The Tropical Rainfall Potential (TRaP) Technique. Part I: Description and Examples

STANLEY Q. KIDDER,* SHELDON J. KUSSELSON,+ JOHN A. KNAFF,* RALPH R. FERRARO,#,@
ROBERT J. KULIGOWSKI,# AND MICHAEL TURK+

*Cooperative Institute for Research in the Atmosphere, Colorado State University, Fort Collins, Colorado
+NOAA/NESDIS/OSDPD/Satellite Services Division, Camp Springs, Maryland
#NOAA/NESDIS/Center for Satellite Applications and Research, Camp Springs, Maryland
@Cooperative Institute for Climate Studies, University of Maryland, College Park, College Park, Maryland

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ABSTRACT

Inland flooding caused by heavy rainfall from landfalling tropical cyclones is a significant threat to life and property. The tropical rainfall potential (TRaP) technique, which couples satellite estimates of rain rate in tropical cyclones with track forecasts to produce a forecast of 24-h rainfall from a storm, was developed to better estimate the magnitude of this threat. This paper outlines the history of the TRaP technique, details its current algorithms, and offers examples of its use in forecasting. Part II of this paper covers verification of the technique.

1. Introduction

For centuries, the wind and waves caused by tropical cyclones have menaced mariners and coastal dwellers. Enormous resources have been invested in observing and forecasting these killers. Today, largely because of weather satellites, no tropical cyclone anywhere on earth goes undetected or evades the eyes of forecasters. As the storm approaches, most people are able to escape the storm's fury by moving inland. Consequently, attention has shifted to a different threat from tropical cyclones. Rappaport (2000) found that in the contiguous United States during the period 1970–99, freshwater floods accounted for more than half of the 600 deaths directly associated with tropical cyclones. Elsewhere in the world the toll can be much higher. Thus, forecasting the rainfall potential of tropical cyclones has taken on new importance in our struggle to protect life and property.

One would like to rely on numerical weather prediction models to make such forecasts, but while the storm is offshore, few observations are available, and initializing models with sufficient details of the storm so that accurate rainfall forecasts can be made is beyond the state of the art. Radar observations of storm rain rate and rain area are valuable, particularly for short-term (~1 h) forecasting of urban flash flooding and landslides, but only when the storm is within radar range of the coast. Twenty-four hours before landfall, when warnings and evacuation orders need to be issued, tropical cyclones typically are beyond radar range. Weather satellite observations, and in particular microwave observations, have, therefore, become the chief source of data in forecasting tropical rainfall potential (TRaP), or the amount of rain to fall from a tropical cyclone in a (usually) 24-h period.

This paper details the TRaP technique. Section 2 summarizes the history of the TRaP technique, with the current approach presented in section 3. The performance of the current technique is illustrated in section 4 via several examples, followed by discussion in section 5. The second part of this paper (Ferraro et al. 2005, hereafter Part II) describes verification of the TRaP technique.

2. TRaP history

Because of the importance and danger of flooding caused by tropical cyclones, TRaP has a long history, which is summarized in this section.

Corresponding author address: Stanley Q. Kidder, CIRA, Colorado State University, Fort Collins, CO 80523-1375.
E-mail: kidder@cira.colostate.edu

a. Rule of thumb

Perhaps the first method for estimating rainfall from tropical cyclones was the "rule of thumb" [attributed to R. H. Kraft by Pfost (2000)] that 100 divided by the speed of the storm in knots yields an estimate of the 24-h rainfall in inches. This rule takes into account the fact that faster-moving storms reside over a point for less time than slower-moving storms, and therefore, rainfall at a point should be inversely related to storm speed. This rule, however, makes no allowance for storm size or rain rate, both of which can vary considerably from storm to storm.

b. Observational studies

Several survey studies have been conducted to determine the average rainfall associated with tropical cyclones. Riehl and Malkus (1961) and Simpson and Riehl (1981) reported that rainfall decreased exponentially with distance from the cyclone center. Within 20 n mi (37 km) of the center, rain rates averaged about 1.3 in. h^{-1} (33 mm h^{-1}). In successive 20 n mi annuli, the rain rates averaged 0.66, 0.33, and 0.16 in. h^{-1} (16.8, 18.4, and 4.1 mm h^{-1}). Using these findings, a relationship for the maximum 24-h rainfall (R_{24}) as a function of the speed of translation of storm (V) was developed:

$$R_{24} = a(b^V), \qquad (1)$$

where a = 31.1 in. (790 mm) and b = 0.915 for V in miles per hour (or b = 0.926 for V in knots, or b = 0.946 for V in kilometers per hour). This constituted the first operational tropical cyclone rainfall estimation method (Pfost 2000). While this technique is an improvement on Kraft's rule of thumb, rain rates are highly variable from storm to storm.

