P1.7 LOCATION OF HEAVIEST RAINFALL RELATIVE TO FRONTAL BOUNDARIES DURING THE WARM SEASON

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1. INTRODUCTION

Forecasting heavy rainfall is very challenging. Many heavy rainfall events occur in the vicinity of fronts during the warm-season across the eastern United States, as processes near fronts (e.g. isentropic lift, convection, low-level convergence) encourage lift and precipitation if sufficient moisture is available. Clearly, there are many avenues of research, which may examine the relationship between heavy precipitation and fronts. Regional differences in geography and topography also create a more varied set of synoptic variables that one must consider to explore why and how heavy rain events develop near fronts. Thus, there should be a research emphasis to understand how synoptic features vary regionally across the U.S with respect to heavy precipitation near frontal boundaries.

When comparing the synoptic environments of heavy rainfall events, it is useful to first categorize the events according to their location relative to fronts. Previous research using analogue models suggest that synoptic patterns vary between events centered on the warm vs. cool side of a frontal boundary (e.g. Maddox et al., 1979; Winkler, 1988). In the Maddox et al. (1979) scheme, for example, the frontal type event was identified on the cool side of a frontal boundary generally oriented W-E embedded within a weak, large scale pattern. In contrast, synoptic type events were distinguished by their occurrence on the warm side of a quasi-stationary frontal boundary usually oriented SW-NE, near a strong cyclonic system. Another study categorized events occurring near cyclonic disturbances by their location relative to the nearest front (Heideman and Fritsch 1988). In this study, surface weather analyses associated with 3426 defined heavy rain events were examined in order to quantify the location of fronts relative to the center of each heavy rainfall event during the six-hour period in which the heaviest rainfall occurred. Since the locations of surface fronts are not archived in any known digital database, this research develops a multi-regional climatology of heavy precipitation events and frontal boundaries. Study results are related to physical processes that enhance precipitation development near fronts (i.e. the low-level jet, Mesoscale Convective Systems) and the landmark Maddox et al., (1979) analogue model.

Regional synoptic climatologies of precipitation (e.g. Konrad, 1997; Harnack et al., 1999) imply that the relationships identified between heavy rainfall and the larger scale environment are stable across the study region, (e.g. they do not show significant intra-regional variations). However, the validity of this assumption depends on the size of region. Larger study regions (e.g. Maddox et al., 1979) and factors that dictate the synoptic climatology of precipitation, (i.e. terrain; proximity to bodies of water; semi-permanent circulation features like the Bermuda High) can vary significantly across the region. As a result, one portion of the study region may experience a different mix of heavy rain scenarios when compared to another portion of the study region (Konrad et al. 2005).

2. METHODOLOGY

The first step of this study was to identify a large sample of heavy precipitation events across the eastern U.S. The precipitation events database was developed by Konrad (2001) from *Cooperative Summary of the Day* CD-ROMs data (NCDC, 1997). To identify precipitation events, two-day precipitation totals from all stations in the cooperative observer network within the eastern two-thirds of the U.S. were interpolated onto a 279 by 263 grid containing a 10 by 10 km grid spacing. This effort was carried out daily, thus providing temporally overlapping, two-day precipitation totals for each day of the 47-year period. Due to large volume of data Konrad used the method of Thiessen Polygons, which proved to be computationally efficient and was used to interpolate the precipitation amounts. It is of note that this method of extrapolation has deficiencies including the high weighting of isolated stations. Also, stations along the Atlantic and Gulf coasts are weighted more strongly since their values are interpolated beyond the coastline. These extrapolations were not carried out beyond 28 km from any station. Precipitation amounts were not defined in pixels beyond the zone of extrapolation, which began at 28 km from the nearest shore. Therefore, pixels were not defined over large bodies of water (e.g. Gulf of Mexico, Great Lakes, Atlantic Ocean).

