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On the trajectory of cyclones likely to affect the Mexican Republic

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RESUMEN

Utilizándose un refinamiento del modelo baroclínico filtrado del Centro de Ciencias de la Atmósfera, UNAM, se presenta su aplicación al pronóstico de la trayectoria de los huracanes con posibilidades de afectar a la República Mexicana, el modelo integra las ecuaciones baroclínicas de pronóstico dadas por Buendía *et al.* (1984) sobre la región cuarta empleando una malla de 69×77 puntos reticulares sobre una proyección cónica de Lambert tangente a 30°. Los resultados obtenidos son satisfactorios y de gran utilidad para los ciudadanos de nuestro país.

ABSTRACT

Using the filtered baroclinic model of the Center for Atmospheric Sciences of the National University of Mexico, an application to forecast hurricane tracks possibly affecting the Mexican Republic is presented. This application solves the baroclinic equations given by Buendía *et al.* (1984) over the WMO Region IV using a lattice of 69×77 points over a Lambert projection tangent on 30°. The results are favorable and useful for Mexican activities.

Introduction

Since the first decade of weather forecasting by means of numerical methods initiated by Charney *et al.* (1950), there has been a great interest in using the available models to forecast the trajectory of hurricanes. In 1968 Sanders and Burpee solved the equation for the filtered barotropic model using wind-velocity data averaged vertically at the ten standard levels. They employed this variable because errors in the measurement of geopotential height were of the same order of magnitude as its natural variation. Integration of this model (known as SANBAR) was done on a Lambert conical projection where the area considered extends from the equator up to 55°N and from 36.5°W to 123.5°W. The time interval used was 30 minutes and a grid was chosen with a distance of 1.5 degrees from point to point. This distance is adequate for the resolution of the large-scale flow and of the aerial structure of the tropical cyclone.

These considerations account for the good results obtained in prediction of the position of the vorticity maximum, despite of the merely manual analysis of isotachs and isogons.

Improvements to this model came later on with respect to wind initialization (Pike, 1972) and storm vortex parameterization (Sanders *et al.*, 1975).

To many meteorologists interested in the tropics, the SANBAR model was a great inspiration-similar to the work of Charney *et al.* (1950). Its forecasts for the trajectory of hurricanes surpassed in efficacy the ones obtained by purely statistical models (Miller and Chase, 1966), near the continent (Neumann, 1972), for the first 24 hrs. Consequently, researchers were motivated to adopt the SANBAR model-with slight modifications of the techniques to create an initial wind field and of the manner to solve the equations (which varies depending on each researcher's interest area).

De las Alas and Guzmán (1976) applied the barotropic model to the seas surrounding the Philippines. Their grid, centered on the equator, had 19×13 points with an interval distance of 1 degree. Wind velocity was averaged vertically in terms of various weight factors at 700 mb, 500 mb and 300 mb.

Tsay (1976) constructed his forecast for tropical storms in the vicinity of Taiwan, considering Lagrangian motion on a 38×28-point grid with a separation of 240 km from point to point; he also used another grid with a distance of 160 km between points, his results are encouraging.

Pelissier (1979) reported the balanced barotropic model (by Y. Okamura) employed by the Electronic Computation Center of the Japan Meteorological Agency, applied to typhoons or storms moving in a northward direction from low latitude towards the Japanese area. The model uses a 381-kilometer distance between grid points, with internal feed-back on a 51×51-point grid. Despite its feedback mechanism, this model has been deemed to be of little use, because of the magnitude of the distance between points on the grid. Forecasting hurricane trajectories with barotropic and baroclinic models (Buendía and Morales, 1976-77; Buendía *et al.*, 1979; Buendía and Delgado, 1981) is very difficult with a grid of approximately 50 km larger than the one mentioned above. It is not possible to follow the dynamics of these phenomena with a wavelength less than twice this distance between points.

Birchfield (1960) applied the barotropic forecast equation on a nested grid of 15×15 points, separated by 150 km, inside a coarse grid of 25×22 points spaced every 300 km. He proposed feed-back from the nested to the coarse grid and viceversa. This model was integrated over part of the Atlantic Ocean's WMO region four, and his results are acceptable.

