Eastern Region Technical Attachment
No. 2012-02
June 2012

WFO Binghamton, New York Flash Flood Climatology

Christopher M. Gitro
NOAA/National Weather Service
Binghamton, New York

ABSTRACT

In an effort to assist forecasters with the identification of favorable flash flood-producing environments, a synoptic classification study of flash flood events occurring in central New York and northeast Pennsylvania was completed following the Maddox et al. (1979) classification scheme. In total, 41 events covering a time period from January 1996 through September 2010 were investigated and subjectively classified as either Frontal (6 events), Synoptic (21 events), Meso High (2 events), Tropical (3 events), or Unclassified (9 events) type flash flood events. The classification was based on the 0000/1200 UTC 500 hPa patterns, the analyzed HPC surface map valid at the time of the initial flash flood report, and local radar animations.

Using the local Weather Forecast Office (WFO) Binghamton BUFKIT model sounding archive, North American Mesoscale Model (NAM) and step mountain eta coordinate model (ETA), proximity soundings were analyzed using data interpolated to the forecast point closest to the initial report of flooding. Several variables were investigated to help establish values characteristic of each flash flood type. Results indicate Synoptic flash flood-producing environments were most common, however these events were associated with the widest range of parameter values examined in this study. Meanwhile, events with weak large scale forcing such as Meso High and Frontal flash flood scenarios were less common and were accompanied by a smaller range of parameter values prior to flood occurrence. Furthermore, results of this study suggest that some of the thresholds for the Binghamton area may be different than thresholds determined in previous studies for other parts of the country.

Corresponding author address: Christopher M. Gitro, NOAA/NWS 32 Dawes Dr. Johnson City, New York 13790
E-Mail: christopher.gitro@noaa.gov

1. INTRODUCTION

Flash flooding remains one of the most serious and potentially deadly weather related phenomenon across the United States. Over the past 30 years, flash flooding has killed more people than any other weather related occurrence (National Weather Service 2010). Anticipation of meteorological events capable of widespread flash flooding remains a top priority for the National Weather Service (NWS) and its partners. As the NWS takes steps to enhance its decision support services, the ability to identify synoptic patterns capable of producing widespread flash flooding will help ensure decision makers are keenly aware of the seriousness of an impending flood scenario.

It is widely known that some areas are more susceptible to significant flash flooding than others. Key factors such as proximity to a major moisture source, antecedent soil characteristics, and urban effects are all factors that influence flash flood frequency (Davis 2001). In addition, flash flooding can also be enhanced by complex terrain, which can act to increase runoff and channel rising flood waters into raging torrents (LaPenta et al. 1995). Complex terrain can also act as an anchoring mechanism where developing storms remain positioned over the same location for an extended period of time due to a constant influx of low-level moisture and enhanced lifting due to orographic effects (Davis 2001).

The terrain of central New York and northeastern Pennsylvania is considered complex due to favorable positioning along the northern extent of the Alleghany Plateau. The Binghamton, NY (BGM) county warning area (CWA) is also comprised of the Pocono and Catskill Mountain ranges, where numerous fast responding year-round streams flow into the main stem Susquehanna and Delaware Rivers (Fig. 1). Not surprisingly, the BGM CWA is susceptible to major flash flooding as a result of the area's close proximity to the western Atlantic moisture source and the fact that the region contains numerous small tributaries which flow into the main stem rivers. These factors, combined with the complex terrain characteristic of the area, makes flash flooding the single greatest weather threat to residents of northeastern Pennsylvania and central New York [*Storm Data* (NOAA 1996-2010)].

In an early attempt to classify synoptic patterns responsible for widespread flash flooding, Maddox et al. (1979), hereafter referred to as M79, investigated over 150 events from the years 1973 through 1977. In the investigation, three patterns were identified as favorable setups for central and eastern U.S. flash flood scenarios. Under the Synoptic flash flood scenario, the upper-level atmosphere was often characterized by a highly-amplified longwave trough to the west of the main flash flood region. At the surface, a slow moving cold or stationary front was often configured in a northeast to southwest fashion to the west of the main flood region. Convergence along this boundary coupled with upper-level forcing both act as catalysts for shower and thunderstorm development in the warm sector ahead of the front. Deep southwesterly winds parallel to the front embedded in cyclonic flow aloft allowed showers and storms to train over the same areas repeatedly, often resulting in high rainfall totals and flash flooding.

For Frontal and Meso High type flash flood situations, the upper-level pattern was often dominated by upper-level ridging aloft. A low amplitude shortwave traveling along the northern periphery of the upper ridge combined with isentropic ascent along and north of a warm or stationary front provided enough forcing to initiate thunderstorm development north of the boundary. In the case of a Meso High type environment, the low-level forcing for ascent was often provided by an outflow boundary from previous convection, whereas the primary low-level forcing mechanism for Frontal environments was the presence of a synoptic scale warm or stationary front. In both cases, thunderstorms form on the cold side of the front or outflow boundary and when combined with steering level winds parallel to the low-level boundary, often results in the training of storms moving over the same areas repeatedly.

During the period of this study, 29 people lost their lives in the BGM CWA due to flash flood related circumstances (Fig. 2; Storm Data 1996-2010). In a study documenting NWS Eastern Region (ER) flash flood forecasting challenges, LePenta et al. (1995) showed that New York and Pennsylvania led the Eastern Region of the National Weather Service with the number of reported flash flood events from 1955-1989. While these statistics serve as the primary motivation behind the development of this flash flood climatology, it is also realized that knowledge of favorable synoptic patterns conducive to significant flash flooding could serve as a recognition tool for future flash flood situations. While other studies have documented flash flooding in both the BGM CWA (Jessup and DeGaetano 2008) and the northeastern US (LaPenta et al. 1995; Cope 2009; Jessup and Colucci 2012, this is the first local attempt to classify major flash flood occurrences locally following the M79 classification scheme.

2. DATA AND METHODOLOGY

In an effort to identify all significant flash flood events in the BGM area of responsibility, flash-flood Storm Data reports from January 1996 through September 2010 were investigated. A significant flash flood event was identified if one or more of the following occurred:

- *Five or more flash flood reports from a single event*
- *Damage totals ≥ $500,000 (unadjusted for inflation)*
- *At least one confirmed fatality*

In the 15-year period of investigation, a total of 41 events were identified meeting these criteria. Once an event was identified, archived surface maps from the Hydrometeorological Prediction Center (HPC) and 500 hPa maps (available from HPC and the Storm Prediction Center) were inspected to determine upper-level and surface patterns characteristic of each event. Following the synoptic patterns described by M79, this approach served as the initial event classification methodology. If the synoptic patterns did not cleanly fit into any of the flash flood patterns previously discussed by M79, the event was labeled Unclassified. If a major flash flood event was caused by a remnant tropical circulation, the event was classified as Tropical.

After initial classification, the event classifications were confirmed with archived KBGM WSR-88D radar data to potentially identify storm-generated, storm-scale features that may have been responsible for thunderstorm generation and subsequent flash flooding. If a storm-scale feature such as an outflow boundary was found via radar to directly influence the development of thunderstorms, the event was then classified accordingly. This procedure was generally used to find outflow boundaries to identify Meso High events. If radar data from KBGM was unavailable for an event, data from adjacent radar sites surrounding the BGM CWA was interrogated. The main sources used for radar interrogation included both GR Analyst and the local Weather Event Simulator (WES) at WFO BGM.

