aer

Atmospheric and Environmental Research, Inc.

Final Report

on

IMPROVED USE OF SATELLITE IMAGERY TO FORECAST HURRICANES

A research program funded by

NASA

through Procurement Instrument

NASW-99043

Submitted by:

Jean-François Louis

Principal Investigator

Atmospheric and Environmental Research, Inc.

131 Hartwell Avenue, Lexington, MA 02421

21 September, 2001

Table of Content

[redacted]

Introduction

Hurricanes and typhoons are amongst the most devastating natural phenomena in coastal areas. Accurate predictions of hurricane path and strength are critical for minimizing the loss of life and damage to property.

Currently in the US, the forecast of the evolution of hurricanes is based on several statistical and numerical models: AVN (Global baroclinic), NOGAPS (Global baroclinic), UKMET (Global baroclinic), GFDL (Limited-area baroclinic), GFDI (Interpolated GFDL), LBAR (Limited-area barotropic), BAM (Trajectory), NHC90/NHC91 (Statistical) and CLIPER (Statistical). The multiplicity of models is indicative of the fact that no single model or method is entirely satisfactory. Forecasting hurricanes is difficult because they are phenomena of relatively small scale, not well represented by operational global forecast models, they develop over the oceans where there is a limited amount of data, and they involve very complex dynamical and physical processes. One of the major problems, which is the main focus of our research, is the difficulty of obtaining a good initial state for the numerical forecast models.

Without special intervention the models tend to develop cyclonic circulations in the wrong places. In large scale models the vortices are usually too weak and, once they develop, it is difficult to bring them back to the right track, mainly because there are not enough data over the oceans for the data assimilation system to overcome the wrong tendencies of the model.

An example of this problem is shown in Figure 1, which compares the track of Hurricane Guillermo (1997), as analyzed by the Medium Range Forecast (MRF) model of NCEP from 8/1/97 through 8/9/97, to the so-called "best track" data issued by the National Hurricane Center and obtained from the Unisys web site[1]. The average difference in positions is about 75 km. The analyzed central pressure of the hurricane is not nearly as low as the observed central pressure, as can be seen in Figure 2.

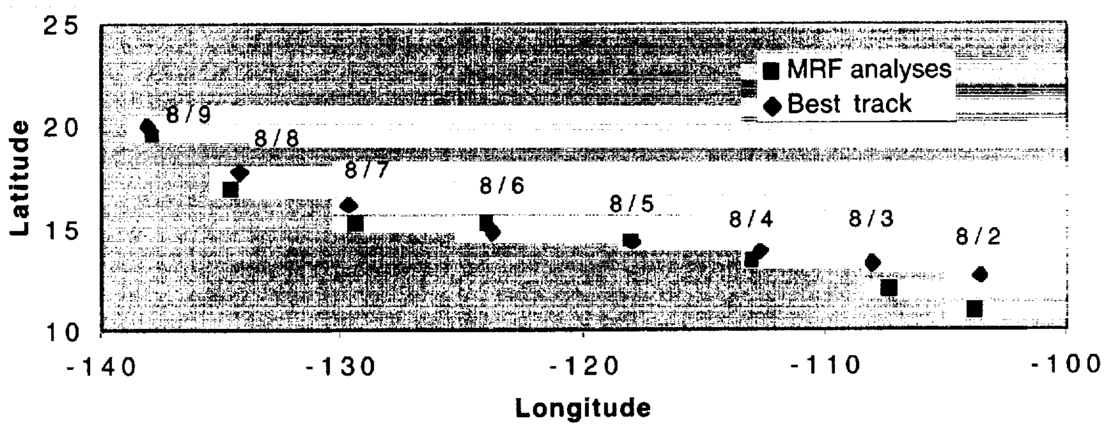

Figure 1: Track of Hurricane Guillermo (1997).

[1] http://weather.unisys.com/hurricane/index.html

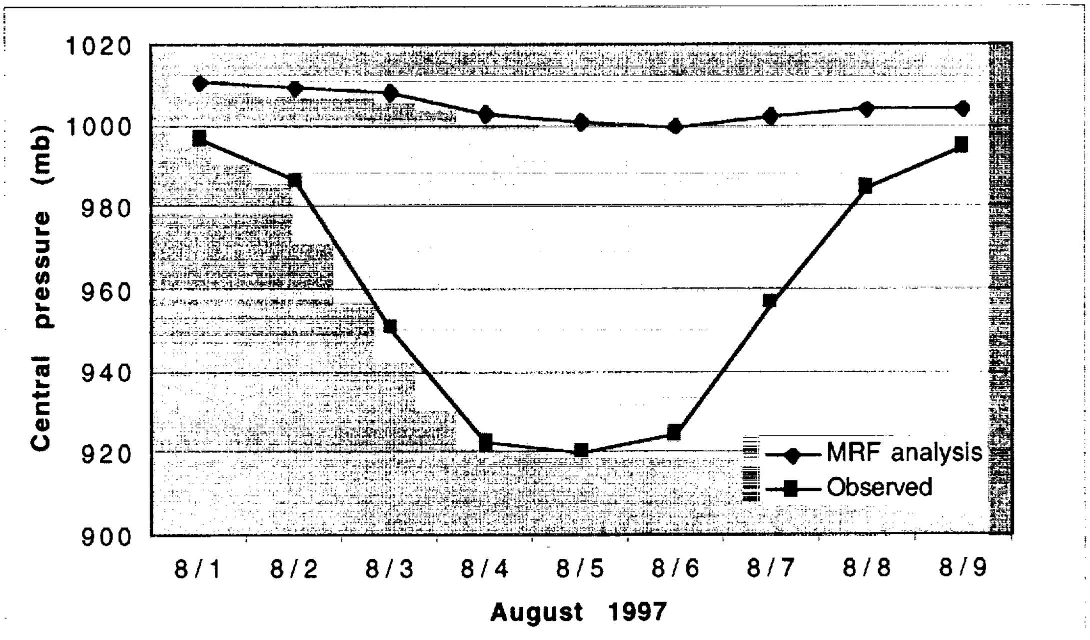

Figure 2: Central pressure of Hurricane Guillermo.

To mitigate these problems, all operational models that are specifically designed for hurricane forecasting modify the initial state in such a way as to spin up a vortex of the right intensity at the right place. This is done by introducing a bogus vortex, based on conceptual models, in a fairly empirical and rather unsatisfactory way, since the philosophy of numerical weather forecasting is to build models based on first principles. A summary of these procedures can be found in Elsberry, 1995[2].

AER has been developing a technique called "Feature Calibration and Alignment" (FCA), which uses satellite imagery or other data to identify and correct the phase errors of the background field in the data assimilation system (Hoffman and Grassotti, 1996[3] and Grassotti et al., 1999[4]). This method allows the data assimilation system to force tropical cyclones to follow their correct course, without the need for bogus data. It is expected that, by improving initial conditions, the forecasts of hurricanes should also be improved.

To test this method in the context of hurricane forecasting, we developed a prototype system by combining FCA with a mesoscale data assimilation system based on optimal interpolation - the Theater Analysis Procedures (TAP), and the NCAR/PSU mesoscale model MM5. These items have been developed or used at AER, but were combined for the first time in this project. Testing was performed on a few archived Pacific hurricane cases.

---

[2] Elsberry, R. L., 1995: Global Perspectives on Tropical Cyclones, Chapter 4. WMO Tropical Cyclone Programme Report 38. R. L. Elsberry, Ed., WMO, Geneva, Switzerland.

[3] Hoffman, R. N. and C. Grassotti, 1996: A technique for assimilating SSM/I observations of marine atmospheric storms. J. Appl. Meteor., 35, 1177-1188.

[4] Grassotti, G, R. N. Hoffman, and H. Iskenderian, 1999: Fusion of ground-based radar and satellite-based rainfall data using feature calibration and alignment. *J. Appl. Meteor.*, **38**, 677-695.

Our experiments each cover about one week in the life cycle of the hurricanes. They consist of several days of data assimilation and daily 72 hour forecasts. We compare the results of the complete system to those obtained with data assimilation only (witout FCA) and to forecasts that use bogus data for initial conditions. The intensity model of Emanuel[5] is used to provide bogus data.

Section B of this document describes all the elements of the system. Section C explains how the experiments were set up and Section D displays the main results. These results are discussed in Section E, which also suggests lines of research for the future. Some technical aspects of the work are detailed in appendices.

B Elements of the system

B.1 Forecast model

The forecast model we are using is the NCAR/PSU MM5. Originally developed at the Pennsylvania State University (Anthes and Warner, 1978), this model has been adopted by NCAR as a community model for mesoscale research. It is supported by NCAR and well documented. The Fifth-Generation Mesoscale Model (MM5) supports (i) a multiple-nest capability, (ii) nonhydrostatic dynamics, which allows the model to be used at a few-kilometer scale, (iii) multitasking capability on shared- and distributed-memory machines, (iv) a four-dimensional data-assimilation capability, and (v) a wide array of physics options. The model is supported by several auxiliary programs, which are referred to collectively as the MM5 modeling system. We have used version 3.4 of the MM5 without modifications and with the following options.

Physics Options:

IMPHYS = 4	Dudhia's simple ice for explicit precipitation scheme
ICUPA = 7	Betts-Miller cumulus parametrization scheme
IBLTYP = 5	MRF planetary boundary layer scheme (Hong and Pan 1996)
FRAD = 2	Dudhia's long- and short-wave radiation scheme with clouds
ISOIL = 1	Multi-layer soil temperature model
ISHALLO = 0	No shallow convection

We were not able to run the model with a triply nested grid and innermost grids following the hurricane, as originally planned, since the MM5 does not actually allow this option. Our chosen configuration was then to run the model with two fixed grids with a fairly large inner grid with a resolution of 40 km. The innermost grid is shown in Fig. 4 and other figures which follow. We performed all the data assimilation on our own computer system, but ran 72 hour forecasts at the Maui High Performance Computing Center (MHPCC).

We used the MRF analyses and forecasts of NCEP to provide the first initial conditions and lateral boundary conditions for our forecast experiments. In the case of Iniki we used the NCEP re-analysis fields.

[5] Emanuel, K. A., 1999: Thermodynamic control of hurricane intensity. Nature, 401, 665-669.

B.2 Data Assimilation

There are many kinds of data assimilation systems. The system that is distributed with the NCAR MM5 is in two parts. First the data are analyzed with a successive correction method, and this is followed by Newtonian relaxation (also called nudging) of the forecast fields. The nudging allows the data to affect the forecast in a smooth manner, without generating too many unwanted gravity waves. However, the successive correction method is a rather outdated method, which does not allow the proper handling of observations with different error characteristics (e. g. radiosondes and satellite retrievals).

Most operational weather forecasting centers are now using or developing variational data assimilation methods, in which the difference between the background forecast and the observations during an assimilation period is minimized by modifying appropriately the initial state of the background forecast. These methods are very expensive in terms of computer resources because they are iterative methods that require many integrations of the model and its adjoint over the assimilation period.

We used an analysis system that we developed under USAF sponsorship. It is a mesoscale data assimilation system, called Theater Analysis Procedure (TAP), which is based on optimal interpolation (OI) (Nehrkorn and Hoffman, 1996[6]; Nehrkorn, et al., 1997[7]).

For ease of development, most of the components of TAP were originally written in the Splus interpretive language distributed by MathSoft. This language makes it easy to create prototypes. However, for efficiency and portability, the code not already converted to FORTRAN under USAF support, was converted to FORTRAN during the second year of the project.

We have written software to substitute TAP for the standard MM5 analysis. However we still use the MM5 nudging procedure since the fields generated by TAP are not in perfect dynamical balance. The whole procedure is rather complex and more details on the software can be found in Appendix F.2.

We perform the data assimilation only over the inner grid of the MM5. The data used are described in Section C.2.

B.3 Feature Calibration and Alignment (FCA)

Like all standard data assimilation schemes, TAP suffers from the inability to account for background phase errors. This is because forecast errors are defined as the differences between observation and background at the point of observation. That means that all the errors in the background forecast are implicitly assumed to be amplitude errors. To address this problem we have developed a technique we call Feature Calibration and Alignment (FCA),

---

[6] Nehrkorn, T. and R. N. Hoffman, 1996: Development of a small-scale, relocatable optimum interpolation data analysis system. 11th Conference on Numerical Weather Prediction, Amer. Meteor. Soc., Norfolk, VA, 19-23 Aug. 96, pp 91-93.

