A PRECIPITATION AND FLOOD CLIMATOLOGY WITH SYNOPTIC FEATURES OF HEAVY RAINFALL ACROSS THE SOUTHERN APPALACHIAN MOUNTAINS

David M. Gaffin and David G. Hotz

NOAA/National Weather Service
Morristown, Tennessee

Abstract

A climatological study was conducted to identify the spatial distribution of 'normal' precipitation, to compile and interpret the reported flood statistics, and to identify and evaluate the synoptic patterns and sounding parameters associated with heavy rainfall across the southern Appalachian Mountains. It was found that a large variability in precipitation amounts exists across the southern Appalachian region, due in most part to the mountainous terrain. The 'normal' precipitation was found to be greatest across southwest North Carolina due to the upslope southerly wind flow created by the typical synoptic-scale storm track across the southern Appalachian region. The least amount of precipitation was observed across northeast Tennessee and across portions of the French Broad River Valley, where downslope flow developed as a result of these southerly winds. The precipitation distribution during the summer months revealed that local terrain effects act as the dominant focusing mechanism for the development of thunderstorms in the sub-tropical airmass typically in place.

August was found to be the most active month for reports of flash flooding across the southern Appalachian Mountains due to the influence of local thunderstorms. Flash flood reports during the spring and summer months peaked during the afternoon and evening hours, while the winter and autumn months exhibited a peak during the morning hours between 0700 and 1200 LST. River or long-term flooding was found to peak during the late winter and early spring months, while the months of August through October revealed a secondary peak in river/long-term flooding which was likely due to the influence of tropical systems.

Heavy rain events, defined as producing 3 inches or more in a 6-hour or less time period and/or 4 inches or more in a 12-hour or less time period, were found to occur mainly during the summer months across the southern Appalachian region due to the prevalence of convective events, while the winter months experienced none due to the prevalence of stratiform events. 'Synoptic' systems were the most frequent heavy rain events, usually occurring during the spring months and at night. Most 'frontal' events occurred during the summer months, while most 'tropical' events occurred during the autumn months. Roughly two-thirds of the heavy rain events exhibited a southwest mid-tropospheric flow, while none of the heavy rain events exhibited a mid-tropospheric flow with a northerly wind component. Heavy rain events were nearly equally distributed between the daytime and nighttime hours, with most of the 'synoptic', 'frontal' and 'tropical' events occurring at night and the 'meso-high' events occurring almost exclusively during the day.

Common values of sounding parameters for heavy rain events across the southern Appalachian region were K-index above 30, negative Lifted Index, surface dewpoints at or above 60° F, 850-mb temperatures above 13° C, 850-mb dewpoints above 10° C, 700-mb temperatures above 5° C, and 700-mb dewpoints above 2° C. Southerly winds were typically observed in the low levels with uni-directional southwest winds above 850 mb during synoptic and frontal events, while meso-high events typically exhibited weak uni-directional southwest flow between the surface and 500-mb level prior to the onset of the heavy rains. CAPE values did not seem to show a direct relationship to the occurrence of heavy rain.

1. Introduction

Heavy rain and flash flooding are major concerns across the southern Appalachian Mountain region of the southeast United States due to the mountainous terrain and proximity to the Gulf of Mexico and Atlantic Ocean. The southern Appalachian region is generally located across northern Georgia, eastern Tennessee, western North Carolina and northwest South Carolina. The mountainous terrain varies significantly (Fig. 1) and has a major impact on the precipitation climatology and flash flooding threat, as well as local temperatures (Gaffin 2000). Many peaks in the southern Appalachian Mountains are above 6000 feet MSL and generally rise between 3500 and 4500 feet above the surrounding terrain.

Previous studies of heavy rain in the southeast United States identified synoptic features and parameters associated with warm season heavy rainfall (Konrad 1997). Other flash flood and heavy rainfall studies have focused on the central Appalachian region (Crysler et al. 1980; Guttman and Ezell 1980) and Tennessee (Muller and Maddox 1979; Crysler et al. 1982). The purpose of this study is to identify the spatial distribution of normal precipitation, to compile and interpret the reported flood statistics, and to identify and evaluate the synoptic patterns and sounding parameters associated with heavy rainfall across the southern Appalachian Mountains.

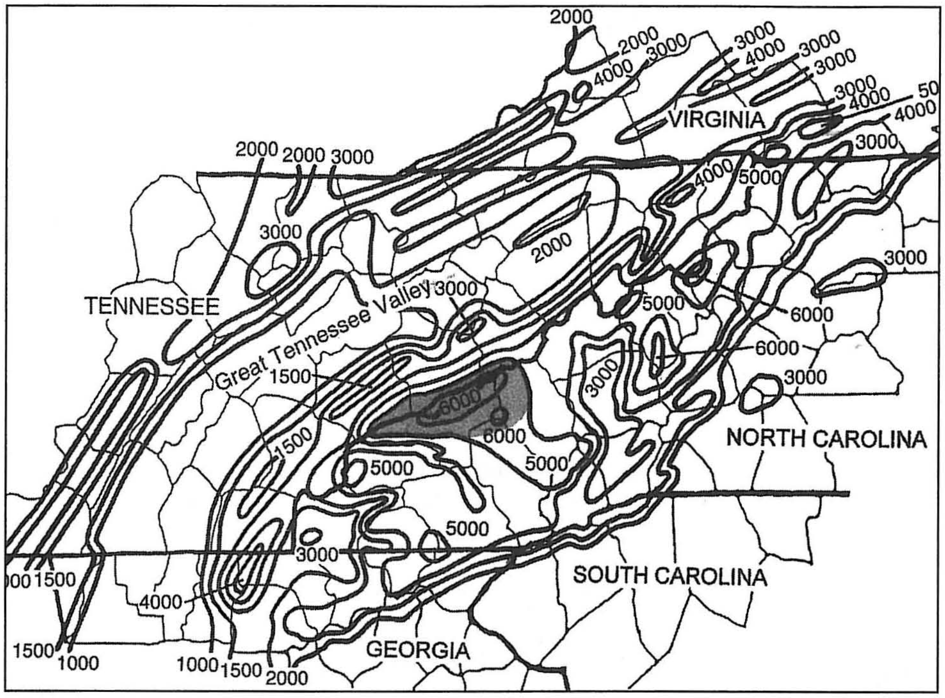

Fig. 1. Smoothed elevation map of the southern Appalachian Mountains (contours in feet MSL; shaded area denotes Smoky Mountains; state and county borders are also outlined).

Fig. 2. Location of cooperative observing stations across the southern Appalachian Mountain region reporting precipitation data to determine 'normals' (1961-1990).

2. Spatial Patterns of Normal Precipitation

The spatial distribution of 'normal' (thirty-year averages between 1961-1990) precipitation across the southern Appalachian region was constructed using data from cooperative observing stations (Fig. 2) published in the *Climatography of the United States (No. 81)* series from the NOAA/National Environmental Satellite, Data and Information Service's National Climatic Data Center (NCDC). A large variability in precipitation amounts was found to exist across the southern Appalachian region (Fig. 3), due in most part to the mountainous terrain. Although surface winds are generally variable throughout the year across the southern Appalachian Mountains, low-level southerly winds normally develop across the southern Appalachian region in association with synoptic-scale systems, bringing abundant moisture from the Gulf of Mexico and the Atlantic Ocean. Since the upslope flow of these southerly winds is greatest across the southeastern portion of the mountains, the annual 'normal' precipitation was found to be greatest across southwest North Carolina. The lowest amount of annual precipitation occurred across western North Carolina near Asheville and across northeast Tennessee. These areas are most affected by downslope flow in the southerly wind regimes, with the Asheville area situated in the French Broad River Valley and the northeast Tennessee area located in the northern section of the Great Tennessee Valley.