Following the event classification, several atmospheric variables such as low-level jet (LLJ) wind speeds, precipitable water (PWAT) values, 850-500 hPa shear, and warm cloud layer depths, were derived from model forecast data using BUFKIT software (Mahoney and Niziol 1997) via a local WFO BGM archive which dates back to 1998. The BUFKIT proximity sounding valid at the time of the initial flash flood report was used in an effort to ascertain values common for each flash flood type. For the sounding analysis, 34 of the 41 cases identified were examined. No sounding analysis was performed for the seven cases that occurred prior to 1998 due to the lack of BUFKIT data. Based on the limited number of forecast points available and the fact that no stability indices were interrogated during this study, no attempt was made to eliminate soundings which may have suffered from convective contamination (Baldwin et al. 2002). Under this methodology, both the North American Mesoscale (NAM; Rogers et al. 2001) and step mountain eta coordinate model (ETA; Black 1994) proximity soundings were interrogated. For cases that occurred in 1998 or 1999, data from 0 to 11 hour ETA forecasts were examined, with the forecast valid at the time closest to the first flash flood report used for the sounding analysis. For cases after 1999, data from 0 to 5 hour ETA or NAM forecasts were used, (depending on the operational model at the time) with valid times closest to the initial flash flood report. For all cases in which BUFKIT data was available, one proximity sounding was identified for each event. Once selected, data was derived from either an initial-hour analysis or forecast hour sounding depending upon the initial report time. In an effort to achieve as much forecast model continuity as possible, only NAM or ETA model forecast data was interrogated. It is recognized however that both models received numerous updates during the course of this study (COMET retrieved 2012; available online at http://www.meted.ucar.edu/nwp/pcu2/) which prevents total model continuity through the period of interest. Additionally, there were more NAM and ETA forecast points available in BUFKIT for the BGM forecast area than for any other available model, which increased the ability to select the closet proximity sounding to the initial report of flash flooding.

3. RESULTS

a. Flash Flood Maddox Type Classification

From January 1996 through September 2010, 41 total flash floods met the criteria outlined in Section 2. A listing of the events is given in Table 1. Flash flooding across the BGM CWA is a year-long issue as shown by the distribution of events throughout the year (Fig. 3a). These results agree with findings by Cope (2009), who while using all flash flood reports for ER WFOs between the years of 1986 to 2007, also showed that flash flooding is a year-round issue for the BGM CWA. The summer months had the highest frequency of occurrence, with 19 of the 41 events occurring during the months of June, July, and August. These results support previous research completed by Jessup and DeGaetano (2008) which showed that flash flooding across the BGM CWA was most common during the months of late July and August. Spring was the second most active part of the year with nine total events occurring from March through May. The winter months of December through February had eight total occurrences which validates that frozen ground combined with highly amplified weather systems can serve to keep flash flooding a serious year-round problem for the BGM forecast area of responsibility. The occurrence of major flash flood events during the winter months supports findings by LaPenta et al. (1995) who showed that the loss of vegetation in the winter months combined with lack of soil infiltration due to frozen ground, could lead to flash flood concerns year-round across the NWS Eastern Region. Lastly, the fall months of September through November saw five total occurrences with three of the events occurring as a direct result of remnant tropical circulations moving over the area (Fig. 3a).

Of the 41 flash flood events reviewed for this study, Synoptic setups were the most common flash flood producing environments. Synoptic environments accounted for approximately 21 of the 41 cases, or 51% of the total events. Synoptic events were typically easy to classify as most cases displayed a highly-amplified upper-level trough approaching from the west. Synoptic type flash flood environments occurred in each season but were most common during the winter months (8-total events) and least common during the fall (1-total event; Figs. 3b-d).

Unclassified events were the second most common flash flood producing environment which accounted for 9 of 41 events or roughly 22% of the cases. For these events, both upper-level and near surface features did not display similar upper and lower level characteristics as those offered by M79. For several of these events, a closed upper-level low pressure system was positioned near the BGM CWA at the time of flash flooding. While this pattern does not correspond to the flash flood patterns described by M79, this pattern has been recognized in previous research as another pattern capable of flash flooding in the Eastern US (Spayd 1982; Elsner et al. 1989). Unclassified events were most common during the summer months (6 events) and less frequent during the spring (2 events) and fall (1 event). For most Unclassified cases, upper-level and surface features were fairly weak, which supports no occurrences during the winter months when conditions are typically more baroclinic in nature (Figs. 3b-d).

Frontal events were the third most common setup for flash flooding in the BGM CWA. In total, 6 of the 41 events were classified as Frontal, which accounted for approximately 15% of the total cases. Frontal-type flash flood situations were most common during the summer months, with 5 of the 6 events occurring during the months of June through August (Figs. 3b-d).

Three flash flood events were attributed to remnant tropical circulations moving over the area with these events predominant during the fall months. And lastly, 2 of the 41 events were classified as Meso High cases in which flash flooding occurred along the cool side of an outflow boundary. Both Meso High events occurred during the summer with well-established upper-level ridging prevailing south of the forecast area. Of interest, the two Meso High events that did occur across the BGM CWA unfortunately resulted in multiple fatalities for each case (Figs. 3b-d).

In an effort to determine timeframes in which significant flash flooding was most common in the BGM CWA, the initial report time for all 41 events was determined from Storm Data reports. Based on the initial report times, the onset of significant flash flooding occurred most frequently during the daylight hours from mid-morning through late afternoon. Surprisingly, the onset of significant flash flooding was less common after 0000 UTC, and nonexistent between the hours of 0600 and 0900 UTC where no initial flash flood reports were received. The lack of significant flash flood reports between the hours of 0600 and 0900 UTC corresponds well with locally observed storm spotter trends, in which the number of reports received normally declines during the overnight hours. In general, the above results indicate that the onset of significant flash flooding was most common during the peak heating hours, when the diurnal cycle would normally support the highest levels of instability that result from daytime heating (Fig. 4).

b. Flash Flood Forecast Variable Results

In addition to classifying events based on the large-scale flow pattern, several forecast variables were also investigated in hopes of establishing criteria favorable for each flash flood setup in the BGM CWA. Forecast variables investigated included the low-level jet (LLJ) wind speeds, 850-500 hPa speed shear, precipitable water (PWAT), and warm cloud layer depths. All forecast variables were taken from archived BUFKIT forecast proximity soundings to include multiple variables derived from the heavy rain selection of the program. While it is recognized that the small number of cases of each event type precludes the ability to generate any statistically significant relationships, the results can still suggest possible connections.

The first variable investigated was the LLJ speed (Fig. 5) which BUFKIT defines as the maximum wind speed at a level between the surface and 800 hPa layer (E. Mahoney 2011 personal communication). The presence of a LLJ is often necessary for significant flash flood events as these features act to ensure a constant replenishment of moisture into a flash flood region. In addition, LLJs can serve to increase low-level convergence and forcing for ascent when they interact with pre-existing surface fronts or complex terrain. Of the 5 flash flood environments classified, Synoptic-type flash flood events had the greatest variability with 2 events displaying a LLJ speed of 76 kt, while one event only had a speed of 12 kt. This is not surprising since Synoptic events were found to occur year-round which increases the variability of the dataset as it contains weaker LLJ wind speeds from summer events which are normally associated with weaker wind fields aloft. For Frontal and Meso High events, LLJ speeds displayed a smaller range of values (median values less than 30 kt). This relatively small range was likely due to the smaller number of Frontal and Meso High events, along with the fact that these events typically occurred during the summer, when winds fields are normally weaker. Tropical events did display a higher median LLJ wind speed which is not surprising as strong wind fields can accompany remnant tropical systems as they move up the East Coast. In general, LLJ wind speeds greater than 20 kt appear to be a favorable benchmark for BGM forecasters to use when determining if low-level moisture transport will be sufficient enough to result in possible flash flooding.

