The Influence of the Great Lakes on Snowfall Patterns in the Southern Appalachians

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ABSTRACT

Low-level moisture from the Great Lakes is occasionally advected as far south as the Southern Appalachian Mountains in periods of northwest flow, enhancing snowfall on windward slopes and at higher elevations. Although several cases of enhanced snowfall resulting from favorable air trajectories have been documented, considerable uncertainty remains as to their climatology and associated influence on snowfall patterns in the region. This paper assesses the influence of low-level moisture from the Great Lakes on snowfall patterns in the Southern Appalachians through backward air trajectory analyses of northwest flow snowfall events. Hourly observations from first order stations and daily snowfall data from cooperative observer stations are used to define snowfall events. NCEP reanalysis data are utilized to identify northwest flow snowfall events on the basis of 850-hPa northwesterly flow (270 to 360 degrees) at event maturation hour. The NOAA Hysplit Trajectory Tool is used to calculate 72-hour backward air trajectories at the event maturation hour and the spatial patterns of snowfall are analyzed and mapped with a GIS.

Key Words: Great Lakes, northwest flow snowfall, Southern Appalachians

INTRODUCTION

Abundant low-level moisture in association with periods of northwest flow occurs frequently in the Southern Appalachian Mountains from the late fall through the spring. As the low-level moisture encounters the northwestern slopes of the mountains, orographic lifting often produces periods of accumulating snowfall (**Fig. 1**). Schmidlin (1992) and Perry and Konrad (2004) have shown that at least 25–30 percent of average annual snowfall in parts of the Southern and Central Appalachians occurs in conjunction with low-level northwest flow. Johnson (1987) has also suggested that much of the snow that accumulates in periods of northwest flow in the Southern Appalachians has a Great Lakes Connection (GLC). The influence of the Great Lakes on available low-level moisture during periods of northwest flow snowfall (NWFS), however, remains unclear. Several cases of enhanced snowfall resulting from favorable air trajectories over the Great Lakes have been documented in the Southern Appalachians, but little is known about this climatology or the influence on snowfall patterns across the region.

Low-level moisture increases substantially as a result of sensible and latent heat fluxes that develop when cold air flows across the relatively warm waters of the Great Lakes in the late fall and winter months (Niziol et al. 1995). This low-level moisture, along with the destabilization of the lower troposphere, generates lake-effect snowfall on the leeward shores and immediately downwind of the Great Lakes. Even modest topographic rises of 100 m downwind of the lakes can

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generate additional lifting through orographic forcing, resulting in dramatic increases in snowfall (Niziol et al. 1995, Hjelmfelt 1992). Under favorable synoptic patterns, lake-effect snowfall may extend considerable distances downwind, even as far away as the northern mountains of West Virginia (Schmidlin 1992, Kocin and Uccellini 1990). It is quite plausible, under the right conditions, for the even higher terrain of the Southern Appalachians to extract residual low-level moisture from the Great Lakes via orographic processes to produce accumulating snowfall.

This paper strives to improve our understanding of the influence of the Great Lakes on snowfall patterns in the Southern Appalachians with three major research objectives: 1) conduct a backward air trajectory analysis for a sample of NWFS events, 2) compare composite mean and max snowfall totals between non-GLC events and GLC events, and 3) compare synoptic fields between the two groups of events.

