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SATELLITE DERIVED ENSEMBLE TROPICAL RAINFALL POTENTIAL (eTRaP): 2008-2009 RESULTS

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1. INTRODUCTION

Tropical storms and cyclones are among the most damaging natural hazards worldwide. In addition to strong winds and storm surge, the heavy rainfall produced by these storms can lead to dangerous inland flooding. Freshwater floods associated with hurricanes were responsible for more than 300 deaths in the United States during the period 1970-1999, including 50 deaths alone from Hurricane Floyd in 1999 (Rappaport 2000).

To address the need for cyclone-related heavy rain information, the National Oceanic and Atmospheric Administration's (NOAA) Satellite Data and Information Service (NESDIS) has been producing operational areal Tropical Rainfall Potential (TRaP) forecasts for landfalling tropical cyclones since the early 2000's. TRaP forecasts (called TRaPs in this paper) are essentially 24 h extrapolation forecasts of satellite-estimated rain rates that give the expected location and intensity of the rain maximum as well as the spatial rainfall pattern (Kidder et al. 2005). As of January 2010, TRaPs are derived from rain rate estimates from passive microwave sensors on polar orbiting satellites, and include the Advanced Microwave Sounder Unit (AMSU) on NOAA-15, 16, 17 18, 19 and Metop-A, the Tropical Rainfall Monitoring Mission (TRMM) Microwave Imager (TMI) and the Advanced Microwave Scanning Radiometer for the Earth Observing System (AMSR-E) on NASA's Aqua satellite (first used for TRaP in 2008). Radar calibration (RADCAL) beacon interference in 2006 and the failed last recorder in November 2009, have prevented generation of TRaPs from the DMSP Special Sensor Microwave Imagery (SSM/I) F-15 and 13, respectively. TRaPs from the operational NESDIS Hydro-Estimator (H-E; Kuligowski et al. 2004), which generates rainfall estimates from infrared data from geostationary satellites, have been made for US hurricanes since 2004, but are experimental and have not been officially validated.

TRaP forecasts are conceptually quite simple. To produce an areal TRaP a satellite "snapshot" of instantaneous rain rates is propagated forward in time following the predicted path of the cyclone using track forecasts made at operational tropical cyclone warning centers, including the Joint Typhoon Warning Center (JTWC) and Regional Specialized Meteorological Centers (RSMCs) in the region under threat. Every 15 minutes a new position is calculated and the spatial rain rates are applied over a rectangular grid of approximately 4 km resolution, then the 15-minute accumulations are summed over a period of 24 hours (Kidder et al. 2005). Three basic assumptions are made in the calculation of TRaP forecasts: (a) the satellite rain rate estimates are accurate, (b) the forecasts of cyclone track are accurate, and (c) the rain rates over a 24 h period can be approximated as steady state following the cyclone path. Errors in TRaP rainfall predictions can be attributed to flaws in one or more of these assumptions. Other errors attributed to the extrapolation of the rain rates will be addressed in the future improvements section at the end of the paper.

Studies by Ferraro et al. (2005) and Ebert et al. (2005) on the accuracy of 24 h TRaP forecasts over the US and Australia, respectively, have shown that in general the TRaPs give reasonable estimates of both the maximum rainfall accumulation and its spatial distribution but underestimate the total rain volume by about one third in both regions. The overall accuracy is similar to that of mesoscale models. The results from both validation studies suggest that the errors in TRaP forecasts are more likely to be related to errors in satellite rain rates and the assumption of steady state rainfall than to errors in operational track predictions. While there is some systematic error in the TRaPs (e.g., underestimation of rain volume), the variability

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in TRaP performance from storm to storm, and indeed among different TRaPs for a single storm, is very large. This large random error component means that it is difficult to estimate *a priori* the accuracy of a particular TRaP forecast.

One way to reduce the random error is to average several forecasts together in an ensemble. Kidder et al. (2005) and Ebert et al. (2005) both suggested ensemble TRaP as a way to improve the TRaPs first generated by either a single track forecast or satellite. This ensemble approach was shown to smooth the rain field (Ebert, et al., 2009), with associated advantages and disadvantages. The mean field was less likely to produce very large errors when compared to the observations; however, the averaging damped the high rain intensities, which was the original motivation for making TRaP forecasts. A more intelligent, compromising approach was to retain information on the distribution of forecasts within the ensemble, making use of the uncertainty (variability) among the TRaP forecasts comprising the ensemble. One can now generate probabilistic forecasts of rain exceeding certain critical thresholds in locations of interest, an approach that is very amenable to risk management and mitigation strategies.

In recent years 6 h TRaP rainfall accumulations have been produced and archived as part of the operational processing of 24 h TRaPs. These provide useful short-period forecasts that can be used to generate time series of predicted rain evolution at locations of interest. These short period forecasts can also be combined in multiple permutations to make an ensemble of TRaP forecasts for 6 h and 24 h accumulations.

In principle an ensemble TRaP, henceforth called eTRaP, can be made up of forecasts using observations from several microwave sensors, initialized at several observation times, using several different track forecasts as seen in figure 1 for Tropical Storm Ida initialized within 3 hours of 12 UTC on November 10, 2009. The diversity among the ensemble members helps to reduce the large (unknown) errors associated with a single-sensor, single-track TRaP. The large number of perturbations leads to ensembles with many members, allowing probability forecasts to be issued with good precision and potentially good reliability.

The next section will briefly describe the methodology for generating eTRaPs. We then demonstrate eTRAP forecasts of heavy rain associated with the landfall of Tropical Storm Ida in November 2009. The accuracy of the ensemble TRaP quantitative precipitation (QPFs) and probabilistic forecasts was demonstrated by Ebert et al. (2009) for 145 heavy rain forecasts in eighteen Atlantic tropical storms and hurricanes making landfall in the United States during 2004-2008. This section will briefly discuss the most recent changes made in the methodology in the past year before eTRaP became operational at: http://www.ssd.noaa.gov/PS/TROP/etrap.html (see figure 2) in August, 2009. In section 3, several cases from 2009 will be shown with qualitative comparisons to observations and/or numerical model data, taking note of why the eTRaP was successful or not successful. Finally the paper concludes with suggestions for future work that will further improve the eTRaP products.

