Improving the Validation and Prediction of Tropical Cyclone Rainfall

Joint Hurricane Testbed
Final Report
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1. Motivation for project

Through funding from the Joint Hurricane Testbed (JHT), this project proposed to improve the validation and prediction of tropical cyclone rainfall. Improved validation of rainfall will enable the forecaster to identify errors and biases in the models, which can aid the forecaster in interpreting numerical guidance of rainfall and adjusting their forecasts accordingly. There are several aspects of a rainfall validation scheme that are desirable for TC quantitative precipitation forecasting (TC QPF): 1) accounts for the varying abilities of the models to reproduce elements of the storm (e.g., structure, track, and intensity); 2) performs comparisons of the entire rainfall distribution in addition to peak rainfall; 3) focuses on storm-related rainfall. Only then can objective evaluations of the TC QPF from various models be performed, allowing for the identification of biases in the models and ways to improve them.

In addition to the development of new TC QPF validation techniques described above, there are refinements to existing forecasting tools that can be implemented to provide additional rainfall guidance. For example, the rainfall climatology and persistence model (R-CLIPER) is a simple scheme that has been developed to provide a benchmark against which forecasts of rainfall can be compared. However, the current version of R-CLIPER assumes a circularly symmetric distribution of rainfall and translates this distribution in time. It does not incorporate processes that create asymmetries in the rain field, such as those related to vertical shear of the horizontal wind. Shear information can be added to the R-CLIPER to increase the amount of variance in the rainfall field explained by this forecasting tool and provide an additional rainfall product to the forecaster.

2. Summary of work proposed

To accomplish the goals stated above, several deliverables were proposed to be completed by the end of this 2-year project: development of new rainfall validation schemes that provide a baseline of comparison for different forecast systems; production of rainfall forecast error statistics for historic United States landfalling storms using traditional and new validation techniques for the operational GFDL, Eta and GFS models, and the benchmark Rainfall CLIPER (R-CLIPER) model; and design of a new forecasting tool based on the R-CLIPER model that incorporates information related to vertical shear. With these goals in mind, the following deliverables were proposed to be provided by the end of the project:

1. Development of new validation techniques that provide a baseline measure of rainfall forecast skill that accounts for storm structure, considers the entire rain distribution, and is reasonably independent of track error;
2. Calculation and delivery of error statistics using conventional and alternative validation schemes for GFDL, Eta, GFS numerical models, and R-CLIPER;
3. Development of modified R-CLIPER that incorporates vertical shear.

This report will present the results achieved during this project.

3. Accomplishments

1) Summary of accomplishments

The following list summarizes the results achieved during the project. Further explanations are provided in subsequent sections.

Development of new validation techniques

- Radial distribution of rain rates
- Probability distribution functions (PDFs) of rain flux (a variable that we use as a proxy for rain volume, defined as P_g*A_g , where P_g is the accumulated rain in a grid box and A_g is the area of that grid box)
- Track-relative rain flux PDF in swaths surrounding the storm
- Comparisons of extreme rain amounts for different forecasts
- Storm-relative grid-shifted rainfall statistics (i.e., shifted ETS, shifted correlations)

Calculation of validation statistics

For all tropical cyclones making landfall in the U.S. from 1998-2004, the following four attributes were selected as being of primary significance and error statistics for all models (GFDL, GFS, Eta, and R-CLIPER) were calculated based on them:

- Pattern matching
    - Equitable Threat Scores (ETS)
    - Correlation coefficients
- Distributions of rain amount and volume
    - Radial distribution of mean rain
    - Rain flux PDFs for the large scale
    - Track-relative Rain flux PDF in swaths surrounding the storm
- Extreme amounts
    - Comparisons of top 95th percentile of rain flux
- Sensitivity to track errors
    - Storm-relative grid-shifted ETS
    - Storm-relative grid-shifted correlation coefficient

Development of a version of R-CLIPER that accounts for vertical shear

- Formulation of algorithm to account for impact of shear and its incorporation in operational R-CLIPER code
- Test of algorithm in various storms from 2004

2) Data and methodology

Rainfall observations were provided by Stage IV hourly 4-km gridded rainfall data (Stage II prior to 2002) provided by the Environmental Modeling Center (EMC) at NCEP. This data consists of multi-sensor (i.e., rain gauges, radar) rainfall maps covering the entire contiguous United States. It is available on an hourly basis for all times back to 1998. The models used were the real-time configurations of the NCEP operational models used in forecasting hurricanes: the 2003 version of the GFDL hurricane model, the GFS, and the Eta model. The GFDL model is a nested, hydrostatic regional model whose current configuration runs at 1/6 degree grid length, the GFS is a global model run at 1/2 degree resolution, and the Eta is a limited-area model with a minimum grid length of 12 km. The R-CLIPER model is run for all storms, using the TPC official forecast track positions, to provide a benchmark against which the other models are compared. The R-CLIPER can be run at any resolution; in this case it is run at 4 km grid length.

The storms used in this study were all U.S. landfalling storms between 1998 and 2004. A total of 35 storms are included, ranging in intensity from tropical depression (Henri of 2003) to Category 4 strength (Charley of 2004) at landfall. One forecast from each storm is included in the database. The cases that were selected had initial times that were always from the last 12 UTC time within 24 hours of landfall, in order to coincide with the storm database used by Tuleya et al. (2005). Forecast and observed data for each storm were included in the database until advisories from the National Hurricane Center were no longer issued for them. The storms in the database took a variety of tracks over the Gulf and Atlantic Coast states, passing over a variety of topographies with different translational speeds, and they span a wide spectrum of conditions that can produce many different rainfall distributions.

When calculating the forecast statistics, all of the forecasts and observations use a land-sea mask, and Canada and Mexico are excluded from the analyses. For some of the validation statistics (e.g., equitable threat score, correlation) only those areas within 600 km of the storm track are included. This restriction is to limit the inclusion of rainfall that is not directly related to the tropical cyclone, such as rainfall from a frontal boundary or mid-latitude cyclone well-removed from the TC. All of the statistics in this study are for storm total rainfall and include data up to a maximum cutoff forecast time of 72 hours within each forecast.