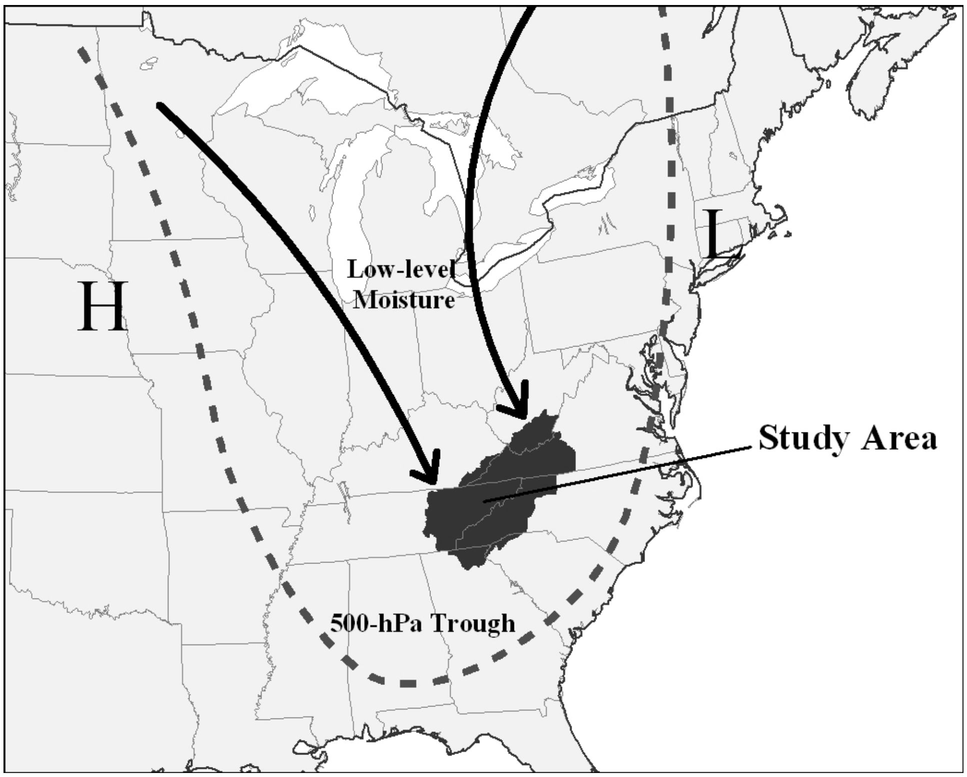


Figure 1. Synoptic ingredients associated with Northwest Flow Snowfall (NWFS) in the Southern Appalachians.

DATA AND METHODS

Daily snowfall records for the period: 1975 to 2000 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 121 cooperative observer stations in the Southern Appalachian Mountains (**Fig. 2**). We defined a snowfall event as having occurred if at least one coop station in the region reported snow accumulation on a given date. To improve the temporal resolution of each event, we then referenced hourly surface observation summaries from five nearby first order stations (**Fig. 2**). 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 hour in which the spatial extent of snowfall was greatest across the network of 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 five first order stations for more than six hours, we defined the event as having ended at the hour precipitation was last reported.

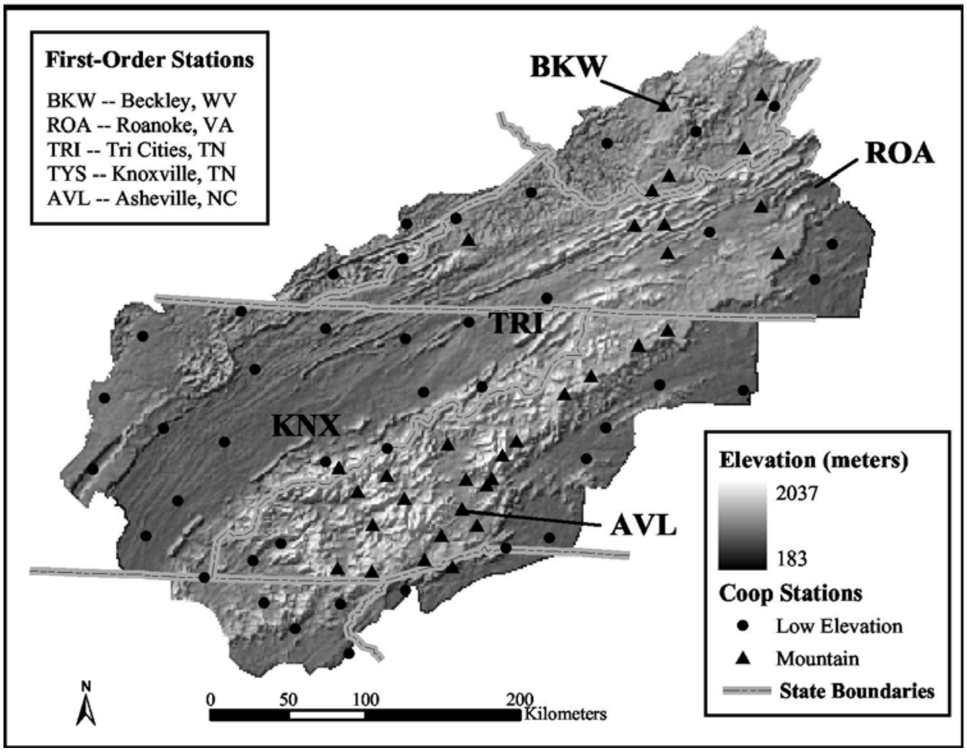


Figure 2. Coop and first-order stations in the Southern Appalachians.

