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ADVANCED MODELING OF TROPICAL CYCLONES

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ABSTRACT Advanced tropical cyclone models of sufficiently fine resolution are capable of representing important internal structure of the vortex. In the model, a vortex should interact with ocean and land in a realistic manner. Interaction with the ocean can significantly moderate the storm intensity. Inclusion of the heat budget of the soil layer retards the storm intensity over land. How to improve the treatment of deep convection is an issue which is wide open for future study. Specification of a realistic, yet model-adapted vortex in the initial condition of the model is essential for improvement of tropical cyclone track and intensity prediction.

I. INTRODUCTION

The use of numerical models to simulate the structure and behavior of tropical cyclones to a high degree of realism will advance the understanding of the basic mechanisms governing the life of these intense storms. These models should also be combined with real data to make dynamical predictions of tropical cyclones, the results of which will be scrutinized and utilized for further improvement of the models. Using the tropical cyclone modeling activity at the Geophysical Fluid Dynamics Laboratory/NOAA (GFDL) as an example, a guideline for comprehensive modeling and areas for future study are suggested in this paper. Issues of model resolution are treated in Section 2 and those of model physics, including the energy fluxes at the ocean and land surfaces, in Section 3. In Section 4, an initialization technique of tropical cyclone models is briefly described and results of its application to experimental predictions are presented. Finally, some remarks concerning the observation and prediction of tropical cyclones are made in Section 5.

II. MODEL RESOLUTION

The resolution of advanced tropical cyclone models must be fine enough to describe important features of these storms such as the eye, eyewall, warm core and rain bands. Indeed, it has been demonstrated that these features appear in high resolution tropical cyclone models, although the degree of validity of the model physics producing these features is somewhat uncertain. Also, the robustness of the evolved structure to a further increase in resolution is not clear. Nevertheless, analysis of the obtained results have suggested possible mechanisms responsible for sustaining the internal structure of tropical cyclones. For example, the heat budget of the eye of a mature tropical cyclone simulated in a model of 5km finest resolution indicated that the adiabatic warming due to mean subsidence in the eye was balanced with the cooling due to the outward flux of heat by the model resolved eddies (Kurihara and Bender [4]). The moisture budget in the eye was a balance between drying due to the mean sinking motion and moistening due to the inward flux of moisture by the resolved eddies. These pictures are informative although they are not conclusive because of the simplicity of the precipitation process assumed in the model.

An axially symmetric vortex on the earth in a calm environment cannot remain unchanged and stationary because an asymmetric structure, called the beta-gyres, inevitably evolves as a result of the advection of planetary vorticity. The beta-gyres cause the tropical cyclone propagation and may affect the rainfall distribution in the vortex. Furthermore, the beta-gyre structure may be modified by the vorticity gradient of a basic flow. The vertical shear of the basic flow yields an apparent source and sink of heat and vorticity, thereby inducing an asymmetric secondary circulation.

The horizontal resolution needed to accurately represent the above internal structures of a tropical cyclone is on the order of 10 km. This resolution corresponds to a wave number truncation at ~1300 in the triangular spectral decomposition of a global domain. In practice, the resolution does not have to be uniformly fine over the entire model domain. The use of a multiply-nested grid configuration is practical at present. In the GFDL model, telescopically meshed inner domains are relocated to center the moving vortex within the inner meshes at all times. An example of a triply-nested grid system is shown in Table 1.

Table 1 An example of triply-nested movable meshes

Mesh	Resolution	Domain size	
	degrees	*degrees*	*(points)*
1		75	(75x75)
2	1/3	11	(33x33)
3	1/6	5	(30x30)

The vertical resolution of tropical cyclone models has to be adequately fine for representing the vertical variation of the wind, temperature and moisture in the entire domain. Conditions of the storm's environment strongly control the life of a tropical cyclone. This was demonstrated by a case study in which the development or non-development of a tropical depression was dependent largely on the vertical profile of vorticity and equivalent potential temperature budgets including significant effects due to the large scale environmental flow (Tuleya [10]). The large scale flow, of course, affects the movement of tropical cyclones. Accurate estimation of such effects of the large scale flow is important.