[7] Nehrkorn, T., R. N. Hoffman, J. Sparrow, M. Yin, S. Ryckman and M. Leidner, 1997: Theater Analysis Procedures (TAP). Final Report, Contract # PL-TR-97-2146, Phillips Laboratory, Hanscom Air Force Base, MA, 138 pp.

which attempts to identify and correct phase errors in the background field (Hoffman and Grassotti, 1996[8] and Grassotti et al., 1999[9]).

The essence of the technique is a new way of computing the difference between two fields or, in the case of data assimilation, between a background forecast field and a field of observations. We decompose the difference into a deformation (corresponding to a large scale phase error), an amplification (large scale amplitude error) and a residual (random, small scale error). The phase and amplitude errors are mainly due to deficiencies in the model physical or numerical representations and should be smooth, large-scale and of relatively small magnitude. In practice we represent the adjustment as a truncated series of basis functions, with few degrees of freedom. We determine the adjustments by a constrained minimization of the difference between the aligned and calibrated background field and the observations.

In our first tests the procedure consisted of finding the optimum fields of horizontal displacement which, when applied to the MM5 forecast fields of integrated water vapor (IWV), resulted in adjusted model fields that more closely matched the observed SSM/I IWV fields. Additional constraints on the solution are imposed which insure that the adjustments are not unrealistically large or too rough. We found that, often, the IWV field did not define the position of the hurricanes accurately enough. We then used an additional constraint that forced the alignment vector near the center of the hurricane to point towards the position defined by the best track data.

B.4 Hurricane Intensity model

In the experiments in which we use a bogus vortex, we used Emanuel's hurricane intensity model to generate a series of soundings around the hurricane center. This model is described in Emanuel (1995)[10] and Emanuel (1999)[11]. It is based on the idea that hurricanes may be best understood as thermodynamic heat engines.

This model uses the observed track data to evaluate the structure of the hurricane. It assumes that the storm is axisymmetric and that the airflow is never very far from a state in which the horizontal and vertical pressure gradient accelerations are balanced by centrifugal and gravitational accelerations, respectively. It also assumes that the vortex is always close to a state of neutral stability with respect to a combination of gravitational and inertial forces. These constraints place very strong restrictions on the structure of the vortex so that, with the exception of the water-vapor distribution, the vertical structure is determined by a very limited set of variables. Moist convection is represented by one-dimensional plumes whose mass flux is determined in such a way as to ensure approximate entropy equilibrium of the boundary layer. The model variables are cast in "potential radius" coordinates (Schubert and

[8] Hoffman, R. N. and C. Grassotti, 1996: A technique for assimilating SSM/I observations of marine atmospheric storms. J. Appl. Meteor., 35, 1177-1188.

[9] Grassotti, G, R. N. Hoffman, and H. Iskenderian, 1999: Fusion of ground-based radar and satellite-based rainfall data using feature calibration and alignment. *J. Appl. Meteor.*, **38**, 677-695.

[10] Emanuel, K.A., 1995: The behavior of a simple hurricane model using a convective scheme based on subcloud-layer entropy equilibrium. J. Atmos. Sci., 52, 3959-3968.

[11] Emanuel, K. A., 1999: Thermodynamic control of hurricane intensity. Nature, 401, 665-669.

Hack, 1983)[12], which is proportional to the square root of the absolute angular momentum per unit mass about the storm center. A mass flux scheme is used for the cumulus cloud model. The model is forced by atmospheric and oceanic data along the hurricane track.

C Experiments

C.1 Test cases

Since this work was performed in connection with the Pacific Disaster Center, we chose Eastern Pacific hurricanes that have, or could have, affected the Hawaiian Islands for our test cases. We concentrated on three hurricanes:

Name	Dates	Max. Wind (knots)	Category
Hurricane FELICIA	14-22 JUL 97	115	4
Hurricane GUILLERMO	30 JUL-15 AUG 97	140	5
Hurricane INIKI	05-13 SEP 92	125	4

The first two are fairly recent hurricanes. Therefore the observations available for these cases are similar to what is available today. Hurricane INIKI is a particularly interesting case because its center went right over the island of Kauai and it seriously affected the Waianae coast of Oahu. The track of these hurricanes is shown on Figure 3

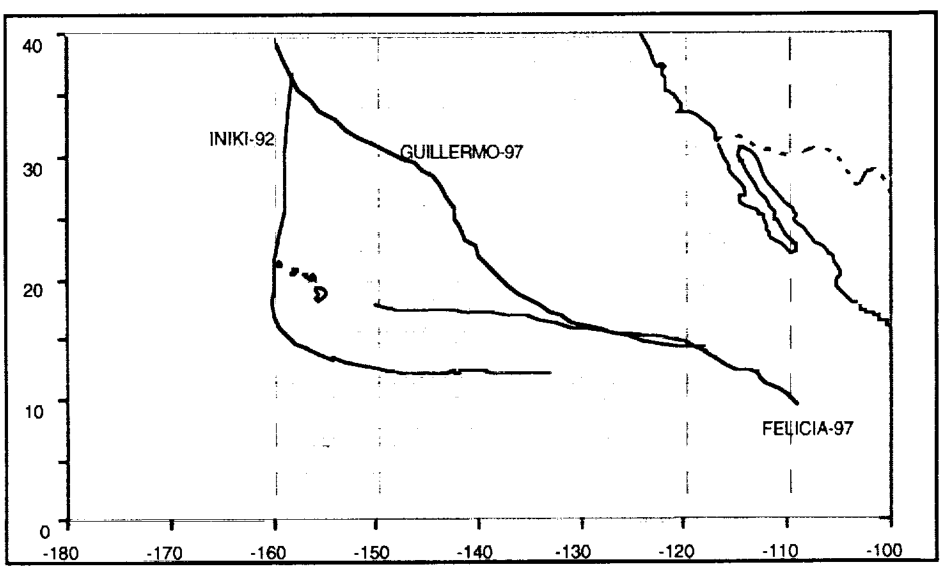

Figure 3: Tracks of the potential test cases.

[12] Schubert, W. H., and Hack, J. J., 1983: Transformed Eliassen-balanced vortex model. *J. Atmos. Sci.*, **40**, 1571-1583

C.2 Data

The following data sources were used in this project:

Surface data, including ships and buoys

These are available at the National Center for Atmospheric Research (NCAR) for every synoptic hour. The Pacific buoy data for surface wind, air temperature and sea surface temperature are archived with a 2 month lag.

Radiosondes

The US controlled radiosondes are archived at NCAR. Since there are very few radiosondes in the Pacific, this is not a major source of data for this project.

Aircraft reports

The aircraft reports (wind and temperature data) are also archived at NCAR. These data are not quality controlled. They are concentrated along the air traffic corridors.

HIRS soundings from TOVS satellites

Satellite soundings from TOVS are available on the web. However the data available in this fashion are raw radiances. Since we did not want to handle the retrieval and quality control problems we obtained the retrieved soundings from NCDC.

SSM/I integrated water vapor from DMSP satellites

These data are available on the Internet from Remote Sensing Systems, Inc., as daily maps on a 0.25 degree regular grid. The data also contains surface wind speed, precipitation rate and integrated cloud liquid water. However, measurements of surface wind speed are strongly affected by precipitation and are generally missing around hurricane centers. Precipitation rates and cloud liquid water data are of course not available everywhere. Integrated water vapor is therefore the most complete dataset and most suitable for use with the FCA technique. We have used it successfully in previous research. The only problem with these data is that the DMSP satellites are sun synchronous with morning/evening orbits and the measurement swaths do not overlap. However several satellites are flying at the same time, making the coverage reasonably good. Our FCA code is able to use data from all the concurrent SSM/I instruments and from several passes near the same time.

Sea surface temperature

Sea surface temperature is part of the MRF analyses that have been used for boundary conditions.

Model data

Some model data are also needed to provide the lateral boundary conditions and the background field for the TAP analysis system. We used the NCEP Medium-Range Forecast (MRF) model analyses and forecasts for Guillermo and Felicia. It is a global model and the data are available at NCAR. For Iniki, we used the NCEP re-analyses.

Hurricane estimated best tracks and official forecasts

These are needed for the intensity forecast model and for verification and comparison purposes. We have obtained those from the Central Pacific Hurricane Center in Honolulu and from the Air Force Weather Agency.

C.3 Set-up

For each hurricane we performed three sets of experiments. In all cases we use the MRF analysis or NCEP reanalysis as the source for the first initial state and for the boundary conditions. These data are interpolated to the MM5 model resolution (120 km for the outer grid and 40 km for the inner grid).

The control experiment approximates the current operational procedure, as far as hurricane forecasting based on numerical models are concerned. At the start of each forecast we run the Emanuel intensity model to generate bogus soundings near the center of the hurricane at hour 3 of the forecast. We then run the TAP analysis at hour 3, using the bogus soundings in addition to any other available data to modify the background field provided by the interpolated MRF data. This creates a target field towards which the MM5 is nudged during a two-hour period (hours 2 to 4 of the forecast). The forecasts are then integrated out to 72 hours.

The second set of experiments is called TAP-only. Its purpose is to determine whether, once a vortex is identified, there are enough data to keep it in its correct track with a standard data assimilation procedure. In this experiment we use bogus soundings only at the first analysis time. Subsequent analyses, every 6 hours, only use available radiosondes, surface and buoy observations, aircraft reports, cloud drift winds and TOVS soundings converted to thickness. A three-day forecast is run daily from these analyses.

The third experiment, TAP&FCA, is similar to TAP-only except that, every 12 hours we perform FCA to correct the drift of the hurricane. The 12-hour interval was chosen because, in the Eastern Pacific region, the SSM/I data are available within a few hours of 03 UTC and 15 UTC. The TAP analyses are performed at the synoptic times: 00, 06, 12 and 18 UTC. A diagram explaining this procedure can be found in Appendix F.1.

TAP and FCA both require a background, which is a previous MM5 forecast. This background is modified either by alignment, in the case of FCA, or by the assimilation of data in the case of TAP. We cannot just replace the background fields by the output of TAP or FCA. These outputs are not sufficiently balanced and the model would immediately generate large oscillations. Instead, we use the standard nudging procedure included in the MM5 system, by which the forecast fields are relaxed towards the output of FCA or TAP (which we call the nudging fields or target fields) over a two-hour period.

D Results

D.1 Control experiments

D.1.1. Hurricane Guillermo (1997)

On 8/2/97, 00UTC Hurricane Guillermo was situated at 13.0N, 104.0W, with a central pressure estimated at 983mb. The MRF analysis for that day (Figure 4) shows a very weak vortex in that position, with a pressure of about 1009 mb.

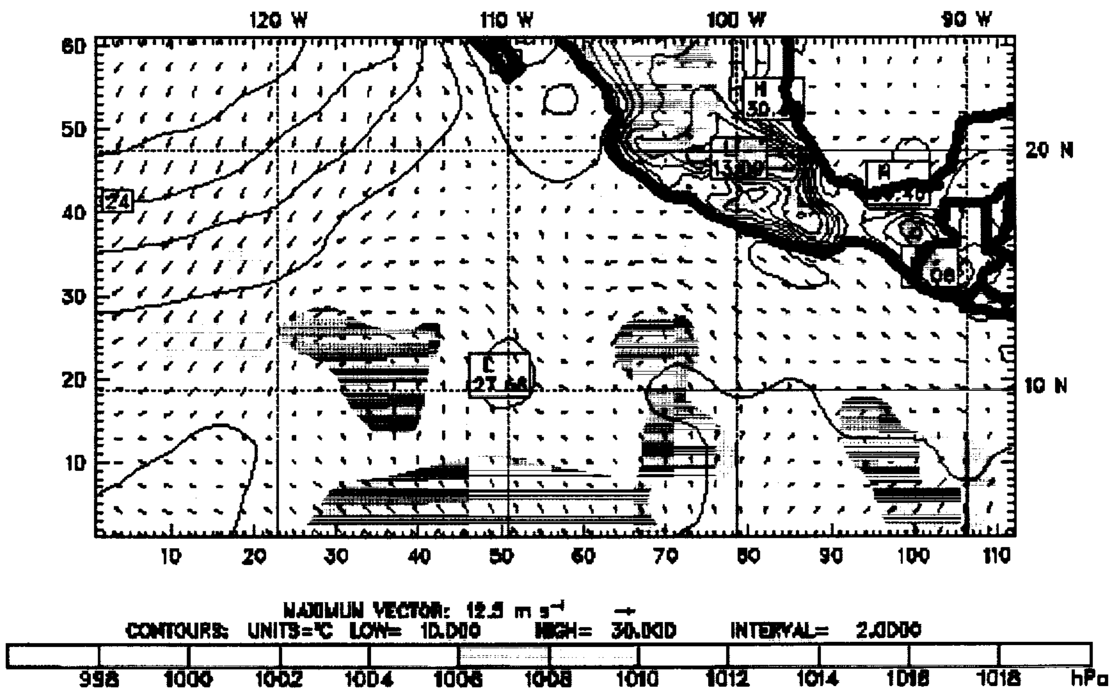

Figure 4: MRF surface analysis on 8/1/97, 00 UTC. The colored shades are the surface pressure, contours are the surface temperature and the surface wind is shown by arrows.