The normal precipitation patterns during the winter months (Fig. 4) and spring months (Fig. 5) revealed a large gradient from southwest North Carolina and northeast Georgia into the Asheville area of western North Carolina and northeast Tennessee. This can be attributed to the typical synoptic-scale storm track, occurring especially during the cool season, which takes storm centers to the west and north of the southern Appalachian Mountains, except for the occasional coastal cyclogenesis occurring to the east or southeast (Reitan 1974; Zishka and Smith 1980). These typical synoptic-scale storm tracks usually produce a strong southerly upslope flow into the mountains, especially across the southeastern portions of the mountains, while advecting abundant moisture northward from both the Gulf of Mexico and the Atlantic Ocean. Also, downslope flow from these southerly winds and weaker moisture advection across the mountains typically occurs across northeast Tennessee and the Asheville area of western North Carolina contributing to the lower precipitation amounts observed there during the winter and spring months.

During the summer months (Fig. 6), a different pattern emerged. Stations near the highest elevations of the southern Appalachian Mountains across east Tennessee and western North Carolina, especially the Smoky

Mountains, revealed higher rainfall amounts compared to other areas. With fewer synoptic-scale systems affecting the region and a weaker overall wind field, the weak upslope flow generated by the elevated heating source of the mountains likely acts as the dominant focusing mechanism for thunderstorm development in the subtropical airmass typically in place. The fact that July is the wettest month across northeast Tennessee indicates that lighter and more variable winds during the summer months enable local terrain effects to dominate the precipitation distribution along with a decrease in the downslope flow effects.

The autumn months (Fig. 7) are typically the driest months of the year across the southern Appalachian region, and the southeast-to-northwest precipitation gradient returns as synoptic-scale systems begin to become more frequent across the region. High-pressure systems usually dominate during the autumn months, bringing cool and dry conditions. However, precipitation can be highly variable during the autumn months as land-falling tropical systems occasionally affect the southern Appalachian region bringing large rainfall amounts. Tropical systems which have directly affected the southern Appalachian Mountains since 1960 include: Isbell (October 1964; rainfall up to 10 inches), Abby (June 1968; rainfall up to 5 inches), Edith (September 1971; rainfall up to 12 inches), Eloise (September 1975; rainfall up to 4 inches), Babe (September 1977; rainfall up to 9 inches), Danny (August 1985; rainfall up to 9 inches), Hugo (September 1989; rainfall up to 6 inches), Andrew (August 1992; rainfall up to 7 inches), Beryl (August 1994; rainfall up to 9 inches), Opal (October 1995; rainfall up to 6 inches), and Danny (July 1997; rainfall up to 4 inches). All of these tropical systems, with the exception of Isbell, Abby, and Hugo, made land-fall along the northern Gulf of Mexico coast, while Isbell, Abby, and Hugo made land-fall along the Atlantic Ocean coast.

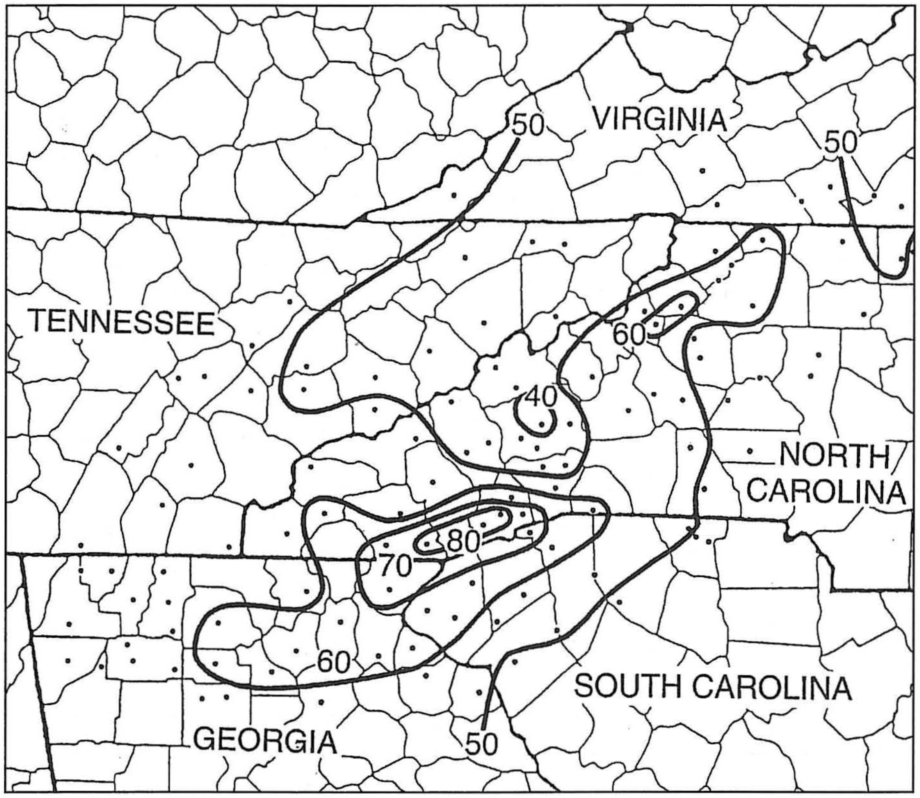

Fig. 3. Spatial distribution of annual 'normal' rainfall (in inches) across the southern Appalachian Mountain region (dots indicate locations of cooperative observing stations).

3. Flood Statistics

Because of the mountainous terrain across the southern Appalachian region, flash flooding (defined by the National Weather Service as flooding that occurs within six hours of heavy or excessive rainfall) is a major concern for local forecasters. Flash flood statistics from the mountainous counties of Tennessee and North Carolina comprising most of the southern Appalachian Mountains (Fig. 8) were compiled for this study using storm reports published by NCDC in *Storm Data* between the years 1960 and 1999. A report from a single county was treated as a single separate report even though multiple counties may have been affected by the same thunderstorm complex or synoptic system. Some limitations with using flash flood reports from *Storm Data* include the general and sometimes vague nature of the reports and the fact that many flash flood events in more remote areas may not have been reported. Guttman and Ezell (1980) found that only 25 flash floods were reported in *Storm Data* or *Climatological Data* out of 190 events that produced at least an inch of rain in an hour across a 12 county region of central Appalachia. However, since flash flooding depends on many factors other than rainfall (such as soil moisture, topography, degree of urbanization, vegetative cover, etc.), it was determined that the limitations of flash flood reports in *Storm Data* would mainly be apparent in the yearly and county distribution of reports.

In general, flash flood reports across the southern Appalachian Mountains have increased dramatically during the past decade (Fig. 9). This is likely due to the recent increased emphasis by the National Weather Service on volunteer spotter networks and warning verification. Some notable widespread flash flooding events across the southern Appalachian Mountains which significantly influenced the statistics include: November 5-6, 1977 (affected 16 counties); May 6-8, 1984 (affected 10 counties); September 22, 1989 (affected 13 counties; Hurricane Hugo); August 16-17, 1994 (affected 14 counties; Tropical Storm Beryl); and, January 7-8, 1998 (affected 17 counties).

Flash flood reports across the southern Appalachian Mountains reached a peak during the summer months, especially in August (Fig. 10), but flash flooding was generally a threat throughout the year mainly due to the

