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An intercomparison of hurricane forecasts using SSM/I and TRMM rain rate algorithm(s)

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With 10 Figures

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Summary

Three different Special Sensor Microwave Imager (SSM/I) rain rate algorithms are evaluated as a means of improving both the physical initialization and the hurricane forecast output of the Florida State University Global Spectral Model (FSU GSM). These SSM/I rain rate algorithms are known as Cal/Val, NESDIS, and GPROF 4.0. In addition the Tropical Rainfall Measuring Mission (TRMM) TMI – 2A12 rain rate algorithm is validated, and its impact on FSU GSM hurricane forecasts is also studied.

Validation results of the Cal/Val rain rate algorithm show a bias toward gross underestimation. Both the NESDIS and GPROF 4.0 algorithms produce robust rain rates, in agreement with surface based observations. However, the NESDIS SSM/I rain rate algorithm proves to be the most consistent and accurate in this study. Surface rain rates as estimated by the TRMM/TMI – 2A12 algorithm can be inconsistent, mainly due to satellite observational coverage gaps.

The impact of different magnitudes of rain on the FSU GSM is significant. In theory, the application of more accurate and consistent rain rates should produce an improvement in model-calculated latent heat release and cumulus parameterization. The net effect is a more representative, modeled global circulation and improved hurricane track prediction. This research has shown that the use of NESDIS SSM/I rain rates in the physical initialization of the FSU GSM provides the most accurate hurricane track forecasts.

1. Introduction

Since the late 1980's, the Special Sensor Microwave Imager (SSM/I) has made significant contributions to the remote sensing of global precipitation. The precipitation estimates derived from the SSM/I have been and continue to be utilized for various meteorological applications, including numerical weather prediction (NWP). In data sparse regions such as the oceans, the SSM/I has proven itself to be an immensely valuable tool to obtain daily precipitation values in such areas where ground and radar based observations are not available. This constitutes a key element in the physical initialization of certain numerical weather prediction models, including the Florida State University Global Spectral Model (FSU GSM).

The Tropical Rainfall Measuring Mission (TRMM) is solely dedicated to the passive and active measurement of tropical and subtropical rainfall. Unlike SSM/I satellites, TRMM does not achieve global coverage. According to Kummerow et al. (1998), the main objective of TRMM is to measure rainfall and its associated energy exchange between the tropical and subtropical regions of the world. The TRMM satellite hosts microwave, visible, and infrared sensors, as well as the first space-based rain radar. It has been proposed that once validation of TRMM's numerous instruments is complete, other platforms such as SSM/I satellites will become obsolete. While this may become true for the tropics, other satellites will still be needed for *complete* global coverage, such as the polar orbiters.

Since the late 1980's, the tropical meteorology research laboratory of Dr. T. N. Krishnamurti at the Florida State University has developed and implemented a method to physically initialize the FSU GSM environment. This physical initialization process is highly dependent upon surface rain rates. The addition of surface precipitation estimates derived from SSM/I and TRMM brightness temperature data has greatly enhanced the prediction capability of the FSU global spectral model. This underscores the necessity of a consistently accurate SSM/I and/or TRMM rain rate algorithm in the physical initialization procedure. Physical initialization assimilates satellite-based, surface rain rate estimations into the FSU global spectral model. Since both latent heat release and cumulus parameterization rely on initial values of "observed" surface rainfall, satellite-based precipitation estimates that are either too light or too robust will ultimately distort the modeled global circulation. Consequently, use of a proven, accurate rain rate algorithm is critical to achieve improvement in hurricane prediction.

The author conducted a search for new and improved rain rate algorithms to be both validated and tested as input to the physical initialization of the FSU global spectral model. Two requirements needed fulfillment. First, the algorithms had to be readily available, either through public distribution or through the private owner's consent for use. Second, the algorithms had to be adaptable for daily, real-time use in order to satisfy the time constraints imposed by hurricane forecasting. Since the Calibration/Validation (Cal/Val) SSM/I rain rate algorithm had been the primary code used by FSU since 1992, any improvements beyond the capabilities of this aging algorithm were the objective of this research.

Experiments were conducted using the Cal/Val, NESDIS, GPROF 4.0, and TRMM TMI-2A12 rain rate algorithms as input to the physical initialization of the FSU global spectral model. Significant variations in forecast hurricane track, wind intensity, and minimum central pressure were realized by performing separate model runs using each of the four rain rate algorithms. However, only the improvements in forecast hurricane track will be presented in this publication since they proved to be the most impressive. Brief descriptions of the rain rate algorithms will be highlighted in Sects. 2, 3, 4, and 5. Rain rate validation studies are the subject of Sect. 6. Finally, hurricane prediction results will comprise the remainder of this article.

2. Overview of the Cal/Val SSM/I algorithm

The Cal/Val algorithm is the United States Navy's second generation precipitation retrieval algorithm. Developed by the Calibration/Validation group in the early 1990's, it replaced the Navy's D-Matrix algorithm for operational use. It is important to note that prior to this study, the