The planetary boundary layer structure in the model has to be as realistic as possible, since it is in this layer and at the surface that the major input and transport of heat energy and the significant dissipation of storm kinetic energy take place. Accurate simulation of the boundary layer requires a specification of detailed realistic surface conditions. As clearly suggested from the intensity change of tropical cyclones at landfall, the boundary layer structure rapidly responds to the condition of the underlying surface. The intensity of the storm may be sensitive to even a small change in the temperature of the ocean or land surface. The physical parameters such as the surface roughness, surface albedo and soil wetness (in the case of land) are locally related to the surface exchange of heat and momentum. Another important feature of the surface is the orography. It has been suggested by numerical studies (e.g., Bender et al. [1]) that mountainous islands can deflect the track of tropical cyclones by modifying both the large scale flow and the circulation of the vortex itself. It was also found that a storm can weaken when relatively dry air on the mountains is transported toward the storm center. When large scale waves interact with mountains, the vorticity fields at the lee side of the mountains may become oscillatory, depending on the phase of the waves, and provide a favorable condition for the development of disturbances (e.g., Zehnder [11]). In order to simulate these mountain effects, the detailed shape of the mountains must be included in the high resolution model.

III. MODEL PHYSICS

Processes basic to the life cycle of a tropical cyclone take place at the ocean and land surfaces, in the planetary boundary layer and in areas of deep convection. Efforts to improve the model physics representing these processes serve to increase knowledge about the mechanisms of tropical cyclones and lead to improved prediction capability of the models.

Over the ocean, an essential energy source for the development and maintenance of a tropical cyclone is the latent energy supply. For a tropical storm over the open ocean, the storm's surface wind and the heat exchange at the surface tend to form a positive feedback cycle. Namely, the energy supply to the vortex induces stronger surface winds which, in turn, increase the heat flux. However, the interaction of tropical cyclones with the water underneath causes changes in the condition of the upper part of the ocean. Changes in the sea surface temperature in turn influences the behavior of tropical cyclones. More specifically, the positive feedback cycle described above will gradually be retarded as the sea surface temperature is reduced due to the ocean response to the vortex. In general, a change to a lower sea surface temperature is less favorable for a life of a tropical cyclone.

The heat budget of the ocean mixed layer depends mainly on the entrainment of the colder thermocline water through the base of the layer as well as on the sensible and latent heat fluxes and net radiation at the surface. A schematic figure showing the above processes is presented in Fig.1. It should be noted that the wind stress at the surface affects the current in the mixed layer which induces turbulent motion at the thermocline interface and causes the entrainment. In order to investigate effects of tropical cyclone-ocean interaction, a joint model has been constructed by combining the high resolution tropical cyclone model with an ocean model consisting of a mixed layer, a multi-layer thermocline and the deep sea. During the time integration of the coupled model, the atmospheric model advances in time for a short period with the ocean condition fixed. The exchange of momentum and heat computed during that period is then passed to the ocean model to determine its new state which is used in the following integration of the atmospheric model. Results from recent numerical studies (Ginis, Bender and Kurihara, to be discussed in detail at the present Symposium) clearly indicated that the vortex-ocean interaction reduced the sea surface temperature, thereby moderating the storm intensity as compared with the case in which the sea surface temperature was kept fixed at the initial value. To further improve the modeling of vortex-ocean interaction, studies are needed to better understand the momentum transport into the ocean under stormy conditions. Specifically, further investigation is needed concerning factors which determine oceanic roughness length or drag as well as wave generation and its impact on the mixed layer current.

