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Patterns of Heavy rainfall in the Mid-Atlantic Region

by

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1. INTRODUCTION

The patterns associated with heavy rainfall have long been established as critical knowledge for meteorologists attempting to forecast heavy rain. Junker et al. (1999), studying heavy rainfall events associated with the Midwest floods of 1993, categorized heavy rainfall events based on the aerial extent of the 75 mm (3 in) or greater isohyet. They found only subtle differences existed in the synoptic and mesoscale patterns between the strongest (category 4) heavy rainfall events and the weakest (category 1) events. Unfortunately, they were unable to find an easy method to distinguish between a category 4 and category 1 event.

Following the ingredients based forecast methodology of Doswell et al. (1996), Junker et al. (1999) determined several useful forecast tools including high precipitable water (PW), high relative humidity, and warm mid-tropospheric temperatures. It appeared that their category 3 and 4 events were often associated with higher PW and relative humidity values than lower category events. Junker and Schneider (1997), examining cases associated with the historic Midwest floods of 1993, emphasized the need for forecasters to be able identify conditions conducive for heavy rainfall. Critical thickness and PW values, along with areas of strong low-level inflow were deemed important considerations when forecasting heavy rain.

Grumm and Hart (2000) and Hart and Grumm (2000) examined the climatological and forecast aspects of heavy rainfall events in the eastern United States using the National Centers for Environmental Predictions (NCEP) reanalysis dataset (hereafter, GR: Kalnay et al. 1996). They found several clear signatures associated with many of the larger heavy rainfall events. In general, the 850 hPa specific humidity (q), and u-wind and v-wind components appeared to be good predictors of heavy rainfall events. They found that these fields typically deviated by 2 or more standard deviations from normal during heavy rain events. These standard deviations from normal were computed using the methodology outlined by Grumm and Hart (2000) using 21-day centered means and standard deviations based upon the fixed 30-yr period of record (POR) from 1971 to 2000.

The key parameters varied by event type as defined by Maddox et al. (1979). For example with north-south oriented fronts, the Maddox Synoptic type, heavy rain was often associated with 3 to 4 standard deviations above normal 850 hPa *v-wind* components and q anomalies. However, with cut-off lows, often similar to Maddox frontal type events, the q anomalies were small but there were large (negative) 500 hPa height anomalies and negative (easterly) 850 hPa *u-wind* anomalies. In follow-on studies (Grumm et al. 2002) showed that precipitable water (PW) anomalies were a key parameter in identifying heavy rainfall events. The majority of heavy rain events were associated with precipitable water anomalies over 2 standard deviations (SDs) above normal. A more recent study (Stuart and Grumm 2006) demonstrated the value of *u-* and *v-wind* anomalies in determining the severity of East Coast winter storms.

This study will present the two main heavy rain producing event types in the Mid-Atlantic region. Composites of the synoptic and frontal event types are provided from the perspective of critical fields and their

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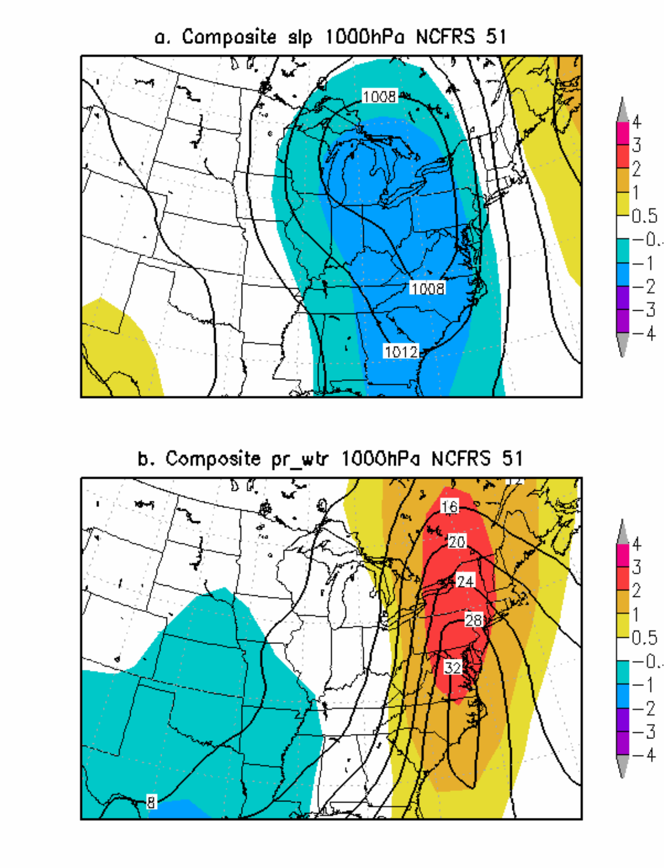

Figure 1. Composite of all cold season Synoptic events showing the a) the composite mean sea-level pressure (hPa) and the mean standardized anomaly and b) the composite precipitable water (mm) and

associated anomalies. Using the global re-analysis data, heavy rain events spanning 1949 through 2006 are investigated and used to produce a composite for these event types in the eastern United States. Cases from 1979-2006 were examined using the finer resolution North American re-analysis data set (N ARR: Rutledge et al 2006). The key anomaly fields can be used to aid forecasters in identifying potential heavy rain events. This preprint will focus on the synoptic event type. Examples of each case type and the application of climatic anomalies to forecast data will be presented at the conference.