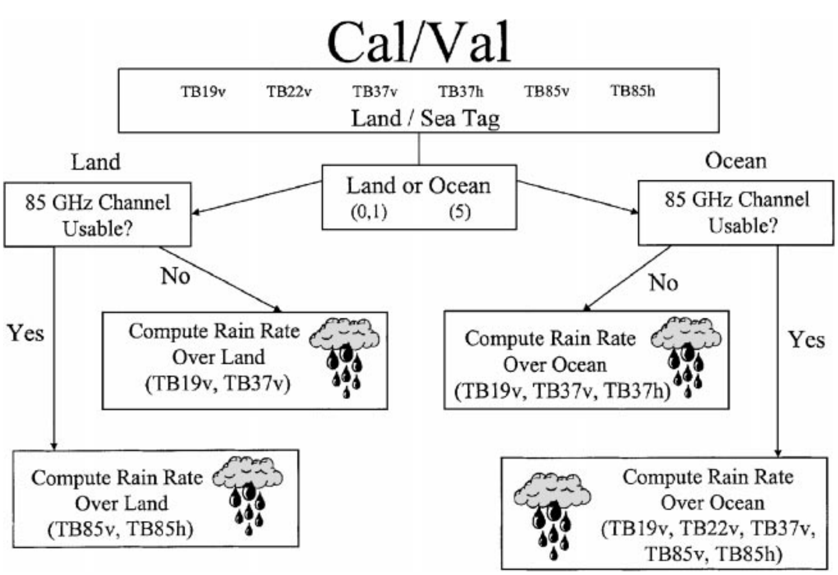

Fig. 1. Cal/Val SSM/I rain rate algorithm flow chart

Cal/Val algorithm served as the primary SSM/I rain rate algorithm used in the physical initialization of the FSU global spectral model.

The Cal/Val algorithm can be described as a statistical rain map, based upon regression of SSM/I brightness temperatures against collocated surface radar measurements of rain rate (Berg et al., 1998). Radar-derived rain rates from Kwajalein Atoll and Darwin, Australia, were used in a regression expression relating the log of the rain rate to five of the seven SSM/I brightness temperatures over the ocean. Only the 85 GHz vertical and horizontal brightness temperatures were initially utilized to obtain a regression expression for land areas. Figure 1 depicts a flow chart of the algorithm.

The Cal/Val algorithm exhibits a major weakness. The original radar-derived, collocated "training" data sets **did not** include any high intensity rain events. In fact, Berg et al. (1998) state that nearly all of the radar derived, area-averaged rain rates were less than 6 mm/hr. Consequently, a bias towards underestimation exists in the algorithm. Precipitation intercomparison projects have concluded that the Cal/Val algorithm underestimates rain rates by an approximate factor of two. However, this study has produced underestimations as large as a factor of four. It is this weakness which causes the Cal/Val algorithm to perform poorly in almost all intercomparisons, especially for intense storm systems.

3. Overview of the NESDIS SSM/I algorithm

The NESDIS SSM/I rain rate algorithm is the Navy's third generation algorithm developed by the National Environmental Satellite, Data, and Information System. The algorithm used in this research is the most recent version of NESDIS, which includes an emission component. Older versions only used an 85 GHz scattering component.

Also known as a statistical rain map, the NESDIS algorithm bases its rain rates on non-linear regression between an 85 GHz scattering index and operational radar measurements (Ferraro et al., 1994; Ferraro and Marks, 1995). The radar data used in the algorithm's original validation study was obtained from three world-wide sites: the 22 platform Japanese Meteorological Agency AMeDAS system; the 14 platform U.K. Meteorological Office FRONTIERS system; and the 13 platform U.S. National Weather Service RADAP-II system.

Similar in nature to the Cal/Val algorithm, the NESDIS algorithm separates land and ocean areas. An 85 GHz scattering based algorithm is used over land, and a combined 85 GHz scattering and 19/37 GHz emission based algorithm is used over the ocean. While older versions of the algorithm only dealt with scattering due to the ice content of a cloud, the newest version handles tropical precipitation much more accurately. Since many tropical precipitation systems have little to no ice embedded in the clouds, an emission component is employed over the oceans to accurately portray precipitation where no ice-scattering signature is present. If rain is not first detected using the NESDIS ocean-based scattering index threshold of 10 K, a liquid water emission technique is applied. In this technique, additional rain retrievals are made using the 19 and 37 GHz components of the cloud liquid water algorithm of Weng and Grody (1994). The net result is an extremely accurate estimation of both tropical and middle-latitude rain rates. Figure 2 depicts a flow chart of the NESDIS algorithm.

4. Overview of the GPROF 4.0 SSM/I algorithm

While the Cal/Val and NESDIS SSM/I rain rate algorithms can be categorized as statistical rain maps, the GPROF 4.0 SSM/I rain rate algorithm can be described as a physical profile algorithm. In general, physical profile algorithms retrieve the vertical structure of various hydrometeor categories. GPROF stands for "Goddard Profiling"-algorithm. The algorithm version used for this study is identified as GPROF 4.0 for SSM/I. It must be referred to in such a specific manner because separate versions of the GPROF algorithm exist for use in the Tropical Rainfall Measuring Mission (TRMM). In fact, GPROF 4.0 for SSM/I was originally developed in anticipation of its adaptation to the future, operational applications of TRMM.

The GPROF algorithm is more complex than the two algorithms highlighted earlier in this article. GPROF 4.0 "profiles" the relationship between raindrops and radiation through the

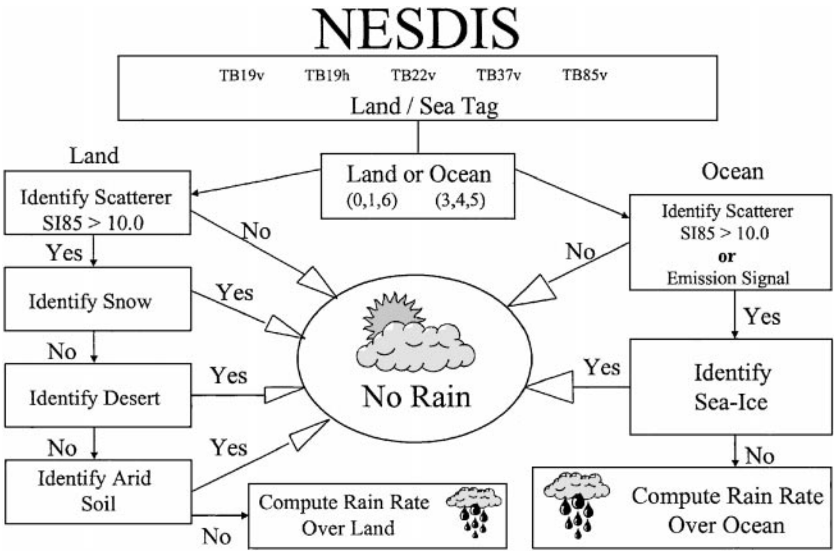

Fig. 2. NESDIS SSM/I rain rate algorithm flow chart, adapted from Ferraro (1997)