It has been recognized (Doswell et al. 1996; Junker et al. 1993; Davis 2001) that strong vertical wind shear aloft leads to entrainment of dry air and subsequent evaporation. Weak winds in the vertical promote greater precipitation efficiency by allowing falling precipitation to cascade towards the surface in a moisture rich environment, thereby reducing the effects of dry air entrainment and evaporation. In addition, strong winds aloft in a high shear environment often promote forward propagating MCSs, which limits the residence time of heavy rainfall cores over a particular area (Corfidi 2003). Of the 34 events in which BUFKIT data was available, Unclassified, Frontal, and Meso High environments were characterized by the weakest values 850-500 hPa of vertical wind shear. Of these three environments, 850-500 hPa vertical wind shear values of less than 15 kt appeared as a favorable first guess at gauging whether storm motion will be slow enough to promote long enough residence times for both Meso High and Frontal-type flash flood setups. Under these scenarios, multicell convection can regenerate in close enough proximity to decaying cells, which combined with a favorable storm motion vector, can result in both backbuilding and echo training over the same areas repeatedly. For both Tropical and Synoptic environments, 850-500 hPa vertical wind shear values were substantially larger and showed much greater spread, thus providing little utility in determining the flash flood potential over the BGM CWA (Fig. 6).

PWAT values were also derived from each BUFKIT proximity sounding and compared to mean climatological values for both the Buffalo, New York (KBUF) and Albany, New York (KALY) sounding locations; with data derived from the Rapid City, South Dakota WFO precipitable water plots (available at http://www.crh.noaa.gov/unr/?n=pw). For each event, either KBUF or KALY values were selected based on which location was closest to the initial flash flood report. Once compared, a simple ratio was calculated to determine the event's percentage above or below the climatological norm. For instance, BGM forecasters following results summarized by Moore et al. (2003) typically associate possible flash flooding when PWAT values increase to at least 150% of normal. As shown in Figure 7, this rule is a fairly good "first guess" for the Synoptic events in the data set; however Frontal and Meso High events displayed a median value at or near the climatological norm, suggesting that warm season flash flood events do not always depart substantially from climatology. It is recognized however that the small sample size of Frontal and Meso High cases precludes substantiated evidence to justify this relationship. In addition, Figure 7 also shows that all events independent of type, contained PWAT values near or above the climatological normal value. In fact, Synoptic events often contain values much above average, with the upper tier events characterized by values as high as 400% above the climatological norm.

Flash flood literature in recent years has emphasized the importance of warm rain processes resulting in greater precipitation efficiency through rainfall production from the coalescence and collision microphysical process (Davis 2001; Davis 2004; Pontrelli et al. 1999). Warm cloud layer depths of at least 3 to 4 km have been shown as a necessary ingredient in some of the most historic floods in recent memory (Davis 2004; Schaffner et al. 2008). As a general first guess threshold used by BGM forecasters, warm cloud layer depths in excess of 10,000 ft (3 km) are generally considered an initial benchmark for conditions which may favor the production of rainfall through warm rain collision and coalescence processes. Of the 34 events in which BUFKIT data was available, nearly all event types displayed a high amount of variability with resultant warm cloud layer depths (Fig. 8). As shown in Figure 8, the general rule of 10,000 ft employed by BGM forecasters is shown to be an adequate first guess for warm season type events (Meso High, Frontal, and Tropical). As with 850-500 hPa speed shear values, this general rule loses operational applicability for cool season Synoptic flash flood events which often display lower freezing level heights due to cooler thermodynamic profiles. However Figure 8 does suggest that a slightly lowered threshold of 8,000 feet may serve as an adequate benchmark for cool season events.

4. DISCUSSION

When comparing the results of this study with long standing empirical rules for flash flood assessment and forecasting at WFO BGM, the most notable deviation from accepted practice occurred with LLJ wind speeds. Funk (1991) suggested 30 kt was a minimum LLJ wind speed necessary for significant heavy rainfall events when the synoptic patterns favored the development of Frontal and Meso High flash flood setups. Despite this, BGM forecasters have generally used 20 kt as an initial benchmark when performing flash flood assessment as orographic effects can often provide significant low-level forcing contributions in addition to the LLJ and its associated forcing from warm thermal advection. The results of this research validate this methodology as the median LLJ wind speeds for seven Frontal and two Meso High events were 24 and 23.5 kt respectively. In an alternate study outlining statistical differences between flash flood and non-flash flood producing environments across the BGM CWA, Jessup and DeGaetano (2008) showed that only 15 of 51 flash flood events between the years 1986-2003 were accompanied by LLJ wind speeds of 20 kt or greater. However, their study was limited to warm season (May through October) events which likely excludes higher LLJ wind speeds which are more typical of cool season flash flood events. In addition, the LLJ wind speeds for the 51 flash flood events investigated in their study were derived from 850 hPa wind speeds, which from operational experience may have been at heights above or below the LLJ maximum. In response to LLJ height variability, BGM forecasters often derive the LLJ wind speed from BUFKIT, which determines the LLJ wind speed by taking the highest wind speed below 800 hPa. Lastly, all warm season flash flood reports during the period of study likely included events resulting from "pulse-type" thunderstorm activity. Under these scenarios, weak wind fields aloft likely prevented LLJ speeds from reaching or exceeding the 20 kt requirement.

Despite subtle differences related to LLJ wind speeds for major flash flood events across the BGM CWA, the results of this study also validate some long standing empirical rules used by operational forecasters in the assessment of heavy rain and potential flash flooding. As discussed in Section 3, warm cloud layer depths in excess of 10,000 ft were found to occur with the majority of Frontal and Meso High flash flood events. These findings support previous research by Pontrelli et al. (1999) and Davis 2004 which states that warm cloud layer depths in excess of 3-4 km can result in tropical rainfall rates and an increased risk of flash flooding through rainfall development from the highly efficient collision and coalescence microphysical process. Unfortunately this relationship was not as strong for Synoptic and Unclassified events which may be a result of Synoptic events dominating year-round and the fact that the main forcing contributions for Unclassified events appears to be from a closed upper low pressure system in close proximity to the

BGM CWA. Both of these situations would result in lower freezing heights and lower warm cloud layer depths. The results of this study also validate that weak 850-500 hPa speed shear values are favorable for warm season flash flood events which support slower storm motions and less entrainment of dry air thus increasing the flash flood potential. Finally, using PWAT values greater than 150% of normal as an initial assessment for potential flash flooding appeared to correspond well with Synoptic flash flood events, however results from this study suggest that a slightly lower threshold is possible for warm season Frontal and Meso High flash flood cases.

5. SUMMARY AND CONCLUSIONS

Forty-one significant flash flood events that impacted the BGM CWA from January 1996 through September 2010 were identified in an effort to develop a Maddox-based flash flood climatology summarizing recognizable surface and upper-level features responsible for flash flooding across the BGM CWA. Of the 41 events classified, Synoptic-type flash flood events were the most common (21 of 41 events). The second most common flash flood event type was Unclassified events in which the upper and lower level patterns did not match any patterns described by M79 (9 of 41events). Frontal-type flash flood environments were the third most common (6 of 41 events) type of flash flood producing environments in the BGM CWA, in which flash flooding develops north of a stationary or warm frontal boundary. Three flash flood events were also attributed to a remnant tropical system moving over the area and 2 cases were classified as Meso High environments in which flash flooding developed north of an outflow boundary from previous convection.

