Relationships between Northwest Flow Snowfall and Topography in the Southern Appalachians

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Abstract

This paper analyzes the relationships between northwest flow snowfall (NWFS) and various topographic and geographic (TOPO/GEOG) variables in the Southern Appalachian Mountains of the southeastern U.S. We identify NWFS events on the basis of low-level wind direction, extract values for the TOPO/GEOG variables from Digital Elevation Models (DEMs), and develop statistical relationships between NWFS and the TOPO/GEOG variables. Results indicate that elevation and northwest exposure are most strongly correlated with NWFS; however, the strength of these relationships is mediated by temperature. We conclude that relationships between snowfall and topography are strengthened when event snowfall totals are explicitly linked to a low-level wind direction and associated synoptic pattern.

Keywords: Topographic influences, northwest flow snowfall, Southern Appalachians

Introduction

Precipitation patterns in mountainous regions are highly complex and strongly influenced by the interaction of the topography and atmospheric circulation through orographic lifting and rainshadow effects. This is particularly the case with snowfall, where the importance of temperature on snow accumulation further magnifies the influence of elevation. The complexity of these spatial patterns of snowfall is not always evident due to the sparse network of precipitation stations in many mountainous regions and their bias towards low-elevation sites. Previous attempts to better understand the relationships between precipitation and topography have used a variety of approaches, from simple linear regression models to physical-dynamical mathematical models of the atmosphere. The need for more accurate, spatially continuous estimates of snowfall is increasing in hydrological modeling in regions where snowmelt is of hydrological and societal importance. Most estimates of snowfall and snowmelt haven been calculated from average annual or monthly precipitation data, which represents the combined effects of many different synoptic patterns of atmospheric circulation. Therefore, a significant need remains to improve the general understanding of the relationships between snowfall patterns and topographic characteristics for low-level wind directions associated with different synoptic patterns in mountainous regions.

This paper develops statistical relationships between northwest flow snowfall (NWFS) and 17 different topographic and geographic (TOPO/GEOG) variables in the Southern Appalachian Mountains of the southeastern U.S. In particular, three research questions serve to guide the paper: 1) what are the statistical relationships between NWFS and TOPO/GEOG variables; 2) how do these relationships vary between different types of NWFS events; and 3) which TOPO/GEOG variables together account for the greatest variance in snowfall totals? The paper also uses map algebra techniques in a GIS to illustrate the spatial patterns of NWFS. Through this methodology, relationships between snowfall and topography are therefore strengthened. Following this brief introduction, a background section discusses previous attempts to model or spatially interpolate precipitation and snowfall in mountainous regions. A brief overview of the synoptic patterns associated with NWFS and the topography in the Southern Appalachians is next, followed by a section on data and methods. The paper continues with sections summarizing and discussing the significance of the results, and ends with a summary and conclusions.

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Background

Precipitation amounts generally increase with elevation in the middle latitudes due to orographic effects as air is forced to rise up a mountain barrier (Barry 1992, Basist, Bell, and Meentemeyer 1994). Most of this enhancement occurs via the seeder-feeder effect, whereby synoptic-scale precipitation falling from middle and high-level seeder clouds grows in size through scavenging of cloud droplets from the low-level feeder clouds produced by upslope orographic flow. In a warm atmosphere with low-level cloud temperatures above 0º C, falling raindrops grow via enhanced collision-coalescence processes in the feeder cloud, whereas at temperatures below 0º C, falling snow crystals grow via riming, or the freezing of supercooled water droplets (Pruppacher and Klett 1997). Snow crystals, due to their lower fall speeds and larger surface area, are much more effective scavengers of low-level moisture from the feeder clouds than raindrops (Choularton and Perry 1986). For this reason, previous theoretical work (i.e. studies) has suggested that orographic effects on windward slopes and at higher elevations are even more pronounced for snow than for rain. Since the low-level feeder cloud is more effectively scavenged by falling snow crystals, significantly less low-level moisture is available on leeward slopes and at lower elevations, resulting in more pronounced shadowing effects as well (Choularton and Perry 1986, Dore et al. 1992). Due to these shadowing effects in response to scavenging of low-level moisture, the relationship between precipitation and elevation is not as straightforward, as exposure to moist low-level winds and the locations of upwind blocking barriers are important influences that in many cases weaken this relationship. Consequently, most studies investigating precipitation relationships in mountains have included elevation plus additional topographic variables such as exposure, slope, and distance to windward slope.

One approach for understanding precipitation-topography relationships has been the development of high resolution physical-dynamical mathematical models of precipitation processes for particular mountain areas (Abbs and Pielke 1987, Oki, Musiake, and Koike 1991, Katzfey 1995, Farley, Hjermstad, and Orville 2000, Poulos et al. 2002). In these numerical models, the topographic variables of elevation and exposure have a strong influence on the modeled spatial patterns of precipitation. The physical interactions among atmospheric circulation, moisture, and topography are not well understood, however, limiting the utility of these numerical models. The results of numerical modeling are very sensitive to initial conditions, which are challenging to measure in mountainous regions where the station network is often sparse. Furthermore, significant computing resources are needed to run the models with a digital elevation model (DEM) of sufficient spatial resolution to adequately capture the meso- and micro-scale nature of the orographic processes.

An alternative approach is to establish statistical relationships between precipitation and topographic characteristics using climatological precipitation data from a sample of stations representing a variety of topographic characteristics. This approach relies on a regression model with topographic variables (i.e. elevation, exposure, slope) as the independent variables and precipitation as the dependent variable. The multivariate regression model then allows precipitation values to be estimated using known values of the topographic variables for other locations. Donley and Mitchell (1939), for example, found a positive linear relationship between elevation and precipitation in the Southern Appalachians, although the slopes of the above varied considerably with the region. Also in the Southern Appalachians, Smallshaw (1953) reported a linear relationship between precipitation and elevation, but found that precipitation totals actually decreased at the top of some steep narrow ridges (i.e. Snake Mountain) due to wind effects.

In the Cascades of western Washington and Oregon, Schermerhorn (1967) showed a curvi-linear relationship between precipitation and elevation, but also stressed the importance of upwind blocking barriers and the large-scale topography in controlling precipitation patterns. For example, in the prevailing westerly flow across the Pacific Northwest, the Olympic Mountains serve as an important upwind blocking barrier for areas to the east, such as Puget Sound and Seattle, by reducing the precipitable moisture. Precipitation amounts can also be considerably enhanced at low elevation stations in close proximity to high elevation peaks due to the enhanced orographic effect. In a watershed in Nevada, Havesi, Istok, and Flint (1992) used elevation as the sole independent variable to estimate average annual precipitation using multivariate geostatistics and found cokriging, a method in which kriging is associated with elevation, to provide the best results. Basist, Bell, and Meentemeyer (1994) developed statistical relationships between precipitation and topographic characteristics in ten different mountainous regions ranging from equatorial to marine west coast and found the combined effects of elevation and exposure to the prevailing wind are the most important factors influencing precipitation. In addition, they found that topographic influences explained much greater variability of average annual precipitation in the middle-latitude mountainous regions than in the equatorial regions. No previous work using these approaches that we are familiar with, however, has used snowfall as the dependent variable.

