OPERATIONAL TROPICAL CYCLONE QUANTITATIVE PRECIPITATION FORECASTING

Russell L. Pfost

NOAA/National Weather Service
Weather Forecast Office
Miami, Florida

Abstract

Floods due to torrential rains associated with landfalling tropical cyclones have always been a big threat for loss of life. Recent research (Rappaport et al. 1999) has shown that since 1970 about 57% of the total deaths reported with tropical cyclones have been from floods due to torrential rains. This paper will present some operational forecasting considerations from an observational perspective, and will propose suggestions for real-time quantitative precipitation forecasting with landfalling tropical cyclones along the Florida and central Gulf of Mexico coasts of the United States.

1. Introduction

While floods from torrential rainfall associated with landfalling tropical cyclones have been known as a threat to human life for many years, the apparently larger threats from storm surge and extreme wind have usually commanded the most attention. However, Rappaport et al. (1999) found that during the period 1970-1998, floods from torrential rains associated with tropical cyclones accounted for 292 out of 510 reported deaths (57%) in the U.S. They also found that floods accounted for 70% of children's deaths that occurred with tropical cyclones.

Several tropical storms have caused a large loss of human lives due to flooding from torrential rains in the history of the United States. Hurricane Agnes (1972) came ashore in the Florida panhandle as a category 1 storm but produced huge rainfall amounts in the mid-Atlantic states that caused flooding and 125 deaths. Tropical Storm Alberto (1994) also came ashore in the Florida panhandle. Alberto slowed down and meandered across Georgia and Alabama producing more than 20 inches of rain, and floods that resulted in 33 deaths. Tropical Storm Amelia (1978) came ashore in Texas and produced floods from torrential rains that resulted in 33 deaths. Even as recently as 1999, Hurricane Floyd came ashore in coastal North Carolina and produced catastrophic flooding resulting from 15 to 20 inch rains, and 56 deaths. Also in 1999, Hurricane Irene resulted in 10 to 20 inches across much of southeast Florida causing $600 million in damage and 8 indirect deaths. Because two of the three biggest U.S. flood producing killer storms were 'only' tropical storms, there appears to be little relationship between tropical cyclone intensity and the number of rainfall induced flood deaths.The relationship between storm movement and rainfall has been known for a long time from common sense and observational studies. An old, widely known empirical relationship has been that an estimate for the maximum rainfall from a landfalling tropical cyclone in inches is 100 divided by the storm speed in knots (Kraft 1960s, from Hebert, personal communication). This paper will use rainfall observations and storm tracks from historical storms to validate this old, simple relationship and perhaps offer additional guidance for operational forecasters when faced with such a situation.

This study is limited to two areas: 1) the northern Gulf of Mexico coast between Lake Charles, Louisiana, and Apalachicola, Florida, and 2) the Florida peninsula between Apalachicola and Fernandina Beach. Data for this study were obtained from U.S. Department of Commerce (DOC), National Oceanic and Atmospheric Administration (NOAA), National Weather Service (NWS) and National Environmental Satellite, Data, and Information Service (NESDIS) publications such as NESDIS National Climatic Data Center (NCDC) *Climatological Data* publications, NWS Tropical Prediction Center historical hurricane tracks, and NWS *Natural Disaster Survey Reports* on individual storms where available.

A great deal of interesting and potentially useful rainfall data for landfalling tropical cyclones in the United States between 1900 and 1955 can be found in Schoner and Molansky (1956) and Schoner (1957). However, Schoner and Molansky's data was not used in this study for the following reasons: 1) for many of the earliest years, the density of the cooperative rainfall network is sparse at best, making the maximum rainfall reports suspect, 2) the maximum rainfall report for Hurricane Easy in 1950 is listed as 24.5 inches at Cedar Key, Florida, but it is well known historically that Yankeetown, Florida, received 38.7 inches during that storm, and 3) for a number of storms where maximum rainfall reports were less than 5 inches, no data is included, thus potentially biasing the data and any derived relationships toward larger rainfall amounts. Even with these identifiable pitfalls, Schoner and Molansky's work can be a valuable reference when trying to forecast rainfall associated with a landfalling tropical cyclone.