The annual frequency of occurrence suggests that significant flash flooding is a serious year-round concern for BGM forecasters with the summer months of June, July, and August holding the highest percentage of significant flash flood cases (19 of 41 events). During the summer months, the decrease in frequency of Synoptic type flash flood environments is replaced by an increase in the number Frontal and Meso High type environments which is consistent with previous research which states these event types prevail with strong upper-level ridging in place. Results show that flash flooding can occur during the winter months where frozen ground enhances runoff.

In addition to event classification based solely on upper-level and surface features, several forecast variables were inspected for 34 events from archived ETA/NAM BUFKIT forecast proximity soundings. Of the variables investigated, forecast parameters associated with Synoptic events showed the most variability, which is likely a result of Synoptic events occurring year-round. For warm season events such as Frontal and Meso High events, forecast variable spreads were much lower, suggesting a higher degree of predictability for future cases displaying similar surface and upper-level patterns. Finally, local empirical rules such as LLJ wind speeds in excess of 20 kt, values of 850-500 hPa shear less than 15 kt, and PWAT values above 150% of the climatological norm were all confirmed as useful parameters to look for when ascertaining the flash flood threat across the BGM CWA.

REFERENCES

Baldwin, M. E., J. S. Kain, and M. P. Kay, 2002: Properties of the convection scheme in NCEP's Eta Model that affect forecast sounding interpretation. *Wea. Forecasting,* **17,** 1063–1079.

Black, T. L., 1994: The new NMC mesoscale Eta Model: Description and forecast examples. *Wea. Forecasting,* **9,** 265–278.

Corfidi, S. F., 2003: Cold pools and MCS propagation: Forecasting the motion of downwind- developing MCSs. *Wea. Forecasting,* **18,** 996–1016.

Cope, A. M., 2009: A climatology of flash flood events for the National Weather Service Eastern Region. ER Tech. Memo. NWS ER-103, NOAA/NWS, Bohemia, NY, 85 pp. [Available online at http://www.erh.noaa.gov/er/hq/ssd/erps/tm/tm103.pdf].

Davis, R. S., 2001: Flash flood forecast and detection methods, *Severe Convective Storms, Meteor. Monogr., No. 50,* Amer. Meteor. Soc., 481-525.

Davis, R. S., 2004: The impact of tropical rainfall rates on flash flood detection. Preprints, *22nd Conf. on Severe Local Storms,* Hyannis, MA, Amer. Meteor. Soc.

Doswell, C. A., III, H. E. Brooks, and R. A. Maddox, 1996: Flash flood forecasting: An ingredients-based methodology. *Wea. Forecasting,* **11,** 560–581.

Elsner, James B., Walter H. Drag, Jeffrey K. Last, 1989: Synoptic weather patterns associated with the Milwaukee, Wisconsin Flash Flood of 6 August 1986. *Wea. Forecasting*, **4**, 537–554.

Funk, T. W., 1991: Forecasting techniques utilized by the Forecast Branch of the National Meteorological Center during a major convective rainfall event. *Wea. Forecasting,* **6,** 548–564.

Jessup, S. M., and S. J. Colucci, 2012: Organization of flash-flood producing precipitation in the northeast United States. *Wea. Forecasting,* **27,** 345–361.

Jessup, S. M., and A. T. DeGaetano, 2008: A statistical comparison of the properties of flash flooding and nonflooding precipitation events in portions of New York and Pennsylvania. *Wea. Forecasting,* **23,** 114–130.

Junker, N. W., and S. L. Fauver, 1999: A study of heavy rainfall events during the Great Midwestern Flood of 1993. *Wea. Forecasting,* **14,** 701–712.

LaPenta, K. D., and Coauthors, 1995: The challenge of forecasting significant rain and flooding throughout the Eastern Region of the National Weather Service. Part I: Characteristics and events. *Wea. Forecasting,* **10,** 78–90.

Maddox, R. A., C. F. Chappell and L. R. Hoxit, 1979: Synoptic and meso-α scale aspects of flash flood events. *Bull. Amer. Meteor. Soc.*, **60,** 115–123.

Mahoney, E.A., and T.A. Niziol, 1997: BUFKIT: A software application toolkit for predicting lake-effect snow. Preprints, *13th Intl. Conf. on Interactive Information and Processing Systems for Meteorology, Oceanography, and Hydrology*, Long Beach, CA, Amer. Meteor. Soc, 388–391.

Moore, J. T., F. H. Glass, C. E. Graves, S. M. Rochette, and M. J.Singer, 2003: The environment of warm-season elevated thunderstorms associated with heavy rainfall over the central United States. *Wea. Forecasting,* **18,** 861–878.

National Oceanic and Atmospheric Administration (NOAA), 1996-2010: *Storm Data* [Available from the National Climatic

Data Center, 151 Pennsylvania Avenue, Asheville, NC 28801-5001].

National Weather Service, 2010: Natural Hazard Statistics. [Available from http://www.weather.gov/om/hazstats.shtml].

Pontrelli, M. D., G. Bryan, and J. M. Fritsch, 1999: The Madison County, VA flash flood of 27 June 1995. *Wea Forecasting*, **14,** 384–404.

Rogers, E., T., Black, B. Ferrier, Y. Lin, D. Parrish, and G. DiMego, 2001: Changes to the NCEP Meso Eta Analysis and Forecast System: Increase in resolution, new cloud microphysics, modified precipitation assimilation, modified 3DVAR analysis. NOAA/NWS Tech. Procedures Bull. 488, 21 pp. [Available online at http://www.emc.ncep.noaa.gov/mmb/mmbpll/eta12tpb/; also available from Office of Climate, Water and Weather Services, National Weather Service, 1325 East-West Highway, Silver Spring, MD 20910].

Schaffner, M., M. Evans, and J. Arnott, 2008: The June 19, 2007 Delaware County flash flood: a meteorological and hydrological analysis. ER Technical Attachment, ER 2008-5, NOAA/NWS, Bohemia, NY, 36 pp. [Available online at http://www.erh.noaa.gov/er/hq/ssd/erps/ta/ta2008-05.pdf].

Spayd, L. E. Jr. 1982: Estimating rainfall using satellite imagery from warm-top thunderstorms embedded in a synoptic scale cyclonic circulation. *International Symposium on Hydrometerology*, June 13-17, 1982, Denver, CO, Amer Meteor. Soc, 139-146.

University Corporation for Atmospheric Research. Cited 2012: Operational Models Matrix: Characteristics of NWP and related forecast models. [Available online at http://www.meted.ucar.edu/nwp/pcu2/].

Table 1. Summary of all 41 Binghamton CWA flash flood events used for the Maddox Classification Study. All events classified and color coded based on Maddox type [Synoptic (yellow); Frontal (blue); Unclassified (red): Meso High (purple); and Tropical (light green)].