2. METHODS

Rainfall events were collected from two independent data sources. For station data, events were obtained from 24-hour precipitation reports from National Weather

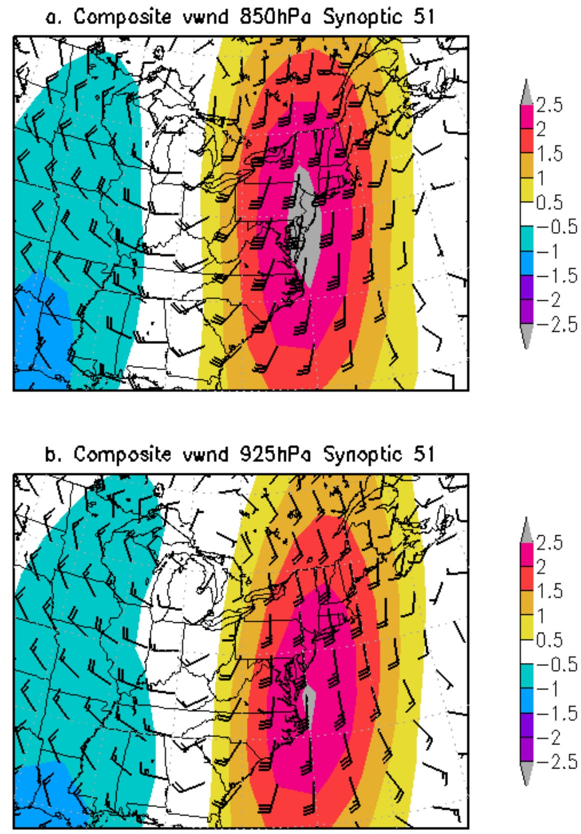

Figure 2 Composite of all cold season Synoptic events showing the a) 850 hPa mean winds and 850 hPa v-wind anomalies and b) 925 hPa winds and v-wind anomalies. Winds are in knots and anomalies in standard deviations from normal.

Service (NWS) Cooperative climate observation (COOP) sites from 1948 through 2006. Independently, rainfall data was obtained from the NARR data to identify heavy rain events over the Mid-Atlantic region from 1979-2006.

Heavy rain in the NARR was identified by the 3-, 6-, 12-, and 24-hour maximum in the data. These data were sorted to identify the top 200 events for each time interval. The majority of the events found with the NARR data were identified by the COOP data set for cases observed after 1 January 1979. The NARR data facilitated identifying the periods when the rain most likely fell, an attribute missing when using 24-hour point data.

Using single points in central Pennsylvania, the value of standardized anomalies for the variables listed in Table 1 was acquired from

1 January 1949 through 31 December 2004. Data for each variable and level were then run through WEKA (Witten and Frank 2005). A 10-fold cross-validation test was run on these data to determine the key predictors and a decision tree showed the predictors that weigh most in identifying heavy rainfall events. The data was trained on heavy rainfall events from 1948-2006. The training process includes a 10-fold cross validation routine where the data set is distributed randomly and broken into 10 equal partitions. Then 10% of the data is held out for testing and the remaining 90% of the data is used for training. This process is repeated 10 times so that all of the data is eventually used for training and testing. This process maximizes the use of limited data sets and helps strengthen the confidence of the predictive model. This methodology produced a split decision tree which identified low level *u*- and *v-wind* anomalies to be the key predictors in distinguishing between Synoptic and Frontal Maddox type heavy precipitation events. These key predictors where used in the compositing process which implied that the Maddox et al (1979; hereafter Maddox) frontal and synoptic heavy rain types dominated the data set.

The GR data was used to make images of the top 200 events and to produce composites by event type. Key fields examined and produced for individual events included mean-sea level pressure, 500-hPa heights, 850 hPa winds (*u*- and *v-components*), 250 hPa winds (*u*- and *v-components*), and precipitable water (PW). Each field was displayed relative to the mean and the departure of this field from normal in standard deviations from normal as described by Hart and Grumm (2001). These *standardized anomalies* facilitated quick evaluation of the salient features and were used to produce a database for analysis and classification purposes. Visual inspection revealed that the majority of the events fit the Maddox synoptic and frontal type events.