2. GENERATION OF ENSEMBLE TRAP FORECASTS

Figure 3 has been updated from Ebert, et al. (2009) and illustrates schematically how eTRaPs are currently generated. eTRaP products include both deterministic and probabilistic quantitative precipitation forecasts (QPFs and PQPFs) (see internet product example in figure 2) generated from weighted ensemble members, where the weights indicate the expected relative accuracy. TRaPs are assigned to the nearest synoptic time of 00, 06, 12, or 18 UTC, which means that they are at most 3 hours offset in time. All forecasts were remapped onto a regular 0.25° latitude/longitude grid prior to combination.

6 h TRaP rainfall accumulations, or segments, are combined into 24 h accumulations as needed. The number of ensemble members in the eTRaP is the number of permutations possible for combining the various segments of the forecast. As seen in figure 1 with the example of Tropical Storm Ida along the Gulf of Mexico coast in November 2009, if there are seven 6-hour TRaPs available for the first six hours of a 24 h forecast, five TRaPs for the second six hour segment, three TRaPs for the third segment, and two TRaPs for the fourth segment, then the number of ensemble members comprising the 24 h forecast is 7 x 5 x 3 x 2 = 210.

Every 6 h TRaP contributing to the ensemble is weighted according to its expected accuracy. The weight assigned to the *i*th TRaP forecast, w_i, is the product of its sensor weight and its forecast latency weight, $w_i = w_{sensor} \times w_{latency}$.

The sensor weights were originally based on the validation results of Ferraro et al. (2005) and Ebert et al. (2005), and presented in Ebert, et al. (2009). Further research in the first half of 2009 continued the weight of 1.0 for AMSR-E but yielded new sensor weights of 1.0 for AMSU and TRMM and were instituted before eTRaP became operational in August 2009.

The weights for forecast latency were first subjectively assigned, with the most recent 6 h segments receiving the most weight and the oldest 6 h segments receiving the least. This too was modified since Ebert et al. (2009) and are presented in Table 1. These new results continue to reflect the expectation that steady state rainfall is a more valid assumption early in the forecast period than later, but less so than before.

Table 1. Forecast latency weights, $w_{latency}$, used in computing eTRaP.

Forecast latency	Weight
0 h	1.0
6 h	0.85
12 h	0.70
18 h	0.55

Both the new weights for the satellite sensors and forecast latency are included in figure 3.

3. eTRAP CASES FOR 2009: QUALITATIVE COMPARISONS WITH OBSERVATIONS AND/OR NUMERICAL MODEL DATA

The most comprehensive eTRaP validation to date was performed by Ebert et al. (2009) for Atlantic basin tropical cyclones that made U.S. landfall from 2004-2008. Since the 2009 Atlantic hurricane season had the fewest named storms and hurricanes since 1997 and no hurricanes and only two tropical storms made landfall in the U.S., it was decided to do a more qualitative comparison of eTRaPs with observations and/or numerical model forecasts and provide reasons for the results. In that regard, Tropical Storm Claudette and Ida 24 h eTRaPs are presented in this section for U.S. landfalling storms. In addition, since eTRaP forecasts are also produced globally, a 24 h eTRaP for Tropical Storm Bill and Tropical Cyclone Laurence and a 6 h eTRaP for Ketsana will be presented for eastern Canada, Northwest Australia and the Philippines, respectively.

3.1 Tropical Storm (TS) Claudette.

TS Claudette formed in the eastern Gulf of Mexico as a depression on 16 August and quickly was elevated to TS status before making landfall along the Florida panhandle coast early on 17 August. Figure 4 compared the eTRaP 24 h deterministic (a) and probabilistic (c) rainfall forecasts just before landfall with the observed amounts (b) for the period 00 UTC 17 August to 00 UTC 18 August. The most noticeable feature in the comparison was the eTRaP forecast predicting higher amounts (maximum 175 mm) versus the observed amounts (maximum 125 mm) and a larger areal extent of rain, especially inland. This was primarily due to the fact that upper level shear strengthened and dry air came into the storm after the initial 00 UTC 17 August eTRaP forecast and weakened the storm along with its rain production. Generally the eTRaP areal rainfall pattern was good because the first two basic assumptions, like accurate satellite rain rates and track forecasts, mentioned earlier in the paper were met. But the reason the areal and maximum rain amounts were too high compared with observations was because the third assumption, steady state rain rates over a 24 h period, was not met. At least there was a good reason for the discrepancy and if the features like upper level shear and even dry air had been incorporated into the forecast, the eTRaP forecast may have been improved.

3.2. Tropical Storm (TS) Ida

The unusual late season TS Ida formed and then intensified to hurricane status in the western Caribbean before entering the Gulf of Mexico. Traveling through the Gulf, Ida weakened to tropical storm classification and held that intensity as it approached Mississippi, Alabama and Florida panhandle coasts on the early morning of November 10. Figure 5 compares the eTRaP 24 h deterministic (a) and probabilistic (c) rainfall forecasts just before landfall with observed amounts (b) for the period 12 UTC 10 November to 12 UTC 11 November. The most noticeable feature in the comparison was the eTRaP forecast predicting higher amounts (maximum 250 mm) and further west versus the observed amounts (maximum 150 mm). But considering this storm encountered shear and its rainfall was displaced away from the center before and weakened to tropical depression status shortly after the start of this eTRaP forecast, the areal extent of the rain was very good. Again, at least there was a good reason for the discrepancy in both the maximum amounts and placement as upper level shear had dislodged the rainfall from the center of Ida and the assumption of steady rain rates from a weakening storm were not met. But a forecaster knowing these possibilities, could have improved the 24 h final rainfall forecast. In addition, figure 6 was included to compare same period forecast from the various numerical models (a, b, c, and d) with the eTRaP (e) and stage IV observations (f), It was especially promising that the eTRaP areal rainfall pattern was comparable to the models, despite the fact that eTRaP maximum amounts were higher than both the model forecasts and observations. So, it is hoped that improvements mentioned in section 4 will further improve eTRaP deterministic and probabilistic forecasts in the future.

