

The Spatial Variations of Mean Annual Snowfall in Western North Carolina

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Western North Carolina's snowfall can be highly variable. For the purpose of this study, the western North Carolina region is divided into four sub-regions. These sub-regions take into account the geographic characteristics of the region. Daily snowfall amounts from 16 National Weather Service Cooperative Observer Stations are compiled into annual means for a 20-year time period. These annual means are then analyzed to identify existing spatial patterns. Geographic characteristics such as elevation, latitude, exposure, as well as other physical and synoptic characteristics of the stations and the sub-regions are considered. Variability within the sub-regions is also analyzed. Results indicate that snowfall variability can vary dramatically between sub-regions. While there are several geographic characteristics that help explain the spatial variations of mean annual snowfall amounts, elevation is the primary one. Typically, snowfall amounts increase at higher elevations. Location and aspect also appear to be important geographic characteristics, depending on the type of weather system. By gaining a better understanding of these spatial variations, the public can potentially be better prepared for this type of weather event.

Introduction

When snowfall in western North Carolina is discussed, many people assume that the entire region receives a lot of snow each winter, certainly more than other areas of the southeastern United States (Doesken and Judson 1997). Freshmen-level physical geography courses often treat southeastern climate as a homogeneous unit (Soulé 1998). However, what most people do not realize is that western North Carolina can experience high spatial variability of mean annual snowfall amounts (Perry and Konrad 2004). These mean annual snowfall amounts can range anywhere from 10cm at the lower elevations to over 100cm at the higher elevations, with some of the highest locations receiving up to 250cm (Perry 2002). The weather and synoptic patterns that produce snowfall in this region can also be highly variable (Soulé 1998). While snowfall variability can be an interesting aspect of winter climate and have a large impact upon society, it has received little attention in climate literature, especially in the Southeast (Mote et al. 1997; Hartley 1999).

Western North Carolina, which is part of the southern Appalachian Mountain chain, lies within two physiographic provinces. These physiographic prov-

inces include the western extent of the Piedmont (Foothills) and the Blue Ridge (Raitz, et al. 1984). Continental and maritime influences both affect the climate of this region, given its relative proximity (500-800km) to the Atlantic Ocean and the Gulf of Mexico. Both of these bodies of water play major roles in determining the amount of snowfall received in this region (Whiteman 2000; Kocin and Uccellini 1990). The elevation varies from 300 meters in low-lying valleys of the Foothills to 2037 meters on top of Mt. Mitchell (USGS 1962). These factors play a key role in the spatial variations of mean annual snowfall amounts and will be considered in the analysis of this study.

Many weather forecasters have stated that the southern Appalachian region is one of the most difficult areas in the country to predict snowfall for (Keeter et al. 1995). There are many geographic, topographic, and synoptic characteristics that cause these difficulties. These geographic characteristics are attributed to the observed spatial variations of mean annual snowfall amounts within the region (Konrad 1996). According to Kocin and Uccellini (1990), some of the

geographic characteristics contributing to the difficulty in snowfall predictions and the observed snowfall variations include the influences of the Atlantic Ocean, the Gulf of Mexico, the position of the Gulf Stream, and the effects of the Appalachian Mountains on low-level temperatures and wind fields. In a study of statistical relationships between topography and precipitation patterns conducted by Basist *et al.* (1994), elevation, slope, orientation, and exposure were important factors in explaining spatial variations of snowfall in mountainous regions.

Synoptic factors that may lead to spatial variations in snowfall for this region include orographic precipitation enhancement (Fishel and Businger 1993; Dore *et al.* 1992; Whiteman 2000), cold-air damming in the lee of the Appalachian Mountains (Keeter *et al.* 1995; Bell and Bosart 1988), the paths of mid-latitude wave cyclones as they move across the southeastern United States (Maglaras *et al.* 1995), and late season cutoff lows (Sabones and Keeter 1989). Additionally, western North Carolina is located between two major winter storm tracks of the eastern United States; the Ohio Valley/eastern Great Lakes storm track and the Atlantic Coast storm track (Mote *et al.* 1997; Hartley 1998). These storm tracks may also help to explain the spatial variations of mean annual snowfall amounts within the region.

The purpose of this study is to identify spatial variations that may exist in mean annual snowfall amounts for western North Carolina. These variations may exist between locations within a certain geographic region or between different geographic regions. While similar studies have been conducted in other parts of the United States, snowfall variations in the southern Appalachian Mountains have not been widely investigated (Hartley 1998). The hypothesis of this study is that spatial variability will be high across the study area, especially in areas of higher elevation. By analyzing this type of information, a better understanding of the existing spatial patterns can potentially lead to more effective and efficient preparations, which may include better forecasts, transportation planning, and emergency preparedness (Doesken and Judson 1997).

Data and Methods

For the purpose of this study, the region of western North Carolina has been divided, on a county basis, into four sub-regions based on the geographic characteristics of each sub-region. The divisions are based on a generalization of the average exposure, elevation, relative location, and latitude of each sub-region. The four sub-regions include the Northwest Mountains, the western Piedmont (Foothills), the Asheville Basin, and the Southwest Mountains (Fig. 1). In the latter three, some counties are excluded from the study due to data availability issues. These issues relate to missing or inaccurate data that Cooperative Observing Stations within these counties contained.