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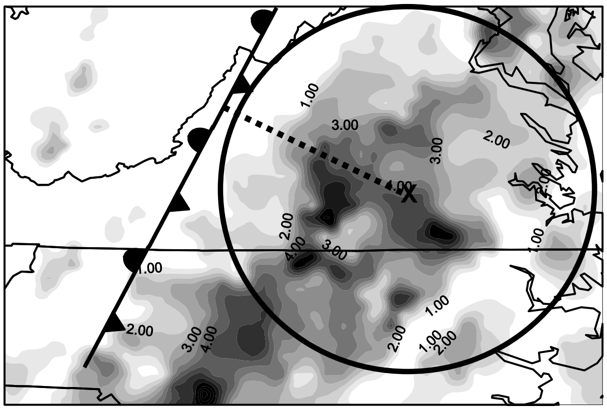

Figure 1: Example of the identification of a heavy rainfall event within the shaded region of 2-day precipitation totals (inches) exceeding 1 inch across Virginia and North Carolina on July 12-13, 1975. This event is centered less than 300 km from the stationary front depicted to the northwest; therefore it is classified as "warm sector" event.

After the daily precipitation totals were interpolated over the eastern two-thirds of the United States, an automated routine was applied to identify the mean precipitation maximums in time (two day periods) and space (100,000 km^2 circular regions). A moving window technique was used to identify the areas containing the greatest two-day precipitation totals (Figure 1). This method required the computation of 73,377 pixels over 17,162 days, as the centroid moved systematically pixel by pixel for each day of the study period. The moving window would center on a pixel recording a two-day precipitation total of at least 2.54 cm (1 inch). If two precipitation regions spatially overlap within a 2 day period, the region with the lesser mean total was eliminated. The criteria also mandated that at least 80% of the pixels within the 100,000 km^2 circular region had to have measurable precipitation for the two-day period, to be defined as a precipitation event. Additionally, if 20% of the pixels within the circular region had no precipitation data available, then it would not be defined a precipitation event. This restriction was enforced to prevent the creation of precipitation regions that extend beyond the study area where precipitation data was unavailable. This also prevented the identification of precipitation maxima over large peninsular regions of the study area (e.g. Florida and New England).

Less than 2.5% of these events were tied to tropical cyclone activity, and given this small contribution to the sample and atypical synoptic environment around these systems they were removed from the study. Additionally, to examine regional differences in heavy precipitation Konrad developed a regionalization scheme. The eastern two-thirds of the United States were divided into nine regions for statistical comparison (Konrad 2001). Regional boundaries were differentiated along topographic features that distinguished regions according to the spatial distribution of heavy rain events (Figure 2). These subjective boundaries take into account regional processes that are associated with the development of precipitation.

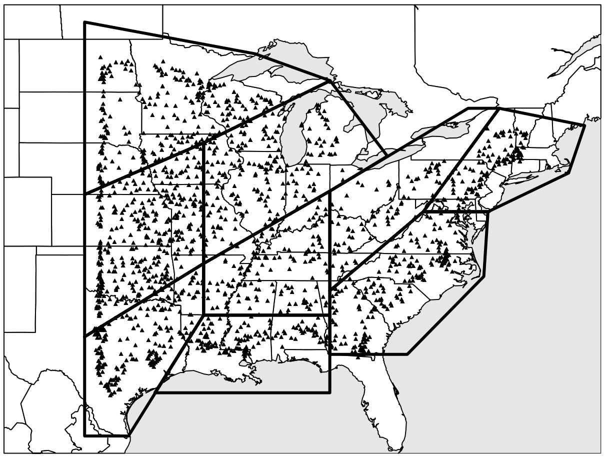

Figure 2: Nine sub-regions of comparison across eastern 2/3 of United States Regional distribution of 3,342 events identified during the 47-year period.

Surface weather maps were used to identify fronts and their characteristics in the vicinity of each heavy precipitation event. The chief task of this research was to examine all 3,342 heavy rain events for the presence of frontal boundaries. Three map collections were used in this effort: North American Surface Charts; Northern Hemispheric Surface Charts; and U.S. Daily Weather Maps Project published by the National Oceanic and Atmospheric Administration (Table 1).