3) Development of new validation techniques

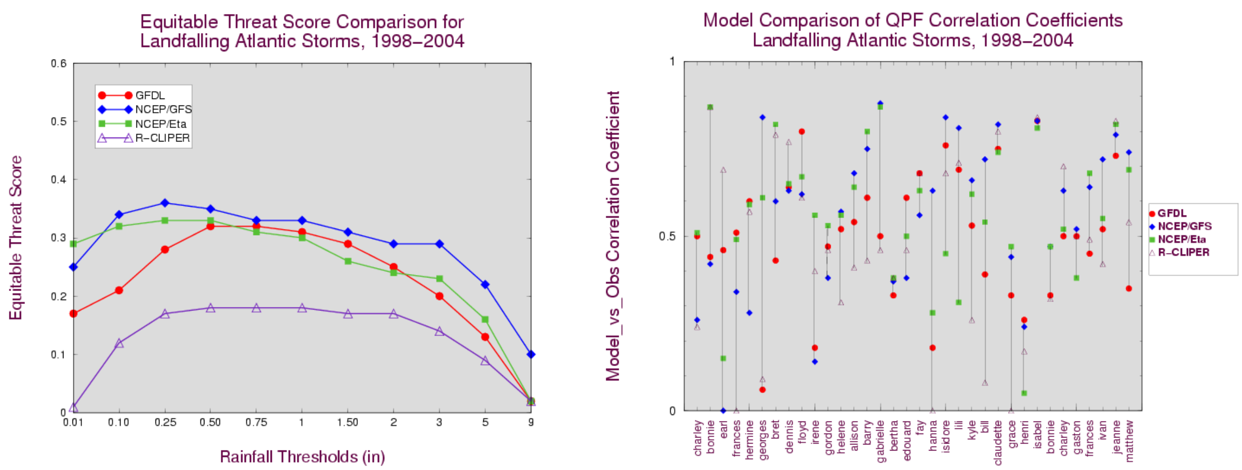
There are many aspects of TC rainfall forecasts that should be compared to assess the skill of a particular forecast and identify possible biases in the forecast. For the comparisons presented here four elements are considered to be of primary importance for TC QPF:

1. A model’s ability to match the large-scale rainfall pattern;
2. A model’s ability to match the mean rainfall and the distribution of rain flux;
3. A model’s ability to produce the extreme amounts often observed in TCs;
4. The impact of a model’s track forecast error on its QPF skill.

(1) <u>Pattern matching</u>

Two metrics, commonly-used in validations of QPF, are used to evaluate the ability of models to reproduce rainfall patterns produced by the landfalling TCs: equitable threat score

(ETS) and pattern correlation. The ETS measures the ratio of the number of forecast "hits" to the total number of forecast hits and misses, where "hits" are defined as locations where the forecasted rainfall amount matches or exceeds the observed rainfall amount for a given rainfall threshold. Pattern correlation simply correlates the amount and location of forecasted rainfall with the observed rainfall, and it is thus dependent on location error. Figure 1 shows the comparisons of the ETS and the pattern correlations for the various models for the U.S. landfalling storms. Comparisons of the ETS for the different models (Fig. 1a) show that the GFS model generally performs the best across all rainfall amounts, including the highest amounts of 9 inches, while the R-CLIPER model does the worst across all rainfall amounts. The most significant difference between the GFS and the other models occurs at the low and high extremes of the rainfall distribution (i.e., < 0.25 inches and > 2 inches). The correlation statistics (Fig. 1b) show significant case-to-case variability in the performance of the models. In general, though, the GFS has the highest correlations (highest correlation for 38% of storms) while the GFDL and the R-CLIPER models have the lowest correlations (highest correlation for 18% of storms).



(a) (b)

Figure 1. Plot of (a) Equitable Threat Score (ETS) and (b) Pattern correlation coefficients for GFDL, GFS, Eta, and R-CLIPER forecasts of all U.S. landfalling storms from 1998-2004.

(2) Mean rainfall and rain flux distributions

Comparisons of the mean rainfall and the distributions of rain flux provide useful indicators of the ability of the various models to produce all aspects of the rainfall distribution, i.e., light, moderate, and heavy rain, and can better identify biases in the models than individual point comparisons with gauge measurements. Figure 2 shows the conditional mean storm-total rainfall in 20-km swaths centered on the storm track. The GFDL model shows the largest bias in mean rainfall, particularly in the regions closest to the path of the storm center. The mean rainfall from the GFDL model is about 40% higher than the observed mean within 150 km of the center of the storm. A similar relationship is seen with the GFS model, with mean rainfall about 10-20% higher than the observations within 150 km of the center. The Eta model produces mean rainfall that is slightly lower than the observations in the innermost portions of the track (within 50 km) and higher than the observations from 50 km outward. The R-CLIPER overall produces a radial distribution closest to that observed.

To approximate the volume of water placed onto the analysis grid, a variable called rain flux is used. This is simply the product of the rainfall value at a grid point and the representative areal coverage of that point (units of in-km^2). Figure 3 shows comparisons of the probability distribution functions (PDFs) and cumulative distribution functions (CDFs) for all points within

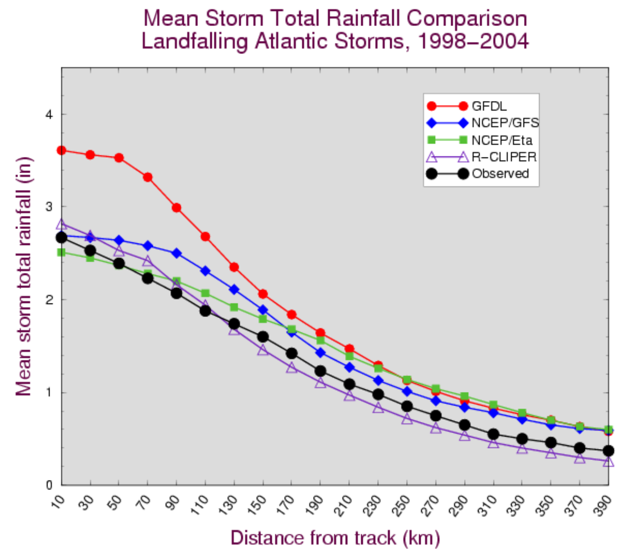


Figure 2. Radial distribution of conditional mean storm total rainfall (in) for all models and observations.