Using a similar compositing approach Goodyear (1968) examined 46 tropical storms and hurricanes making landfall on the Gulf Coast of the United States to produce a 48-h rainfall pattern with respect to the tropical cyclone center. His study showed that the average maximum rainfall of 6 in. (150 mm) occurs roughly 25 to 50 miles (40 to 80 km) inland and 25 to 50 miles (40 to 80 km) to the right of the storm track. Again, much variability was found from storm to storm. However this method is still used to assess potential risks of flooding (Pfost 2000).

Lonfat et al. (2004), in the most comprehensive study of tropical cyclone rain rates to date, used rain-rate information derived from the National Aeronautics and Space Administration (NASA) Tropical Rainfall Measuring Mission (TRMM) to composite rain rates of global tropical cyclones for a 3-yr period to produce climatological rain rates. These rain rates again decreased approximately exponentially with distance from the center, but were found to be a function of intensity and geographic location. Maximum values, which were reported to agree well with rain gauge data, were close to 13 mm h^{-1} near the center of very strong tropical cyclones (maximum winds >49 m s^{-1}) and close to 3 mm h^{-1} near the center of tropical-storm-strength (>17 m s^{-1}) tropical cyclones. In addition to the mean rain rates found in this study, large systematic asymmetries were found in composites that were functions of geographical location, intensity, and forward speed.

c. Spayd and Scofield

Spayd and Scofield (1984) realized that the expected duration of rainfall at a point as a tropical cyclone passes overhead is approximately DV^{-1}, where D is the distance across the storm (measured in the direction of motion), and V is its speed. The total rainfall, then, would be $R_{avg}DV^{-1}$, where R_{avg} is the average rain rate of the storm. The rule of thumb discussed above, then, uses 100-in. knots as the "average" value of $R_{avg}D$.

Spayd and Scofield used infrared satellite imagery to identify storm features or cloud types, and then assigned a rain rate to each cloud type. They defined the tropical rainfall potential as

$$\mathrm{TRaP} = V^{-1} \sum_i R_i D_i, \qquad (2)$$

where D_i is the distance (in the direction of storm motion) across cloud type i, and R_i is the rain rate assigned to cloud type i. The four cloud types used were central dense overcast (CDO), wall cloud (WC), embedded cold convective tops (ECT), and outer banding (OBA). Following Scofield and Oliver (1977), an analyst assigned a rain rate to each cloud type depending on the cloud-top temperature and its trend in the infrared satellite imagery. The rain-rate ranges were 0.01 to 2.00 in. h^{-1} (0.3–50 mm h^{-1}) for CDO, 1.00 to 3.00 in. h^{-1} (25–75 mm h^{-1}) for WC, 0.10 to 2.00 in. h^{-1} (3–50 mm h^{-1}) for OBA, and 0.05 to 4.00 in. h^{-1} (1–100 mm h^{-1}) for ECT. Results of the Spayd and Scofield technique compare well with rain gauge data, but the technique is labor intensive.

d. NESDIS/SSD TRaP

With the arrival of cloud-penetrating microwave observations of tropical cyclones, the rain rate could be more directly estimated, and cloud typing could be eliminated. Since 1992, the Satellite Services Division (SSD, which encompasses the Satellite Analysis Branch) of the National Environmental Satellite, Data, and Information Service (NESDIS) has experimentally used the operational Special Sensor Microwave Imager (SSM/I) rain-rate data from the Defense Meteorological Satellite Program (DMSP) satellites to produce a rainfall potential for tropical disturbances expected to make landfall within 24 h to at most 36 h. The launch in 1998 of the first Advanced Microwave Sounding Unit (AMSU) on the National Oceanic and Atmospheric Administration (NOAA) satellites and the 2001 addition of the NASA TRMM Microwave Imager (TMI) data brought additional microwave-based estimates of rain rate. (The TRMM satellite was launched in 1997; the TMI data became available at SSD in 2001.)