Map Source	Years	Hours Available
N.A. Surface Charts	1950 – 53	0, 6, 12, 18 UTC
	1953 - 56	0, 3, 6, 9, 12 ,15, 18 , 21 UTC
	1959 - 91	0, 3, 6, 9, 12 ,15, 18 , 21 UTC
	8/1995 - 9/1996	0, 3, 6, 9, 12 ,15, 18 , 21 UTC
N.H. Surface Charts	1992 - 7/1995	0, 12 UTC
NOAA Library-U.S. Daily Weather Maps	1957 – 58	1:30 AM and 1:30 PM LST

Table 1: Surface weather map sources used in frontal analysis.

Using this database, a computer, and "Synoptic Suite" software (Konrad 2001), a "+" symbol would mark the center of a heavy rain event, onto a map on the contiguous United States. The researcher then visualized this point from the computer screen onto a synoptic map that was displayed by the microfilm reader. To maintain a consistency of scale among the three map sources, the northern border of Alabama was chosen to be measured (in mm) for each roll of microfilm. When using the on-line NOAA maps, the same computer monitor was used for this measuring consistency. Once all 47 years of analysis were completed, the map distances of this border were converted from mm into km, which would provide a common scale of measuring distance between fronts and heavy rain events.

The following measurements were taken for each heavy rain event: distance between nearest front and the event (mm), frontal type (cold, warm, and stationary, occluded), frontal orientation (90° to -90°) and event location on the warm or cold side of fronts. A protractor was used to measure the angle of the front with respect to nearest lines of longitude. The possible angles of frontal orientation ranged from 90° to -90°. The researcher would add this new data for every heavy rain event to the precipitation database developed originally by Konrad.

Identification of frontal features with respect to an event's time and location was sometimes not easy to determine if the event's location straddled along a frontal passage while the event time occur between available map times. The method of "eye-balling" frontal movement with respect to the event location was used between the map periods (e.g. 15Z and 18Z). Occasionally, an event would look to be an equal distance from two frontal types (i.e. near the central low-pressure of a mid-latitude cyclone). This could make it difficult to determine which front was closer to the event (i.e. had the most impact on precipitation). Many times it was needed to observe multiple map times before and after an event to understand the general speed and direction of a front's movement.

The measurement of frontal orientation and the distance between the nearest frontal boundary and heavy rain event was sometimes difficult to determine for fronts found in the southeast region. It was noted that slow moving or stationary frontal boundaries displayed a serpentine, irregular pattern, which may be attributable to a cool wedging scenario that occurs in the southeast region due to the Appalachian Mountains to the west. This serpentine frontal pattern was not found in any other of the nine regions. Dissipating, weak frontal boundaries may also display a serpentine pattern when unconnected to mid-latitude cyclones and dynamics, which are more commonly found in the northern regions during the warm season. However, a serpentine pattern for fronts was not a common occurrence given the volume of maps analyzed.

Frontal types were categorized into four groups of equal distance relative to the nearest front: 0-100, 101-200, 201-300, and 300+ km. There was little previous work, experimental or theoretical, to suggest other divisions of distance. However, one possibility as a result of the present database development and research would be a re-analysis based on more realistic values. As will be shown, this study found many heavy rain events occurred within 0-100 km of a front and few within 101-200 km. Therefore, a further refinement of these distance categories may be of interest. The scales of distance were arbitrarily defined from a frontal boundary and were not based on any physical justification. The 300+ km category was also arbitrarily defined in this study to classify when a precipitation event was "non-frontal" (precipitation event less affected by the presence frontal boundaries). A caveat to the 300+ km "non-frontal" event distance is that heavy precipitation north of a warm or stationary front (cool side) may still be connected to the front at a distance greater than 300 km (i.e. LLJ transport over front). All heavy rain events were located on either the warm or cold side of the nearest frontal boundary. A precipitation event's location on the warm or cool side of a front was recorded even for "non-frontal" events. Frontal orientation was also recorded by defining it into eight groups: N-S, SSW-NNE, SW-NE, WSW-ENE, W-E, WNW-ESE, NW-SE, and NNW-SSE). Each of these orientation groups represents 22.5° of separation from a north to south range of angles, 90° to -90°. The following map illustrates the analysis for a few heavy precipitation events (Figure 3).