Among the models developed to forecast trajectories of tropical and extratropical storms using primitive equations on nested grids, from the barotropic point of view, Hinsman (1977) deserves to be mentioned as well as the several-level baroclinic model of Hovermale and Livezey (1977). The latter of these two highlighted the vital importance of considering atmospheric baroclinity, and showed that this kind of model is more accurate than a barotropic model.

In order to save computing time in this work, another version of the filtered baroclinic model integrated by Buendía and Delgado (1981) is presented. Solution is made over 89×77-grid-point on the WMO region four with an interval distance of 108 km between points enough for the studied hurricanes to interact with the major-scale flux and react to the changes at this scale (Haltiner, 1980). The time interval considered for the iteration is 30 minutes, and it is cyclic along the east-west boundaries similar to Hinsman's model (1977). The results obtained are satisfactory, indicating that filtered baroclinic models are also a reliable tool to forecast trajectories for tropical storms and hurricanes.

The model

The presentation of the cyclic filtered baroclinic model applied to the WMO region fourth has already been done by Buendía and Delgado (1981). The following is a refinement that provides forecasts for systems smaller in scale than synoptic ones, such as hurricanes and cut-off lows affecting the Mexican Republic. The weather forecast model regularly integrated at the Center of Atmospheric Sciences (Centro de Ciencias de la Atmósfera, UNAM) does not follow the dynamics of these perturbations with a distance of 432 km existing from one point to another on the grid. The grid is based on a Lambert conical projection tangent at 30° which simulates adequately the model's cyclicity.

The cyclicity is formed by extending the WMO region fourth, five grid sizes eastward in order to simulate that the Atlantic and Pacific oceans, are joined and we obtain $F(i, 1) = F(i, 76)$ and $F(i, 2) = F(i, 77)$; where F represents any geopotential height or stream function (Buendía *et al.*, 1981).

With the increasing quality of the instruments for meteorological measurements, geopotential height data at standard levels 700 mb, 500 mb and 250 mb are good enough to run baroclinic models for the forecasting trajectories of hurricanes. In this model, data analysis is subjective, and the Jacobian used for vorticity advection agrees with Arakawa's (1966) method for the conservation of vorticity and energy.

General equations for a two-level baroclinic model are given by Holton (1979) and Haltiner and Williams (1980). Equations applied in particular to the fourth region with east-west cyclicity were reported by Buendía *et al.* (1981):

$$\frac{\partial}{\partial t}\nabla^2 A = J(m^2\nabla^2\Psi_1,\ \Psi_2) + J(m^2\nabla^2\Psi_3,\ \Psi_3) + J(f,\ A)$$

$$\frac{\partial}{\partial t}(\nabla^2 B - \frac{\lambda^2}{m^2}B) = J(m^2\nabla^2\Psi_1,\ \Psi_1) - J(m^2\nabla^2\Psi_3,\ \Psi_3) + \lambda^2 J(A,\ B) + J(f,\ B)$$

where Ψ_3 and Ψ_1 stand for the stream function at the 750 mb and 250 mb levels respectively; ∇^2 is the Laplacian operator applied on a Lambert conical projection tangent at 30°on the WMO region fourth; m stands for the map scale parameter (Saucier, 1955); f is the Coriolis paramenter; $B = \Psi_1 - \Psi_3$; $A = \Psi_1 + \Psi_3$; J represents the Jacobian operator; $\lambda^2 = f_o/\alpha(\Delta p)^2$; $\frac{\partial}{\partial t}$ is the local variation with respect to time; $\Delta p = 500$ mb; α stands for the static stability parameter and f_o for Coriolis parameter at 35°N, where $\Psi_3 = gZ_{750}/f_o$ and Z_{750} obtained by interpolating from geopotential height Z_{700}.