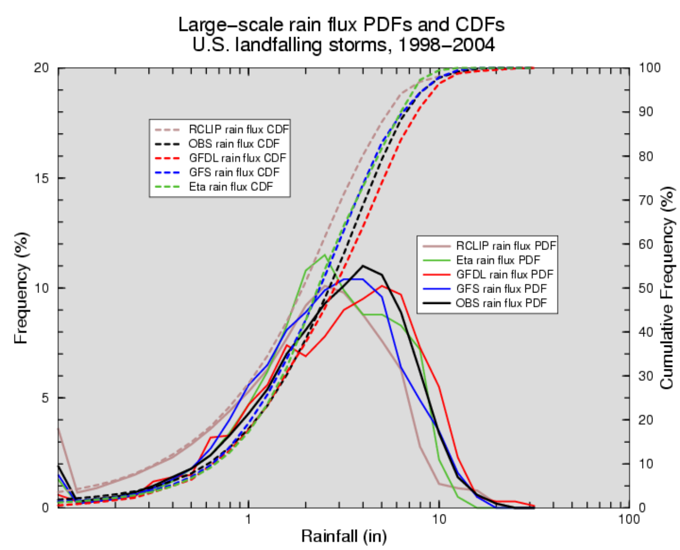


Figure 3. Probability distribution function (PDF; solid lines) and Cumulative distribution function (CDF; dashed lines) of rain flux within 600 km of storm track for all models and observations.

600 km of the observed storm track. Compared to the observations, a larger proportion of the total rain flux is accomplished at the high rain amounts (> 6 inches) for the GFDL model, while a smaller portion of the rain flux occurs in the light-to-moderate rain amounts (1-3 inches). The inverse is true for the Eta and R-CLIPER models. For the GFS model there is a slight overrepresentation of rain flux for the light-to-moderate rain amounts, and the rain flux in the heavy rain amounts (> 10 inches) compares very well with the observations.

PDFs of rain flux are then calculated in a track-relative manner for 100-km wide bands surrounding the forecasted and best tracks. Figure 4 compares rain flux distributions for each of the four models for two bands, the inner-core (0-100 km) band and the 300-400 km band. Figure 4a shows the PDF of rain flux for the GFDL, Eta, and observed rainfall fields within the 0-100 km band around the storm track, where rain from the inner core would predominate. The GFDL has a clear tendency to produce too much rain flux in the high to extreme rain amounts, while