3.3. *Tropical Storm (TS) Bill*

After brushing by Bermuda, the storm center of TS Bill weakened as it entered colder waters off the Northeast U.S. coast. Figure 7 (top) shows the 24 h eTRaP (a) initialized near 12 UTC 23 August as it approached the Nova Scotia coast with the August 23-24 storm rainfall total. Since 24 h rainfall observations for the eTRaP period were not available, a true comparison can not be made, but some speculative conclusions may be made. Even though the time of the storm total observations was probably longer than the 24 h eTRaP, the areal extent and maximum rainfall may have been comparable, especially if you consider that the higher maximum amounts with the longer observational period probably included additional rainfall far ahead of the storm that was not directly related to the center of Bill. Past experience with the former TRaP and now eTRaP forecasts suggests they perform best when most of the rain rates are closer and related to the storm center. Usually the farther away the satellite derived rain rates are from the storm center, the lower the confidence of the eTRaP results because external factors unrelated to the storm may produce more or less rainfall. For the most part, all three criteria mentioned in section 1 were generally met, but it was still difficult to do a true comparison with data from two different time periods. A better comparison occurred between the numerical model 24 h rainfall forecast of the GFS (c) and NAM (d) (bottom of Figure 7) with the same period eTRaP (a). They all appeared to be comparable and should have increased forecaster confidence in predicting both areal extent and maximum rain amounts for Bill affecting eastern Canada.

3.4. *Typhoon Ketsana*

Typhoon Ketsana's rain intensity and areal coverage increased and organized as it approached the Philippines on 25th of September. Prior to landfall around the 26th, the satellite derived rain rates around the center of Ketsana were already high. Being able to include these high rain rates in the 00 UTC 26 September run of eTRaP, helped allow the 6 h forecast (a) in Figure 8 to produce a maximum amount of 250 mm for the period 00 UTC to 06 UTC for the central part of the Philippines. To go along with the deterministic product, a small but significant 90% chance of greater than 100 mm was forecasted by the 6 h eTRaP probabilistic forecast (c). The results were the worst flooding in Manila (b) in over 40 years with maximum rainfall of around 341 mm between 00 and 06 UTC 26 September. For this extraordinary rain event the eTRaP forecast compared favorably to the observed maximum because all of the basic assumptions were met for this 6 h period of the forecast ending at 06 UTC on the 26th. Even though the eTRaP maximum rainfall forecast was almost 100 mm lower than the maximum rainfall reported, it was encouraging to see the 4 km resolution eTRaP catch such an unusual once in a lifetime rain event.

3.5. *Tropical Cyclone (TC) Laurence*

TC Laurence made landfall not once but an unusual twice in Western Australia. The eTRaP products comparison to observations is for the second landfall shortly after 00 UTC on 21 December 2009. Figure 9 compared the eTRaP 24 h deterministic (a) and probabilistic (c) rainfall forecasts with observed amounts (b) for the period 00 UTC 21 December to 00 UTC 22 December. The areal extent of the eTRaP compared favorably with observations near the coast and inland. Seen by the authors a number of times in the past for Western Australia tropical cyclone landfall, the eTRaP 24 h maximum rain amount of 325 mm was again in this case larger than the maximum observed 200 to 300 mm. It is conceivable this could have resulted from at least one of the assumptions not being met, like steady rain rates overland for part of the 24 h forecast period. On the other hand, it may be equally conceivable that the eTRaP forecasts were more accurate or even too low, since the storm went inland across an area of Australia with few observations and the addition of high winds made Joe Courtney, meteorologist with the Severe Weather Section of the Bureau of Meteorology comment, "...I'd say there was a lot more rain that didn't make it into the guage as rain was going horizontal!" In any case, for such a severe, heavy rain event, the eTRaP products compared favorably with what actually happened and Mr. Courtney also commented that he had made use of the eTRaP during the event and he considers it "a good additional tool to have for rainfall forecasting".

4. DISCUSSION AND IMPROVEMENTS

Operational eTRaP provides predictions of 6 h and 24 h rainfall amounts and probabilities of exceeding various rainfall thresholds in landfalling tropical cyclones. As shown in Ebert et al., (2009), the eTRaP QPFs were more accurate than single-sensor TRaP forecasts for the: maximum rainfall amount, spatial pattern, RMSE, rain intensity distribution and location. This paper looked at operational eTRaP product cases for the second half of the 2009 northern hemisphere tropical cyclone season and for the very beginning of the 2009 southern hemisphere tropical cyclone season. and showed comparisons with observations and/or numerical model forecasts. In the cases studied and presented, eTRaP comparisons with model rainfall forecasts were comparable and were for the most part able to provide either a confident consensus to the forecaster's final rainfall forecast or another independent method for consideration. It was satisfying to know that when eTRaP forecasts and observations compared favorably, most, if not all of the basic TRaP assumptions, mentioned earlier in this paper, had been met; when they did not compare favorably, at least there was a good reason/explanation why the forecasts were not accurate and can form the basis for future improvements that will be mentioned in the following paragraphs. Importantly, the more forecasters understand the assumptions that go into the TRaPs that produce an eTRaP, the better they will be able to modify their final tropical rainfall forecast. In addition, eTRaP forecast information provides probabilistic forecasts for decision makers. Based on forecaster response to an informal questionnaire on the different types of eTRaP probabilistic forecasts that can be generated, the overwhelming response from users was the desire to give the probability of exceeding that threshold somewhere within 40 or 25 km of the grid box of interest, similar to what the NOAA NWS/NCEP Storm Prediction Center issues for their severe weather probability forecasts. This approach would be less precise as far as location, but would give a better picture of the overall risk of heavy rainfall in a general area.