If we start an MM5 forecast from this data, the vortex does not develop. It drifts to the north and disappears in a few hours. Our procedure to spin-up the hurricane is to run Emanuel's intensity model from the time at which the maximum wind exceeds 30 knots (7/30/97) until the current time. We then compute vertical profiles at the center of the vortex and at up to three times the radius of maximum tangential wind and use these profiles as bogus soundings in the TAP analysis module.

The result of this procedure is shown on Figure 5. At that point the MM5 fields have been nudged for 2 hours towards a target generated by TAP, which includes the bogus soundings. The central pressure of the vortex is 996 mb, which is much closer to the observed. The horizontal scale of the hurricane, however, is rather large, probably due to the error structure functions used in TAP, which are defined mainly for mid-latitude synoptic scale features and not specialized for the small scale of tropical cyclones.

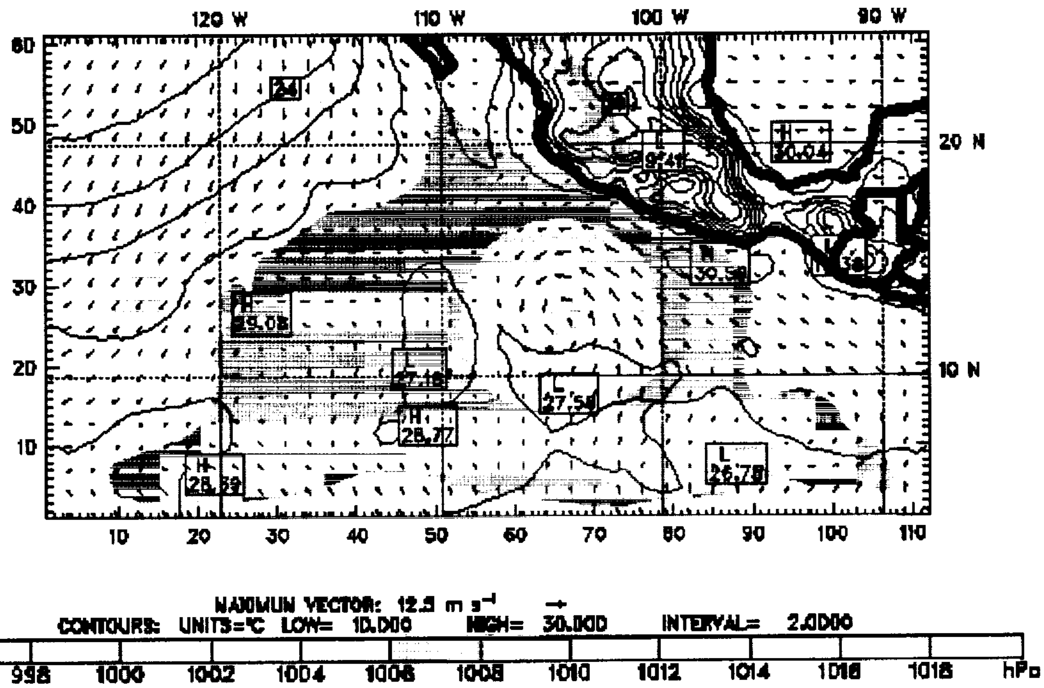

Figure 5: Hurricane Guillermo on 8/1/97, 04 UTC, at the end of the nudging period with bogus soundings.

In the control experiment, the MM5 continues to run for 72 hours without any additional forcing. The MM5 rapidly shrinks the vortex and increases the tangential wind velocity near the center, as can be seen in Figure 6. As an example of the kind of structures that develop during the forecasts, Figure 7 shows one of the control forecasts on 8/4/97, 18 hours into the forecast. The surface pressure field is contoured, and integrated cloud liquid water generated by the model is shown in color. This can be compared to the cloud liquid water measured by SSM/I at approximately the same time. Note that the color schemes of the two figures are different. Even though details of the structure of the hurricane are different in the two figures, one can see that the MM5, even at 40 km resolution, can generate quite realistic features such as spiral cloud bands with accompanying precipitation. The overall size of the hurricane is also quite reasonable.

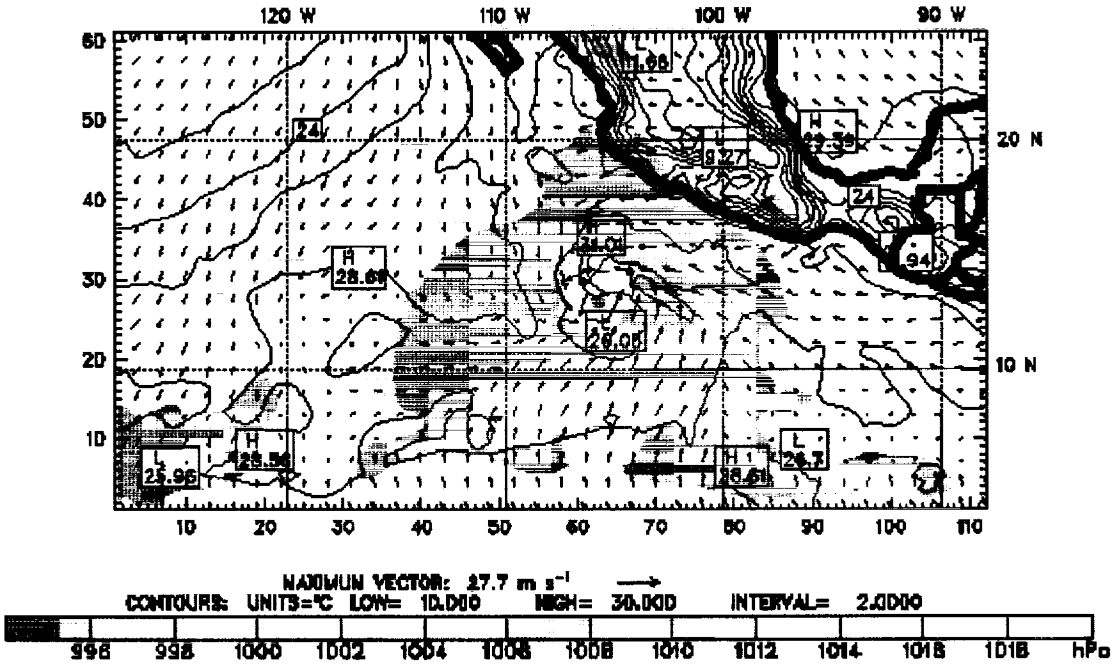

Figure 6: Hour 18 of the first Guillermo control experiment.

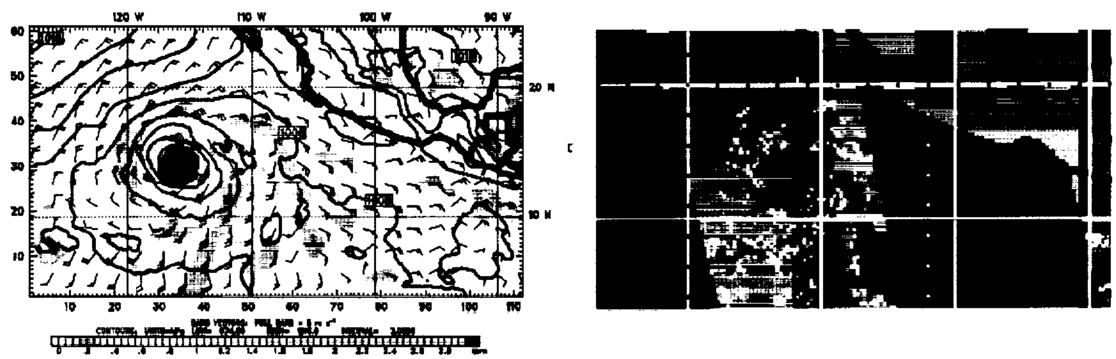

Figure 7: Hurricane Guillermo, 18 hour control forecast from 8/4/97, 00 UTC (left), compared to SSM/I cloud liquid water data[13], at approximately the same time. Black regions on the SSM/I panel are areas between the data swaths.

We performed four 72 hour forecasts, from August 2, 3, 4 and 5, 1997, each starting at 00 UTC with the bogussing procedure outlined above. The tracks of Guillermo in the four forecasts are shown on Figure 8, together with the so-called "best track", which is the best estimate of the actual track, derived from all available data such as satellite fixes or reconnaissance flights. The best track is the blue line, with marks every 3 hours. The symbols on the forecast curves are 6 hours apart. It can be seen that all the computed tracks have a tendency to drift too far to the north. The translation speed of the hurricane is also a little too fast.

[13] From the Remote Sensing Systems web site http://www.ssmi.com/ssmi_browse.html

The intensity of the forecast hurricanes is compared to the actual value on Figure 9. Since there were reconnaissance planes that released dropsondes in the eye of Hurricane Guillermo several times during that period, we can be confident that the best track values of the surface pressure at the center of the hurricane are quite accurate. It is clear that, even though the Emanuel intensity model generates soundings that have approximately the correct surface pressure, the TAP/MM5 system does not fully accept this information, and at six-hours into the forecast, the initial vortex has weakened. The circulation subsequently intensifies but not sufficiently.

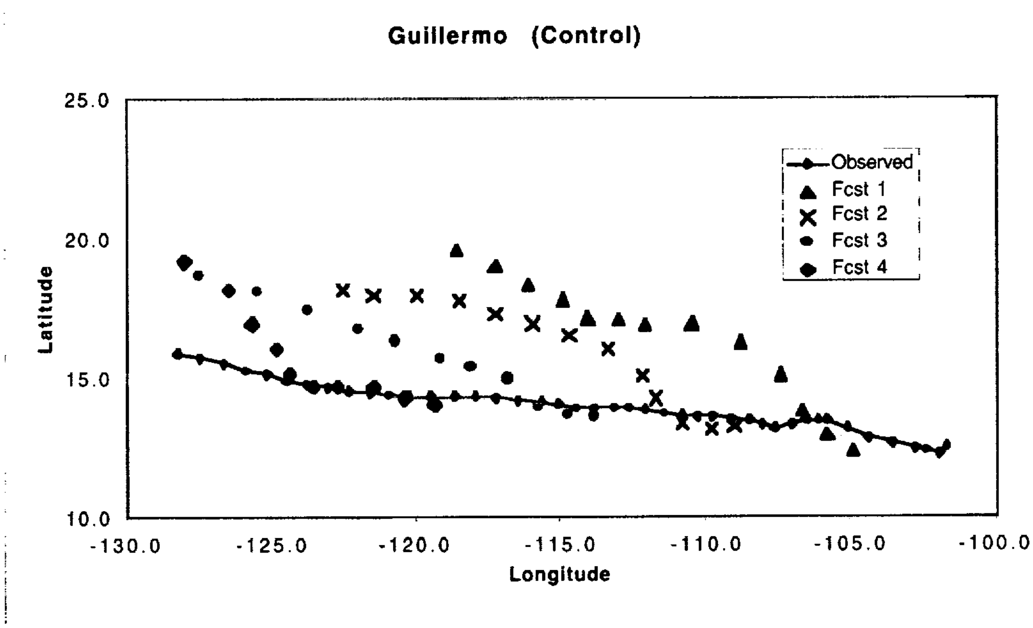

Figure 8: Hurricane Guillermo, best track (blue line) and 4 control forecast tracks