2. Background

Rainfall in tropical latitudes is characterized by high temperature and high liquid water content when compared to precipitation in the mid latitudes (except for tropical cyclone environment). The higher liquid water content combined with very strong convection in the central part of a tropical cyclone (or 'eye wall' in hurricanes) provides potential for extreme amounts of rain. However, most of the heavy rainfall occurs in the high-wind area, making measurements very difficult. Simpson and Riehl (1981) estimated that not more than half the falling rainwater is caught by the typical manual rain gage at wind speeds above 50 knots. Automated rain gages, notably tipping buckets, are prone to even more error due to the inability of the tipping mechanism to keep up with the torrential rains and error from the effect of the wind itself on the tipping mechanism.

Factors to consider when trying to forecast tropical cyclone rainfall include the storm's movement, intensity (arguably), size, rainband progression (training effects), topography, and mesoscale atmospheric features such as fronts. The combined effects of all of these factors have resulted in widely varying reports (from a trace to more than 100 inches in a typhoon) of rainfall amounts associated with tropical cyclones. Indeed, sometimes the heaviest rainfall with tropical cyclones occurs well after the storm has moved inland and has apparently lost all tropical characteristics.

Based on a host of assumptions and calculations using aircraft data on the amount of moisture transport, several researchers (Riehl and Malkus 1961; Simpson and Riehl 1981) found that the rainfall rate in hurricanes decreases logarithmically with distance from the center. From graphs of three hurricane precipitation profiles in work done by these researchers, the maximum computed rainfall rate of about 1.3 inches per hour extends out to only about 22 statute miles from the center, while from 22 to 44 miles the computed rainfall rate is about 0.66 inches per hour, decreasing to 0.33 inches per hour from 44 to 68 miles from the center, and 0.16 inches per hour from 68 to 93 miles from the center. Assuming then a storm motion of about 10 mph, disregarding the existence of an eye, and assuming that the hypothetical storm moves directly over the point in question in order to obtain the maximum rainfall possible, the maximum hypothetical rainfall would be about 11 inches. If the storm motion is doubled to 20 mph, the maximum estimated rainfall is halved to 5.5 inches. If the storm motion is halved to 5 mph, the maximum estimated rainfall is doubled to 22 inches. From these rough points, one can fit a theoretical logarithmic curve with the equation (1):

$$y = 31.1 \bullet (0.915)^{x} \tag{1}$$

where x is the speed of the storm in mph and y is the estimated maximum rainfall in inches. This is the first maximum rainfall prediction equation for use in the field in real time. Note that for a stalled storm (x = 0 mph) the highest rainfall possible is 31.1 inches, so caution must be exercised when using this equation below about 5 mph.

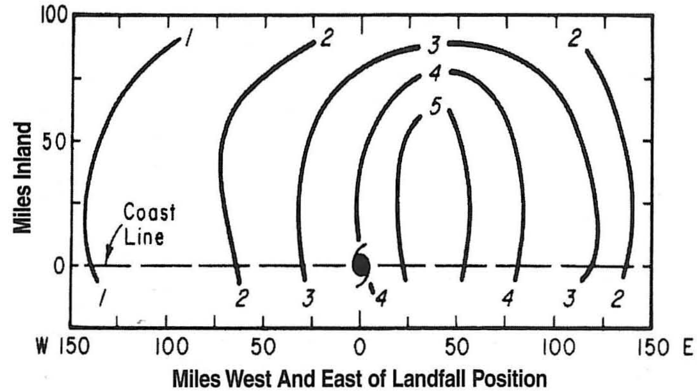

Fig. 1. Average 48-hour rainfall (in.) pattern for 46 Gulf coast tropical storms and hurricanes (from Goodyear 1986, reproduced in Atkinson 1971).

Testing equation (1) on historical data is a logical next step. For Hurricane Andrew, which struck south Dade County, Florida, in August of 1992, the movement was relatively fast; around 17 knots or 18.7 mph. Using that speed, equation (1) predicts a maximum of 5.9 inches of rain. Andrew produced a reported maximum 7.5 inches of rain at Tamiami Airport, although most reports were less than 4 inches.