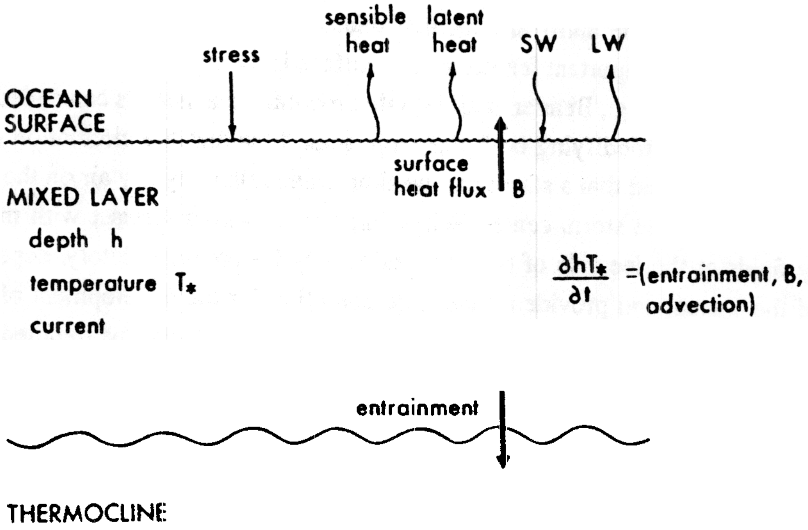

Fig. 1 Heat budget of the ocean mixed layer.

Tropical cyclones do not form over land and those developing over ocean basin decay after making landfall. Tropical cyclone models should be able to correctly reproduce the process of disintegration over land. An obvious difference between the land and ocean is the surface roughness length. After landfall, the surface wind speed of a tropical cyclone decreases due to the larger roughness over land. However, the boundary layer wind convergence can increase because of the increase in the wind backing angle. For a tropical cyclone to decay, the absolute humidity in the boundary layer must decrease after landfall. Previous numerical studies (e.g., Tuleya et al. [9]), suggested that either dryness or relatively cool land surface temperature can produce a drier boundary layer.

In the GFDL tropical cyclone model, the roughness length, evapotranspiration efficiency and surface albedo at each gridpoint are respectively related to the prescribed vegetation type at that point. In the future, specification of these parameters may be made on the basis of satellite derived data and land wetness information. The land surface temperature is predicted with a simple one-layer soil model. A schematic figure similar to Fig.1 but for the land case is presented in Fig.2. In contrast to the case of the ocean mixed layer, the subsurface layer is motionless. The surface temperature is dependent on the net heat flux at the surface and the thermal property of the layer. The surface albedo is an important factor in defining the net flux of radiation. As mentioned before, its value in the GFDL model is prescribed from the distribution of the vegetation type. The thermal property is defined as the squareroot of the product of the heat capacity and the thermal conductivity of the subsurface layer substance. According to a recent study (Tuleya, to be published), the evolution of a vortex over moist land was sensitive to the thermal property of the subsurface layer. In the case of a storm over the typical soil condition, the dominant factor in the heat budget of the soil layer was the evaporation, which caused surface cooling. The lower surface temperature implies a reduction of potential evaporation. Thus, the tropical cyclone could not form over the land even when maximum evapotranspiration efficiency such as that for a tropical rainforest region was assumed. The land surface temperature in the center area of the remaining weak disturbance was noticeably lower than the ocean surface temperature of the corresponding no-land control experiment. It is not surprising that, when the thermal