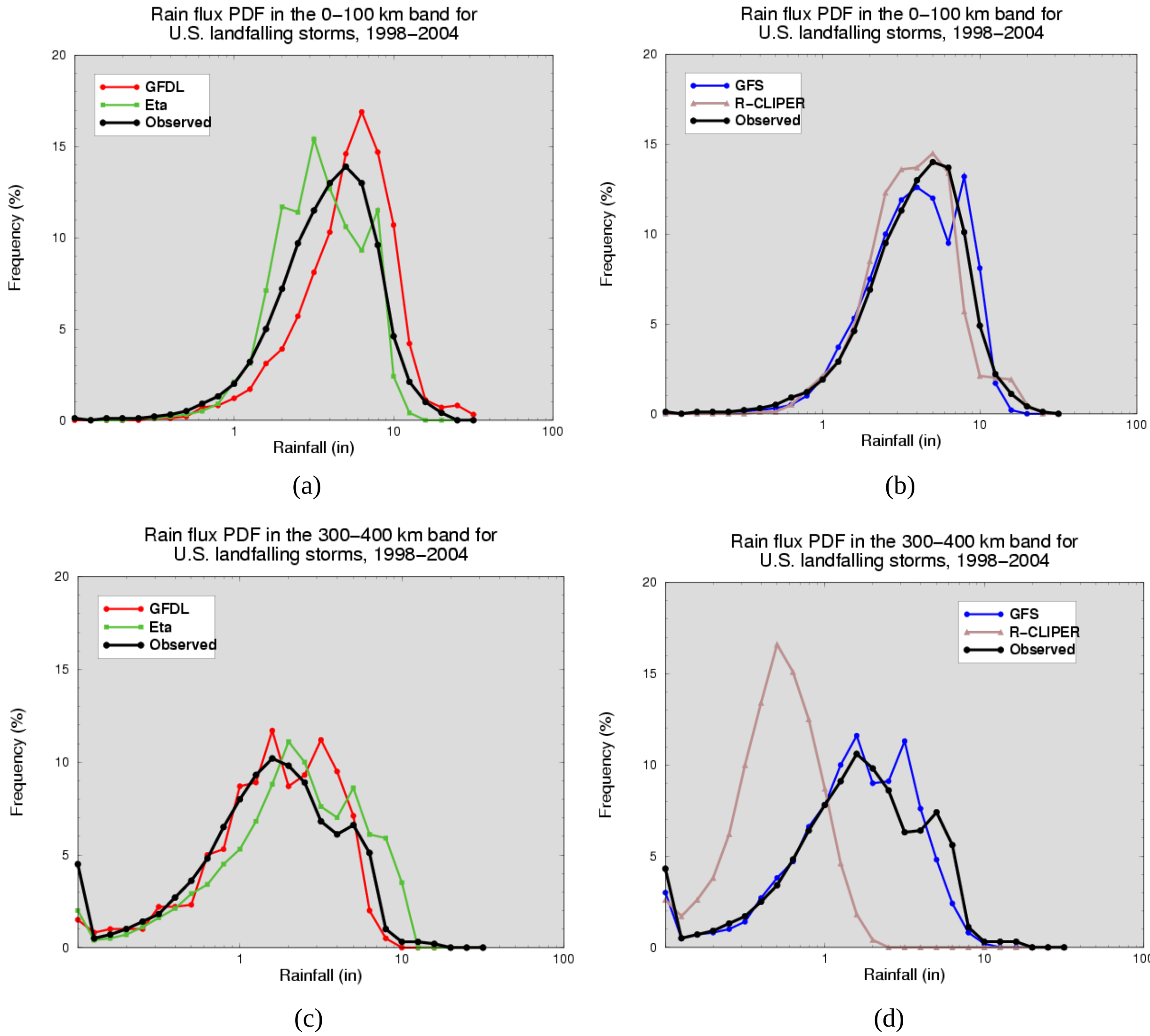


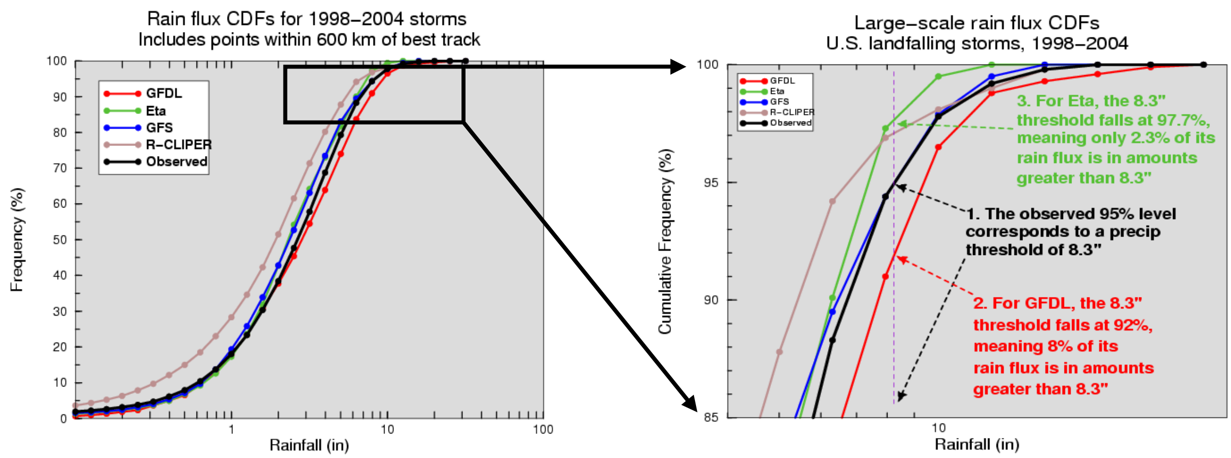
Figure 4. PDFs of rain flux for all models and observations. (a) PDFs of rain flux within 0-100 km swath for GFDL, Eta, and Stage IV; (b) As in (a), but for GFS, R-CLIPER, and Stage IV: (c) PDFs of rain flux within 300-400 km swath for GFDL, Eta, and Stage IV; (d) As in (c), but for GFS, R-CLIPER, and Stage IV.

the Eta produces too much rain flux in the light to moderate rain amounts, suggesting that the GFDL overpredicts inner-core rain while the Eta underpredicts inner-core rain. The GFS and R-CLIPER comparisons in this swath (Fig. 4b) show that the GFS slightly overproduces rain flux for values less than 10 inches, but it underproduces rain flux for values greater than 10 inches. The R-CLIPER has the closest resemblance to the observed flux distributions in the inner core, showing the ability to produce rain flux for light, moderate, heavy, and extreme rain amounts.

At larger distances from the storm track (Figs. 4c,d), the flux PDF from the GFDL model shows good agreement with the observations, while the Eta model produces peak rain flux values in higher rain amounts than the observed distribution. The GFS (Fig. 4d) slightly overpredicts rain flux for the light to moderate amounts and underpredicts rain flux for the heavy rain amounts. The R-CLIPER is the most different from the inner-core results. Whereas the inner-core flux PDF agrees very well with the observations, the 300-400 km flux PDF is significantly skewed toward lighter rain rates. The R-CLIPER significantly overproduces rain flux for the light rain amounts and significantly underproduces rain flux for the moderate to heavy rain amounts at this distance.

(3) <u>Extreme rain amounts</u>

Another area of TC QPF that is important to evaluate is how well each model produces the extreme rain events. Two evaluation techniques are developed for this. The first technique consists of comparing the rain flux CDF (cf. Fig. 3) for the observed rainfall against that of each model and determining how far the model-produced CDF curve deviates from the observed rainfall's 95th percentile. This calculation is shown in Fig. 5. As can be seen from the black curve in Figure 5(b), the 95th percentile in the observed rain flux distribution corresponds to a rainfall threshold of 8.3 inches. For the GFDL model, the 8.3 inch threshold falls at 92%, meaning that 8% of the rain flux occurs in values greater than 8.3 inches (compared with 5% from the observations). Thus more of the rain flux in the GFDL occurs in rain amounts greater than 8.3 inches, which is consistent with the comparisons shown above (cf. Figs. 3 and 4). By contrast, the 8.3 inch threshold for the Eta and R-CLIPER both fall at the 97-98%, meaning that a smaller proportion of the rain flux occurs at rain amounts above 8.3 inches. The 8.3 inch threshold for the GFS falls at 95%, exactly matching the observed value.



(a) (b)

Figure 5. Calculation of 95th percentile comparison among models. (a) CDF of rain flux for all models and observations; (b) As in (a), but magnified to emphasize the top 15% of the rain flux curves and illustrate comparison of rainfall thresholds corresponding to 95th percentile (i.e., top 5%) of rain flux curves for various models.

(4) <u>Sensitivity to track error</u>

A final attribute that is valuable to compare with different models is the performance of the models when the track error is explicitly removed. Removing the impact of the track error can be used to quantify the impact of track error on track-dependent validation algorithms such as the ETS and pattern correlations. It can also be used to more directly compare the contributions to the rainfall forecast error from other sources, such as resolution and parameterization deficiencies. Track-error removal is accomplished by shifting the 6-hour forecasted rainfall pattern by a distance equal to the difference in position of the forecasted vs. the observed storm location. These shifted rainfall analyses are then summed over the lifetime of the storm, producing storm-total shifted rainfall analyses.