Numerous recent studies have coupled the statistical approach described above with the spatial analytical capabilities of GIS to assess the relationships between precipitation and topography (Daly, Neilson, and Phillips

1994, Martínez-Cob 1996, Goovaerts 2000, Ninyerola, Pons, and Roure 2000, Weisse and Bois 2001, Marquínez, Lastra, and García 2003). Values for the different topographic variables are first extracted from raster grids developed in a GIS. Statistical relationships between precipitation totals and the various values taken from the raster grids are then developed. Lastly, average annual precipitation totals are estimated for each grid cell using a multivariate regression model and map algebra techniques. Such approaches improve upon traditional geostatistical procedures for precipitation analysis in mountainous regions (i.e. Phillips, Dolph, and Marks 1992) by incorporating various topographic variables to create a spatially continuous map of precipitation. Due to the sparse network of precipitation stations in mountainous regions and the inherent challenges of adequately conveying the spatial variability and complexity of precipitation patterns, these GIS approaches have created more accurate and detailed precipitation maps for climate atlases. Once again, however, no work that we are familiar with has developed statistical relationships in conjunction with GIS techniques to assess the relationships between snowfall and different topographic characteristics in mountainous regions. Perhaps it has been done implicitly, by modeling monthly and annual precipitation in areas where the vast majority falls in the form of snow.

The most significant limitation of the reviewed approaches is the use of average annual or average monthly values of precipitation. Precipitation totals over a monthly or annual time scale generally result from a variety of synoptic patterns and associated low-level wind directions. Southeasterly low-level flow may predominate in some events, whereas other events may be characterized by northwesterly low-level flow. The physical processes responsible for precipitation development and enhancement will therefore be quite different among synoptic patterns, as will the locations of windward and leeward slopes. The relationships between precipitation and topographic characteristics other than elevation are therefore weakened. Only a handful of studies that we are familiar with investigate relationships between precipitation and topographic characteristics by low-level wind direction and associated synoptic pattern. Houghton (1979) analyzed precipitation-topography relationships in the Great Basin of the western U.S. by using mean monthly wind direction at the 700 hPa level. His work, however, did not consider wind at the event scale and the associated variability of synoptic patterns within a month. Hill (1983) calculated the average annual orographic enhancement of precipitation by low-level wind direction in England and Wales and plotted maps of the results. Lastly, Konrad (1995, 1996) analyzed relationships between precipitation event type and topography in part of the Southern Appalachians in the southeastern U.S. and found major differences in the strength of the relationships for different low-level wind directions.

This paper builds on the approaches discussed in the preceding paragraphs by developing statistical relationships between precipitation and topographic characteristics in the Southern Appalachians, and makes a significant contribution to this body of literature by 1) focusing specifically on snowfall, 2) linking event snowfall totals with a particular low-level wind direction and associated synoptic pattern, and 3) using GIS techniques to develop raster grids of the topographic variables and produce snowfall maps by event type.

Study Area

The study area is the Southern Appalachian Mountains (**Fig. 1**), including areas from northern Georgia to southern West Virginia, along with the Cumberland Plateau in the west and the Blue Ridge foothills in the east. The study area trends southwest to northeast, capturing the general orientation of the topography. The highest elevations and associated greatest relief are found in the mountains of Tennessee and North Carolina, where, for example, the Great Smoky Mountains rise from less than 500 m (1,404 ft) to over 2,000 m (6,562 ft). Elevations above 1,850 m (6,070 ft), in fact, are confined to the Great Smoky Mountains (NC/TN), Balsam Mountains (NC), Black Mountains (NC), and the Unaka Mountains (NC/TN), whereas 1,500-m (4,921 ft) elevations extend into southwestern Virginia and northern Georgia. Elevated terrain extends northward along the spine of the Appalachians through Virginia and West Virginia, but elevations remain below 1,500 m (4,921 ft). The Cumberland Plateau in Tennessee and Cumberland Mountains extending northeastward through eastern Kentucky and extreme southwestern Virginia is characterized by maximum elevations above 1,000 m (3,280 ft), but less than 1,500 m (4,921 ft). The Blue Ridge of North Carolina and Virginia rises abruptly from the adjacent foothills to the southeast, but elevations generally range between 1,000 and 1,500 m (3,280 to 4,921 ft), although Grandfather Mountain at 1,818 m (5,964 ft) is an exception. The Tennessee Valley is an expansive low elevation area in eastern Tennessee between the Cumberland Plateau and the North Carolina border. The New River Valley, somewhat higher in elevation than the Tennessee Valley, extends from southwestern Virginia into southern West Virginia.

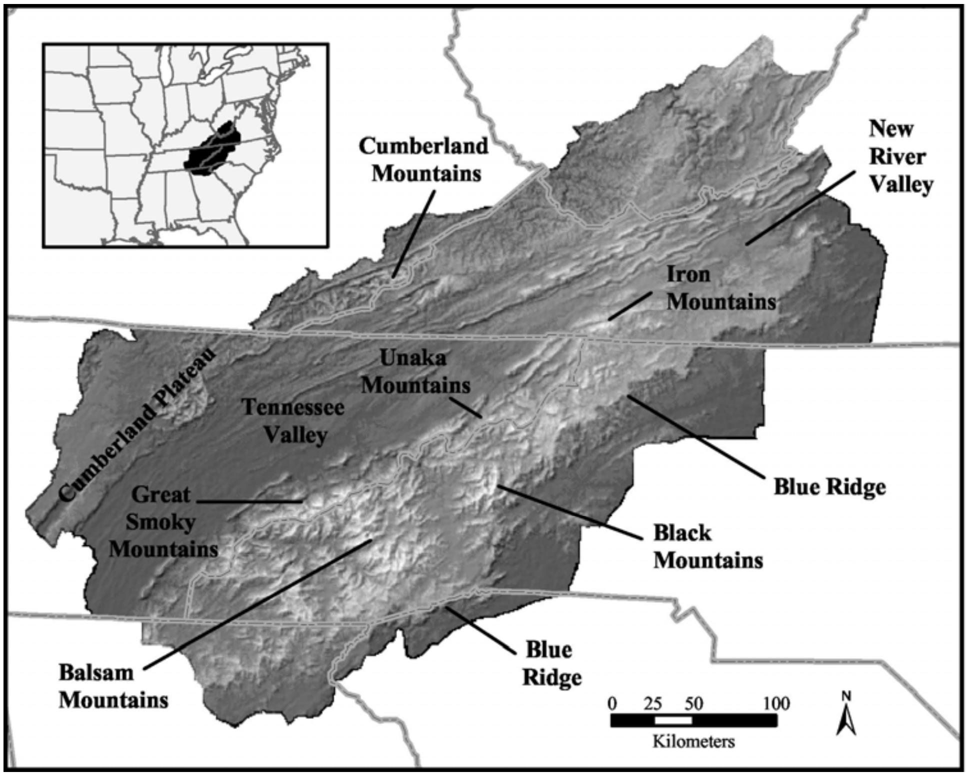

Figure 1. The study area and important topographic features.