Results and concluding remarks

Using geopotential height values on each point of a coarse grid (19×22 points spaced every 432 km), obtained by hand analysis, an interpolation is made by weighted averages to obtain the geopotential height field over a 69×77-point grid (spaced every 108 km) which extends over the same region of integration. The points on the grid in the center of the storm are analysed subjectively with the aid of the tropical weather discussion of the National Weather Service. This grid is employed only in the presence of atmospheric phenomena with a scale smaller than the synoptic one and with the possibility of affecting the Mexican Republic.

In Figure 1 Hurricane Gilberto can be seen south of Hispaniola and Puerto Rico and north of Venezuela. The small circle drawn in the area of low geopotential height on the 700 mb map represents the reported position of the eye of the hurricane and the vortex accompanying it agrees with the corresponding satellite image (not presented).

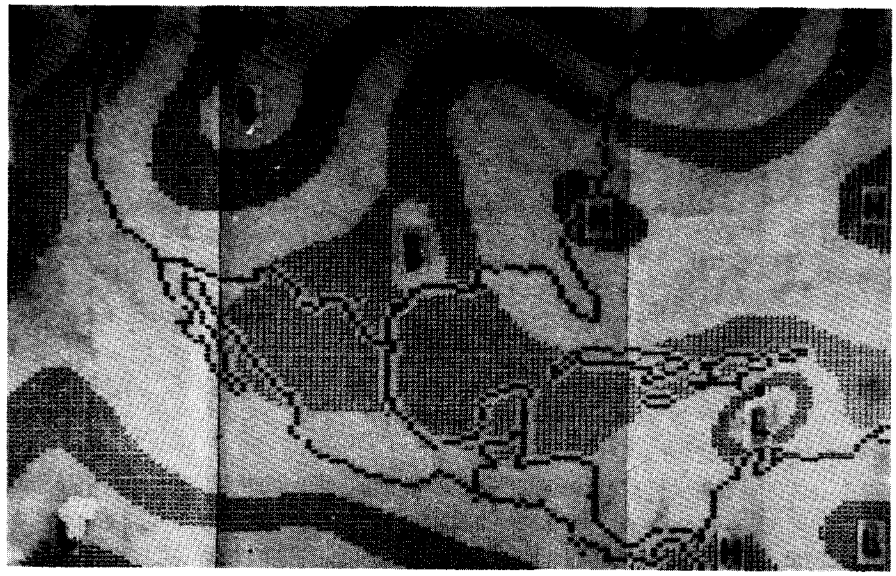

Fig. 1. Geopotential height field at 700 mb on September 11th, 1988 at 1200Z. Black circle marks the position of the eye of hurricane Gilberto.

The Mexican Republic is being fed by an easterly wind circulation associated with a semipermanent anticyclonic system over the Atlantic Ocean, which steered the trajectory of Hurricane Gilberto. The eye of the hurricane moved westward finding itself south of Haiti 12 hrs later, the large cyclonic system phenomenon has suffered a rotation of approximately 90 degrees following the current flux of the synoptic system near it, as shown on Figure 2a. The forecast for 24 hrs from initial data shows that the system of low geopotential height around Hurricane Gilberto, is affecting Jamaica, Haiti, the Caribbean and its vicinity. The eye of the hurricane is found east of Jamaica according to Figure 2b, which illustrates the forecast field and the observed position of the cyclonic center on September 12th, 1988 at 1200Z. On September 13th at 0000Z (Figure. 2c) the eye of the hurricane was reported over the western coast of Jamaica; this position is found inside the area of the cyclonic system forecast for 36 hrs by the model.

The hurricane continued its westward trajectory, being found 12 hrs later (1200Z) south of Cuba and north of Honduras; the center of the storm is again inside the forecast area for the system of cyclonic circulation that accompanies it (Fig. 2d). The forecast for 60 hrs (Fig. 2e) shows displacement of the storm westward on the coast of the Yucatán Peninsula; the observed storm center was located southwest of Cuba. Finally, the forecast for 72 hrs (Fig. 2f) shows that the hurricane has entered land over the Yucatán Peninsula; with its eye between Puerto Morelos and Puerto Juárez in accordance with what was observed on September 14th at 1200Z.