Goodyear (1968) used observational data from 46 tropical storms and hurricanes making landfall on the Gulf coast of the U.S. during the period 1940-65 to come up with an average 48 hour rainfall pattern with respect to the tropical cyclone center. His work shows the average maximum rainfall of nearly 6 inches occurring from 25 to 50 miles inland from the coast approximately 25 to 50 miles to the right of the storm track (Fig. 1). However, the individual storms showed a wide range in actual rainfall amount, due in part to the speed of movement of each respective storm. Operational forecasters can readily use this information as they decide where to post flood watches and forecast average rainfall amounts.

Enman (1993) and Dutcher (1993) developed rainfall amount prediction models based on seven independent variables (maximum sustained wind speed, central pressure, heading, forward speed, angle at which it strikes the coast, and diameter of the largest closed isobar) to forecast rainfall distribution of hurricanes only. The Enman model was for the Gulf of Mexico and the Dutcher model was for the U.S. East Coast respectively. Enman also used Dutcher's data to create a combined model. The predictions for these models were called average storm total rainfall assigned to 50 km by 50 km bins rather than point totals. Thus the equation is a function of row and column values that is easily adaptable to a personal computer or workstation environment as long as good information for the predictors is known.

The Scofield/Oliver technique (Spayd and Scofield 1984) has been used operationally on hurricanes and tropical storms since 1978. At its inception, the Scofield/Oliver technique was a manual procedure using half-hourly visible and enhanced infrared (IR) GOES satellite imagery. With the advent of digital satellite imagery and better computer power, the technique has been automated and improved. Today, accurate, real-time, operational rainfall estimates are made by NESDIS using an auto-estimator algorithm (Vicente et al. 1998). Precipitation rates are primarily based on the cloud-top temperature obtained from GOES 8 and GOES 10 (10.7 micron) satellite imagery. Instantaneous, 1-hour, 3-hour, 6-hour, and 24-hour precipitation estimates are available. Numerous other factors, including the cloud-top geometry, the available atmospheric moisture, stability parameters, radar data, and local topography, are used to further adjust the rain rate. The estimates are available to all NWS Forecast Offices through the NESDIS Flash Flood Home Page on the Internet World Wide Web. In addition, a new publication on satellite techniques for estimating rainfall from tropical cyclones has recently become available through the World Meteorological Organization (WMO 1999).

Extreme rainfall amounts are likely with very slow moving tropical cyclones. History provides a number of excellent examples at several different time scales. The South Florida hurricane of 11-12 October 1947 dropped 1.32 inches of rain in 10 minutes and 3.62 inches of rain in one hour at Hialeah, and 6 inches in just over one hour at other locations in the Miami area (Barnes 1998). During the 17-18 September 1926 hurricane, 16.4 inches of rain fell in a few hours in Blountstown. A Florida record 38.7 inches of rain in 24 hours fell at Yankeetown during Hurricane "Easy" in 1950. Over 40 inches of rain fell at Dauphin Island, Alabama, in Hurricane Danny in July 1997. The U.S. record of 43 inches of rain in 24 hours occurred at Alvin, Texas during Tropical Storm Claudette in 1979.

Tropical Storm Alberto is an excellent example of a slow moving tropical cyclone that caused torrential rainfall and flooding (NOAA 1995). Alberto made landfall in July 1994, in the Florida panhandle and then drifted erratically across Georgia and Alabama. Alberto dropped over 20 inches of rain in a few spots and caused major flooding on rivers and streams in southwest Georgia, southeast Alabama, and northwest Florida.

Low rainfall or even dry conditions are possible and are usually associated with fast-moving tropical cyclones. The 1941 hurricane at Miami dropped less than 0.5 inch. Hurricane Andrew, mentioned earlier, is another example of a relatively fast-moving storm that was drier than would normally be expected.