Many improvements can still be made to eTRaP. One enhancement is to include additional types of rainfall forecasts in the ensemble. For example, Kuligowski et al. (2006) demonstrated that TRaP could be constructed from Hydro-Estimator (H-E) rainfall estimates based on geostationary infrared observations. The spatial and temporal resolution of geostationary data are much greater than for passive microwave data, offering more detailed rainfall estimates and potentially very large ensembles. Kuligowski et al. (2006) found that spatial and temporal averaging of the H-E rainfall estimates prior to extrapolation in the TRaP process improved the quality of the forecasts. Judicial use of the H-E TRaPs may not only improve the ensemble by providing independent rainfall estimates, but it would also provide data during periods where few or no microwave TRaPs are available and as a result all eTRaP forecasts would be generated through 24 h.

eTRaP could also benefit from adding R-CLIPER and/or NWP models to the ensemble. NWP has the advantage that its forecasts extend out much longer than 24 h. It may be advantageous to blend eTRaP into longer range model forecasts in order to make time series products for locations at risk. An improved R-CLIPER (Lonfat et al. 2007) called Parametric Hurricane Rainfall Model (PHRaM) includes the effects of topography and vertical wind shear and would most likely improve the eTRaP rainfall trend through 24 hours.
Some improvements to eTRaP will involve modifications to the TRaP forecasts themselves. Topographic enhancement of TRaP land-based rainfall estimates could be included to increase rainfall in upslope flow and reduce it in downslope flow (e.g., Vicente 2002). For cyclones making landfall in mountainous regions such as Central America, some Caribbean islands, and many parts of Asia, this may be an important factor in better estimating the maximum rainfall.

The existing TRaP scheme does not include storm rotation; this would be a valuable improvement to increase the physical realism of the forecasts. Liu et al (2008) included estimates of storm rotation from geostationary cloud drift winds in past TRaP extrapolation forecasts and found that this one enhancement alone reduced the mean absolute errors by 40% compared to original TRaP forecasts for tropical cyclone rainfall over Taiwan. Low level cyclone wind fields from AMSU and other data (Knaff and DeMaria 2006) should be available from which it would be possible to estimate storm rotation rates.

Finally, inclusion of DMSP Special Sensor Microwave Imager/Sounder (SSMI/S) along with future new satellites in the NPOESS and GPM era should play an important role in providing adequate rain rate input so that 24 h eTRaP forecasts are generated more frequently, especially in areas where there is only one RSMC track forecast input.

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6. ILLUSTRATIONS AND TABLES

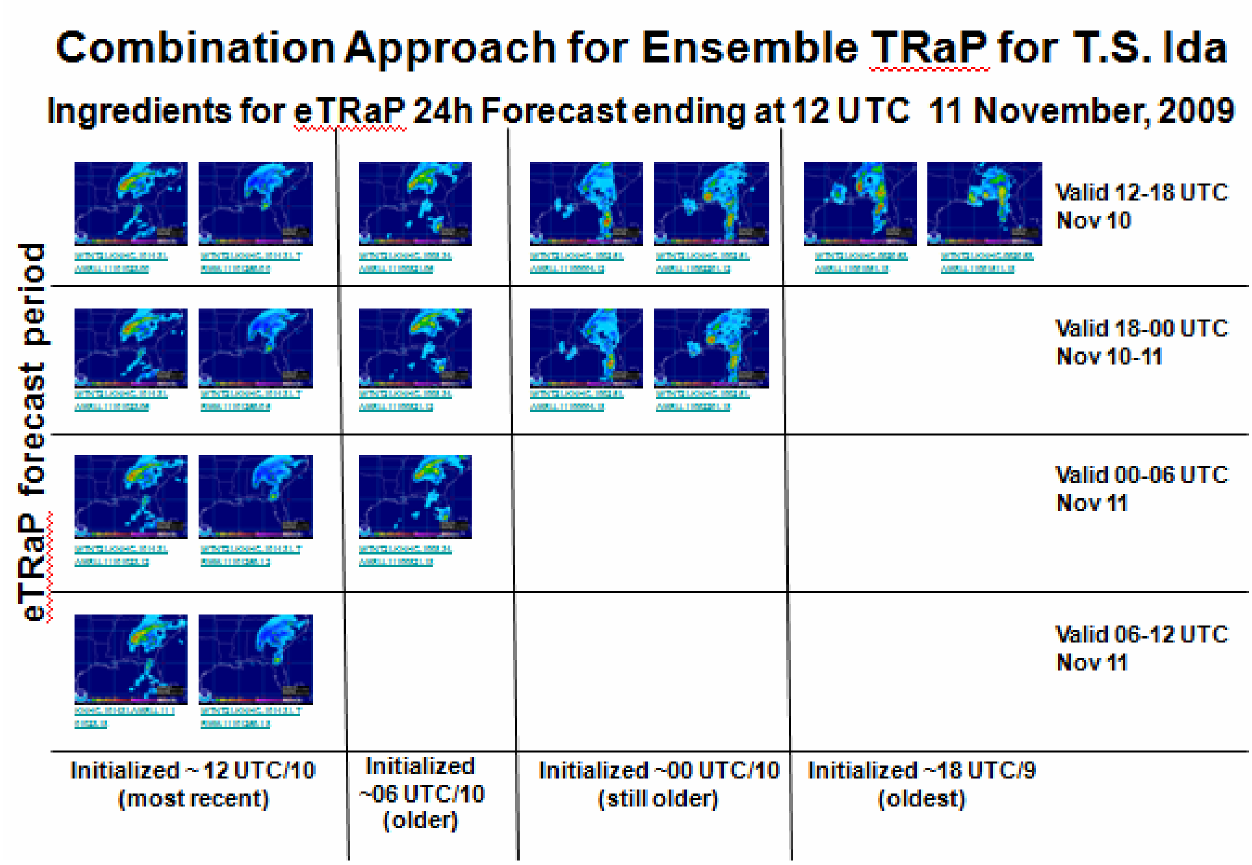

Figure 1. 6 h TRaP segments available within 3 hours of 1200 UTC on 10 November 2009 for Tropical Storm Ida, that were used to construct ensemble TRaPs for the subsequent 24 h period.