In Figure 3, the observed trajectory of Hurricane Gilberto and the forecast one using maximum vorticity can be seen at 12, 24, 36, 48, 60 and 72 hrs for the days 11, 12, 13, 14, 15, 16, 17 and 18 September 1988. In each case, the forecast is initiated at 1200Z; black circles report the observed position of the hurricane eye every 12 hrs, and white circles stand for the position forecast for the same time intervals (0000Z and 1200Z).

The predicted trajectory on September 11th is close enough to the observed center of the storm at 72 hrs, barely a degree away from the observed position. This error is smaller than the errors commonly reported by other authors whose forecast average interval error is 6 degrees (Plante and Guard, 1989).

700 mb

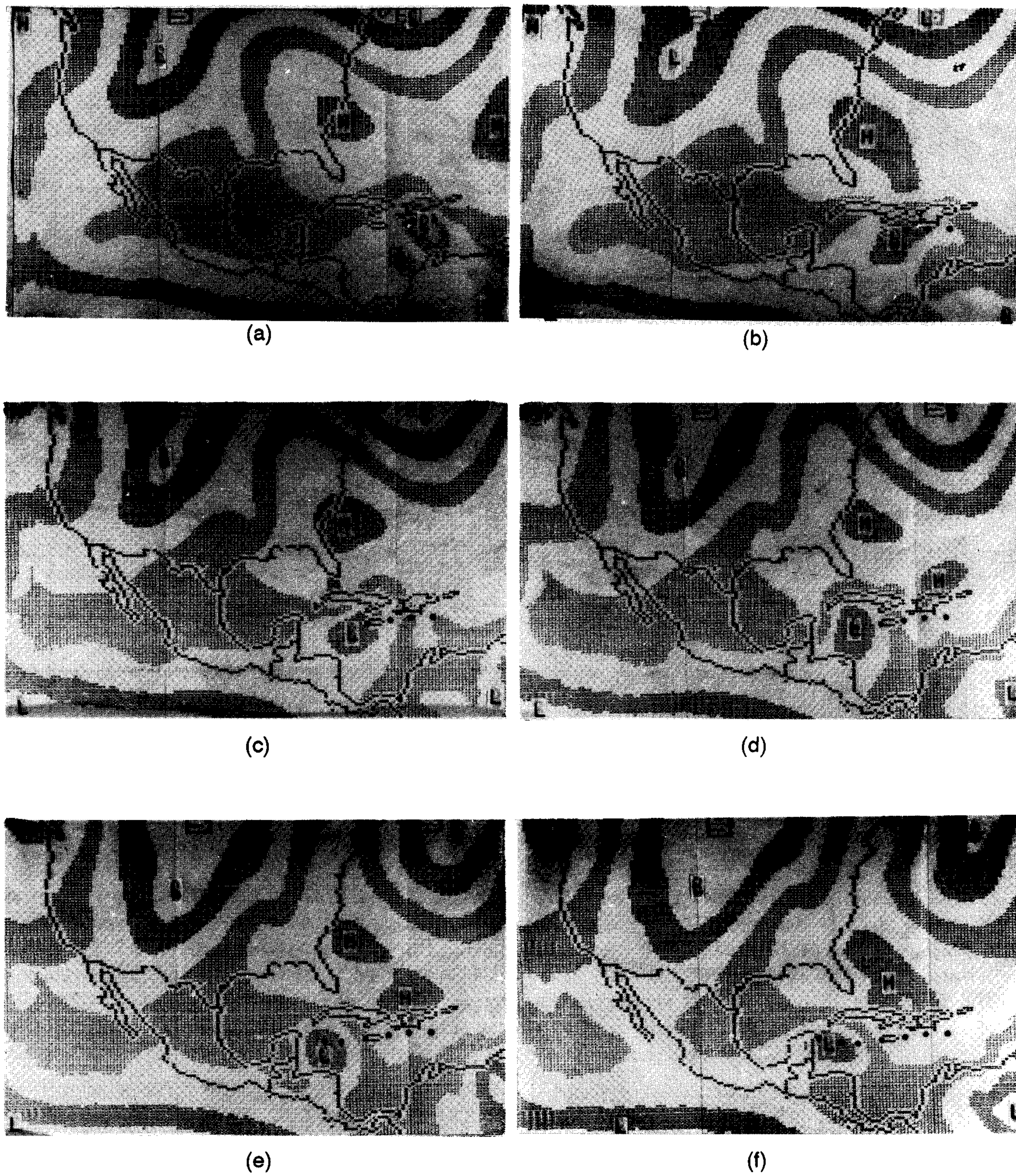

Fig. 2. Geopotential height forecast fields for 12 hrs (2a); 24 hrs (2b); 36 hrs (2c); 48 hrs (2d); 60 hrs (2e) and 72 hrs (2f) from the observed field on the 11th.