3. Data and Analysis

A method of anticipating extreme rainfall associated with landfalling tropical cyclones would be of great value for operational forecasters along the southern U.S. coastline. In order to assess the relative location and amount of extreme rainfall for tropical cyclones making landfall along the U.S. Gulf coast between Lake Charles, Louisiana, and Apalachicola, Florida, it was necessary to first identify tropical cyclones that crossed this part of the coast between 1960 and 1999. The NWS Tropical Prediction Center's Atlantic Tropical Storm and Hurricane Tracks provided this information as well as a general speed and direction of motion as the storm crossed the coastline. The monthly NESDIS NCDC publication *Climatological Data* for the states of Louisiana, Mississippi, Alabama, and Florida provided rainfall reports for the affected counties and supplemental reports such as *Natural Disaster Reports* were used if available.

A plot of each storm's path and the associated rainfall were then assembled. Subjective decisions were made in each individual storm case on how many days to include in the storm total based on speed of storm movement and path. These subjective decisions were necessary since most of the reports available in *Climatological Data* were once daily 24-hour reports of accumulated rainfall. The highest rainfall amount and its direction and shortest distance from the path of the storm, as well as distance inland, were identified and tabulated. Angle of incidence with the coast was noted for analysis, with 90 degrees indicating a perpendicular path of landfall, and 0 degrees indicating a parallel path along the coast.

The data were entered into a spreadsheet program and plots generated. The method of least squares was applied to fit a line where appropriate. After the Lake Charles to Apalachicola segment was complete, a segment from Apalachicola to Fernandina Beach including the entire Florida peninsula was completed the same way. Although the Gulf coast west of Lake Charles and the Atlantic coast north of Fernandina Beach were not considered, hopefully these results can be applied in a general way for those coasts with some success. No consideration was made for 'special cases', which might include important interactions of the tropical cyclone with baroclinic zones or topography or 'hybrid' tropical cyclones making the transition from warm core to cold core.

Of course, the climatological and hydrologic data networks are probably not dense enough to capture the true maximum rainfall associated with a landfalling tropical cyclone. Those rainfall reports that are available are suspect due to wind effects and a host of other possibilities. In some cases, rainfall reports from cooperative reporting sites are missing or represent several day storm totals as rain gage sites were abandoned.

4. Results

a. Amount

The first forecast problem for the operational meteorologist is to estimate the amount of rainfall from a landfalling tropical cyclone. The results of the analysis for the Gulf coast between Lake Charles and Apalachicola are shown in Fig. 2. There were roughly 30 tropical cyclones in the sample. Note that for storm speeds greater than 6 knots, the maximum observed rainfall lies roughly along a line near 9 or 10 inches regardless of speed. For storm speeds less than 6 knots a more exponential distribution is apparent. Similar results for the Florida peninsula between Apalachicola and Fernandina Beach are shown in Fig. 3 with about 33 tropical cyclones in the sample.

The method of least squares was applied through a spreadsheet program to find an equation that would describe a 'best-fit line' excluding speeds less than 6 knots. For northern Gulf coast landfalling storms, a first guess maximum rainfall of 9.75 inches is appropriate

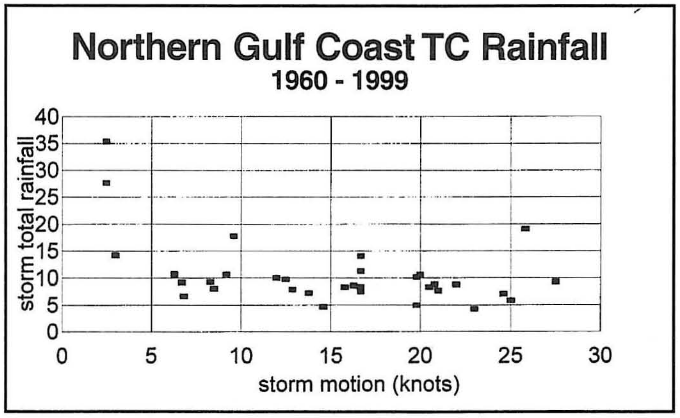

Fig. 2. Maximum rainfall (in.) plotted against estimated storm movement (kt) for landfalling tropical cyclones between Lake Charles, LA and Apalachicola, FL.