Each of the regions include geographic characteristics that make them distinctively different from one another. While topography was the main geographic characteristic considered when creating the sub-regions (Fig. 2), other features such as prevailing weather patterns were considered as well. In addition, some consideration was given to how western North Carolina counties are divided by the National Weather Service (NWS) into three different county warning areas. However, it is crucial to understand that within each sub-region, and within each individual county, there can be great spatial variability in the geographic characteristics, which can also lead to great spatial variations of mean annual snowfall amounts. These sub-regions are a way of grouping together stations that may exhibit similar snowfall patterns and using them to demonstrate spatial variability throughout western North Carolina.

The data analyzed for this study were extracted from the National Climatic Data Center's Cooperative Summary of the Day CD-Rom (NCDC 2003). It includes data from the National Weather Service's (NWS) Cooperative Observer Stations that are located across western North Carolina. Since snowfall in this region is generally limited to late fall, winter, and early spring, the data that were acquired only contain daily reports from October through May of each year. Four stations with complete or nearly complete data were chosen for the analysis from each western North Carolina sub-region for a total of 16 stations. The time period of this analysis is from October 1979 to May 1999.

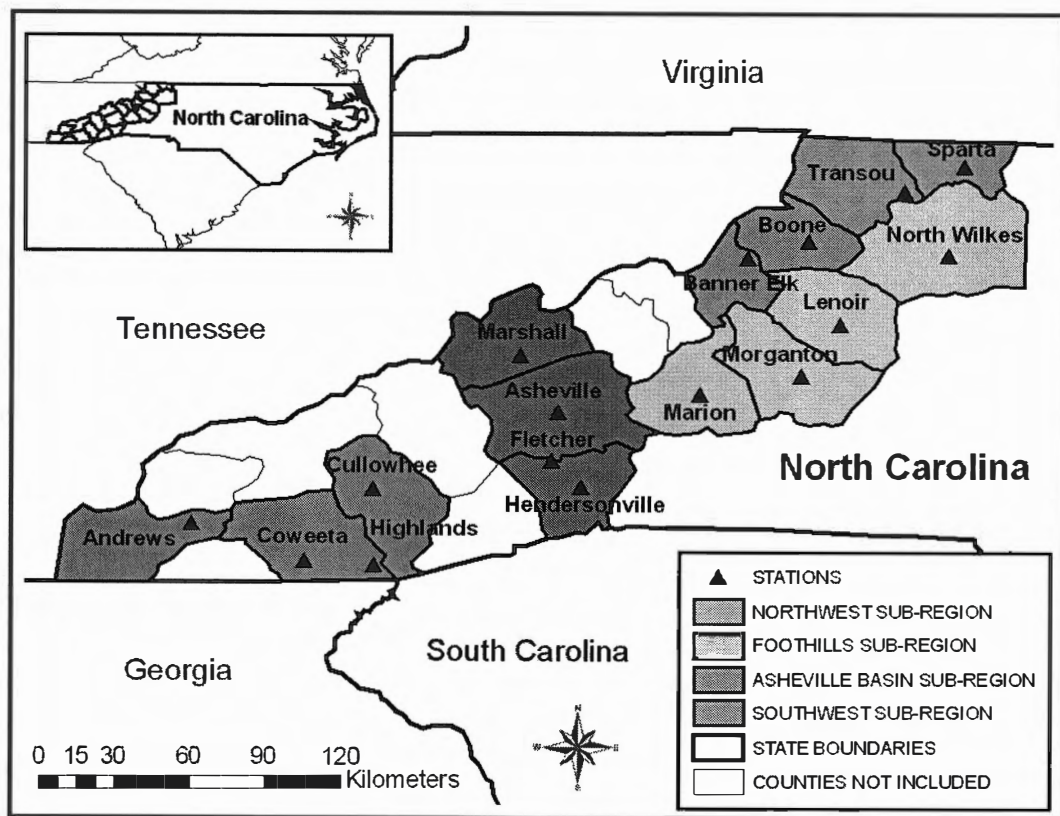


Figure 1. Area of study, including locations and names, and sub-regions.

This time period was chosen due to these 16 stations containing continuous reports for the 20-year period and not having entire years of missing data. Missing data from daily reports was treated as such and no substitutions were made. For all 16 stations that were analyzed for the 20-year period, the data completeness was 97.7%. Individual data completeness statistics for each station can be seen in Table 1.

A frequent problem with snowfall data, especially from Cooperative Observer Stations, is missing data (Suckling 1991; Robinson 1990). According to Robinson (1989), missing snowfall data is especially problematic in areas where snowfall is rare, which does include some parts of western North Carolina. Even when snowfall measurements are recorded by the

Cooperative Observers, they are not necessarily accurate. This is probably due to the lack of training that many of these Cooperative Observers receive (Robinson 1989; Doesken and Leffler 2000). This helps explain why more stations could not be utilized for the analysis of this study.