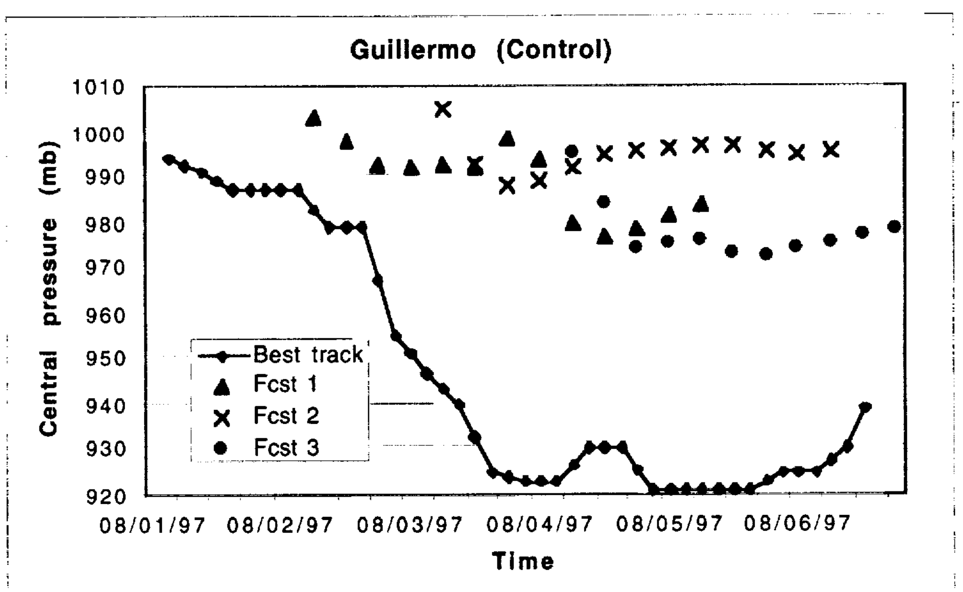

Figure 9: Hurricane Guillermo, central pressure. Solid blue line: observed; symbols: control forecasts.

D.1.2. <u>Hurricane Felicia (1997)</u>

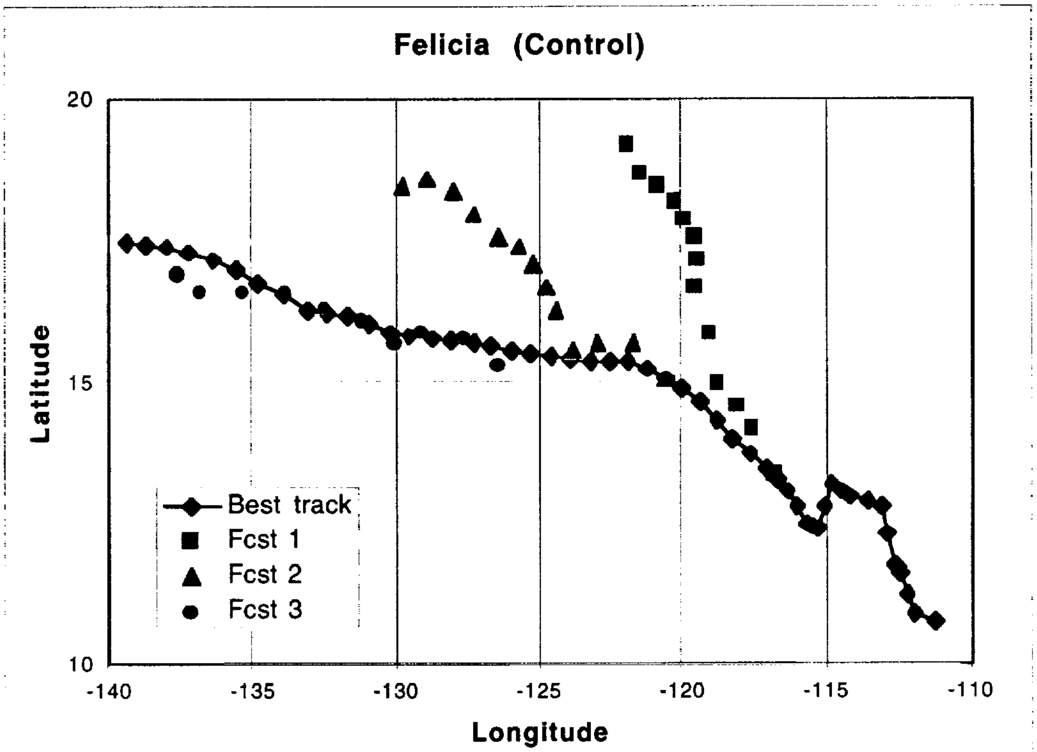

Figure 10: Hurricane Felicia. Best track and control forecasts.

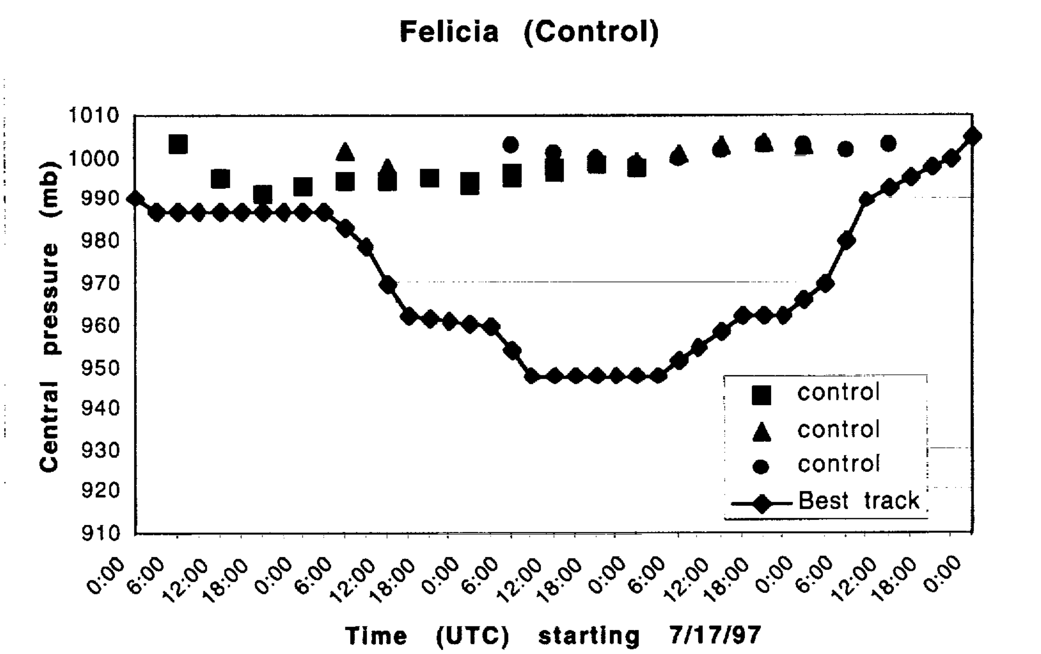

Figure 11: Hurricane Felicia. Observed and control forecast central pressure.

We started the Felicia experiments on 7/15/97, 00 UTC. At that point Felicia was still a tropical depression. Its center meandered somewhat while its circulation was getting organized and it became a category-1 hurricane 48 hours later, amplifying to a category-4 hurricane at 7/19/97, 15 UTC before weakening to a tropical depression on 7/22/97.

We performed three control forecasts starting from 00 UTC on July 17, 18 and 19. Figure 10 shows the track for these forecasts, compared to the best track data. The results are analogous to those of Guillermo. The first two forecasts follow the observed track quite well during the first day, but later diverge sharply towards the North. The third track is very good, though a little slower than observed.

As in the case of Guillermo, the central pressure obtained from the bogus soundings is not maintained in the six-hour forecast, which is the first data point in each of the control forecasts of Figure 11. The intensification is too weak and the vortex barely reaches hurricane force.

D.1.3. Hurricane Iniki (1992)

From 9/8/92 to 9/10/92 Hurricane Iniki moved rapidly westward. It then slowed down considerably, recurved sharply to the north and accelerated again, crossing the island of Kauai during the night of the 11th.

We performed four control forecasts, from 00 UTC on each day from 9/8 to 9/11/92. The first three forecasts started out by moving too far to the North and too slowly, as can be seen in Figure 12. They all indicate the recurvature at about the right time but, since they are too slow, it occurs too far to the east. The last forecast is quite good though its initial state is a little too far to the west. This is due to the fact that the NCEP analysis has the center of Iniki too far to the south-west at that time and, even with the bogus soundings, TAP is not able to move the center to its correct position.

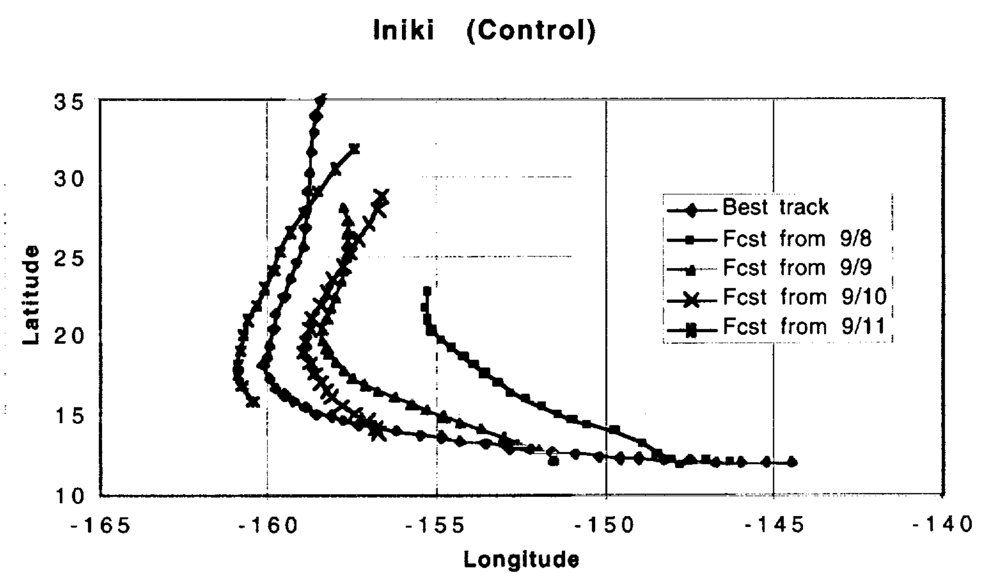

Figure 12: Hurricane Iniki. Best track and control forecasts.

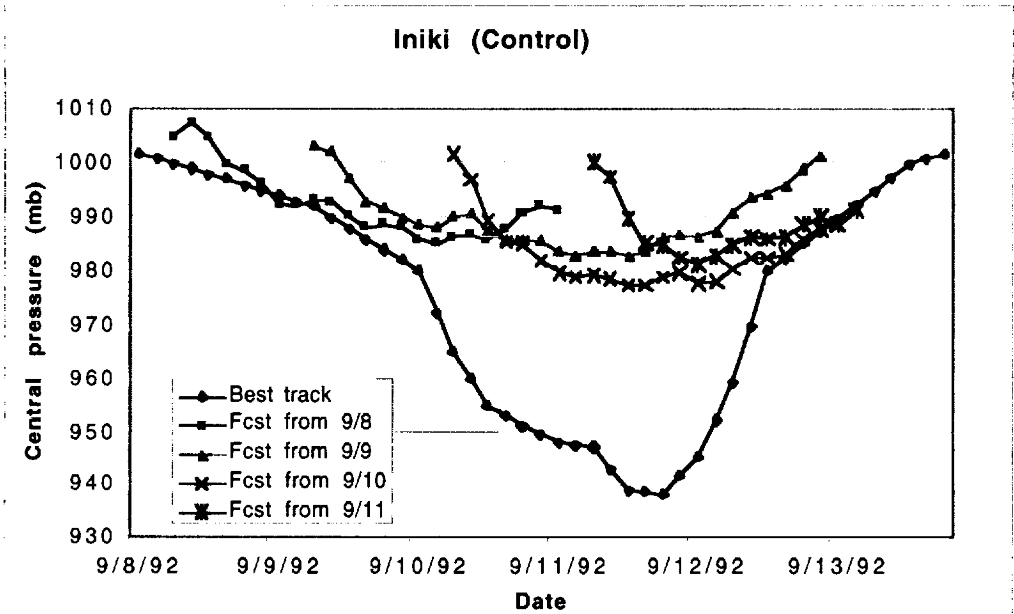

Figure 13: Hurricane Iniki. Observed and control forecasts central pressure.