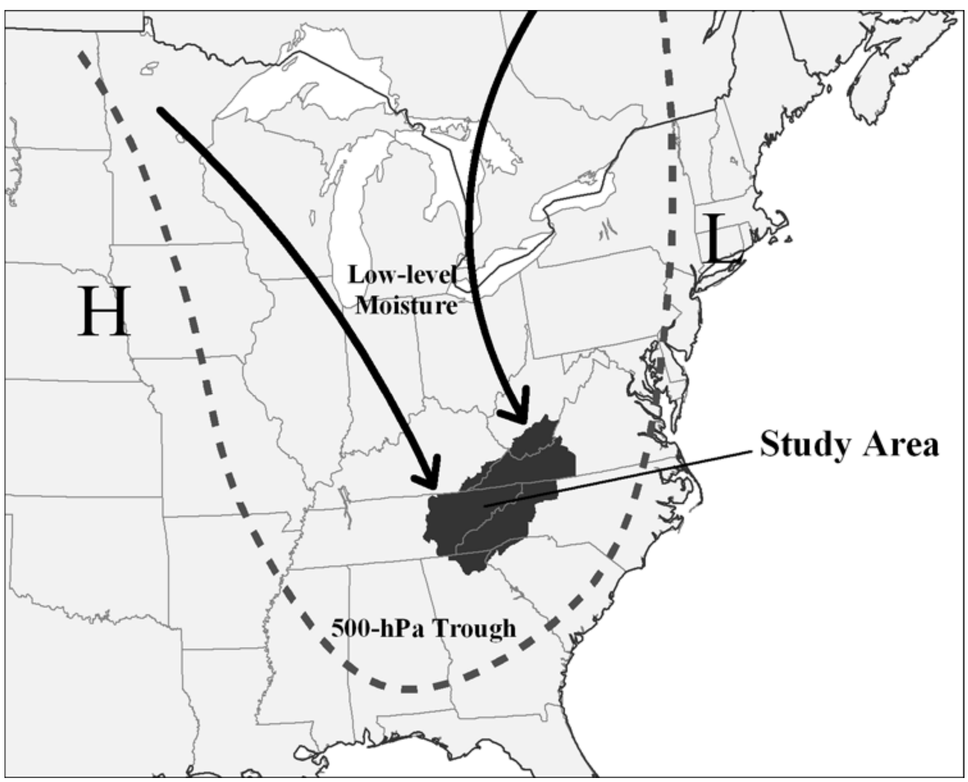

Figure 2. Typical synoptic pattern for NWFS.

Northwest Flow Snowfall

NWFS results when low-level northwesterly flow forces cold air to ascend the northwestern slopes of the Southern Appalachian Mountains. Periods of northwesterly flow typically occur in the wake of a synoptic-scale surface cyclone and cold frontal system, with a cold anticyclone upstream (**Fig. 2**). Due to the general southwest to northeast orientation of the Southern Appalachians, northwesterly low-level flow is close to perpendicular to the large-scale topography, producing ideal conditions for orographic lifting. Upslope flow is maximized on northwestern windward slopes, whereas downslope flow associated with warming and drying occurs on the southeastern leeward slopes (**Fig. 3**). Previous work has indicated that NWFS accounts for at least 25 to 30 percent of annual snowfall totals on higher elevation windward slopes in the region, and possibly quite more (Schmidlin 1992, Perry and Konrad 2004).

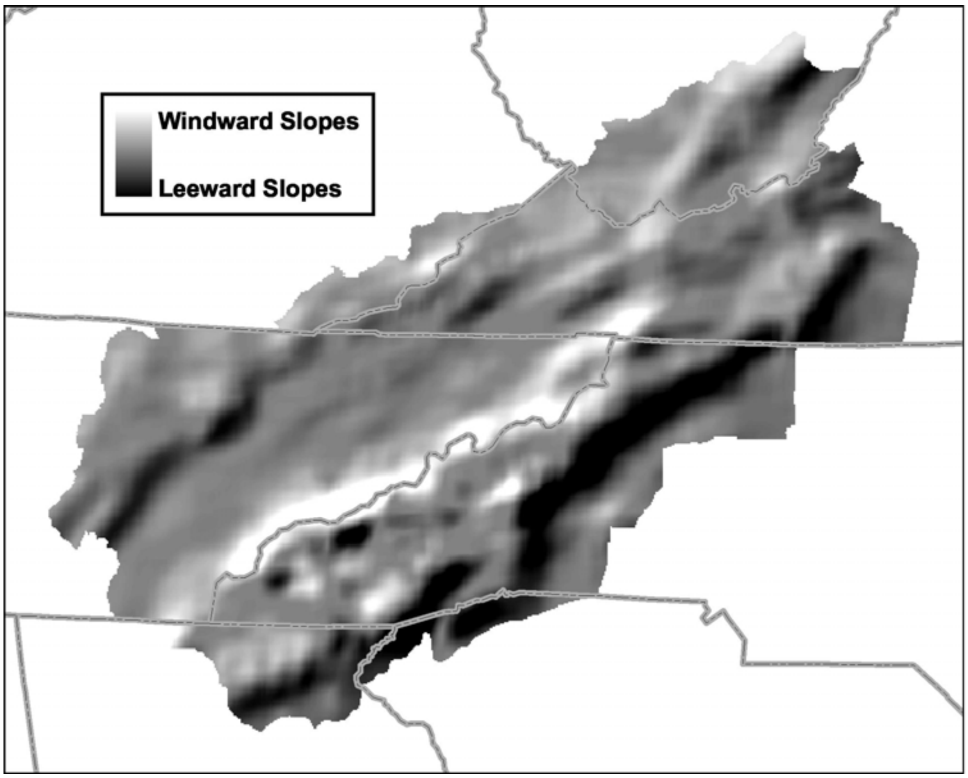

Figure 3. Locations of windward and leeward slopes during periods of northwest flow.

Data and Methods

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. 4**). 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.

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 surface temperature. 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 used an inverse distance technique to carry out all spatial and temporal interpolations. Using these spatially and temporally interpolated data, we identified 188 NWFS events from all of the snowfall events on the basis of northwesterly (270 to 360 degrees) 850 hPa wind direction at maturation hour. The 850-hPa level, found at approximately 1,500 m (4,921 ft), is a good indication of the mean wind direction between 1,000 and 2,000 m

(3,280 to 6,562 ft), where much of the orographic enhancement in association with NWFS likely occurs. We further stratified the sample of NWFS events between cold (<2º C) and warm (>2º C) events using the NCEP reanalysis surface temperature field at event maturation hour, which yielded 84 cold and 104 warm events. Preliminary work showed that the influence of elevation on temperature overwhelmed the role of exposure and the other topographic variables. The influence of the other topographic variables, therefore, may be strengthened when temperatures are cold enough for snow at nearly all elevations.

