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The GFDL Multiply-Nested Moveable Mesh Hurricane Model System

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This Technical Procedures Bulletin was written by Robert Tuleya, Morris Bender, and Yoshio Kurihara of The Geophysical Fluid Dynamics Laboratory (GFDL), and Stephen Lord of the National Meteorological Center's Development Division.

The current dynamical Quasi-Lagrangian Model (QLM) was replaced by a new hurricane forecast model system, the GFDL Multiply-Nested Moveable Mesh Hurricane Model System (GHM), as of 1200 UTC Tuesday, June 6, 1995. This model has a more sophisticated physics package and initialization scheme than the QLM. The GHM will also produce experimental forecasts of hurricane intensity for comparison with other operational models. The GHM is integrated for 72 hours with lateral boundary values taken from AVN forecast data at 6-h intervals. The major feature of the GHM is its unique and highly successful method of vortex specification which uses filtering procedures to remove the original vortex from the AVN analysis and replaces it with a vortex that is compatible with the GHM. In a test sample for the 1994 hurricane season, the average track forecast errors were improved by approximately 20% over the QLM. The GHM was among the top performers in the NHC forecast suite at all forecast hours.

The GHM forecasts will be available at approximately 5 hours after the synoptic times of 0000 and 1200 UTC. The basic model forecast for each storm is transmitted in the standard Automated Tropical Cyclone Forecast (ATCF) system format to NHC. The GHM system also produces wind swath maps that show the storm track and distribution of the maximum winds at the surface and the top of the boundary layer for the period of storm passage. Intensity forecasts are recorded in the same ATCF format as the track forecasts.

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The GFDL Multiply-Nested Moveable Mesh Hurricane Model System

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1. Introduction

The National Meteorological Center (NMC) has a long history of operational dynamical forecasting for hurricanes beginning with the Moveable Fine-mesh Model (MFM, Hovermale and Livesey, 1977). This model, which was operational from 1976-1988, had a 60-km horizontal resolution over a 3000x3000-km domain with 10 vertical layers and was driven by boundary conditions from the NMC global model. The vortex initialization technique consisted of implanting a "canned" model-generated vortex over smoothed fields from the global model. In 1988, in response to additional computer resources and other factors, the Quasi-Lagrangian Model (QLM, Mathur, 1988) was implemented with a 40-km horizontal resolution over a 4000x4000-km domain with 18 vertical layers. The vortex initialization technique consisted of merging an analytically-defined, axisymmetric, baroclinic vortex and asymmetric steering along the current track from an analytical "Beta-gyre" model (Mathur and Shapiro, 1992).

With the advent of considerably increased computer power at NMC (the Cray C90), it is now feasible to implement a hurricane forecast model with higher resolution and a more sophisticated physics package and initialization scheme than the QLM. The model has been developed at the Geophysical Fluid Dynamics Laboratory (GFDL) by Dr. Yoshio Kurihara and his collaborators Robert Tuleya, Morris Bender and Rebecca Ross. The model, designated as the GFDL Hurricane Model (GHM), and its associated vortex initialization scheme are described in this Bulletin. The GHM will produce operational track forecasts and experimental forecasts of hurricane intensity. The experimental intensity forecasts will be compared with statistical and dynamical models used by the National Hurricane Center (NHC).