The heavy rainfall patterns for events observed after 1 January 1979 were produced using the NARR accumulated precipitation field (Rutledge et al. 2006). These data indicate where the heavy rain

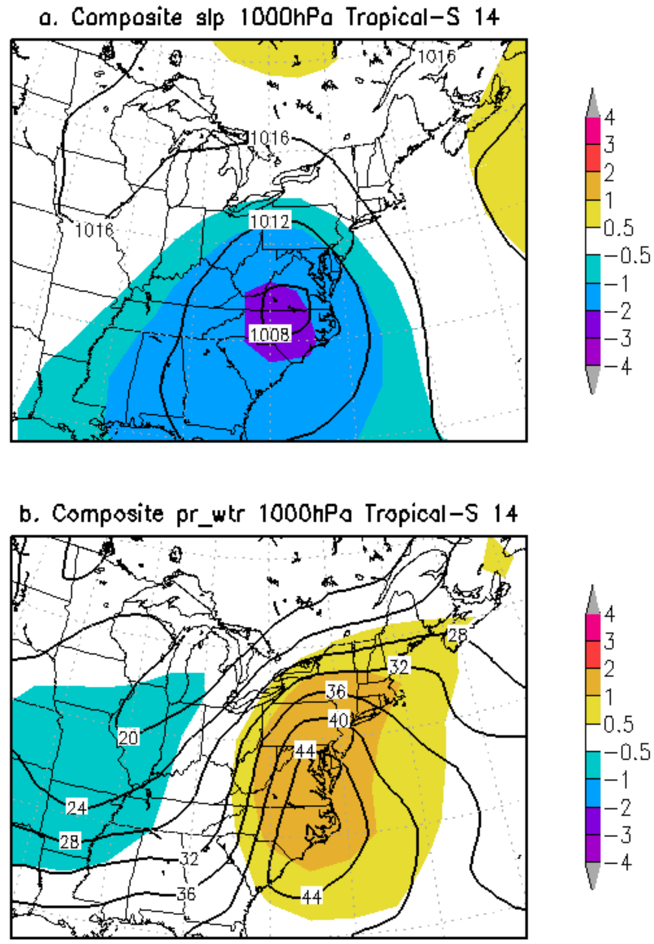

Figure 3 As in Figure 7 except composites for synoptic-tropical systems.

was observed in a spatial context. However, these data are posted on a coarse 32-km grid and do not reflect the higher amounts likely observed during the event. A comparison with regional precipitation data reveals that the NARR precipitation field shows the heavy rainfall pattern but under estimates the higher rainfall amounts by a factor of 2 or more.

3. RESULTS

The composites of both Synoptic and Frontal event types are presented here but for brevity we only show examples of the Synoptic type events. The synoptic type included the more common north-south frontal system described by Maddox. A hybrid type, the synoptic-tropical (ST) event was identified in the data. The ST events have the same quasi-north south frontal zone associated with the classic Synoptic type but also show an additional interaction with the remnants of named and unnamed systems of tropical origin or the influx of high PW from the subtropics. This important difference from the classic Synoptic type event distinguishes itself as major contributor to heavy rainfall. For example, this hybrid event type dominated the top 10 heavy rain producing events in the data set.

i. Synoptic event composite

The composite MSLP and PW for the synoptic event type are shown in Figure 1. The corresponding 850 and 925 hPa winds and *v-wind* anomalies are shown in Figure 2. These data show the key attributes of the synoptic event type including the area of low pressure and the implied north-south oriented frontal trough. Below normal pressure is present with the cyclone and above normal pressure is associated with the retreating anticyclone. Above normal PW values dominate ahead of the system. A strong low-level southerly jet is present ahead of the frontal system aligned with the surge of high PW.

In the ST sub-type the southerly jets are displaced eastward and strong south-southeast winds dominate (not shown). At the surface, the PW values are higher than in the cold-season synoptic type though the anomalies are not as large (Fig. 3b). Additionally, the tropical low or wave interacting with the front creates a negative pressure anomaly to the south and east