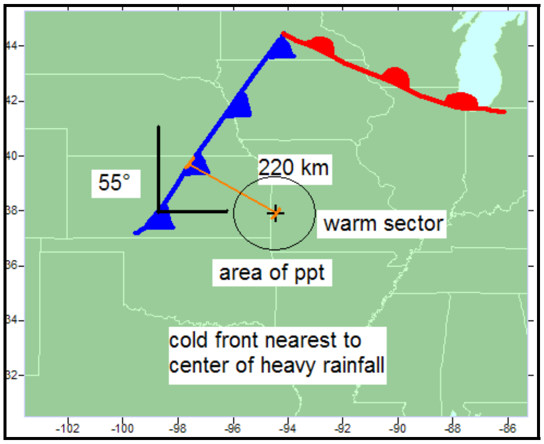

Figure 3: Measuring distance from cold front to event center (220 km), frontal orientation (55°) and identifying event location on warm or cold side of front (warm). Circular area around event center denotes area of precipitation (ppt) (Smith 2005).

The use of three precipitation variables examined the number of frontal events on warm and cold side to find subtle regional and local scale trends in precipitation. These variables analyzed the heavy rain event data by regional changes in 1. Areal_ppt (*regional-scale precipitation*: areal mean precipitation total within the 100,000 km^2 circular region of a heavy rain event); 2. Max_ppt (*local-scale precipitation*: heaviest precipitation total observed in a 10 x 10 km pixel within the 100,000 km^2 circular region); 3. Max_ar_ratio (*local vs. regional scale precipitation*: the ratio of the heaviest precipitation total observed in a 10 x 10 km pixel within the 100,000 km^2 area of a heavy rain event *over* the areal mean precipitation total of the 100,000 km^2. This data was then categorized by only the "heaviest" (4^{th} quartile) and "lightest" (1^{st} quartile) of the (frontal) heavy rain events for each variable (Table 2). The primary focus of this research was to examine heavy rain events near frontal boundaries.

3. RESULTS

This climatology found more *frontal* heavy rain events (2,066) than *non-frontal* (1,266) events during the warm-season months from 1950-1996. The frontal heavy rain events were found almost evenly on the cold and warm sides of fronts - 1,037 on the cold side and 1,029 on the warm side.

This research reports that stationary fronts were associated with 45% of the "frontal" events in this study, while cold and warm fronts were found 36% and 16% of the time, respectively. The number of cold fronts near heavy rain was more frequent in the southern regions, while warm fronts were most common in the northern regions. Stationary fronts were most commonly found in southern regions (e.g. Texas, Gulf, Southeast).

It was also discovered that the number of heavy rain events decreased with distance from the front. Of all frontal events, 49% were within 0-100 km, 33% within 101-200 km, and 18% within 201-300 km. There were more "non-frontal" (300+ km) events than any other of the individual frontal distance categories. Yet, this was to be expected since the "non-frontal" category represented a larger range of distance values from a frontal boundary.

(Front, side)	**Regional-scale precip (Areal_PPT)**		**Local-scale precip (Max_PPT)**		**Local / Regional scale precip (Mx_ar_ratio)**	
Quartiles	*1^{st}*	*4th*	*1^{st}*	*4th*	*1st*	*4th*
Cold, cold	34	20	34	17	25	27
Warm, cold	18	24	27	20	34	13
Stationary, cold	20	29	22	29	30	23
Cold, warm	33	21	30	20	20	28
Warm, warm	26	24	23	23	24	17
Stationary, warm	22	29	15	37	20	33
All occluded	26	14	40	5	44	4

Table 2: Percentage of heavy rain events associated with the 1^{st} and 4^{th} quartiles of three precipitation variables. 1^{st} quartile is lowest (0-25%) of the sample mean; 4^{th} quartile is highest (75-100%) of sample mean.