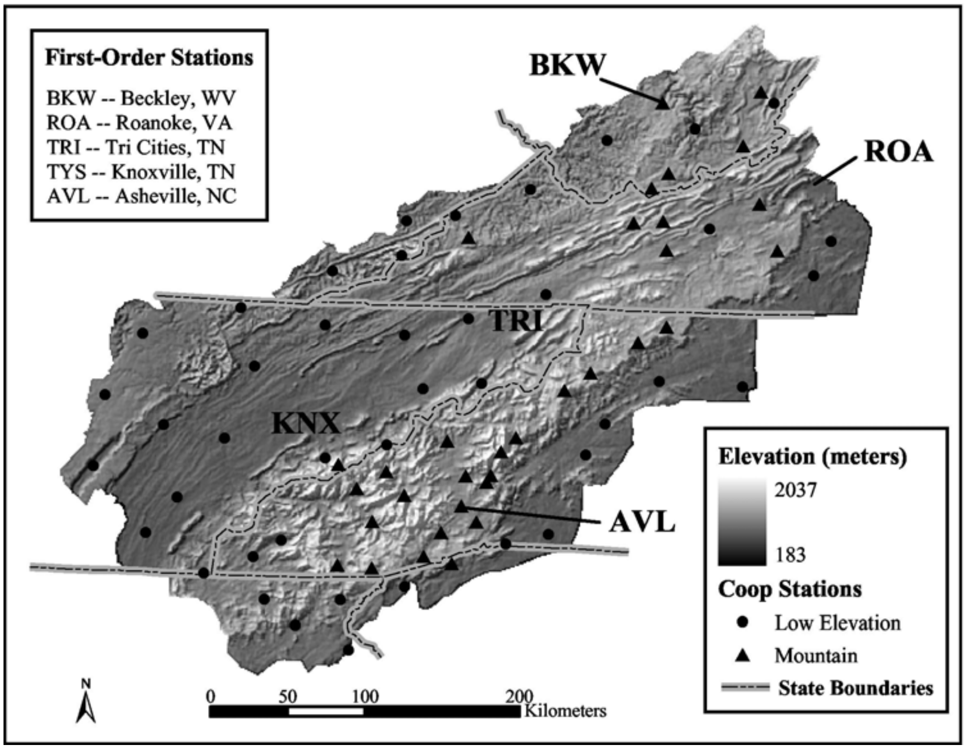

Figure 4. Topographic maps with weather stations used in the study.

The TOPO/GEOG variables (**Table 1**) used in this study were obtained from GIS raster grids at 1-km spatial resolution, except for the coop station point elevation values, which came from the coop station metadata (NCDC 2002). The original source for the topographic grids were the 1:250,000 scale digital elevation models (DEMs) from the United States Geological Survey (USGS 2004), which we resampled from approximately 90-m to 1-km spatial resolution. In addition to a 1-km elevation grid, we also developed standardized z-values for each 1-km grid cell and calculated the mean elevation for a 10-km^2 and 20-km^2 area centered on each grid cell (**Fig. 5**). Positive relationships have been identified between precipitation and elevation in the Southern Appalachians (Donley and Mitchell 1939, Smallshaw 1953, Konrad 1996) and in other mountainous regions (Barry 1992, Basist, Bell, and Meentemeyer 1994). Pedgley (1970) and Konrad (1996) further suggested that the ‘smoothed topography’ may actually be a better measure of the influence of elevation on precipitation.

The exposure to the northwest (EXPONW) grids (**Fig. 6**) were derived by subtracting the elevation of each 1-km grid cell from the elevation of the highest point within a specified radius (50, 100, or 150 km) to the northwest (270 to 360 degrees) and then standardizing these values. An example from two stations in the Great Smoky Mountains further illustrates this methodology. Oconaluftee, North Carolina, at 622 m (2,041 ft) elevation, is 1,357 m (4,452 ft) below the highest point to the northwest, thus yielding a highly negative z-value of -2.24 z (**Fig. 7**). On the other hand, Mt Leconte, Tennessee, at 1,979 m (6,493 ft) is the highest point in the region and therefore exhibits a positive z-value of 1.15 z. Konrad (1996) employed a similar technique to calculate exposure in his study of precipitation in the southern Blue Ridge, while Basist, Bell, and Meentemeyer (1994) also incorporated an exposure variable. These two previous studies defined exposure as the distance upwind to a blocking barrier 150 m (Konrad 1996) or 500 m (Basist, Bell, and Meentemeyer 1994) higher than the station. Our measure defines exposure on the basis of the elevation of the highest upwind blocking barrier within a specified distance, which we believe better captures the differing shadowing effects from upstream relief.

Table 1. Topographic and geographic variables analyzed in this study.

Variable	**Full Name**	**Units**
ELEV_pt	Station Elevation	Meters
ELEV01	1-km mean elevation	Meters
ELEV01_z	1-km mean elevation	Z-value
ELEV10	10-km mean elevation	Meters
ELEV20	20-km mean elevation	Meters
EXPONW_a	50-km exposure towards NW	Z-value
EXPONW_b	100-km exposure towards NW	Z-value
EXPONW_c	200-km exposure towards NW	Z-value
ELEVEXPONW_a	ELEV01_z + EXPONW_a	Z-value
ELEVEXPONW_b	ELEV01_z + EXPONW_b	Z-value
ELEVEXPONW_c	ELEV01_z + EXPONW_c	Z-value
DISNWSLOPE	Distance upwind to a NW slope	Kilometers
SLOPE01_10KNW	1-km mean slope at 10 km to NW	Z-value
SLOPE10_10KNW	10-km mean slope at 10 km to NW	Z-value
SLOPE20_10KNW	20-km mean slope at 10 km to NW	Z-value
LAT	Latitude	Decimal Degrees
LONG	Longitude	Decimal Degrees

We calculated the elevation plus exposure to the northwest (ELEVEXPONW) grids (**Fig. 6**) by adding together the standardized z-values of 1-km elevation (ELEV01) and exposure to the northwest (EXPONW). Utilizing the example in the preceding paragraph, the values are -1.41 z for Oconaluftee and 7.30 z for Mt. Leconte. The interaction of exposure and elevation is perhaps a better indicator of the potential for orographic lifting than just exposure or elevation along. For example, one location may be highly exposed but at too low an elevation for significant orographic lifting of air parcels. On the other hand, a high elevation station may be heavily shadowed by an even higher ridge upwind. A high elevation station that is highly exposed, however, is likely to experience maximum orographic enhancement of precipitation, and indeed this has been noted by previous studies (Houghton 1979, Basist, Bell, and Meentemeyer 1994, Konrad 1996).

Distance to a northwest slope (DISNWSLOPE) is a variable that attempts to capture the spillover effects of orographic snowfall. Previous work by Dore et al. (1992) indicates that snowflakes produced or enhanced through orographic lifting may travel considerable distances downwind of the windward slope depending on wind speed. Strong winds may actually displace the maximum snowfall some distance downwind of the windward slope before accumulating on the ground. Mt. Leconte is on a northwest slope and therefore has a value of 0 km, whereas Oconoluftee is 21.7 km downwind. Slope (SLOPE01_*) is a final topographic variable included in the analysis and again builds on previous work (Dore et al. 1992, Basist, Bell, and Meentemeyer 1994, Konrad 1996). As with elevation, the slope grids (**Fig. 5**) include measures of the smoothed topography, with a 10-km mean slope (SLOPE10_10KNW) and a 20-km mean slope (SLOPE20_10KNW) to the northwest. The exposure units are standardized, with steep northwesterly slopes having the highest values and steep southeasterly slopes the lowest. In situations of low-level northwesterly flow, terrain-induced rising motions are expected to be strongest where the northwesterly slopes are steepest (i.e. just upwind of Mt. Leconte). Conversely, terrain-induced subsidence is expected to be strongest on the steeper southeasterly slopes (i.e. just upwind of Oconoluftee).

We calculated correlation coefficients for average annual NWFS by event type and the TOPO/GEOG values. The TOPO/GEOG values other than ELEV_pt were extracted from the GIS grids and therefore represent the average value across the 1-km grid cell and may vary substantially from the actual point location of the coop station. Multivariate regression modeling was carried out in SPSS 13.0 (SPSS 2004) using a stepwise routine and the models selected for each event type included only those variables with regression slopes statistically significant at the p <

0.05 level. The model with the highest adjusted R^2 was not always chosen; rather, the simplest model (i.e. fewer independent variables) with a lower adjusted R^2 was frequently chosen over a more complex model (i.e. more independent variables). An analysis of the residuals for heteroscedasticity and autocorrelation supported original assumptions of the approximately linear relationships in the data. Lastly, the average annual NWFS map was produced by applying the multivariate regression model to the GIS grids of the independent variables using map algebra techniques in a GIS.