The forecast from 1200Z on September 12th 1988, when the hurricane was east of Jamaica, was satisfactory for 12 hrs and 24 hrs, later on its displacement was slower than that observed. For 72 hrs, the forecast position (for September 15th) was adjacent to the observed corresponding to September 14th. The forecast position instead should have been localized over the Gulf of Mexico on the zone marked by the appropriate black circle.

The predicted trajectory starting from September 13th differs at 72, 60, 48 and 36 hrs from the observed field by approximately one grid size length, with forecast positions being slightly north of the observed.

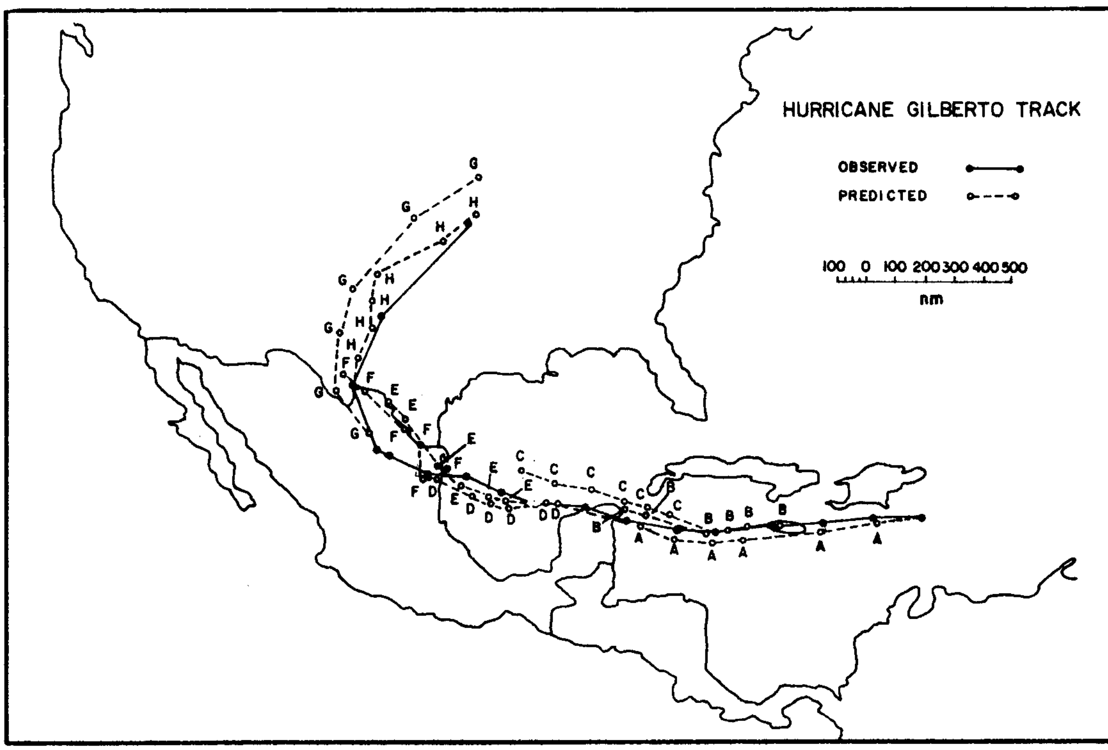

Fig. 3. Observed trajectories (black circles) and predicted (white circles) for 11th (A), 12th (B), 13th (C), 14th (D), 15th (E), 16th (F), 17th (G) and 18th (H) September at 1200Z, for hurricane Gilberto.