2. Model Description

The GHM was introduced by Kurihara and Bender (1980) and most recently described by Kurihara, Bender, Tuleya and Ross (1995, hereafter described as KBTR). Specific model details have been outlined in previous publications (e.g., Tuleya et al., 1984; Bender et al., 1987; Bender et al., 1993). The model is a primitive equation model formulated in latitude, longitude, and sigma coordinates, with 18 vertical layers (Table 1). The grid geometry is summarized in Table 2. A typical grid configuration is shown for Hurricane Emily (1993) in Fig. 1. The outermost domain extends 75^o in the meridional and longitudinal directions. The GHM physics include cumulus parameterization after Kurihara (1973) with some modification (Kurihara and Bender, 1980, Appendix C), a Monin-Obukhov scheme for the surface flux calculation, and the Mellor and Yamada (1974) level-two turbulence closure scheme for vertical diffusion with a background diffusion coefficient added. The most recent improvements, introduced by Kurihara, Bender, Tuleya and Ross (1990), include the Schwarzkopf and Fels (1991) infrared and Lacis and Hansen (1974) solar radiation parameterizations with diurnal variation and cloud specification, the use of vegetation type (Matthews, 1983) to specify the surface roughness length, evaporation efficiency and surface albedo, and the inclusion of a bulk subsurface layer with explicit prediction of land surface temperature (Tuleya, 1994). Over the ocean, where z_o is determined by Charnock's relation (e.g., Kurihara & Tuleya, 1974), the Charnock constant of .032 has been modified to a value of .0185 (Wu, 1982). Finally, the 3-point smoothing that had been used in previous versions of the model has now been modified to include a desmoothing operator (see Bender et al., 1993). The GHM is typically integrated for 72 hours with specified lateral boundary values taken from grid point forecast data at 6-h intervals from the "Aviation" (AVN) global model run. Boundary data are interpolated linearly in time to 6-h values, and the model solution is forced toward the future hourly values at every time step using the lateral boundary forcing scheme of Kurihara et al. (1989).

3. Model Initial Condition and Vortex Specification

As in KBTR, the initial conditions are obtained from the current AVN run and interpolated horizontally onto the GHM domain for each mesh. The distribution of surface height is obtained from the global topography data set prepared by the U.S. Navy's Fleet Numerical Oceanography Center, Monterey, California. The temperature, surface pressure and moisture fields over land are then adjusted for the differences between the AVN and the Navy topographical heights. The sea surface temperatures are taken from the AVN initial conditions and remain fixed for each forecast.

The vortex specification technique used is based on that described by Kurihara, Bender, and Ross (1993, hereafter described as KBR) and recently modified by KBTR. This technique uses two filters to remove the original vortex from the AVN analysis while retaining features of the near-storm environment. First, using a scale selective filter, all AVN fields (denoted symbolically as A, which includes wind, temperature, height, etc.) are partitioned into a large-scale component called the basic field (B) and a deviation denoted as the disturbance field (D):

$$A = B + D . \qquad (1)$$

The disturbance field includes the smaller-scale features in the AVN analysis including the vortex and any other smaller scale features such as a wave disturbance in which the hurricane is embedded. Next, the analyzed storm, called the hurricane component (H), is separated from the remainder of the disturbance field, called the non-hurricane component (NH):

$$D = H + NH . \qquad (2)$$

It is assumed that the hurricane component in the AVN analysis is improperly specified for the purposes of the GHM (inaccurately positioned, too weak, too large, etc.) and must be replaced by a more realistic vortex that is also more compatible with the GHM resolution and physics. Furthermore, after KBR, it is assumed that the hurricane component is confined within an appropriately determined domain, called the filter domain. After defining the center of the vortex as the geographical location that maximizes the azimuthally averaged tangential wind, the radial extent of the filter domain is determined at each of 24 azimuthal angles by considering the decrease of the tangential wind with radius from the vortex center. The axisymmetric hurricane component (H) is separated from the disturbance field within the filter domain by a second filter. The filter domain is not constrained to be circular.

The disturbance field outside of the filter domain consists only of the non-hurricane component whereas within the filter domain, the disturbance field is composed of both the hurricane and non-hurricane components (eq. 2). The non-hurricane component, which must be retained in the GHM initial conditions, is difficult to evaluate accurately. This is due to errors in the hurricane component, which is usually larger. For this reason, the non-hurricane component within the filter domain is determined from the disturbance field at the filter domain boundary by the method of optimal interpolation (Gandin, 1963). The environmental field (E) is then obtained by combining the non-hurricane component with the basic field over the entire model domain:

$$E = B + NH . \qquad (3)$$

The separation of the total wind field into the environmental and hurricane components, and geometry of the filter domain is illustrated in Fig. 2 for Hurricane Florence (1988). Note that the environmental field is identical to the global analysis outside the filter domain. Within the filter domain, the hurricane component of the disturbance field is effectively removed from the global analysis.