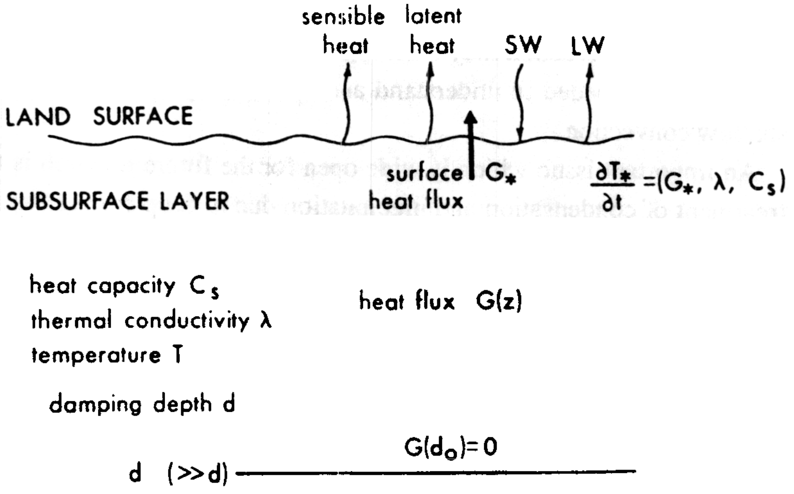

Fig.2 Heat budget of the soil layer.

property of the land subsurface layer was set to a hypothetical condition of the ocean mixed layer, a disturbance developed to almost the same intensity as the storm over the ocean. A significant influence of the land surface condition was also demonstrated in the simulation study of tropical cyclones during the Australian Monsoon Experiment, 1987. The forecast skill of the model was greatly improved when the surface temperature over a desert region was predicted by the soil model with diurnally varying insolation. The diurnal change of insolation affected the storm behavior not only through a direct effect on the energy budget but also through the diurnal variation of the conditions surrounding the storm.

Radiation influences the tropical cyclone behavior in various ways. It causes destabilization of the lower troposphere in cloud free areas, which may affect boundary layer structure of the outer region of the storm possibly through the mixing at the boundary layer top. When radiation-cloud coupling is incorporated in the model, differential heating occurs between the cloud area and its surroundings. Also, the cloud canopy reduces short wave radiation reaching the surface. Over the open ocean, the latter effect on the sea surface temperature is probably small for a short time scale. The former effect on the eyewall cloud seems to enhance the development of the storm (Kurihara and Tuleya [3]). In contrast to the ocean case, the cloud canopy above the land significantly affects the surface temperature, making the cloud effect on the intensity of the storm more sensitive to the cloud coverage.

The role played by shallow convection in modifying the boundary layer structure and, hence, in the development of storms cannot be overlooked (Emanuel [2]). The direct effect of shallow convection over the ocean is to entrain the relatively dry air of the lower troposphere into the moist boundary layer. Note that this drying effect is reduced when the moisture of the lower troposphere increases. Interestingly, the drying effect of shallow convection, which is detrimental to tropical cyclone development, contributes to the increase of evaporation from the ocean surface that is favorable for the storm intensification. Another effect of shallow convection may exist in the momentum transport at the boundary layer top. More studies are needed to understand and numerically treat all these processes involving the shallow convection.

An important issue which is wide open for the future research is the improvement of the treatment of condensation and precipitation due to deep convection. The mode of latent heat release by deep convection, e.g., the profile of convection, either vertical or slantwise, and the budget of liquid substances, either suspended in or falling from clouds, will determine the cloud scale heat source or moisture sink. Presumably, how these cloud scale effects spread and finally affect the vortex scale fields will influence the evolution of tropical cyclones. If the energy supply to the vortex scale motion is continuous, the storm will smoothly develop. To treat the above processes of scale interaction between clouds and the tropical cyclone vortex, two approaches can be considered in future models. In one scheme, cloud elements will be explicitly simulated through time integration of the non-hydrostatic equation system. The behavior of model cloud elements depends on the specification of the cloud microphysical parameters. In the other approach, an improved cumulus parameterization scheme may be formulated to estimate the ultimate effect of deep convection. This approach will be valid as long as the convective activity is correlated with resolvable scale meteorological fields and the latter is accurately represented in the high resolution model.

IV. TROPICAL CYCLONE PREDICTION

A challenging issue in tropical cyclone research is how much we can improve tropical cyclone prediction with the use of a more comprehensive three dimensional dynamical model, in particular to 48 hours.