The NESDIS/SSD technique was summarized in Kidder et al. (2000). At that time it used either the SSM/I 14 km × 16 km resolution (Ferraro 1997; Ferraro et al. 1998) or the AMSU-A 48-km-resolution (Grody et al. 1999) rain-rate estimates. Figure 1 shows the AMSU rain rates for Hurricane Georges (1998) as it was heading for the keys of south Florida. The SSD analyst drew line *A* through Key West (EYW) in the direction of motion of the storm. Line *A* resulted in an average rain rate (R_{avg}) of 0.224 in. h^{-1} (5.69 mm h^{-1}); the storm diameter (D) of the line was 6.0° latitude (667 km); and the speed (V) of the storm was 12 kt (22.2 km h^{-1}). The tropical rainfall potential was calculated according to

$$\mathrm{TRaP} = R_{\mathrm{avg}} D V^{-1}, \qquad (3)$$

and resulted in a maximum rainfall potential of 6.72 in. (171 mm). The observed rainfall in Key West was 8.38 in. (213 mm).

3. The areal TRaP technique

In 1999 the TRaP technique was improved in several ways. First, we wished to automate the technique so that it would not have to be performed manually by an analyst and so that it can be performed throughout the life cycle of the storm, not just within 24 to 36 h of landfall. Second, we wanted to improve upon the assumption that storms move in a constant direction at a constant speed by using official track forecasts from NOAA's Tropical Prediction Center (TPC) or Central Pacific Hurricane Center or the Department of Defense's Joint Typhoon Warning Center (JTWC). Third, we wanted to create a graphical product—maps of accumulated rainfall that can be quickly analyzed and can serve as guidance for forecasters who issue public forecasts. To emphasize this third goal, we call the technique "Areal TRaP" to distinguish it from the manual TRaP described above, which produced only a point estimate of accumulated rainfall.

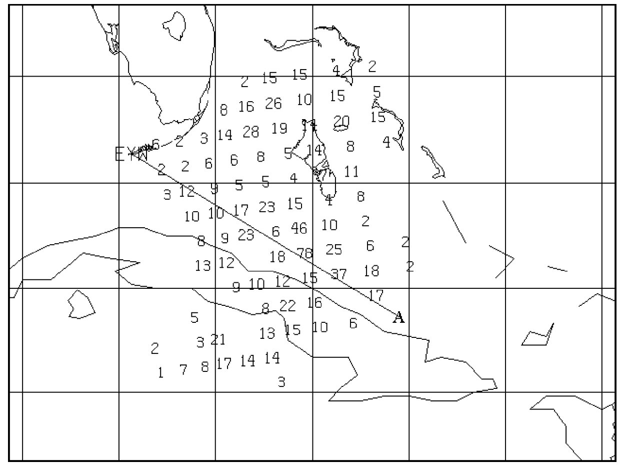

FIG. 1. *NOAA-15* AMSU-A rain rates (0.01 in. h^{-1}) in Hurricane Georges at 0023 UTC on 25 Sep 1998. TRaP was calculated along line A. (After Kidder et al. 2000.)

The Areal TRaP technique (Kidder et al. 2001a,b) starts with a satellite-based estimation of rain rate. The Cooperative Institute for Research in the Atmosphere (CIRA) uses rain rates from the AMSU-B instrument (16-km resolution at nadir) produced by the NOAA/NESDIS Office of Research and Applications (Weng et al. 2003). SSD also uses the technique with rain rates from SSM/I and TMI. The technique could also be used with the IR-based, operational NESDIS Auto-Estimator (Vicente et al. 1998, 2002)/Hydro-Estimator (Scofield and Kuligowski 2003). At CIRA, to try to exclude rain that is not associated with the tropical cyclone, we draw a circle around the storm at the observation time and do not process rain outside of the circle. The radius of the circle is 600 km (seventy-five 8-km Mercator pixels) in the Western Hemisphere and 900 km in the Eastern Hemisphere (where storms are larger). A better way to do this needs to be investigated.

Next, track information is acquired from a forecast center (such as TPC). The track consists of the current storm position (the "zero hour" position), two past positions (at –12 and –24 h), and up to five forecast positions (at +12, +24, +36, +48, and +72 h). If no forecast positions are available, the –12 and 0 h positions are extrapolated to +12 and +24 h. At CIRA (but not at SSD), a cubic spline is fitted to the past, current, and forecasted positions so that it is easy to interpolate positions at different times.

The observation time of the storm is determined by iteratively calculating the positions of the slowly moving storm and the rapidly moving satellite. The interpolated position of the storm in the –12 to 0 h period is compared to the position of the satellite calculated from the orbital elements. The time of closest approach is taken as the time of observation (t_{obs}). The interpolated position of the storm at t_{obs} is the observation position (x_{obs}, y_{obs}). All calculations are performed on a Mercator map grid with 8-km resolution at the equator.