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 (Kalnay et al. 1996) to obtain the u and v components of 850 hPa wind direction and vertical velocity. These fields were spatially interpolated to the center of each snowfall event. 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. Using these spatially and temporally interpolated data, we identified 432 NWFS events during this period on the basis of northwesterly (270 to 360 degrees) 850 hPa wind direction at maturation hour. The 850-mb level, found at approximately 1,500 m, is a good indication of the mean wind direction between 1,000 and 2,000 m, where much of the orographic enhancement in association with NWFS likely occurs. We further narrowed this sample of 432 NWFS events by identifying only those events with synoptic-scale sinking motions (e.g. vertical velocity > 0) with durations between two and three days. Events with rising motions were eliminated because a portion of the precipitation may be tied to synoptic features (e.g. approaching troughs) that operate independent of any lake influence. Exceptionally short and long events were also eliminated from the sample to control for event duration. We also excluded events in the months of April and May due to the important role convectional lifting plays in springtime snowfall in the region. The remaining 191 NWFS events served as the sample for the backward air trajectory analysis.

The NOAA Hysplit Trajectory Tool (http://www.arl.noaa.gov/ready/hysplit4.html) was utilized to calculate 72-hour backward air trajectories for air parcels at 1450 m, or approximately the 850 hPa level. The Hysplit Trajectory Tool uses u and v components of the horizontal wind, temperature, height, and pressure at different levels of the atmosphere to calculate the backward trajectories (Draxler and Hess 1998). We used the weighted spatial mean or centroid of each event and the event maturation time as the starting point and time for the backward air trajectory analysis. A visual analysis of the computed trajectory allowed us to classify each six-hour segment according to a trajectory classification grid developed for this project (**Fig. 3**). The Great Lakes (grids 3a and 3b) are roughly divided into the western lakes of Superior and Michigan and the eastern lakes of Huron and Erie; Lake Ontario is not specifically included in this study due to its location to the north-northeast of the study area. Since the classification grids for the western and eastern Great Lakes are the same spatial dimensions, it is possible to make direct comparisons between the two. The limited spatial resolution of the NCEP reanalysis data used to compute the backward air trajectories also supports using a more generalized classification grid, and not focusing on the precise lake-water boundary. Additionally, the concept of the lake-aggregate effect as recognized by Sousounis and Mann (2000), among others, suggests that the combined influence of the Great Lakes moistens the lower troposphere and lowers surface pressures across the Great Lakes region, and not just over or immediately downwind of individual lakes.

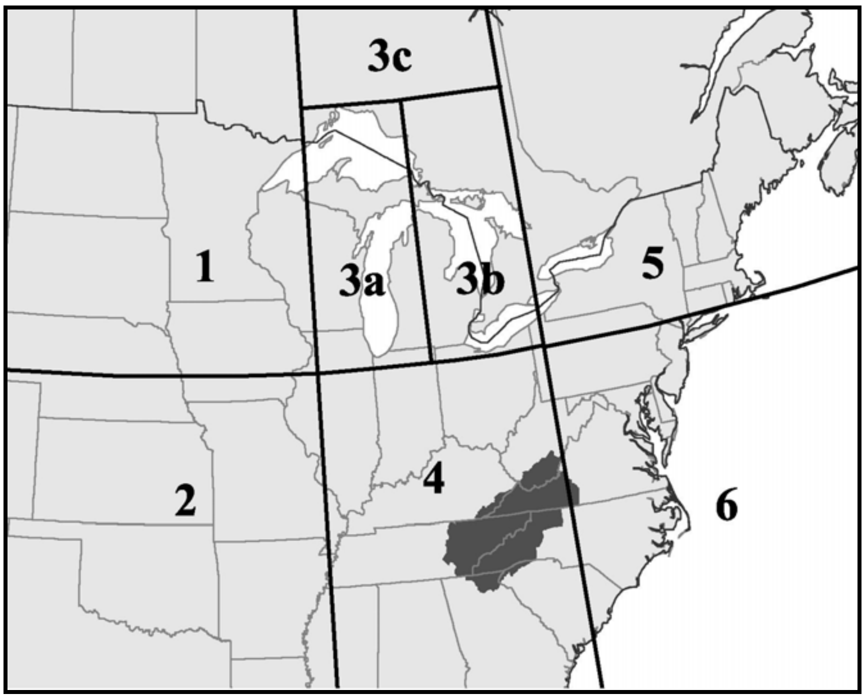


Figure 3. Trajectory classification grid.

