

Impact of CAMEX-4 Data Sets for Hurricane Forecasts using a Global Model

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Abstract

This study explores the impact on hurricane data assimilation and forecasts from the use of dropsondes and remote-sensed moisture profiles from the airborne Lidar Atmospheric Sensing Experiment (LASE) system. We show that the use of these additional data sets, above those from the conventional world weather watch, has a positive impact on hurricane predictions. The forecast tracks and intensity from the experiments show a marked improvement compared to the control experiment where such data sets were excluded. A study of the moisture budget in these hurricanes showed enhanced evaporation and precipitation over the storm area. This resulted in these data sets making a large impact on the estimate of mass convergence and moisture fluxes, which were much smaller in the control runs. Overall this study points to the importance of high vertical resolution humidity data sets for improved model results. We note that the forecast impact from the moisture profiling data sets for some of the storms is even larger than the impact from the use of dropwindsonde based winds.

1. Introduction

A dominant factor for the improvement of weather forecasts is the quality and space-time distribution of atmospheric measurements. The spatial distribution of in-situ atmospheric measurements is highly inhomogeneous, largely being confined to Northern Hemisphere continents, shipping routes at the surface, and a limited set of commercial airways confined to a rather narrow range of altitudes and routes between major cities. Data-sparse regions include much of the Tropics, the Southern Hemisphere, the Arctic, and much of the oceanic regions, at least between the surface and commercial flight altitudes. The recent inclusion of space and ground based remote sensing data compensates to some degree for the lack of in-situ measurements. Satellite observations now cover the entire globe, and are relatively frequent in time. Space-based remote sensing has the advantage of yielding relatively good coverage of measurements with high temporal and horizontal resolutions.

Numerical weather prediction requires an accurate representation of the initial state of the atmosphere. An error in the analysis of the initial state can amplify through the modeling process and result in drastic errors in the predicted state. This is especially true in the case of hurricanes and tropical storms. If the initial vortex is not well defined because of lack of data, models may fail to predict the track and intensity of the storm.

Many field experiments (viz., STORM-FEST, FASTEX, WSR) have been conducted and forthcoming experiments (viz., THORPEX) are to be carried out to enhance the database over oceanic regions. The National Oceanic and Atmospheric Administration's (NOAA) Hurricane Research Division (HRD) and its predecessors recognized that oceanic field experiments were necessary back in the 1970's, and they have been conducting annual field experiments in the Atlantic and Pacific since even before that time. The Storm Scale Operational and Research Meteorology Program Fronts Experiment Systems Test (STORM-FEST) field experiment was

conducted in the central United States between 1 February and 15 March 1992, and additional soundings were taken along the west coast on several occasions to assess their effect on forecasts downstream over the STORM-FEST area. This experiment was followed by the Front and Atlantic Storm Track Experiment (FASTEX) (Thorpe and Shapiro, 1995), which involved major operational forecast centers in an effort to improve operational numerical weather prediction. Many different platforms were used to collect special data sets for testing various proposed objective and subjective targeting strategies and for collecting data necessary for evaluating forecasts over the open ocean. Later it was noticed that hurricane field experiments were necessary over other oceanic regions adjacent to the United States; these regions are located off the west coast, the Gulf of Mexico and the Caribbean Sea (Burpee et al., 1982; Simpson, 2003).

Recent sensitivity experiments on the observing network in the context of modern data assimilation methods have indicated that the impact of data strongly depends on the location of the data relative to dynamically sensitive parts of the flow. These sensitivity experiments identify an important component to a successful sampling strategy, i.e., the identification of areas in which initial condition errors are likely to amplify rapidly (owing to some dynamical instability). Areas in which the initial condition errors are likely to be both large and rapidly growing would be preferred areas to obtain supplementary observations. However, the recent work by Abernethy (2002, 2003) on hurricane targeting revealed that the way the targets are sampled is the most important issue to be addressed. Studies by Graham (1990), Heming (1990), Pailleux (1990), Rabier et al. (1996), Pu et al. (1997a) and Lord (1996) contain good examples of definite positive impacts due to very few additional vertical profiles.

Sensitivity tests at the U.K. Meteorological Office (UKMO) (Graham and Anderson, 1995) and the National Centers for Environmental Prediction (NCEP) (Lord, 1993) have demonstrated that improved wind observations have the greatest positive effect on one- to three-

day forecasts. Also, accurate dropsonde wind measurements in the vicinity of western Atlantic and Caribbean hurricanes have markedly improved landfall predictions (Franklin and DeMaria, 1992). Certain specific forecast problems have been linked to lack of observations in most of the regions. One example is hurricane track and intensity forecasting, which is one of the most important forecast problems. Franklin and DeMaria (1992) and Burpee et al. (1996) showed that dropwindsonde data collected by research aircraft demonstrably led to improved track forecasts, which shows the importance of direct measurements in otherwise data-sparse regions.

Special reconnaissance aircraft operated by NOAA and by the U. S. Air Force continue to provide valuable information for the prediction of hurricanes and severe winter storms. Quantitative assessments of hurricane forecast improvements from including dropwindsonde data from reconnaissance aircraft may be found in Burpee et al. (1996). Heming (1990) discussed the impact of surface and radiosonde observations from two Atlantic ships on a storm forecast. Smith and Benjamin (1993) demonstrated the benefits of wind data assimilation on short-range forecasts in the eastern half of the United States. Recently Qu and Heming (2002) discussed the impact of dropsonde data on forecasts of Hurricane Debby by the U.K. meteorology office unified model.

The Convection and Moisture Experiment (CAMEX) consists of a series of field experiments sponsored by the National Aeronautics and Space Administration (NASA). The first two CAMEX field studies were conducted from Wallops Island, Virginia, during 1993 and 1995, and a third field study (CAMEX-3), which was specifically designed for hurricane studies, was conducted from Patrick Air Force Base near Cocoa Beach, Florida, between 3 August to 28 September 1998. Recently, a fourth field campaign in the CAMEX series (CAMEX-4) was conducted from 16 August to 24 September 2001 from a base at the Jacksonville Naval Air Station, Florida. This field experiment was conducted in collaboration with the National

Oceanic and Atmospheric Administration's (NOAA) Hurricane Research Division (HRD) and the United States Weather Research Program (USWRP). CAMEX-4 was focused on the study of tropical cyclone (hurricane) development, tracking, intensification, and landfalling impacts using NASA-funded aircraft and surface remote sensing instrumentation. One of the main objectives of CAMEX is focused on studies of atmospheric water vapor and precipitation processes using an array of airborne, space and land-based remote sensors. Our previous studies showed promising impacts on hurricane forecasts using several CAMEX campaign data sets (Bensman, 2000 and Rizvi et al., 2002). These studies provided the opportunity to address some of the model failures in hurricane predictions.

In the present paper we have made an attempt to analyze the available CAMEX-4 data sets using a three-dimensional variational analysis scheme (3DVAR). Medium range hurricane predictions were carried out by integrating the NWP model out to 5 days with these new initial conditions. This study was done using the FSU global spectral model. This paper is organized as follows. Section 2 describes the CAMEX-4 data sets and the experimental plan using these new data sets. Details of the analysis scheme and forecast model are provided in Section 3. The numerical results are discussed in Section 4. Concluding remarks are provided in Section 5.

2. CAMEX-4 Data Sets

During CAMEX-3 and CAMEX-4, numerous observations were collected at various stages of hurricane development. During the CAMEX-3 campaign, the observations were targeted using an adaptive observational strategy based on a technique recently developed by Zhang and Krishnamurti (1999). NASA's ER-2 and DC-8, NOAA's Gulfstream-IV (G-IV) and WP-3D, and the US Air Forces's WC-130 weather reconnaissance aircraft were available during this campaign.

a. Dropsonde

One of the NASA aircraft (DC-8) provided a high altitude research platform for a variety of remote sensors, dropsondes and microphysical measurements in the inner core of the storm, while another NASA aircraft, the ER-2, provided in situ data over the lower stratosphere, and remotely sensed measurements through the troposphere. The flight altitude of the DC-8 was generally from 30,000 to 40,000 ft and the ER-2 was at nearly 65,000 ft. Two NOAA P-3s were used for both hurricane research and reconnaissance. The P-3s penetrated the eyewall repeatedly at altitudes from 1,500 to 20,000 ft. The NOAA G-IV was used to derive a detailed picture of the upper atmosphere surrounding the hurricanes as well as to provide dropwindsonde measurements. It provided measurements of the upper level hurricane steering winds that are important for determining the track of a hurricane. The G-IV flew between 350 and 1500 km from the eye of the hurricane and at altitudes up to 45,000 ft. The US Air Force's WC-130 reported hurricane conditions through a combination of visual observations and onboard in situ instruments. Our data assimilation includes these data sets at about 3-minute intervals. The assignment of error for this analysis assumes that these measurements are of the same quality as data sets from commercial aircraft. Further details of these instruments can be found on the CAMEX-4 website (<http://camex.msfc.nasa.gov>).

This mission was designed to collect, process and transmit analyses of vertical atmospheric soundings in the environment of a hurricane. Dropsondes provide invaluable information about winds in the mid-level hurricane vortex and also the vertical temperature distribution within the eye. The dropsonde system uses Global Positioning System (GPS) dropwindsondes to measure vertical profiles of pressure, temperature, humidity and wind during descent to the surface. These data were measured every 0.5 s (2 Hz) during the descent. The Airborne Vertical Atmospheric Profiling System (AVAPS) was used for monitoring the

dropsondes from the operational and research aircraft. Additional information on the GPS dropwindsondes can be found in Hock and Franklin [1999]. During this campaign, up to 150 dropsondes were deployed from both the NASA DC-8 and ER-2, and nearly 70 of those were dropped on the last three days of the experiment.

Figure 1 shows the sample dropsonde data coverage at various levels from multiple aircraft on 23 September 2001 in conjunction with study of Hurricane Humberto. The bottom panel of Fig. 1 shows the coverage at lower levels (850 hPa); the middle panel shows the coverage at middle levels (500 hPa); and the top panel shows the upper level (200 hPa) coverage. On this day, the G-IV aircraft covered the large-scale environment of the hurricane and the other aircraft covered the eye and inner region. The upper level data were provided by the DC-8, ER-2 and G-IV. The low level cyclonic and the upper level anticyclonic patterns can be clearly seen in the wind data. This intensive data coverage was a highlight of the CAMEX experiments.

b. LASE (Lidar Atmospheric Sensing Experiment)

The LASE instrument was developed at the NASA Langley Research Center as the first autonomously operating Differential Absorption Lidar (DIAL) system, and it was initially flown on the NASA ER-2 aircraft for profiling water vapor, aerosols and clouds through the entire troposphere (Browell et al., 1995, 1997; Moore et al., 1997). The accuracy of the LASE water vapor profile measurements was first demonstrated in the 1995 LASE Validation Experiment where comparisons of the LASE water vapor measurements with in situ water vapor measurements on two additional aircraft (C-130 and Lear Jet), radiosonde profiles, and profiles from a ground-based Raman lidar showed agreement to be better than 6% or 0.01 g/kg, whichever is greater throughout the troposphere (Browell et al., 1997). Subsequently LASE was flown on the ER-2 during the Tropospheric Aerosol Radiative Forcing Observation Experiment (Ismail et al., 2000; Ferrare et al., 2000a,b) and in seven other major field experiments onboard

the NASA P-3 and DC-8 aircraft. Intercomparisons performed during the CAMEX-3 (Ferrare et al., 1999; Browell et al., 2000), Pacific Exploratory Mission (PEM) Tropics B (Browell et al., 2001), and CAMEX-4 (Kooi et al., 2002) missions produced results consistent with the initial LASE validation experiments.

The impact of including LASE data in the hurricane analysis compared to the ECMWF (European Centre for Medium-Range Weather Forecasts) analysis without LASE data was recently described by Kamineni et al. (2003). The result of combining the LASE and dropsonde data in hurricane analysis is described in this study.

c. Design of Experiments

A special dataset on 0.5 degree latitude by 0.5 degree longitude at 28 vertical levels without inclusion of dropwindsonde data has been provided to us by ECMWF. We have used these data in our analysis. This analysis also included operational global sets from the stream of the world weather watch, cloud track winds, commercial aircraft winds reports, surface data sets from marine ships of opportunity, oceanic buoy surface reports, ocean surface winds from satellite based scatterometers, sounding of temperature and humidity from polar orbiting satellites. The microwave radiances provided by TRMM (Tropical rainfall Measuring Mission) and DMSP (Defense Meteorological Satellite Program) satellites (F13, F14 and F15) provide rain rate estimates via NASA Goddard algorithms (Olson et al. 1990). The Florida State University (FSU) model at a T126 resolution makes use of these data to perform a physical initialization (Krishnamurti et al., 1991). The T126 resolution of the FSU model was noted to be adequate for exploring the extent to which the larger scale hurricane was resolved by the aircraft data sets. Our definition of a first control (CTRL) forecasts includes the ECMWF plus rain rate estimates in its initial state at the T126 resolution. Subsequent to that we generated another control run (CTRL1), where all the available winds (flight level plus dropsonde winds) using

CTRL as background were assimilated. This is the NEW control run which is now being used as background field for all other experiments. Here we have used both the dropsonde and the flight level data, since our aim is to utilize more and more wind information to define the hurricane structure. However, the experiments were designed mainly to focus on the impact of water vapor measurements (either dropsonde or LASE), which is a goal of our study. The objective of this analysis is to forecast the broad scale evolution of hurricanes.

Dropwindsonde data from the six aircraft (two NOAA P-3's, US Air Force C-130, NASA ER-2 and DC-8, and NOAA G-IV), flight level in situ data from the DC-8 and P-3 aircraft, and LASE water vapor profiles collected from the DC-8 aircraft were used in the following experiments:

CTRL: Control analysis at T126L14 (Triangularly truncated at 126 wave in horizontal and 14 sigma levels in vertical) by using ECMWF analysis at 0.5-deg resolution + FSU Physical Initialization.

CTRL1: CTRL + all the available wind data during CAMEX-4. It served as background field for the following experiments.

EXP1: CTRL1 + dropsonde moisture data sets

EXP2: CTRL1 + LASE data sets

EXP3: CTRL1 + dropsonde moisture + LASE data sets. This includes all of the available data sets.

3. Data Assimilation

A typical data assimilation system is composed of a forecast model that provides a background, first guess of the atmosphere by extrapolating information forward from previous observations, and an analysis that combines information from the background and from the entire

set of widely scattered observations into a model-compatible form for extrapolation to the next analysis time. Since data assimilation has observational, analysis and the modeling components, improvements in one or more of these components are expected to improve forecasts.

a. Analysis scheme

Analysis is a process by which various meteorological observations distributed in space and time from different observing systems are integrated with other information, like short range weather predictions (6 hours) from a NWP model, previous analysis, climatology etc., to form a numerical representation of the initial atmospheric state. CAMEX-4 data were analyzed using a three-dimensional variational analysis scheme which is mainly based on Lorenc's (1986) concept of minimizing a generalized cost function using the Spectral Statistical Interpolation (SSI) technique (Parrish & Derber 1992). The cost function used in this scheme is as follows.

$$J(X) = 1/2 [(X-X_b)^T B^{-1}(X-X_b) + (Y_{obs}-H(X))^T R^{-1}(Y_{obs}-H(X))] \quad (1)$$

Where, X = N -component vector of analysis variables; X_b = N -component vector of first guess variables; Y_{obs} = M -component vector of observations; B = $N \times N$ background error co-variance matrix; R = $M \times M$ observational error co-variance matrix; H = an operator from analysis to observation space (possibly non-linear); N = analysis degree of freedom; M = number of observations; and $()^T$ = transpose of the matrix.