A cubic spline interpolation of the position of the storm center every 15 min throughout the forecast period (0 to +24 h) is calculated. At time t_i, the storm is at position (x_i, y_i) in the Mercator map. Further, the relative position between the storm center at time t_i and at t_{obs} is given by a set of offsets (Δx_i, Δy_i), where

$$\Delta x_i = x_i - x_{\text{obs}}, \quad \Delta y_i = y_i - y_{\text{obs}}. \tag{4}$$

At every point (x_j, y_j) in the output image (j ranges from 1 to the number of pixels in the output image), the rainfall is calculated as

$$\text{TRaP}(x_j, y_j) = \int_{0\text{h}}^{24\text{h}} R(x_j, y_j, t)\, dt. \tag{5}$$

Since the rain-rate pattern is assumed to move with the storm center,

$$R(x_j, y_j, t) = R(x_j - \Delta x, y_j - \Delta y), \tag{6}$$

where Δx and Δy represent the motion of the storm center between t_{obs} and t; that is, we simply pick the rain rate of the pixel that will be over point (x_j, y_j) at time t. Finally, the integral (5) is approximated as

$$\text{TRaP}(x_j, y_j) \approx \sum_{i=0}^{96} w_i R(x_j - \Delta x_i, y_j - \Delta y_i)\Delta t, \tag{7}$$

where $\Delta t = 0.25$ h, Δx_i and Δy_i are the 15-min offsets calculated in (4), and w_i are the trapezoidal-rule weights: 0.5 for $i = 0$ or 96, 1.0 otherwise. Since the satellite-estimated rain rate R is in millimeters per hour, TRaP is the 24-h rainfall in millimeters, which is then converted as necessary to inches to communicate the forecast. This calculation is easy to do because Δx_i and Δy_i do not depend on j; they are calculated once and applied to every point.

Note that this algorithm for TRaP eliminates a problem with previous techniques: as the speed of the storm approaches zero, the 24-h rainfall no longer approaches infinity. Rather the maximum 24-h rainfall is simply 24 times the maximum hourly rain rate.

The Areal TRaP calculation has been entirely automated at CIRA. Triggered by receipt of a track forecast, the AMSU rain-rate data are accessed, and the Areal TRaP forecasts are made.

SSD performs a similar calculation, but the cubic spline is not applied to the track forecast. Instead, the forecast is linearly interpolated between forecast positions. SSD automated TRaPs also are generated when a new rain-rate image over the storm is available in addition to whenever a new track forecast is issued. One other important difference is that SSD analysts, working around the clock, provide quality assurance of the automated TRaPs and send them to their Internet home page (http://www.ssd.noaa.gov/PS/TROP/trap-img.html) only when a storm has wind speeds greater than 65 km h^{-1} (35 kt) and is within 24 to 36 h of landfall. The CIRA TRaPs are not quality controlled and are automatically posted to a Web site (http://amsu.cira.colostate.edu/TRaP) regardless of storm intensity or distance from land.

In summary, the assumptions used to generate the Areal TRaP are as follows:

(a) The forecast storm track is correct.
(b) The satellite-estimated rain rates are correct.
(c) The spatial pattern of rain rates relative to the storm center does not change in either coverage or magnitude, and thus moves with the storm center along the forecast track. This assumption neglects outside influences on the storm that can increase rain rates (e.g., interactions with fronts or with terrain) or decrease them (e.g., intrusion of dry air or wind shear).

4. Results

Three storm cases are presented here to illustrate how the Areal TRaP technique works and how it can be used. These cases were chosen because corroborating rainfall data are available. Detailed validation of the Areal TRaP technique is presented in Part II of this paper and in Ferraro et al. (2002).

a. Tropical Storm Allison

Allison produced devastating rainfall over a large region of the United States, resulting in the most extensive flooding ever associated with a tropical storm. Damage exceeded $5 billion, and 41 deaths were directly attributable to the storm. Much of the damage and most of the fatalities occurred in the Houston, Texas, metropolitan area, where more than 30 in. (760 mm) of rain were reported.