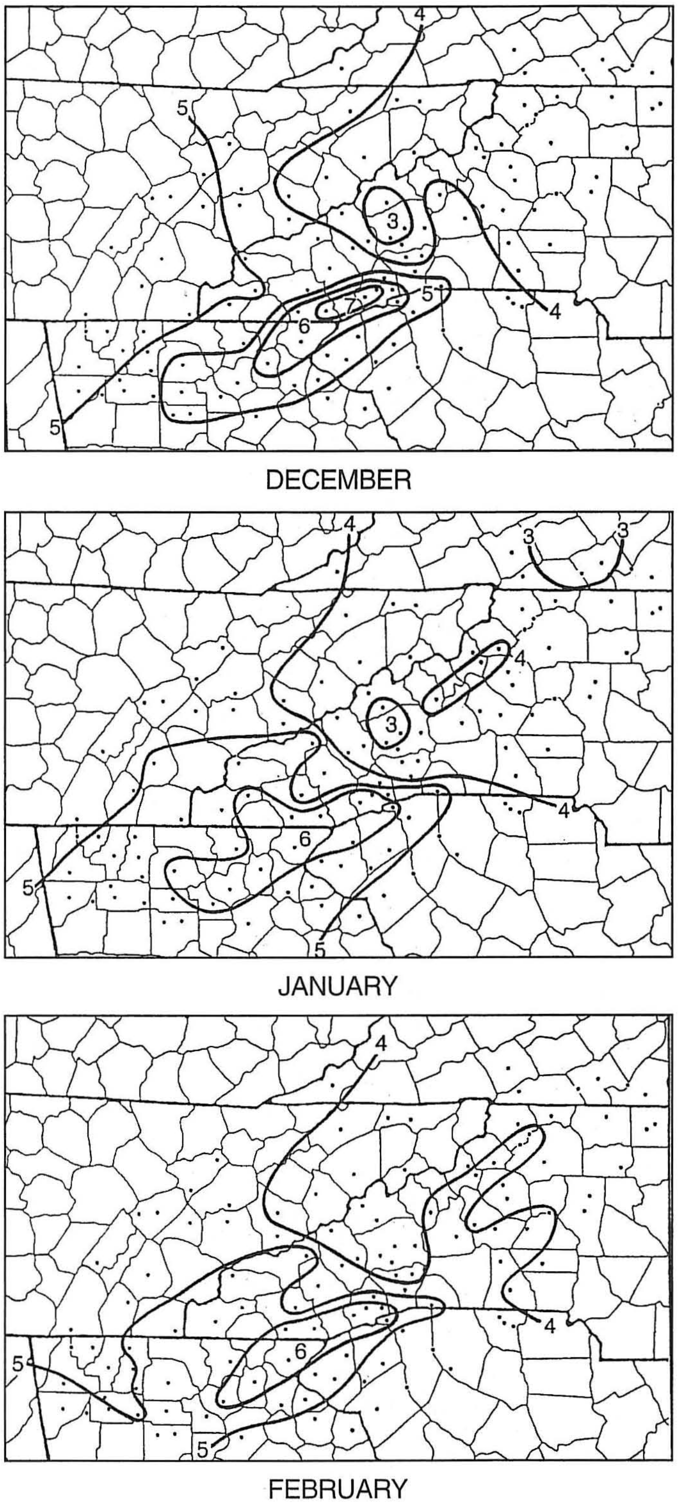

Fig. 4. Same as Fig. 3, but for winter months.

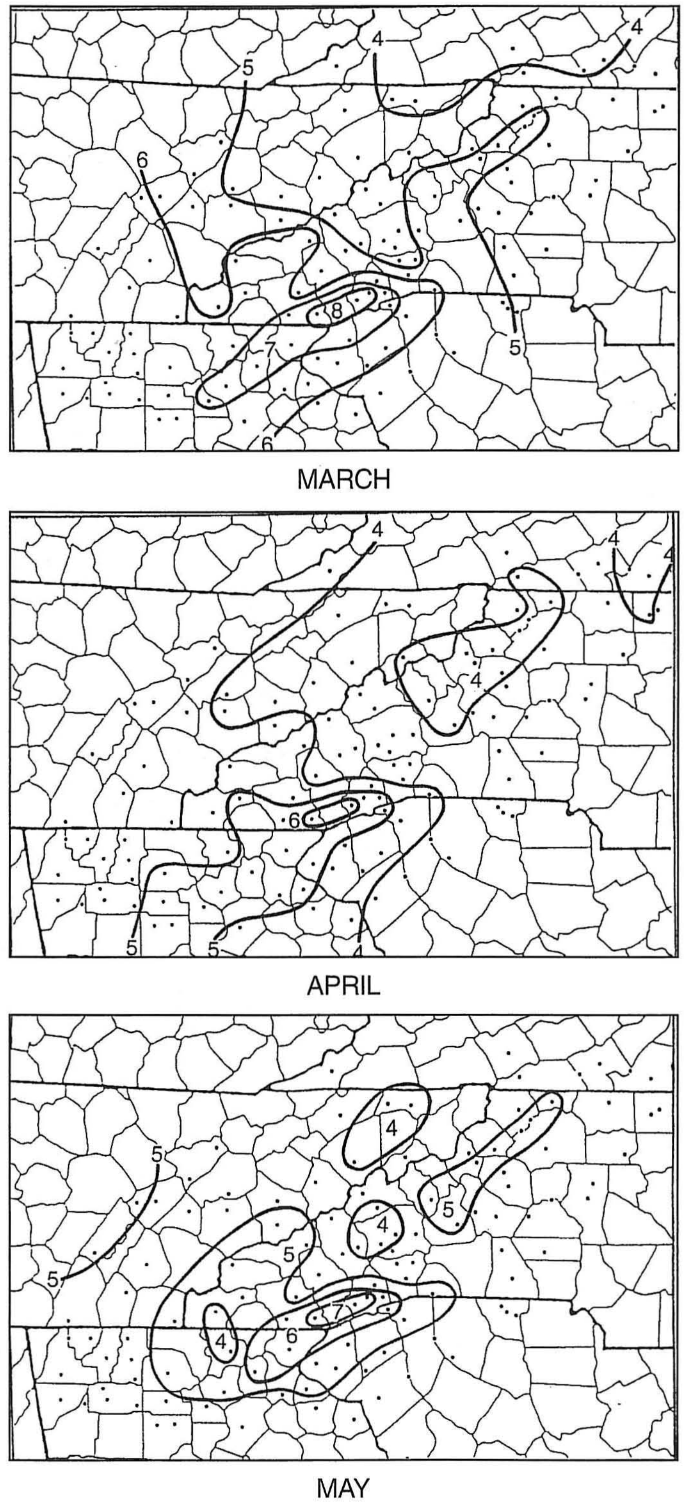

Fig. 5. Same as Fig. 3, but for spring months.

steep topography characteristics of the southern Appalachian Mountains and their proximity to the Gulf of Mexico and Atlantic Ocean moisture source regions. Figure 11 shows that the majority of flash flood reports during the spring and summer months occurred during the afternoon and evening hours, which is typical of convectively driven events. Meanwhile, reports during the autumn and winter months reached their diurnal peak during the early morning hours between 0700 and 1200 LST, surpassing the spring and summer reports during this time period. These results seem to indicate that flash flooding across the southern Appalachian Mountains during the autumn and winter months is caused primarily by large, long-lived, organized weather systems, such as tropical and extratropical cyclones. Both Wallace (1975) and Winkler et al. (1988) associated a