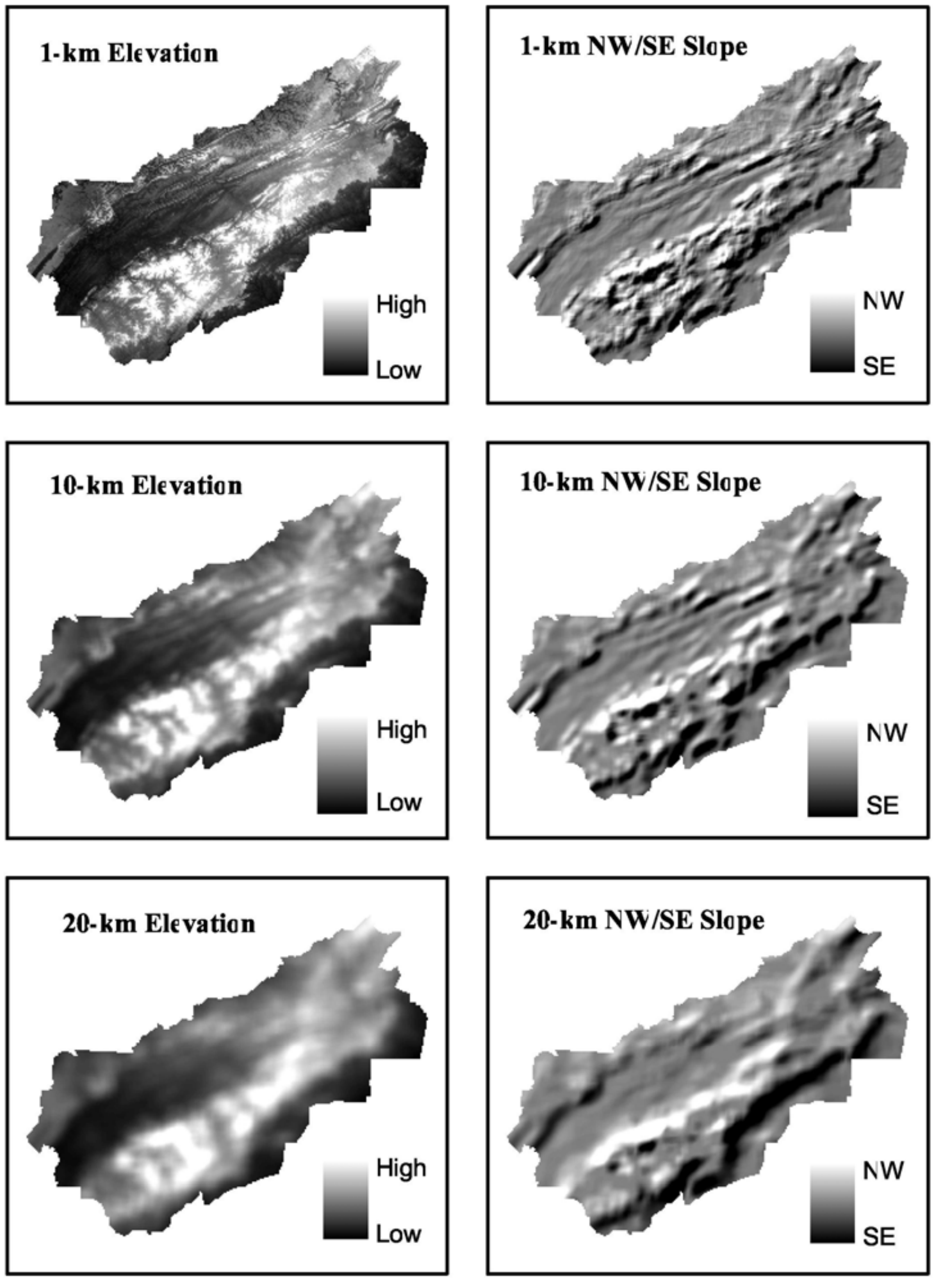

Figure 5. Maps of mean elevation and slope at 1-km, 10-km, and 20-km resolutions.

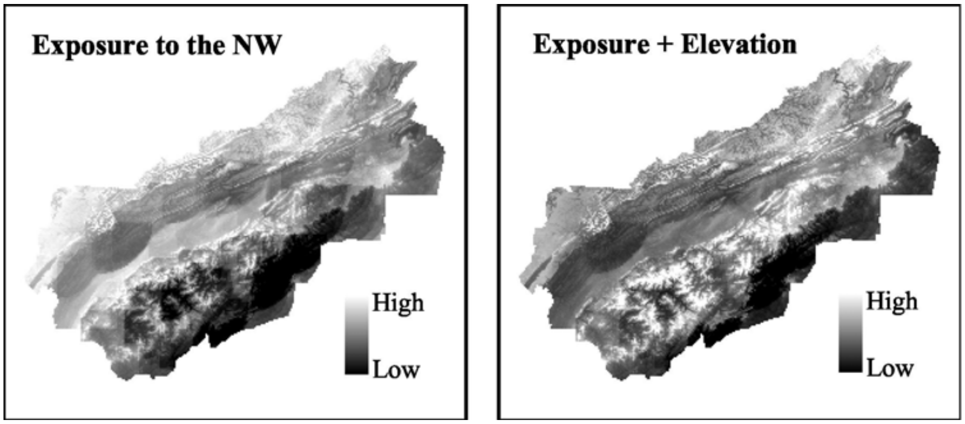

Figure 6. Maps of exposure and elevation plus exposure.

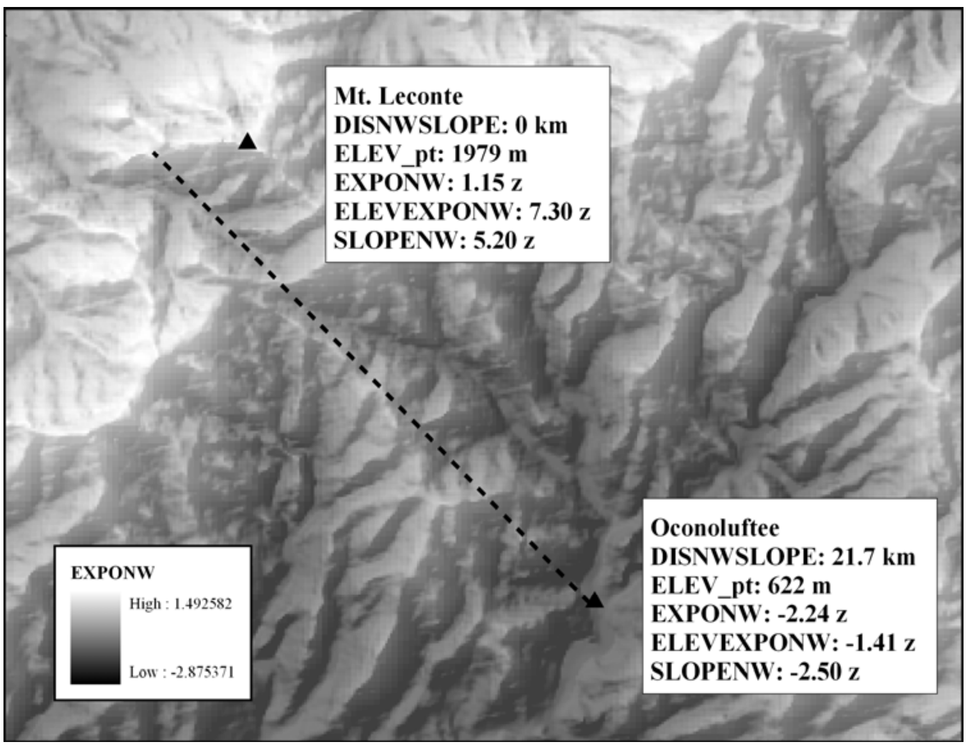

Figure 7. Exposure to the northwest (EXPONW) in the vicinity of the Great Smoky Mountains with topographic variables summarized for Mt. Leconte, Tennessee, and Oconoluftee, North Carolina. The distance and direction to the highest northwest slope from Oconoluftee is illustrated by the dashed line.