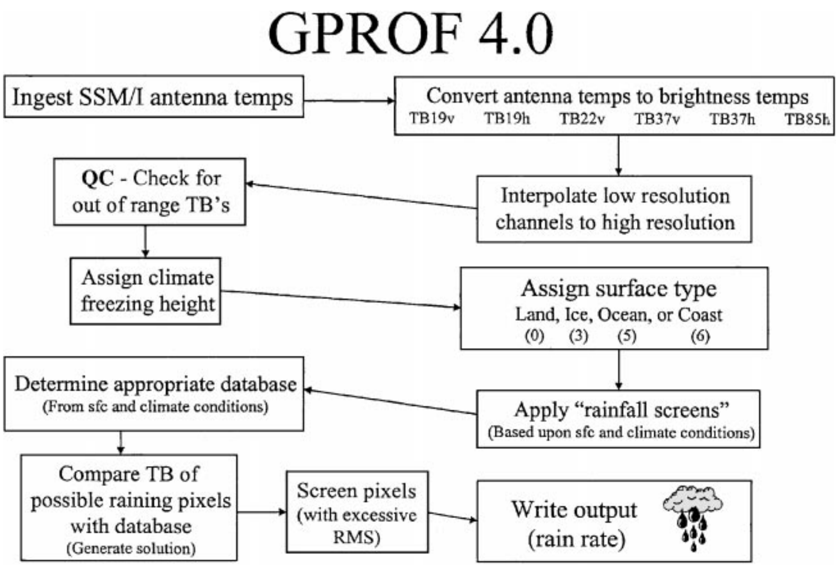

Fig. 3. GPROF 4.0 SSM/I rain rate algorithm flow chart, adapted from Kummerow et al. (1996)

variation of an assumed rain structure, which serves to minimize the difference between the observed and modeled radiances (Kummerow et al., 1996). A "retrieval method" is utilized to compare calculated parameters to the set of SSM/I sensor observations. Various radiative transfer equations and the Goddard Cumulus Ensemble model create a large database of atmospheric profiles and associated brightness temperatures. These modeled brightness temperatures are compared to the set of observed SSM/I brightness temperatures, and a minimum variance solution is obtained. Based on the deviation(s) from the observed SSM/I brightness temperatures, a probability density function is used to obtain weighted rainfall profiles. This probability density function is an extension of Bayes theorem. The final result is a rainfall solution profile based upon the weighted database profiles. Figure 3 depicts a highly simplified flow chart of the GPROF 4.0 SSM/I algorithm.

5. Overview of the TRMM/TMI-2A12 algorithm

As previously written in section 4, the GPROF 4.0 SSM/I rain rate algorithm was originally developed in anticipation of its adaptation to the future, operational applications of TRMM. Now that TRMM is operational, the original GPROF 4.0 SSM/I rain rate algorithm (with minor modifications) is indeed being used to calculate rain rates from the TRMM microwave imager (TMI) raw brightness temperature data. This modified GPROF algorithm is known as TMI-2A12.

It is important to assert that TRMM based rain rates used within this research were measured solely by the TMI. Rain rate data from other TRMM instruments, such as the TRMM precipitation radar (PR), was not used in order to maintain similarities between TRMM and SSM/I rain rate estimations. The TRMM microwave imager (TMI) is a nine-channel, passive radiometer based upon the SSM/I. According to Kummerow et al. (1998), two main differences exist between the TMI and the SSM/I. First, the TMI benefits from the addition of a pair of 10.7 GHz channels (both horizontal and vertical polarizations). Second, the TMI changes the frequency of the water vapor channel from 22.235 GHz to 21.3 GHz. Kummerow et al. (1998) states that this adjustment off the center of the water vapor "line" was made in order to avoid saturation in the tropical orbit of TRMM. While increased spatial resolution is characteristic of TMI versus SSM/I, this is not due to the sensor changes described above. It is due to the lower earth orbit of the TRMM satellite.

One would expect GPROF and TMI-2A12 estimated rain rates to be relatively similar in magnitude. Surprisingly, this is not necessarily the case. This research has concluded that notable differences exist. It is difficult to determine, however, if the differences are solely a function of the additional TRMM microwave frequencies. The differences between GPROF and TMI-2A12 rain rates may be the result of recent, more significant modifications to the TMI-2A12 algorithm which are currently unknown to the author.

6. Rain rate algorithm validation

Global rain rate averages were computed for daily rain totals calculated by the Cal/Val, NESDIS, and GPROF 4.0 algorithms. A cosine weighted average of the latitudes was incorporated to account for the curvature of the earth. Based upon 84 days of calculated rain rates from June 16th, 1998, to November 5th, 1998, the mean global rain rate average for the Cal/Val algorithm proved to be 1.89 mm/day. As expected, the NESDIS algorithm produced a higher mean global rain rate average of 2.44 mm/day. In addition, the GPROF 4.0 algorithm produced a mean global rain rate average of 2.51 mm/day. A global rain rate average was not computed for the TMI-2A12 rain rate algorithm since TRMM does not provide global coverage.

The meteorology research community commonly accepts global rain rate averages between 2 to 3 mm/day to be valid. More specifically, Manabe et al. (1965) states that the global precipitation mean is approximately 1 meter per year, which converts to 2.74 mm/day. It must be noted that both the NESDIS and GPROF 4.0 global rain rate averages computed in this study are in accordance with the global mean of 2 to 3 mm/day. The Cal/Val mean global rain rate average, however, is significantly lower.