We saved the latitude and longitude hourly coordinates associated with each backward air trajectory and computed composite values of each according to the trajectory classification scheme presented in the following section. The composite latitude and longitude coordinates for each trajectory class were then imported into a GIS for visualization purposes. For each event with a GLC (≥ 6 hours of the trajectory in trajectory grids 3a or 3b) we consulted the Great Lakes Ice Atlas DVD (Assel 2003) and noted the percent ice cover for the western and eastern Great Lakes. Lastly, we used NCEP reanalysis data (Kalnay et al. 1996) to develop composite plots of 1000 hPa height for each trajectory class.

RESULTS

Table 1 summarizes the results of the trajectory classification. The most common air trajectory associated with NWFS in the Southern Appalachians is trajectory Class 3a, followed closely by Class 1. Interestingly, almost half (47.1%) of the 191 NWFS events analyzed in this study exhibit a GLC and approximately three-quarters (73.8%) of the events display a northwesterly trajectory. Of the events with a northwesterly trajectory (Trajectory Class 1, 3a, 3b, and 3), a much higher percent (63.8%) exhibit a GLC influence than for the entire sample. Trajectory Class 2, 4, and 5 together formed 26.2 percent of the sample, but were not included for further analysis due to the absence of a prolonged northwesterly trajectory. In addition, the excluded trajectory classes are characterized by a wide range of trajectories and synoptic patterns, precluding meaningful comparisons. Therefore, for the purposes of this study, we only analyzed events with a northwesterly trajectory, comparing trajectory Class 1 (no GLC) with trajectory Class 3a, 3b, and 3 (GLC). The number of NWFS events with a GLC display maxima in the months of November, December, and February, with the percentages highest in October and November (**Fig. 4**). More significantly, the vast majority of NWFS events in October and November display a GLC.

Table 1. Summary of backward air trajectory analysis:
Percent of events and description for each trajectory class.

Class	Percent	Description
1	26.7%	≥36 hrs in Region 1, No GLC
2	7.9%	≥36 hrs in Region 2, No GLC
3a	30.9%	≥6 hrs in Western Great Lakes
3b	5.2%	≥6 hrs in Eastern Great Lakes
3	11.0%	≥6 hrs in both W and E Great Lakes
4	8.4%	≥36 hrs in Region 4, No GLC, <36 hrs in either 1 or 2
5	9.9%	Remainder

