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SPATIAL DISTRIBUTION OF TROPICAL CYCLONE INDUCED PRECIPITATION AND OPERATIONAL APPLICATIONS IN SOUTH CAROLINA

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1. INTRODUCTION

During the warm season, the mesoscale nature of precipitation events limits the forecast skill of quantitative precipitation forecasts (QPF). While the prediction of precipitation during the cool season has shown significant improvement during the last decade, these convective storms continue to provide operational meteorologists with further challenges beyond the single variable of total precipitation (Fritsch and Carbone, 2004). One primary concern is the application of QPF in the realm of river forecasting to determine the flood stage, region or local area to be affected, and the time-efficient issuance of watches and warnings to the public. The transition of tropical cyclones to extratropical storms over the southeastern United States provides further challenges, including baroclinic enhancement of precipitation and high winds (Jones et al., 2003).

In 2004, six tropical cyclones impacted South Carolina with high winds, a record number of tornadoes, and heavy rainfall that led to moderate to major flooding, particularly with Hurricane Gaston along the coast and Frances, Ivan, and Jeanne in the northwest portion of the state. In an attempt to improve the prediction of tropical cyclone-induced precipitation in South Carolina, the State Climatology Office (SCO) developed a web-based tool to provide a climatological reference of storm-total precipitation from a selection of 54 past storms from the period 1950-2003. The methodology used to acquire the precipitation climatology is presented in section 2 with the initial results presented in section 3. The historical set of tropical cyclones is used to determine the accuracy and bias associated with the methods in section 4. The performance assessment of the method for the 2004 season in section 5 includes a side-by-side comparison of the climatological methodology with actual forecasts from the Hydrometeorological Prediction Center (HPC) and the Southeast River Forecast Center (SERFC) during two of the events (Frances and Jeanne). Section 6 describes the accessibility and information included as part of the web-based QPF tools. A summary of the results, any conclusions, and future work concludes the work in Section 7.

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2. METHODOLOGY

South Carolina experiences a direct landfall from a tropical cyclone every four to five years; however, some portion of the state is typically affected by their strong winds, high surf, or heavy precipitation each and every year (Purvis et al., 1986). Positioned in the southeastern United States with the Atlantic Ocean to the east and the Gulf of Mexico to the southwest, South Carolina is located in a region that is vulnerable to the effects of tropical storms that make landfall along the Gulf Coast, as well. In the period 1950-2003, a total of 70 tropical storms passed in or near the state, including the remnants of several ‘back door’ storms (e.g., Alma, 1966; Marco, 1990) that caused extensive flooding across the region. The geographical features of South Carolina can enhance the mesoscale variations found in warm season precipitation through orographic and moisture source contributions. The Appalachian Mountains extend across the northwest corner of South Carolina from southwest to northeast. The cyclonic flow around tropical cyclones can produce an upslope component to the vertical motion (ascent) in easterly flow while westerly winds can reduce the production of precipitation through low-level drying and subsidence. The goal of the present study is to delineate the set of 70 storms from 1950-2003 relative to the track and landfall location of the storm. Eight divisions (storm trajectories) were chosen for the categorization of the storms as presented in Figure 1.

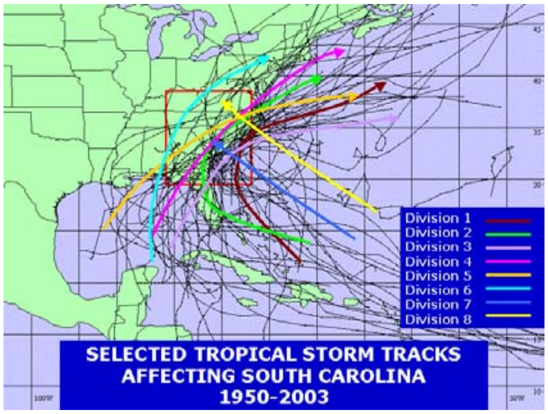

FIGURE 1

Applying the subjective filter, 54 of the 70 storm tracks could be reasonably fit into the eight divisional categories (Table 1). To determine the precipitation distribution across South Carolina, the storm total precipitation data from the 54 storms were collected at 37 daily cooperative observation sites (COOP) using radar and satellite imagery when available to determine the length of the event. The eight divisional means created a climatological expectation of total precipitation from storms for the given trajectory. The storm total precipitation at each COOP site was then