The initialization is completed with the addition of the storm vortex, which is generated from size and intensity parameters specified operationally by the NHC. This vortex (V) represents the new hurricane component which is added to the environmental field at the correct storm position to produce the initial field (I):

$$\begin{aligned} I &= E + V \\ &= B + NH + V \\ &= A - H + V \,. \end{aligned} \tag{4}$$

The new specified vortex consists of both axisymmetric and asymmetric components of all fields and is a perturbation quantity. It has zero value at its outermost edge and non-zero value inside.

As outlined in KBR, the axisymmetric component of the specified vortex is generated by time integration of an axisymmetric version of the GHM. During the axisymmetric integration, the tangential wind field is forced toward an estimate of the observed storm tangential wind profile while the moisture, mass and radial wind profiles are free to develop a model consistent structure. The information provided by NHC to determine the profile of the tangential wind is summarized in Table 3. The vortex specification technique has been designed to produce the best estimate of the radial profile of the tangential wind even when the data are incomplete.

Since a significant component of tropical cyclone motion can result from its asymmetric structure (e.g., Carr and Elsberry, 1990; Smith et al., 1990), the axisymmetric flow is used to generate an asymmetric wind field. Time integration of a simplified barotropic vorticity equation with the beta effect included (Ross and Kurihara, 1992) ensures that the axisymmetric and asymmetric components are mutually consistent. The sum of the symmetric and asymmetric components yields the specified vortex which is added to the environmental field. Finally, a new mass field is recomputed from the divergence equation with its time tendency appropriately controlled. Initialization of the mass field ensures a smooth start of the integration of the prediction model. The improvement in the structure of the specified vortex is readily apparent in Fig. 3 for the case of Hurricane Gilbert, 1200 UTC 14 September, 1988. The specified vortex is much more compact and considerably more intense than the vortex in the global analysis with the radius of maximum wind decreasing from 350 km to about 60 km.

4. Model Products

The GHM's tracking algorithm (Kurihara and Bender, 1980) is based on following the apparent center of gravity of pressure variation from the minimum sea-level pressure on the innermost grid. This algorithm is also used to move the nested grids as the storm moves during the forecast. In the past, this scheme sometimes was unable to distinguish between the disturbance field and high terrain when the surface pressure was reduced to sea level. Revisions by KBTR allowed for tracking storms at a height surface near the maximum height of the underlying topography rather than at sea level.

The basic model forecast for each storm is transmitted in the standard Automated Tropical Cyclone Forecast (ATCF) system format to NHC. The GHM system also produces wind swath maps that show the storm track and distribution of the maximum winds at the surface and the top of the boundary layer for the period of storm passage. From this product the maximum forecast wind for any particular location and the extent of high winds can be assessed for each storm. Four wind swaths of forecast maximum low-level winds during the passage of Hurricane Emily (1993) are shown in Fig. 4. Intensity forecasts are recorded in the same ATCF format as the track forecasts.

Initial and forecast basic meteorological fields are interpolated to 1° resolution and output at 6-h intervals on isobaric surfaces at 50-mb intervals from 1000 to 100 mb in WMO Standard "GRIB" format (U. S. Department of Commerce, 1994). The GHM also produces a graphics file depicting the environmental wind obtained in the vortex specification step (Sec. 3 above). This wind field gives important information concerning the size of the AVN vortex as well as an approximate steering direction for storm movement. Other available fields include the inner nest data for high resolution analysis and the graphical file of the grid configuration used for each specific model forecast (Fig.1).

The GHM forecasts are run after the mesoscale Eta model (Meso-Eta) and will be available at approximately 5 hours after the synoptic times of 0000 and 1200 UTC.

5. Forecast Evaluation

a) Track

During the 1994 season, the GHM system forecast 60 cases for the Atlantic and 148 cases for the Eastern Pacific in all stages of development from tropical depression to hurricane. The average track forecast error in the Atlantic basin is presented in Table 4, together with the errors from other hurricane models. The GHM is among the top performers out to 36 hours and is superior to other models at 48 and 72 hours. Examples of the forecast track for Hurricane Gordon (Fig. 5) show that the GHM was the first model to forecast, three days in advance, the storm's westward movement in the Florida Straits, turning to the northeast and crossing the Florida peninsula. Later, the prediction with the GHM hinted at Gordon's abrupt U-turn toward the south off the East Coast of the United States.