The forecast from September 14th, at 1200Z, is virtually ideal until 60 hrs, where the maximum vorticity is slightly delayed with respect to the observed center. At this moment, vortices are situated northeast of Tamaulipas on the continent near Boca de Jesús María. The 72 hrs forecast position is near the observed 60 hrs later (Fig. 3). The forecast from the 15th shows the landing of the hurricane in the continent around Santa Teresa, Tamaulipas, slightly north of the observed position and delayed 12 hrs (the model was slower than the observed movement). Later it was displaced towards Río Grande river over Nuevo Laredo, Tamaulipas (60 hrs) and Piedras Negras, Coahuila (72 hrs).

For the period comprised between the 16th at 1200Z and the 19th at 1200Z it is observed again an adequate forecast. Taking into consideration the dimensions of the cyclonic vortex, the forecast detects the areas that were considered disaster zones in the Mexican Republic.

In general it is observed that in forecasting the trajectories of Hurricane Gilberto (once it has entered the continent) the model has less kinetic energy than the observed situation. Also, forecasts after 24 hrs remain considerably behind with respect to what is observed, probably due to the influence that orography plays on the phenomenon. This orographic factor is not considered by the model. In order to avoid these inconsistencies, experimentation will be done with primitive-equations models in sigma coordinates.

Forecasts of cyclonic circulation surrounding the eye of the hurricane to dictate prevention and protection measures are optimum at 24 hrs and even useful at 48 and 72 hrs, as was the case on the period from the 11 to the 16 of September 1988.

Due to the fact that the model does not account for orographic influences once the storm enters the continent, only the 24 hrs forecast is fully acceptable. For longer periods, the model loses dynamical force, and the theoretical hurricane becomes much slower than the observed motion.

Even though Hurricane Hugo did not affect the Mexican Republic, its initial position indicated a possibility of reaching this part of the continent. Thus, we present in this article its observed position every 12 hrs (white circles) from September 18th, 1989, at 1200Z (Fig. 4).