Table 1
Storm Names By Division

Division 1	Division 2	Division 3	Division 4	Division 5	Division 6	Division 7	Division 8
Helene 1958	Cleo 1964	Donna 1960	TS #7 1953	Hilda 1964	Danny 1985	Able 1952	Connie 1955
Ginny 1963	Dora 1964	Gladys 1968	Florence 1953	TS #1 1965	Andrew 1992	TS #3 1953	Diane 1955
Amy 1975	Dawn 1972	Dennis 1981	Flossy 1956	Babe 1977	Alberto 1994	Hazel 1954	Ione 1955
Arthur 1996	ST #3 1976	Ana 1991	TS #1 1957	Marco 1990	Beryl 1994	Cindy 1959	TS #6 1961
	David 1979	Irene 1999	Brenda 1960	Helene 2000		Gracie 1959	Diana 1984
	Isidore 1984		Alma 1966			Hugo 1989	Bertha 1996
	Chris 1988		Alma 1970				Bonnie 1998
	Jerry 1995		Agnes 1972				Floyd 1999
	Kyle 2002		Kate 1985				
			Allison 1995				
			Josephine 1996				
			Earl 1998				
			Gordon 2000				

interpolated using the inverse distance weighting (IDW) method with the five nearest neighboring stations included in the analysis. In section 3, a discussion of the details and findings from the climatology is presented, including regional values based on the county warning areas of the National Weather Service Weather Forecast Offices in Greenville-Spartanburg, SC (GSP), Columbia, SC (CAE), Charleston, SC (CHS), and Wilmington, NC (ILM) (Figure 2).

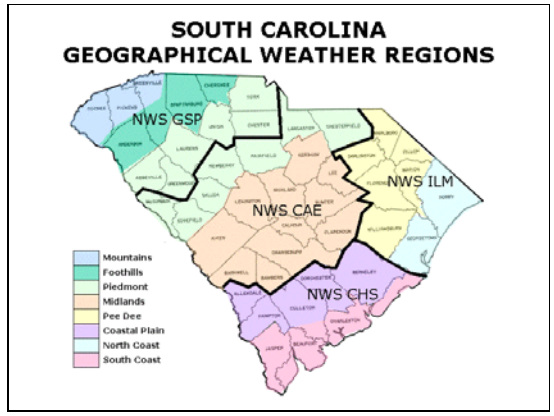

FIGURE 2

3. CLIMATOLOGY

Initially, the eight divisions are considered to determine the mean and extreme values of storm total precipitation from the tropical cyclones based solely on track and landfall location (Table 2). Of the eight divisions, Divisions 2 and 5 produced the largest statewide mean precipitation totals of 3.00 and 3.84 inches, respectively. Both of the storm trajectories from these two divisions approach South Carolina from the southwest and cross the state to the east of the Appalachian Mountains. This storm track allows moisture influx from the Atlantic Ocean and Gulf of Mexico and some enhancement of precipitation in upslope regions of the northwest parts of the state. The smallest precipitation means of less than one inch were calculated for Divisions 1 and 8 for offshore tracks near the South Carolina coast and direct landfalls in North Carolina.

Table 2
Descriptions of Tropical Divisions

Division 1	Offshore Track
Division 2	East Florida Landfall/South Carolina Track
Division 3	West Florida Landfall/Coastal Track
Division 4	East Panhandle Florida Landfall/Coastal-Inland Track
Division 5	Northern Gulf Coast Landfall/East of Appalachians Track
Division 6	Northern Gulf Coast Landfall/West of Appalachians Track
Division 7	Direct Landfall in South Carolina
Division 8	Direct Landfall in North Carolina

For these cases, a westerly component of the wind flow across South Carolina would enhance down-slope drying and reduce moisture availability from the Atlantic. These two factors, coupled with the lack of any significant Gulf of Mexico contribution, would explain the reduced statewide mean precipitation with the primary precipitation region along the northern coastline (Table 3).