Figure 6 shows comparisons of the ETS and pattern correlations for all of the storms from 1998 to 2004, once the impact of track error is removed. For the ETS comparisons (Fig. 6), the unshifted scores show that the GFS model performs the best across all rainfall thresholds while the R-CLIPER performs the worst, consistent with Fig. 1a. Once the rain fields are shifted to account for track error, however, the Eta and GFDL models show significant improvement, while the GFS model shows little improvement. The shifted GFDL and Eta models show comparable skill to the shifted GFS model over almost all rainfall thresholds. The shifted R-CLIPER also improves, but its ETS is still worse than the other three models. These results indicate that the deficiencies in the ETS for the Eta and GFDL, compared to the GFS, are mostly due to the deficiencies in their track forecasts. Once the track forecasts errors are accounted for, the remaining deficiencies are attributable to other aspects of the forecasting system, such as deficient model resolution or physical parameterizations.

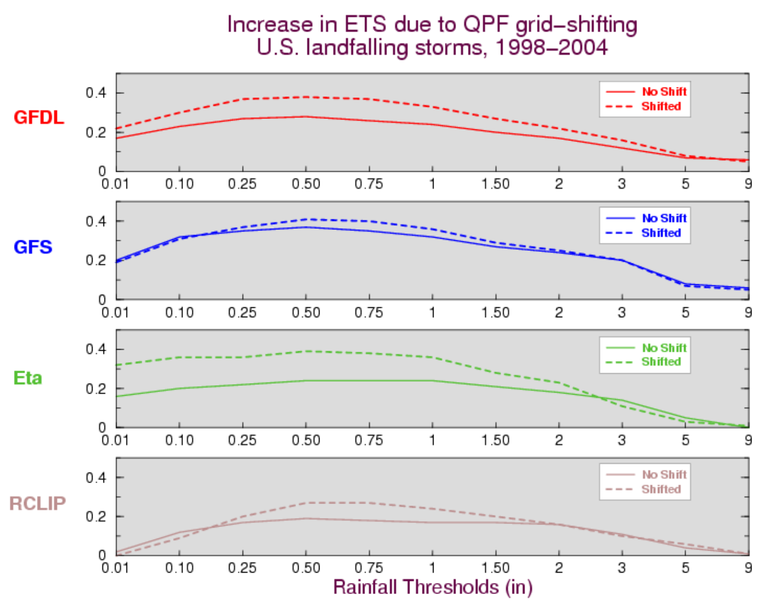


Figure 6. Comparison of ETS for all models before (solid line) and after (dashed line) performing grid shift.

4) Calculation of error statistcs

The validation algorithms described above were then synthesized into a set of error statistics for each of the four TC QPF attributes (pattern matching, mean rain and volume distributions, extreme amounts, sensitivity to track error). The error statistics are shown in Fig. 7 and described in Table 1. For the pattern matching (Fig. 7a), the GFS performs the best, though all numerical models (GFS, GFDL, Eta) show skill relative to R-CLIPER. The GFDL performed the worst among the numerical models for pattern matching. For the mean rainfall and distributions of rain flux (Fig. 7b), all of the numerical models were essentially equivalent, and they all showed skill over the R-CLIPER. The GFDL (Eta) produced too much (too little) rain in the inner core (Table 1). The R-CLIPER produced too little rain at distances far-removed from the track of the system. For the extreme rain amounts (Fig. 7c), the GFS performs the best. The GFDL produces too much of the heaviest rain (Table 1), but both show skill over R-CLIPER. The Eta shows no skill over R-CLIPER. For the sensitivity to track error (Fig. 7d), the GFS is the least sensitive to track error. The GFDL and the Eta models are more sensitive to track error than R-CLIPER. In summary, the GFS performs the best for all four attributes considered here.