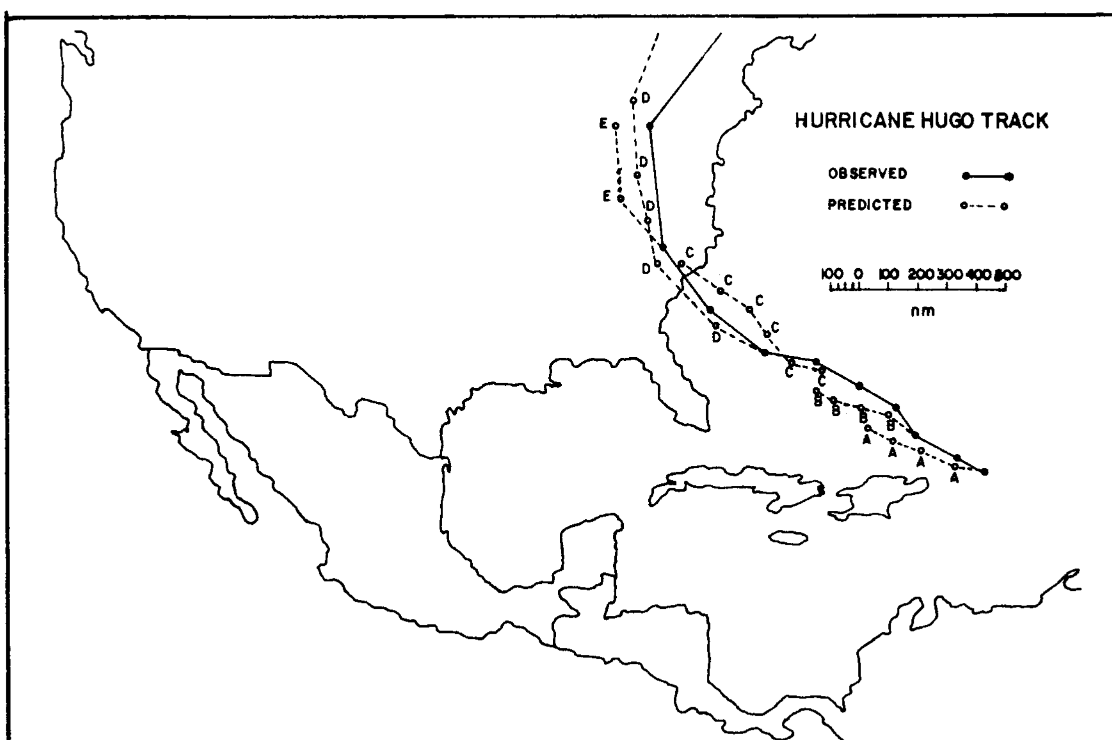

Fig. 4. Observed trajectories (black circles) and forecast trajectories (white circles) on the 18th, 19th, 20th and 21th September, 1989, at 1200Z, for Hurricane Hugo.

Each white circle represents the forecast initial position of Hurricane Hugo every 12 hrs. It can be seen that the more the forecasting time is increased, the more the forecast storm position is delayed with respect to the actual observations. For example, the forecast for 72 hrs for September 20th was approximately 100 km away from the position of the hurricane on the 22th. This differed a lot from the position of the vortex on the 23th again, the continental influence on the dynamics of the storm is clear.

Figure 5 shows the forecast error in kilometers for Hurricane Hugo track forecast by our model (CCA) and the forecast error in kilometers for the same hurricane by the Clipper model, Beta

Advection Model (BAM), NHC 83 model and the Quasilagrangian model given by Ward (1990) for September 18th, 1989.

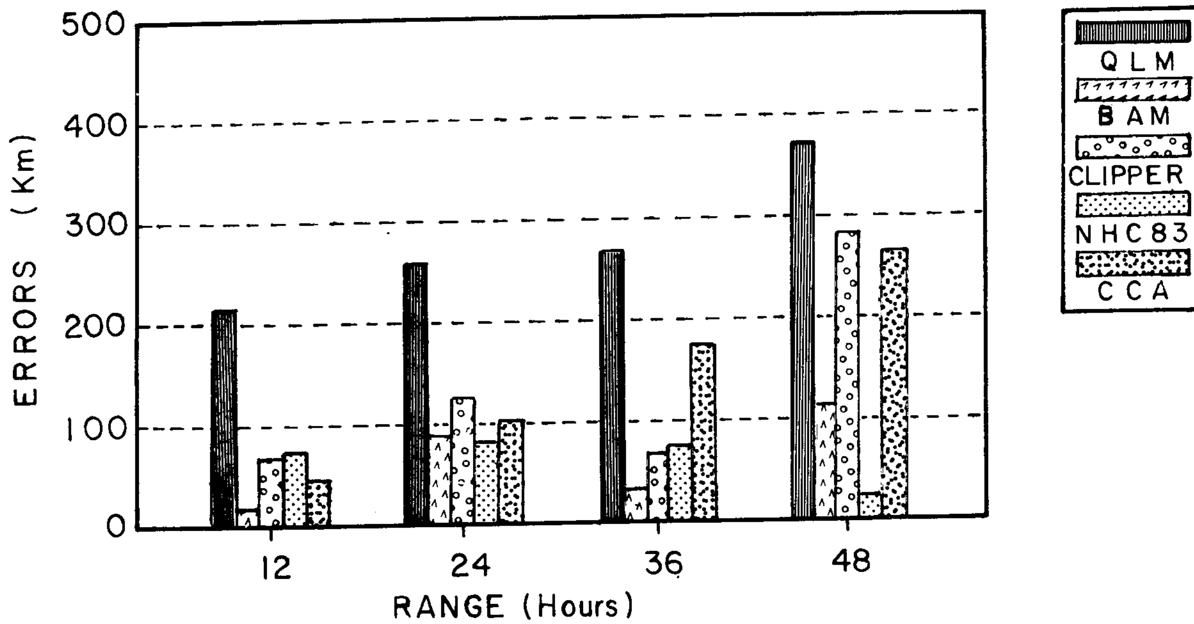

Fig. 5. Forecast errors in kilometers for the hurricane track forecasts, valid at 1200Z, 18th September 1989.