Figure 13 confirms the results of Guillermo and Felicia as far as the intensities of the control forecasts are concerned. In the case of Iniki the storm is also much too weak after 6 hours of forecast. If we look in more detail at the evolution of the sea-level pressure field at the beginning of the forecast (Figure 14) we can see the rapid filling of the storm after the end of the nudging period at hour 4.

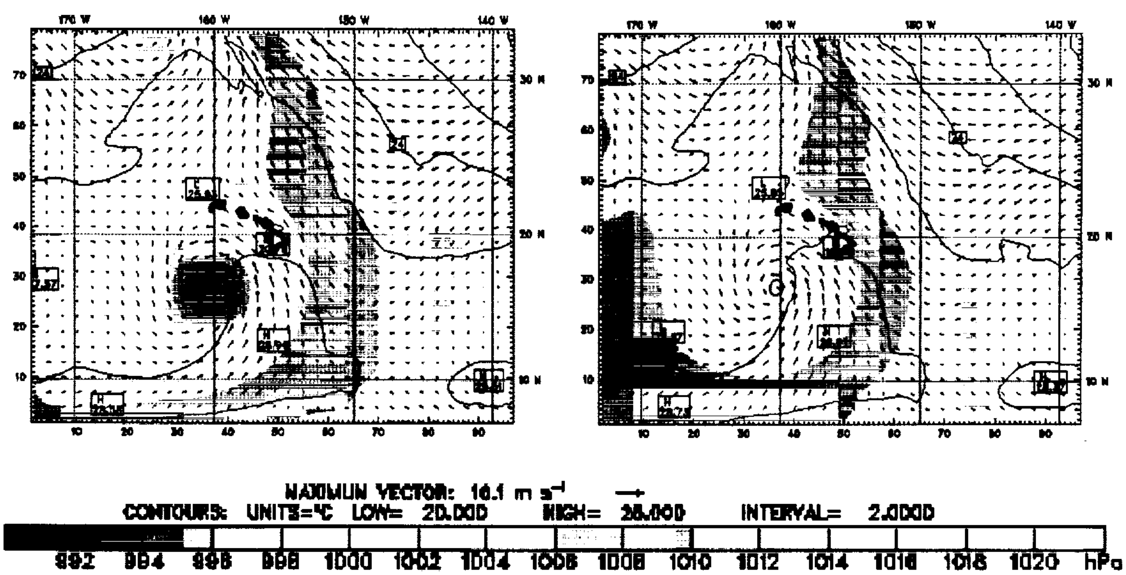

Figure 14: Hurricane Iniki. Hours 4 (left) and 5 (right) of the control forecast from 9/11/92, at the end of the nudging period.

D.2 TAP-only experiments

For the TAP-only experiment we show only the case of Hurricane Felicia. The other test cases behave similarly. We started the experiment on 7/15/97, 00 UTC with an analysis that included bogus soundings from the Emanuel intensity model. After that, TAP analyses are performed every 6 hours with all the available data, and with the background field provided by an MM5 forecast from the previous forecast segment. This analysis cycling was performed until 7/19/97, 00 UTC.

The track of the analyzed hurricane is plotted in Figure 15, along with the best track. Both tracks have symbols plotted every 3 hours. In addition, the figure shows the tracks of three different forecasts, started on the 17th, 18th and 19th at 00 UTC. The symbols defining the forecast tracks are plotted every 6 hours. The last forecast is truncated because the vortex loses its identity after about one day.

It is clear from this figure that the tracks of the forecasts are almost identical to that of the TAP-only analysis. This means that TAP is not able to correct the northward drift of the storm, and the analyzed track is essentially that of a free forecast starting at the beginning of the experiment. This will be discussed further in section E.

The speed of translation of the hurricane at the beginning of the track in the TAP-only cycling is much too fast. By the time we start the first forecast, the hurricane is already nearly 1000 km away from its observed position.

On the basis of these results and similar ones for Iniki and Guillermo, it is evident that TAP-only data assimilation, in the current configuration, is inferior to the control data assimilation.

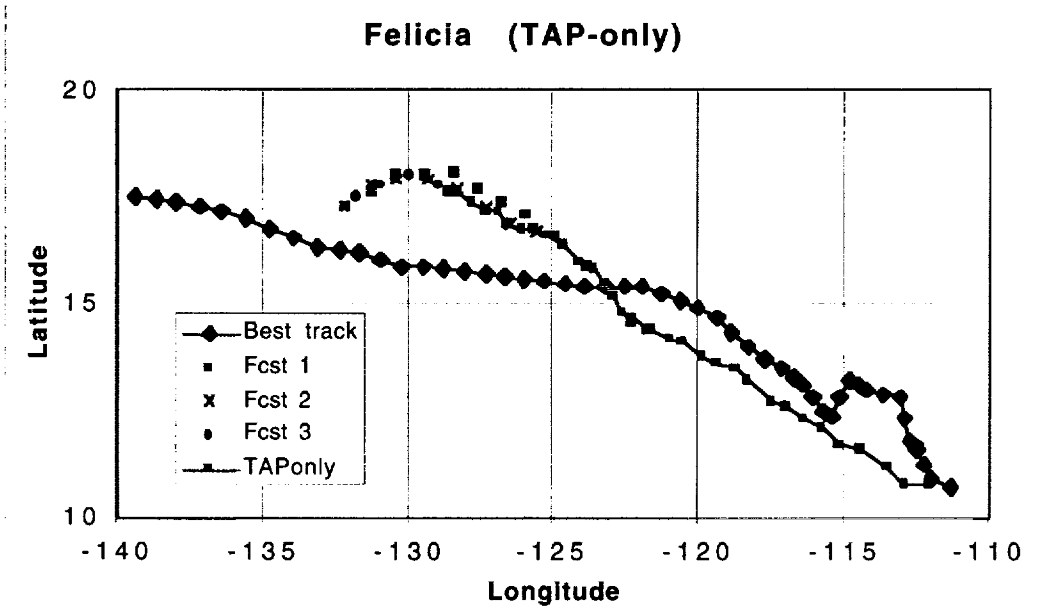

Figure 15: Hurricane Felicia. Tracks for the TAP-only experiment. The best track and TAP-only analysis are the connected lines.

D.3 TAP&FCA experiments

The first few hours of the TAP&FCA experiments are identical to the TAP-only experiments. However, we insert an FCA adjustment at 03 and 15 UTC during the data assimilation cycling. This is done by applying FCA to the existing MM5 forecast at those times and creating a target field towards which the MM5, restarted one hour before, is nudged during the first 2 hours of the new forecast segment.

The track of Guillermo during the TAP&FCA analysis cycling and four daily forecasts is shown on Figure 16. It can be compared to the control experiment in Figure 8. The effect of FCA can be seen clearly in the analyzed track, which exhibits a sawtooth pattern but never strays very far from the best track. During the 12 hours between two applications of FCA, the track essentially follows that of a free forecast, even though TAP is applied twice during that period. As we have seen in the control experiment, the forecasts tend to move the hurricane too far to the North, a drift that TAP alone cannot correct. FCA, however, is efficient at bringing the vortex back on the right track. It is evident, however, that FCA, as applied here, does not address the causes of the northward drift of the hurricane during the forecasts. In fact, the drift in this experiment is a little larger than in the control forecasts, as can be seen in Figure 17. This will be discussed later.

On the other hand, if we compare Figure 18 to Figure 9, it can be seen that the intensity of Guillermo is a little better in this experiment than in the control forecasts.

Figure 19 to Figure 22 show the results of the TAP&FCA experiments for Felicia and Iniki. They are similar to those for Guillermo.

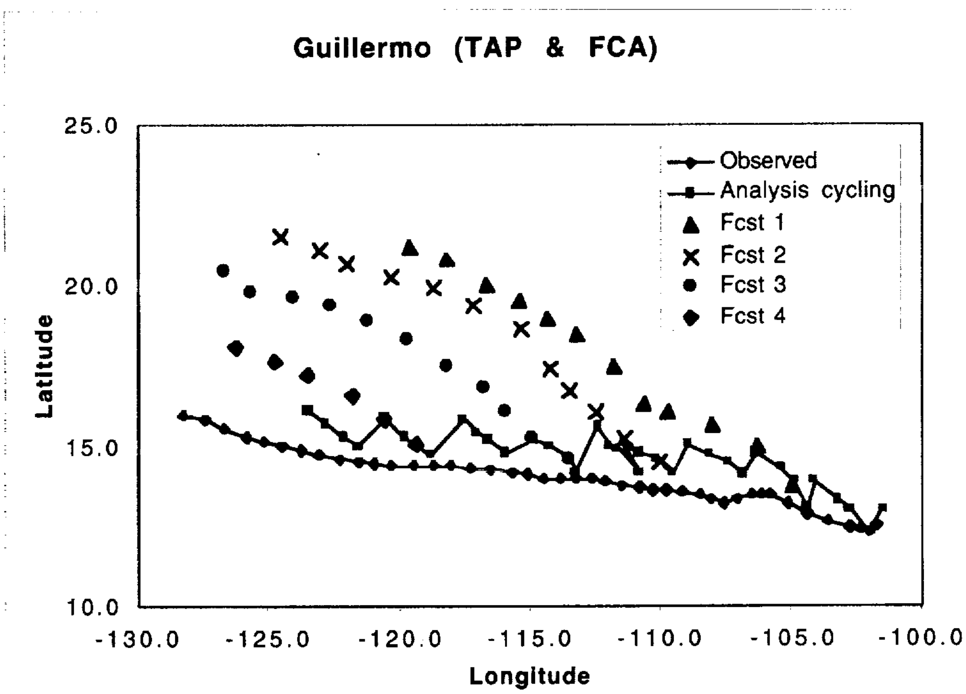

Figure 16: Same as Figure 8, but for the TAP&FCA experiment and with the analyzed track added (green line).

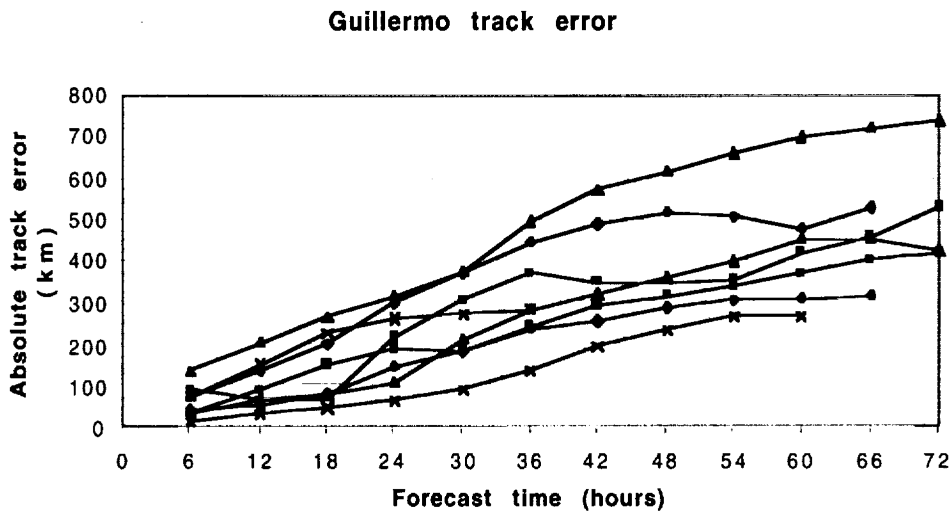

Figure 17: Comparison of forecast track errors in control experiment (blue) and TAP&FCA (magenta), for Hurricane Guillermo.