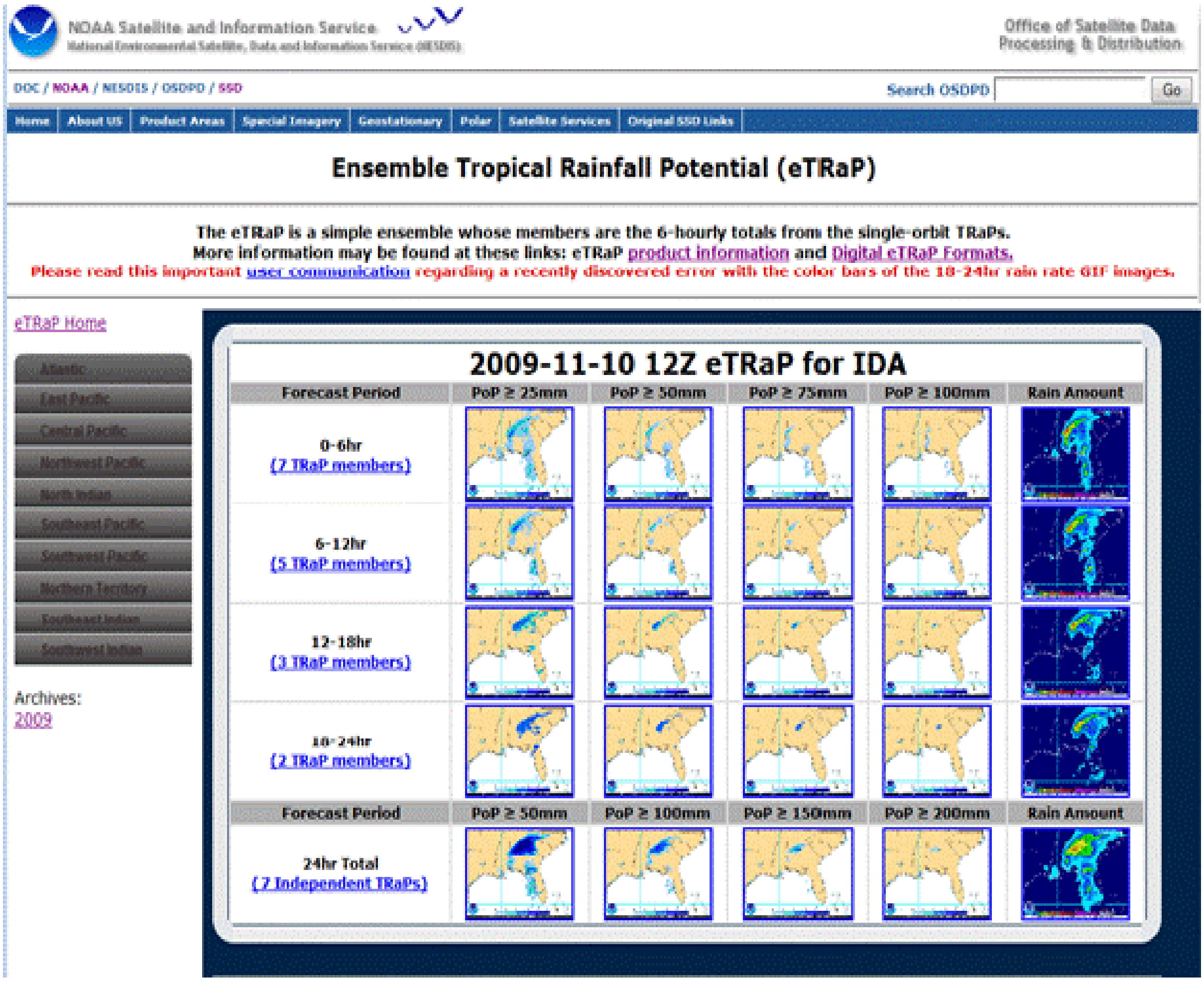

Figure 2. Operational NOAA/NESDIS ensemble Tropical Rainfall Potential (eTRaP) internet page at http://www.ssd.noaa.gov/PS/TROP/etrap.html ; Tropical Storm Ida initialized at 1200 UTC 10 November 2009 as an example.