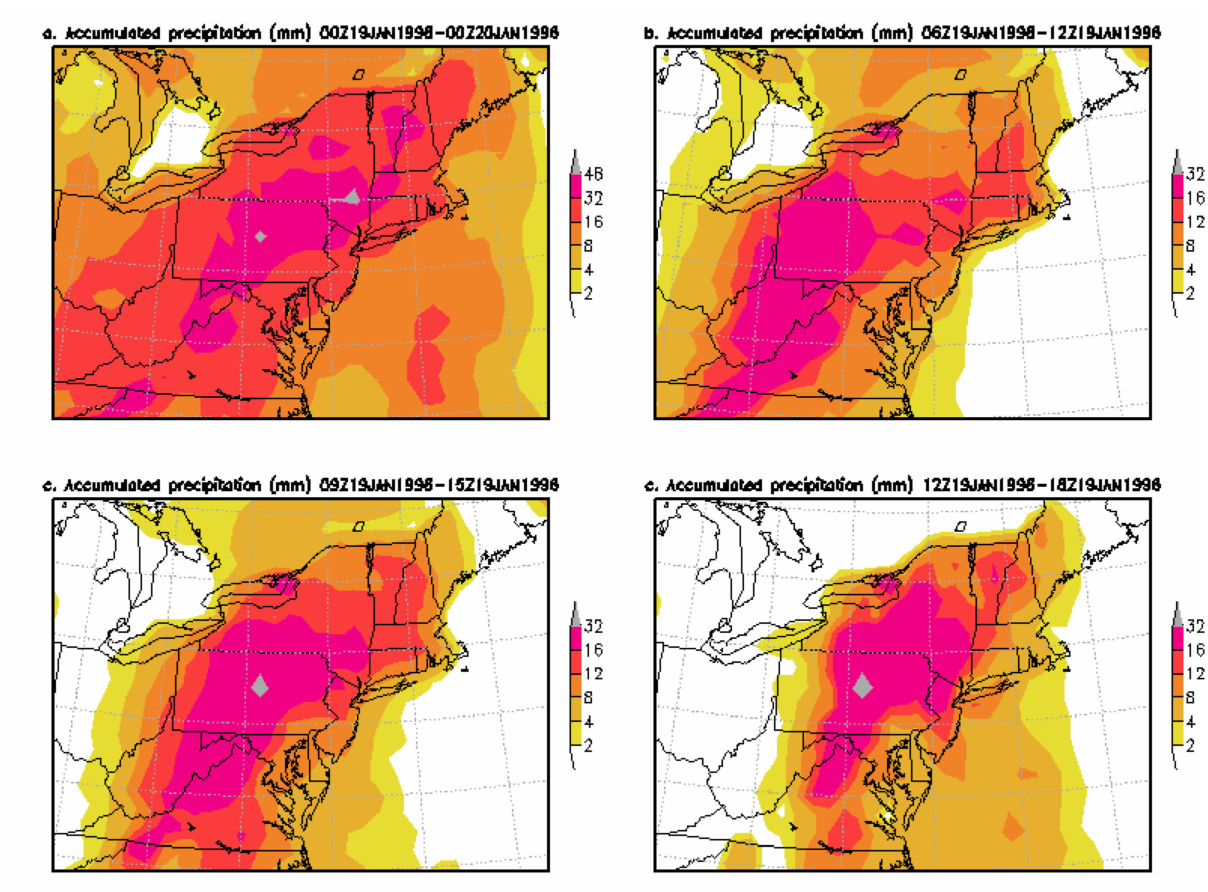

Figure 4. NARR total accumulated precipitation showing a) total accumulated precipitation from 0000 UTC 19 January through 0000 UTC 20 January 1996, b) total accumulated precipitation from 0600 UTC 19 January through 1200 UTC 19 January 1996, c) total accumulated precipitation from 0900 UTC 19 January through 1500 UTC 19 January 1996, and d) total accumulated precipitation from 1200 UTC 19 January through 1800 UTC 20 January 1996.

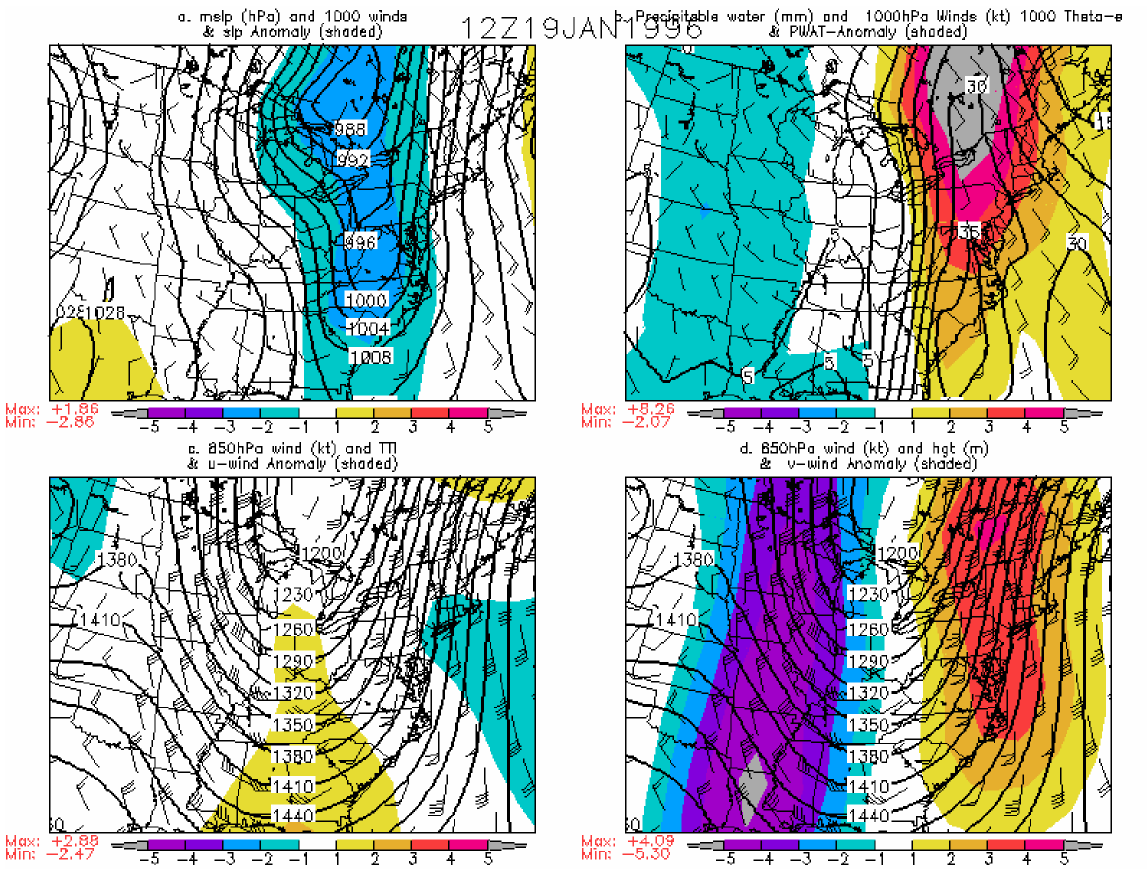

Figure 5. Global re-analysis data valid at 1200 UTC 19 January 1996 showing a) mean sea level pressure (hPa), 1000 hPa winds, and MSLP anomalies, b) precipitable water (mm) and anomalies, c) 850 hPa heights (m), winds (kts), totals-totals index, and U-wind anomalies, and d) 850 hPa heights, winds, and V-wind anomalies. Isobars every 4 hPa, heights every 30 m, winds are in knots, PW every 5 mm.