WFO Binghamton Major Flash Flood Events (1996 - 2010)		
Event	**Classification**	**Notes**
1/19/1996	Synoptic	7 Fatalities
11/8/1996-11/9/1996	Synoptic	
12/2/1996	Synoptic	
12/13/1996	Synoptic	
1/8/1998-1/9/1998	Synoptic	
7/8/1998	Frontal	
8/24/1998	Synoptic	
7/4/1999	Frontal	
9/16/1999	Tropical	Tropical remnants (Floyd)
4/4/2000	Synoptic	
5/10/2000	Synoptic	
5/13/2000	Synoptic	
8/12/2000	Unclassified	Upper closed low/No discernable fronts
12/17/2000	Synoptic	
6/23/2001	Synoptic	
5/28/2002	Frontal	
6/14/2002	Frontal	
6/13/2003-6/14/2003	Meso High	Eastern Broom Co. event (5 Fatalities)
7/22/2003	Synoptic	
8/6/2003	Unclassified	Upper low
8/9/2003-8/10/2003	Unclassified	Weak Sfc Trough/Upper low to the west
9/4/2003-9/5/2003	Unclassified	Cold front west/Warm front south - Cyclonic flow aloft
5/12/2004	Unclassified	Weak sfc trough/Upper forcing
5/13/2004	Unclassified	Weak surface trough/Upper forcing
8/12/2004	Synoptic	
8/30/2004	Synoptic	
9/9/2004	Tropical	Tropical remnants (Francis)
9/17/2004-9/18/2004	Tropical	Tropical remnants (Ivan)
3/28/2005-3/29/2005	Synoptic	
4/3/2005	Synoptic	
6/10/2005	Unclassified	Unclassified (No fronts)
6/26/06-6/27/2006	Synoptic	$1 Billion+ in damage
7/12/2006	Frontal	
7/28/2006	Unclassified	MCV/Surface trough)
11/16/2006	Synoptic	
6/19/2007	Meso High	Colchester, NY event (4 Fatalities)
3/8/2008	Synoptic	
7/23/2008	Frontal	
8/10/2009	Unclassified	Large upper ridge/Cold front well west
1/25/2010	Synoptic	
9/30/2010	Synoptic	

Figures

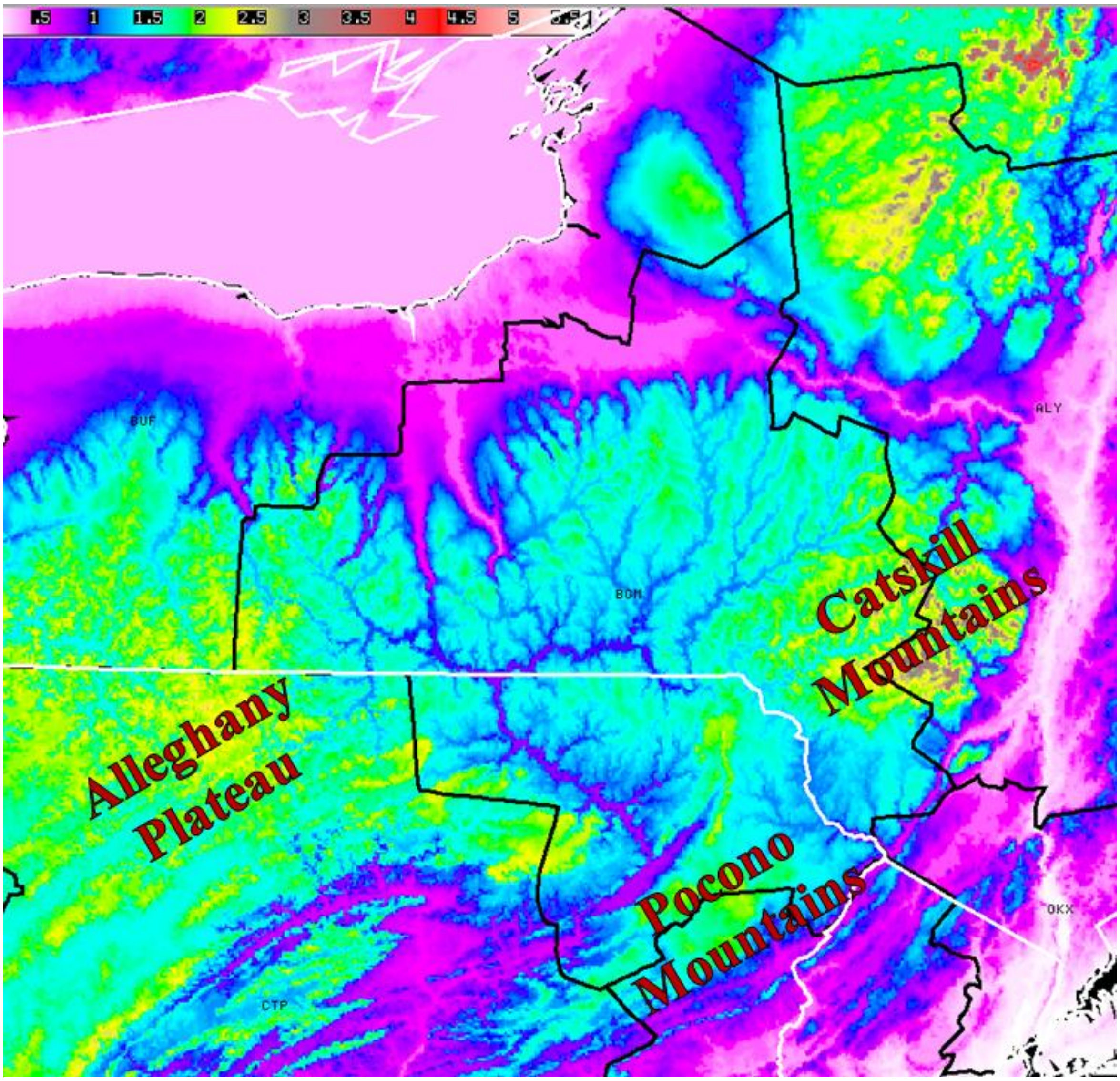

Figure 1. Topographical map of central New York and northeast Pennsylvania. White lines represent State boundaries; black lines are NWS CWA borders. Color legend at the top represents elevations (ft x 1000 MSL).