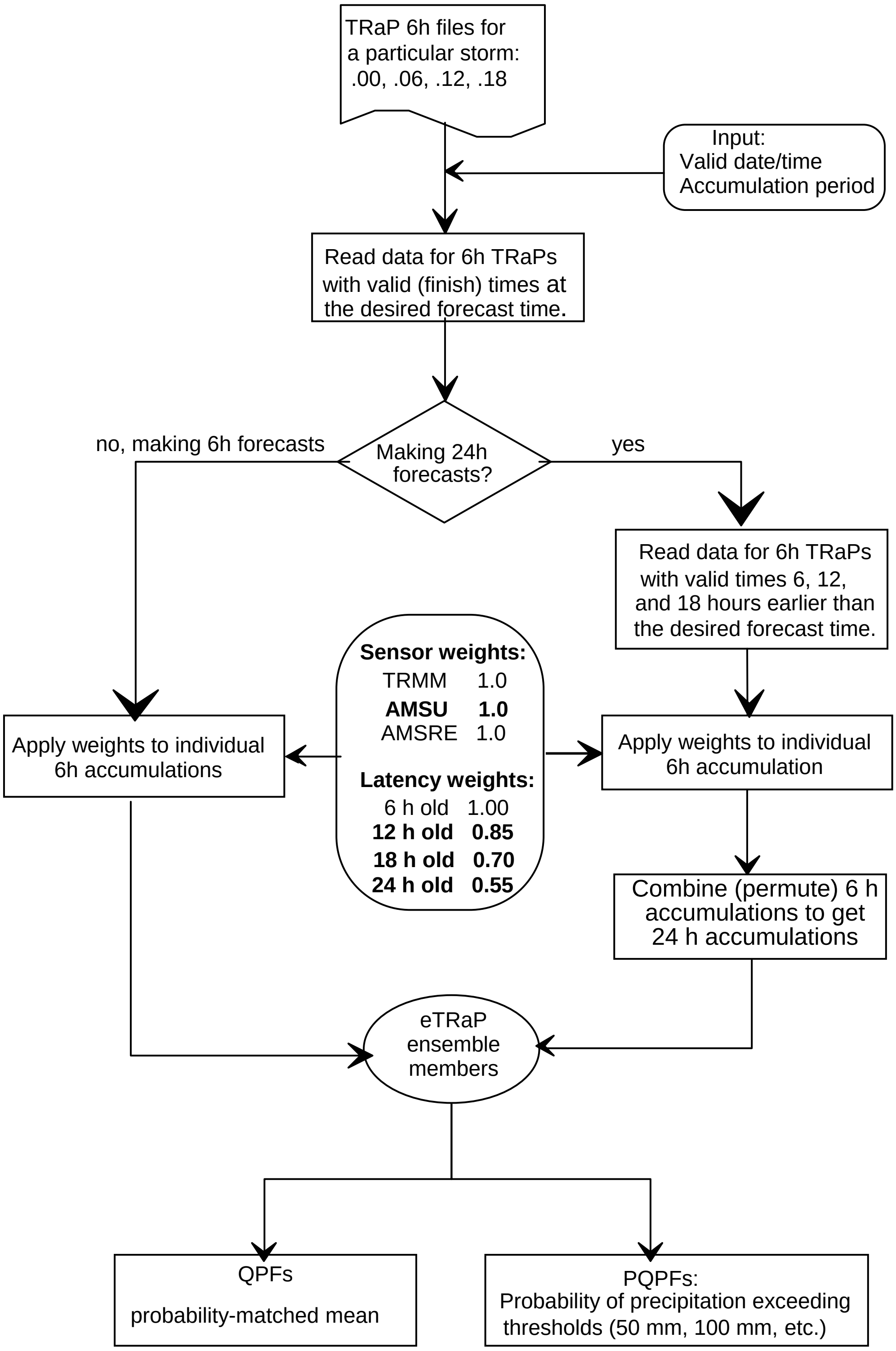

Figure 3. Steps in the generation of 24h eTRaP forecasts. Changes made in 2009 are in **bold**.

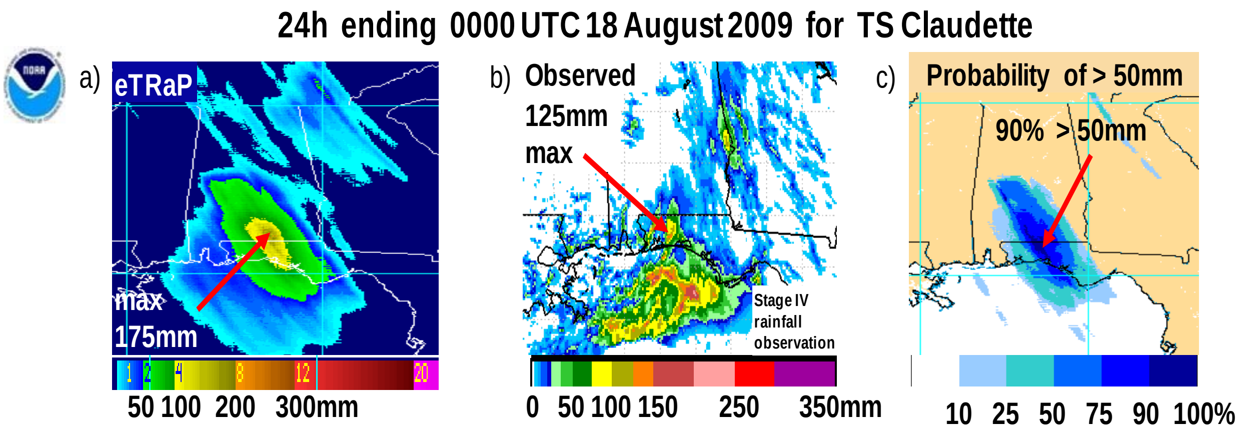

Figure 4. Comparison of eTRaP 24 h rainfall (a) and probability of >50 mm forecasts (c) with Stage IV observations (b) ending at 0000 UTC 18 August 2009 for TS Claudette.

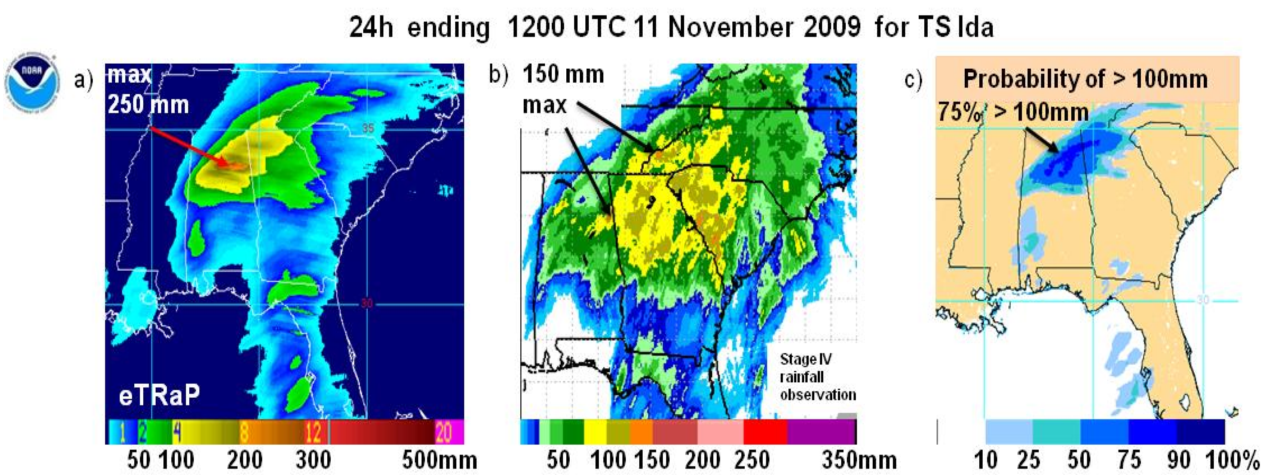

Figure 5. Comparison of eTRaP 24 h rainfall (a) and probability of >100mm forecasts (c) with Stage IV observations (b) ending at 1200 UTC 11 November 2009 for TS Ida.