According to Beven et al. (2003), Allison originated from a tropical wave that moved off the west coast of Africa on 21 May 2001. By 5 June 2001, the wave had entered the western Gulf of Mexico, and deep convec-

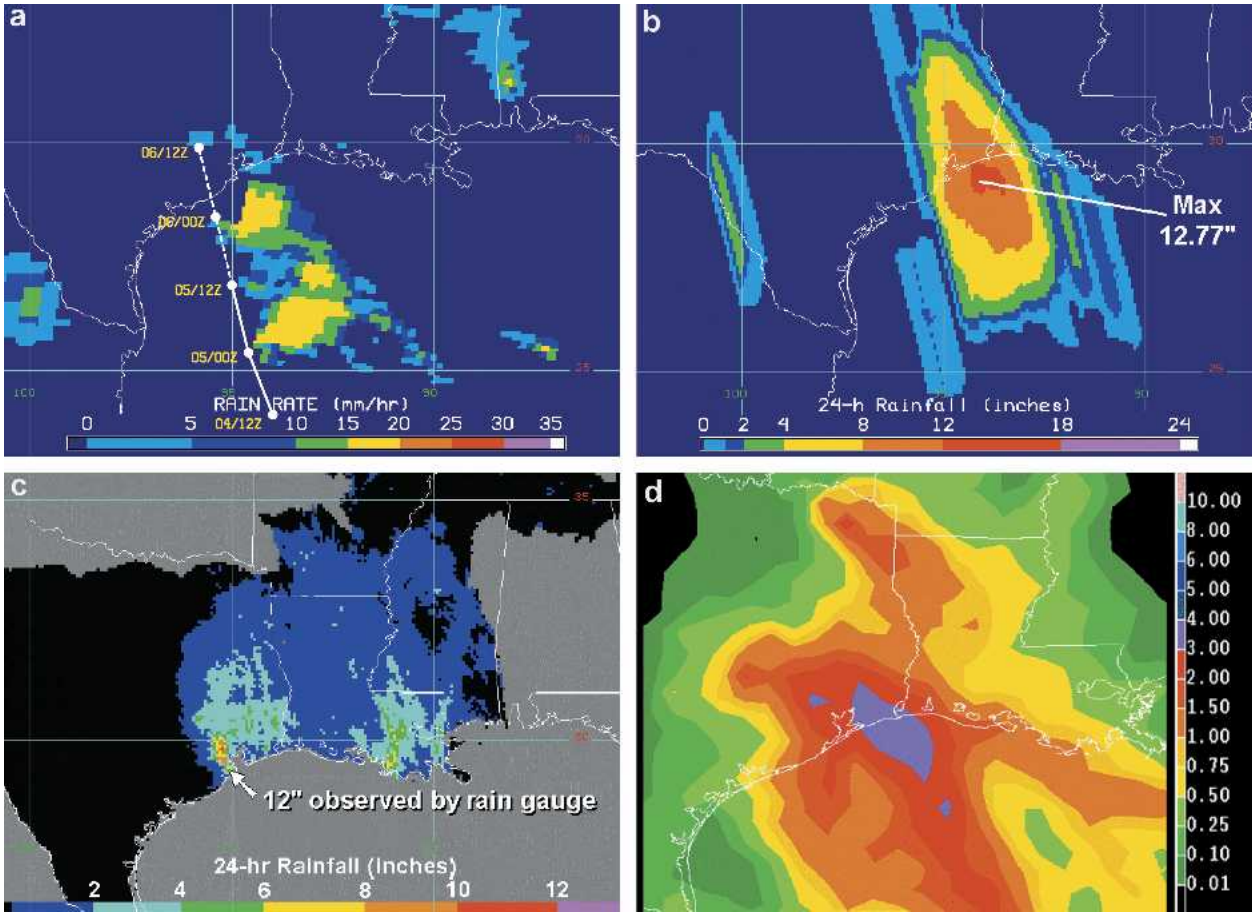

FIG. 2. (a) *NOAA-16* AMSU-B rain rates for Tropical Storm Allison at 0812 UTC on 5 Jun 2001. (b) The 24-h TRaP for the period ending 1200 UTC on 6 Jun 2001. (c) Stage III rain gauge–adjusted radar rainfall estimates for the 24-h period ending at 1200 UTC on 6 Jun 2001. (d) Eta Model forecast of precipitation for the 24-h period ending 1200 UTC on 6 Jun 2001. The maximum is less than 4 in. (300 mm).

tion developed. Figure 2a shows the *NOAA-16* AMSU-B rain rates at 0812 UTC on 5 June 2001. Near 1500 UTC on 5 June 2001, TPC issued a track bulletin for the storm (later to be named Allison). TPC did not issue forecast locations in this bulletin; only the 1200 UTC 5 June 2001 position and two previous positions were noted. These three positions are indicated in Fig. 2 by the solid line. The track between 0000 and 1200 UTC on 5 June 2001 was extrapolated for 24 h. These positions are indicated by dashed lines. Using the positions in Fig. 2, the TRaP calculation for the 24-h period ending at 1200 UTC 6 June 2001 was performed and is shown in Fig. 2b.