The first step of the analysis was calculating annual means and standard deviation for each station. Second, the 20-year mean was calculated for each station, as well as the 20-year mean for each sub-region. Third, a Pearson correlation coefficient was calculated between each station within each sub-region. Finally, a coefficient of variation was calculated using the mean and standard deviation of annual snowfall amounts for each station. In addition, comparisons were made

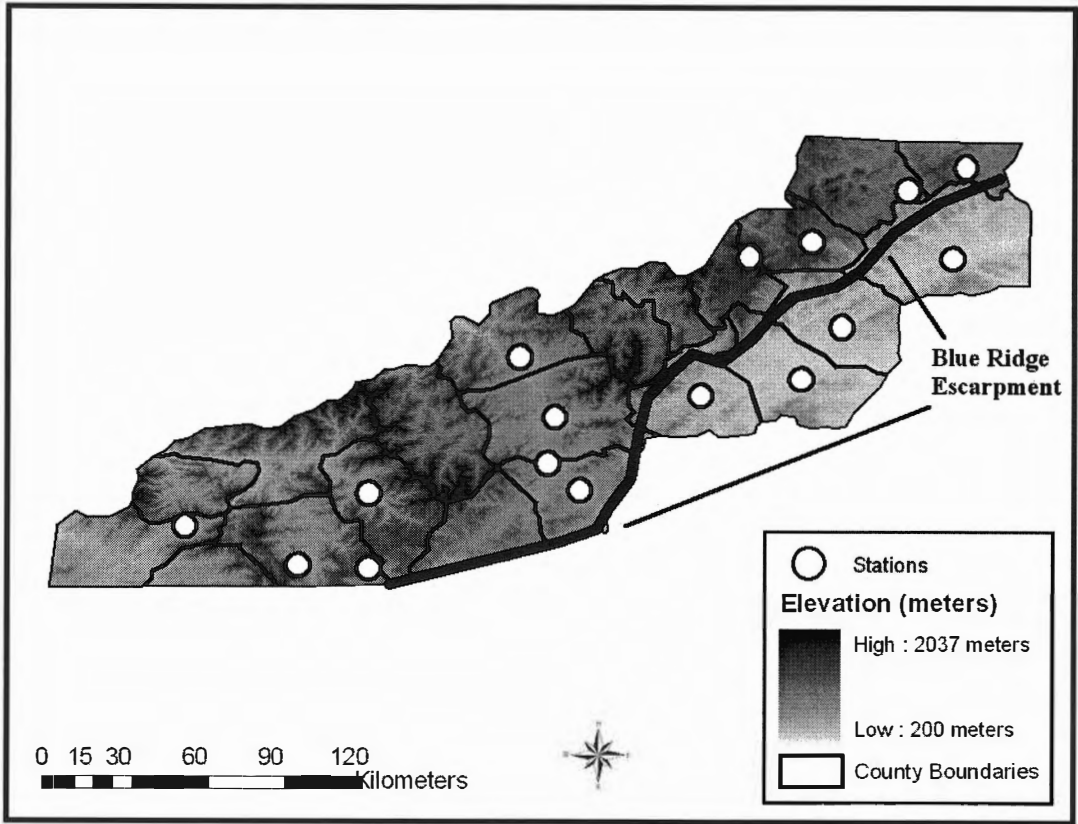


Figure 2. Digital elevation model showing the topography of the study area.

to show relationships between snowfall amounts and elevation, coefficient of variation and elevation, and snowfall amounts and latitude.

Results

Annual snowfall values for each station are presented in Table 1 and Figures 3-6. Additional results are shown in Table 2 and Figures 7-9. The Northwest sub-region clearly received the most annual snowfall for the 20-year period with a mean of 78.3cm for the entire sub-region (Fig. 3). Banner Elk and Boone received similar amounts of annual snowfall, as did Sparta and Transou. However, Banner Elk and Boone received considerably more. The Pearson correlation coefficients between Banner Elk and Boone, as well as

Sparta and Transou, were significant at the 99% confidence level (Table 2).

The Foothills sub-region received the least amount of snowfall of the four sub-regions for the 20-year period with a mean of 17.7cm (Fig. 4). All four stations in this sub-region experienced similar annual snowfall amounts. The Pearson correlation coefficients between each station were significant at the 99% confidence level (Table 2).

The Asheville Basin sub-region had the second highest 20-year mean of annual snowfall, which was 30.1cm (Fig. 5). Three of the stations in this sub-region exhibited similar annual snowfall amounts. However, Marshall received noticeably more snowfall during several winter seasons. The Pearson correlation coefficient between Marshall and the other three

Table 1. Each station's elevation in meters, mean annual snowfall in centimeters, standard deviation, coefficient of variation, and data completeness for the 20-year period.

Station	Sub-Region	Elevation	Snowfall	Std. Dev.	CV	Data Completeness
Boone	Northwest	1024	92.0	37.3	40.5	99.3%
Banner Elk	Northwest	1142	103.0	45.8	44.5	96.9%
Sparta	Northwest	916	52.5	40.6	77.3	98.2%
Transou	Northwest	876	65.8	40.5	61.5	99.5%
Lenoir	Foothills	366	17.8	21.1	118.5	99.8%
Marion	Foothills	447	19.7	19.7	100	91.5%
Morganton	Foothills	354	11.2	17.0	151.8	98.1%
North Wilkes	Foothills	341	22.1	19.8	89.6	97.8%
Asheville	Asheville Basin	683	34.3	19.3	56.3	99.9%
Fletcher	Asheville Basin	631	25.1	18.6	74.1	99.8%
Hendersonville	Asheville Basin	658	23.3	18.4	79	99.6%
Marshall	Asheville Basin	610	37.6	42.0	111.7	90.1%
Andrews	Southwest	533	21.7	20.7	95.4	96.9%
Coweeta	Southwest	686	16.6	21.0	126.5	98.6%
Cullowhee	Southwest	668	17.9	15.2	85	97.6%
Highlands	Southwest	1170	45.7	22.8	49.9	99.9%

Table 2. Relationship between stations within each sub-region based on Pearson's correlation coefficients. * Correlation significant at $\alpha = 0.05$. ** Correlation significant at $\alpha = 0.01$.