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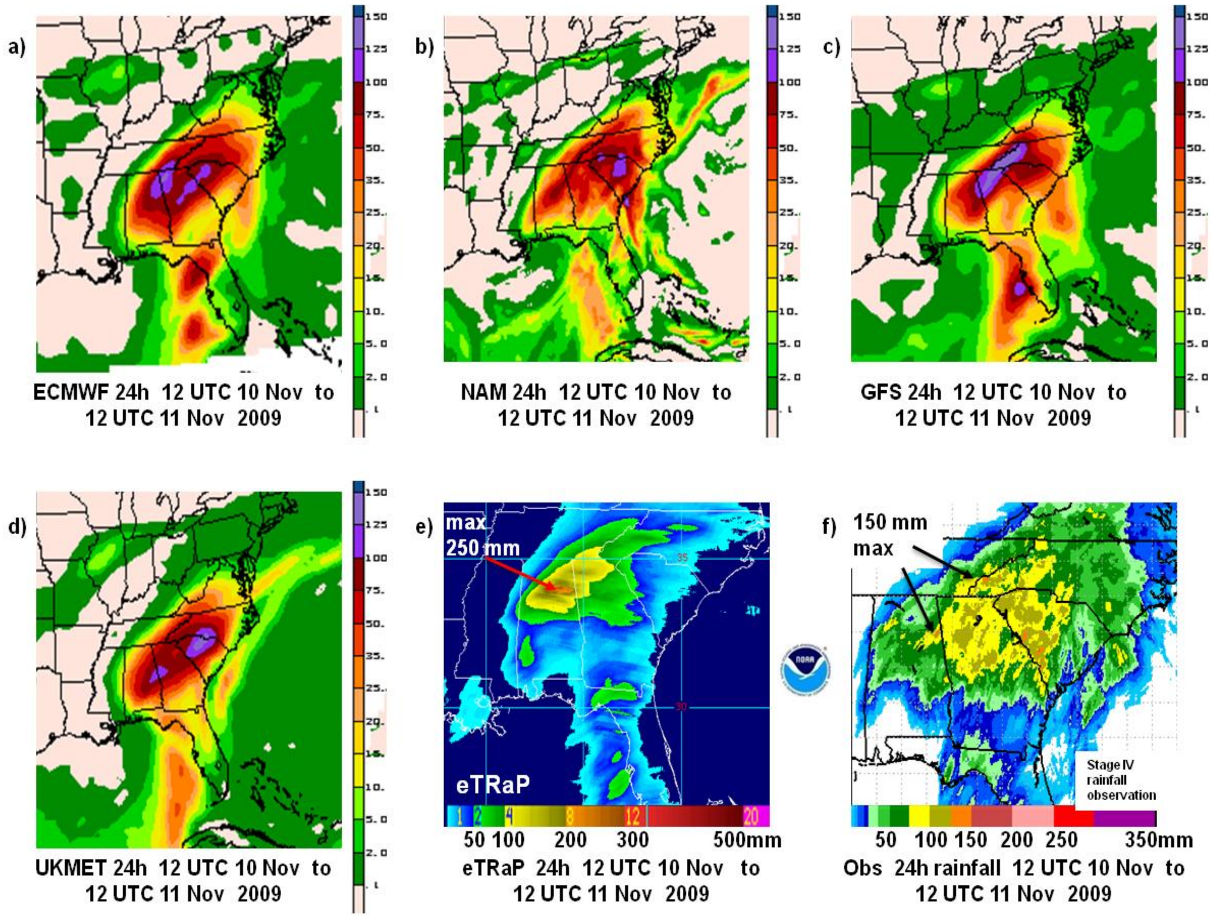

Figure 6. Comparison of 24 h numerical model rainfall forecasts from the ECMWF (a), NAM (b), GFS (c), UKMET (d) with the 24 h eTRaP forecast (e) and observed rainfall (f) for the period 12 UTC 10 November to 12 UTC 11 November 2009