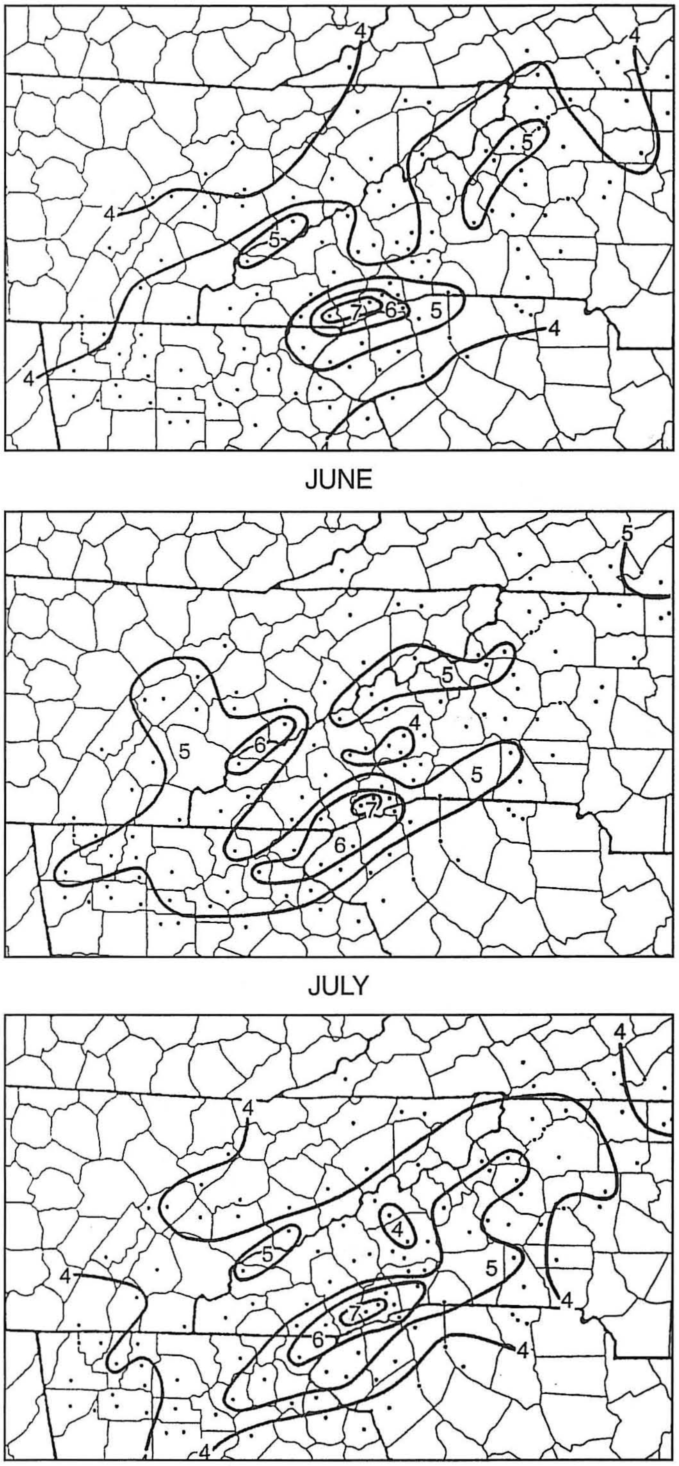

Fig. 6. Same as Fig. 3, but for summer months.

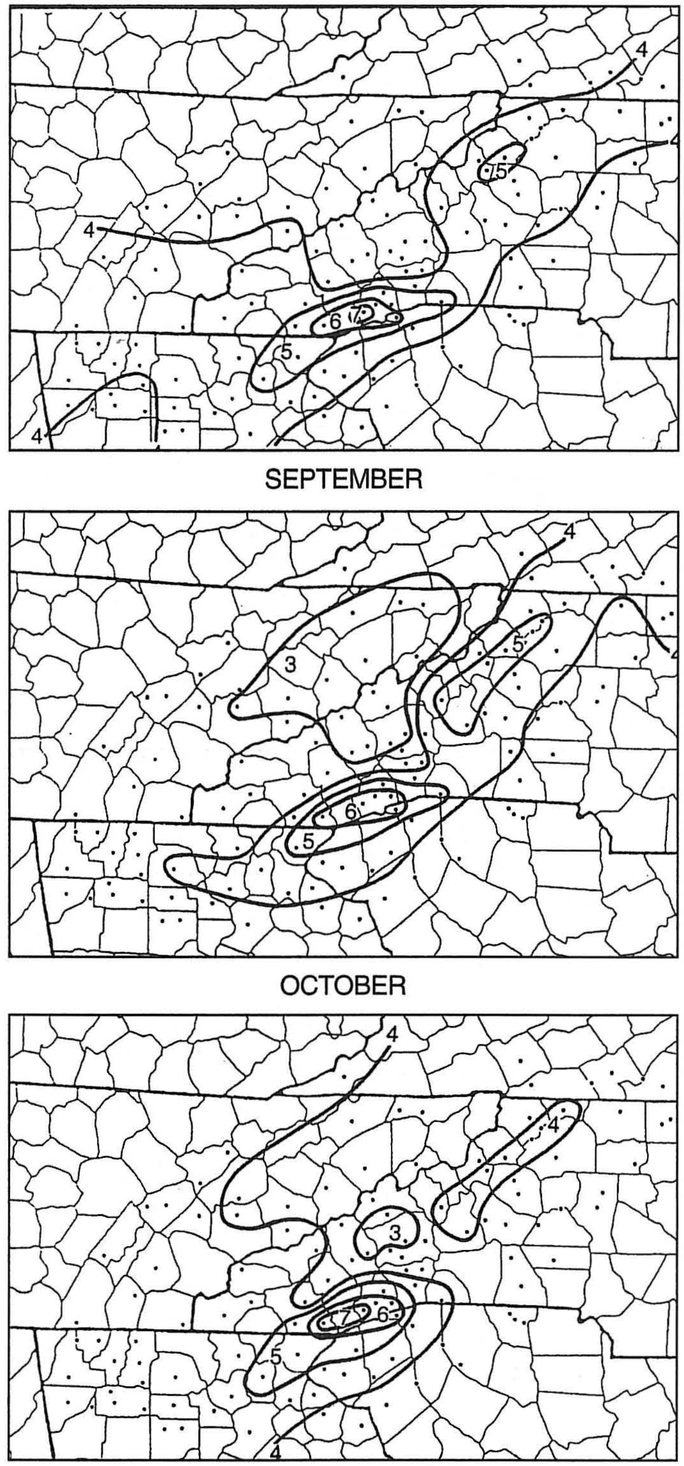

Fig. 7. Same as Fig. 3, but for autumn months.

nocturnal/early morning precipitation maximum during the winter months across the eastern United States with warm fronts and their passages. Gray and Jacobson (1977) theorized that a peak in heavy rainfall over land shifts from afternoon/evening to late night/early morning as the degree of convective organization increases. Also, Crysler et al. (1982) found that an early morning (0600 to 0800 LST) peak in very heavy rainfall occurs across Tennessee, although their work did not address seasonal variations. It is clear that previous research has shown the importance of large, long-lived, organized weather systems in generating heavy nocturnal rainfall across the eastern United States, especially during the cool season.

The flash flood statistics across the southern Appalachian Mountains also showed a bias toward the most populated counties as Buncombe (city of

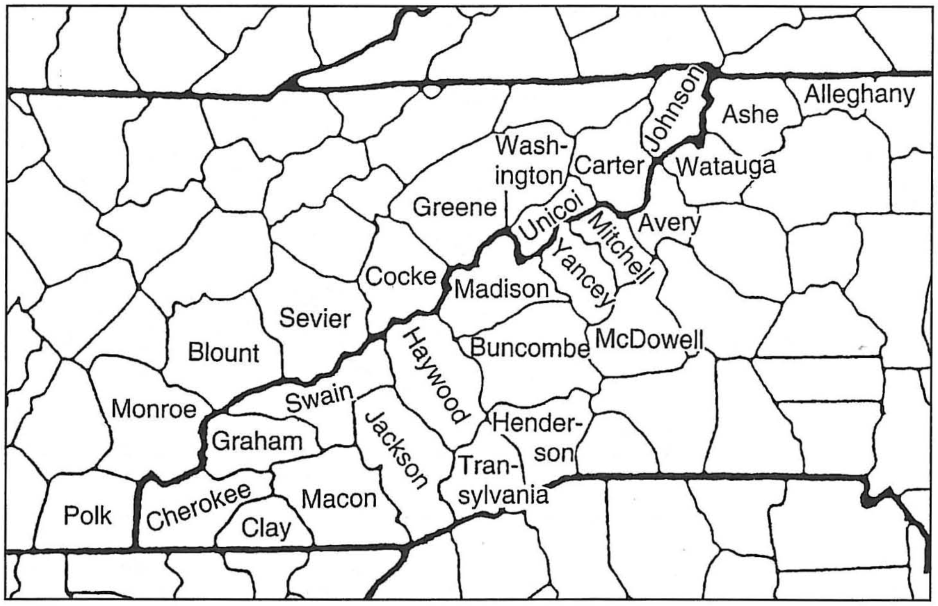

Fig. 8. Tennessee and North Carolina counties comprising the southern Appalachian Mountains.

Asheville), Transylvania (city of Brevard), and Watauga (city of Boone) counties of western North Carolina and Sevier (cities of Gatlinburg/Pigeon Forge) and Washington (city of Johnson City) counties of east Tennessee reported the highest occurrences of flash flooding. Also, the greatest number of flash flood reports with damage in excess of $500,000 occurred in Sevier county of east Tennessee where the Smoky Mountain resort towns of Gatlinburg and Pigeon Forge reside.