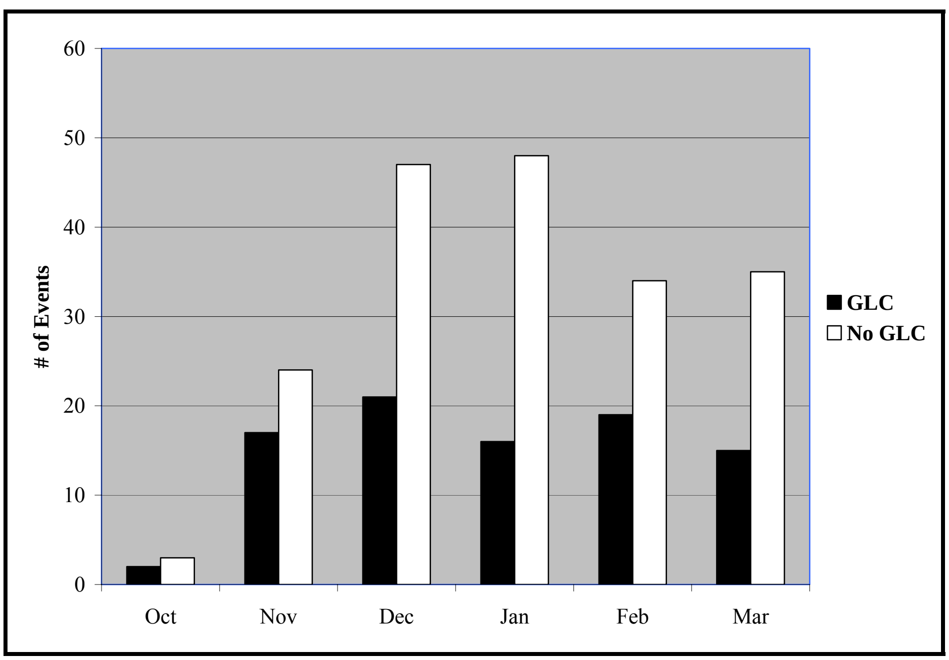


Figure 4. Number of NWFS events with a Great Lakes Connection (GLC) by month.

The composite trajectories and associated surface pressure patterns for trajectory Class 1, 3a, and 3b (**Fig. 5**) highlight several interesting findings. Composite mean and max snowfall totals are lowest for trajectory Class 1, slightly higher for Class 3a, and highest for Class 3b, suggesting a possible Great Lakes influence on snowfall totals. The composite trajectory for Class 3a just clips the southern portion of Lake Michigan, possibly resulting in diminished lake enhancement of snowfall totals. Cyclone tracks across the region have an important influence on the air trajectories. From these results, it appears that a more southerly location of the cyclone (e.g. off the mid-Atlantic coast) favors low-level airflow from the Great Lakes, whereas trajectories to the west of the Great Lakes normally occur when the synoptic-scale cyclone is farther to the north, or off the New England coast.

The spatial patterns of snowfall across the Southern Appalachians in association with different trajectories are best illustrated by comparing air trajectories for two samples of events: a) ones in which the highest totals occurred in the south (eastern Tennessee or western North Carolina) and b) ones in which the highest totals occurred in the north (southeastern West Virginia). When considerably more snow fell in the south, air trajectories for southern portions of the study area appeared to line up approximately with the long axis of Lake Michigan (**Fig. 6a**), whereas farther north air trajectories were much less favorable for lake interaction (e.g. across lower Michigan). For events in which the highest totals occurred in the north, air trajectories are most favorable for lake interaction in the northern portion of the study area (**Fig. 6b**). To the south, only trace amounts of snowfall in the higher elevations occurred in association with air trajectories well west of the western Great Lakes. Caution is advised in interpreting these particular results, however, due to the limited number ($n = 7$) of events for each sample.

Comparison of Trajectory Class 1 (no GLC) with trajectory classes 3, 3a, and 3b (GLC) suggests that trajectories with a GLC do in fact result in higher composite mean and max snowfall totals across the study area, with the influence the greatest in northwestern North Carolina and southeastern WV (Table 2). In both of these regions, the composite mean and max snowfall totals are significantly greater ($p < 0.05$) for events with a GLC, with the composite max approximately 2.0 cm greater. This increase in snowfall totals appears to be tied to higher values of moisture and humidity, particularly in the low levels (Table 3). This difference is most pronounced and statistically significant ($p < 0.05$) with 850 hPa relative humidity, suggesting that the relative

