest flow is tied to favorable conditions for upslope flow, whereas southeast flow results in more pronounced shadowing due to the high terrain to the southeast. Miller A cyclones not only contribute the greatest amount to mean annual snowfall totals at all elevations, but they also result in the heaviest snowfalls. Heavy Miller A events are differentiated from light events by the presence of low-level northwest upslope flow, longer storm durations, lower 500 hPa heights, lower 850 hPa temperatures, and stronger mid- and upper-level dynamics. The presence of an anomalously deep 500 hPa trough is particularly important in controlling snowfall totals in Miller A cyclones.

Although this paper has focused solely on the GSMNP due to the homogeneity and quality of the data from different elevations, we feel that the results – particularly the significance of northwest upslope flow and Miller A cyclones – are broadly representative of the entire North Carolina/Tennessee border region. Understanding the synoptic patterns that produce snowfall across the GSMNP and associated snowfall distribution will be very useful information for the area forecasters. The paper also provides a clearer picture of the significant contribution of low-level northwest flow to mean annual snowfall totals across the GSMNP.

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