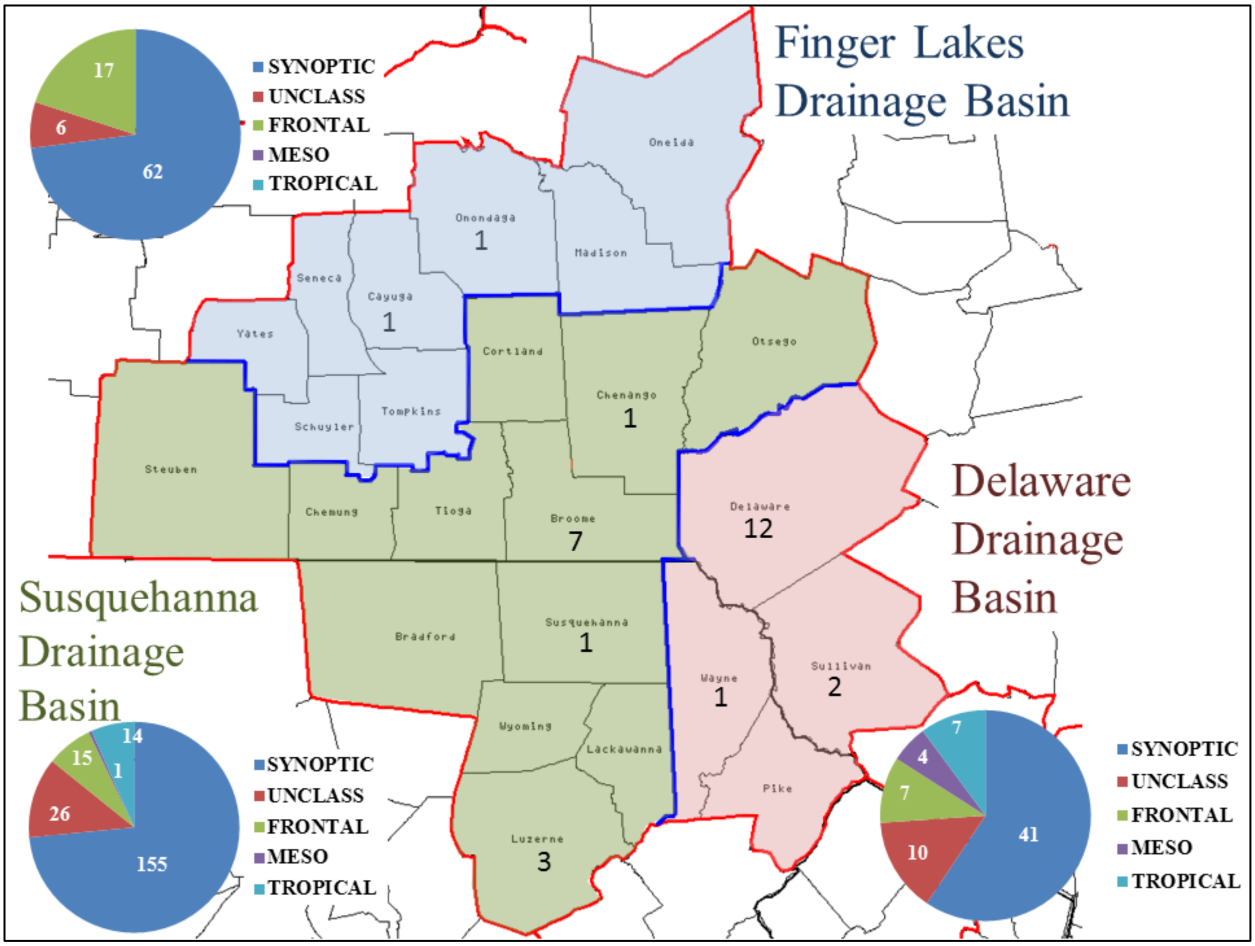

Figure 2. WFO Binghamton, NY drainage basin map where shading represents individual drainage basin [(blue) Finger Lakes; (green) Susquehanna; (maroon) Delaware]. Pie graphs show the percentage of flash floods per drainage basin based on results from the Maddox (1979) classification study. White numbers represent the total number of flash flood reports per Maddox flash flood type. Black numbers under county names are total number of fatalities per county during the period of study. State boundaries are shown as thick black lines, county boundaries by thin back lines, drainage basin boundaries by thick blue lines, and CWA borders by thick red lines.

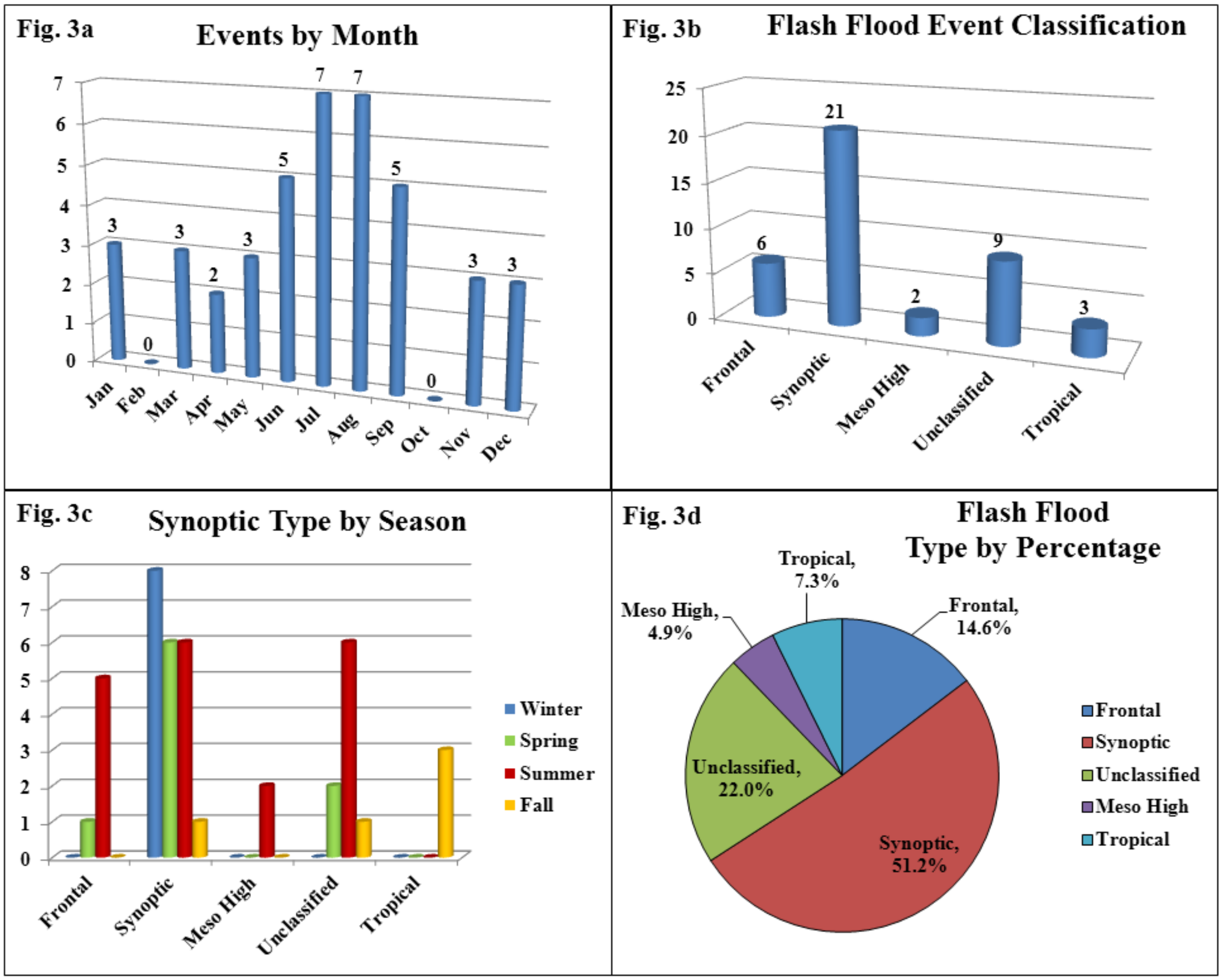

Figure 3. Local flash flood climatology results for the BGM CWA from Jan 1996-September 2010. (a) Flash flood events by month; (b) Maddox flash flood classification results based on surface and 500 hPa patterns; (c) Maddox flash flood type by season; and (d) Maddox flash flood type by percentage.