The most important aspect of this climatology was the discovery of how the character of heavy precipitation near fronts changed regionally. First, it was evident that the number of the frontal types (cold, warm, stationary, occluded) varied with latitude. Cold frontal events were noticeably more frequent in the south, and became less frequent with increasing latitude across the nine regions. In contrast, warm frontal events were much more frequent in the northern regions (e.g. Northeast, Northern) with very few in the south (only one event in the Gulf region). The stationary frontal events were fairly common across all the regions, but were still the most frequent in the southern regions (e.g. Texas, Gulf and Southeast). As expected, occluded fronts were found almost exclusively in the northern regions. All of these regional patterns may be explained by the mean position of the mid-latitude cyclone's path during the warm-season months. Warm and occluded frontal events were found more frequently in the northern regions since those frontal types are generally closer to the cyclone's center of low-pressure, which develops and tracks far to the north during the summertime. In contrast, cold and stationary fronts were more frequently found in the southern regions since they may extend down and affect areas south of the cyclone's central low-pressure.

The orientation angle (90° to -90°) of the frontal types also displayed regional trends. The most pronounced trend was displayed by the cold front. Southern regions had a majority of cold frontal boundaries at a SW-NE angle, while the northern regions displayed a N-S angle of orientation. This dissimilarity in orientation indicated that the mid-latitude cyclones were more mature and organized along northern regions, as would be expected, and less organized and developed in the south. Stationary fronts were much more homogenous across the regions, as a typical W-E orientation was dominant. Additional work may be done using this frontal orientation data with the steering wind vector (e.g. 850, 500, 200 hPa wind vectors), as estimated over the center of each event. This could provide a coarse estimate for the speed and direction of movement of individual thunderstorm cells responsible for the precipitation and develop a more complete synoptic picture for heavy rain development near fronts.

Discussion of precipitation totals on a regional-scale and local-scale is extensive and is excluded for brevity. These results are included in the summary map (Figure 4), which summarizes high or low precipitation totals on a regional-scale and local-scale; determines if the heavy rain events are predominantly more widespread vs. localized; lists any frontal type that dominates a region's heavy rain events; indicates possible MCS-LLJ influence on precipitation based on "frontal / side" event analysis; and shows if a region fits the Maddox "frontal' or "synoptic" types based on number and intensity ("heaviest" vs. "lightest" events) of "frontal / side" events.

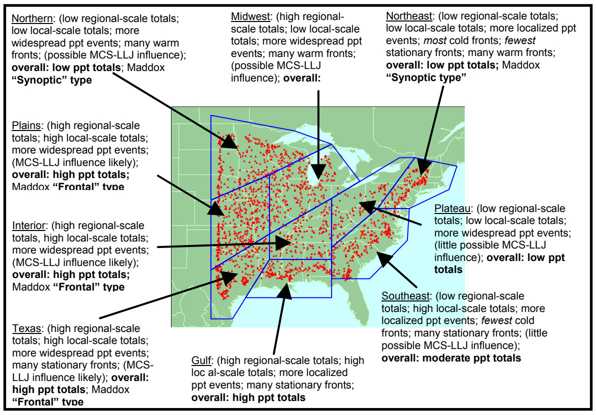

Figure 4: Regional summary of precipitation trends.

A follow-up to this study was being done using National Center Environmental Prediction (NCEP) Reanalysis data to estimate the values of ten synoptic fields over the center of the region of heaviest rainfall for each event (Konrad et al. 2005 *in review*). Surface weather analyses were examined to classify each event into one of three general synoptic situations (warm or cool sector, and non-frontal) according to the location of the event's center relative to the nearest frontal boundary. Statistics were developed and compared across the nine sub-regions and three synoptic situations in order to reveal the proportion of events associated with exceptionally high and low synoptic field values (i.e. precipitable water, 500 hPa vorticity advection, 850-500 hPa lapse rate). This paper is in review for the International Journal of Climatology.

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