Results and Discussion

Correlation coefficients between each TOPO/GEOG variable and average annual NWFS for all stations, mountain stations, and low elevation stations are presented in **Table 2**. Point elevation displays the highest correlation coefficients for the elevation variables, with the smoothed topography yielding progressively lower coefficients. The low elevation stations are one exception, as 1-km mean elevation shows the highest correlation. Point elevation is likely tied to the strongest correlations because of the strong negative relationship between elevation and temperature. Higher elevations are more likely to be at or below freezing (0˚ C), thus encouraging the accumulation of snow. These results are in contrast to previous precipitation-topography studies, which found the strongest relationships between precipitation and the smoothed topography (Pedgley 1970, Konrad 1996). In this work, the majority of the precipitation in the lower elevations occurred as rain, thereby negating the importance of point elevation on precipitation type or accumulations. The remainder of the topographic variables display the highest correlation coefficients for the mountain stations, which is not surprising since the orographic effects are likely strongest where the relief is the greatest. Little variation in the correlation coefficients is noted for the different search radii (50, 100, or 150 km) for the exposure grids or the smoothed topography for the slope grids. The geographic variables of latitude and longitude, however, display higher correlation coefficients for the low elevation stations, suggesting the greater relative importance of synoptic-scale processes in influencing snowfall totals.

Table 2. Correlation coefficients between each variable and average annual NWFS.

Variable	All Stns	Mtn	Low Elev
ELEV_pt	0.75	0.71	0.45
ELEV01	0.69	0.60	0.70
ELEV10	0.58	0.47	0.43
ELEV20	0.47	0.31	0.35
EXPONW_a	0.54	0.78	0.55
EXPONW_b	0.56	0.81	0.56
EXPONW_c	0.56	0.82	0.56
ELEVEXPONW_a	0.82	0.84	0.64
ELEVEXPONW_b	0.83	0.86	0.65
ELEVEXPONW_c	0.83	0.84	0.65
DISNWSLOPE	-0.32	-0.55	-0.33
SLOPE01_10KNW	0.52	0.68	0.26
SLOPE10_10KNW	0.55	0.71	0.26
SLOPE20_10KNW	0.44	0.71	0.19
LAT	0.39	0.40	0.72
LONG	0.26	0.15	0.29

Table 3 also presents correlation coefficients between TOPO/GEOG variables and snowfall totals, but partitions NWFS events into cold (< 2º C) and warm (>2º C) events. The correlation coefficients for the elevation variables are considerably higher for the warm events than for the cold events, particularly for the mountain stations. In the cold events, temperatures are cold enough for snow at almost all elevations, and therefore topographic influences on precipitation rather than temperature are more pronounced. The correlation coefficients for the exposure variables are slightly higher in the cold events, consistent with a diminished influence of elevation as noted above. It is also possible that the stronger relationships between snowfall and exposure are a product of the cloud microphysical environment. Cloud temperatures are more likely to be in the optimal range for dendritic snow crystal growth (-14˚ to -17˚ C) in the cold events, suggesting a greater precipitation efficiency on the windward slopes. The seeder-feeder effect produced by orographic lifting is also maximized when dendritic snowflakes are present due to

their larger surface area and slower fall speeds (Dore et al. 1992, Whiteman 2000). Scavenging of supercooled liquid water from the low-level feeder clouds is therefore maximized, leaving substantially less low-level moisture for leeward locations downwind. The correlation coefficient for distance to a northwest slope is also slightly higher in the cold events, further supporting the importance of temperature on the cloud microphysical environment.

Table 3. Correlation coefficients between each variable and NWFS totals for warm vs. cold events.

	Cold Events			Warm Events		
Variable	**All Stns**	**Mtn**	**Low Elev**	**All Stns**	**Mtn**	**Low Elev**
ELEV_pt	0.68	0.61	0.42	0.79	0.78	0.49
ELEV01	0.64	0.50	0.68	0.70	0.67	0.68
ELEV10	0.54	0.39	0.41	0.58	0.54	0.43
ELEV20	0.45	0.24	0.34	0.48	0.38	0.36
EXPONW_a	0.56	0.77	0.56	0.49	0.75	0.46
EXPONW_b	0.59	0.82	0.57	0.50	0.77	0.49
EXPONW_c	0.60	0.82	0.58	0.50	0.77	0.48
ELEVEXPONW_a	0.79	0.78	0.65	0.82	0.87	0.58
ELEVEXPONW_b	0.80	0.79	0.65	0.83	0.88	0.60
ELEVEXPONW_c	0.79	0.77	0.65	0.83	0.88	0.60
DISNWSLOPE	-0.37	-0.60	-0.37	-0.24	-0.48	-0.21
SLOPE01_10KNW	0.47	0.60	0.27	0.55	0.72	0.22
SLOPE10_10KNW	0.49	0.64	0.26	0.58	0.75	0.26
SLOPE20_10KNW	0.39	0.63	0.19	0.47	0.76	0.19
LAT	0.48	0.49	0.71	0.26	0.27	0.68
LONG	0.30	0.23	0.27	0.20	0.05	0.35

The correlation coefficients for the slope variables display a pattern similar to the elevation variables, and are highest for all stations and mountain stations for the warm events. This is likely due to the relationship between high slopes and high elevations, rather than an independent influence of slope on snowfall. Our results with respect to slope are similar to those reported by Konrad (1996) for light northwest flow precipitation events in the cool season in the Southern Appalachians The correlation coefficients associated with the geographic variables of latitude and longitude are somewhat higher for the cold events, particularly in the mountains, suggesting an association between cold temperatures and a synoptic pattern that supports more snowfall to the north and west.

The slope of the regression line and the strength of the relationships between the TOPO/GEOG variables and NWFS vary considerably between the low elevation and mountain stations. Differences are particularly evident for point elevation and elevation plus exposure for the warm NWFS events (**Fig. 8**). In the lower elevation regions (i.e. Tennessee Valley and Foothills), topographic relief and elevation are generally low, resulting in weak orographic effects. In the mountains, however, the greater relief and higher elevations translate into greater spatial variability of snowfall resulting from the topographic influences of elevation, exposure, distance to a northwest slope, and slope. Conversely, in the lower elevations the geographic variable of latitude is more highly correlated with NWFS totals than it is in the mountains. The correlation coefficients for longitude are also higher in the lower elevations than the mountains, but the influence of longitude on NWFS remains rather low.