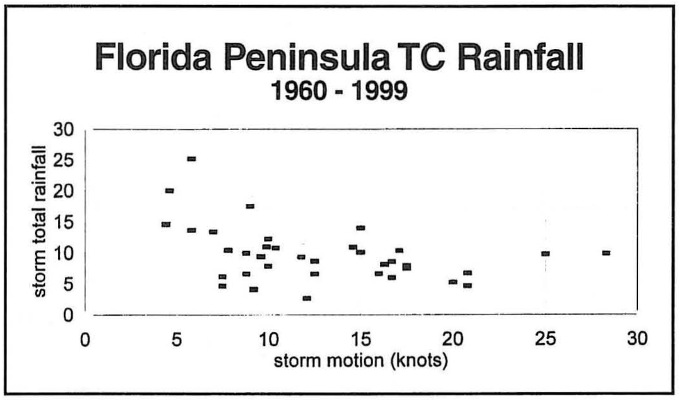

Fig. 3. Maximum rainfall (in.) plotted against estimated storm movement (kt) for landfalling tropical cyclones on peninsula Florida between Apalachicola, FL and Fernandina Beach, FL.

with a small negative correction for speed as shown in equation (2). The Florida peninsula landfalling storms show a similar regression, but with a slightly smaller first guess maximum rainfall of 9.37 inches and a larger negative correction for speed as shown in equation (3).

$$R = 9.75 \text{ in.} - 0.039(\text{movement (kt)}) \quad (2)$$

$$R = 9.37 \text{ in.} - 0.063(\text{movement (kt)}) \quad (3)$$

From this simple analysis, operational forecasters confronted with a typical rainfall forecast problem from a tropical cyclone moving faster than 6 knots between Lake Charles and Fernandina can expect a maximum storm total rainfall amount of 9 to 10 inches with a standard deviation of 3.3 inches for the northern Gulf coast and 3.2 inches for peninsular Florida. This is more than what Goodyear found in his study and does not show the variability with speed expected from the simple Kraft relationship or the Riehl studies. Even so, the best forecasting aide for such a situation will be to use all four ways to obtain a good idea of what can be expected as a maximum rainfall.

b. Distribution

A second forecast problem for the operational meteorologist is whether or not to issue a flood watch for a landfalling tropical cyclone, and, if so, where to position the flood watch. Tropical cyclones make landfall in summer and fall months when soil moisture content is normally lower due to actively growing vegetation and sporadic rainfall from scattered summer showers and thunderstorms. Therefore, the soil and the vegetation can often absorb a great deal of rainfall from hurricanes and mitigate excessive flooding. In Louisiana and Mississippi during the passage of Hurricane Andrew in August of 1992, maximum rainfall amounts were near 11 inches. However, very little flooding occurred due to the dryness of the soil (Pfost 1993). Contrast that situation with the disastrous flooding in North Carolina in September 1999 from Hurricane Floyd associated rainfall, which came after Tropical Storm Dennis rainfall had increased soil moisture just a week or two earlier. Because of the rainfall potential, ***a flood watch is always in the best interest of the public safety regardless of the dryness of the soil when a tropical cyclone moves ashore.***

Positioning the flood watch is relatively easy using Goodyear's work. From Fig. 1 (subjectively using the 3 inch isohyet as a guide for potential flood producing rainfall), the flood watch should be posted from 25 miles west to 125 miles east and 100 miles inland from where the center of the tropical cyclone makes landfall. To test this conclusion, the geographical positions of the highest rainfall report available were plotted relative to the position where the center of the tropical cyclone crossed the coast. Two distances, shortest distance from the coast and shortest distance to the subsequent path of the center of the tropical cyclone, were measured and plotted. The results for the northern Gulf coast are shown in Fig. 4, and for the Florida peninsula are shown in Fig. 5.