from where the classic Synoptic type position is located (Fig 3a).

ii. Synoptic event type example

The heavy rain event of 19 January 1996 produced widespread flooding over a large portion of the eastern United States. The flooding was the result of the combination of heavy rain which fell over a short period of time (Fig. 4) and rapid snow melt (Leathers et. al 1998). Figures 4b-4d shows the accumulations over discrete time windows. With the exception of New York and New England, these data imply that the heaviest rains were observed after 0900 UTC 19 January and before 1800 UTC 19 January. The relatively short period of time in which the heavy rain fell contributed to the flash flooding.

The rainfall was associated with a strong north-to south oriented frontal boundary as shown in Figure 5. This event was a prototypical Maddox synoptic type and the anomaly fields facilitate identification of the key features. This event had PW anomalies between +3 to +5 SDs above normal in the warm sector (Fig. 5b). Strong southerly winds, nearly parallel to the front were present at 850 hPa (Figs. 5c & 5d) and the 850 hPa V-wind anomalies were on order of +3 to +5 SDs in the warm sector ahead of the front as estimated by the mean sea-level pressure trough (Fig. 5a) and the PW gradient. The MSLP fields did show a significant trough with MSLP anomalies in the -1 to -2SD range.

iii. Synoptic tropical event example

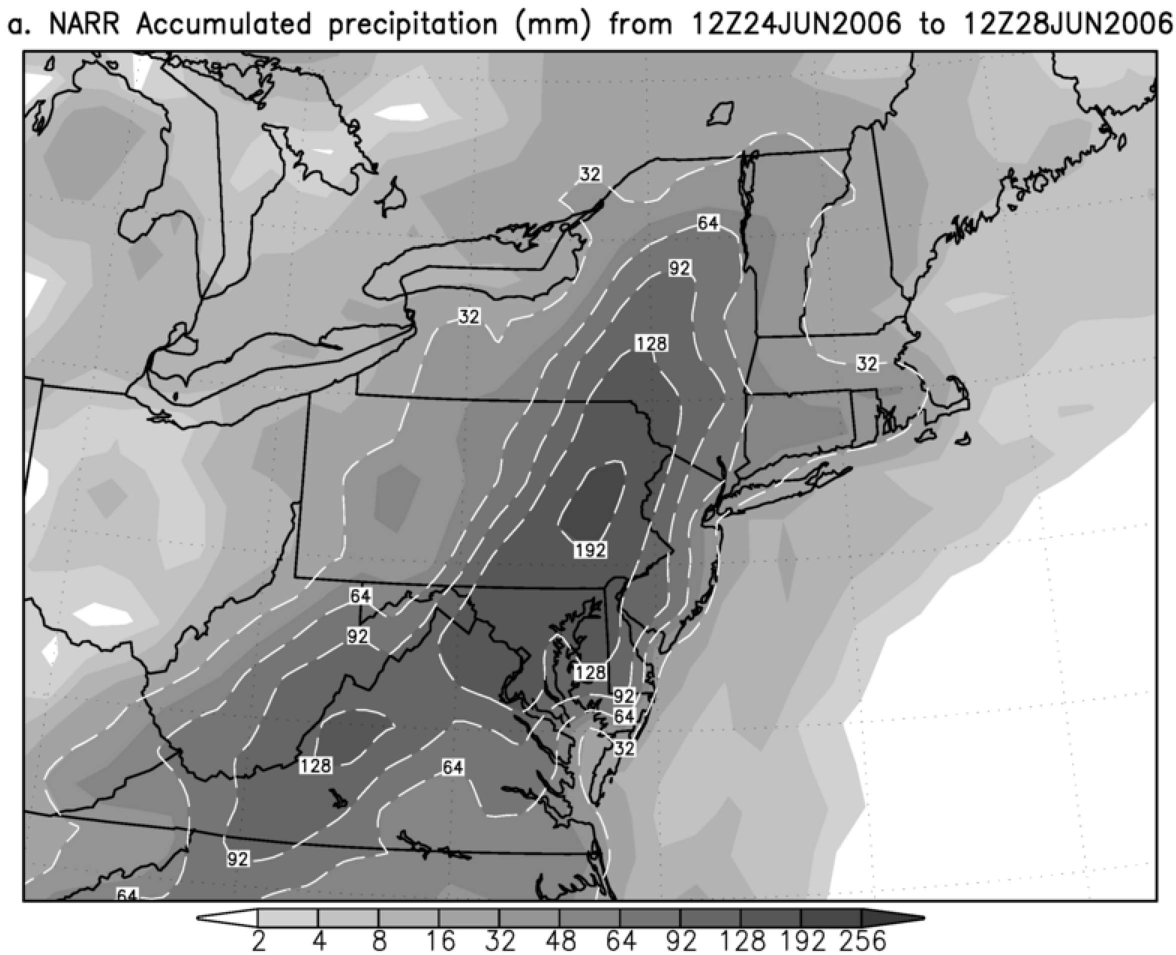

Figure 6. NARR precipitation (mm) valid for the 4 day period ending at 1200 UTC 28 June 2006. Shading is as indicated by the gray scale, dashed contours begin at 32 mm to provide contrast.