The two terms in J on the right hand side of Eq. (1) deal with the fit of the first guess field and the observations with the desired analysis, respectively. In order that the analysis should fit best with both the first guess and the observations, J should be minimized with respect to the analysis variable X . The minimization is accomplished by using a standard conjugate gradient (CG) (Chandra, 1978) descent algorithm, which allows R to be non-linear.

$$\text{Let us define a variable } W \text{ as: } W = C^{-1}(X-X_b) \quad (2)$$

$$\text{The matrix } C, \text{ is related to the forecast errors and is given by } B = C C^T \quad (3)$$

Minimization of J leads to the following analysis equation: $A \delta = f$ (4)

Where $L (= \partial H / \partial X)$ is the tangent linear operator of the operator H ; $A = [I + C^T L^T R^{-1} L C]$; and $f = C^T L^T R^{-1} [Y_{\text{obs}} - H(X_b + C W)] - W$.

Using a perturbation technique, the solution of the analysis equation (4) is obtained for W . Finally the state vector X , which minimizes J , is determined using (2) and (3). The following iterative algorithm is used for solving the analysis equation.

Set $X = X_b$, $W = 0$

Do $k = 1, n$ outer (Outer iteration)

evaluate $f = C^T L^T R^{-1} [Y_{\text{obs}} - H(X_b + C W)] - W$

solve $A \delta = f$ using an iterative conjugate gradient algorithm (5)

$W = W + \delta$

$X = X + C \delta$

End do

Here one important thing to be noted is that the tangent linear operator is always evaluated with the latest X and the non-linearity in H , which results from the dependence of the sigma co-ordinates on the surface pressure, is not included in L . However, each time the vector f is evaluated, a complete H -operator is utilized.

Further details about the choice of the analysis variables, balance between the mass and the wind field, vertical coupling, the statistical parameters used, etc., are given in Parrish and Derber (1992), and Rizvi and Parrish (1995). The statistical parameters, like the background error covariance, Empirical Orthogonal Functions (EOF) for vorticity, divergence, temperature, moisture and various other statistical parameters defining the partitioning between the fast and the slow part of the flow, are computed using the difference between the day-1 forecasts and the corresponding verifying analysis for that date. A 40-day data set (August - September 1998) was

used to compute these statistics. The amplitudes and scales of the background errors have to be tuned to represent the (6-hr, 3-hr) forecast errors in the guess field. This is the reason for the tuning parameters mentioned above. The statistics that project multivariate relations among variable are also derived from the NCEP method.

b. Forecast model

The global model used in this study is identical in all respects to that used in Krishnamurti et al. (1991). This comprehensive model carries the spectral transform method with the semi-implicit time differencing scheme for the dynamics. An array of physical parameterization schemes are used for shallow and deep cumulus convection, dry convective adjustment, radiative transfer based on a band model for short and long wave radiances, surface fluxes, surface energy balance, definition of clouds for radiative transfer, and the use of the sigma coordinate surface for the treatment of orography. The relevant references on these model components are provided in Krishnamurti et al. (1991). The current horizontal resolution for the CAMEX studies is T126 and in vertical we use 14 layers. In addition to these features the model includes a physical initialization component based on Krishnamurti et al. (1991, 2001). The sequence of steps in our modeling starts with a special operational level-three analyzed data set from the ECMWF. This data set is received at FSU at a resolution of 0.5° latitude/ 0.5° longitude at 28 vertical levels. These data are interpolated to the FSU transform grid at the resolution T126. At this stage precipitation estimates based on microwave radiance data sets from TRMM-TMI (TRMM Microwave Imager) and DMSP-SSM/I (Special Sensor Microwave/Imager) satellites are used for the physical initialization that provides a nowcasting of the initial rain rate for the model. The proposed data assimilation that incorporates the additional data sets from the CAMEX-4 research aircraft (dropwindsonde, LASE and flight level) follows sequentially after the completion of physical initialization. The SST analysis for this modeling was obtained from

NOAA/NESDIS operational real time analysis files that were based on weekly averages (preceding the initial state for each storm) and included datasets from surface ships, buoys and satellite derived estimates.

Several techniques have been developed to assess the influence of new data sets for the analysis/forecast issues. In this study, the data-denial experiment (DDE) procedure was used to assess the impact of new data sets on hurricane analysis and forecasts. In this technique actual forecast/data assimilation cycles are re-run, selectively excluding actual observations, and the relative degradation or improvement noted. By examining many such cases, the effect of the exclusion of certain data sets can be assessed.

4. Numerical Results & Discussion

The outputs of the various experiments that were analyzed and the impacts on the hurricane forecasts are discussed in the following subsections.

a. Impact on hurricane track and intensity

In our sensitivity analysis of the forecasts to the assimilation of CAMEX-4 data sets, we primarily focused on some representative fields such as the mean sea level (MSL) pressure. Comparisons with the verifying ECMWF analysis and officially-issued best track from the National Hurricane Center (NHC) were also made. The various forecast tracks for Hurricanes Erin, Humberto and Gabrielle are presented in Fig. 2 (a, b and c). The legend in these figures distinguishes between the different model runs for each storm. Since the research aircraft flights were limited, generally only one complete set of experiments was possible for each of these storms. Although there were two complete missions flown for Humberto, only one data set is used here. For Erin and Gabrielle, the forecast track for the control run was generally in the approximate heading of the storms, moving northeastward, but was behind the actual storm position due to the erroneously slow translation speed. On the other hand, forecast tracks with

CAMEX-4 data sets were almost parallel to each other and followed the best track closely. However, the initial storm positions in the control and the experiments were very close to the best track position. In the case of Humberto, the forecast track of the control run showed the tendency of recurvature; however, the slow forecast speed increased the distance error substantially reaching 340 km at 72 hours forecast. Assimilation of the maximum amount of available data (EXP3) resulted in the smallest distance errors of 120 and 150 km at 72- and 96-hour forecasts, respectively.

Overall we note that, in general, there is a sequential improvement in track forecasts as more and more data sets were added. The best track forecasts, in general, were found when the flight level data, the dropsonde data (wind, and humidity) and the LASE moisture profiles were all incorporated within the data assimilation. These data sets were added to those of the control run which only included the ECMWF analysis. The addition of moisture data from all the distributed dropsondes improved the forecast errors well beyond what was possible from LASE data alone. This is due to the much larger coverage of moisture profiles from the 100 or so dropsondes from six aircraft. LASE provided moisture profiles from one aircraft (DC-8) and mainly in cloud free areas.

These results for Hurricanes Erin and Gabrielle essentially demonstrated that as more and more data were introduced (beyond those of the control experiment) the left bias of the control experiments was generally reduced with the addition of each new data set. This left bias is largely related to the positive surface vorticity tendency that arises from the larger scale horizontal advection of vorticity in the lower troposphere. This feature is similar for all of the above experiments and occurs downwind from the wind maximum of the hurricane. As dropsonde and LASE data sets were sequentially introduced, the hurricane was better resolved on a smaller scale. The model showed a pronounced center of rising motion, precipitation and

positive vorticity tendency where this storm was now being resolved. This occurred to the right of the track of the control run, and the control run's track appeared to be mostly dictated by the larger scale vorticity advection. The local enhancement of the diabatic processes appears to display a positive tendency for the precipitation enhancement from the storm's newer data sets. It is easy to see how that pushes the positive vorticity maxima to the east of the control experiment. In a related study, Krishnamurti et al (1997) noted that if several different initial analyses were deployed within the same model, then either a left or a right bias developed in the forecasts depending on which initial analysis was used within the same model. This appears to be related to differences in the initial vorticity advection downwind of the velocity maxima of a hurricane, which was located at different places for various analysis used in that study. This suggests that a left or a right bias could be reduced somewhat simply from the enhancement of the initial data sets or from ensemble forecasts that use several initial analyses.

The MSL pressure of all the three storms was examined for all the experiments. The forecast intensities of the minimum MSL pressure from all the experiments were 4-8 hPa lower than those in the control run. Figure 3 shows the MSL pressure on day 3 of forecasts for Humberto for the various experiments. The pressure forecasts for the same sequence of experiments (Analysis, CTRL, CTRL1, EXP1, EXP2, and EXP3), as shown in Fig. 3, are 990, 998, 996, 994, 996 and 990 mb, respectively. The minimum MSL pressure estimated by NHC was 992 mb. Nearly the same differences were found for Erin and Gabrielle (not shown). Figure 4 shows track errors for these hurricanes. In the case of Humberto and Erin, the initial errors were small, and these errors were further reduced in the experiments. In case of Gabrielle the initial large errors were amplified during model integration; however, these errors were reduced in the experiments. Overall these errors were reduced significantly up to day-3 forecasts. A combination of LASE plus the dropsonde data provided the best result.

Furthermore, the results from EXP1 were better than those of EXP2. The possible reason is that the dropsondes from different aircraft provided coverage over many different locations over and around the hurricane. However, all the experiments had improved forecast tracks with stronger intensity and faster movement in comparison with the control run.

The intensity forecast errors for the maximum storm winds for Erin, Humberto and Gabrielle are shown in Fig. 5. The wind speed errors are shown in knots at the 850 hPa level. Here we compared the relative error for the two control runs with those of the dropsonde, LASE and combined observation based experiments. The best results in all cases came from the use of all humidity data sets (dropsonde plus LASE, i.e., EXP3). These show a major improvement over the control results where none of the CAMEX data sets were used. The major message of Fig. 5 is that there is a positive impact on hurricane intensity from the inclusion of improved humidity data sets.

Given the wind forecasts on a latitude/longitude grid, it is possible to use coordinate transformation to cast data sets in polar co-ordinates with respect to the storm center, i.e., in storm relative coordinates. This is an objective algorithm that facilitates the examination of a storm's intensity after an azimuthal averaging is performed. This was done for day 3 of the forecasts derived from the control run (CTRL), CTRL1, EXP3 and for the validated analysis.

In Fig. 6 we show the results for the tangential wind. The abscissa is the radial distance from the storm center in km and the ordinate shows the azimuthally averaged tangential velocity at the 850 hPa level. The legend identifies these different data sets. The crosses show the results for the experiment that carries the most data sets. The three panels show results for the different storms Erin, Gabrielle and Humberto. Overall we note that the intensity forecasts do show some improvement as we add more and more data sets. What is most interesting here is that there is marked improvement in the intensity forecast as we proceed from CTRL1 to EXP3. This simply

means that the addition of humidity data from both the dropsonde and LASE had a significant positive impact on the intensity forecasts over and above what was possible from the addition of winds from dropwindsonde and the flight level measurements. A surprising lack of improvement in the inner radii (< 200 km) for Gabrielle may be related to the lack of the effectiveness of humidity measurements in rain areas.

b. Impact of extended moisture data coverage on hurricane forecasts

In storm relative co-ordinates the moisture transport vector $\bar{V}q$ has an interesting structure. We have vertically averaged this vector over 200-1000 hPa to examine the moisture transports for Erin at 12UTC on 10 September 2001. This is displayed in Fig. 7 as streamlines of $\bar{V}q$. One of the major moist swaths (red) of air enters the storm from the south, whereas a dry air swath (yellow) is seen to spiral in from the north. The LASE data were provided by the DC-8 aircraft flights over a portion of the storm where, in storm relative coordinates, a moist band of air enters the storm. The motivation for displaying structure was to see the active quadrants of the storm where moisture enters the hurricane center. The ranger markers are arbitrarily marked at every 30 degrees and the radial distance from center to outer radii is 370 km. The flight track along this moist band was designated as an “optimal data assimilation flight plan,” and this type of flight plan was used during the CAMEX-3 (Danielle) and CAMEX-4 (Erin) campaigns. The goal of this flight plan was to assess the impacts of high-resolution water vapor and wind measurements on the forecasts of hurricane intensity and tracks.

Figure 8 illustrates the aircraft flight track of the DC-8 during a moisture transport mission for studying Hurricane Erin during CAMEX-4. A similar mission was also flown for Hurricane Danielle during CAMEX-3. These tracks were specifically designed to provide moisture data sets to the south of the hurricane (over relatively clear sky areas). The design of this mission was specifically aimed at obtaining a detailed description of the moisture transports

($V_n q$) at two different radii from the storm center. This moisture transport was provided by the dropwindsonde data from the DC-8 and LASE profiles of moisture. Two versions of data assimilation, with and without the LASE data, were used to estimate these humidity transports. We also examine the differences between the LASE-based transports and those of the control experiment which did not include the LASE data sets. For this purpose we determined the vertical cross-sections proceeding from west to east following the outer and inner segments of the flight tracks that are shown in Figs. 9.1 and 9.2. In this case, dropwindsondes provided the vertical profiles of winds and LASE provided the vertical profiles of specific humidity. Figure 9.1 displays the results based on Hurricane Erin's analysis (Fig. 9.1 a, b, c and d) and 72-hour forecasts (Fig. 9.1 e, f, g and h), respectively. The left panels (Fig. 9.1 a, b, e and f) show the results for the inner segment of data, and the right panels (Fig. 9.1 c, d, g and h) show the results for the outer segment. We see here that the moisture transports that included the LASE data were invariably larger (Fig. 9.1 a and b) than those of the control (Fig. 9.1 c and d) where LASE data were excluded. The moisture transport in the inner segment was found to be conspicuously larger than the transport in the outer segment. This suggests a divergence of moisture flux between the outer and inner segments. The resulting strong evaporation in the storm's vicinity may have been a factor in producing the stronger intensity of Erin which had reached a category-3 level.