The experimental TRaP estimates for Allison were provided by NESDIS/SSD to the National Weather Service River Forecast Center (RFC) at Fort Worth, Texas, and the Tropical Prediction Center (in real time, via e-mail and telephone, respectively) and to the Hydrometeorological Prediction Center (verbally, in person) hours before the storm's landfall.

The stage III rain gauge–adjusted radar data (Fulton et al. 1998) produced operationally by the West Gulf and Lower Mississippi RFC (corresponding to the TRaP produced in Fig. 2b) is shown in Fig. 2c. A comparison of Figs. 2b and 2c indicates that even though the TRaP technique misplaced the location of the maximum rainfall, it did a credible job both of indicating the general location of the heavy rain threat area and of estimating the peak rainfall amount over Texas. The TRaP forecast compares quite favorably with the corresponding Eta Model forecast (Fig. 2d), which depicted a maximum precipitation amount of less than 4 in. (100 mm), or approximately one-third of the observed and TRaP-predicted maximum. However, TRaP did not capture the secondary maximum of rainfall over southeastern Louisiana, which resulted from rainbands that developed on the eastern flank of Allison after the time of the AMSU-B observation.

b. Hurricane Gabrielle

Gabrielle reached tropical storm strength over the Gulf of Mexico, crossed Florida, and subsequently strengthened into a hurricane (Beven et al. 2003). It weakened, curved northward, and took aim at Newfoundland, Canada. Figure 3a shows the *NOAA–16* AMSU-B-estimated rain rate at 1758 UTC on 18 September 2001 and the TPC track, issued near 0300 UTC on 19 September. Figure 3b shows the TRaP for the 24-h period ending at 0000 UTC on 20 September. Generally, the forecast showed 100–200-mm amounts over southeast Newfoundland with the possibility of amounts exceeding 200 mm. Figure 3c shows an analysis of the rain gauge totals for 19 September. It appears that the precipitation maximum was southeast of the forecast maximum, but the amounts were quite compatible with the TRaP.

c. Tropical Storm Fay

Fay developed in the Gulf of Mexico, becoming a tropical storm at 0000 UTC 6 September 2002 (Beven et al. 2003). Figure 4a shows the SSM/I-estimated rain rates at 0222 UTC on 7 September. At this time, the storm was traveling west-northwestward at about 3.7 kt (6.9 km h^{-1}; Fig. 4b). The TRaP (Fig. 4c) exceeded 12 in. (305 mm) in a broad area to the right of the track between Matagorda Bay and Galveston Bay. The TRaP maximum was about 18 in. (457 mm). The stage III rain gauge–adjusted radar rainfall (Fig. 4d) shows a maximum of 14 in. (356 mm). Though the TRaP areal rain amount was larger than observed, the location and the maximum amount would have been very useful to forecasters because most of the assumptions for this particular TRaP were met: 1) little change in both area and magnitude of rain rates; 2) a good 24-h forecast of the storm's movement/speed; 3) a rain area that did move in the forecast direction/speed of storm; and 4) minimal outside influences.

5. Conclusions and suggestions for future work

The TRaP technique has a long history and provides an important tool in a challenging forecast problem:

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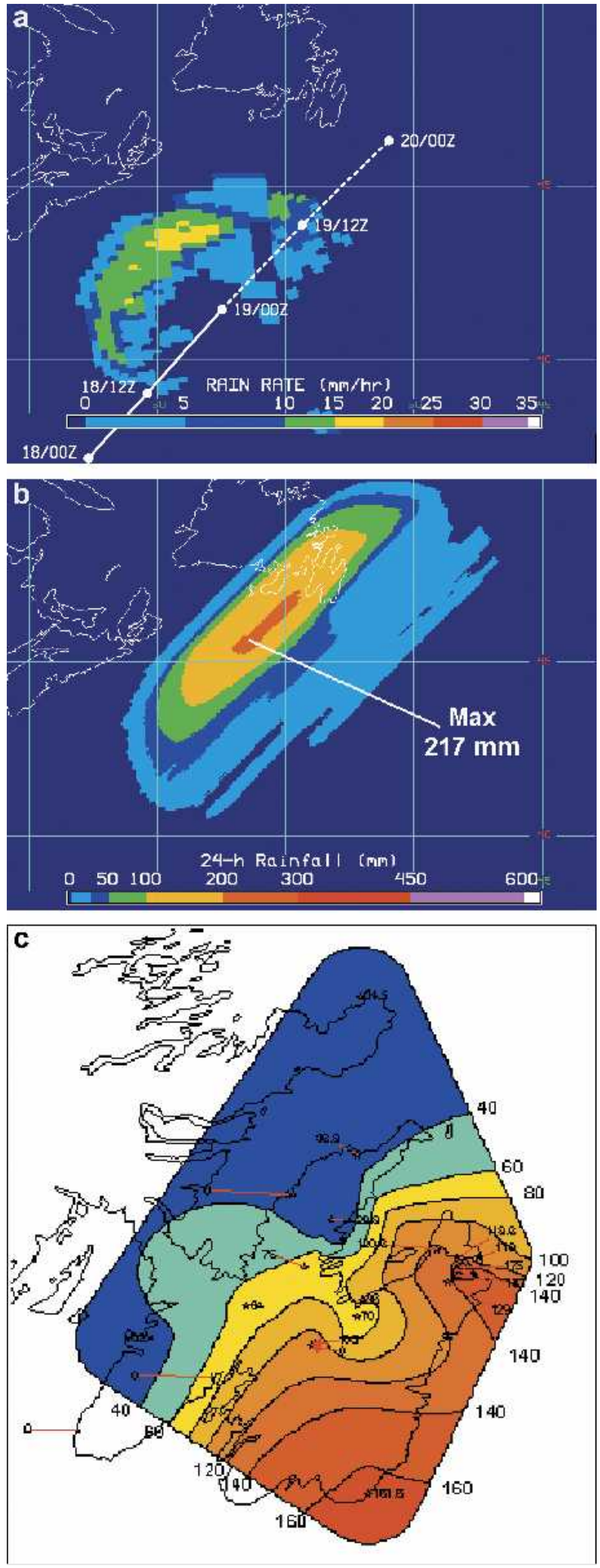

FIG. 3. (a) *NOAA-16* AMSU-B rain rates for Tropical Storm Gabrielle at 1758 UTC on 18 Sep 2001. (b) The 24-h TRaP for the period ending 0000 UTC on 20 Sep 2001. (c) Analysis of Newfoundland rain gauge data (mm) for 19 Sep 2001. (Courtesy of J. Abraham, Meteorological Service of Canada.)