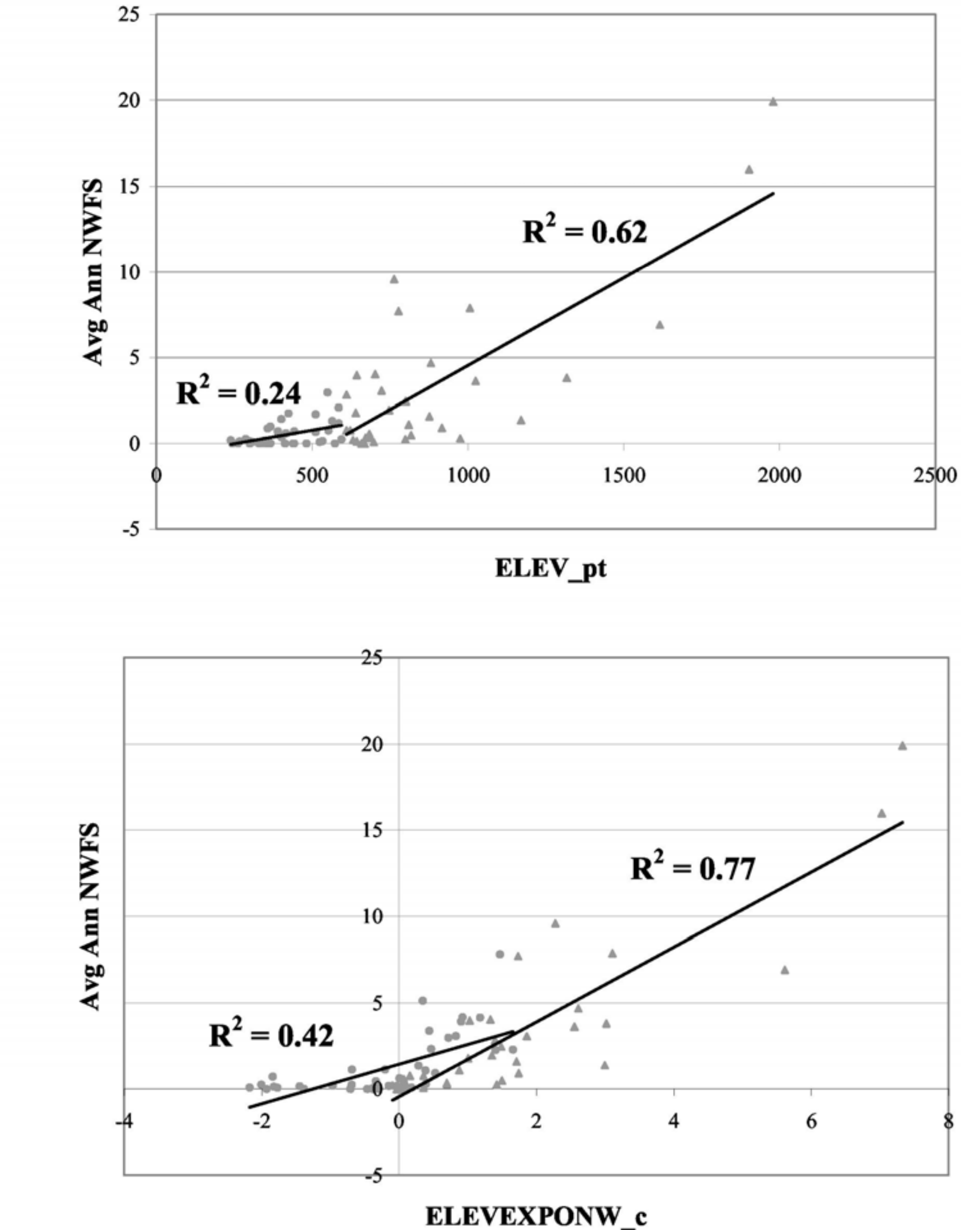

Figure 8. Plots of average annual NWFS against elevation for warm (>2º C) events (top) and elevation plus exposure for cold (<2º C) events (bottom). Low elevation stations are denoted by a circle while mountain stations are denoted by a triangle.

Table 4 summarizes the multivariate regression models developed by station groupings and event type. The best model identified using a stepwise routine for average annual NWFS and all stations included the TOPO/GEOG variables of point elevation, exposure, and latitude and explained approximately 73 percent of the variance in snowfall across the region. This multivariate regression model was applied to the GIS grids to generate a spatially interpolated map of average annual NWFS across the Southern Appalachians (**Fig. 9**). Similar maps could also be developed using the additional multivariate regression models, but elevation remains a dominant influence in all of the models, thereby diminishing the variability in the spatial patterns among different event types. The strong weighting on elevation in the regression model results in over predictions of snowfall (i.e. negative residuals) at high elevations along the Blue Ridge—such as Highlands and Sparta, North Carolina, which are situated to the southeast and well downwind of the northwest slopes (**Fig. 10)**. Moisture is significantly depleted through snowfall and riming upstream that by the time the low-level northwesterly flow reaches these areas little if any accumulation results, even though elevations may be above 1,000 m (3,280 ft). In fact a substantial barrier effect is evident, similar to that noted by Schemerhorn (1967) in the Pacific Northwest. Conversely, NWFS totals are underestimated (i.e. positive residuals) on the windward slopes, particularly for the most exposed coop stations of Mt. Leconte, Tennessee, Wise, Virginia, and Beckley, West Virginia (**Fig. 10**). These biases in the model may be related to the relative absence of coop stations along the highly exposed windward slopes.

Table 4. Multivariate regression models developed in this study.

Dependent Variable	**Regression Equation**	**Adj-R^2**	**SE**
Avg Ann NWFS			
All Stations	-81.249 + 0.014ELEV_pt + 2.159LAT + 1.395EXPONW_a	0.730	3.642
Mtn Stations	-0.342 + 7.910EXPONW_c + 0.010ELEV_pt	0.759	4.522
Low Elev Stations	-48.783 + 1.321LAT + 0.007ELEV01	0.701	1.311
Avg Ann Cold NWFS			
All Stations	-59.637 + 0.007ELEV_pt + 1.62LAT + 0.701EXPONW_a	0.707	2.066
Mtn Stations	2.031 + 4.746EXPONW_c + 0.003ELEV_PT	0.702	2.652
Low Elev Stations	-39.529 + 1.065LAT + 0.005ELEV01	0.677	1.005
Avg Ann Warm NWFS			
All Stations	-1.816 + .007ELEV_pt + 0.941EXPONW_a	0.702	1.839
Mtn Stations	-430.587 + 0.011ELEV_pt - 3.037LONG + 4.851LAT	0.852	1.761
Low Elev Stations	-14.152 + 0.002ELEV01 + 0.380LAT	0.644	0.407