6.1 Hurricane Mitch

Hurricane Mitch has been described as the strongest hurricane to plague the Atlantic basin and the first to reach category 5 on the Saffir/Simpson scale in the past decade. Due to the massive destruction caused by Hurricane Mitch, very few surface rainfall measurements from the Honduran mainland survived the flooding and mudslides. The only reliable, published rainfall observations can be credited to Mr. Jon Hellin of the United Kingdom, who spent time in Honduras working on his Ph.D. in soil and water conservation in association with the Corporacion Hondurena de Desarrollo Forestal. Mr. Hellin's study site was approximately 11 km from Choluteca (87 deg 04 min West, 13 deg 17 min North, 100 m altitude).

Despite the fact that his study site was destroyed by heavy rains, Mr. Hellin published rainfall measuremnts from October 28th through November 3rd, 1998. The total amount of rain for this period was an astonishing 933 mm. Figure 4 shows the Cal/Val, NESDIS, GPROF, and TMI-2A12 estimated rain rates for October 29th, 1998, for the Honduran mainland. For this validation study, Jon Hellin's rain totals were summed for the 24 hour period from 00Z to 00Z on October 29th.

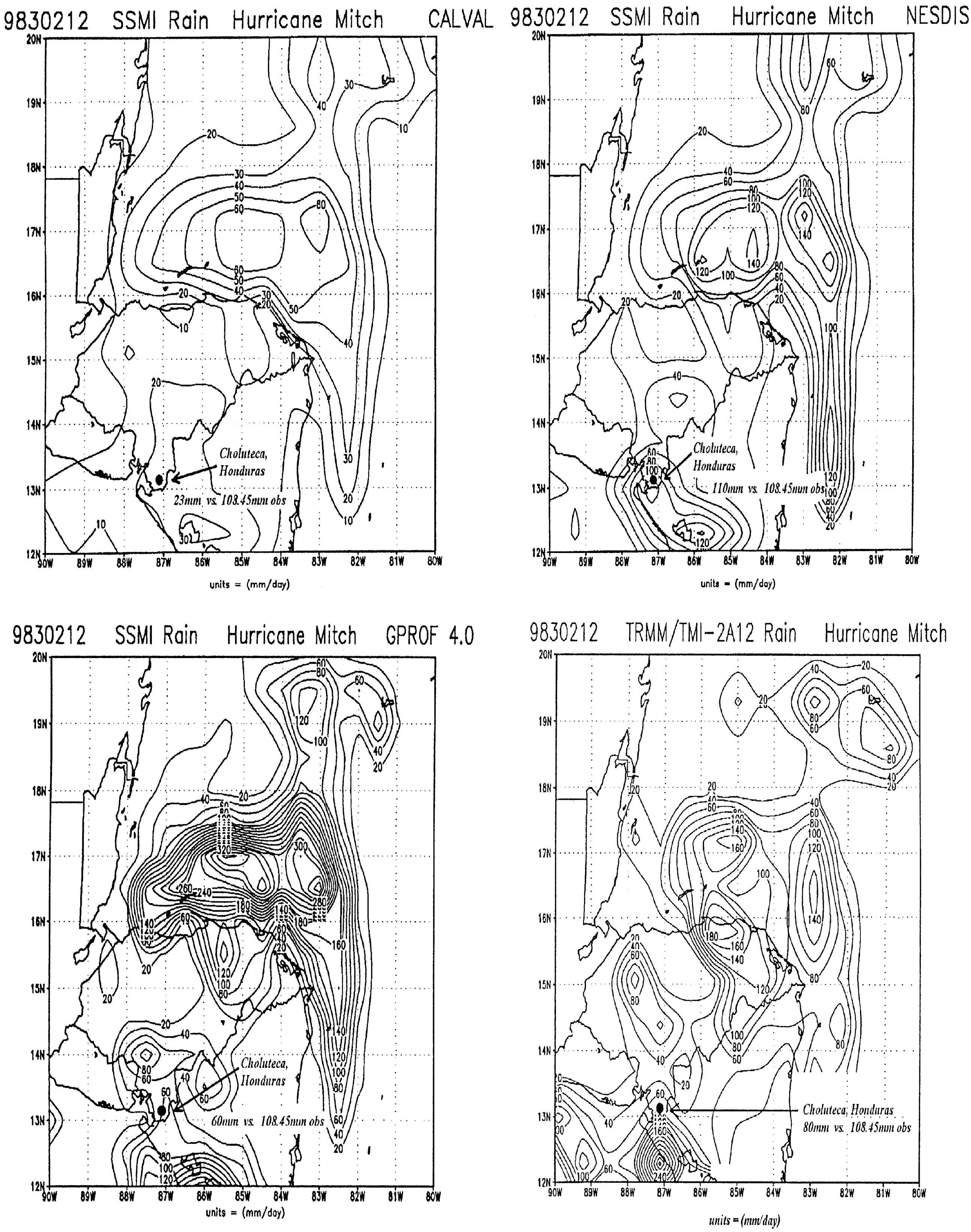

Fig. 4. Surface rainfall estimations from four different rain rate algorithms for Hurricane Mitch. (T170 resolution)

It is apparent from Fig. 4 that the Cal/Val SSM/I rain rate algorithm grossly underestimates the observed, 24 hour rain total of 108.45 mm, producing only a 23 mm estimate. On the other hand, the NESDIS algorithm does a much better job of portraying the intense convection in southern Honduras. The NESDIS rain rate algorithm estimates 110 mm of rain reached the ground in the vicinity of Choluteca. This compares remarkably close to the official observation of 108.45 mm. The GPROF algorithm also depicts the convection in southern Honduras very well. However, the 60 mm of rain in the Choluteca vicinity underestimates the 108.45 mm observed value. Figure 4 also portrays the TMI-2A12 rain rate estimate. While not as accurate as the NESDIS SSM/I algorithm, the TMI-2A12 estimation of 80 mm is quite reasonable. Finally, a significant difference exists between the magnitude of oceanic rainfall calculated by the GPROF 4.0 and TMI-2A12 algorithms, despite the fact that both algorithms have a similar architecture. North of the Honduran coastline, oceanic rainfall is maximized at 340 mm using the GPROF algorithm, while the TMI-2A12 algorithm only calculates a 160 mm maximum for this same area.