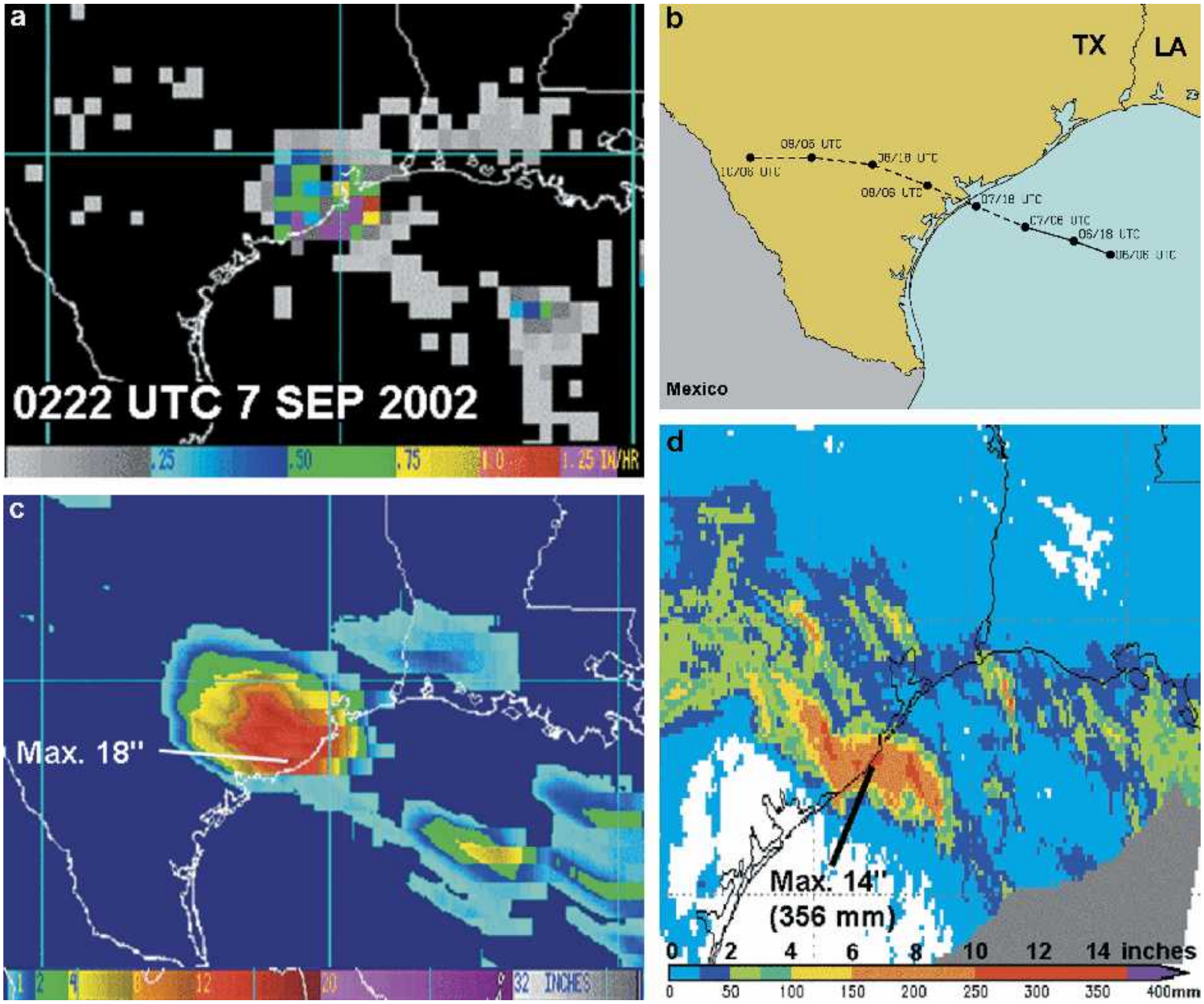

FIG. 4. Tropical Storm Fay (a) DMSP SSM/I rain rates for at 0222 UTC on 7 Sep 2002, (b) NCEP TPC track forecast, (c) 24-h TRaP, and (d) stage III rain gauge–adjusted radar amounts.

alerting people to the amount and location of heavy precipitation from tropical cyclones. Although simple in concept, the technique is easy to implement, it fills an important gap, and its graphical output is quite useful to forecasters. As of this writing, the TRaP technique is in operational use at NOAA/NESDIS/SSD.

There are many ways in which the TRaP technique could be extended and improved. We list some of them here.

1) One of the major assumptions of the TRaP technique is that the rain-rate estimates made from microwave observations are correct, but this is not well tested. In addition, the rain-rate estimation technique probably depends on the precipitation regime; rainfall from tropical cyclones, for example, is probably somewhat differently sensed than stratiform precipitation and even midlatitude thunderstorms over land. A study comparing rain-rate estimates of tropical cyclones from satellite passive microwave observations and coastal radar observations would be helpful.
2) Another assumption of the TRaP technique is that the satellite-observed rain pattern is constant in time for the duration of the forecast period. Clearly it is not, but the question is how variable is it? Is there a way of using multiple satellite observations to get a handle on the variability? At some point in the forecast period should we switch to using a climatological rain-rate distribution, or should the initial rain rate and a climatological rain rate be averaged together in some way?

3) The final assumption in the TRaP technique is that the forecast track is correct. Perhaps TRaP could be improved by using several tracks, or at least known statistical track errors, to make an "ensemble" TRaP.
4) The effects of external factors on TRaP forecasts is yet another area that deserves attention. Terrain probably enhances precipitation, but how much? What about the influence of moisture boundaries or wind shear?
5) Tustison et al. (2001) point out that there are major difficulties in trying to compare rainfall observations on different spatial scales. Comparing radar and rain gauge data is the classic problem in this regard, but verifying model forecasts or TRaP forecasts with radar data also have "representativeness" errors. These require further study (see Part II).
6) Finally, it would be very interesting to attempt to initialize numerical weather prediction models with the satellite-observed rain rates so that the forecasting skill of the models could replace TRaP. Hopefully the models would be able to forecast when tropical cyclone precipitation would reorganize and improved rainfall forecasts over land would result. TRaP could serve as a useful standard with which to compare model forecasts of tropical cyclone rainfall.

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