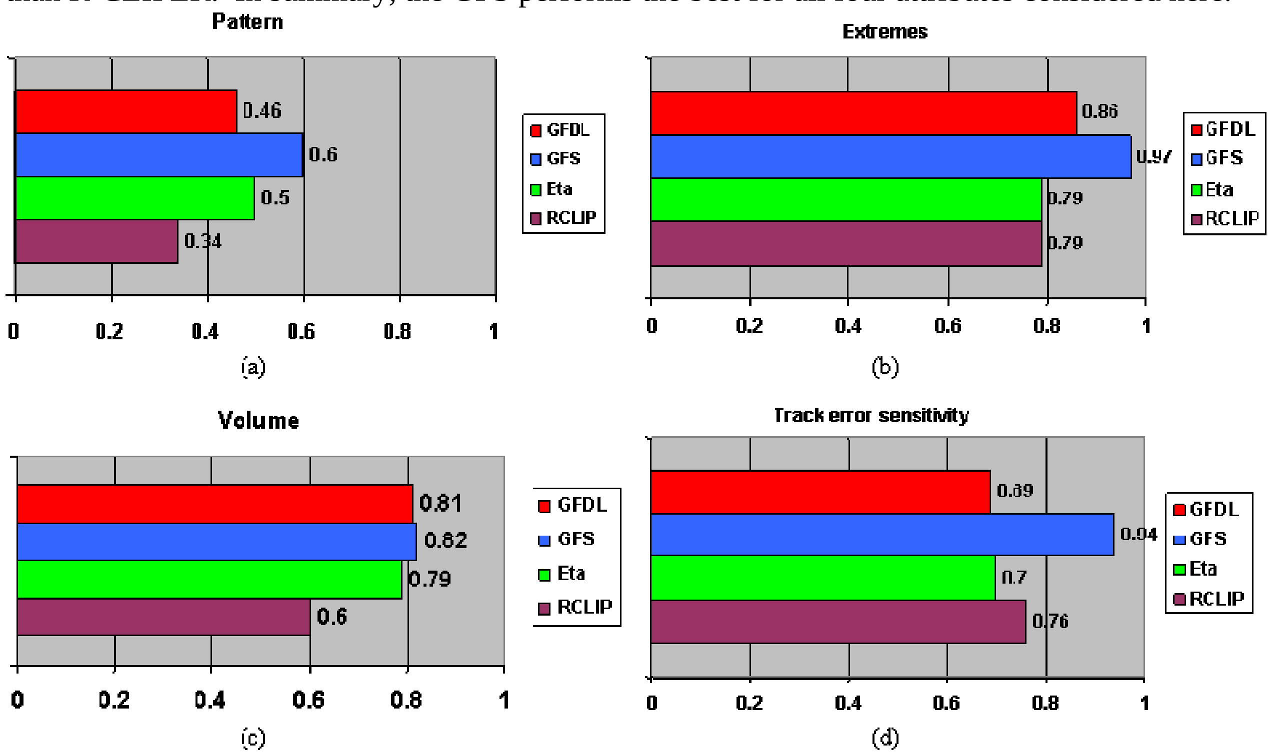


Figure 7. Comparisons of TC QPF from different models showing how well they perform at (a) Pattern matching; (b) Extreme rainfall; (c) Volume and distribution; (d) Track error sensitivity. Scores of 0 (no skill) to 1 (most skill) have been derived by consolidating information from the validation techniques described above in Section 3.

5) Validations using alternate version of GFDL model

The validation techniques presented above were also applied to a version of the GFDL model that replaced slab soil model with the NOAH land-surface model (LSM). The present operational GFDL model uses a simple one layer soil model to forecast skin temperatures over land. The moisture content of the land in the present GFDL model is climatologically based on vegetation type and is time independent. The NOAH LSM model is a comprehensive multiple-level land surface model that predicts both temperature and moisture over land. This same system has recently been made operational in the GFS forecast system this year. In the GFDL NOAH system, the NOAH land model is treated as a separate component model and the interaction with the atmospheric GFDL model is treated in a similar fashion as the POM ocean model interaction.

Comparisons between the two versions of the GFDL model on a subset of the landfalling cases (20 storms total) indicated only small differences between the two. The most noticeable

TC QPF Attribute	Best performer(s)	Worst performer(s)	Comments
Pattern matching	GFS	R-CLIPER	All numerical models show considerable skill relative to R-CLIPER
Volume/distribution	GFS	R-CLIPER	GFDL produces too much inner-core rain, Eta produces too little inner-core rain, R-CLIPER produces too little rain far from track of center
Extreme rain	GFS	Eta, R-CLIPER	GFDL overproduces the heaviest rain rates; GFS nearly exactly matches observations
Track error sensitivity	GFS	GFDL	GFS least sensitive to track error; GFDL and Eta more sensitive than R-CLIPER

Table 1. Table summarizing comparisons in Figure 7.

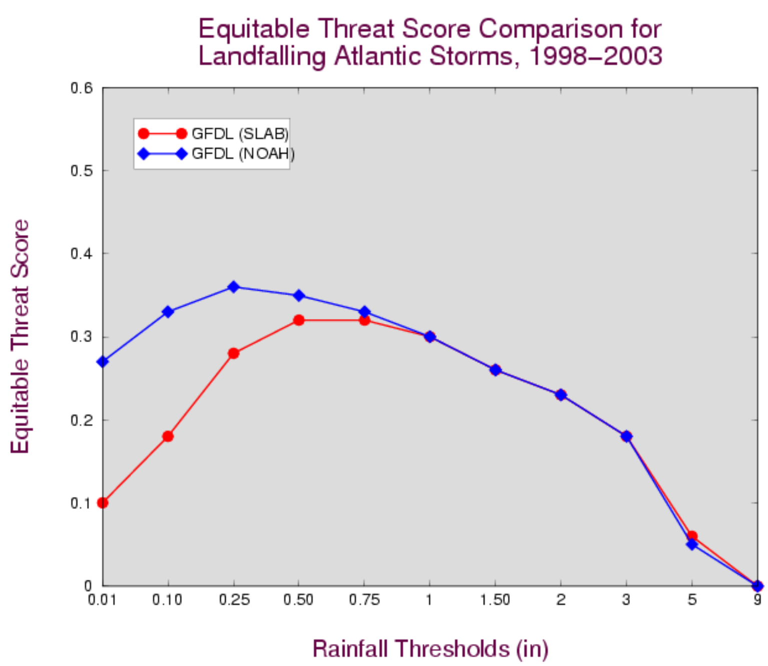


Figure 8. Comparison of ETS for the GFDL model run with the SLAB model (red) and the NOAH LSM model (blue).

difference was in the pattern matching category, where the ETS for the GFDL-NOAH LSM model was significantly better for low rainfall amounts than the GFDL-SLAB model (Fig. 8). For the other categories, the two models were very close in score, with the GFDL-SLAB runs scoring slightly higher for the extreme rainfall category, and the GFDL-NOAH LSM model scoring slightly higher for the volume/distribution category.

6) Development of modified version of R-CLIPER to include effects of shear

Another task that was proposed to be accomplished during the second year of this project was the development of a modified version of the R-CLIPER that would incorporate the impact of vertical shear on the rainfall distribution in landfalling tropical cyclones. The original proposal called for the quantification of azimuthal asymmetries as a function of vertical shear based on GFDL model output. However, recently work has been done (Lonfat et al. 2005) that has shown the ability to quantify these asymmetries based on thousands of overpasses of tropical cyclones over several years from the Tropical Rainfall Measuring Mission (TRMM) satellite.

The calculation of the total rain at a given location is provided by the following equation:

$$R_{tot} = R_{R\text{-}CLIPER} + R_{shear\ mod} \tag{1}$$

where R_{tot} is the total rainfall field, $R_{R\text{-}CLIPER}$ is the rain field produced by the standard version of R-CLIPER, and $R_{shear\ mod}$ is the rain field associated with the vertical shear-generated asymmetry. The formulation of $R_{shear\ mod}$ is provided by:

$$R_{tot}(r,\theta) = a_0(r) + \sum_i a_i(r)\cos(i\theta) + \sum_i b_i(r)\sin(i\theta) \tag{2}$$

where a_0 is the wavenumber-0 component of the rain field (i.e., the standard R-CLIPER), i is the wavenumber (> 0) being considered, and a_i and b_i are Fourier coefficients describing the azimuthal variations of the wavenumber-i fields. In this formulation, only wavenumbers-1 and -2 are considered, so i ranges from 1 to 2.