River or long-term flooding (defined as flooding that occurs greater than six hours after significant rainfall) statistics were also compiled from *Storm Data* to verify the monthly time period that this type of flooding usually occurs. River or long-term flooding was usually only reported in *Storm Data* if it had a major impact on multiple counties. For this study, long-term flooding reports that affected multiple counties were tabulated as a single occurrence if they occurred with the same storm system within the same general time period, instead of the county-by-county basis used with the flash flood statistics. It was found that river or long-term flooding occurred across the southern Appalachian Mountains mainly during the late winter and early spring months (Fig. 12). This is likely due to widespread rainfall, sometimes in combination with snowmelt, becoming more frequent as cold-season synoptic-scale systems continually affect the region. Also, the relative minima in vegetation and evaporation rates during this time period contribute to create higher rainfall-runoff rates. Another interesting result was the secondary peak observed between August and October. This is likely the result of tropical systems that occasionally affect the southern Appalachian Mountains during this time of year. Of the eleven tropical systems, which have directly affected the southern Appalachian Mountains since 1960, nine have occurred between August and October.

4. Synoptic Patterns of Heavy Rainfall

An important aspect of forecasting heavy rainfall events is recognition of the synoptic patterns that can produce heavy rainfall for a given area. Brooks and Stensrud (2000) have recently concluded that, although it is not possible to directly relate heavy rainfall events to flash floods, knowledge of the frequency and distribution of heavy rainfall using hourly precipitation data can help in defining the climatological threat for flash floods. In this study, a heavy rain was defined as one that produced 3 inches or more in a 6-hour or less time period and/or 4 inches or more in a 12-hour or less time period at a single station. This is roughly the maximum amount of rainfall expected once every ten years for any given location across the southern Appalachian region, according to the *Rainfall Frequency Atlas of the United States* (Hershfield 1961). Hourly precipitation data from 36 years (1960-1995) were analyzed from the *Solar and Meteorological Surface Observation Network* CD-ROM produced by NCDC to determine the dates that heavy rain fell at the five first-order stations which represent the southern Appalachian region: Chattanooga, TN; Knoxville, TN; Tri-Cities, TN; Asheville, NC; and Greenville-Spartanburg, SC (Fig. 13). A total of 32 heavy rain events (Table 1) from four of the five stations were found to satisfy the heavy rain criteria, with the Tri-Cities site not reporting a single heavy rain event. This was not too unusual since, as seen earlier, the Tri-Cities area of northeast Tennessee typically received the least amount of rainfall across the southern Appalachian region due to the downslope effects of the southerly winds that usually accompany significant rain events.

The surface synoptic features and 500-mb patterns of each heavy rain event were then analyzed, using the NOAA *Daily Weather Maps* publication, in order to classify each event into one of four categories: synoptic, frontal, meso-high or tropical. This basic classification system was adapted from Maddox et al. (1979), in which flash flood events across the United States were categorized into four categories: synoptic, frontal, meso-high and western. Since the 'western' category concerns flash flood events that occur primarily in the western United States and that do not occur frequently across the southern Appalachians, the 'western' category in this study was replaced by a 'tropical' category to account for heavy rain events that were the direct result of tropical systems. Although Maddox et al. (1979) analyzed flash flood reports, hourly precipitation from five points were used to determine heavy rain dates in this study, because reports of flash flooding vary according to many non-meteorological factors (i.e., local topography, soil type, vegetative cover, time of year, reporting biases, etc.). By determining heavy rain dates using hourly precipitation at five representative points, some consisten-

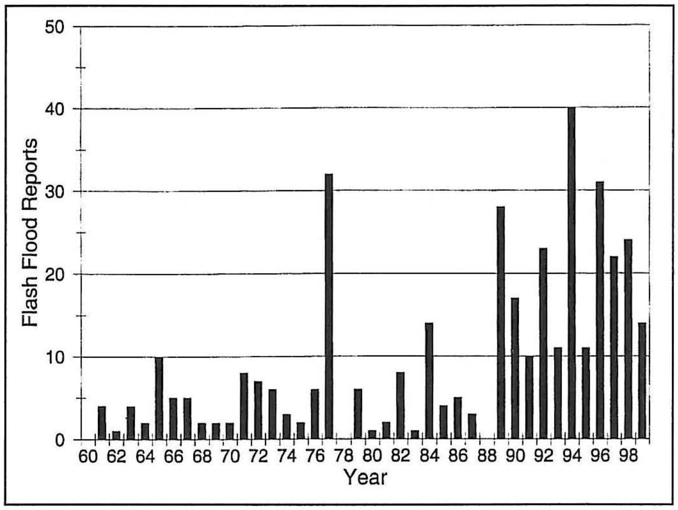

Fig. 9. Flash flood reports by year (1960-1999).

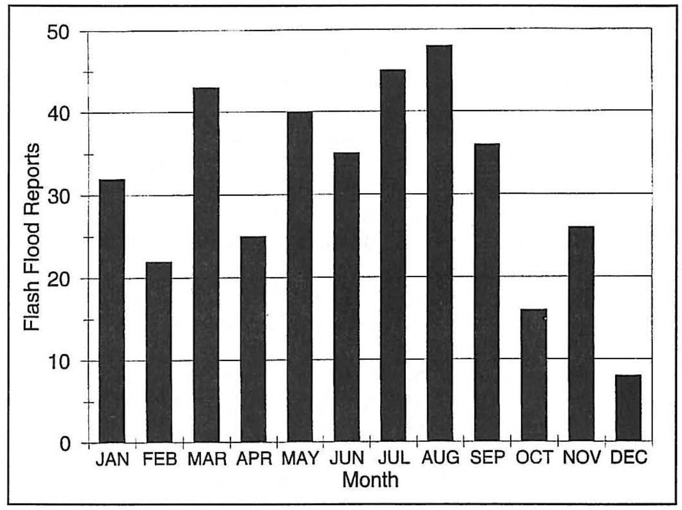

Fig. 10. Flash flood reports by month (1960-1999).

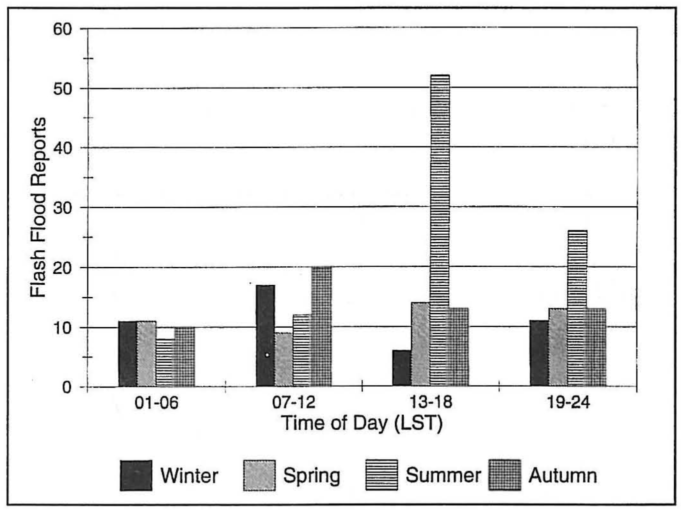

Fig. 11. Flash flood reports by hour (1960-1999).

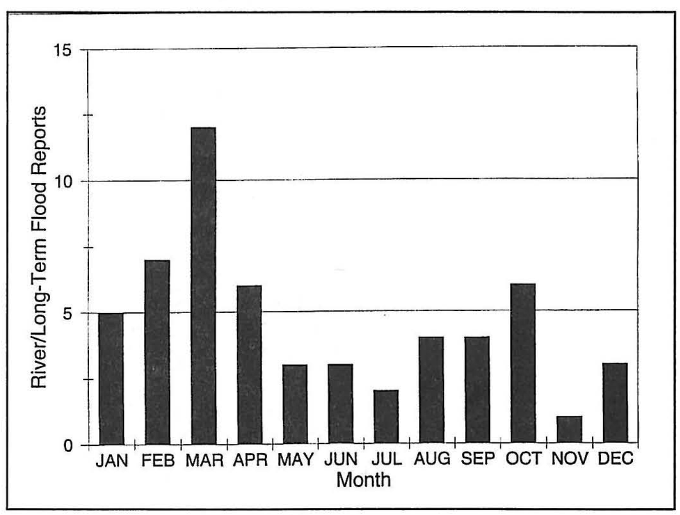

Fig. 12. River/long-term flood reports by month (1960-1999).

cy in evaluating only the meteorological factors could be maintained throughout the 36 years among events, although some events that created heavy rainfall in more remote areas outside of the five points would be overlooked. The most noticeable difference created by this approach versus Maddox et al. (1979) should be in the amount of 'meso-high' events found, which were the most numerous in the study by Maddox et al. (1979) comprising roughly a third of their sample.