The corresponding results for Hurricane Danielle in 1998, where similar flights of the NASA DC-8 were flown, are shown in Fig. 9.2. This shows Danielle's analysis (Fig. 9.2 a, b, c and d) and 72-hours forecasts (Fig. 9.2 e, f, g and h), respectively. The left panels (Fig. 9.2 a, b, e and f) show the results for the inner segment of data, and the right panels (Fig. 9.2 c, d, g and h) show them for the outer segment. Here we found a similar structure in the analysis (i.e., day-0) for the moisture transports, although the magnitudes were considerably less. Hurricane

Danielle was a category-1 storm, and it did not exhibit as much mass and moisture convergence as were seen for Hurricane Erin. The convergences were further reduced when the forecasts for Danielle were examined. The inner and outer moisture transport was nearly equal. In the case of Danielle, the convection became more tightly wrapped around the center and the moisture convergence was closer to the center. Furthermore, the selection of the date and the flights flown around these hurricanes may have been another factor since the storms were going through a life cycle of amplification or decay at these observational times. The time series of the intensity shows that Erin was slightly weakening whereas Danielle was in a decaying stage. Thus, large impacts of these new data sets were noted in the magnitude of the moisture flux convergences that were missed in the control run.

c. Moisture Budget

We shall next discuss the moisture budget of these storms, where the moisture transports appear to have a critical role in the overall hurricane behavior. Basically the water vapor budget contains elements such as: Storage = convergence of flux of moisture + evaporation –precipitation. These are integrals over a mass of the atmosphere where,

$$where \int_m () dm = \frac{1}{g} \int_{p_1}^{p_2} \oint_{\theta} \int_{r_1}^{r_2} () r dr d\theta dp \quad (6)$$

and these mass elements are enclosed inside circles of radii r_1 , and r_2 , around the hurricane from the top of the atmosphere $p = p_1$ to the earth's surface where the pressure is $p = p_2$.

The three storms Erin, Gabrielle and Humberto were in different stages of their life cycle.

1) Erin: On 10 September 2001 at 1200 UTC, Hurricane Erin's minimum pressure was 969 hPa and maximum wind was around 100 kts. In the following 24 hours the minimum pressure rose to 976 hPa and the maximum winds dropped to 80 kts.

2) Gabrielle: On 15 September 2001 at 1200 UTC, the central pressure of Gabrielle (a tropical storm at this stage) had a minimum pressure of 998 hPa and an intensity of 40 kts. In the following 36 hours the central pressure dropped to 991 hPa and the maximum winds reached hurricane strength of 65 kts.

3) Humberto: On 22 September 2001 at 1200UTC, the central pressure of the tropical storm was 1007 hPa and maximum wind of 40 kts. In the next 24 hours the central pressure dropped to 990 hPa and the maximum winds reached hurricane strength of 65 kts.

Given the assimilated data sets and the day-3 forecasts for Hurricane Erin, Gabrielle and Humberto it was possible to evaluate these terms for all of the experiments carried out in this study. Using storm relative coordinates, and a local cylindrical frame of reference about the storm center, the moisture budget is expressed by the following relations:

Moisture Continuity Equation:

$$\int_m \frac{\partial q}{\partial t} dm = - \int_m \nabla \cdot qV dm - \int_m \frac{\partial q \omega}{\partial p} dm + Evap - P, \quad (7)$$

$$\text{Where } \nabla \cdot qV = \frac{\partial q V_\theta}{r \partial \theta} + \frac{1}{r} \frac{\partial q V_r r}{\partial r}$$

The budget was estimated from various data sets generated by our model (i) Control data sets (CTRL), (ii) experiment that includes LASE data sets (EXP2) and (iii) experiment that includes dropsonde and LASE data sets (EXP3). These data sets are all derived using the 3DVAR data assimilation. Figure 10 (a to f) shows these budgets for Hurricanes Erin, Gabrielle, and Humberto in storm relative coordinates for these three data sets. These budget diagrams carry the following information: (i) Local change $(\partial q / \partial t)$, i.e., source or sink, (ii) convergence of flux (positive sign), (iii) precipitation (P) and (iv) evaporation (Evap). These are all quantities

provided by the model at time 0 and at 72-hour forecasts. The following is the summary of moisture budget for these individual storms.

i) Erin: (Fig. 10 a & b). The initial evaporation at a radial distance of 200 to 300 km from storm center increased from 206 to 353 to 503 mm/day as we proceed from the control (CTRL) to LASE (EXP2) and to the final experiment with all data sets (EXP3). There was in fact a spin down of evaporation by day 3 of the forecast at these radii to values of 160, 218 and 298 mm/day, respectively. This is consistent with the observation that Hurricane Erin was weakening somewhat. This spin down of evaporation was also evident at an outer radii near 1000 km. Unlike the evaporation, the precipitation amount did not show a significant decrease in intensity with the spin down. In general, larger rainfall rates were found for the experiments that included more and more humidity data sets in their initial analysis. With the weakening of Erin we also found spin down of the net convergence of moisture flux. It is possible that an increase in evaporation rate and storm intensification are concurrent indicators, and as such, it may not necessarily imply causality.

ii) Gabrielle: (Fig. 10 c & d) Gabrielle was an intensifying storm in these cases. Between 200- and 300-km radii at the initial time the evaporation increased sequentially from 222 to 363 to 608 mm/day as we proceed from the control to LASE to the final full data experiment. The local change ($\partial q / \partial t$), i.e., source or sink, convergence of flux, precipitation and evaporation, of the moisture budget was extremely large at the initial time, perhaps contributing to initial intensification of Gabrielle from a tropical storm to a hurricane. Therefore, the moisture budget reveals an equilibration toward somewhat lower values.

iii) Humberto: Figure 10 e & f displays the moisture budgets for Hurricane Humberto. Here we can see for the day 0 an increase in the convergence of fluxes from 51 to 160 to 245 between 200 and 300 km from the storm center. The forecasts seem to retain some of these

impacts even at day 3. The differences between LASE based and LASE plus dropsonde based forecasts are, however, not as large at 72 hours as they were at hour zero. However, they do have much larger values compared to the control at 72 hours.

In general, for day-0 fields we find a gradual increase in the convergence of fluxes of moisture as we proceed from the control data-based experiment to LASE data-based experiment and on to the all inclusive data-based experiments. It is very clear that as the convergence of moisture flux increases so does evaporation and precipitation within the radial legs (around the storm). Although the detailed precipitation fields are not shown here, in the inner radii inside $r < 500$ km the satellite pictures clearly confirm higher rainfall in those inner belts.

This clearly shows the impact of including the additional moisture data from LASE and the dropsondes as well. The control analysis that only includes the moisture analysis from the world weather watch underestimates the precipitation compared to the observed estimates of rain amounts.

The moisture budgets at 72 hours show increased values for the transports and divergence of flux of moisture as we sequentially compare results of experiments with added data sets, (especially moisture data sets). Furthermore, the impacts from the added moisture data sets are quite robust. The precipitation forecasts in excess of 120 mm/day along those radial legs from the LASE and LASE plus dropsonde experiment are in line with the observed estimates. The precipitation rates were underestimated by the control run. This shows that forecasts that include moisture profile data sets can contribute to a positive impact. Since the moist processes are most important for a hurricane, such profiling data sets of humidity may be important for the modeling of the heavy rain areas.

We have also explored the sensitivity of track forecasts to the use of enhanced moisture profiling observations in the lower versus the upper troposphere. We noted that the track

forecasts were sensitive to these variations in the use of moisture data sets. Figure 11(a) illustrates a comparison of such track forecasts. Here we compare the control (i.e., where no aircraft observations are used) with those results where the low level (below 850 hPa) moisture data were assimilated and where the moisture data sets were enhanced only above the 850 hPa level. These tracks are here compared to the observed best track. We note that, in general, there is a stronger positive impact in improving the track forecast when the lower tropospheric additional moisture data sets are added. Figure 11(a) shows the five-day forecast tracks for Hurricane Erin at intervals of every 12 hours. Similar comparisons (not shown) were carried out for Hurricanes Humberto and Gabrielle where we found a very similar sensitivity.

We have also constructed vertical cross-sections of moisture along the saw tooth flight patterns shown in Fig. 8 and compared the vertical profiles of moisture from LASE and the dropsondes at collocated points. At these locations we found our control analysis to be somewhat too dry compared to the LASE and dropsonde measurements. Figure 11 (b-d) shows vertical profiles of specific humidity at 33°N and 66°W from these direct measurements and those interpolated from the control analysis. In general the dropsondes (Fig. 11c) were slightly more moist compared to the LASE (Fig. 11d) measurements, but both were wetter than the control analysis (Fig. 11a). These differences are more conspicuous when we look at the respective observational vertical distributions of relative humidity that are shown in Fig. 12 (a-d). It is these enhanced moist profiles in our humidity assimilation that seems to impact the forecasts of hurricane Erin.

Figure 13 illustrates hurricane track forecasts from several sources for Hurricanes Erin, Humberto and Gabrielle. This includes the forecast from the aforementioned control run (CTRL-black line), the forecast from the experiment that include the humidity profile data sets (EXP2-blue line), the official forecast of the National Hurricane Center (NHC OFC -red line),

and a forecast based on the FSU superensemble (SUPENS-purple line). Also shown are the observed best track positions (green line). We found in all cases that the experiments that included the humidity profile data sets perform better than the control and at times were better than the official forecasts. The FSU superensemble has the best performance since it assimilates the results from several models (Williford et al., 2003).

The current experiments on Erin, Gabrielle and Humberto using LASE and dropwindsonde data were not part of the real-time forecasting effort. It is interesting to note that only for Erin did the operational superensemble perform better than these new experiments. For the other two storms, Gabrielle and Humberto our forecasts with the LASE and dropwindsonde moisture data appear to have done very well in comparison to the operational forecasts. This suggests that the use of humidity profile data in single forecasts can perhaps provide a useful member for the superensemble. Such a direct test is not possible, since the superensemble requires a training database of as many as 60 forecasts from each member model, and the LASE and dropwindsonde data were not available for such a series of past forecasts.

5. Conclusions

This study explores the impact of additional data sets beyond those that are currently available for operational weather prediction. The conventional data sets include surface and radiosondes, ships of opportunity, oceanic buoys, commercial aircraft platforms, cloud and water vapor tracked winds and satellite based soundings. Those were analyzed via the four-dimensional data assimilation by the European Center for Medium Range Weather Forecasts, which were provided to us. The goal of this study was to examine the impact of dropwindsonde (profiles of winds, and humidity) and/or LASE (moisture profiles) data sets during CAMEX-4 on hurricane analysis and forecasting. These new observations, especially the winds from the dropsondes and aircraft flight levels and moisture profiles from the dropsondes and LASE, were

analyzed sequentially using 3DVAR, and medium range predictions were then carried out by integrating the FSU global spectral NWP model out to 5 days with these new initial conditions.

The forecast of tracks and intensity from the assimilation experiments demonstrate improvement over control experiments. The inclusion of winds only from the dropwindsonde data also shows some improvement in the forecasts over those of control runs that do not include any CAMEX data sets. The additional use of moisture profiling data indicates a clear strong positive impact in several areas.

Three-day track forecasts show positive error reductions by as much as 100 km. Even the intensity forecasts for those storms observed during CAMEX 4 show clear improvements compared to the forecasts from a version of model that does not include moisture profiling data from LASE and the dropwindsondes. We also found that the impact of the water vapor profiling data seems to be even more encouraging than what we noted from the addition of dropsonde winds. A large left bias in the control run was reduced in the track forecasts when the newer data sets were included. The inclusion of CAMEX-4 data sets provided some improvements in the hurricane intensity forecasts as well. A combination of LASE and the dropsonde data also appeared to improve the intensity forecasts. Our study of the moisture budget showed enhanced evaporation and precipitation associated with the use of the additional data sets. A large impact of these new data sets was found in the convergence of mass and moisture fluxes which was missed in the control runs. The experiments with CAMEX-4 data sets generated more precipitation near the storm than the control. The precipitation generated in the moisture-data-added experiments was more concentrated near the storm center than the control run that excluded such data sets, and the overall pattern was closer to the verification. We compared the vertical structure of specific humidity constructed along the saw tooth flight patterns and noted

that the moisture profiles from the control (interpolated) runs were drier than those profiles from the runs that included the dropsonde and LASE data.

The impact of enhanced observations in heavy rain disturbances in the tropics appears to be a very relevant issue. In hurricanes we found that data from enhanced observations positively impacts the analysis of very moist areas, moisture transports, convergence of flux of moisture, and the precipitation forecasts of heavy rains. Improvements in all of these factors have been seen in the analysis and forecasts of hurricanes examined here. We believe that this would also be true for other heavy rain producing disturbances over the tropics and elsewhere. Only one LASE instrument was available for measurements during CAMEX, but in the future, this capability could be on several aircraft and eventually in space. In the meantime, global humidity profiling will be provided by the AQUA satellite; this points to a natural extension of the present work to examine the impact of moisture profiling data sets on global weather forecasts.

A major thrust on mesoscale high resolution modeling of hurricanes has emerged in recent years, see e.g., Kurihara et al. (1995, 1998), Cocke (1998), Zhang and Altshuler (1999), Tao et al. (1999), Zhang et al. (2002), and Wang and Wu (2003). It has been possible to observe detailed features of the inner precipitating areas (eye wall convection and rain bands) and the matching radar reflectivity (as seen from a computed proxy radar reflectivity using microphysics output and observed radar reflectivity). Furthermore, these models have also addressed details on the tracks, intensity and timing of landfall for a number of storms. These recent studies are quite promising for mesoscale thrusts on data assimilation and forecast experiments on new observing systems.

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Figure Captions

Figure 1: Sample coverage of dropsonde data from multiple aircraft for CAMEX-4 on 23 September 2001, Hurricane Humberto, at (a) upper level (300-200 hPa), (b) middle level (400-600 hPa), and (c) lower level (900-750 hPa)

Figure 2: (a) 120hr forecast track of Hurricane Erin with IC (Initial Condition): 12UTC 10 September 2001, (b) 120hr forecast track of Hurricane Humberto with IC: 12UTC 22 September 2001, and (c) 96hr forecast track of Hurricane Gabrielle with IC: 00UTC 15 September 2001

Figure 3: 72hr forecast of sea level pressure (mb) for Humberto with IC: 12UTC 22 September 2001.

Figure 4: Forecast track errors of the Hurricanes (a) Erin, (b) Humberto, and (c) Gabrielle

Figure 5: Forecast intensity errors at 850 hPa for Hurricanes (a) Erin, (b) Humberto and (c) Gabrielle

Figure 6: Azimuthally averaged tangential velocity (m/s) versus radial distance (km) from the center of the storm of 72hr forecast for (a) Erin with IC: 12UTC 10 September 2001, (b) Gabrielle with IC: 00UTC 15 September 2001 and (c) Humberto with IC: 12UTC 22 September 2001.

Figure 7: Moisture transport vector Vq (a) vertically averaged from 200 to 1000 hPa

Figure 8: DC-8 flight path around Hurricane Erin on 10 September 2001.

Figure 9.1: Moisture transport $[(m/s)(g/kg)]$ of Hurricane Erin for the (a-d) analysis valid on 12UTC 10 September 2001 and (e-h) 2hr forecast with IC: 12UTC 10 September 2001.

Figure 9.2: (a-d) Moisture transport $[(m/s)(g/kg)]$ of Hurricane Danielle, during CAMEX-3, for the (d) analysis valid on 00UTC 31 August 1998 and (e-h) 72hr forecast with IC: 00UTC 31 August 1998.

Figure 10: (a) & (b) Day-0 and Day-3 Moisture Budget for Hurricane Erin ; (c) & (d) Moisture Budget For the Hurricane Gabrielle; and (e)&(f) Day 0 and Day 3 Moisture Budget for Hurricane Humberto for three Experiments.