Application of a tropical cyclone model to the dynamical prediction of real storms requires formulation of a model initialization scheme. A guideline for the successful formulation is that a vortex included in the initial condition of a prediction model be reasonably realistic and well adapted to the model resolution as well as to the model physics. The database for the initialization of the GFDL model is obtained from the U. S. National Meteorological Center (NMC) global analysis. However, the tropical cyclone vortex analyzed in the global model at the present-day resolution is inevitably different from the corresponding real storm, often too large and too weak. In a scheme devised at GFDL (Kurihara et al., to be published), an analyzed vortex is replaced with a more realistic, model consistent vortex. Without the initialization, adjustment of an analyzed vortex to the tropical cyclone model, including a possible false spin-up, takes place. The false spin-up makes prediction of intensity out of the question. Reorganization of the vortex structure during the adjustment period also can cause error in the vortex movement (Kurihara et al. [6]).

In the GFDL initialization scheme, an analyzed vortex is removed from the global analysis through application of two types of filters. This process does not affect the analysis beyond the vortex area, the center and radius of which are determined from the inspection of the analyzed wind field. Filters are designed so that the field remaining after the removal of the vortex smoothly connects to the surrounding region. This field is called the environmental field. Thus, the global analysis is split into two components, i.e., the environmental field and the deviation from it representing the analyzed vortex. A new vortex is merged with the environmental field.

At present, it is not realistic to assume that the wind associated with a vortex and its environment can be observed and analyzed with high resolution. In very rare cases in which this was done (e.g., Lord and Franklin [7]), the corresponding fields of temperature, moisture and surface pressure were not necessarily available. Under such circumstances, a realistic new vortex is instead specified in a physically reasonable manner by utilizing a limited amount of information about the vortex structure. Such a vortex, often called a bogus vortex, is then implanted into the environmental field.

The new vortex consists of both symmetric and asymmetric components. The former is generated from the time integration of an axisymmetric version of the prediction model.

This ensures consistency in the fields of wind, temperature, moisture and surface pressure in the vortex as well as adaptation of the vortex to the model physics, model resolution and numerical schemes used in the prediction. During the vortex generation, the tangential wind is forced to a target tangential wind profile determined from observational information. This makes the generated vortex uniquely similar to the corresponding real storm. In the scheme presently used at GFDL, only low level information such as the maximum surface wind and its radius, the radii of gale and hurricane force winds in four quadrants and the radius of the outermost closed isobar are utilized to specify the target wind field. A study is in progress to use additional data such as dropsonde and radiosonde observations. At the end of the above vortex generation, the deviation of the obtained fields from an appropriate reference state is computed, which defines the symmetric component of the bogus vortex.

The simplest and perhaps most studied asymmetry within the vortex is the one resulting from the advection of earth vorticity by the symmetric flow. This mechanism causes the production of negative relative vorticity in the eastern half of the vortex and positive vorticity in the western half (in the northern hemisphere). This tendency is combined with other nonlinear effects of advection to establish a quasi-steady asymmetry, i.e., the beta gyres. The structure of the beta gyres is strongly controlled by the radial profile of the symmetric flow. In the GFDL initialization scheme, the asymmetric flow is derived from time integration of the simplified barotropic vorticity equation (Ross and Kurihara [8]). In this case, the symmetric wind generated in the preceding step is used for the initial condition. Thus, the dynamical consistency between the symmetric and asymmetric flow is satisfied. The beta gyres yield a flow blowing through the central area of the vortex. This wind of 1 - 2 m/s, or more in certain cases, can make a significant contribution to the movement of the vortex. The sum of the asymmetric wind and the previously obtained symmetric wind defines the wind field of the bogus vortex. In real storms, asymmetric features can also develop from the interaction of the vortex, both horizontally and vertically, with the environmental flow. Also, band structure may develop from dynamical instability. How to treat these asymmetries in the specification of the initial condition is a future issue.