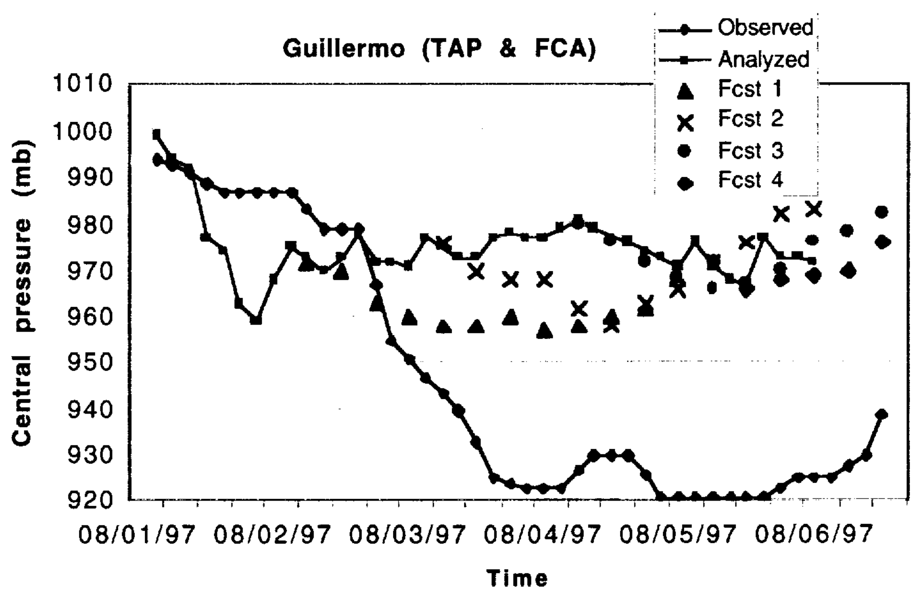

Figure 18: Same as Figure 9, but for the TAP&FCA experiment and with the analyzed track added (green line).

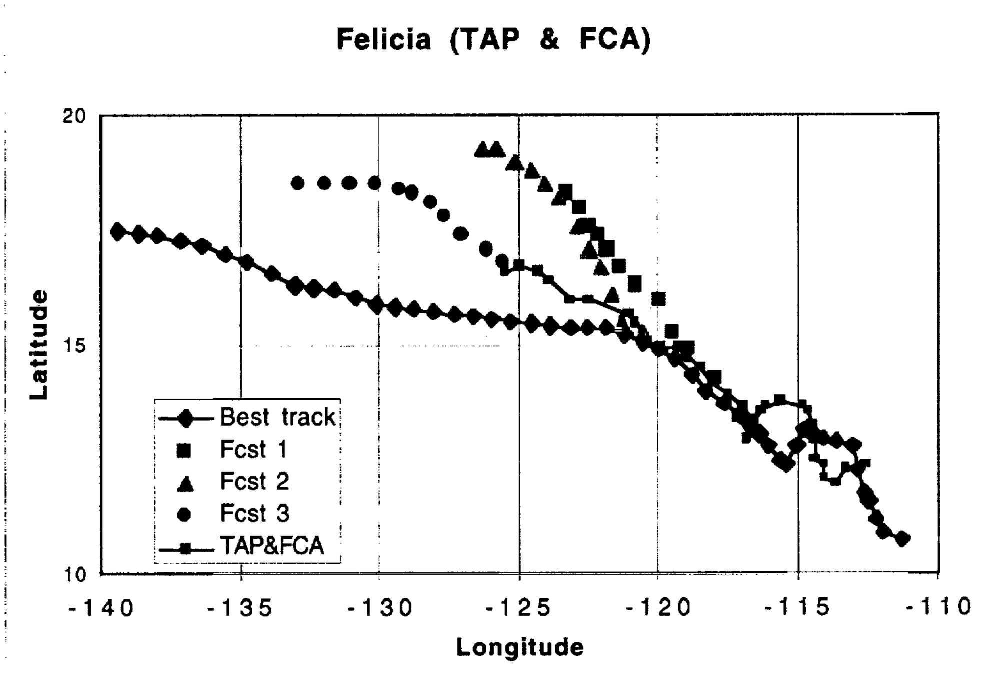

Figure 19: Same as Figure 16 but for hurricane Felicia.

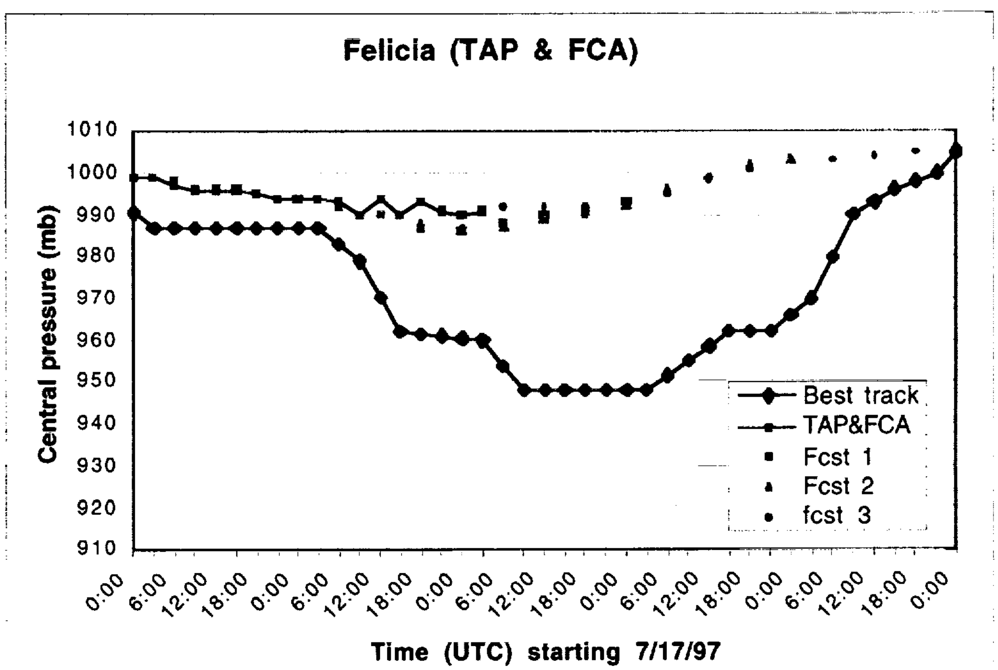

Figure 20: Same as Figure 18 but for hurricane Felicia.

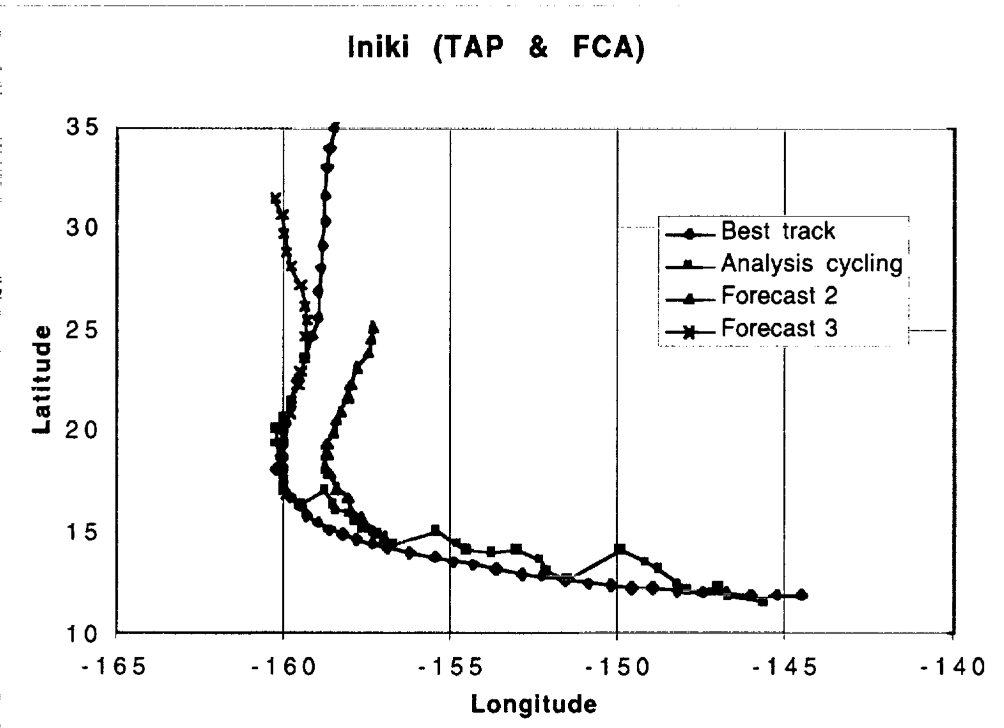

Figure 21: Same as Figure 16 but for hurricane Iniki.

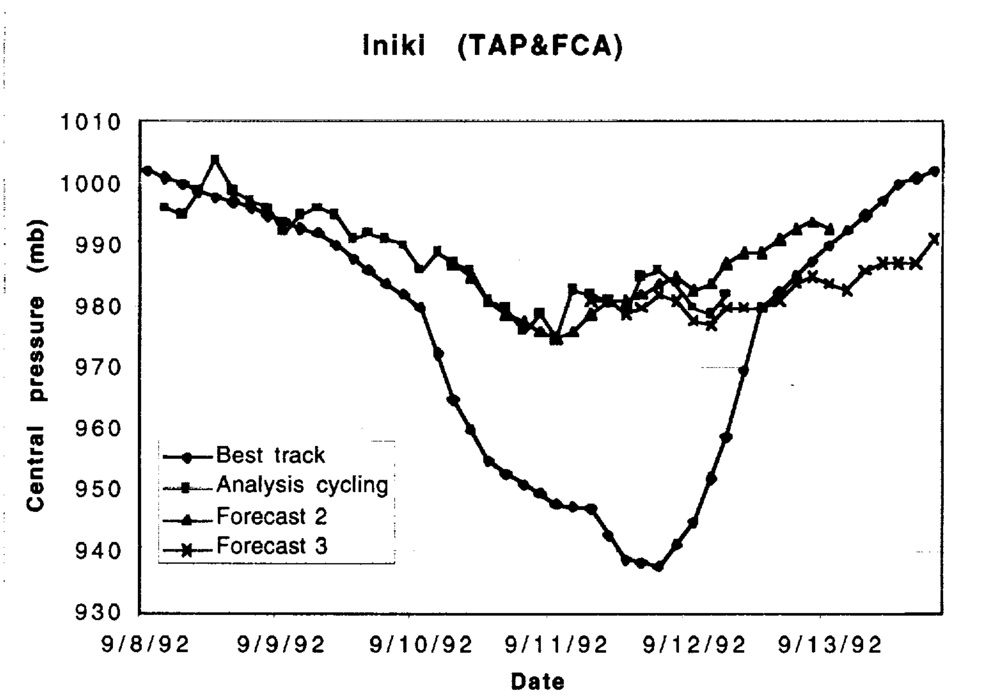

Figure 22: Same as Figure 18 but for hurricane Iniki.

E Discussion and outlook to the future

There is no doubt that adding FCA to TAP produces a much better analysis and forecasts of the hurricane than TAP alone. The main question to be considered, though, is how the FCA phase error correction procedure compares to standard operational methods in its ability to forecast hurricanes. In the context of a high resolution system that is run intermittently on a limited region when a hurricane threatens, our work confirms the need for using some sort of bogus data to spin-up the vortex, as is done operationally in most numerical weather prediction centers.

Our control forecast simulates the procedure used in almost all hurricane forecasting centers, by which a bogus vortex is introduced in the analysis to spin-up the hurricane. We do it in a simple way, by generating bogus soundings that are then used by our data assimilation module. Other methods substitute part of the analysis by a complete vortex, sometimes with some degree of asymmetry.

In the TAP&FCA experiment, once the initial vortex is spun-up, we let it evolve in the data assimilation cycling, but periodically the fields are repositioned to keep the vortex on track. The questions to be addressed next are: Is this sufficient to generate accurate forecasts? If not, are there further improvements to our method which might improve the accuracy?

Figure 23 displays the absolute track error for all the control (blue) and TAP&FCA (magenta) forecasts we performed. Some curves are truncated before the normal length of 72 hours, either because the vortex moved outside the inner MM5 domain, or the storm had weakened so that its center could no longer be determined accurately.