Table 3					
Statewide Divisional Precipitation Climatologies					
	Mean	Max	Avg Max	Min	Avg Min
Division 1	0.35	5.91	0.65	0.00	0.17
Division 2	3.00	12.69	6.55	0.00	0.04
Division 3	1.67	9.69	3.50	0.00	0.98
Division 4	2.42	10.14	4.09	0.00	0.65
Division 5	3.84	12.64	7.87	0.00	1.31
Division 6	1.95	16.12	3.78	0.00	0.59
Division 7	2.50	9.79	4.56	0.00	0.23
Division 8	0.86	13.84	2.12	0.00	0.03

Table 4				
Regional Precipitation Means By Division				
	CAE	CHS	GSP	ILM
Division 1	0.13	0.60	0.15	1.22
Division 2	3.07	4.40	2.13	3.50
Division 3	1.24	3.33	0.57	3.91
Division 4	2.61	2.64	2.01	2.68
Division 5	3.94	3.61	4.01	3.40
Division 6	1.53	0.89	3.35	0.94
Division 7	2.63	3.04	1.66	3.58
Division 8	0.39	1.08	0.34	3.33
All Divisions	2.07	2.60	1.76	2.94

In Figure 3, the IDW analysis for each division and all divisions are presented to indicate the spatial distribution of storm total precipitation across South Carolina. Regionally, the spatial analyses of the divisional means indicate the heaviest precipitation to fall within the Division 2 and Division 5 categories as in the divisional overview. However, a closer inspection (Table 4) of the ILM region indicates that Division 3 storms actually produced the most significant value for mean storm total precipitation of 3.91 inches. For the Columbia area, divisional precipitation means ranged from 0.13 inches for offshore tracks in Division 1 to 3.94 inches in Division 5. Similarly, the Upstate regions near Greenville-Spartanburg averaged only 0.15 and 3.35 inches in the two divisions, respectively. The CHS region exhibited the least precipitation in Division 1, as well, with a mean of only 0.60 inches. The coastal regions, of course, exhibited the largest overall mean for all divisions with 2.60 inches in the CHS service area and 2.94 inches in ILM. Despite the regional tendency for the highest mean precipitation, the maximum storm total precipitation for a single storm for all sites across the state ranged from 7.02 inches at Fort Mill in the north-central part of the state to 16.12 inches at Jocassee and Long Creek in the northwest

4. HISTORICAL PERFORMANCE

In an effort to test the forecast skill of the climatology-based methodology for QPF, the divisional means for each station are used to forecast the total precipitation expected for that station in each of the historical storms categorized in the division. Lending some appreciation to the inclusion of that storm into the climatological mean, the range of errors associated with each division is presented along with the tendency of the storm to under- or over-predict the precipitation for a given region. Following the initial testing, the seven case studies from 2004 are considered alongside a comparison of the current method results with the QPF output statistics from HPC and the SERFC for the two storms, Frances and Jeanne. The range of errors for each division (Table 5) indicated errors of –4.29 inches to +2.96 inches. The largest errors are associated with the highest values for mean absolute error (Charba et al., 2003) in Divisions 2 and 5. Although the under-predicted values were more extreme than the

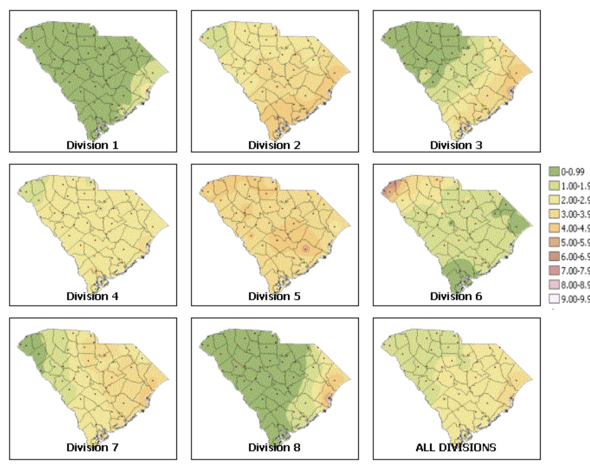

FIGURE 3

over-predictions, the historical performance evaluation indicates that for a total of 1998 forecasts statewide, the method over-predicted the precipitation 1195 times or 59.8 percent of the time. Approximately 40 percent of the forecasts would have under-predicted the precipitation and less than 1 percent would be exact. Given this, the historical performance evaluation indicates that the under-predicted forecasts are less frequent events and are more extreme in comparison to a more frequent and less extreme over-predicted forecast.