Similar to the Atlantic basin, the forecasts in the East Pacific basin and some in the Central Pacific showed a good performance at the later forecast periods (Table 5). It was found that many forecast position errors in earlier periods were caused by directional differences in the initial movement from the observed. Also, the model storms tended to move faster than the observed storms during the entire forecast period. The GHM predicted a few days in advance the recurvature of East Pacific Hurricanes Olivia and Rosa (Fig. 6).

When the forecast errors of the GHM and the QLM are plotted together (Figs. 7 and 8) the improvement is clearly seen. In these figures, the large majority of circles are below the dotted line where the QLM errors are greater than the GHM forecast errors. There were only three cases in which the QLM 72-h Atlantic basin forecasts were superior to that of the GHM compared to 23 cases in which the GHM was superior.

The GHM was also run for a limited number of hurricane cases in 1992 and 1993 at GFDL in near real time. The revised system of KBTR was run on 71 cases during the 1993 season, 36 forecasts in the East Pacific and 35 forecasts in the Atlantic basin. In both the East Pacific and Atlantic basins in 1993, the GHM exhibited considerable skill in the forecast storm track compared to other models. Relative to both the AVN and the QLM, the GHM demonstrated superior skill for each forecast period when averaged over all cases for both the East Pacific and Atlantic basins (Fig.9). In the East Pacific the GHM yielded improvements compared to climatology/persistence (CLIPER) of 15, 27, 30 and 15 percent at 24, 36, 48, and 72 hours, contrasted to -6, 11, 14 and 19 percent improvement for the medium Barotropic Advection Model (BAM). Especially encouraging were the track forecasting skills relative to CLIPER at and beyond the 24-h forecast period. The GHM successfully tracked both westward moving East Pacific systems such as Dora and Fernanda as well as those paralleling the Mexican coast such as Hilary and Lidia. The forecasts of Lidia were especially good ranging from 20% better at 12 hours to more than 50% better at and beyond 36 hours. The GHM was the first model to predict recurvature of Lidia toward the coastline.

In the Atlantic basin, the GHM was run for 14 cases of Hurricane Emily in 1993. The model successfully forecast the movement of Emily toward the coast of North Carolina several days in advance as well as the subsequent recurvature of the storm just offshore.

The model also correctly predicted over 48 hours in advance the occurrence of winds exceeding hurricane force along the tip of Cape Hatteras (Fig. 4). The system yielded improvements compared to CLIPER of 64, 69, 72 and 55 percent for all fourteen cases compared to 38, 48, 54 and 55 percent respectively for the medium BAM model.

b) Intensity

Past results from the GHM have demonstrated the feasibility of intensity prediction for cases of intense hurricanes (Bender et al. 1993). Predicted maximum wind speeds in a large number of cases in the 1994 season were compared against reported winds. A positive bias in the intensity forecast, i.e., overestimation by the model, was found in many cases in which the observed storms were weaker than hurricane intensity (64 kts or ~33 ms^{-1}). On the other hand the predicted winds tended to be less than the observed when storms were stronger than the hurricane intensity. Reexamination of the past cases showed a similar tendency.

The underestimation of maximum wind in intense storms may be partly related to the insufficient horizontal resolution, whereas the positive bias in weak storms suggests that the behavior of model storms should be investigated further. For example, some model storms in positive bias cases apparently did not respond realistically to weak and moderate vertical shear of the wind. Also, many of the storms observed in the Atlantic basin during 1994 exhibited a highly asymmetric structure, implying uneven energy flux at the surface to the storm. This feature could have affected the real storm's motion and intensity, but was absent from the model initial conditions because of the incapability of the initialization method used.

6. Future Improvements

Future efforts will concentrate on improving the skill of intensity forecasts, including the tendency for overdevelopment in weaker storm cases and in the presence of strong wind shear. It is expected that some revisions to the formulation of the entrainment rate for the cumulus parameterization, e.g., to make it more dependent on vertical wind shear, will be needed. Furthermore, some revision of the initialization scheme to include the observed wind asymmetry will also be required.