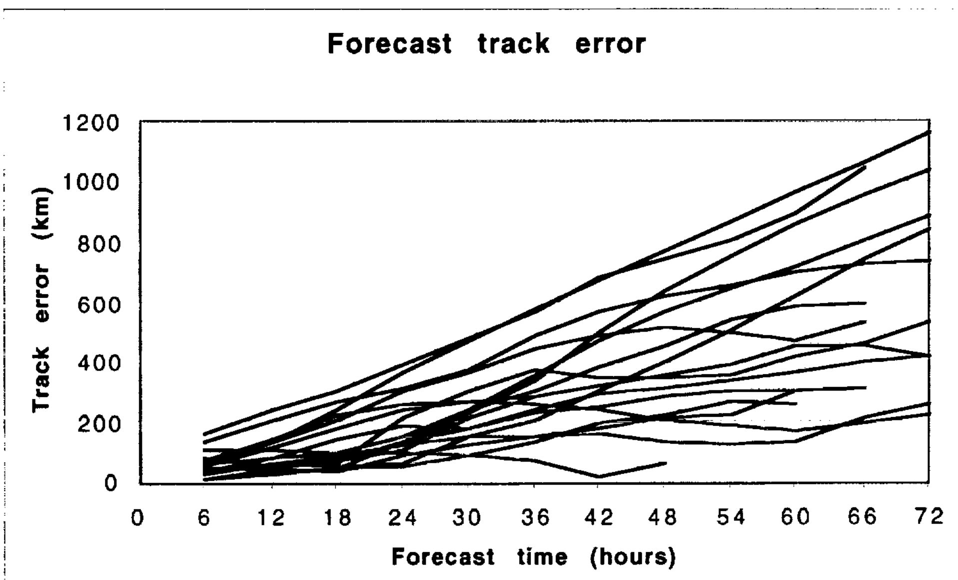

Figure 23: Comparison of the forecast track errors of the control experiments (blue lines) and those of the TAP&FCA experiments (magenta).

There is a large dispersion in the results, with errors at 72 hours ranging from slightly over 200 km to nearly 1200 km. There is also a clear tendency for the control forecasts to be better than the TAP&FCA forecasts. This is confirmed by Figure 24, which compares the average absolute track errors in the two experiments. In the mean the TAP&FCA error is about 60% larger than the error of the control experiment. Note that the control is slightly better even at the start of the forecast, which may explain subsequent faster growth of the error in TAP&FCA. As far as the forecast intensity is concerned, Figure 25 confirms that the TAP&FCA forecasts, in the mean, predict the central pressure of the hurricanes a little better than the control forecasts.

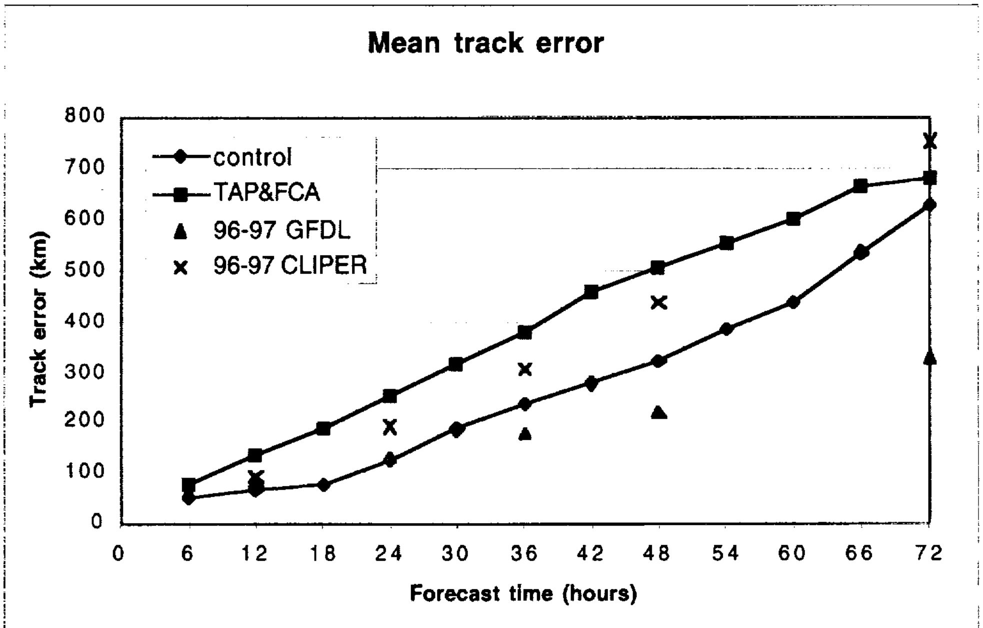

Figure 24: Mean forecast track error for the control (blue) and TAP&FCA (magenta) experiments.

In Figure 24 we also show error statistics taken from DeMaria (1997)[14] for CLIPER and GFDL for the years 1996 and 1997. CLIPER is a statistical method, used as a standard against which other methods are judged. The GFDL model is now the operational numerical hurricane forecast model of the US. The fact that for the first 24 hours our control forecasts have an accuracy similar to GFDL shows that, despite its simplicity, our bogussing method is a good representation of operational methods. Many factors may contribute to the faster growth-rate of the error of the control forecasts than GFDL, but it may be due to the fact that the MM5 model was not optimized for hurricane forecasting. We have not made an exhaustive study of the various physics packages available for the MM5, and it is likely that there is a better configuration for hurricane forecasting. Furthermore, our horizontal resolution (40 km) is coarser than GFDL's (~20 km).

Let us now consider the factors that affect the accuracy of our system and improvements that might be considered.

We have noted that in the TAP-only experiment the data assimilation system was unable to keep the vortices on track. This was not unexpected. It must be remembered that the availability of data is quite limited. There are almost no radiosondes over the oceans and surface observations from ships and buoys are few and far between, especially in the vicinity of

[14] DeMaria, M., 1997: Summary of the Tropical Prediction Center/National Hurricane Center Tropical Cyclone Track and Intensity Guidance Models. Informal reference http://www.nhc.noaa.gov/aboutmodels.html

tropical cyclones, which are avoided by ships. Airplane reports are also infrequent near hurricanes and even satellite soundings are, for the most part, absent near the hurricane center because of the presence of clouds.

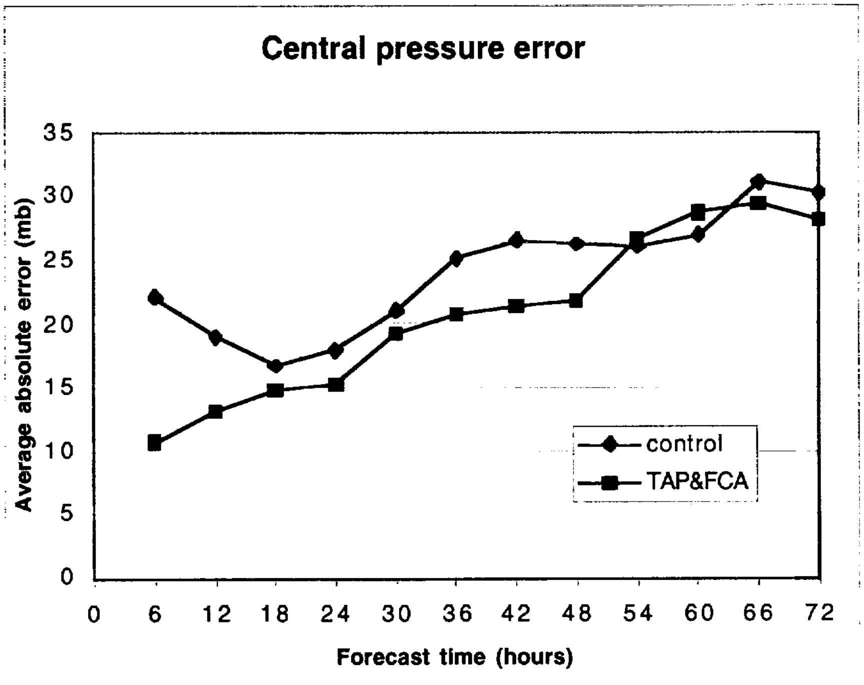

Figure 25: Comparison of average absolute error of the central pressure for the control and TAP&FCA experiments, all forecasts combined.

The biggest problem is the lack of surface pressure data. Satellite soundings, which contain only temperature data, can do little to correct the surface pressure field. Observations of surface winds by satellite-borne scatterometers are now beginning to be used by operational centers. These observations may provide a much better picture of the circulation around tropical cyclones. However, it is well known that wind observations at a single level are not easy to use to good effect and without distorting the vertical structure of the fields. This kind of data will be most effectively used in the 4-dimensional variational (4DVar) analysis systems that are now beginning to be implemented.

There are several possible improvements to the FCA module. We have been using vertically integrated water vapor (IWV) data from SSM/I as target for the FCA adjustment. There are a few problems with this procedure. First of all, since the data are vertically integrated, we have no information on the possible vertical structure of the phase errors and we make barotropic corrections. However, the SSM/I IWV is predominantly a measure of the humidity in the lowest layers. Secondly, the SSM/I IWV data is less capable of delineating the center of tropical cyclones than we expected. In various tests that are not described here, we found that relying on SSM/I IWV only was not sufficient to correct the position of the hurricane. We then added a constraint in the FCA procedure which forced the displacement vectors around the center of the vortex to point towards the position defined by the best track data. This may have introduced more unbalanced distortions than could be assimilated by the MM5 model.

Looking at the results summarized by Figures 24 and 25, one may be tempted to dismiss the FCA method and conclude that using bogus data is the only way to obtain reasonably accurate hurricane predictions. One should remember, however, that these are, to a large extent, preliminary results. FCA is a very new technique that is a long way from maturity, and anyone with operational experience knows how difficult it is to "beat" operational models or techniques.

Using bogus data also has many problems. For example, it is very difficult to introduce a realistic vortex that is sufficiently balanced and will not be rejected by the model. Indications of this problem are clear in our experiments.

It should be noted that, with the increasing resolution of the global models and better use of satellite data, the need for bogus data may disappear. Lam (1999)[15] found that tropical cyclone forecasts based on output of the ECMWF model (which does not use bogussing) were at least as skillful as subjective forecasts. To quote from her article: "It is pleasing to note that numerical modelling has become a reliable means of improving TC position forecasting".

The best way to further develop the FCA technique probably is to combine it with 4DVar, which certainly is the future of data assimilation. In fact, FCA is ideally suited to be part of 4DVar, being itself a variational method. Only a relatively small change to the cost function that is minimized in 4DVar is necessary to include FCA. This would mean that FCA would not be a separate module, but an integral part of the data assimilation. Instead of using only one kind of data to define displacement vectors that modify the background that is then passed to the assimilation system, all data would be treated the same way. In every estimation of differences between analysis and data, a possible phase error would be included instead of assuming that all errors are local amplitude errors. Work is currently under way at AER to estimate the covariance of the alignment vector, which is needed to include FCA in 4DVar.

[15] Lam, Q. C. C., 1999: Recent performance of the ECMWF model in forecasting the track of tropical cyclones over the western North Pacific and the South China Sea. *ECMWF Newsletter*, **85**,2-7.

F Technical appendices

F.1 Experimental set-up

The steps of a TAP&FCA experiment are as follows.

1) Interpolate MRF analyses and forecasts, to create initial conditions at 00 UTC on the first day and boundary conditions at 12 hour intervals. These boundary conditions will be later interpolated in time to the appropriate forecast times.
2) Run the MM5 for 3 hours, writing output files every hour and a restart file at hour 2. (Restart file is a complete description of the model state.)
3) Using best track data up to 03 UTC, run Emanuel's intensity model to create bogus soundings.
4) Using the output of the previous MM5 run at 03 UTC as background, run TAP with the bogus soundings. This creates a TAP nudging target.
5) Run the MM5 from the 02 UTC restart file until 06 UTC, observations nudging towards the TAP analysis for the first 2 hours. Save a restart file at 05 UTC.
6) Run TAP at 06 UTC with all available data (no bogus).
7) Run the MM5 from the 05 UTC restart file until 12 UTC, nudging towards the TAP analysis for the first 2 hours. Save a restart file at 11 UTC.
8) Run TAP at 12 UTC with all available data .
9) Run the MM5 from the 11 UTC restart file until 18 UTC, nudging towards the TAP analysis for the first 2 hours. Save a restart file at 14 UTC.
10) Using the output files, SSM/I data and the best track, run FCA to compute a nudging target with a nominal time of 15 UTC.
11) Restart the MM5 at 14 UTC and run for at least 4 hours, nudging towards the FCA analysis for the first 2 hours of the forecast. Write output every hour and a restart file at 17 UTC.
12) Run TAP at 18 UTC with the available data.
13) Run the MM5 from the 17 UTC restart file until 00 UTC the next day, nudging towards the TAP nudging files for the first 2 hours. Save a restart file at 23 UTC.
14) Run TAP at 00 UTC with all available data.
15) Run MM5 from 23 UTC, nudging for the first 2 hours. At that point we can run a 3-day forecast.
16) The procedure continues in a similar way, with 2 TAP analyses and one FCA step every 12 hours, (i.e., repeat steps 8 - 15). MM5 runs from 23 UTC are extended to 72 h with nominal start time of 00 UTC on the next day.