NORTHWEST	<i>Banner Elk</i>	<i>Boone</i>	<i>Sparta</i>
<i>Boone</i>	0.83**		
<i>Sparta</i>	0.47*	0.81**	
<i>Transou</i>	0.40	0.76**	0.93**
FOOTHILLS	<i>Lenoir</i>	<i>Marion</i>	<i>Morganton</i>
<i>Marion</i>	0.79**		
<i>Morganton</i>	0.82**	0.85**	
<i>North Wilkes</i>	0.78**	0.93**	0.88**
ASHEVILLE BASIN	<i>Asheville</i>	<i>Fletcher</i>	<i>Hendersonville</i>
<i>Fletcher</i>	0.90**		
<i>Hendersonville</i>	0.87**	0.91**	
<i>Marshall</i>	0.62**	0.47*	0.36
SOUTHWEST	<i>Andrews</i>	<i>Coweeta</i>	<i>Cullowhee</i>
<i>Coweeta</i>	0.75**		
<i>Cullowhee</i>	0.61**	0.71**	
<i>Highlands</i>	0.65*	0.67**	0.73**

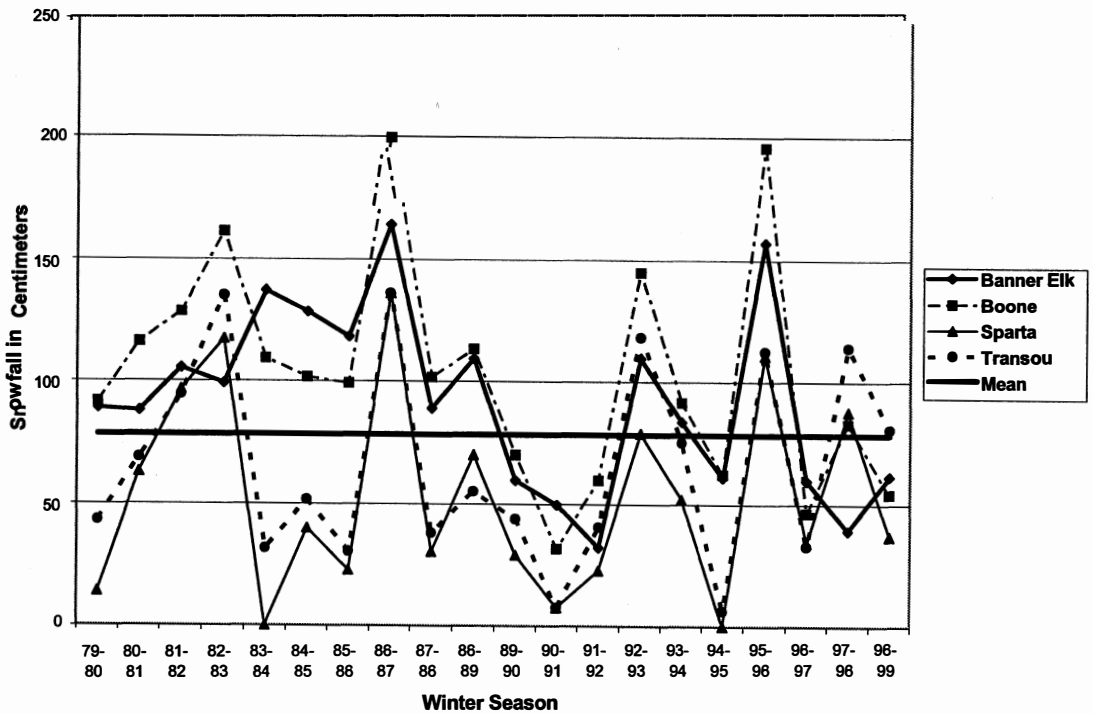


Figure 3. Graph showing the annual snowfall amounts and the sub-region 20-year mean for the Northwest sub-region.