7. Summary

The GHM has been run in test mode for the 1992 and 1993 seasons at GFDL and run in parallel mode at NMC for the 1994 season. Results indicate that the GHM has shown significant superiority in track prediction for periods beyond 24 hours compared to the

QLM and any other objective track guidance for this period. Standard GHM output products give storm intensity and distributions of quantities such as the extent of gale and hurricane force winds and rainfall amounts. The GHM has shown some skillful forecasts of storm intensity, but overall little skill has been demonstrated, especially for weak systems. A systematic bias has been found such that weak storms tend to be overpredicted and strong storms are usually underpredicted. The initialization scheme works quite well for strong tropical cyclones, probably because these storms tend to be nearly symmetrical and the surface energy flux into the generated vortex is not significantly affected by the addition of the environmental winds. Weak systems often exhibit noticeable asymmetry in the wind field, in addition to the beta gyre, which the present scheme cannot simulate. Also, the distribution of the surface energy flux into a vortex after the addition of the environmental winds can be quite different from that computed for a vortex in a quiet environment during the generation. Developmental work is underway to correct this problem. Predicted rainfall and the extent and distribution of gale and hurricane force winds using the GHM have not yet been objectively verified. The usefulness of this product, as mentioned previously, will depend on the skill of the particular track forecast.

8. References

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TABLE 1. Summary of the vertical sigma layers for the GHM.

k layer	sigma
1	.0207469
2	.0739862
3	.1244004
4	.1745733
5	.2246687
6	.2747291
7	.3247711
8	.3748014
9	.4248250
10	.4974484
11	.5935378
12	.6881255
13	.7772229
14	.8563145
15	.9204018
16	.9604809
17	.9814907
18	.9949968

TABLE 2. Grid system for the triply-nested model configuration.

Mesh	Grid resolution (degree)	Longitude (deg)	Longitude (points)	Latitude (deg)	Latitude (points)	Timestep (sec)
1	1	75	(75)	75	(75)	120
2	1/3	11	(33)	11	(33)	40
3	1/6	5	(30)	5	(30)	20

TABLE 3. List of storm parameters supplied by NHC for Hurricane Gordon (1994).

Storm No.: 12L
Storm Name: GORDON
yymmdd: 941118
time (UTC): 1200
Storm Lat.: 337N
Storm Lon.: 0757W
Storm Hdg.: 270
Storm Movement (m/s*.1): 015
Storm Central Pressure (mb): 983
Pressure of outermost closed isobar (mb): 1006
Radial extent of outermost closed isobar (km): 0371
Max. Winds (m/s): 36
Radius of Max. Winds (km): 111
NE Quad. Extent of Gale Winds (km): 0324
SE Quad. Extent of Gale Winds (km): 0324
SW Quad. Extent of Gale Winds (km): 0139
NW Quad. Extent of Gale Winds (km): 0111
Vertical depth of Storm (D,M,S): D
NE Quad. Extent of 50 knot Winds (km): 0278
SE Quad. Extent of 50 knot Winds (km): 0278
SW Quad. Extent of 50 knot Winds (km): 0093
NW Quad. Extent of 50knot Winds (km): 0074
NHC Forecast Period (72 hours): 72
NHC Forecast 72h Position of Storm Lat.: 400N
NHC Forecast 72h Position of Storm Lon.: 0600W

TABLE 4. Hurricane track forecast errors for the Atlantic basin in the 1994 season. Average errors are in km, compared with operational positions for all cases including tropical depressions. VBAR is the quasi-operational VICBAR model, BAMM is the medium-depth Barotropic Advection Model, A90L is the NHC statistical dynamical model (NHC90), and CLIPER is the Climatology and Persistence model.

Forecast	GHM	VBAR	QLM	BAMM	A90L	CLIPER
12-h (60 cases)	111	102	111	110	113	124
24-h (53 cases)	186	185	220	194	201	258
36-h (45 cases)	248	243	293	294	251	359
48-h (39 cases)	322	348	415	442	348	491
72-h (28 cases)	464	581	822	844	564	746

TABLE 5. Same as Table 4 except for Eastern Pacific basin and some Central Pacific storms. P91E is the NHC statistical dynamical model (NHC91).