To do a TAP only experiment we skip step 10 and extend each intermediate forecast to the next synoptic time.

A control run uses steps 1 to 5 and extends the last forecast to 3 days. The same procedure is repeated each day.

F.2 Computing the nudging fields

The computation of the nudging fields involves several modules, summarized in Figure 26. This diagram warrants some explanation. Each light blue box represents a separate system module, identified by the name in its upper left hand corner, unless it comprises a single software module, in which case the system module name is the same as the software module name (e.g. combine MM5.) Processes are identified by rectangular boxes and files by parallelograms. The fields are identified by a name, the type of surface on which they are defined and a symbolic name for the file format. The main input and output files are colored yellow. The files within the system modules are not saved but the files that appear in white boxes between modules are saved temporarily.

If we start from the top of the figure, the module in the middle, called "MM5 fcst to native p" represents the transformation of the output of the MM5 forecast to AER's internal (or "native") format. Since the TAP and FCA processes are performed on constant pressure surfaces but the MM5 output is on σ surface[16], it is also necessary to interpolate vertically between σ and p levels. An MM5 routine (interpb) is available for this interpolation, but only for version 2 files of the MM5. Hence we first have to transform version 3 files to version 2 files with process V32V2.

The system box to the left of center ("Apply TAP") is the optimal interpolation analysis module. In addition to the observation files it requires error covariance estimates for all the different types of data and for the background model. TAP combines the observations and the background model fields to produce a preliminary analysis on pressure levels.

To the right of center are the FCA modules. First we have to compute, from the MM5 output, quantities that can be compared to the satellite observation used in FCA. In the current tests we use the SSM/I integrated water vapor (IWV measurements), so one of the modules computes integrated water vapor from the MM5 output. The next module calculates the alignment field that, when applied to the MM5 output, minimizes the difference between the computed and measured IWV. Finally the alignment field is applied to all the MM5 variables.

Both TAP and FCA are represented in the same diagram but, as indicated above, they are not performed at the same time.

Once MM5 output, modified by either TAP or FCA, is available on p surfaces, in native AER format, we need to convert this file back to MM5 version 3 format on σ levels. This is done by the "Native p to MM5 IC" module. The INTERPF interpolation routine does exist for the version 3 of MM5, hence we do not need to do any version conversion. However, the MM5 files contain fields such as terrain definition, etc., which are not used in TAP or FCA and are lost in the MM5_to_native process. These fields are generated when the MM5 initial conditions for the very first run are created by "MRF GRIB to MM5 IC". We therefore repeat this step and use its output as a template when recreating the MM5 files in native_to_MM5. We also need to re-compute the mean sea level pressure from the analyzed 1000 mb height.

[16] A σ (sigma) level is defined as the pressure scaled by the difference between the surface pressure and a reference pressure at the top of the model. That reference pressure may be 0 or a constant pressure.

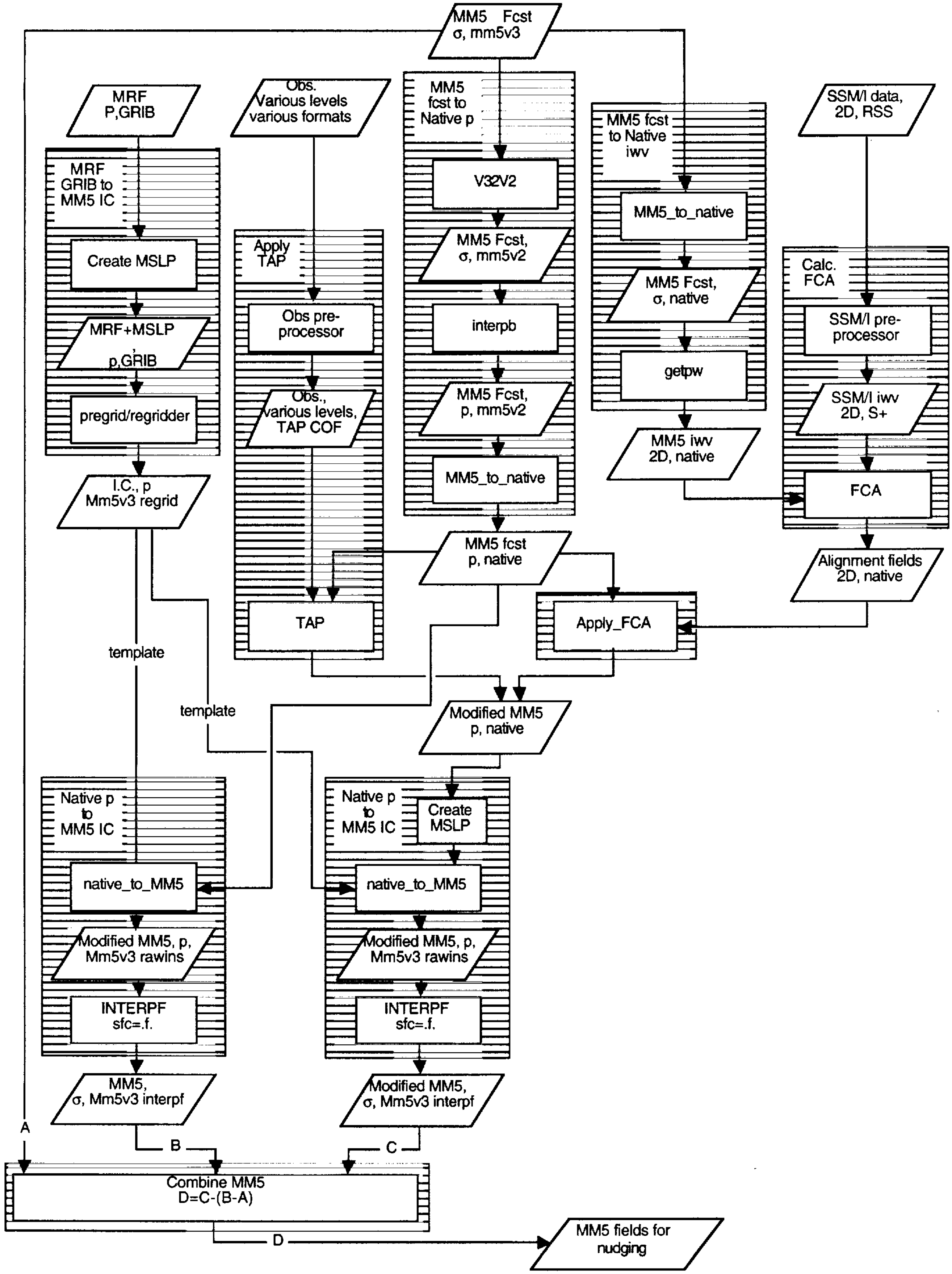

Figure 26: Flow diagram for creation of nudging fields. See text for details.

Finally we must account for the effect of the interpolation back and forth between p and σ levels. Even without any TAP or FCA effects these interpolation would introduce changes to the MM5 fields. In many cases the interpolation effects can be as large as the TAP or FCA changes. In order to eliminate the effect of interpolation, we apply the p to σ interpolation steps to the files that have not been modified by TAP or FCA and subtract the interpolation increments (B-A) from the modified fields (C). The end result are the fields used in the nudging process during the next forecast.

F.3 List of software modules

The following list (Table 1) describes the main software elements of the system and how the various pieces of software interact.

The AER data format is a self-descriptive format used by most software developed in the Numerical Weather Prediction group at AER, including TAP and FCA.

Table 1 does not include all the codes that have been developed to ingest the observational data into TAP and visualize the output. Additional codes to automatically process the output and compute statistics have yet to be written.

Table 1: Main elements of the hurricane forecast system

	Input	Functions	Code names	Output
		Create boundary conditions:		
1	MRF analyses and forecasts	Compute mean sea level pressure Convert GRIB format Interpolate to MM5 grid	getmslp pregrid regridder	MRF initial state (first forecast only) Boundary conditions
		Estimate hurricane strength:		
2	Best track data up to initial time	Run Emanuel intensity model	predict5	"Bogus" wind and surface pressure data
		Feature calibration and alignment:		
3	MM5 output (version 3)	Convert to AER format	mm5_to_native	MM5 output in AER format (sigma level)
4	MM5 output in AER format	Compute vertically integrated water vapor	get_pw	Forecast IWV
5	Forecast IWV SSM/I IWV data	Run feature calibration and alignment (FCA)	minimize. function	Alignment fields
6	MM5 output (version 3)	Convert to MM5 version 2 format	V32V2	MM5 output (version 2)
7	MM5 output (version 2)	Interpolate from sigma to pressure levels	interpb	p level MM5 output

	Input	Functions	Code names	Output
8	p level MM5 output	Convert to AER format	mm5_to_native	MM5 output in AER format (p level)
9	MM5 output in AER format (p level) Alignment fields	Apply FCA alignment fields	apply_fca	Aligned MM5 output, used for nudging
		Data assimilation:		
10	Observation data "Bogus" wind and surface pressure data MRF initial state (first forecast only) Aligned MM5 output (subsequent forecasts)	Run data assimilation (TAP)	run_tap	Preliminary analyzed fields on p levels
11	Preliminary analyzed fields on p levels	Convert to MM5 version 3 format	regridder native_to_mm5	Preliminary analyzed fields on p levels V3 format
12	Preliminary analyzed fields on p levels V3 format	Interpolate to sigma levels	interpf	Preliminary analyzed fields on sigma levels
13	MM5 output in AER format (p level)	Compute effect of vertical interpolations	native_to_mm5 interpf	Vertically interpolated MM5 output
14	MM5 output (version 3) [a] Preliminary analyzed fields on sigma levels [c] Vertically interpolated MM5 output [b]	Subtract effect of vertical interpolation by computing [c] - ([b] – [a])	combine_mm5	Fields for nudging
		Forecast:		
15	Initial analysis Boundary conditions Restart files Nudging fields	Run MM5	mm5.deck.pl	MM5 output (version 3) Restart files

REPORT DOCUMENTATION PAGE

Form Approved OMB No. 0704-0188

1. AGENCY USE ONLY *(Leave blank)*	2. REPORT DATE	3. REPORT TYPE AND DATES COVERED
	September 21, 2001	Final 9/21/99 to 9/20/01

4. TITLE AND SUBTITLE
Improved use of satellite imagery to forecast hurricanes
Final Report

5. FUNDING NUMBERS
C:
NASW-99043

6. AUTHORS
Jean-François Louis

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)
Atmospheric and Environmental Research, Inc.
131 Hartwell Ave., Lexington, MA 02421

8. PERFORMING ORGANIZATION REPORT NUMBER
P864QR7

9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)
NASA
Goddard Space Flight Center
Headquarters Procurement Office, Code 210.H
Greenbelt, MD 20771

10. SPONSORING/MONITORING AGENCY REPORT NUMBER

11. SUPPLEMENTARY NOTES

12a. DISTRIBUTION/AVAILABILITY STATEMENT
Public distribution. No limitation.

12b. DISTRIBUTION CODE

13. ABSTRACT *(Maximum 200 words)*

This project tested a novel method that uses satellite imagery to correct phase errors in the initial state for numerical weather prediction, applied to hurricane forecasts. The system was tested on hurricanes Guillermo (1997), Felicia (1997) and Iniki (1992). We compared the performance of the system with and without phase correction to a procedure that uses bogus data in the initial state, similar to current operational procedures.

The phase correction keeps the hurricane on track in the analysis and is far superior to a system without phase correction. Compared to operational procedure, phase correction generates somewhat worse 3-day forecast of the hurricane track, but better forecast of intensity.

It is believed that the phase correction module would work best in the context of 4-dimensional variational data assimilation. Very little modification to 4DVar would be required.

14. SUBJECT TERMS
Weather prediction, hurricane forecasts, phase errors, satellite data

15. NUMBER OF PAGES
8

16. PRICE CODE

17. SECURITY CLASSIFICATION OF REPORT	18. SECURITY CLASSIFICATION OF THIS PAGE	19. SECURITY CLASSIFICATION OF ABSTRACT	20. LIMITATION OF ABSTRACT
UNCLASSIFIED	UNCLASSIFIED	UNCLASSIFIED	UL