Figure 11: (a) 120Hr forecast tracks of Hurricane Erin, (b-d): The vertical profile of moisture from (b) CTRL, (c) Dropsonde and (d) LASE for Hurricane Erin.

Figure 12: 12UTC 10 September 2001: Observational vertical profiles of specific humidity(g/g) for Hurricane Erin at 33°N. (a) CTRL (b) Dropsonde (c) LASE (d) LASE+Dropsonde.

Figure 13: (a) 120hr forecast tracks of Hurricane Erin with IC (Initial Condition): 12UTC 10 September 2001, (b) 120hr forecast track of Hurricane Humberto with IC: 12UTC 22 September 2001, and (c) 96hr forecast track of hurricane Gabrielle with IC: 00UTC 15 September 2001.

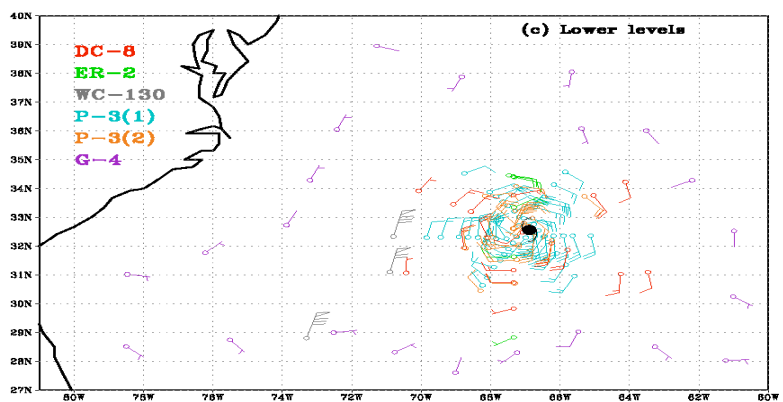
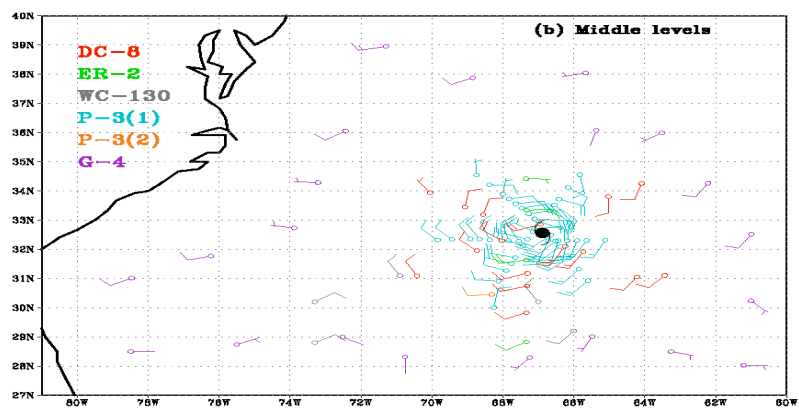
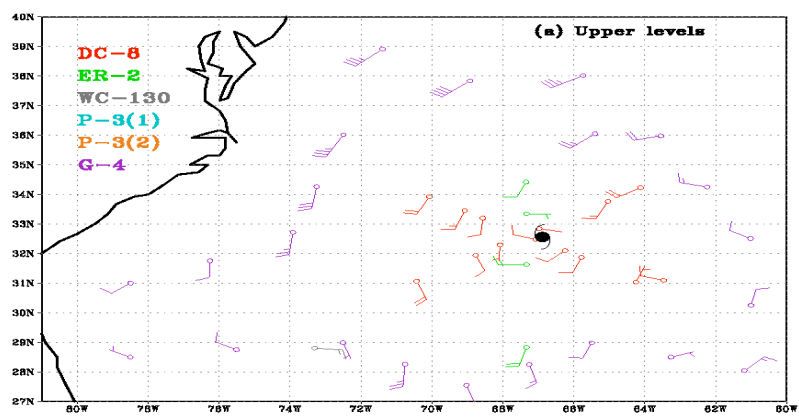
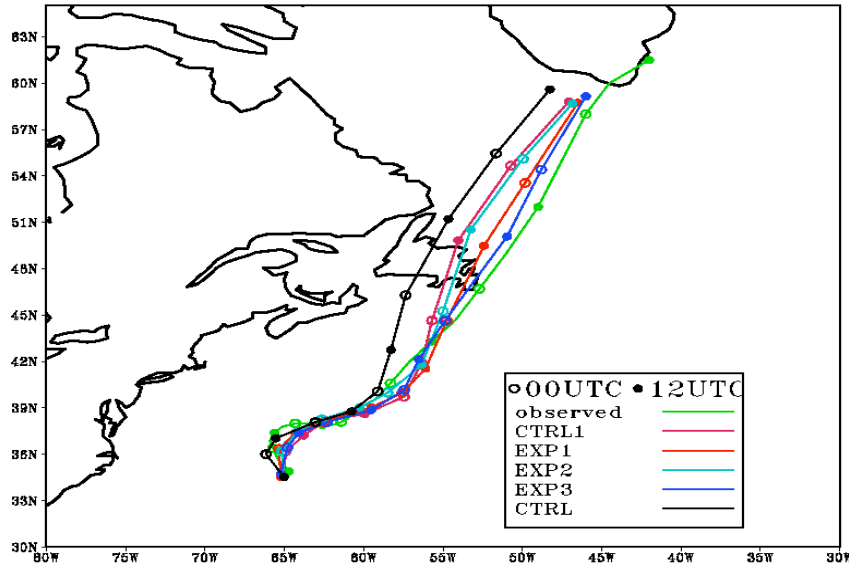


Fig. 1.

**(a) 120hr forecast track of Hurricane Erin
IC: 12UTC 10 September 2001**



**(b) 120hr forecast track of Hurricane Humberto
IC: 12UTC 22 September 2001**

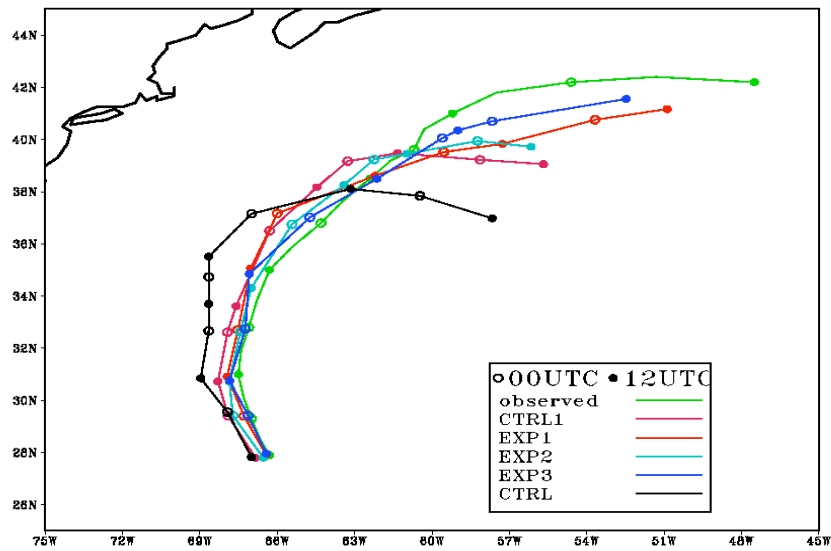


Fig.2 (a) & (b).

(c) 96hr forecast track of Hurricane Gabrielle
IC: 00UTC 15 September 2001

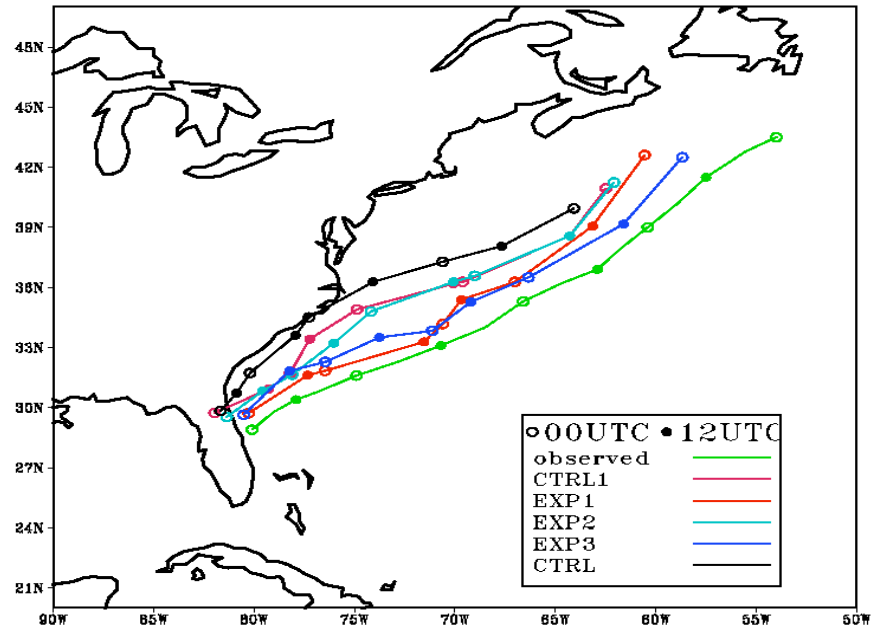
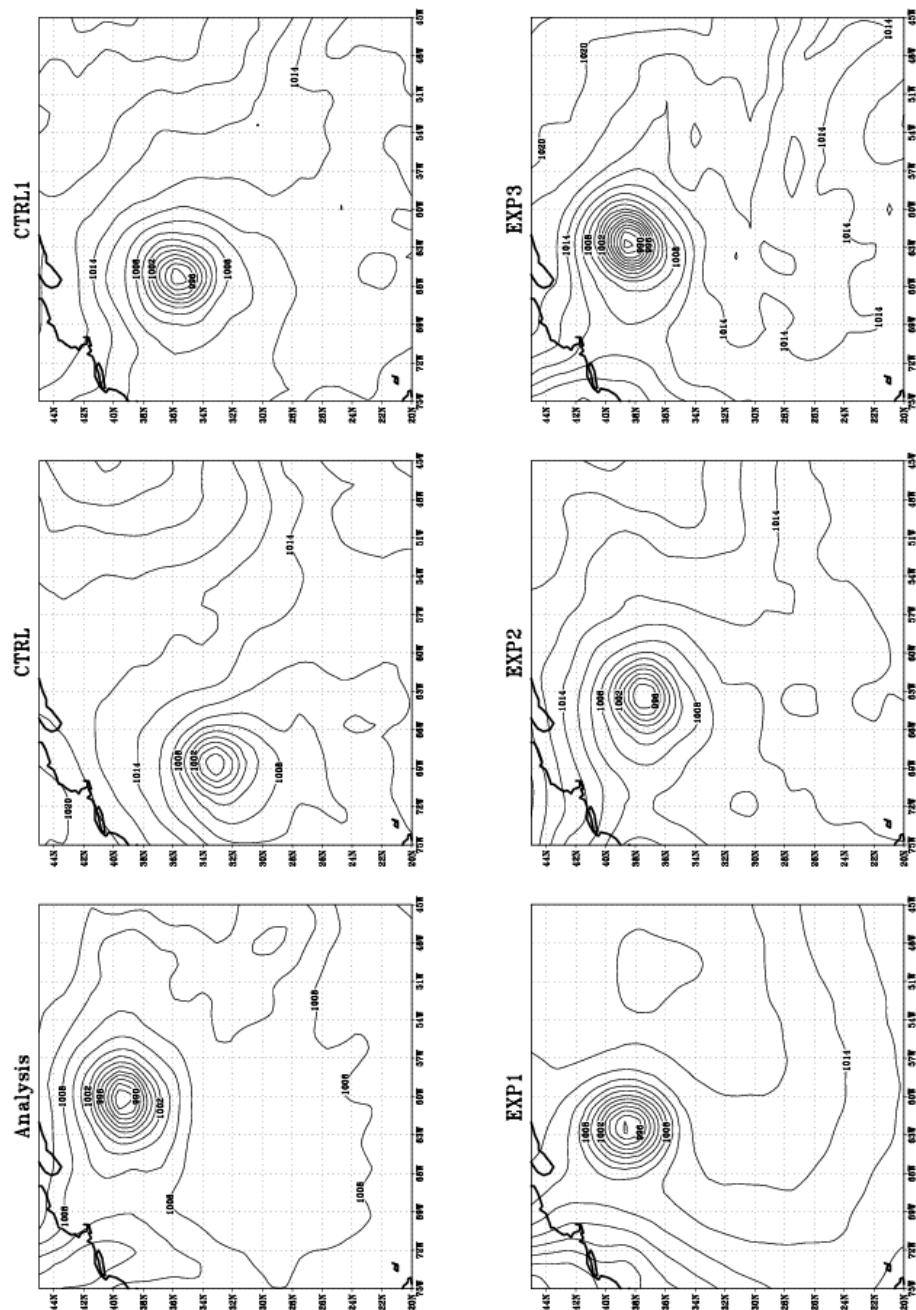


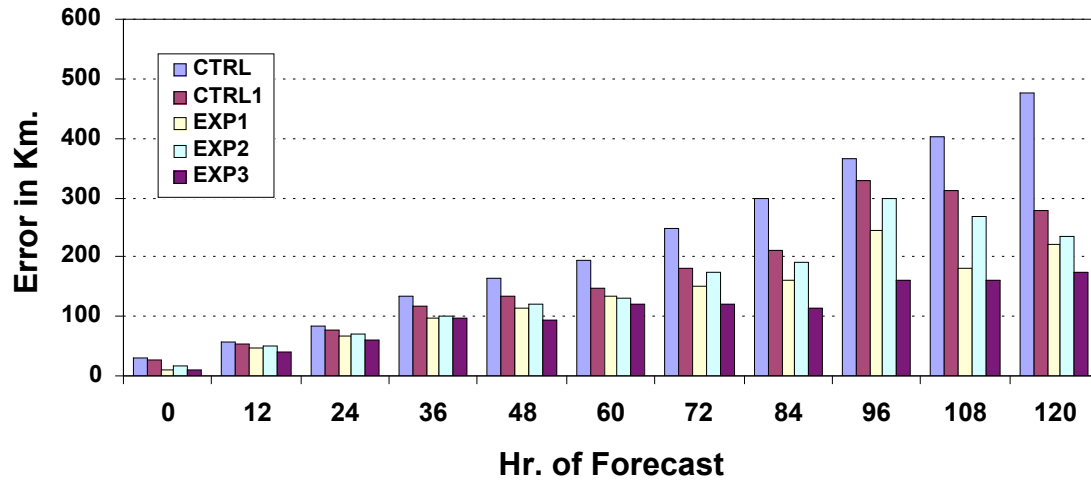
Fig. 2(c).

Fig. 3.