An illustration of how the asymmetry is imposed is provided in Fig. 9. This figure shows a hypothetical hurricane in the Gulf of Mexico experiencing moderate westerly shear. The wavenumber-0 pattern shown in Fig. 9a shows the rainfall field produced by the standard R-CLIPER. The wavenumber-1 and -2 fields shown in Fig. 9b show the contribution to the total rain field attributable to vertical shear. As can be seen from the figure, a positive contribution to the total rain is produced on the downshear and on the downshear left regions of the storm, while a negative contribution is evident on the upshear and upshear right portion of the storm. The impact of including these contributions on the accumulated rain field is shown in Fig. 8c. Here the hurricane is moved toward the northwest over a several-day time period. A positive contribution to the accumulated rain field is seen on the right side of the track and a negative contribution is seen on the left side of the track. Such a relationship has been seen in observations and numerical model simulations of tropical cyclones experiencing vertical shear (Rogers et al. 2003).

This algorithm was implemented and tested for several storms from 2004. The shear values were obtained from the SHIPS database. An example of the performance of this scheme is shown for Hurricane Frances (2004) in Fig. 10. The SHIPS-derived 850-200 hPa shear during the 24-h time period just prior to landfall was 19 kts at 282 degrees (i.e., west-northwesterly shear). Figure 10a shows the observed 72-h rainfall amounts from Hurricane Frances as it made landfall along the southeast Florida coast. The impact of the shear is seen in the observed rain accumulation, as a pronounced maximum greater than 15 inches is located on the right side of the track and little rainfall occurs to the left of the track. For the standard R-CLIPER (Fig. 10b),

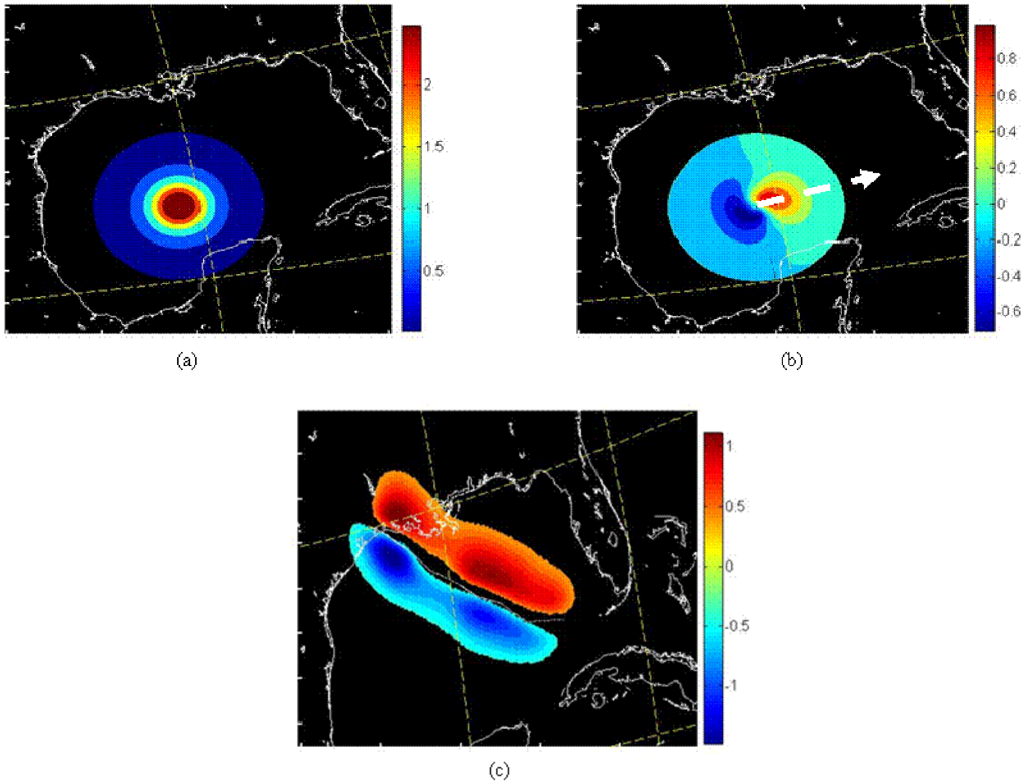


Figure 9. Illustration of generation of rainfall footprint and its accumulation over time for a hypothetical storm (hurricane intensity) in the Gulf of Mexico experiencing moderate westerly shear. (a) Wavenumber-0 component of rain rate (mm/hr); (b) Wavenumbers-1 and -2 summed components of anomalies of rain rate (mm/hr); (c) 72-h accumulation of anomalies caused by inclusion of wavenumbers-1 and -2 fields. Direction of shear vector indicated by dashed white arrow in (b).

the rainfall maximum is centered along the path of the center of the storm, and the rainfall field is symmetrically-distributed away from the track. For the R-CLIPER that includes shear (Fig. 10c), the rainfall maximum is shifted to the right of the track in a manner consistent with that observed. However, the presence of rainfall to the left of the track is inconsistent with the observations. Nonetheless, these comparisons show that incorporating vertical shear in R-CLIPER can improve the overall pattern of rainfall relative to the track of the storm.

4. Deliverables

This project proposed to provide several deliverables upon completion. They are discussed below.