6.2 Hurricane Georges

Hurricane Georges struck Puerto Rico and the surrounding islands of St. Thomas and St. Croix on September 21st–22nd, 1998. Figure 5 represents a two-day accumulation of rain rates as estimated by all four algorithms for Hurricane Georges. Official rain rate observation totals for the same 48 hour period are annotated on the figure. It is clear that the Cal/Val algorithm is performing poorly, with official rainfall observations being on the order of 125 mm greater than the estimation at all three observation stations. Moreover, the Cal/Val SSM/I algorithm completely fails to initialize *any* surface rain at St. Thomas, in comparison to the official observation of 124.75 mm at this island location.

Figure 5 also depicts NESDIS calculated rain rates for the same location(s) and period. A remarkable improvement in the SSM/I estimated rain rates is evident when comparing the NESDIS result to the Cal/Val product. Only a 25 mm differential exists between the observed and SSM/I at St. Thomas. In addition, only a 21 mm differential is evident at San Juan. While not as low as the Cal/Val based rain rates, the GPROF based and TMI-2A12 based rain rates also underestimate the official observations. However, both algorithms provide robust oceanic rain rates south of St. Croix and southwest of Puerto Rico.

7. Hurricane forecasts

The FSU GSM is a high resolution, multi-level global spectral model based on primitive meteorological equations. All FSU GSM forecast experiments highlighted in this research began with the use of SSM/I or TRMM rain rate data to physically initialize the model environment. A horizontal resolution of triangular truncation T-170 and 14 vertical sigma levels were used to generate the model output. No more than two nodes of an IBM SP2 were tasked to generate the forecasts. Storms were individually bogussed and merged into the global dataset. Forecasts began three and two days prior to potential landfall.

Great circle distance calculations were performed for each of the hurricane track forecasts. Great circle distance measures the average deviation of each six hourly *forecast* storm position from each official, six hourly *observed* "best track" storm position published by the National Hurricane Center (Tropical Prediction Center) according to

$$\sqrt{(lat - lato)^2 + [(lon - lono) \cdot \cos(0.5(lat + lato))]^2}, \tag{1}$$

where *lat* and *lon* refer to the *forecast* storm position at each six hourly interval and *lato* and *lono* refer to the *observed* "best track" storm position at each six hourly interval in a 72 or 48 hour duration. Great circle distance measures how far away, on the average, each forecast latitude/longitude storm position is from the observed latitude/longitude storm position at *each* six hourly interval in the forecast. The cosine term in Eq. (1) accounts for the curvature of the earth's surface.

The following subsections focus on four hurricanes from the 1998 Atlantic hurricane season: Hurricanes Bonnie, Danielle, Georges, and Mitch. *Separate* model runs were initiated