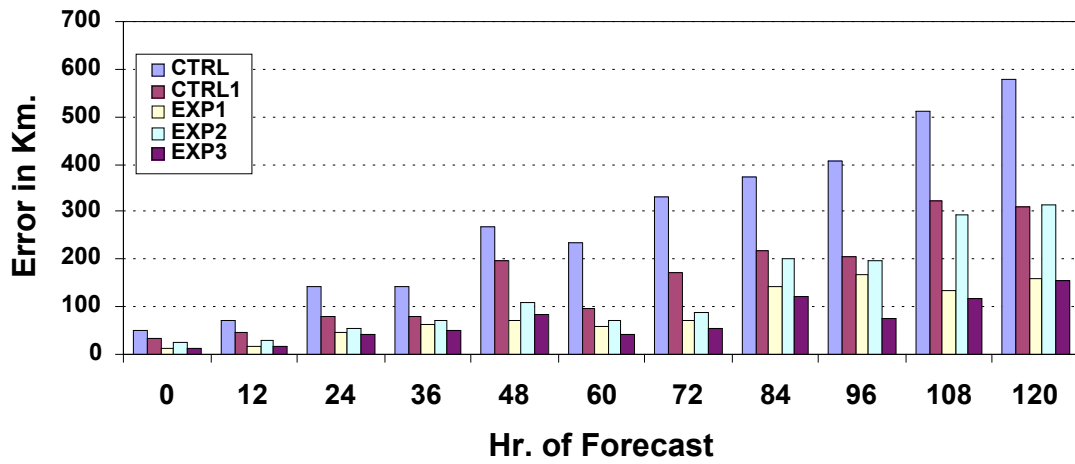
72 hr Forecast of Sea Level Pressure (mb)
Hurricane Humberto IC: 12UTC 22 Sep 2001



(a) Erin



(b) Humberto



(c) Gabrielle

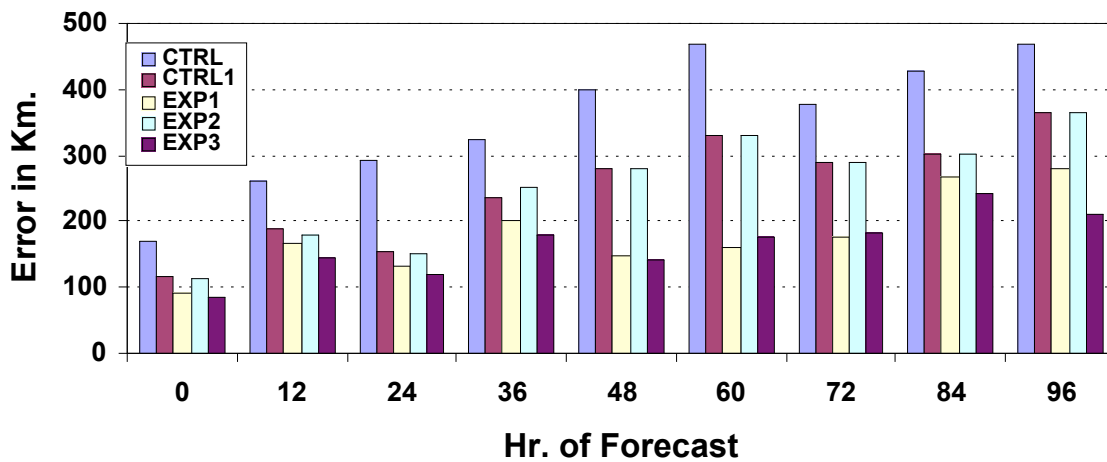
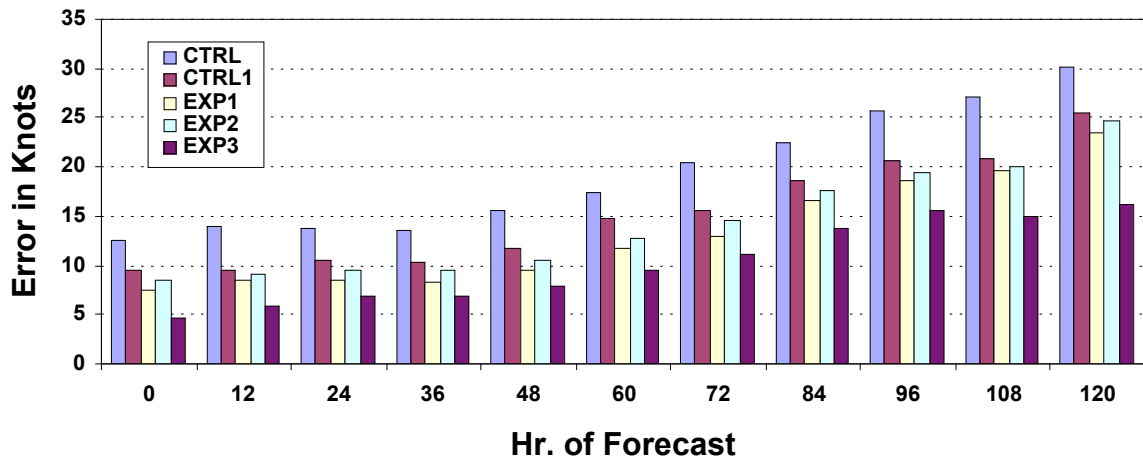
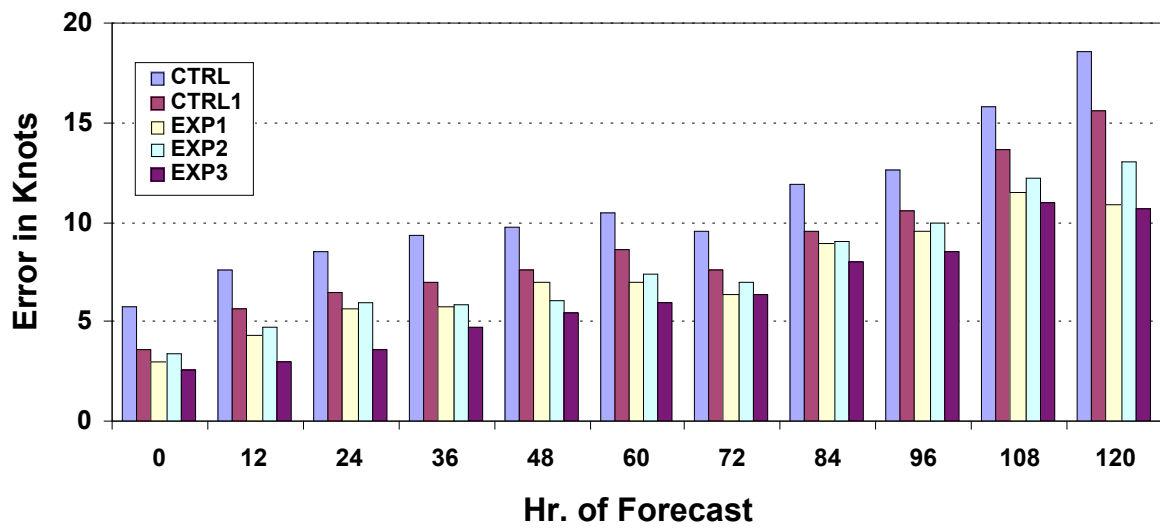


Fig. 4.

(a) Erin



(b) Humberto



(c) Gabrielle

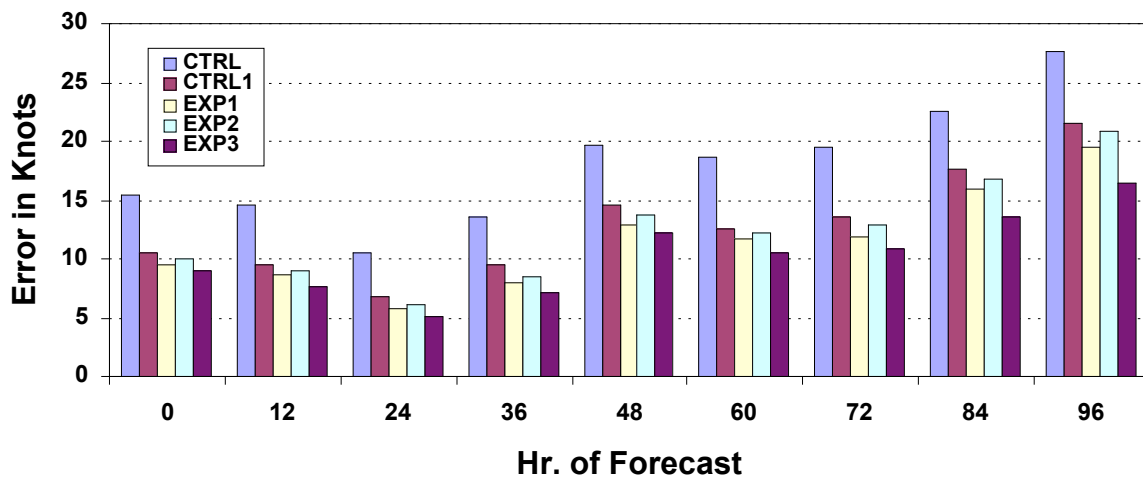
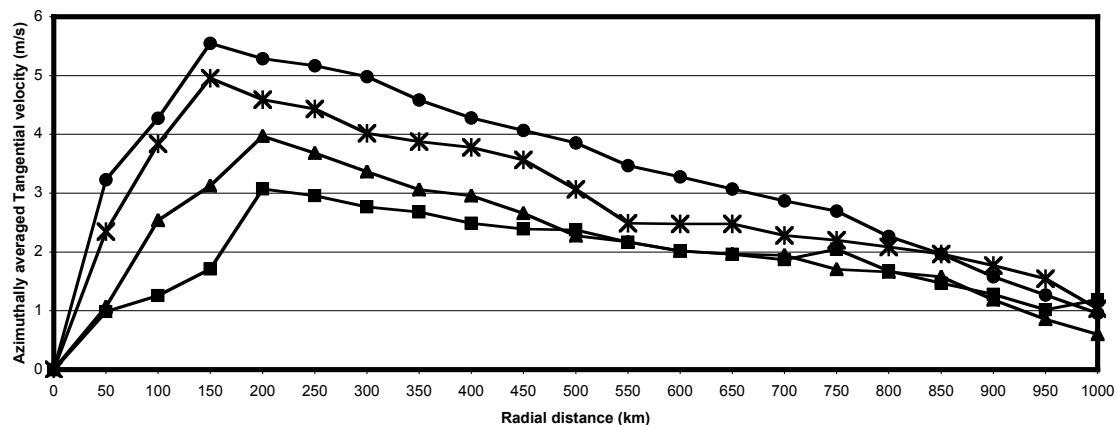
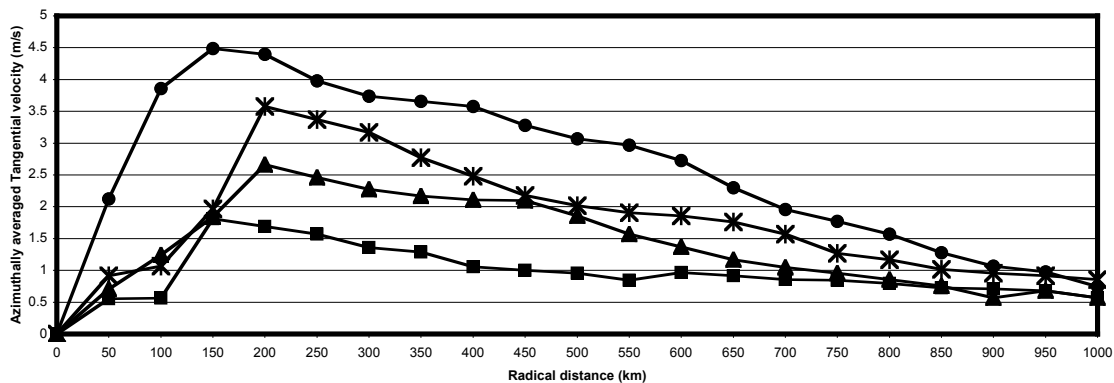


Fig. 5.

(a) Hurricane Erin 72hr Forecast



(b) Tropical storm Gabrielle 72hr Forecast



(c) Hurricane Humberto 72hr Forecast

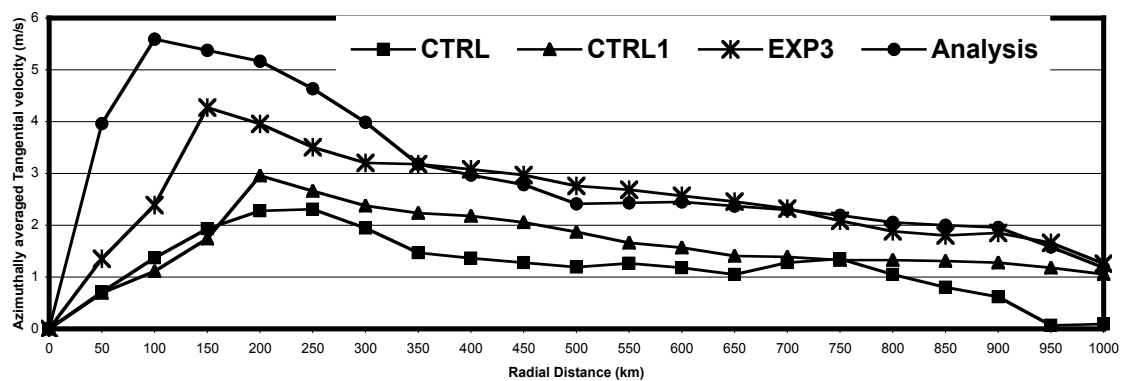


Fig. 6.

**Average Vertically Integrated (200-1000) hPa
Moisture Transport (Vq) of Erin**

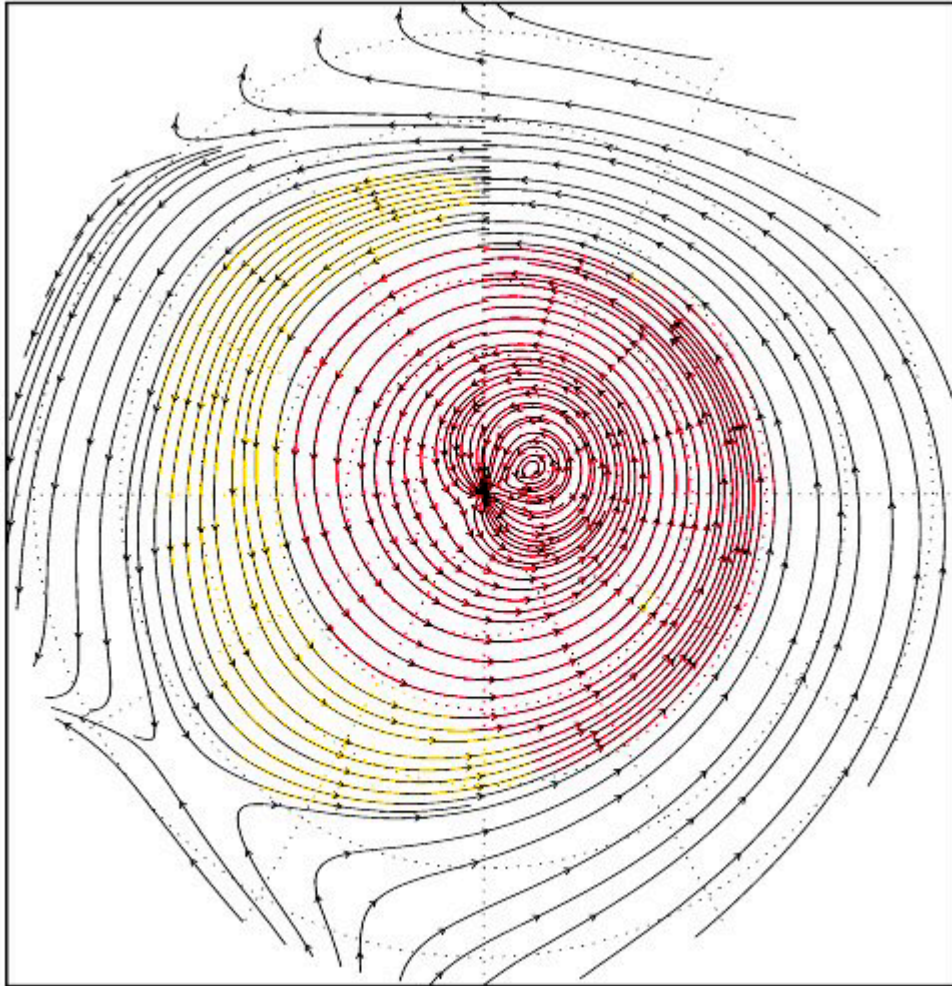


Fig.7.