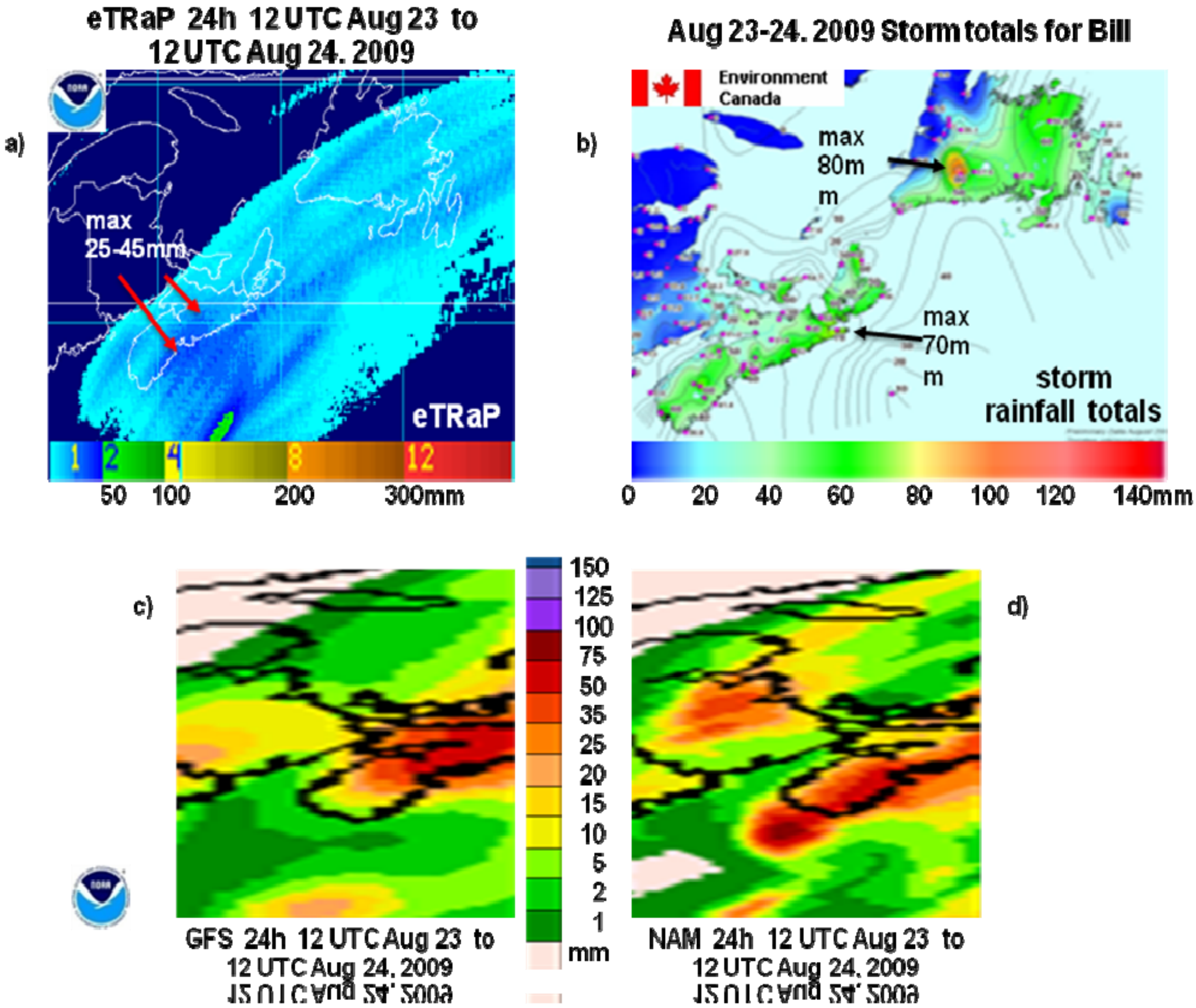

Figure 7. Top - Comparison of 24 h eTRaP rainfall forecast (a) with storm total rainfall observations for TS Bill affecting eastern Canada. Bottom - numerical model 24 h rainfall forecast from GFS (c) and NAM (d) for the same time period as the eTRaP forecast (a).

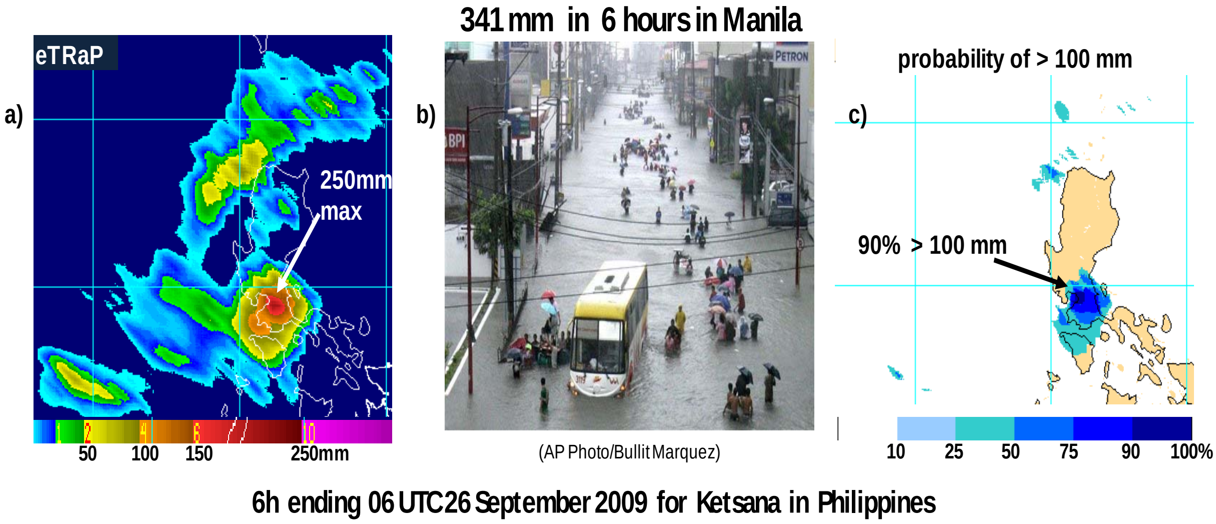

Figure 8. Deterministic (a) and probabilistic (c) eTRaP rainfall forecasts for the period 00 UTC to 06 UTC 26 September 2009 with resultant flooding (b) and record breaking observed rainfall amounts in those same 6 hours.

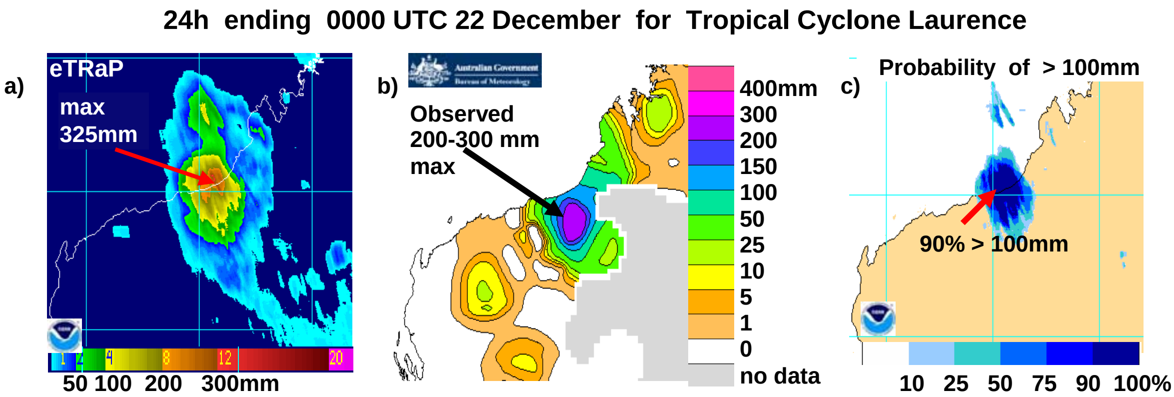

Figure 9. Comparison of the eTRaP 24 h rainfall (a) and probability of >100 mm forecasts (c) with rainfall observations (b) ending at 0000 UTC 22 December 2009 for Tropical Cyclone Laurence into Western Australia.