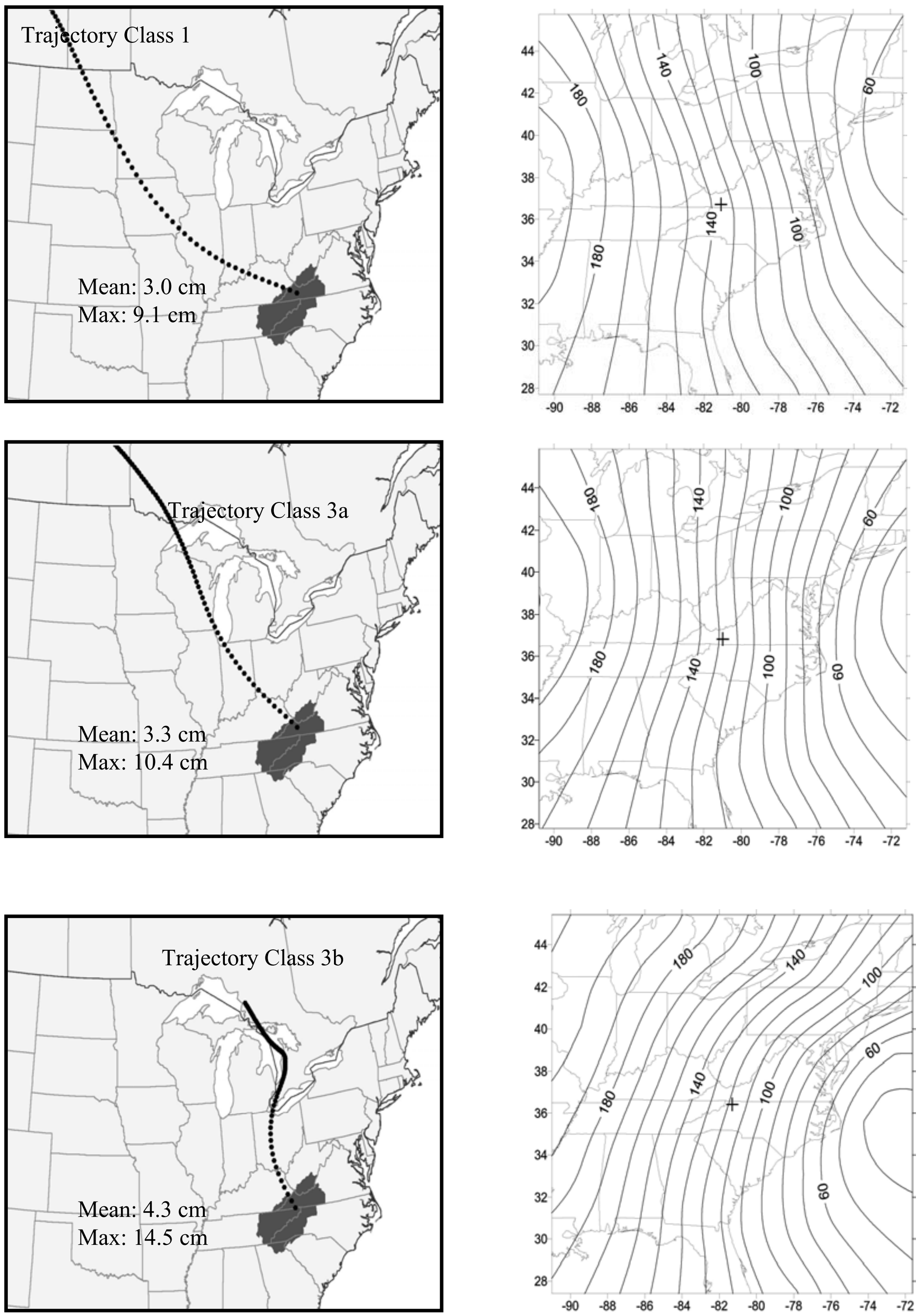
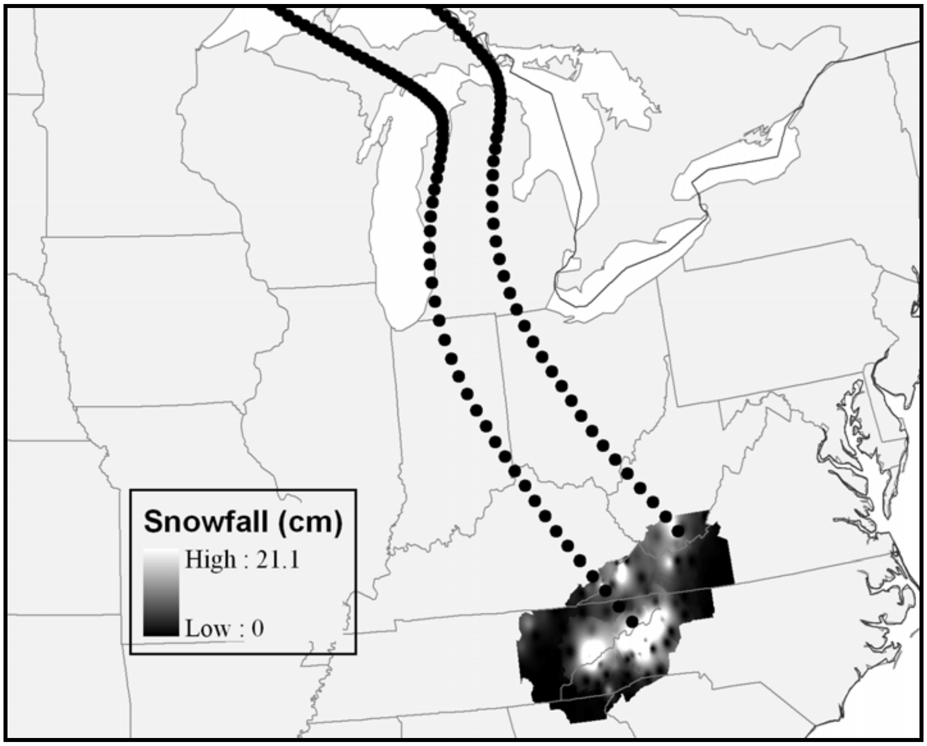