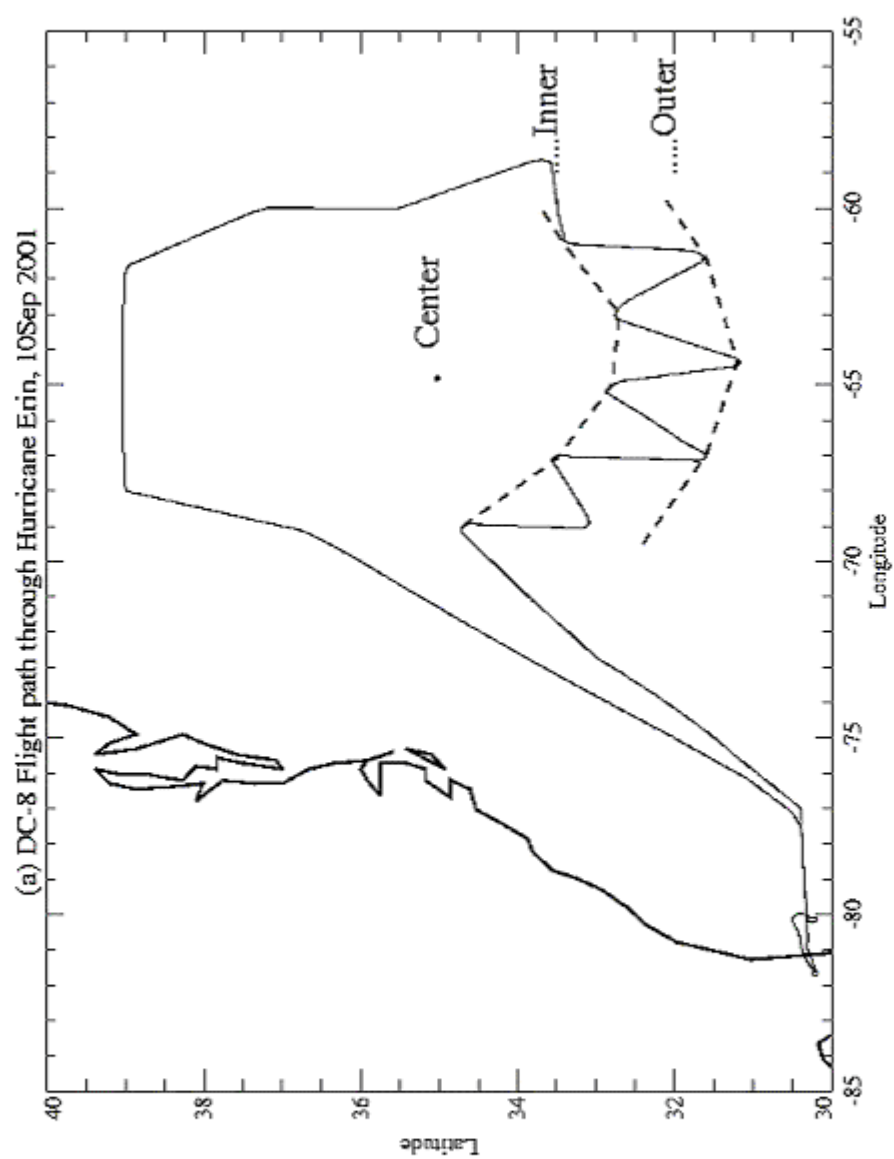


Fig. 8.

Hurricane Erin IC: 12UTC 10Sep 2001

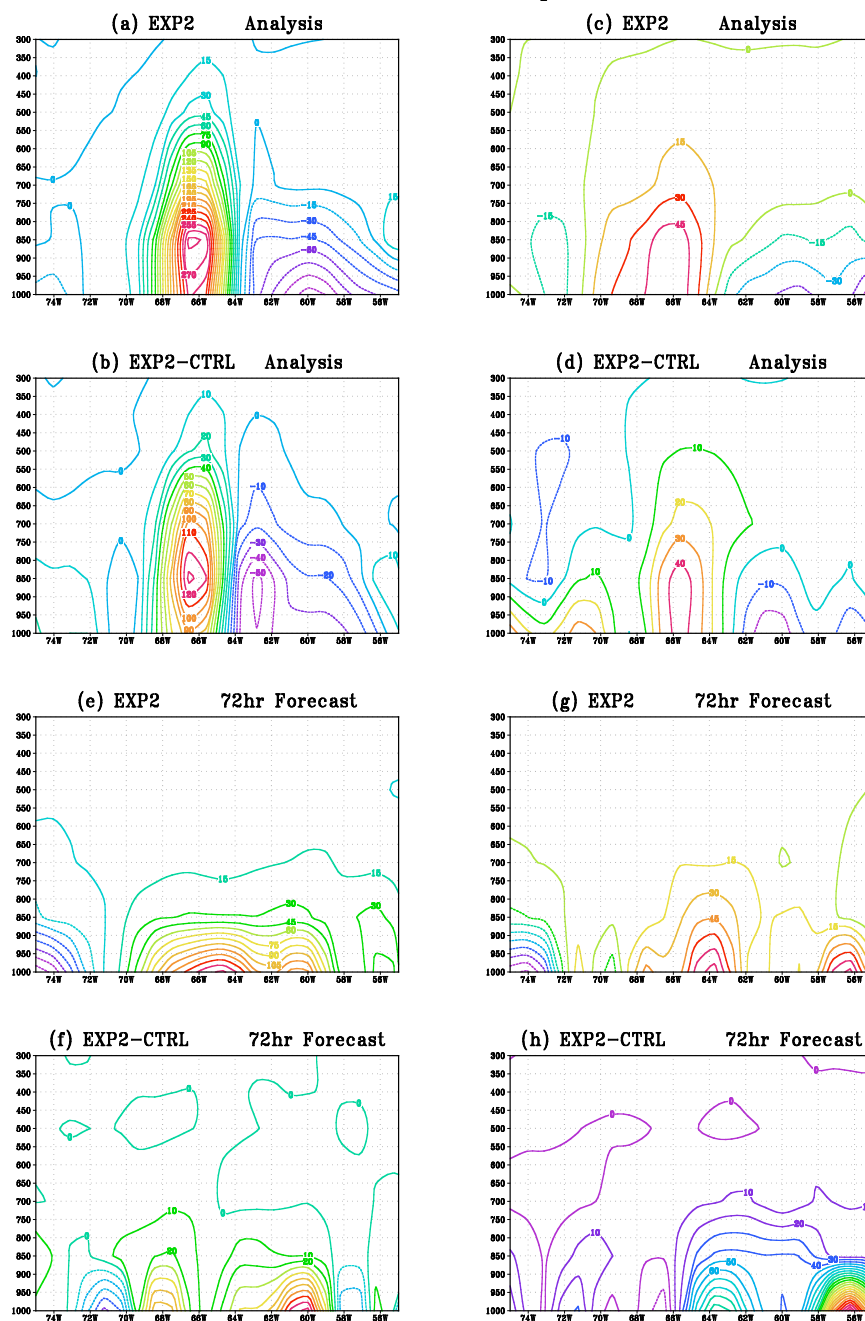


Fig. 9.1.

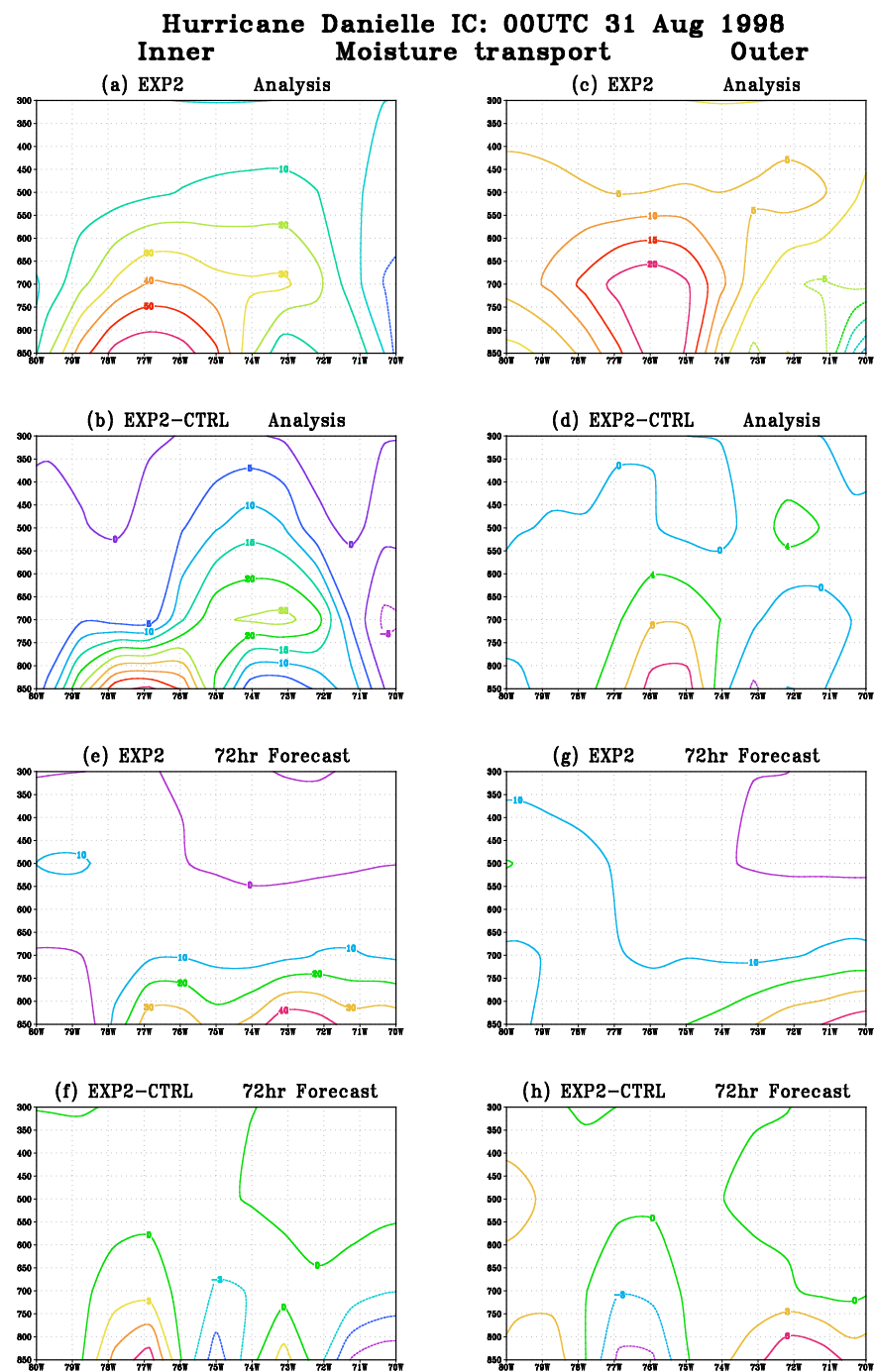


Fig. 9.2.

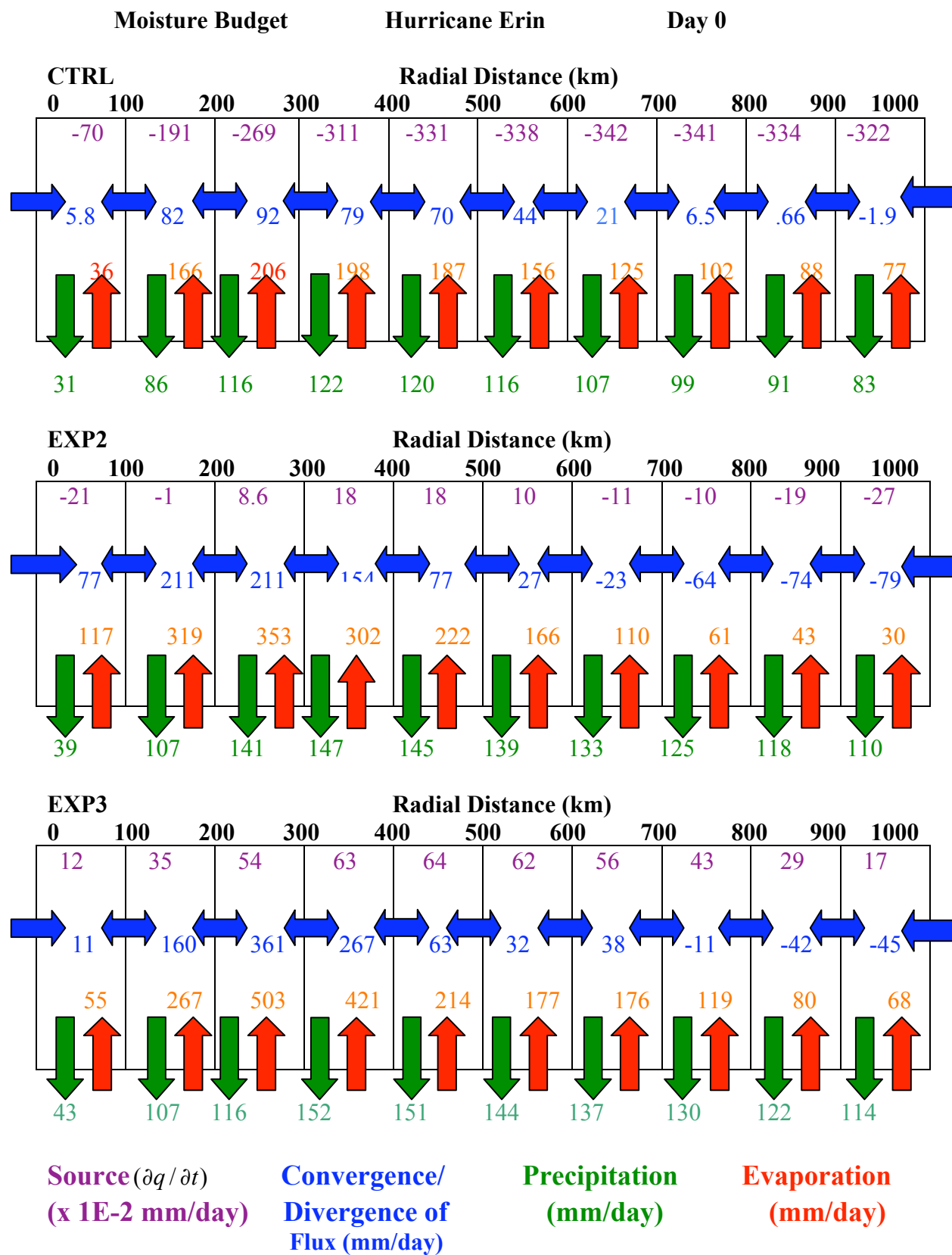


Fig. 10 (a).