Assuming that a goal of the flood-watch-issuing forecaster is to post a flood watch area that will include the position of the maximum rainfall report, some general conclusions can now be made. For the northern Gulf of Mexico coast, the flood watch should be posted from 50 miles west to 125 miles east and 125 miles inland from where the center of the tropical cyclone crosses the coast. This is slightly larger than the 3-inch based Goodyear flood watch area. For the Florida peninsula coast, the flood watch should be posted from 25 miles west to 100 miles east and 50 miles inland from where the center of the tropical cyclone crosses the coast. The much smaller inland distance is most likely due to the variety of tracks that are possible for a peninsula like Florida, as well as the fact that the peninsula is only about 140 miles across at its widest point. Of course, if a tropical cyclone is forecast to cross the peninsula, it is logical to include the entire storm swath across the peninsula in any posted flood watch.

The sample size was apparently not large enough for many conclusive results about the relationship of the maximum rainfall associated with a landfalling tropical cyclone and the angle of incidence with the coast. In general, the northern Gulf coast experienced higher rainfall totals with south to north and southeast to northwest moving tropical cyclones. Such movement was conducive for longer training effects on the wetter east side of the tropical cyclone to produce higher rainfall amounts. For

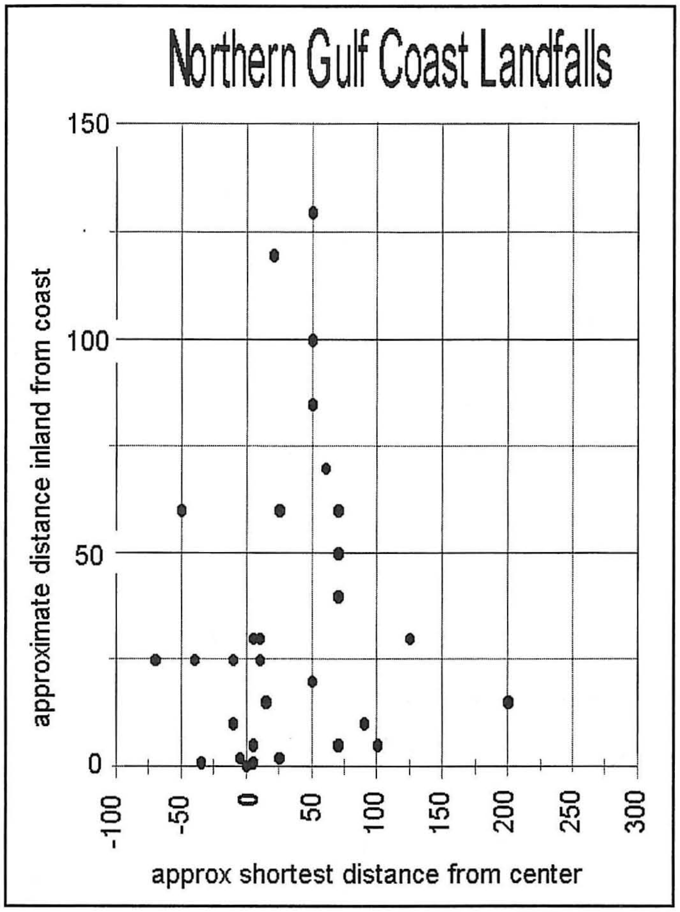

Fig. 4. Location of maximum rainfall report for landfalling tropical cyclones along Gulf Coast between Lake Charles, LA and Apalachicola, FL (1960-1999). Relationship shows shortest distance inland from the coast (miles) and shortest distance from the path of the center of the tropical cyclone (miles). Negative distances denote maximum rainfall was observed west of the location where the center crossed the coast; positive distances are east.