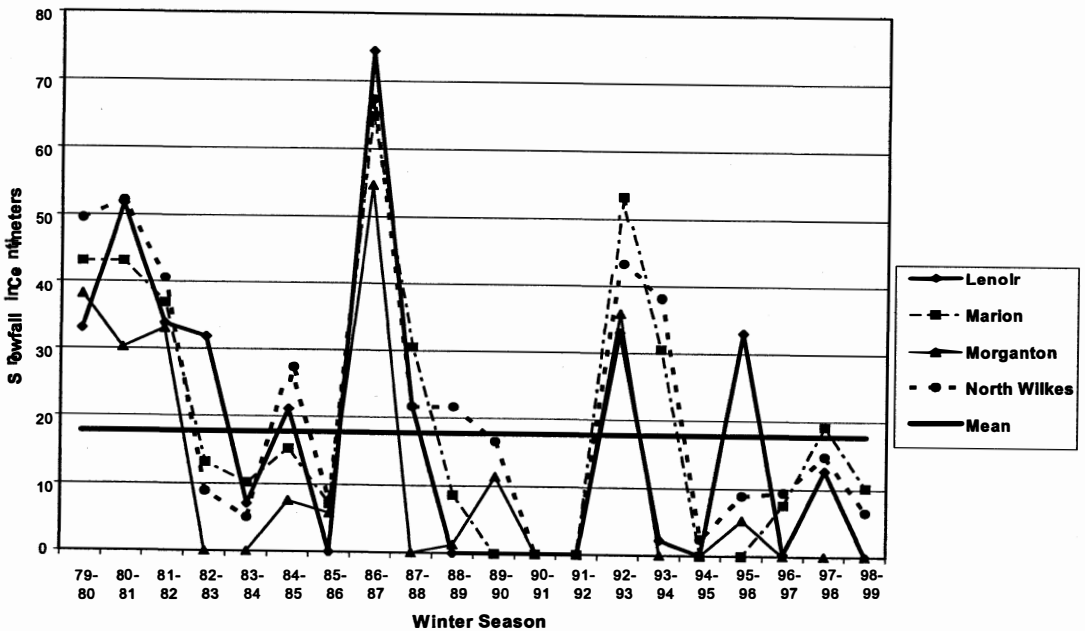


Figure 4. Graph showing the annual snowfall amounts and the sub-region 20-year mean for the Foothills sub-region.

stations was less significant than the coefficients between each of the other three stations individually (Table 2).

The Southwest sub-region had the second lowest 20-year mean of annual snowfall, which was 25.4cm (Fig. 6). Like the Asheville Basin sub-basin, three of the stations received similar mean annual snowfall amounts and have similar Pearson correlation coefficients (Table 2). However, Highlands received considerably more mean annual snowfall than did the other three stations in almost every winter season analyzed. In fact, its mean annual snowfall amount for the 20-year period was 46cm. This station exerts a large influence on the mean annual snowfall for the sub-region. Without Highlands, the Southwest sub-region 20-year mean would only be 18.6cm. A mean of 18.6cm is similar to the 20-year mean of the Foothills sub-region. Highlands was grouped within this sub-region due to geographic characteristics that will be discussed in the next section.

Discussion

In the Northwest sub-region, Boone and Banner Elk received considerably more snowfall on average than did Sparta and Transou, even though they are only 100-300 meters higher in elevation. According to Barry (1981), elevation is often a key factor with snowfall in mountainous terrain, with higher elevations potentially receiving more precipitation. The combination of elevation and colder temperatures at increased elevations could also result in more snowfall (Christopherson 2003). However, given the difference in elevation is not great, perhaps a better explanation for the observed differences could be the relative locations of the two sets of stations. Boone and Banner Elk are situated farther west of the Blue Ridge escarpment, which means they are farther away from the rain/snow line that often develops near the edge of the escarpment as a result of warmer air filtering into the area (Fig. 2). In this scenario, they are typically in the snow sector of snowfall events. Additionally, they have a better opportunity to receive increased snowfall amounts from northwest flow snowfall events (Perry and Konrad 2004).

In the case of the drastic snowfall variations that were observed between the Northwest and Foothills sub-regions (Figs. 3-4), despite their proximity to one another, elevation again may be the primary geographic characteristic causing the observed spatial variations. The Foothills sub-region is uniquely located at the foot of the Blue Ridge escarpment (Fig. 2). This escarpment is situated in a northeast-southwest elongated position. Elevations below the escarpment average around 300 meters while elevations on top of the escarpment average around 1000 meters (USGS 1962). This change in elevation takes place in a relatively short planar distance. The abrupt change in elevation often leads to an enhancement of the orographic process in which precipitation is enhanced as it is lifted up and over the mountains (Whiteman 2000; Dore *et al.* 1992). The orographic enhancement process is significantly greater for snowfall than for rainfall (Dore *et al.* 1992). As a result, all four stations in the Northwest sub-region have the potential to experience an increase in snowfall. However, this situation only occurs during certain types of snowfall events. The precipitation source, typically a mid-latitude wave cyclone, must have a southeasterly flow off of the Gulf of Mexico, or in some cases the Atlantic Ocean. The common path for storm systems in this region is to move from west to east (Mote *et al.* 1997). When these mid-latitude wave cyclones move directly south and east of the Foothills sub-region, the orographic process can affect the Northwest sub-region.

Another situation that often develops over the Foothills sub-region is a cold-air damming event. During these situations, cold arctic air at the surface funnels down the eastern spine of the Appalachians from New England and becomes trapped against the Blue Ridge escarpment (Keeter *et al.* 1995; Bell and Bosart 1988). When this occurs, elevations below the escarpment tend to receive more freezing rain and sleet, limiting the total amounts of snowfall.

In the Southwest sub-region, the orographic enhancement process also affects Highlands. It is located at the edge of the Blue Ridge escarpment at an elevation of approximately 1170 meters (USGS 1962). It is actually higher than the stations of Boone and Banner Elk in the Northwest sub-region, but its mean annual snowfall amount was less than half of what