Table 5

Range of Errors by Division

	Maximum	Minimum	MAE
Division 1	0.28	-0.49	0.42
Division 2	2.96	-3.95	2.10
Division 3	1.32	-2.18	1.48
Division 4	2.18	-3.42	1.38
Division 5	2.86	-4.29	2.03
Division 6	1.56	-2.43	1.69
Division 7	2.33	-3.05	1.87
Division 8	0.84	-2.08	1.10

5. 2004 CASE STUDIES

In 2004, South Carolina experienced moderate to significant impacts from six tropical cyclones, including Bonnie, Charley, Frances, Gaston, Ivan, and Jeanne. To further test the climatological methodology, the observed storm total precipitation values at the 37 observation sites are compared to the climatological means for the division in which each storm can be categorized (Table 6). Because this methodology is subjective in nature, the storm track of Charley is chosen based more on the trajectory of the approaching storm than on the actual landfall location. While Hurricane Charley actually made direct landfall on the South Carolina coast, the actual forecast called for the storm to remain offshore, therefore, it is placed in Division 3 instead of Division 7.

For the 2004 storms the regional performance is considered alongside the forecast skill at the local sites in order to prepare for the HPC/SERFC comparison. Similar to the historical performance the errors in precipitation tended to over-predict for each storm in each given region with positive anomalies ranging from +0.04 inches to +1.41 inches and negative anomalies, or under-predictions, observed at the regional level for only two storms, Frances and Jeanne. These two storms also exhibited the largest range of errors among stations with over 12 inches between maximum and minimum error values (Table 7).

Table 6

Categorization of 2004 Storms

Bonnie	*Division 4*	*Panhandle FL Landfall/Inland Coastal Track*
Charley	*Division 3*	*Western FL Landfall/Coastal Track*
Frances	*Division 2*	*East Florida Landfall/South Carolina Track*
Gaston	*Division 7*	*Direct Landfall SC*
Ivan	*Division 6*	*Gulf Coast Landfall/W of Appalachians Track*
Jeanne	*Division 2*	*East Florida Landfall/South Carolina Track*

Table 7

Range of Error for Climatology Forecasts in 2004 Storms

	Regional	COOP Sites
Bonnie	+0.04 to +0.95	-2.34 to +2.09
Charley	+0.24 to +1.42	-1.71 to +3.58
Frances	-2.19 to +0.06	-11.36 to +3.88
Gaston	+0.44 to +0.88	-4.42 to +2.81
Ivan	+0.20 to +1.30	-4.43 to +2.44
Jeanne	-0.06 to +1.41	-7.36 to +4.63

Generally, the over-predictions at the station level ranged from +2 to +5 inches with under-forecasted values between –1 and –12. It is of particular note that both Frances and Jeanne took relatively similar paths and were of the same approximate strength at landfall. These results were consistent with the historical climatology in that the extreme values were primarily under-predicted values associated with local maxima and the over-predictions were smaller with a more normal distribution.

In comparing the observed precipitation amounts by region with the forecast output from HPC, SERFC, and the climatology presented herein, the regional values at CAE and GSP for Frances and Jeanne are considered. Coincidentally, the data provided by the hydrological service areas forecaster Kent D. Frantz (Personal Communication, 2005) at the SERFC represents the two systems with the largest errors in the climatological performance analysis. The mean area precipitation (MAP) analysis values represent the HAS used by the SERFC to determine QPF performance. There are several important discrepancies to note regarding the method of MAP including the fact that several observation stations outside of South Carolina are used in the adjacent regions of North Carolina and Georgia and that a different subset of stations is used in the gauge-related climatological analysis. The actual forecasts and MAP observations are presented in Table 8.

Table 8

REGIONAL QPF FORECASTS AND OBSERVATIONAL ANALYSIS

FRANCES	SERFC	HPC	CLIMO	MAP
GSP	4.33	3.57	2.88	5.58
CAE	2.18	1.72	3.06	2.8
JEANNE	SERFC	HPC	CLIMO	MAP
GSP	3.18	4.22	2.8	2.59
CAE	2.87	3.09	3.06	2.86