Figure 6 shows the total rainfall for the multi-day Synoptic Tropical rain event from 24-28 June 2006. This event produced significant river flooding from the Mohawk Valley of New York southward into the Delaware River basin of New York, Pennsylvania, and New Jersey. The relatively coarse NARR precipitation data did not capture the local maximum rainfall which exceeded 300 to 400 mm in isolated areas of Pennsylvania and Maryland.

The conditions valid at 1800 UTC 28 June 2006 are shown in Figure 7. This was the time of the peak anomalies during the 24-hour period from 1200 UTC 27 to 1200 UTC 28 June 2006 when 64 to 92 mm of rainfall was observed in the NARR data over eastern Pennsylvania and southern New York (not shown). This rainfall contributed to the large area covered by the 128 mm contour shown in Figure 6.

The low-level southeasterly jet had +2 to +4 SD *v-wind* anomalies and the PW anomalies were on the order of 1 to 3 SDs above normal over the region. The larger *v-wind* anomalies were at 925 hPa. The PW fields shows the connection to the tropics, which is better viewed over several days of mean-sea level pressure data which showed a weak low pressure system moving into the north-south frontal zone on the 26th. This quasi-stationary north-south frontal zone and the tropical moisture connection were the main contributors that to the heavy rains observed during this event.

iv. Frontal type composite

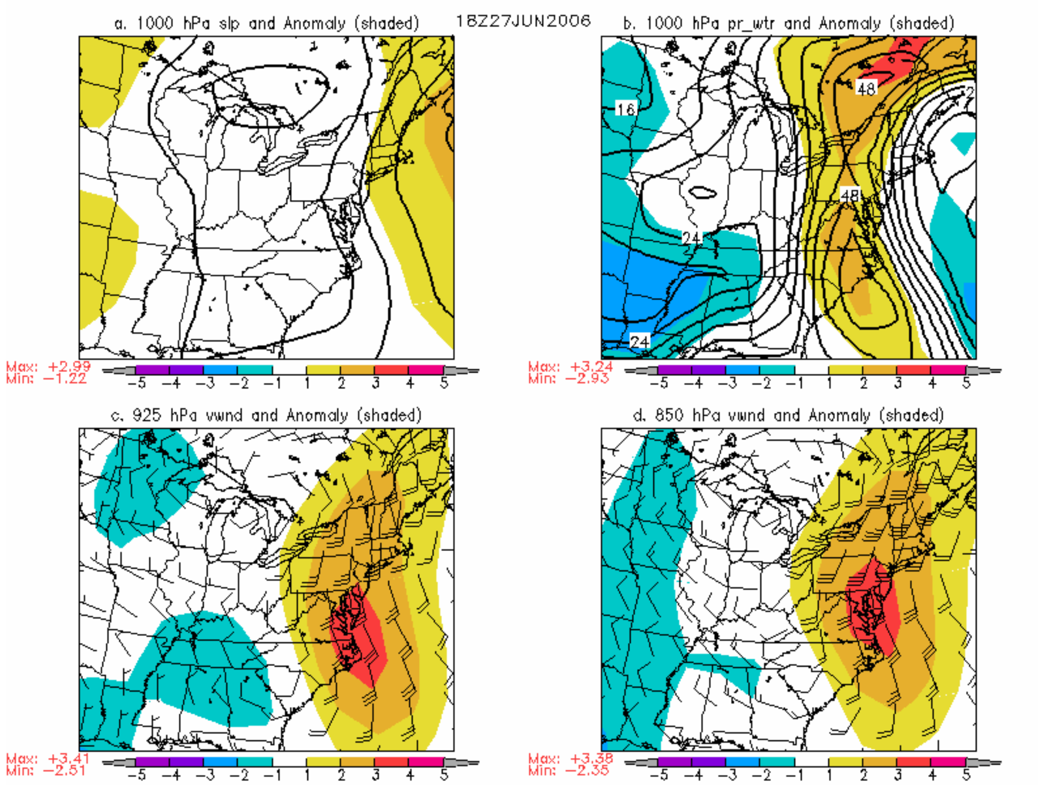

Figure 7 Re-analysis data valid at 1800 UTC 27 June 2006 showing a) mean sea level pressure (hPa) and anomalies, b) precipitable water (mm) and anomalies, c) 925 hPa winds and v-wind anomalies, and d) 850 hPa winds and v-wind anomalies. Isobars are every 4 hPa, precipitable water is every 4 mm, winds in knots, and anomalies in standard deviations from normal.