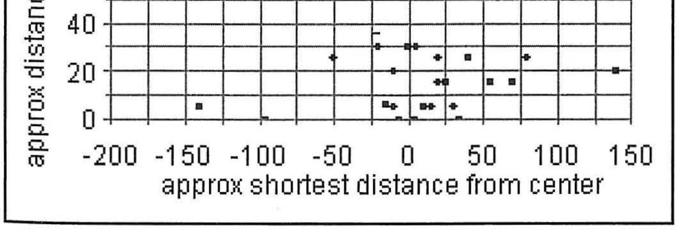

Fig. 5. Location of maximum rainfall report for landfalling tropical cyclones on Florida peninsula between Apalachicola, FL and Fernandina Beach, FL (1960-1999). Relationship shows shortest distance inland from the coast (miles) and shortest distance to the left or right of the path of the center of the tropical cyclone (miles). Negative distances are to the left of the location where the center crossed the coast; positive distances are to the right.

peninsular Florida, storms moving from southwest to northeast seemed to produce higher rainfall amounts than other possibilities.

5. Conclusions

Four methods of forecasting the maximum rainfall to be expected from a landfalling tropical cyclone along the northern Gulf of Mexico coast or the Florida peninsula have been presented: 1) Kraft's simple empirical estimation, 2) a logarithmic method developed by Riehl, Simpson, and Malkus, 3) Goodyear's study, and 4) regression results presented in this paper. Using all four methods is probably the best way to approach the problem of forecasting the maximum rainfall. However, for most landfalling tropical cyclones (moving at speeds greater than 6 knots) between Lake Charles, Louisiana, and Fernandina Beach, Florida, the maximum rainfall will be between 9 and 10 inches with a standard deviation of about 3.3 inches. For tropical cyclones moving at speeds of 6 knots or less, predicted rainfall amounts should be at least double the 9 to 10 inch amount.

Two methods of deciding where to post a flood watch have been presented: 1) Goodyear's study, and 2) plots of the position of observed maximum rainfall relative to the coastline where the center of the tropical cyclone crosses the coast. To include a factor of safety, the flood watch should be posted from 50 miles west to 125 miles east and 125 miles inland of the location where the center of the tropical cyclone crosses the coast between Lake Charles and Fernandina Beach. Flood watches should continue to accompany any identifiable center of circulation and banding features remaining as the storm moves farther inland for as long as several days after the initial landfall.

The angle of incidence of the path of the tropical cyclone with respect to the coast does not seem to have as great an influence on the amount of rainfall produced as might be believed. In general, for the northern Gulf of Mexico coast, southeast to northwest and south to north moving tropical cyclones produced more rain than southwest to northeast moving storms. For the Florida peninsula, southwest to northeast moving tropical cyclones produced more rain than any of the other possible path orientations, but there were several exceptions.

Acknowledgments

Special thanks are due Steve Brueske, Science and Operations Officer at the National Weather Service Forecast Office, Charleston, South Carolina; and Dr. Raymond Zehr, scientist for NOAA in the Colorado Institute for Research in the Atmosphere (CIRA) in Fort Collins, Colorado, for their formal reviews of the manuscript. Thanks also to Dr. Frank Marks, research meteorologist for the Hurricane Research Division (HRD) at the Atlantic Oceanographic and Meteorological Laboratory (AOML) in Miami; Alan Gerard, Science and Operations Officer at the National Weather Service Forecast Office, Jackson, Mississippi; James Lushine, Warning Coordination Meteorologist at the National Weather Service Forecast Office in Miami; Max Mayfield, Director of the NWS Tropical Prediction Center; and Dr. Edward Rappaport, Chief of the Technical Support Branch, Tropical Prediction Center, for comments and helpful suggestions.

Author

Russell (Rusty) Pfost is Meteorologist-in-Charge (MIC) of the National Weather Service Weather Forecast Office (WFO) in Miami, Florida. He earned his B.S. degree in meteorology from Florida State University in Tallahassee in 1977 and his M.S. degree in Earth and Atmospheric Sciences from Georgia Tech in Atlanta in 1990. He has held positions in both meteorology and hydrology with the National Weather Service in Jackson, Mississippi (twice); Key West, Florida; Atlanta, Georgia; and Slidell, Louisiana before moving to Miami in 1998 as MIC. Rusty is a member of the American Meteorological Society and the National Weather Association, and has been with the National Weather Service since 1978.

References

Atkinson, G. D., 1971: *Forecaster's Guide to Tropical Meteorology*, Technical Report 240, United States Air Force, Air Weather Service (MAC).