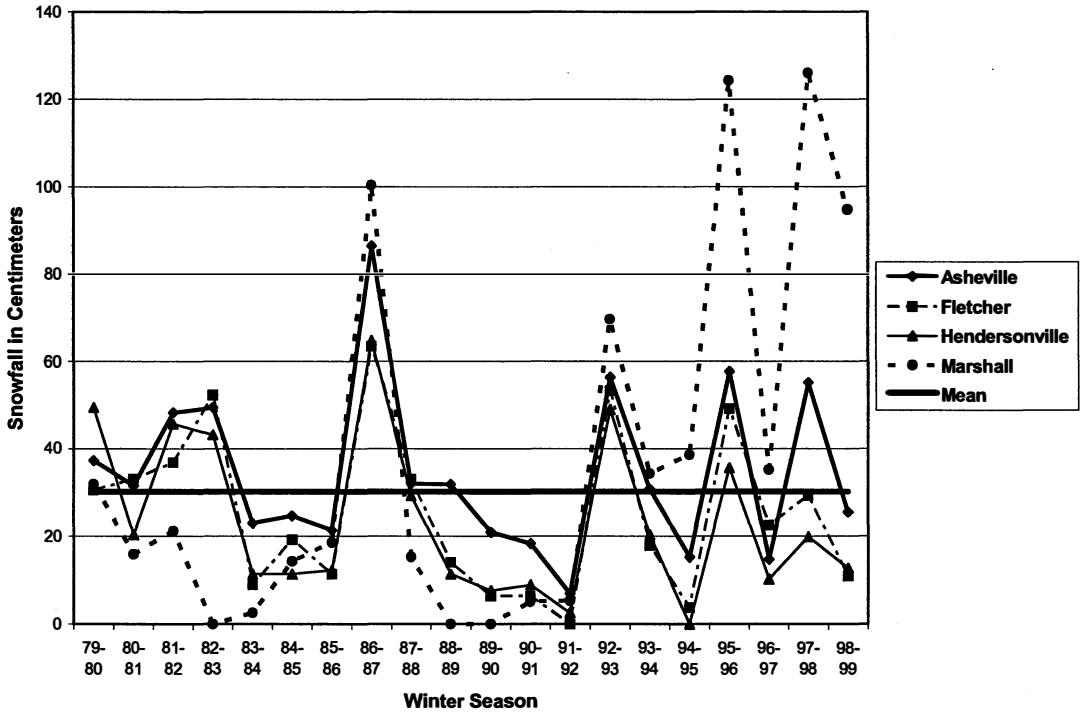


Figure 5. Graph showing the annual snowfall amounts and the sub-region 20-year mean for the Asheville Basin sub-region.

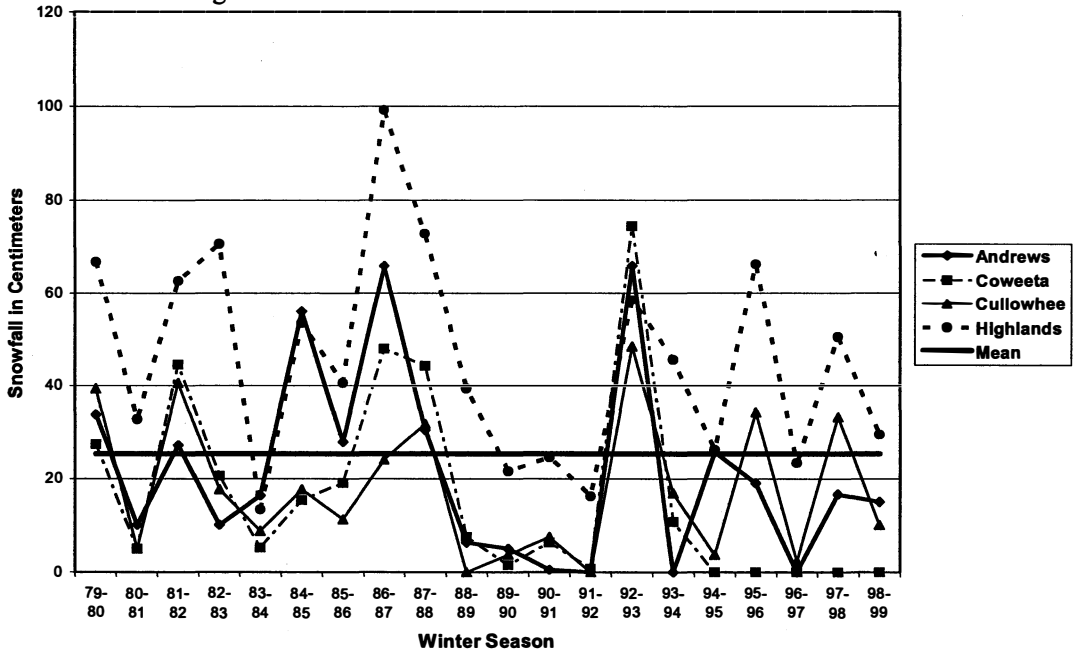


Figure 6. Graph showing the annual snowfall amounts and the sub-region 20-year mean for the Southwest sub-region.

they received for the 20-year period. This is likely a result of its more southerly location, which supports previous research findings that an increase in elevation does not always lead to an increase in snowfall amounts in western North Carolina (Konrad 1995). The southwestern extent of this study area, which includes all of the Southwest sub-region, typically experiences warmer temperatures during the winter season than areas in the northwestern part of the study area and is often caught in a transition zone between rain and snow during snowfall events (Perry 2002). However, elevation and location is the most likely explanation for Highlands receiving more snow than the rest of the stations in this sub-region.

The Asheville Basin sub-region also included one station receiving more snowfall than the other three stations during some winter seasons of the 20-year analyzed period (Fig. 5). Marshall had considerably more snowfall during the winter seasons of 1986-1987, 1992-1993, 1995-1996, 1997-1998, and 1998-1999. It is more difficult to determine why this may have occurred. The elevation factor is ruled out since it is actually lower than the other stations. One likely explanation, however, is its more northwesterly location than the other stations. Again, most weather and precipitation patterns affect this study area from west to east. This is especially true of the northwest flow snowfall events that move into the western Appalachian Mountain range, often originating in the Great Lakes region (Perry and Konrad 2004; Niziol et al. 1994; Schmidlin 1992). Northwest flow snowfall can also occur as wrap-around moisture from mid-latitude wave cyclones that have moved off to the north and east. Typically, by the time these events have moved over the mountains from the west, most of the precipitation has diminished and once they move south and east of Marshall, all of the precipitation has ended. Another explanation could be due to Marshall's location in the French Broad River Valley. It is exposed to the northwest, which could allow more cold air and snowfall to affect this station by funneling up through the river valley.