According to Maddox et al. (1979), 'synoptic' flash flood events were associated with an intense synoptic-scale cyclone or frontal system and strong tropospheric wind fields. 'Synoptic' events normally developed in association with a quasi-stationary or slow-moving front, usually oriented from southwest to northeast, with a strong 500-mb level trough moving east to northeast. Heavy rains occurred in the warm sector ahead of the front. 'Frontal' flash flood events were associated with a quasi-stationary or very slow-moving front, generally oriented west to east, embedded within weak large-scale patterns. Heavy rains occurred in the cool sector behind the surface front, which is in contrast to 'synoptic' events, and usually occurred near the 500-mb level ridge position. 'Meso-high' flash flood events were associated with quasi-stationary, cool-air outflow boundaries which were generated by previous thunderstorm activity. The heaviest rains usually occurred near the 500-mb level large-scale ridge position and on the cool side of the surface boundary, usually to the south or southwest of the meso-high pressure center.

In this study, ten 'synoptic' heavy rain events were identified along with nine 'frontal' heavy rain events, eight 'meso-high' heavy rain events and five 'tropical' heavy rain events (Table 2). No heavy rain events were identified during the winter months (December, January, and February) which can be attributed to rainfall during the winter being typically stratiform in nature and accumulating over a long time period, with the less frequent cool-season convective events occurring outside of the five points used in this study. The summer months (June, July, and August) experienced the most number of heavy rain events (15) which can normally be expected of convective events which typically dominate the summer months. The spring months (March, April, and May) experienced mainly 'synoptic' nighttime heavy rain events with six of the ten 'synoptic' events identified occurring during the spring months. Six of the nine

Table 1. Dates, features and classifications of 'heavy rain' events across the southern Appalachian Mountains.

Date of Events	Surface Features	500-mb Pattern	Classification
March 5-6, 1963 (Nighttime event)	Strong cold front (N-S) with warm front (W-E) intersecting over southern Appalachians	Strong southwest flow (90 knots) ahead of deep trough over the middle MS valley	Synoptic
March 11-12, 1963 (Nighttime event)	Warm front (W-E) over TN valley w/approaching low pressure and associated cold front (N-S)	Strong southwest flow (70 knots) ahead of trough over Plains states	Synoptic
June 1, 1964 (Nighttime event)	Quasi-stationary front (W-E) located over southern AL and southern GA	Southwest flow (35 knots) ahead of trough over the lower MS valley	Frontal
October 4, 1964 (Daytime event)	Slow moving cold front (SW-NE) over OH valley w/ strong tropical low pressure ('Milda') over the lower MS valley	Southwest flow (30 knots) ahead of deepening trough over the middle MS valley	Synoptic
October 16, 1964 (Nighttime event)	Strong tropical low pressure slowly moving along the Carolina coast	Southeast flow (40 knots) to the northeast of a closed low over the Deep South	Tropical ('Isbell')
September 13, 1966 (Daytime event)	Quasi-stationary front (SW-NE) located over southern GA and southern SC	Weak southwest flow (15 knots) ahead of a short-wave trough over the southern Appalachians	Frontal
June 7, 1968 (Daytime event)	Quasi-stationary tropical low pressure along the GA/SC border	Weak east flow (20 knots) north of closed low over eastern GA	Tropical ('Abby')
June 16-17, 1969 (Nighttime event)	Quasi-stationary front (SW-NE) located over southern GA and the SC coast	Weak west flow (20 knots)	Frontal
July 27, 1969 (Daytime event)	Outflow boundaries located over southern Appalachians	Weak southwest flow (20 knots) w/closed low over Great Lakes region	Meso-high
August 4, 1969 (Nighttime event)	Weak stationary front (SW-NE) over southern Appalachians	Southwest flow (30 knots) within trough located over TN valley	Frontal
May 27-28, 1973 (Nighttime event)	Quasi-stationary front (N-S) over southern Appalachians w/prefrontal squall line approaching from west	Strong southwest flow (60 knots) ahead of closed low over the middle MS valley	Synoptic
August 13, 1973 (Daytime event)	Outflow boundaries over southern Appalachians w/stationary front (W-E) over OH valley	West to southwest flow (25 knots) within a short-wave trough over the southern Appalachians	Meso-high
Sept 13-14, 1973 (Daytime/Nighttime event)	Quasi-stationary front (W-E) over TN valley w/weak tropical low pressure over lower MS valley	Weak southwest flow (20 knots) ahead of trough over the central Plains	Frontal
May 22-23, 1974 (Nighttime event)	Frontogenesis (SW-NE) over the Carolinas w/weakening cold front (SW-NE) over OH valley	West to southwest flow (30 knots) within a short-wave trough over TN valley	Frontal
October 17, 1975 (Daytime event)	Strong low pressure centered over southern Appalachians w/cold front (N-S) over the Deep South and warm front (W-E) over NC	Strong southwest flow (50 knots) ahead of trough over the middle MS valley	Synoptic
May 28-29, 1976 (Nighttime event)	Strong, slow moving low pressure over west TN w/occluded front (NW-SE) extending across southern Appalachians	Closed low over TN valley w/south flow (35 knots)	Synoptic
July 27, 1976 (Daytime event)	Outflow boundaries located over southern Appalachians w/pre-frontal trough (W-E) over the OH valley	Weak southwest flow (15 knots) ahead of short-wave trough over TN valley	Meso-high
July 29, 1976 (Daytime event)	Outflow boundaries located over the southern Appalachians	Weak west flow (20 knots)	Meso-high

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Date of Events	Surface Features	500-mb Pattern	Classification
September 7, 1977 (Daytime event)	Weakening tropical low pressure over AL approaching stationary front (W-E) over southern Appalachians	Southwest flow (25 knots) embedded in weak trough	Tropical ('Babe')
Oct. 25-26, 1977 (Nighttime event)	Low pressure system moving northeast across the TN valley with occluded front (NW-SE) extending across the southern Appalachians	Southwest flow (30 knots) ahead of closed low located over OH valley	Synoptic
Nov. 5-6, 1977 (Nighttime event)	Weakening tropical low pressure over GA w/trough located over southern Appalachians	Closed low over AL w/southeast flow (40 knots)	Tropical (Unnamed)
July 20, 1979 (Daytime event)	Quasi-stationary front (W-E) over TN valley and southern Appalachians	Weak southwest flow (20 knots) ahead of trough over middle MS valley	Frontal
Sept. 29, 1979 (Daytime event)	Outflow boundaries over the southern Appalachians	Weak southwest flow (20 knots) ahead of trough over the Deep South	Meso-high
March 20, 1980 (Daytime event)	Warm front (W-E) moving north w/approaching low pressure and associated cold front (N-S)	Deepening trough over Plains w/southwest flow (40 knots) and weak ridge over Mid-Atlantic states	Synoptic
June 25, 1980 (Nighttime event)	Quasi-stationary front (W-E) located over central GA and central SC	Closed low located over southern Appalachians w/weak west flow (10 knots)	Frontal
July 29, 1982 (Daytime event)	Quasi-stationary front (W-E) located over northern GA and upstate SC	Weak west flow (10 knots)	Frontal
June 1, 1987 (Daytime event)	Outflow boundaries over the southern Appalachians	Weak short-wave trough over middle MS valley w/southwest flow (25 knots) and ridge over Mid-Atlantic states	Meso-high
June 19-20, 1987 (Nighttime event)	Outflow boundaries over the southern Appalachians	Weak southwest flow (15 knots)	Meso-high
August 21-22, 1990 (Daytime event)	Outflow boundary (W-E) located near quasi-stationary front (N-S) over southern Appalachians	Weak trough w/weak west flow (15 knots)	Meso-high
March 27, 1994 (Nighttime event)	Surface trough (W-E) located over the southern Appalachians ahead of approaching strong cold front (SW-NE) over TN valley	Strong southwest flow (75 knots) ahead of deep trough over Plains	Synoptic
June 26, 1994 (Nighttime event)	Prefrontal trough (SW-NE) over TN and OH valleys ahead of approaching cold front (N-S)	Deepening trough over TN valley w/strong southwest flow (50 knots)	Synoptic
October 4-5, 1995 (Nighttime event)	Strong tropical low pressure approaching stationary front (SW-NE) over TN valley	Closed low over AL w/strong south flow (50 knots)	Tropical ('Opal')

'frontal' events identified occurred during the summer months. Seven of the eight 'meso-high' events identified occurred during the summer months, while four of the five 'tropical' events occurred during the autumn months (September, October, and November). Also, roughly two-thirds of the heavy rain events exhibited a southwest mid-tropospheric flow, while none of the heavy rain events exhibited a mid-tropospheric flow with a northerly wind component. The 'typical' surface and 500-mb level synoptic features for three of the four categories of heavy rain events were constructed (Fig. 14) from the *Daily Weather Maps*. The average or most frequently occurring location of the surface fronts and 500-mb patterns were determined around the onset of the heavy rains reported at the five first-order stations across the southern Appalachian region. Since the surface and 500-mb level features varied widely with the tropical events according to the path of the system, the tracks of the four named tropical heavy rain events from Table 1 were plotted separately.