After adding the specified vortex to the environmental field, the temperature and surface pressure fields are recomputed to be in dynamical balance with the wind field. The mass diagnosis is based on the full divergence equation in which the time tendency term is bounded by a slow propagation mode. The wind field which includes important vortex structures is kept unchanged in this final stage of initialization.

Recently, an effort has been made at GFDL to automate the initialization and prediction system. In the automated system, datasets of the analysis and predictions from the NMC global model as well as the observational information of the tropical cyclone are fed in. Then, the values of various parameters required for removal of the analyzed vortex and generation of the bogus vortex are computed with the use of empirical formulas and rules. The initialization phase is immediately followed by the time integration of the limited domain hurricane prediction model (at present, without coupling to the ocean model). The time dependent open lateral boundary condition is imposed by a scheme utilizing the global model forecasts (Kurihara et al. [5]).

Numerical results from experimental predictions using the automated system are very promising. In Fig.3, the surface wind field from the global analysis and the one initialized for the high resolution nested mesh model are compared. (Figures cover the domain of the

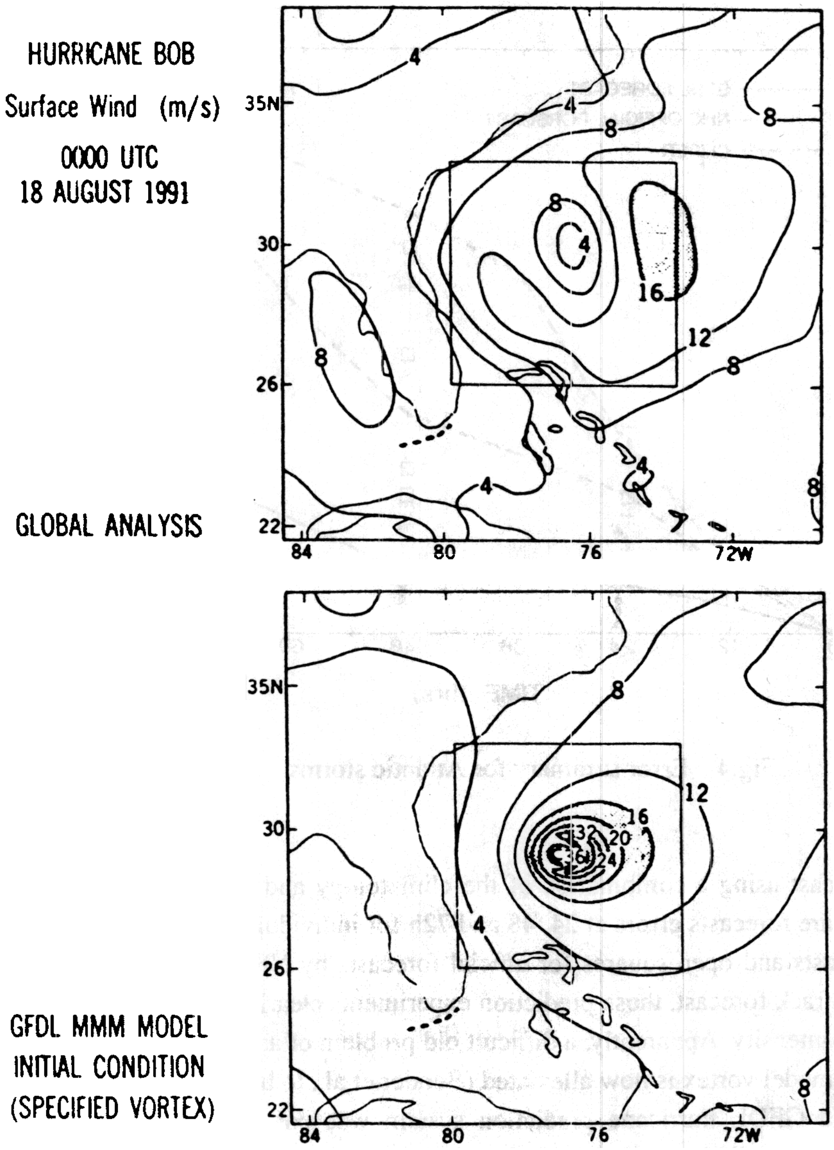

Fig.3 Surface wind: global analysis (top) and the initialized field (bottom).