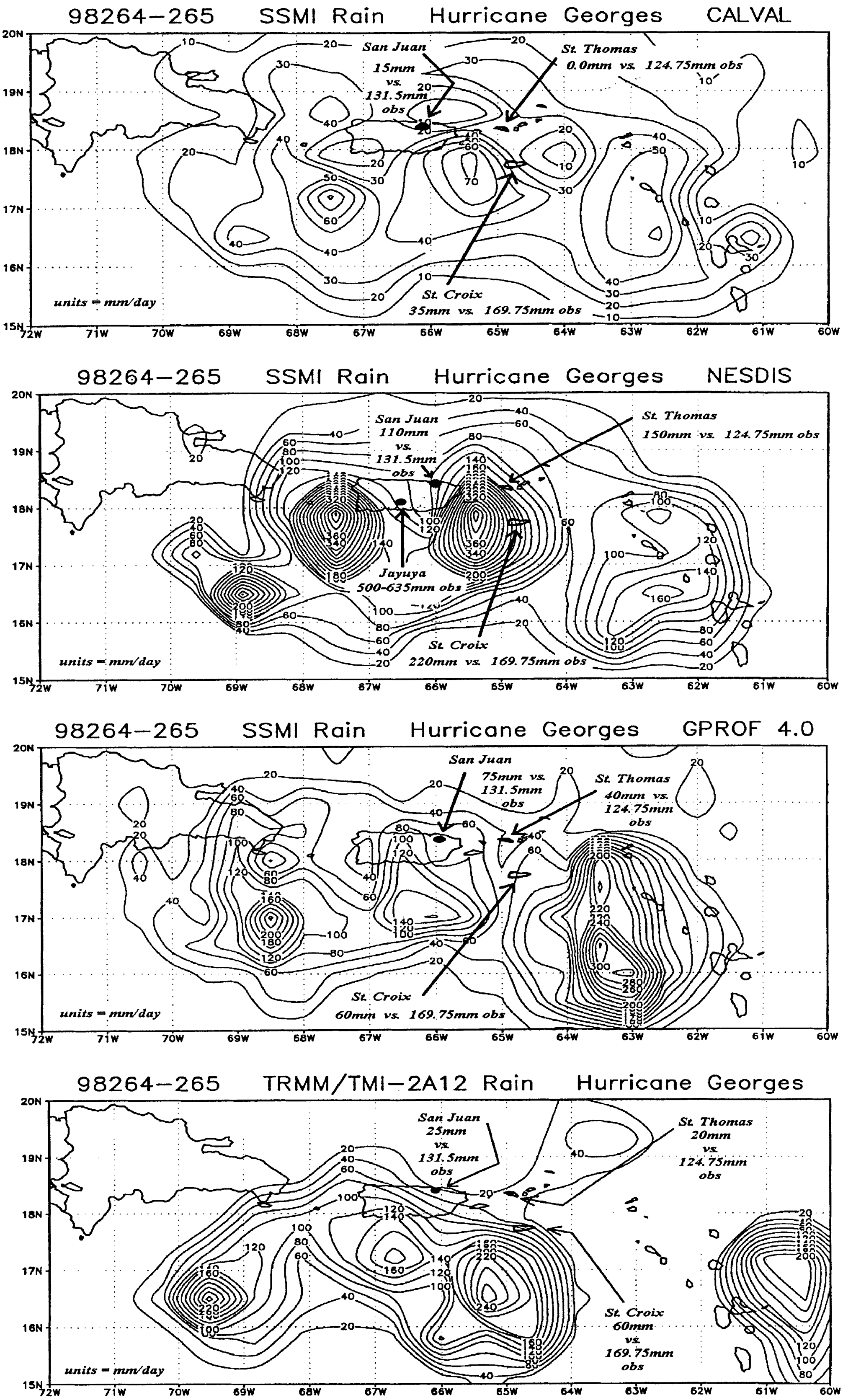

Fig. 5. Surface rainfall estimations from four different rain rate algorithms for Hurricane Georges. (T170 resolution)

using *each* of the Cal/Val, NESDIS, GPROF 4.0, and TMI-2A12 rain rates in the physical initialization of the model. All other model parameters remained consistent for each run. Due to the fact that the TRMM satellite does not provide global coverage, NESDIS SSM/I rain rate data was inserted into all grid points on the globe where TRMM/TMI data was not available. This is referred to in the following figure legends as *TRMM/NESDIS Blend*. This blended set of rain rate data provides mostly TMI-2A12 estimated rain rates for the tropics, and NESDIS SSM/I estimated rain rates for the middle and upper latitudes. While this blended dataset technique is still in its experimental stages, it provides a reasonable solution to the lack of global TRMM coverage.

7.1 Hurricane Bonnie

After a long trek across the Atlantic Ocean, Hurricane Bonnie maintained a northwesterly course toward North Carolina during the two days preceding landfall at Cape Fear. Figure 6 depicts four separate FSU GSM track forecasts for Hurricane Bonnie using either the Cal/Val, NESDIS, GPROF 4.0, or TMI-2A12 rain rates as input to the physical initialization of the model.

At first inspection, all four forecast tracks look reasonable. However, closer inspection reveals the Cal/Val based experiment predicts the center of the storm will recurve east of the North Carolina coast. Moreover, the GPROF based experiment severely underestimates the northerly progress of Hurricane Bonnie, especially during the last 24 hours of the forecast period. Similar to the Cal/Val based track, the TRMM based experiment predicts exaggerated recurvature, completely missing the coast. The NESDIS based model run is the *only* forecast which predicts landfall.

7.2 Hurricane Danielle (3 day forecast)

Hurricane Danielle progressed on a west to northwest course from its point of origin until it experienced recurvature on August 31st, 1998, only 523 kilometers east of Cape Canaveral, Florida. Figure 7 portrays a three day storm track forecast for Hurricane Danielle, beginning on August 29th, 1998. All three SSM/I based

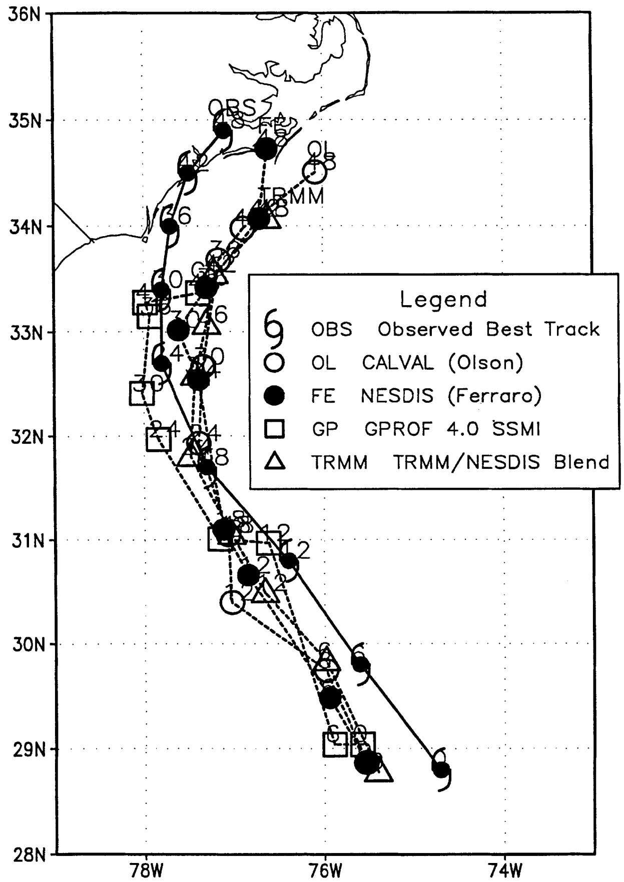

Fig. 6. Hurricane Bonnie: 48 hour track forecast(s) using four different rain rate algorithms to physically initialize the FSU GSM

forecasts perform quite well in predicting the recurvature of Danielle 48 hours into the period. Moreover, the forecast timing of the three SSM/I based experiments closely resembles the observed movement of the storm. On the other hand, the TRMM based forecast shows significant deviation from the observed track in the last 24 hours of prediction. In general, the Cal/Val and GPROF experiments exhibit some track fluctuation. The NESDIS based experiment, on the other hand, provides the most accurate forecast with the least amount of track fluctuation or deviation.