In discussing spatial variations for all of the sub-regions in western North Carolina and their 20-year mean annual snowfall amounts, one common char-

acteristic is that all stations in each sub-region experienced similar temporal patterns of year-to-year variability in their snowfall amounts. That is, years of high or low snowfall amounts were typically shown for each station within each sub-region. There were cases in which some stations in a particular sub-region received substantially more or less snowfall than its neighboring stations, but usually most of the stations experienced similar patterns (Figs. 3-6).

For the entire study area during this 20-year period, there appeared to be a positive relationship between the amount of snowfall that a station received and the elevation of the station (Fig. 7). Typically, stations with higher elevations experienced higher amounts of snowfall on an annual basis (Table 1). This agrees with the principle that higher locations receive higher amounts of precipitation and snowfall, as well as cooler temperatures (Barry 1981; Whiteman 2000). However, there are a few stations in this study area where this was not the case. The stations of Asheville and Marshall, located in the Asheville Basin sub-region (Fig. 5), received more snowfall during the 20-year analyzed period than did their neighboring stations to the south, which are located at a slightly higher elevation. These spatial variations can be attributed to weather and synoptic patterns previously discussed, such as northwest flow snowfall events.

Another aspect to the relationship between mean annual snowfall amounts and elevation is that higher elevations were typically less variable from year-to-year during this 20-year period. This indicates that there is a negative relationship between the coefficient of variation for mean annual snowfall and standard deviation as compared to elevation (Fig. 8). This relates to the fact that in any given winter season, higher elevations typically receive more snowfall due to their elevation alone, which leads to less variability between winter seasons (Whiteman 2000). Lower elevations are more dependent upon the tracks of winter storms, which can be highly variable from year-to-year (Soulé 1998). Evidence of this variability was witnessed in the Foothills sub-region (Fig. 4).

Stations located in the northern extent of

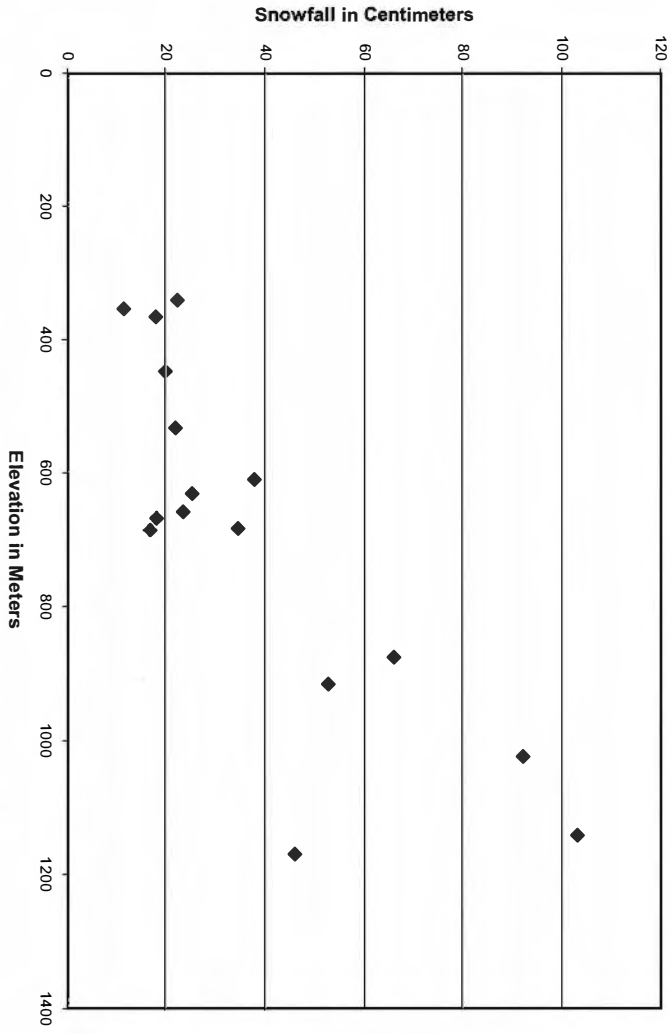


Figure 7. Relationship between mean annual snowfall and elevation.