Maddox et al. (1979) found that most flash flood events across the United States occurred at night, especially with 'frontal' and 'meso-high' events. In this study, most of the 'synoptic', 'frontal' and 'tropical' heavy rain events occurred at night while the 'meso-high' heavy rain events occurred almost exclusively

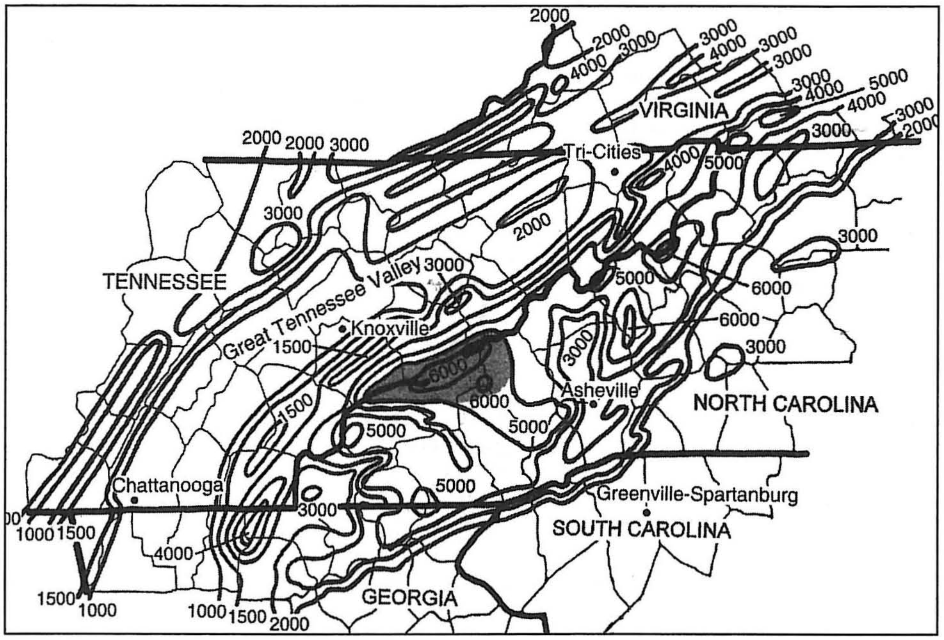

Fig. 13. Location of the five hourly precipitation stations (•) used in heavy rainfall analysis, with smoothed elevation map (contours in feet MSL).

Table 2. Heavy rain events by season and pattern (nighttime events in parenthesis).

	Winter	Spring	Summer	Autumn	Total
Synoptic	0	6 (5)	1 (1)	3 (1)	10 (7)
Frontal	0	1 (1)	6 (4)	2 (1)	9 (6)
Meso-high	0	0	7 (1)	1 (0)	8 (1)
Tropical	0	0	1 (0)	4 (3)	5 (3)
Total	0	7 (6)	15 (6)	10 (5)	32 (17)

during the day. In this study, heavy rain events were classified as occurring primarily during the day or at night (with events that occurred nearly equally during the day and night classified by the time period in which the rain began). One event (13-14 September 1973) was classified as both a daytime and nighttime event, since it produced heavy rains within 24 hours at two separate stations on either side of the Appalachian Mountains. In all, nighttime (17) and daytime (16) heavy rain events were nearly equally distributed in this study. This is in agreement with Muller and Maddox (1979), and with Crysler et al. (1982) who found that heavy rain events can occur anytime during the day or night in Tennessee (and Kentucky), but that the heavier events have a higher probability of occurrence during the early morning hours. Overall, the number of nighttime events in this study was nearly evenly distributed between the spring, summer and autumn months. Meanwhile, the summer months experienced the greatest number of daytime events (nine), and the spring months experienced the least (one).

5. Sounding Parameters of Heavy Rainfall

Several parameters were evaluated using soundings from the *Radiosonde Data of North America* CD-ROM at three area sounding sites (Nashville, TN, Athens, GA and Greensboro, NC) from the 32 heavy rain dates. The parameters evaluated include those that measure instability (K-index, Lifted-Index, CAPE), moisture content (precipitable water, surface/850/700-mb dewpoints), wind shear between the surface and 500 mb, and low-level advection (850-mb temperature, dewpoint, wind speed and direction). In order to obtain the most representative instability parameters, the morning soundings (1200 UTC) were modified using the observed high temperature of the day from the heavy rain sites if the heavy rain occurred later in the day. Soundings were evaluated to see if they were launched prior to the onset or during the time of heavy rain, and if they were considered representative of the airmass which produced the heavy rain. A total of 56 soundings were evaluated for this study.

The K-index values were typically in the 30s, with four soundings in the lower 40s and seven soundings in the 20s. This indicates that a deep layer of moisture was usually in place over the region before each heavy rain event. The K-index was highest for meso-high events (typically in the 35 to 40 range). This was not unexpected since the meso-high events were exclusively found during summer when a subtropical airmass is typically in place over the region. The Lifted Index was typically a negative number, which indicates that an unstable airmass was in place. However, a few (four) soundings with slightly positive numbers were observed during autumn and spring. The Lifted Indexes that were the most negative were observed during summer and also with the meso-high events. The Convective Available Potential Energy (CAPE) values exhibited a wide variation between events. The only consistent relationship noted was with the meso-high events, which typically exhibited values above 1500 J kg^{-1}. Konrad (1997) also found that the magnitude of CAPE values did not effectively discriminate extremely heavy rainfall events from more modest events over the interior southeast United States.

Concerning the moisture content of the airmass, the precipitable water values were nearly always above 1.30 inches (53 out of 56 soundings), with the vast majority (46 out of 56) above 1.50 inches. Surface dewpoints were nearly always above 60° F (55 out of 56), with the vast majority (49 out of 56) above 65° F. The 850-mb temperature was typically observed above 13° C (55° F) (52 out of 56), and above 17° C (63° F) during summer (21 out of 30). The 850-mb dewpoint was typically observed above 10° C (50° F) (50 out of 56), and above 14° C (57° F) during summer (16 out of 30). The 700-mb temperature was usually above 5° C (37° F) during autumn and spring (18 out of 26), and above 6° C (43° F) during summer (26 out of 30). The 700-mb dewpoint was typically above 2° C (43° F) (30 out of 40) during spring and summer, and above 4° C (39° F) (8 out of 16) during autumn.