Barnes, J., 1998: *Florida's Hurricane History*, Univ. of North Carolina Press, Chapel Hill, NC, 175.

Dutcher, D. D., 1993: *A Hurricane Rainfall Prediction Model for the East Coast*, M.S. Thesis, North Carolina State University, Raleigh, NC, 110 leaves.

Enman, J. A., 1993: *Quantitative Precipitation Forecast Models for Hurricanes Making Landfall in the United States*, M.S. Thesis, North Carolina State University, Raleigh, NC, 119 leaves.

Goodyear, H. V., 1968: Frequency and Areal Distributions of Tropical Storm Rainfall in the United States Coastal Region on the Gulf of Mexico, *ESSA Technical Report WB-7*.

Hebert, P., 1998, 1999: Personal communications.

Pfost, R., 1993: Rainfall Patterns and Hurricane Andrew: A Hydrometeorological Survey, National Weather Service Southern Region *Administrative Notes*, Fort Worth, TX, Technical Attachment SR/HSD 93-2, 7 pp.

Rappaport, E. N., M. Fuchs, and M. Lorentson, 1999: The Threat to Life in Inland Areas of the United States from Atlantic Tropical Cyclones, Preprints, *Vol. I, 23rd Conference on Hurricanes and Tropical Meteorology*, Dallas, TX, Amer. Meteor. Soc., 339-345.

Riehl, H., and J. Malkus, 1961: Some Aspects of Hurricane Daisy (1958), *Tellus*, XIII, 181-213.

Schoner, R. W., and S. Molansky, 1956: Rainfall Associated with Hurricanes (And Other Tropical Disturbances), Preprint volume, *National Hurricane Research Project, Report No. 3*, U.S. Dept. of Commerce, Weather Bureau, and U.S. Dept. of the Army, Corps of Engineers, Washington, D.C., 305 pp.

Schoner, R.W., 1957: *Frequency and distribution of areal rainfall averages associated with tropical storms entering the coast of the United States (Texas to Maine)*, U.S. Weather Bureau, Washington, D.C., 17 leaves.

Simpson, R. H., and H. Riehl, 1981: *The Hurricane and Its Impact*, Louisiana State University Press, Baton Rouge, LA, 135-140.

Spayd, L. E., and R. A. Scofield, 1984: A Tropical Cyclone Precipitation Estimation Technique Using Geostationary Satellite Data, *NOAA Technical Memorandum NESDIS 5*, U.S. Dept. of Commerce, National Oceanic and Atmospheric Administration, National Environmental Satellite, Data, and Information Service, Satellite Applications Laboratory, Washington, D.C., 36 pages.

U.S. Dept. of Commerce, National Oceanic and Atmospheric Administration, National Weather Service, *Natural Disaster Survey Report*, 1995: Tropical Storm Alberto Heavy Rains and Flooding, Georgia, Alabama, and Florida, July, 1994.

U.S. Dept. of Commerce, National Oceanic and Atmospheric Administration, National Environmental Satellite, Data, and Information Service, National Climatic Data Center, *Climatological Data*, (Alabama, Florida, Louisiana, and Mississippi), years 1960-1999.

U.S. Dept. of Commerce, National Oceanic and Atmospheric Administration, National Environmental Satellite, Data, and Information Service, National Climatic Data Center and the NWS National Hurricane Center, 1993: *Tropical Cyclones of the North Atlantic Ocean 1871-1992*, and NWS Tropical Prediction Center Web site historical hurricane tracks.

Vicente, G. A., R. A. Scofield and W. P. Menzel, 1998: The Operational GOES Infrared Rainfall Estimation Technique, *Bull. Amer. Meteor. Soc.*, 79, 1883-1898.

World Meteorological Organization, 1999: Estimating the Amount of Rainfall Associated with Tropical Cyclones Using Satellite Techniques, WMO/TD No. 975, Tropical Cyclone Programme Report No. TCP-42, E. C. Barrett, Chief Editor, World Meteorological Organization, Geneva, Switzerland, 294 pp.