Figure 5. Composite trajectories (left) and 1000 hPa heights (right) for trajectory class 1 (top), trajectory class 3a (middle), and trajectory class 3b (bottom).



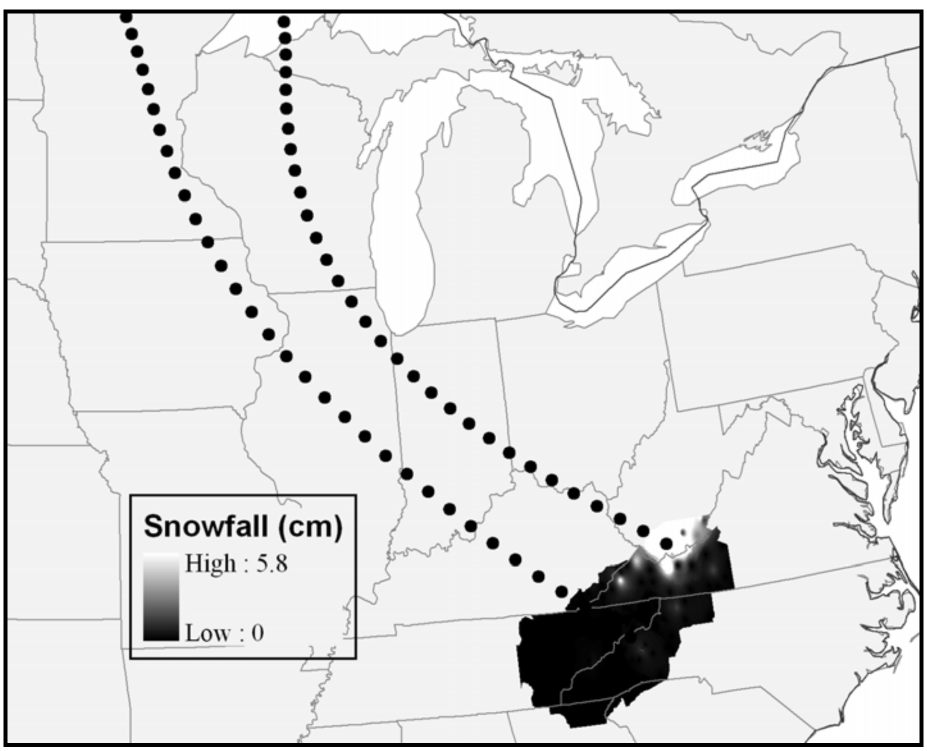


Figure 6. Composite trajectories for a sample of events with max snowfall in NC/TN (top) and southeastern WV (bottom).

humidity of air at 850 hPa for trajectories with a GLC is approximately 4.5 percent higher than no GLC. Interestingly, no significant differences in vertical velocity or 850 hPa temperature were noted. 850 hPa wind direction has a more northerly component for events with a GLC, which is not surprising given the location of the study area relative to the Great Lakes.

Other findings indicate that no significant difference exists in composite mean and max snowfall totals between events with percent ice cover in the top quartile (> 25%) and those in the bottom three quartiles (< 25%). This finding may be explained by the very small number of events in which percent ice cover was greater than 75 percent (n = 3 or 3.3%) or even 50 percent (n = 10 or 11.1%). In these cases, much of the ice cover likely existed on Lake Superior and northern portions of Lake Michigan, leading to a much less pronounced effect on sensible and latent heat fluxes and low-level moisture than would otherwise be expected. Additionally, the number of hours each trajectory spent over the lake classification grids had very little influence on composite mean or max snowfall totals.