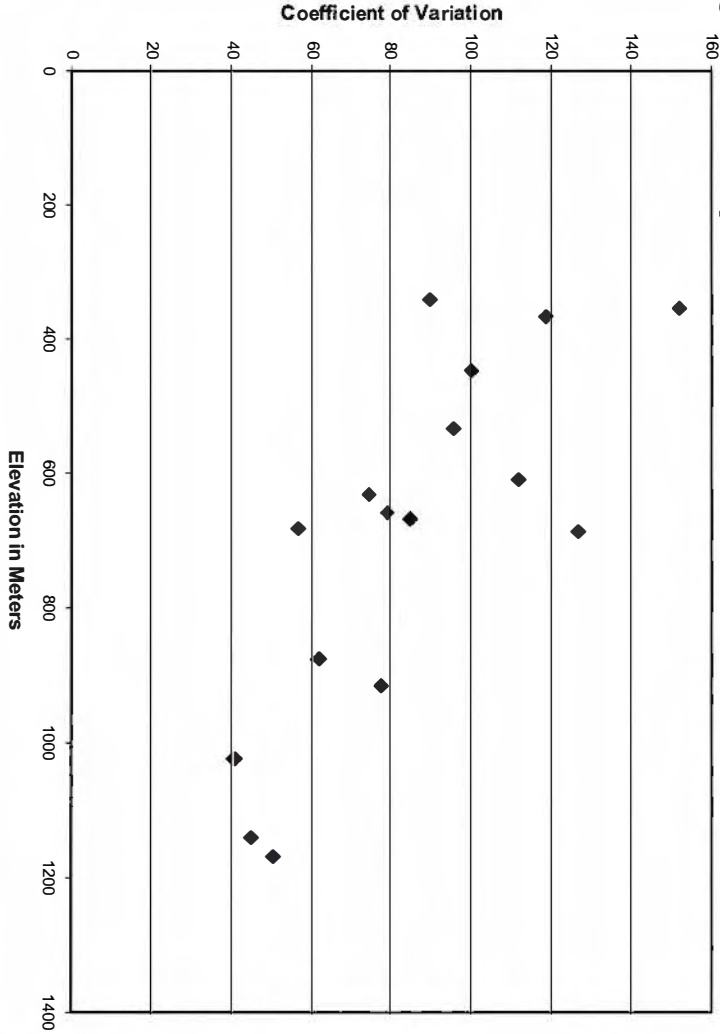


Figure 8. Relationship between the coefficient of variation (of mean annual snowfall) and station elevation.

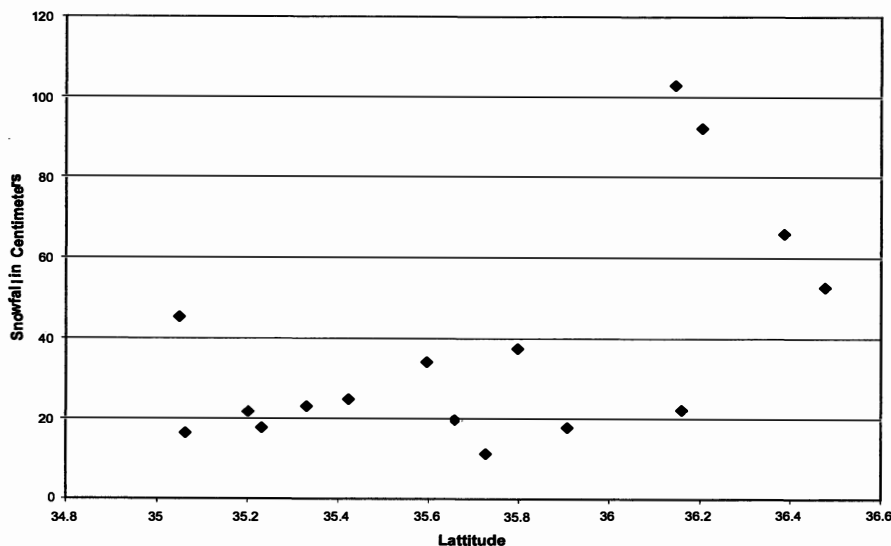


Figure 9. Relationship between mean annual snowfall and latitude.

western North Carolina, or at higher latitudes, also received more snow during the 20-year period regardless of their elevation (Fig. 9). These stations were affected more by troughs, clipper-type systems, and northwest flow snowfall events moving into the area from the north and west. The fact that the higher latitude stations received higher amounts of mean annual snowfall agrees with basic weather and synoptic principles concerning southeastern climate (Hartley 1998; Whiteman 2000). This type of pattern can typically be found anywhere north of the equator.

Summary and Conclusions

Spatial variations of mean annual snowfall were found to exist between each of the four western North Carolina sub-regions. The magnitude of the spatial variations was fairly dramatic and agreed with the initial hypothesis. Variation appeared to be greater between sub-regions as opposed to stations within each

individual sub-region. The variations found between the sub-regions can be attributed to several geographic characteristics, including elevation, latitude, physical location, and weather and synoptic patterns. The greatest magnitude was found between the Northwest and Foothills sub-regions where elevation was the primary geographic characteristic causing the observed spatial variations.

In addition to the variations between the sub-regions, there also appeared to be spatial variation between stations within some of the individual sub-regions themselves. This was the case in the Asheville Basin sub-region between Marshall and the other three stations, as well as in the Southwest sub-region where Highlands received more annual snowfall than the other three stations. These variations were attributed primarily to elevation and exposure to prevailing weather and synoptic patterns. The grouping of the 16 Cooperative Observer stations selected for this study appeared to work well, given that stations within each sub-region typically exhibited similar snowfall

patterns. However, even within individual counties in each sub-region, there can be great spatial variability due to geographic characteristics.

Further research could be conducted to gain an even better understanding of the spatial variations in snowfall that are taking place in western North Carolina. This further research could include: 1) accessing more Cooperative Observer Station data, 2) analyzing a longer time period of data, 3) developing regression models and interpolating the results to understand snowfall amounts in areas that are lacking observer stations or contain missing data and 4) a more detailed analysis of the synoptic processes that are occurring in order to characterize the spatial variations.

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