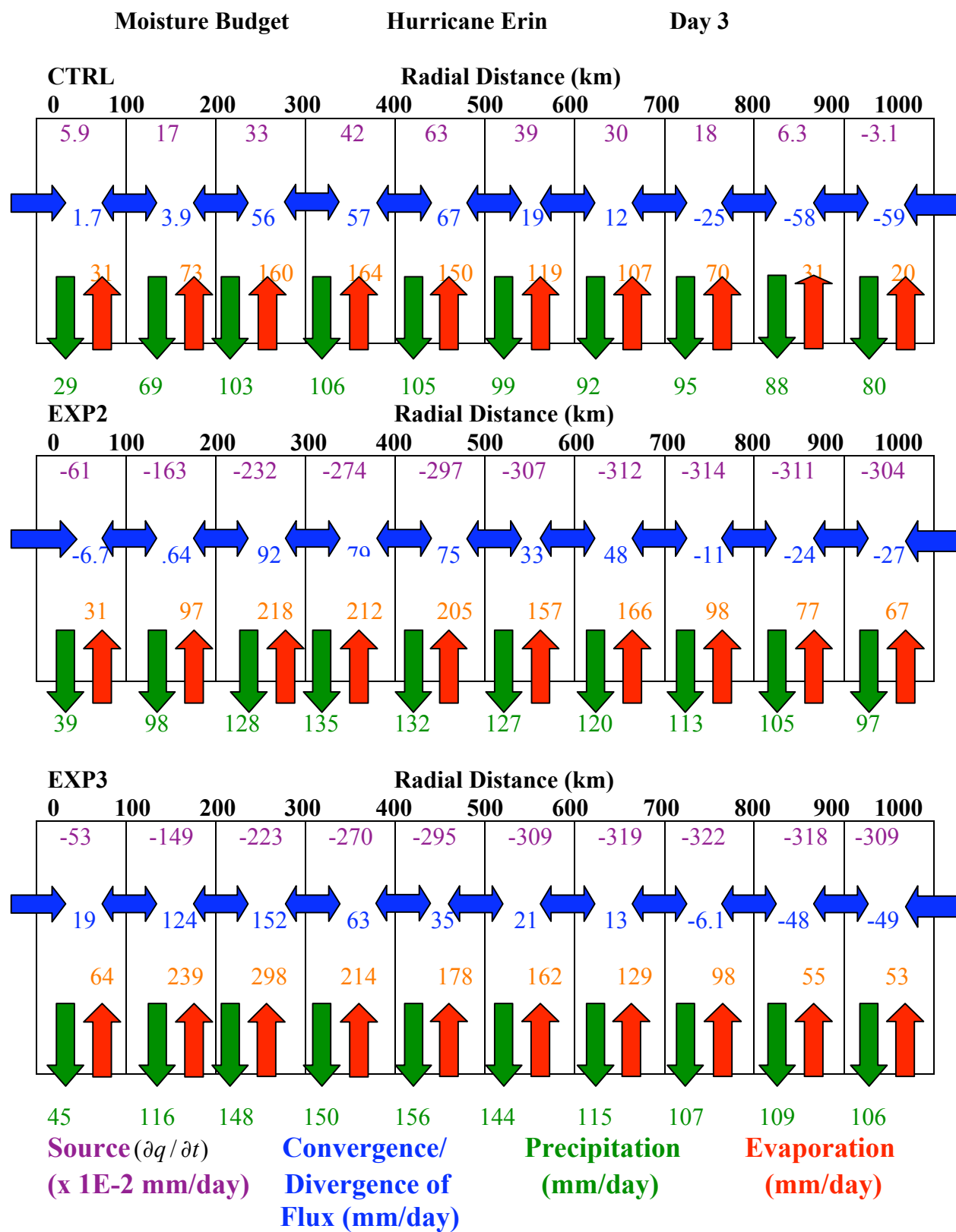


Fig. 10(b).

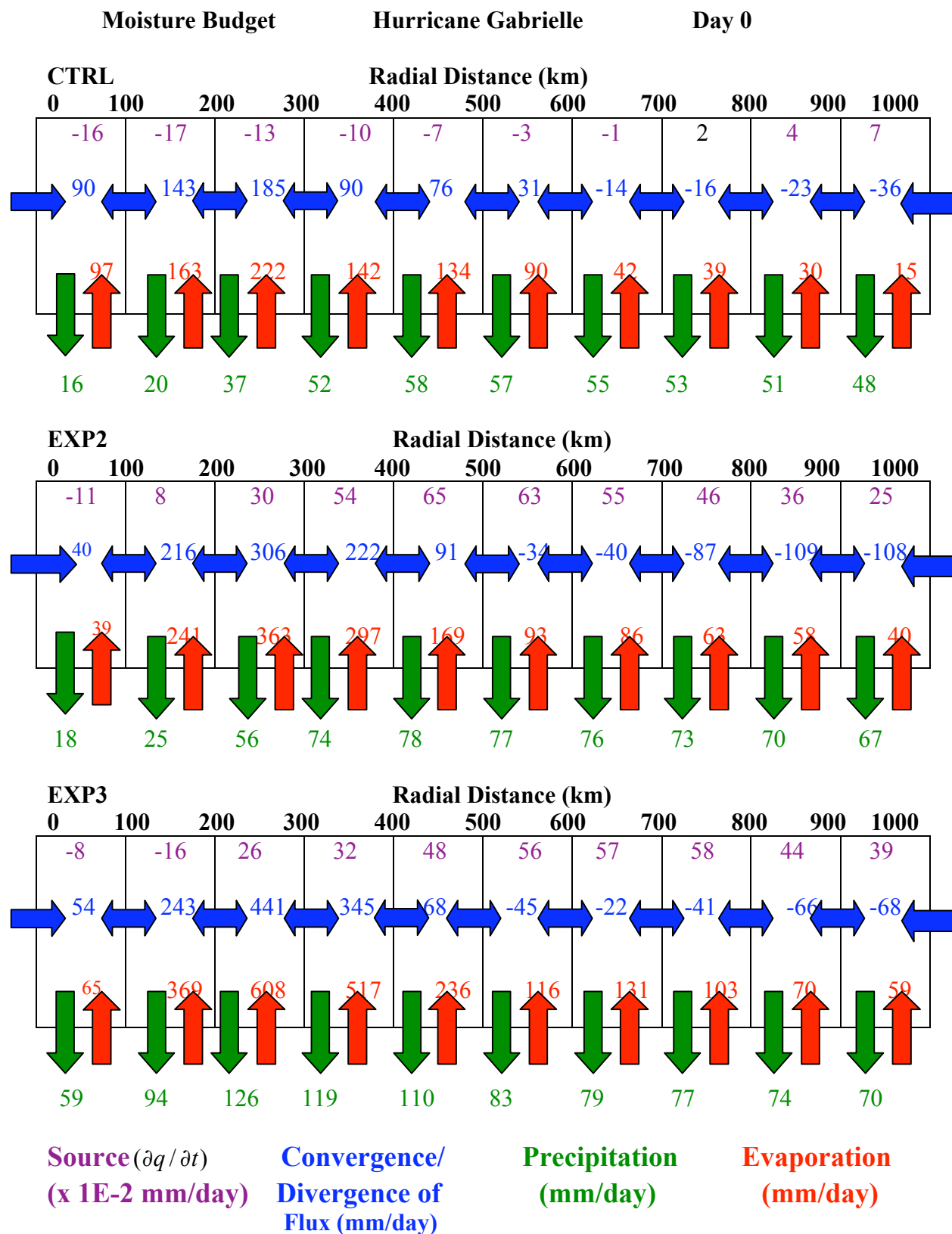


Fig. 10 (c).

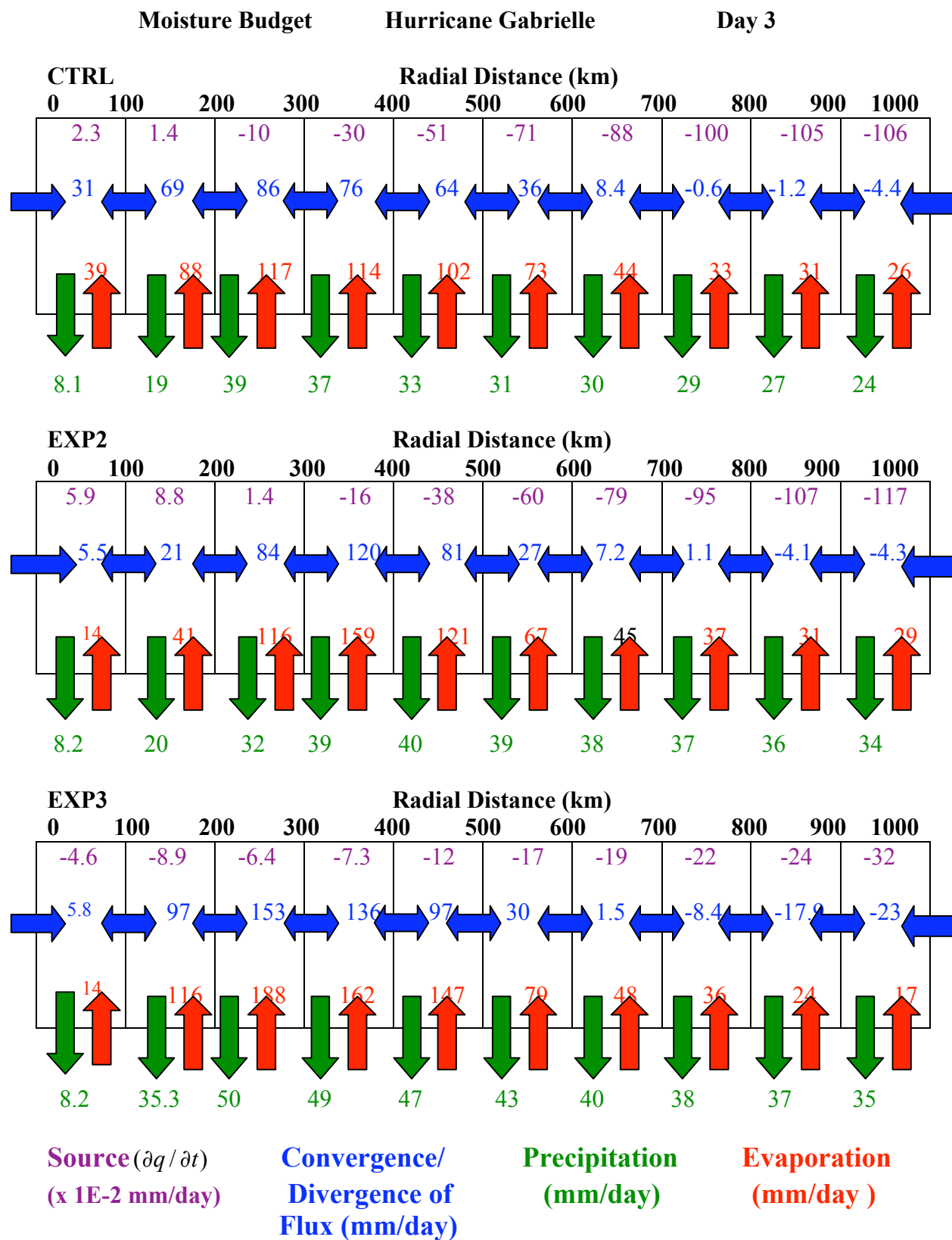


Fig. 10 (d).

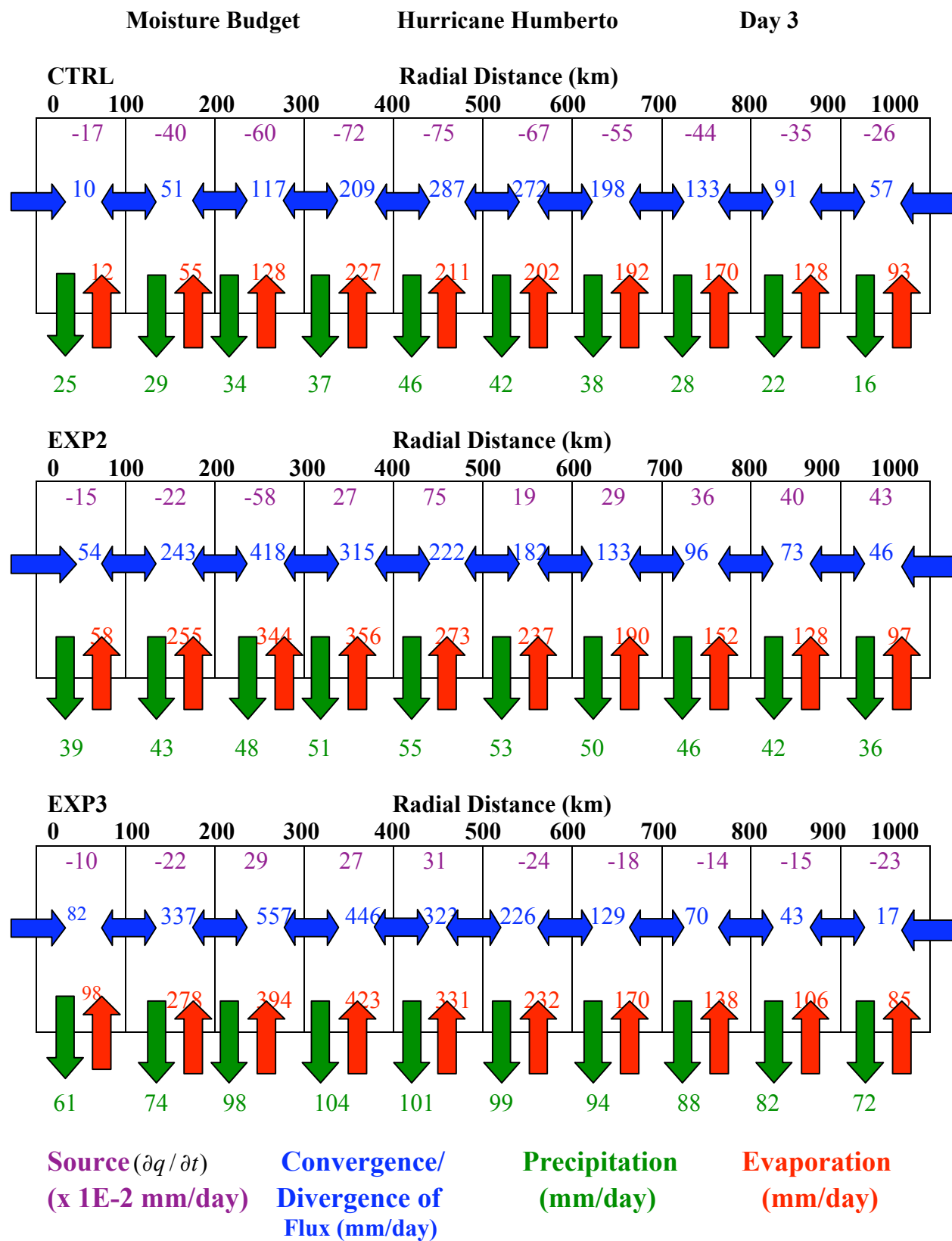


Fig. 10. (f).