7.3 Hurricane Danielle (2 day forecast)

A second experiment of Hurricane Danielle was conducted, only this time the forecasts began 24 hours later. In addition, the forecast period was only 48 hours in duration. Figure 8 portrays the two day track forecast for Hurricane Danielle,

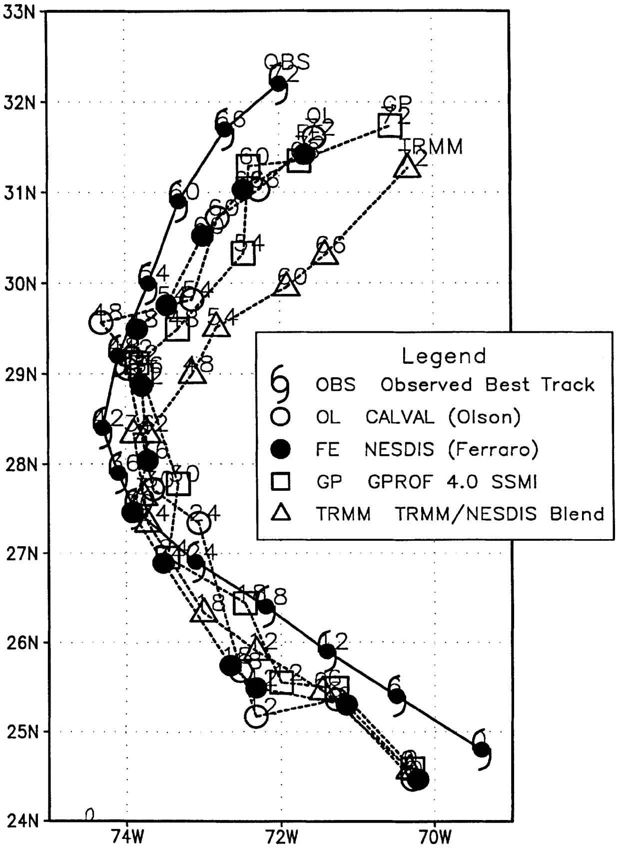

Fig. 7. Hurricane Danielle: 72 hour track forecast(s) using four different rain rate algorithms to physically initialize the FSU GSM

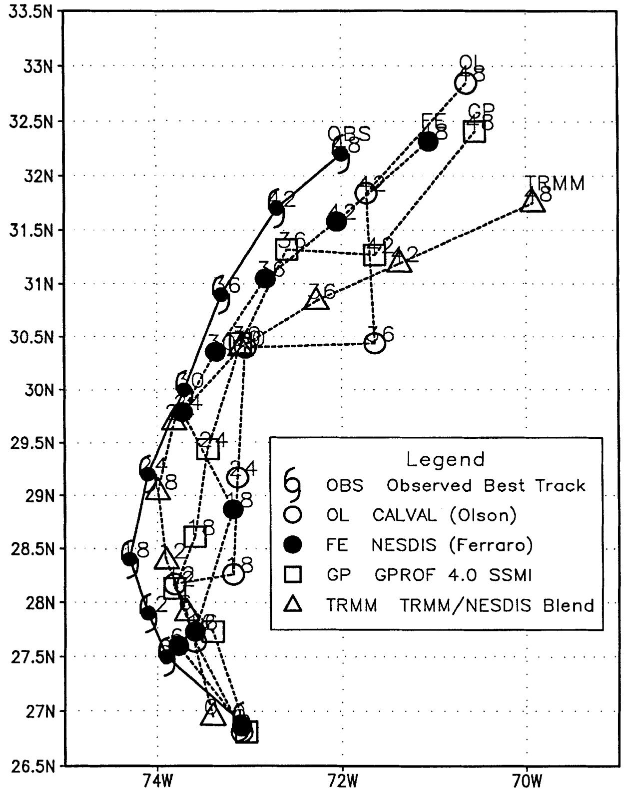

Fig. 8. Hurricane Danielle: 48 hour track forecast(s) using four different rain rate algorithms to physically initialize the FSU GSM

beginning at 12Z on August 30th. While all four forecasts deviate significantly from the observed "best track" in the beginning, the NESDIS based storm track follows a very similar recurvature pattern (after 24 hours) as the observed track. Once again the TRMM based track shows the greatest deviation at the end of 48 hours. While the Cal/Val and GPROF forecasts exhibit unusually large longitudinal fluctuations, the NESDIS based experiment provides the smoothest and most accurate storm track.

7.4 Hurricane Georges

After crossing the Florida Keys, Hurricane Georges initiated a northwesterly course toward the U.S. Gulf Coast States of Louisiana and Mississippi. A weak trough developing in the central United States presented the possibility that Hurricane Georges might recurve into the Florida Panhandle. However, as most of the model guidance suggested, Georges made land-

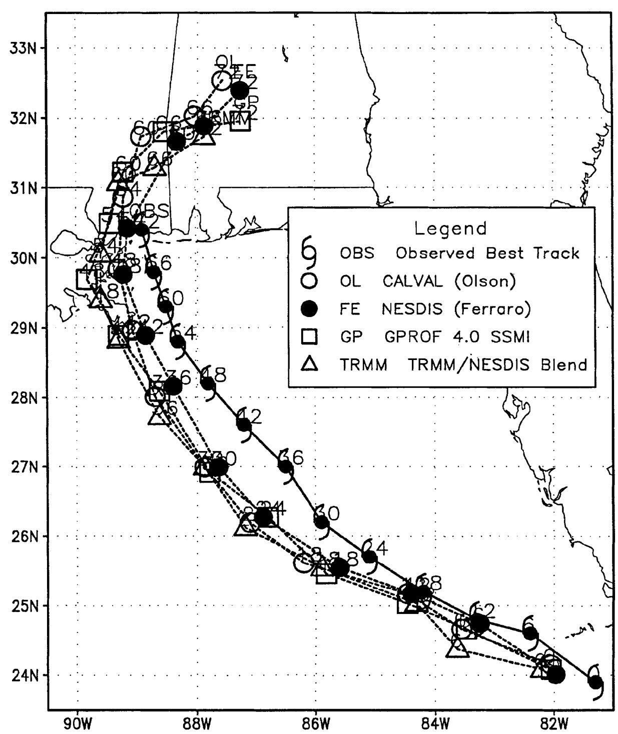

Fig. 9. Hurricane Georges: 72 hour track forecast(s) using four different rain rate algorithms to physically initialize the FSU GSM