There were 103 events identified as frontal event types. A significant number of these events included winter storms which produced both heavy rain and snow. Several tropical storms, such as tropical storm Fran of September 1996, were included in the data set. Fran was the second most prolific rain event of this type second only to the winter storm of 3-4 March 1994, which produced the most precipitation in this event type. None of the events used in the composites was a top 10 rainfall event because they were dominated by the synoptic event type.

The composite surface pressure field, PW, and low-level u-winds for the frontal type events are shown in Figure 8. Key features include the surface low along the coast; the north-south gradient of PW; and the strong low-level easterly jet. The area of above normal PW values on the warm side of the boundary indicates that this event type is also associated with above normal moisture available to the system. The low-level wind fields at 925 and 850 hPa show the anomalously strong easterly winds on the cold side of the implied east-west oriented boundary in the PW field.

4. CONCLUSIONS

Using the GR data, the two primary heavy rain event types over then Mid-Atlantic region were identified and presented. These two types included the Maddox synoptic and Maddox frontal type events. A sub-type of the classic Maddox Synoptic event was identified as the Synoptic-Tropical hybrid type. The heaviest rainfall events were dominated by the synoptic event type and the top 10 heavy rainfall events were produced by the Synoptic-Tropical hybrid.

The synoptic event type was associated with a quasi north-south oriented frontal system. In the warm sector, strong southerly winds

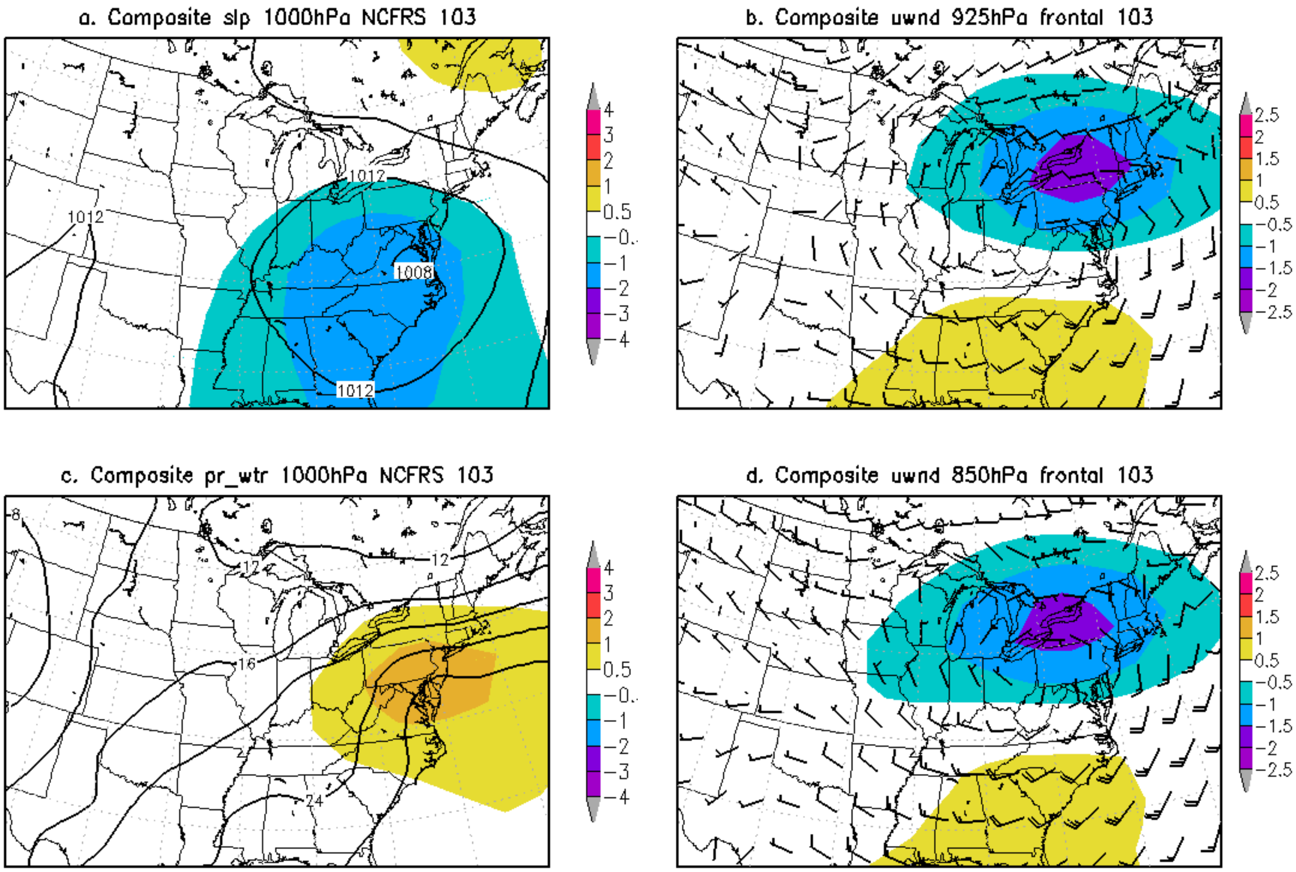

Figure 8. Composite of all frontal type events from 1948 to 2006 which produced over 25 mm of rainfall. Data shown include a) mean-sea level pressure (hPa) and pressure anomalies, b) 925 hPa winds (knots) and u-wind anomalies, c) precipitable water (mm) and anomalies, and d) 850 hPa winds and u-wind anomalies.

and high PW values dominated. The anomalies of these fields indicated that +2SD above normal or greater anomalies were present in most of these fields.