Table 2. Composite snowfall values for trajectory class 1 vs. trajectories with a GLC.

Variable	Class 1	GLC	ABS_DIF	REL_DIF	T-SCORE	$p < 0.05$
Overall mean	3.0	3.6	0.5	0.25	1.50	
Overall max	9.1	11.0	1.9	0.20	1.14	
NW NC mean	2.3	3.1	0.9	0.30	***1.90***	*
NW NC max	3.6	5.4	1.8	0.28	***1.76***	*
SE WV mean	3.4	4.3	0.9	0.30	***1.80***	*
SE WV max	6.0	8.1	2.1	0.34	***2.12***	*

Table 3. Composite values of selected synoptic fields for trajectory class 1 vs. trajectories with a GLC.

Variable	No GLC	GLC	T-SCORE	$p < 0.05$
850 hPa Wind Direction	300.5	306.23	***1.89***	*
Vertical Velocity	20.4	21.4	0.50	
1000–500 hPa Thickness	5257	5266	0.70	
850 hPa Mixing Ratio	1.82	1.95	1.08	
Precipitable Water	0.23	0.25	1.58	
500 hPa Relative Humidity	29.6	30.8	0.56	
850 hPa Relative Humidity	74.5	78.8	***1.85***	*
850 hPa Wind Speed	14.4	13.7	–1.13	
850 hPa Temperature	263.9	264.4	0.67	

SUMMARY AND CONCLUSIONS

Our findings indicate that 47.1 percent of a sample of NWFS events selected from the period 1975–2000 exhibit a GLC, with slightly higher percentages in the northern portion of the study area (southeastern WV) and slightly lower in the southern portions (eastern TN/western NC). Even more significant, 63.8 percent of a sample of NWFS events with northwesterly trajectories exhibits a GLC. In these events, the backward air parcel trajectories were present for at least six hours in the western and/or eastern Great Lakes trajectory classification grids. Trajectories extending from the western Great Lakes are much more common than those that cross the eastern Great Lakes, although composite mean and max snowfall totals for these events are significantly greater for the latter. The spatial patterns of snowfall are strongly influenced by air parcel trajectories in some situations, although further analysis with a larger sample of events is needed for conclusive results. However, from the small sample analyzed in this study, it is evident that composite mean and max snowfall totals are higher when air trajectories with a GLC exist. A distinct monthly pattern in events with a GLC is also apparent, with the late fall months of October and November displaying the highest percentages. It is in these months that the difference between the average water temperature of the lakes and the average air temperature is the greatest, producing the largest sensible and latent heat fluxes (Niziol et al. 1995).

Air parcel trajectories with a GLC result in significant increases ($p < 0.05$) in composite mean and max snowfall totals for the higher terrain of the Southern Appalachians when compared with other northwesterly trajectories that pass well west of the western Great Lakes. Interestingly, the increase in snowfall totals is not significant at lower elevations in the study area, perhaps indicating the importance of topography in forcing the lift to extract the low-level moisture. These results therefore suggest that the Great Lakes do in fact influence snowfall totals under favorable air parcel trajectories in certain portions of the Southern Appalachians. The results of a synoptic analysis allow us to conclude that Great Lakes' trajectories are associated with higher values of lower tropospheric moisture and humidity, particularly relative humidity at 850 hPa. No significant differences in other synoptic fields between the two groups of events were noted, including vertical velocity.

Our ongoing and future work includes developing a better understanding of the differences between heavy vs. light NWFS events in the Southern Appalachians. Although this paper suggests that air parcel trajectories may play a role enhancing snowfall, it is not clear how important air parcel trajectory is for heavy NWFS. Analyses of vertical profiles of moisture and temperature may provide additional information on variables such as the depth of the moist layer and height of the capping inversion associated with different air trajectories. The height of the capping inversion, in particular, could be an important piece of the puzzle, as previous work (e.g. Lackmann, 2001, Niziol 1989) has shown it to be a major control on lake-effect snow events in the vicinity of the Great Lakes. Lastly, analysis of backward air trajectories at different stages of an event (e.g. T-12 hrs, maturation, T+12 hrs) will help in better understanding the evolution of events with a GLC and how trajectories may change over the course of an event.

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