intermediate mesh with the finest resolution domain shown by a square in each panel.) It indicates that the initialization scheme established an intense, compact realistic tropical cyclone. Predictions using specified vortices dramatically reduced the forecast error of the tropical cyclone track. Fig.4 shows the average forecast errors for seven Atlantic storm cases: solid line for the forecast by the GFDL automated system; dashed line for the official forecast by the National Hurricane Center; and dash-dotted line for the CLIPER forecast, i.e., the simple forecast using a combination of the climatology and the persistence. Also plotted in the figure are forecasts errors at 24, 48 and 72h for individual cases: solid triangle for the GFDL forecasts and open squares for official forecasts by NHC. In addition to the improvement of the track forecast, these prediction experiments clearly indicated feasibility in forecasting storm intensity. Apparently, a difficult old problem of an adjustment and false spin-up of an initial model vortex is now alleviated (Bender et al., to be published).

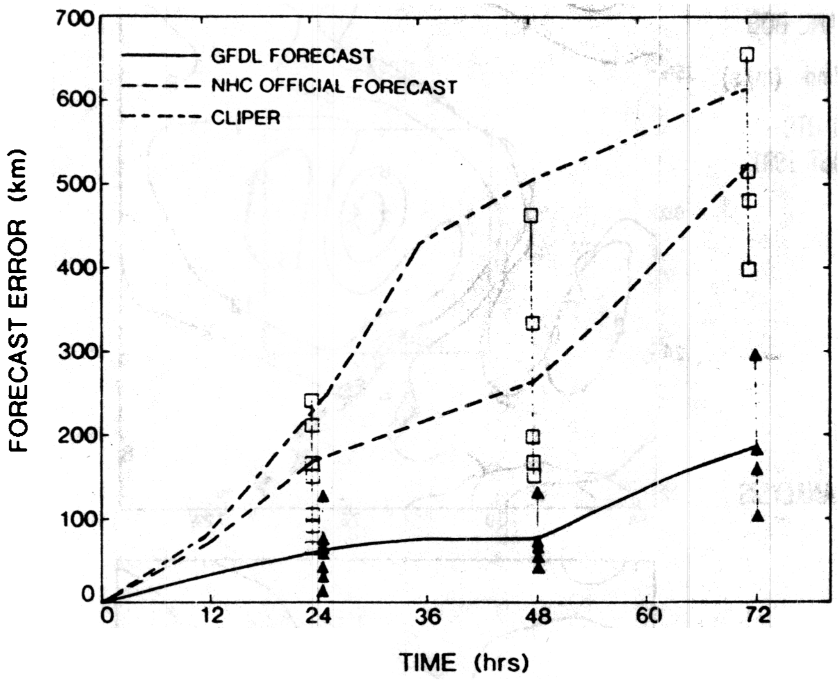

Fig.4 Error summary for Atlantic storms.

The automated GFDL hurricane prediction system was put into semi-operational mode in 1992. Model predictions of the hurricane track, intensity and maximum wind distribution are transmitted to the operational hurricane forecast centers. Overall performance of the model clearly indicates that the dynamical prediction of hurricanes, in particular during the early period of time integration, is now far more reliable than ever before, though room for improvement still exists. As an example, a track forecast made two days before the landfall of Hurricane Andrew onto the Louisiana coast is compared in Fig. 5 against the observed track. This example represents one of the best cases and was obtained during a critical forecasting period. In the case of Hurricane Iniki in the central Pacific, the observed recurvature of the storm toward the north from a westward track and continued movement toward the island of Kauai was successfully predicted in two cases. The considerable improvement in hurricane prediction as mentioned above is attributable to a combination of the use of a high-resolution advanced model and better initial conditions. The latter are determined on the basis of the global analysis and a properly formulated