During the warm season, the synoptic type can interact with tropical storms and tropical air streams. These events produce the heaviest rainfall events over the Mid-Atlantic region, often associated with very high PW values and PW anomalies in excess of +2 SDs above normal. *The combination of tropical systems with quasi north-south frontal zones is a key heavy rainfall pattern in the Mid-Atlantic region*.

The Maddox frontal event type occurs frequently in the Mid-Atlantic region. Over 100 events producing at least 25 mm of precipitation were identified. The key features include a surface cyclone moving toward the region from the south and a strong quasi east-west frontal zone. PW anomalies are observed along and south of the frontal zone. Strong low-level easterly winds are present in the cold air. This event type produces heavy precipitation, which often falls in the form of snow in winter storms. It also produces large amounts of rainfall over a wide region but typically does not produce rainfall amounts has high as those observed in synoptic event types.

The synoptic events interacting with tropical systems can produce extremely heavy rainfall such as the rainfall associated with remnants of hurricane Ivan. These events are a hybrid of the more traditional Maddox Synoptic due to the influx of the tropical circulation and the tropical moisture connection. Hurricane Agnes was a Synoptic-Tropical event type and produced a similar dramatic rain event as it interacted with a quasi north-south frontal zone. The extreme rain event of 24-28 June 2006 was also presented and identified as being a Synoptic-Tropical hybrid due to its association with a quasi-stationary north-south frontal boundary and tropical moisture connection.

Synoptic tropical events generally produced the largest rainfall because of the higher moisture and PW values observed during the warm season. Conversely, the cold season synoptic events typically produced overall lower total precipitation. The month of September was found to be the peak time for the synoptic tropical event type though they have been observed in June (Agnes), August (Connie and Diane), and October.

It should be noted that not every event is easy to classify and there are events which appear to transition from east-west oriented fronts with easterly winds (Frontal Maddox type) to more north-south oriented fronts with strong southerly winds (Synoptic Maddox type). This can be true in East Coast cyclones and tropical systems. Several of the synoptic-tropical events at T-24 hours before the event had a distinct east-west frontal zone which become more north-south in its orientation as the event progressed.

These patterns of heavy rainfall and the associated anomalies can be applied to the ensemble prediction system and deterministic model forecast data. This should facilitate the identification of heavy rainfall producing patterns and gage the potential strength of the system. Furthermore, these data may be used as input into AI algorithms to assess the heavy rainfall threat for decision making purposes.

The NARR provides a good starting point for precipitation analysis and precipitation patterns. Unlike the COOP data and 24-hour datasets, this higher temporal data also more clearly define when the heavy rain fell. Eventually, these data can be used to produce composites with more accurate temporal resolution which may help refine the conditions associated with the periods of maximum rainfall. It should be noted that the NARR will likely underestimate regions of heavy rain and will miss localized heavy rain amounts. Thus the NARR is a good tool with which to identify coarse patterns of large-scale precipitation events. Other finer resolution data sources are required to find the maximum rainfall and areas subject to flash flooding.

5. ACKNOWLEDGEMENTS

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Predictor from the Global Re-analysis data

Variable	Level	Usefulness	Algorithm	Comments
Precipitable water	Surface	high	Primary variable	• Visually observed. • WEKA picked this as a key predictor.
U-winds	925 hPa	High	Secondary variable	• Visually observed. • WEKA picked this as the key predictor behind PWAT when U-winds anomalies were negative.
U-winds	850 hPa	High	Secondary variable	• Visually observed. • WEKA picked this as the key predictor behind PWAT when U-winds anomalies were negative.
V-winds	925 hPa	High	Primary variable	• Visually observed. • WEKA picked this as the key predictor behind PWAT when V-winds anomalies were positive.
V-winds	850 hPa	High	Primary variable	• Visually observed. • WEKA picked this as the key predictor behind PWAT when V-winds anomalies were positive.
U/V-winds	250 hPa	Low	Tertiary variable	• Visually observed and associated with jets. • WEKA showed only limited value to this variable.
Mean-sea level pressure	Surface	Moderate	Tertiary variable	• Visually observed and associated with East Coast cyclones. • WEKA showed only limited utility with this variable, but stronger than thermal and other height variables.
Temperature	850 hPa	Moderate	Tertiary variable	• Visually observed and associated with fronts. • WEKA showed only limited utility but showed more signal when associated with frontal events.
Heights	500 hPa	Moderate	Tertiary variable	• Visually observed associated with strong storms. • WEKA showed some ability to contribute to identifying heavy rain events.

Table 1. List of key variables used to determine the strength of the anomaly and its relation to heavy rainfall. Data include thee variable name, the pressure level, predictive skill based on WEKA, variable rating influence, and comments based on the subjective inspection of the top 200 cases and the WEKA decision tree.