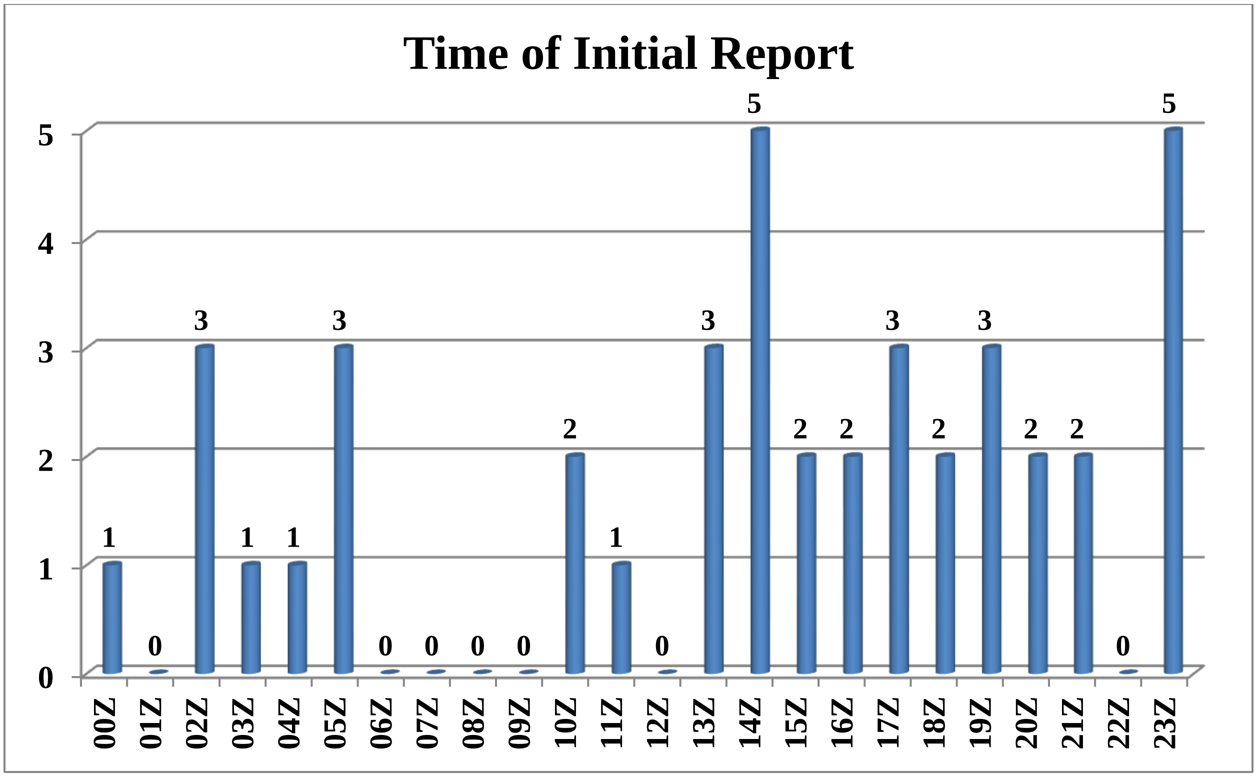

Figure 4. Initial flash flood report time frequency for the 41 events investigated. Times are presented to the nearest hour of initial event report time.

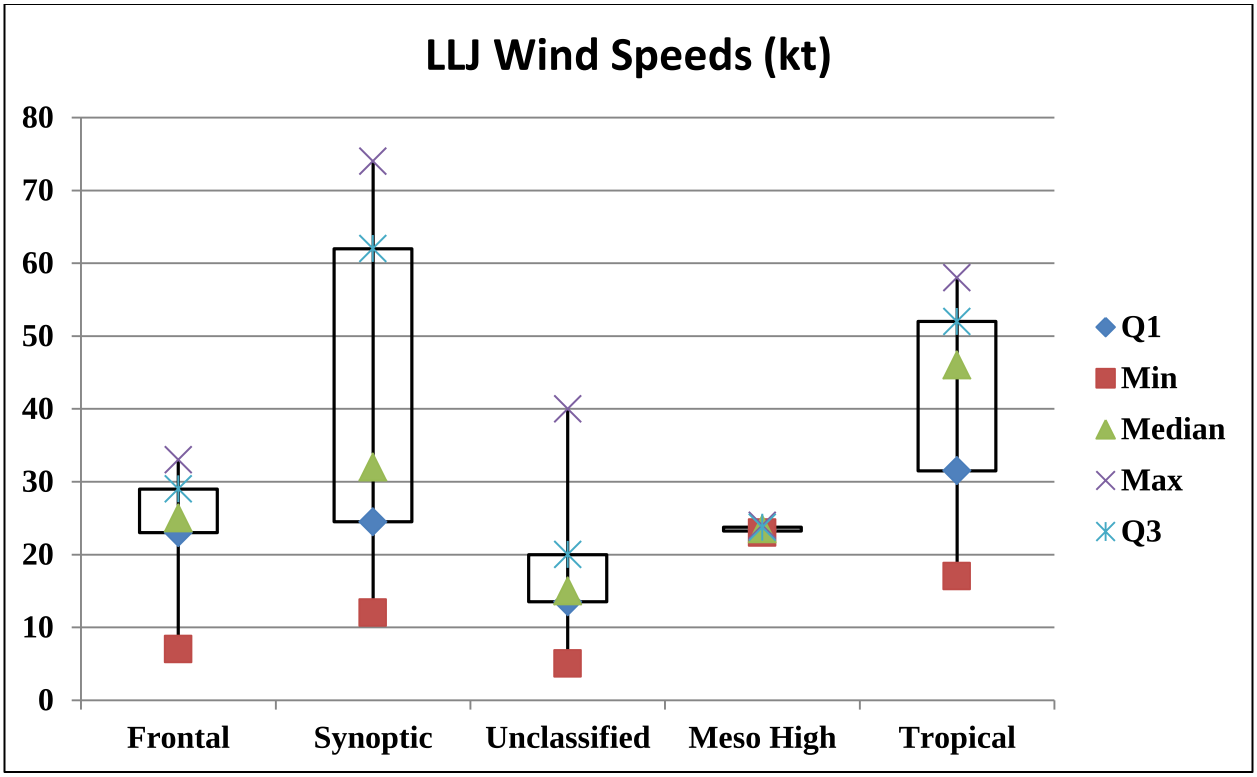

Figure 5. Low-level jet (kt) forecast variable results for Frontal, Synoptic, Unclassified, Meso High, and Tropical flash flood events. All speeds defined from achieved BUFKIT proximity soundings.