The MAP analysis from SERFC indicated that 4.33 inches and 2.18 inches of rain fell in the GSP and CAE regions, respectively (Figures 4 and 5). In the Greenville-Spartanburg region, the forecast skill for Frances was excellent for the HAS forecasters at the SERFC, but fell behind the climatological methodology in the Jeanne case which indicated regional errors of +0.21 inches. For the Columbia area, climatology performed best in Frances with errors again near one-quarter inch (Table 9). For Jeanne, the SERFC again performed best in QPF with regional errors of +0.01 inches. Climatology slightly out-performed the HPC forecasts with +0.20 inches in favor of +0.23. Using a ranking technique (e.g. 1, 2, 3) for the four events with a maximum value of 4 and minimum score of 16, the SERFC, HPC, and climatology method scored at 6, 14, and 7, respectively – indicating that for these two tropical events with high initial errors in the climatology, the method presented in this study performs nearly as well as the SERFC operational forecasters and is much improved over HPC.

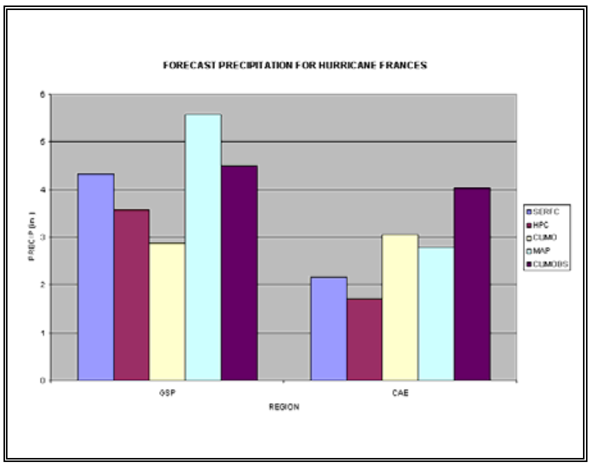

FIGURE 4

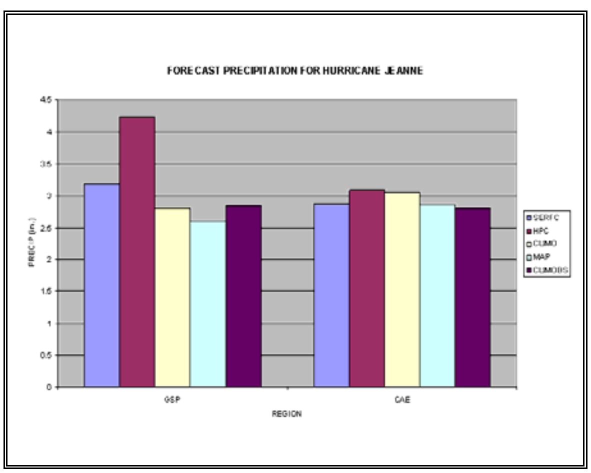

FIGURE 5

Table 9			
REGIONAL QPF FORECAST ERRORS			
FRANCES	SERFC	HPC	CLIMO
GSP	***-1.25***	-2.01	-2.70
CAE	-0.62	-1.08	***0.26***
JEANNE	SERFC	HPC	CLIMO
GSP	0.59	1.63	***0.21***
CAE	***0.01***	0.23	0.20

6. WEB-BASED QPF TOOLS

In an effort to make the climatological precipitation study output available as an operational forecast and planning tool, the South Carolina State Climatology Office developed an interactive web-based tool that will allow plots by division and storm. The introductory page (Figure 6) presents the information presented herein with a link to the web-based application. Upon entering the web-based application, users are presented with the choice of divisional information or a summary of extremes (Figure 7). Within the divisional pages, a plot of the storms considered in each division is provided along with the errors associated with the overall and individual storm performance (Figure 8). The summary and extremes section from the divisional page offers plots of extreme values, error plots, study findings, and information pertaining to the correction required by region for adjusting the climatological forecast for optimal performance.