1) Development of new validation techniques that provide a baseline measure of rainfall forecast skill that accounts for storm structure, considers the entire rain distribution, and is reasonably independent of track error

The new validation techniques were presented in this report. More complete documentation on the techniques will be included in a forthcoming journal manuscript that will

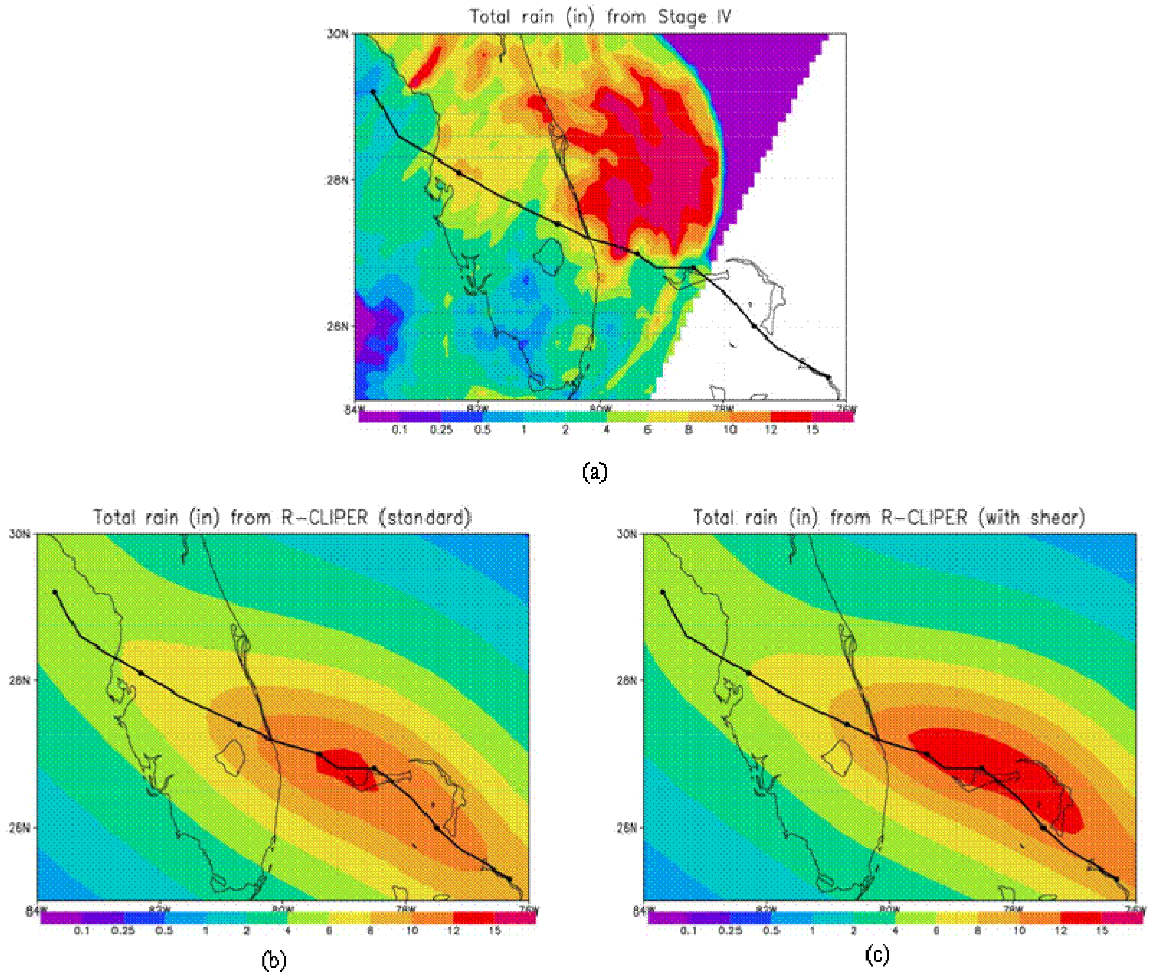


Figure 10. Comparisons of 72-h rain amounts (in) for Hurricane Frances from 12 UTC 4 – 12 UTC 7 September 2004. (a) Stage IV observations; (b) standard R-CLIPER; (c) R-CLIPER run with vertical shear included.

be submitted to *Weather and Forecasting*. Additional documentation can also be provided to NHC upon request.

2) Calculation and delivery of error statistics using conventional and alternative validation schemes for GFDL, Eta, GFS numerical models, and R-CLIPER

The error statistics for the 1998-2004 U.S. landfalling storms are provided in this report. They are summarized in Fig. 7 and Table 1 from this report.

3) Development of modified R-CLIPER that incorporates vertical shear.

The modified R-CLIPER has been developed and described briefly in this report. The modifications were added to the operational version of the code, so it should be relatively straightforward to run this model at NHC. The only thing that needs to be added is the ability to acquire shear information from the forecast SHIPS fields. We can assist NHC in achieving this.

Presentations resulting from this work

Marchok, T., R. Rogers, and R. Tuleya, 2004: Improving the validation and prediction of tropical cyclone rainfall. 58th Interdepartmental Hurricane Conference, Charleston, SC, March 1-5.

Marchok, T., R. Rogers, and R. Tuleya, 2004: A comparison of GFDL, GFS, and Eta rainfall forecasts for U.S. landfalling storms, 1998-2003. 26th Conference on Hurricanes and Tropical Meteorology, Miami Beach, FL, May 3-7.

Rogers, R., T. Marchok, and R. Tuleya, 2004: The development of a new validation technique for tropical cyclone rainfall. 26th Conference on Hurricanes and Tropical Meteorology, Miami Beach, FL, May 3-7.

Rogers, R., T. Marchok, and R. Tuleya, 2005: Improving the validation and prediction of tropical cyclone rainfall. 59th Interdepartmental Hurricane Conference, Jacksonville, FL, March 7-11.

Marchok, T., R. Rogers, and R. Tuleya, 2005: Assessing the skill of tropical cyclone rainfall forecasts. 59th Interdepartmental Hurricane Conference, Jacksonville, FL, March 7-11.

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Rogers, R.F., S.S. Chen, J.E. Tenerelli, and H.E. Willoughby,2003: A numerical study of the impact of vertical shear on the distribution of rainfall in Hurricane Bonnie (1998). *Mon. Wea. Rev.*, **131**, 1577-1599.

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