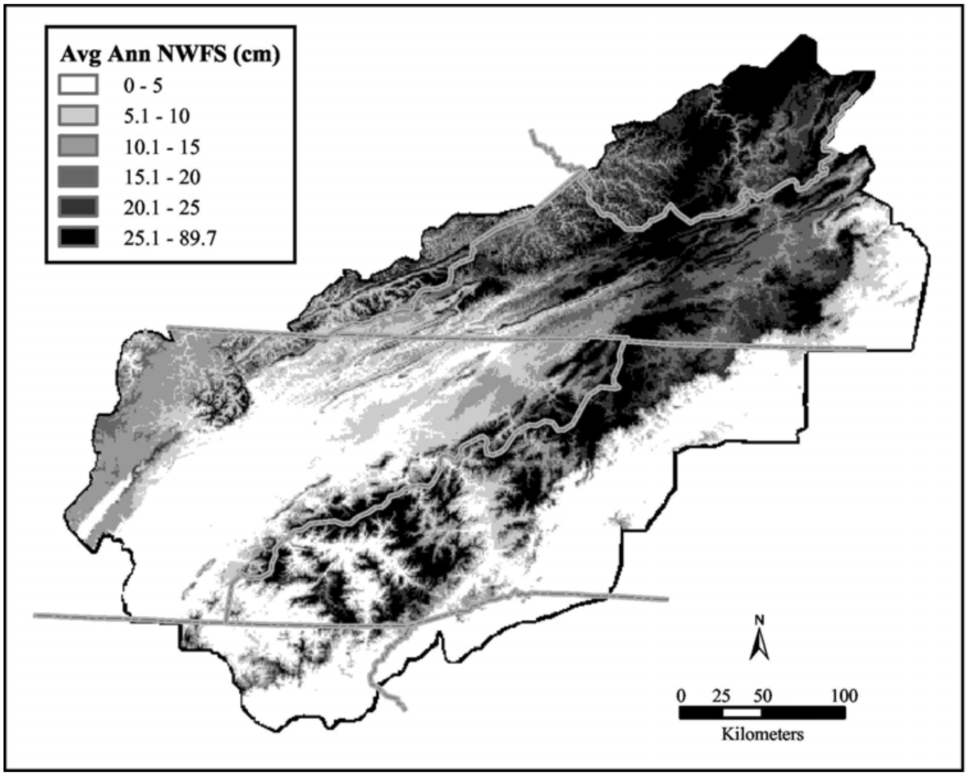

Figure 9. Average annual NWFS as estimated by the multivariate regression model.

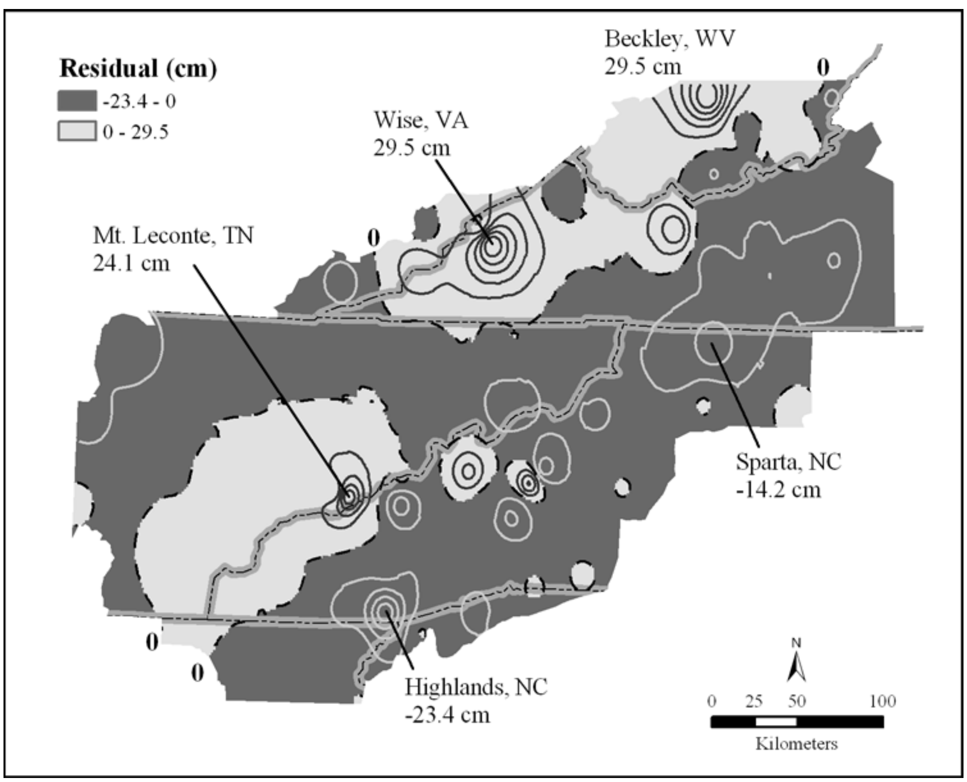

Figure 10. Map of the residuals (i.e. errors) in the multivariate regression model used to construct the map in Figure 9.

Conclusions

In this paper, we have analyzed the relationships between various TOPO/GEOG variables and NWFS in the Southern Appalachian Mountains. Elevation and exposure to the northwest most strongly influence the spatial patterns of NWFS in the region. These topographic variables are particularly significant for the higher elevation stations above 600 m (1,969 ft), and are less significant in the lower elevations where latitude is a more important influence. The relative influence of elevation on NWFS declines in cold (< 2˚ C) NWFS events, thereby allowing the influence of exposure to the northwest and distance to a northwest slope to increase. In warm (> 2˚ C) NWFS events, elevation is of greater significance due to the adiabatic cooling of air parcels resulting from orographic lifting. In these situations, temperatures at lower elevations may be too warm for snow, but as one moves up the mountain slope, temperatures cool, allowing precipitation to fall as snow and accumulate.

In addition to major findings summarized above, this paper also presents a methodology linking synoptic climatology and GIS to analyze the relationships between various TOPO/GEOG variables and snowfall totals. By focusing on snowfall patterns associated with a particular wind direction, the topographic influences become more evident since the locations of windward and leeward slopes are known. This methodology also allows us to derive GIS grids for a variety of TOPO/GEOG variables and extract values for each of the respective coop stations in an automated manner, facilitating multivariate statistical analyses. Lastly, the methodology presented in this paper uses output from a multivariate regression model to develop a map of average annual NWFS using GIS grids of the TOPO/GEOG variables and map algebra techniques in a GIS.

The coop stations used in this study do not adequately represent sites situated at the topographic extremes of the study area, and this may be why relatively stronger (weaker) relationships were identified between snowfall and elevation (other topographic variables). In particular, additional high elevation coop stations would considerably improve the results, since only four coop stations were available above 1,200 m (3,937 ft) elevation. A greater density of coop stations along the Blue Ridge and at higher elevation windward slopes would also be advantageous. The large areal extent and topographic diversity of the Southern Appalachians coupled with subtle differences in the synoptic climatology across the region may also have resulted in weaker relationships. The large areal extent, in particular, may have contributed to slightly weaker (stronger) relationships between topographic (geographic) influences and NWFS in this study. Nonetheless, the results are encouraging given the less than desirable network of coop stations and the problems and challenges associated with measuring snowfall—particularly in the very windy conditions that often occur with NWFS.

In future work, we plan to employ a similar methodology to analyze the relationships between TOPO/GEOG variables and snowfall for additional low-level wind directions. We intend to investigate snowfall patterns in association with southeasterly low-level flow, in particular, since many of the major snowstorms that affect the region have a prolonged period of southeasterly low-level flow. The relationships may not be quite as strong as noted in this paper, however, due to the much stronger synoptic-scale forcing that accompanies these storm systems. Additional opportunities for future work in other mountainous regions also exist, both in terms of snowfall and in the use of this methodology in association with precipitation data for input into a hydrologic model.

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