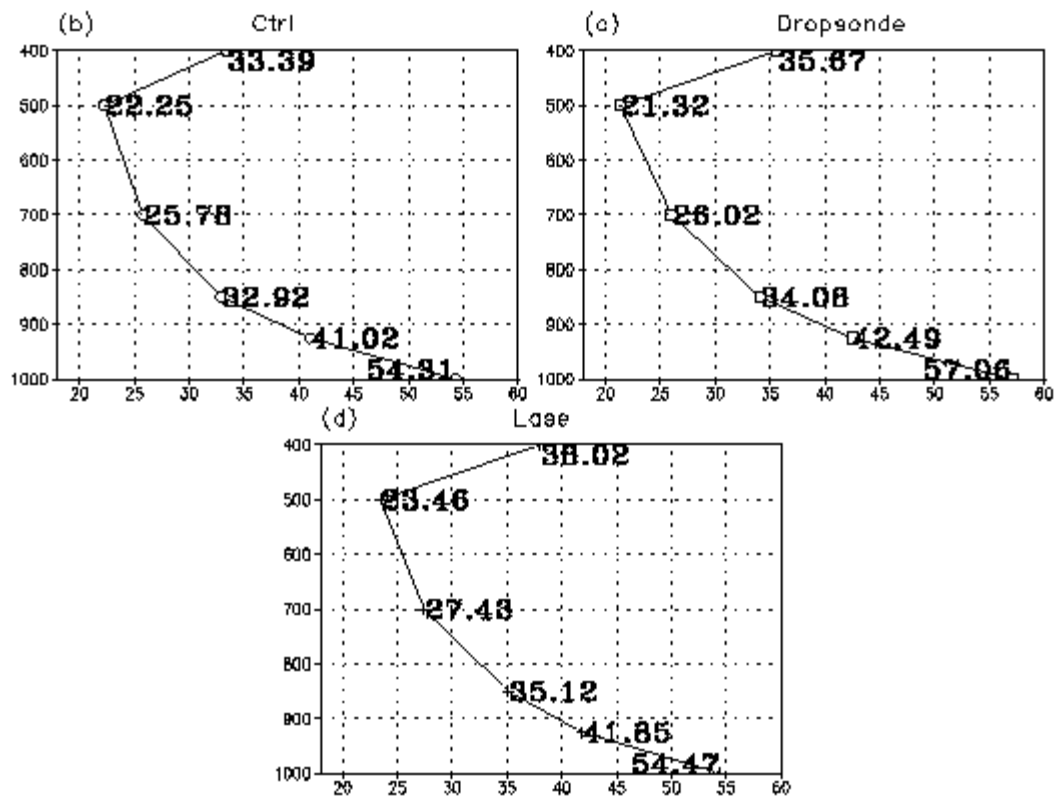
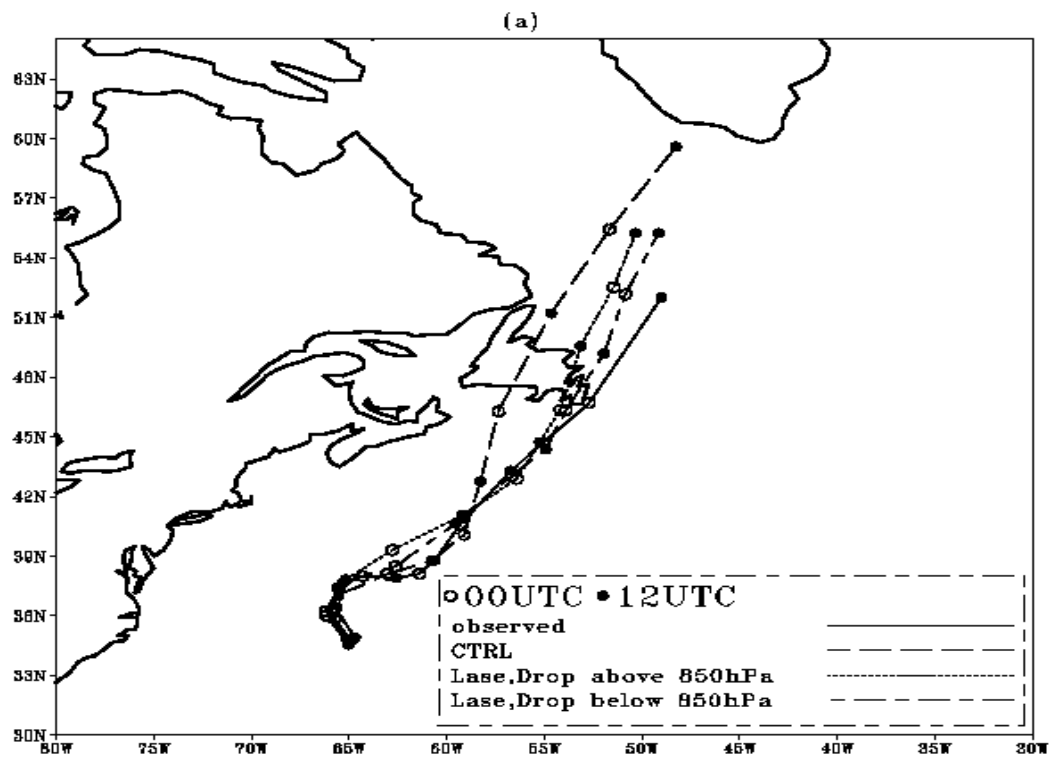


Fig.11 (a-d).

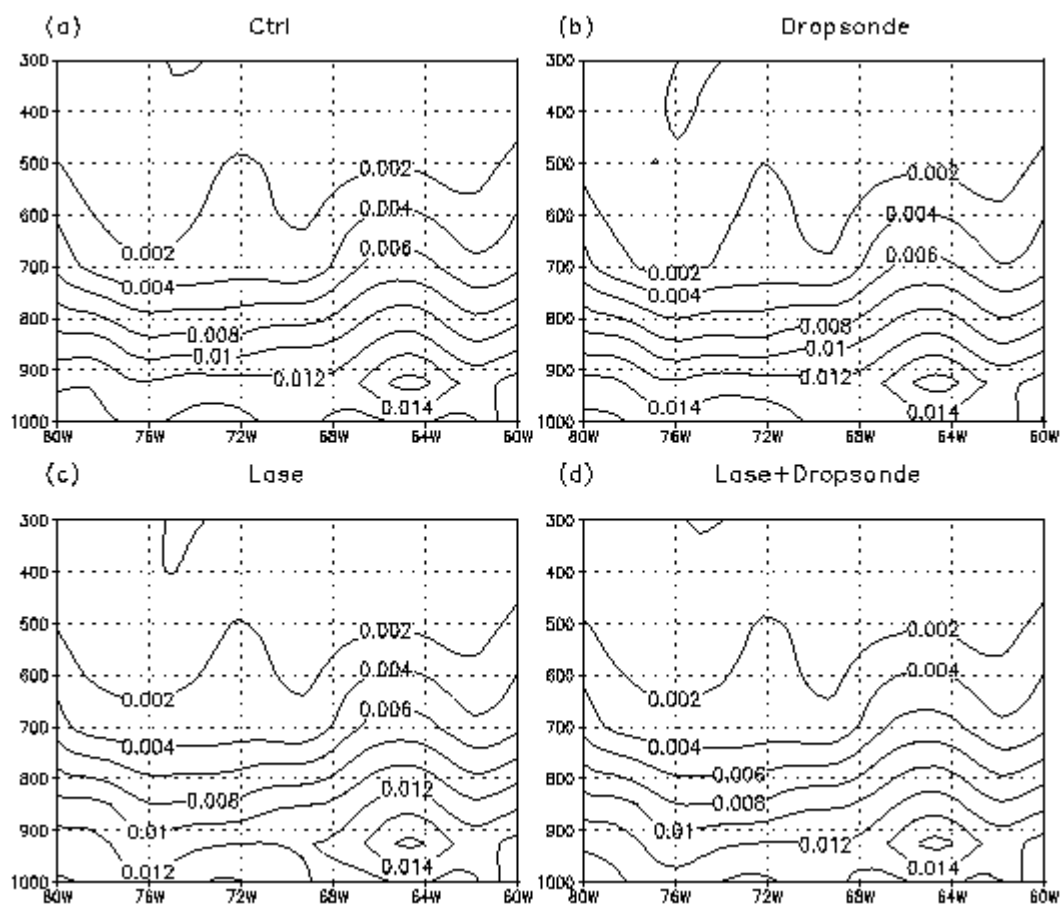
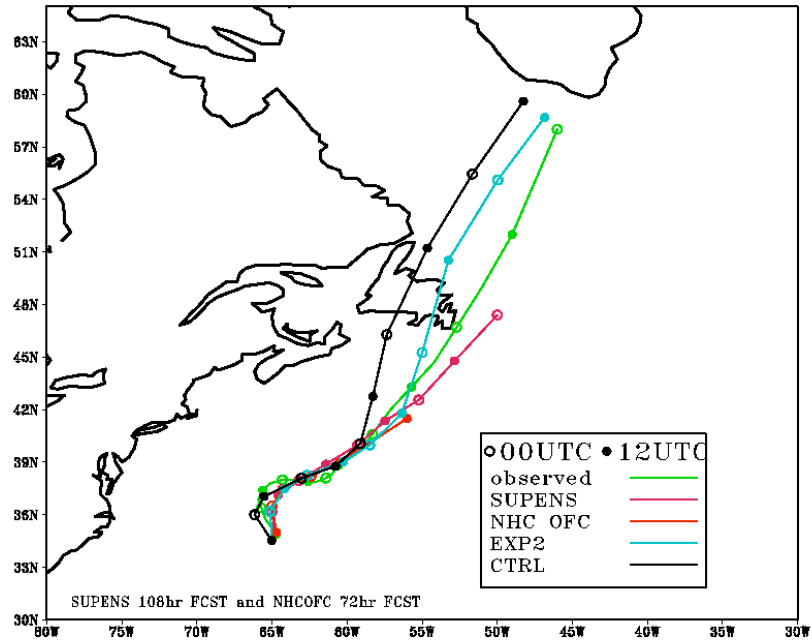


Fig.12.(a-d).

(a) 120hr Forecast track of Erin
IC:12 UTC 10 Sep 2001



(b) 120hr Forecast track of Humberto
IC:12 UTC 22 Sep 2001

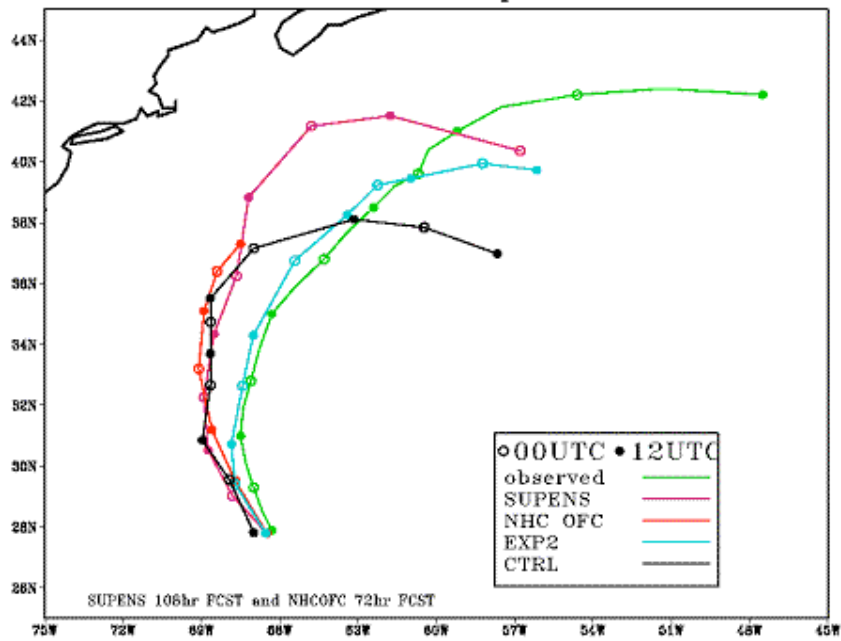


Fig.13 (a) & (b).

(c) 96hr Forecast track of Gabrielle
1C:00 UTC 15 Sep 2001

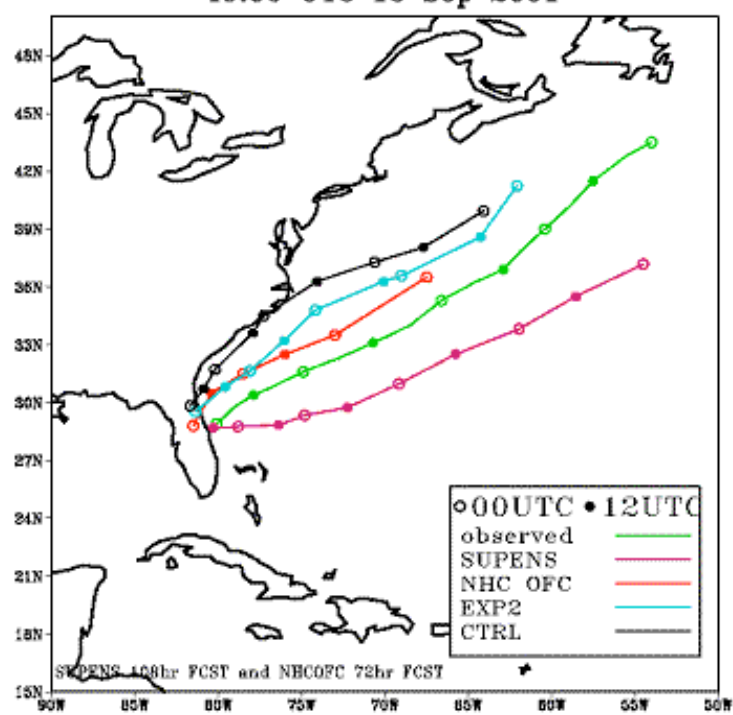


Fig. 13(c).