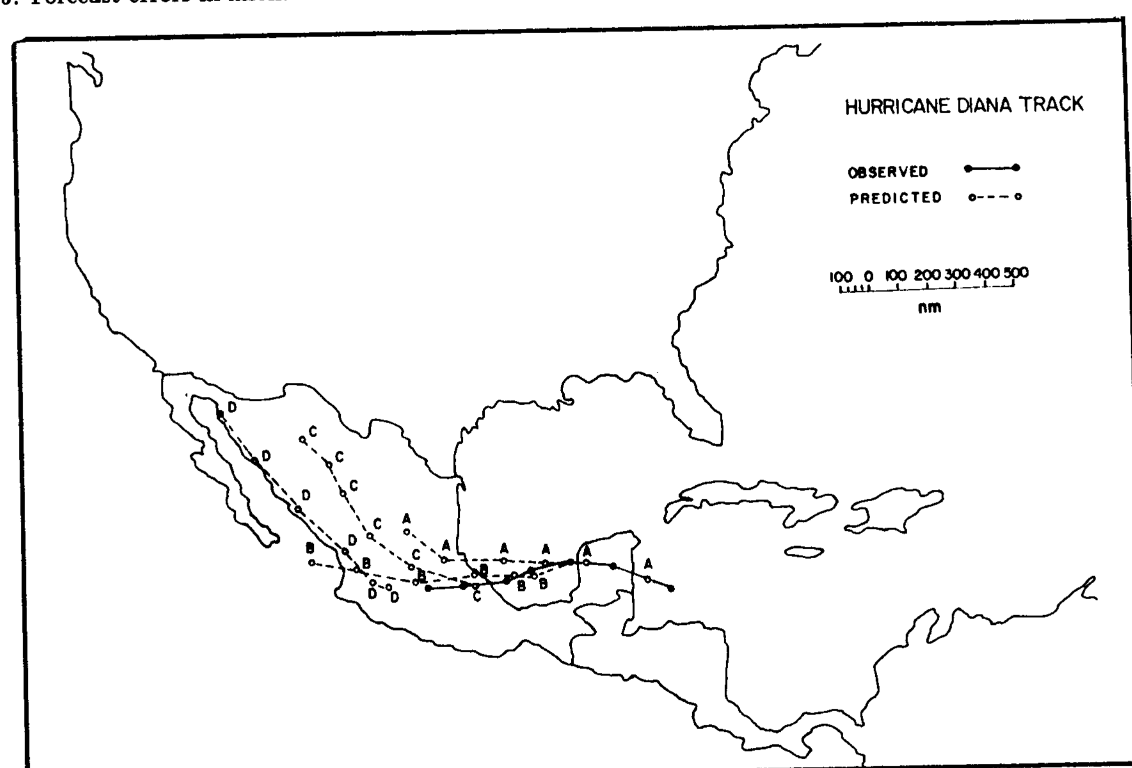

Fig. 6. Observed trajectories (black circles) and forecast trajectories (white circles) for 5th, 6th, 7th and 8th August, 1990, at 1200Z, for hurricane Diana.

The line joining black circles in Figure 6 represents the observed trajectory of tropical storm and Hurricane Diana from August 5th to August 18th, 1990. The forecast trajectory by the model at 12, 24, 36, 48 60 and 72 hrs for the periods August 5-8, 6-9, 7-10 and 8-11 is shown by the line joining the white circles. In each case, the forecast is good until 36 hrs being optimum up to 60 hrs in the case of August 6th, where the proximity of observed and forecast trajectories was good enough to prevent zones of national disaster.

Due to the physical deficiencies of the model, the storm was not predicted to disintegrate on the 8th of August, thus Figure 6 shows also the possible trajectories in case the storm had not been disipated.

With the aim to avoid loss of life and prevent huge material losses in disaster zones in the Mexican Republic, it is necessary to continue this sort of storm forecast because of the satisfactory results obtained up to now, to permit further improvement of the model.

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