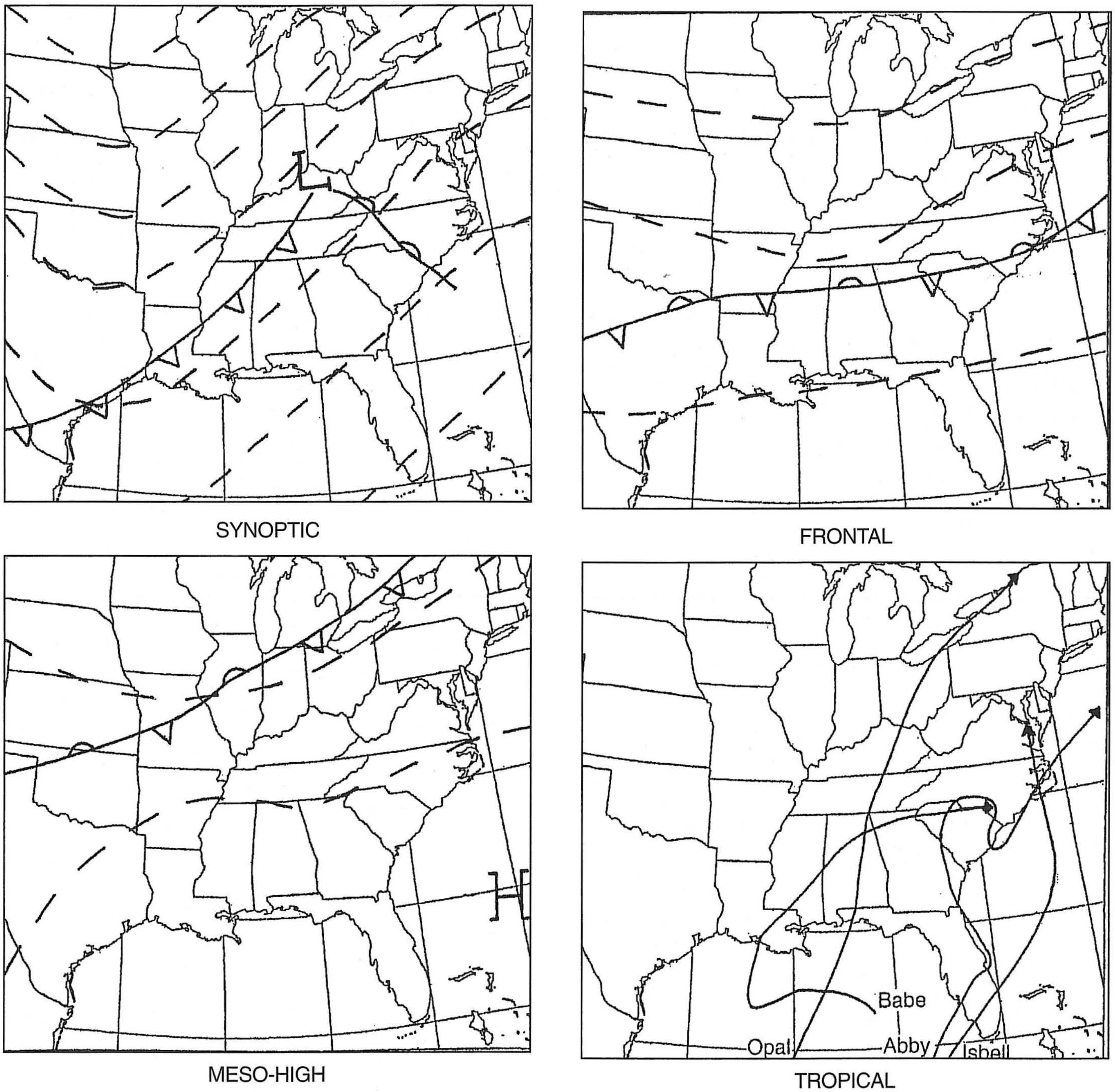

Fig. 14. Typical synoptic features (surface frontal positions, 500-mb heights [dashed lines], and tracks of tropical systems) of the four categories of heavy rainfall events across the southern Appalachian Mountain region.

Concerning the wind shear between the surface and 500-mb levels, soundings from synoptic and frontal heavy rain events typically exhibited southerly winds in the low levels with uni-directional southwest winds generally above 850 mb. Soundings from meso-high events typically revealed uni-directional southwest to west winds between the surface and 500-mb levels with wind speeds usually less than 20 knots. Soundings from tropical events exhibited a wide variety of wind directions, which was expected because the wind field direction is highly dependent on the quadrant of the storm the sounding is released near. Wind speeds with synoptic and tropical events tended to be stronger than meso-high and frontal events, with wind speeds between 30 and 60 knots typically observed above 850 mb. Soundings during summer typically exhibited weak wind fields (5 to 15 knots), while soundings during spring exhibited the strongest wind fields (30 to 60 knots). The 850-mb wind speeds were usually between 10 and 15 knots for meso-high and frontal events and between 30 and 50 knots for synoptic and tropical events.

6. Conclusions

This study indicates that the southern Appalachian region has a large precipitation variation, attributable mainly to differences in terrain, but also to a smaller degree, latitude. Upslope southerly wind flow across the southeastern side of the Appalachian Mountains created by the typical synoptic-scale storm track, combined with the resultant downslope flow across the northwestern side, produces a large precipitation gradient across the region (outside of the summer months). During the summer months, the lighter and more variable winds enable local terrain effects to act as the dominant focusing mechanism for the development of thunderstorms in the subtropical airmass typically in place.

Flash flood reports across the southern Appalachian Mountains exhibit the typical statistical biases: reports have increased recently due to the increase in spotters and verification efforts of the National Weather Service; and reports are skewed toward the populated counties of the region. August was found to be the most active month in terms of flash flooding across the southern Appalachian Mountains, but flash flooding is a problem throughout the entire year mainly due to the steep topography characteristics of the southern Appalachian Mountains and their proximity to the Gulf of Mexico and Atlantic Ocean moisture source regions. Flash flood reports during the spring and summer months peak during the afternoon and evening hours (due mainly to the influence of convectively-driven systems), while the winter and autumn months exhibit a peak during the morning hours between 0700 and 1200 LST (due mainly to the influence of organized systems). River or long-term flooding was found to be a problem during the late winter and early spring months due to the combination of long-term rainfall generated by synoptic systems and higher rainfall-runoff rates created by the loss of vegetation and lower evaporation rates. Another interesting result is the secondary peak of river/long-term flooding reports during the months of August through October, which is likely due to the influence of tropical systems.

In order to maintain consistency in analyzing different events across 36 years, a heavy rain event was defined from hourly precipitation at five representative stations across the southern Appalachian region instead of from flash flood reports. Heavy rain events were found to occur mainly during the summer months across the southern Appalachian region due to the prevalence of convective events, while the winter months experienced none due to the prevalence of stratiform events. 'Synoptic' systems are the most frequent producers of heavy rain events, usually occurring during the spring months and at night. Most 'frontal' events occur during the summer months, while most 'tropical' events occur during the autumn months. Also, roughly two-thirds of the heavy rain events exhibit a southwest mid-tropospheric flow, while none of the heavy rain events exhibited a mid-tropospheric flow with a northerly wind component. Heavy rain events were nearly equally distributed between the daytime and nighttime hours, with most of the 'synoptic', 'frontal' and 'tropical' events occurring at night and the 'meso-high' events occurring almost exclusively during the day.

Common values of sounding parameters for heavy rain events across the southern Appalachian region were:

- K-index above 30
- Negative Lifted Index
- Surface dewpoints ≥ 60° F
- 850-mb temperatures > 13° C
- 850-mb dewpoints > 10° C,
- 700-mb temperatures > 5° C
- 700-mb dewpoints > 2° C

Southerly winds were typically observed in the low levels with unidirectional southwest winds above the 850-mb level during synoptic and frontal events. The meso-high events typically exhibited weak unidirectional southwest flow between the surface and 500-mb level prior to the onset of heavy rains. CAPE values did not seem to show a direct relationship to the occurrence of heavy rain events.

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Authors

David Gaffin has been a forecaster with the National Weather Service at Morristown, Tennessee since August 1998, and began his NWS career at the Forecast Office in Memphis, Tennessee in March 1994. His research interests include wake lows, gravity/mountain waves, and local climatological studies. He has a B.A. degree (1990) in economics from the University of Tennessee-Knoxville and a M.S. degree (1993) in meteorology from Texas A&M University.

David Hotz has been a senior forecaster with the National Weather Service at Morristown, Tennessee since November 1998. He began his NWS career at the Weather Service Office in Bristol, Tennessee in August 1986, then transferred to AWSC Stoneville, Mississippi as an Agricultural Forecaster in January 1988. In December 1990, he transferred to the NWS office in Amarillo, Texas as a Journeyman Forecaster, then to Morristown, Tennessee in September 1994. His interests include developing local computer applications and local climatological studies. He has a B.S. degree (1986) in Agricultural Meteorology from Purdue University.

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