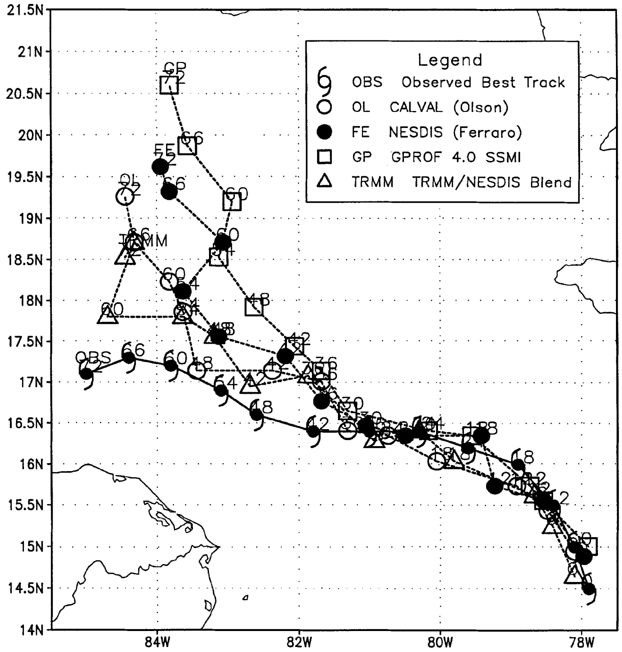

Fig. 10. Hurricane Mitch: 72 hour track forecast(s) using four different rain rate algorithms to physically initialize the FSU GSM

fall near Gulfport, Mississippi, on the 28th of September.

Figure 9 shows the three day storm track forecast(s) for Hurricane Georges, beginning on September 25th, 1998. The figure reflects that the four experiments do not predict Georges' stall prior to reaching Gulfport. However, the NESDIS experiment predicts a track closest to the observed "best track", most notably from 30 to 54 hours into the forecast period.

7.5 Hurricane Mitch

Hurricane Mitch proved to be a prime example of the limits of numerical weather prediction. While most of the model guidance predicted that Mitch would continue its northwesterly movement toward the Yucatan Peninsula, the storm stalled just north of the Honduran coast. After 24 hours, Hurricane Mitch reversed direction and assumed a slow drift to the south, ultimately moving inland over Honduras.

Figure 10 highlights the fact that all three SSM/I based, FSU GSM forecasts did not predict Mitch's unusual drift toward Honduras. After 48 hours into the forecast, all three SSM/I track predictions show rapid acceleration to the northwest. On the other hand, the TRMM based forecast is the only experiment which predicts storm movement to the west after the 48 hour interval.

8. Conclusion

In the past four decades, numerical weather prediction has produced remarkable improvements in forecast skill and accuracy. However, this development did not occur overnight. Throughout the short history of NWP, continuous, small advances have contributed to overall prediction improvements. In other words, current hurricane prediction skill is directly linked to smaller steps in the past. The research highlighted in this article is a prime example of one of those steps.

This study has demonstrated notable improvements in the FSU GSM's hurricane prediction capability. By introducing more credible SSM/I and TRMM/TMI rain rate algorithms into the physical initialization of the model, advances in the prediction of hurricane tracks have been achieved. Table 1 depicts a compilation of forecast track deviations (Great Circle Distance) for all four hurricanes highlighted in this paper. Track deviations for all four storms were averaged (at each 12 hour forecast interval) for each of the rain rate algorithms. A *total* track deviation average was computed for each rain rate algorithm. This value(s) encompasses the

Table 1. Average forecast track deviations for a total of four hurricanes and seven different experiments. Units = kilometers

Hours of Prediction	12	24	36	48	60	72	*total*
Cal/Val (Olson)	61.29	84.09	95.73	106.16	122.96	133.79	100.67
NESDIS(Ferraro)	52.80	73.17	78.91	91.19	115.36	129.83	90.21
GPROF 4.0	62.71	74.29	89.96	107.55	126.61	141.80	100.49
TRMM/NESDIS Blend	60.95	76.87	86.61	103.56	120.60	135.07	97.28

average of all six time increments for all four hurricanes studied, from a total of seven separate experiments (two additional experiments were not presented in this article, but are included in the final calculations).

As Table 1 indicates, the NESDIS SSM/I rain rate algorithm is best suited for use in the physical initialization of the FSU GSM. When compared to the rain rate algorithm (Cal/Val) which had been previously used for real-time, operational hurricane forecasts, *experiments utilizing the NESDIS algorithm have demonstrated an overall 10.46 km forecast track deviation improvement.* As a direct result of this study, the Florida State University Real-Time Hurricane Forecast Center (FSU RTHFC) has retired the Cal/Val rain rate algorithm in favor of the NESDIS algorithm.

Finally, with the exception of the forecast track of Hurricane Mitch, no overall prediction improvement was achieved in this research by using TRMM/TMI rain rate data. This is most likely a result of the following two factors. First, the TMI-2A12 rain rate algorithm is in need of modification. Future, updated versions of the algorithm will hopefully provide more consistent rain rate estimations. Second, the TRMM/NESDIS blended data set needs further work to prevent possible asymmetries in the global rain rate field. While highly accurate, NESDIS calculated rain rate values were used in place of the missing TRMM data, this method still requires modification. The FSU GSM requires a complete, *global* rain rate field for proper physical initialization. A different method must be developed which incorporates TRMM rain rates and also completes the initial, global rain rate field. This will be the subject of further hurricane prediction research at the Florida State University.

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