7. CONCLUSIONS

The complicated nature of mesoscale forecasting, particularly in warm season convective environments is a focal point of local and regional weather forecasters across the nation. Without high-resolution modeling tools and the experience of operational meteorologists, the skill in QPF will remain a challenge. Until that time, it is important to remember that the expertise of operational meteorologists is quite similar to that of climatological methods in that there is an inherent tendency for the forecast (and forecaster) to perform in a given manner given a set of known synoptic conditions. With this in mind, that the current study examined the precipitation distribution across South Carolina associated with

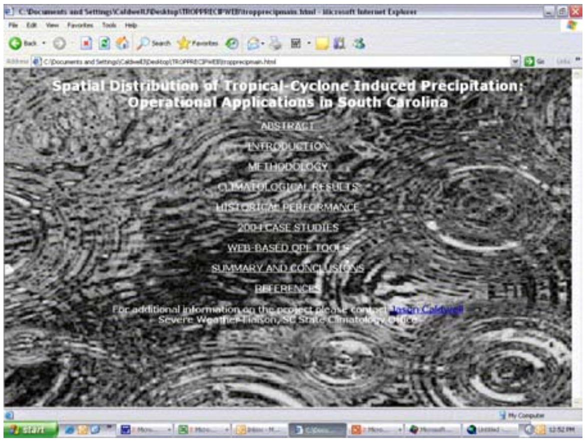

FIGURE 6

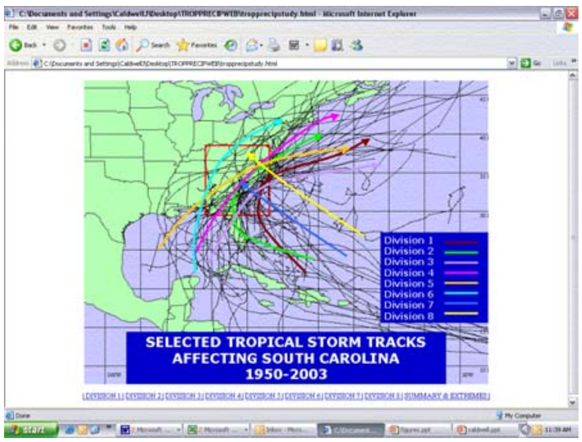

FIGURE 7

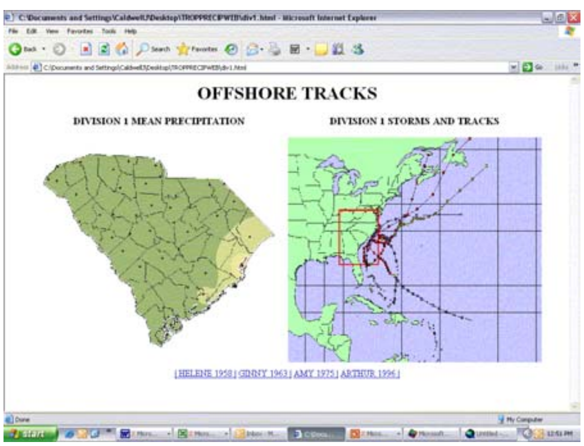

FIGURE 8

tropical cyclones. Through the evaluation of 54 tropical systems from 1950 to 2003, the mean precipitation for 37 stations and for four geographical regions in South Carolina provided a climatological forecast tool to predict the amount of storm total precipitation expected using a given forecast track and landfall location.

The climatological model performance in section 4 indicated that the method over-predicted precipitation more often than under-predicting the total rainfall. The under-predicted values were more extreme, however, and are most likely associated with point maxima from mesoscale, or even microscale, convective processes rather than actual errors observed over a large spatial extent. This was somewhat justified by examination of the regional precipitation from the remnants of Hurricane Frances and Jeanne which exhibited the largest range and most significantly negative biases in the historical evaluation of the climatological forecasts. In fact, the climatological method ranked a close second behind the Southeast River Forecast Center in QPF skill for the Columbia and Greenville-Spartanburg regional precipitation forecasts during the two storms. The HPC forecasts were a distant third overall and only out-performed the climatology in one of four events.

Given the findings of the present study, incorporation of this methodology and further development at the local level by the regional National Weather Service offices that serve South Carolina should provide an enhanced product and increased lead time for flood forecast preparation. It may be assumed that the forecast for rainfall can be made based on climatology as soon as the track forecast is reasonably known within a few hundred kilometers, eliminating the importance of mesoscale variations in the post-24 hour period and the model errors in precipitation forecasts that exist due to moisture and orographic effects. Therefore, the State Climatology Office offers a web-based application (http://www.dnr.state.sc.us/climate/sco/tropprecip.html) that provides the test results from each division, tropical cyclone, and observation site and encourages the use of climatology to prepare for the operational challenges of quantitative precipitation and flood forecasting during tropical cyclone-induced precipitation events.

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