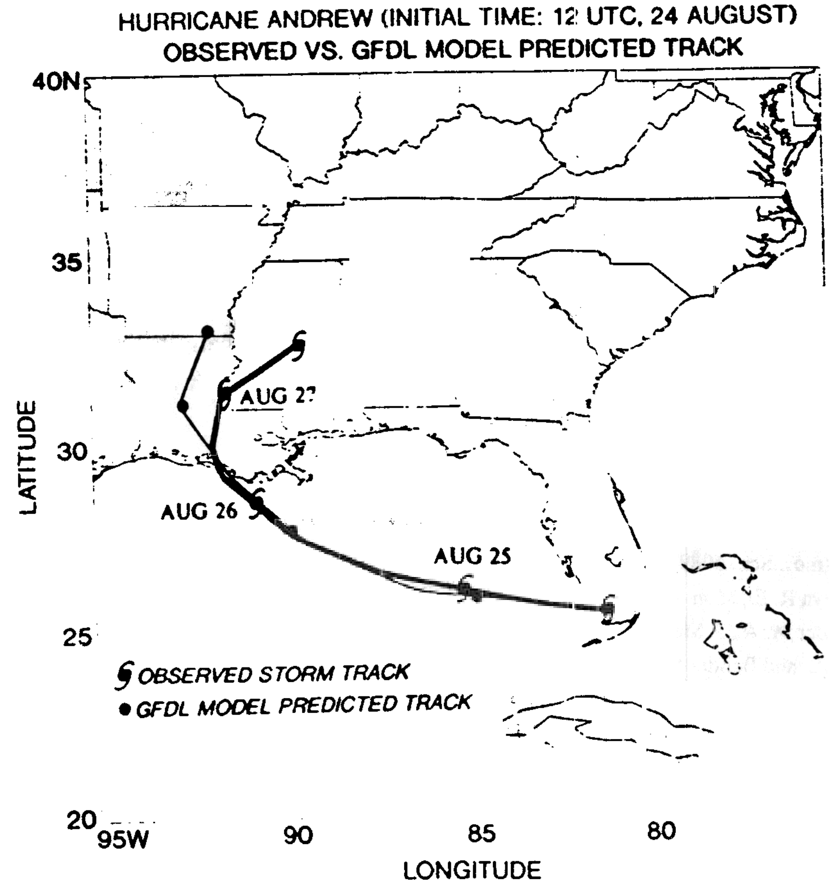

Fig.5 GFDL prediction of the 72 hour track of Hurricane Andrew, from 1200 UTC 24 August 1992.

scheme of vortex specification. Accordingly, further improvement of the forecasting accuracy will possibly result from (1) a further advancement in hurricane model development, (2) an increase in the accuracy of the global analyses particularly through more availability of observations and (3) an upgrading of the vortex specification technique to derive the utmost benefit from the available observations.

V. REMARKS

The data base for the hurricane prediction model is the dataset obtained from the NMC global analysis and predictions. Therefore, high quality of the global model dataset is required in order that capability of the hurricane model be fully demonstrated. Enhancement of the observations of tropical cyclones and their surroundings can serve this purpose. It should be stressed that such observations become truly worthwhile for dynamical prediction only through effective use in the global model analysis as well as in the tropical cyclone model initialization.

An ongoing study suggests that the presence of a tropical cyclone can influence synoptic conditions in a fairly large area (Ross and Kurihara, to be published). This is one aspect of scale interaction and implies that accurate prediction of tropical cyclones may contribute to the improvement of the prediction of synoptic features, e.g., the movement of fronts and precipitation distribution, in the region influenced by tropical cyclones.

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