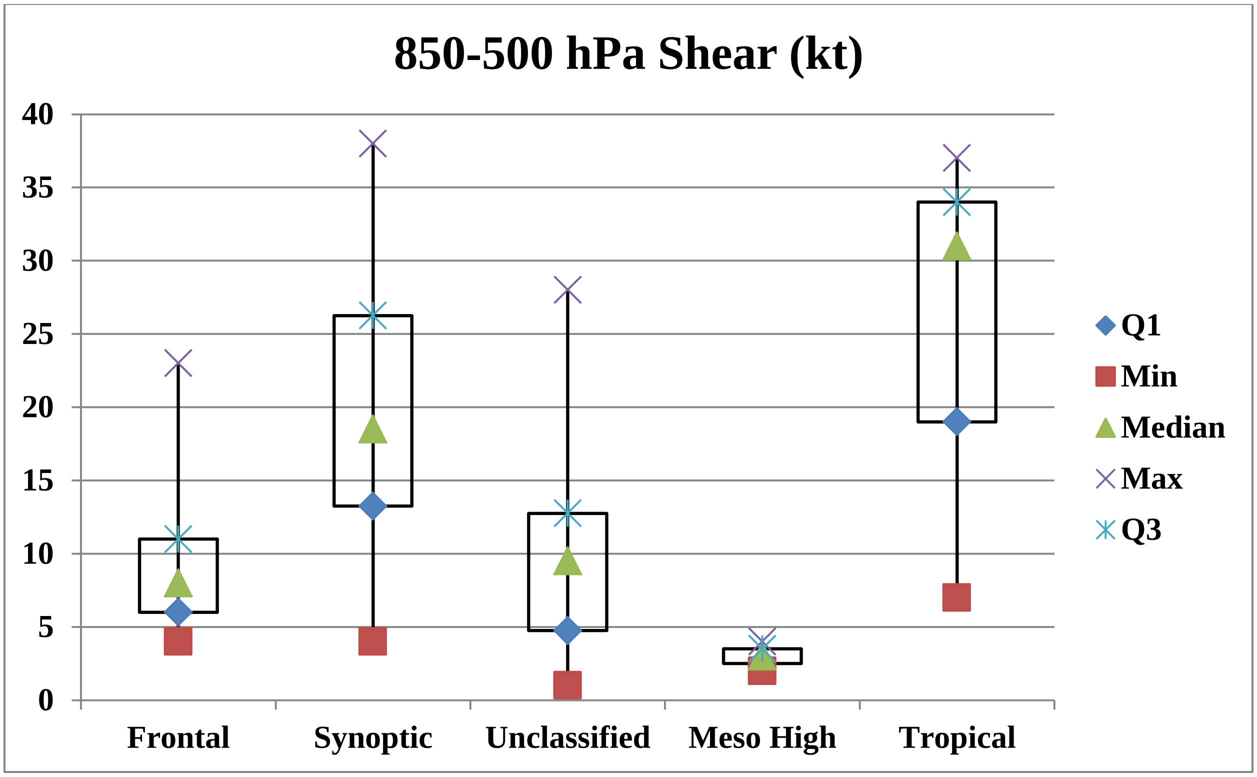

Figure 6. As in Figure 5 but for 850-500 hPa speed shear (kt).

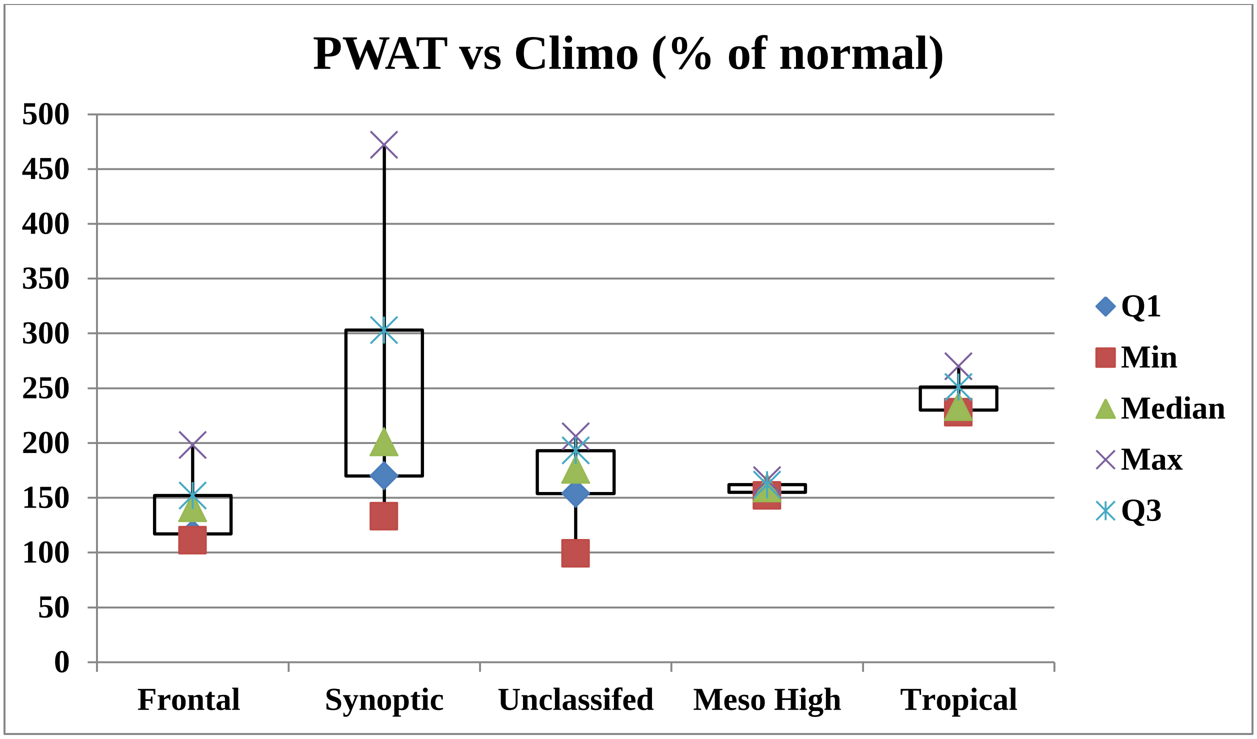

Figure 7. As in Figure 5 but for precipitable water departures from the mean climatological normal value (units of % of normal).

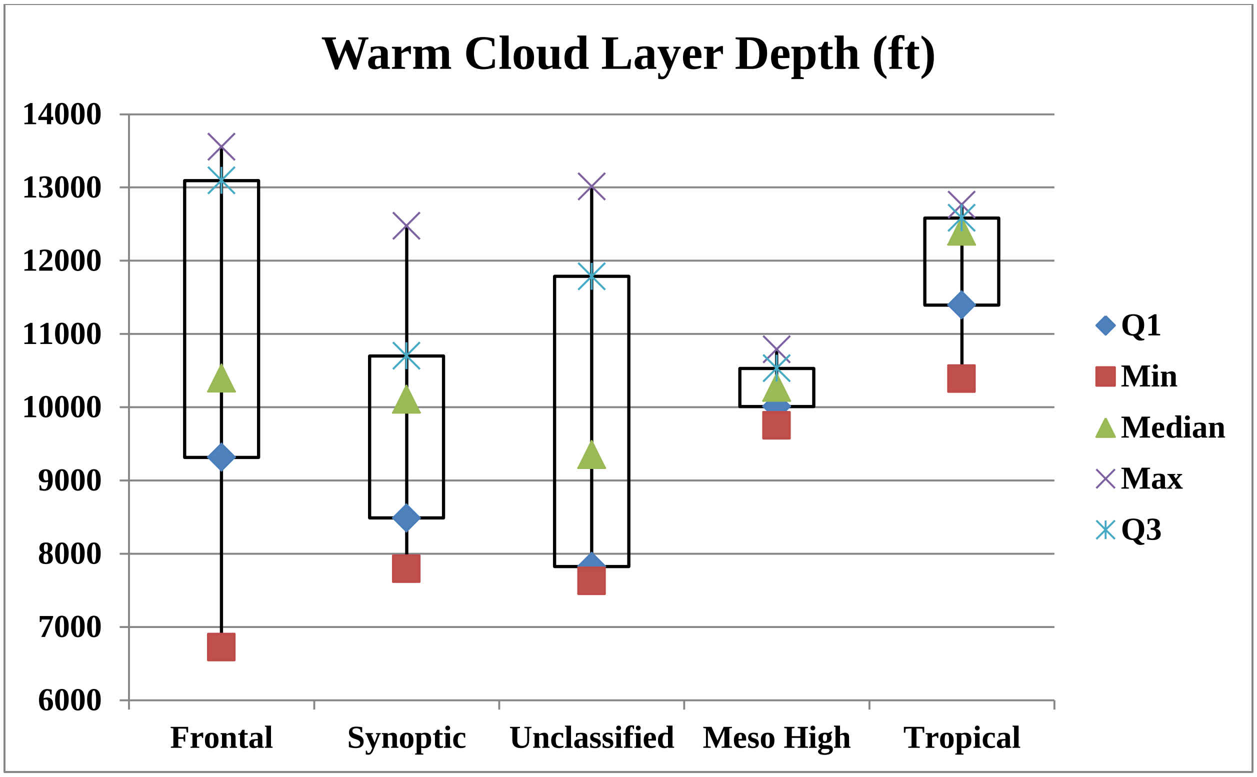

Figure 8. As in Figure 5 but for warm cloud layer depths (ft).