Forecast	GHM	QLM	BAMM	P91E	CLIPER
12-h (148 cases)	82	94	93	86	78
24-h (138 cases)	146	162	169	147	149
36-h (126 cases)	198	247	237	206	232
48-h (111 cases)	249	340	303	256	292
72-h (77 cases)	351	460	451	360	424

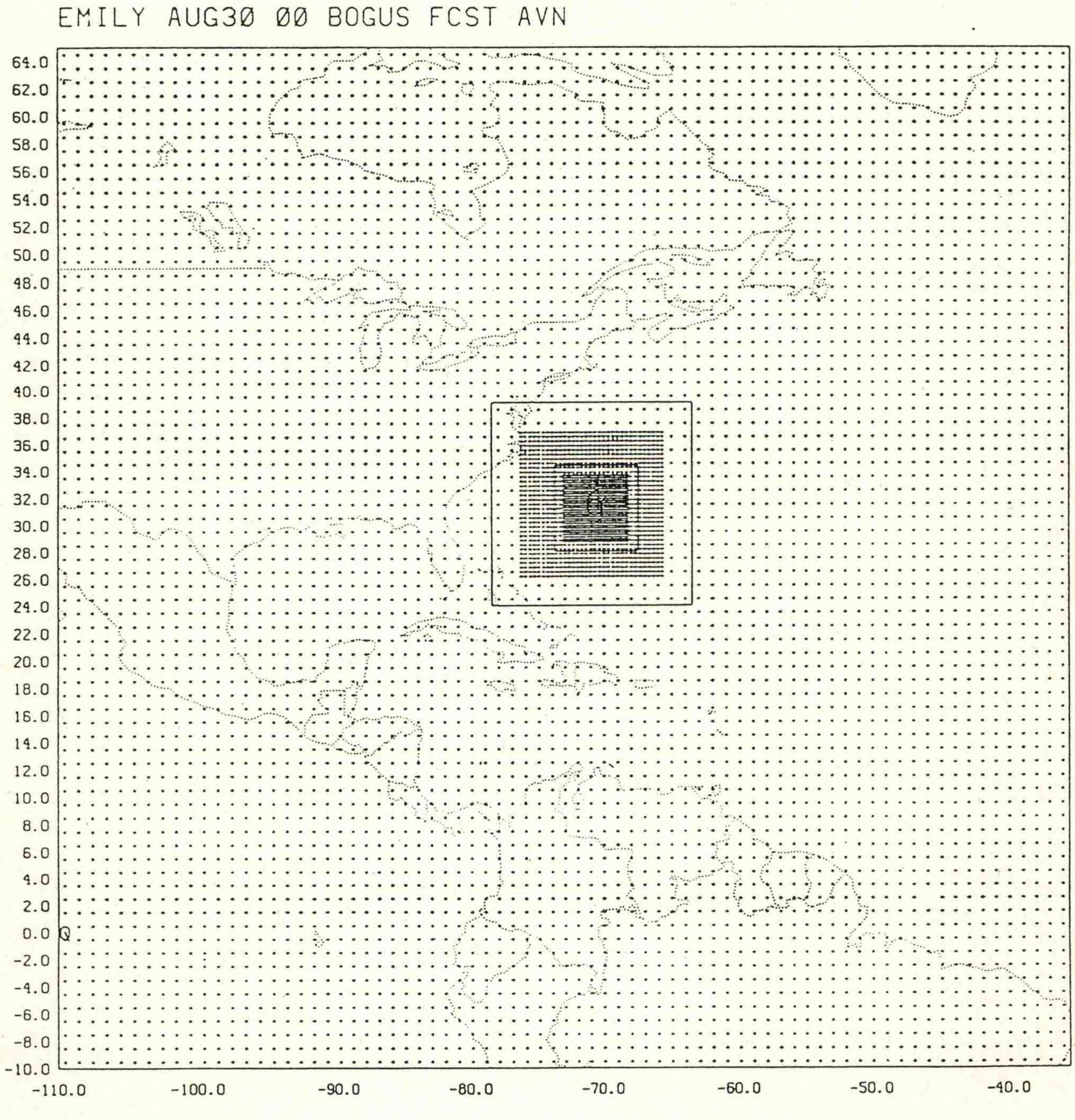


Figure 1. Grid points and model domain for the triply-nested GHM forecast initiated on 0000 UTC 30 August with the inner two grids centered on Hurricane Emily (1993).

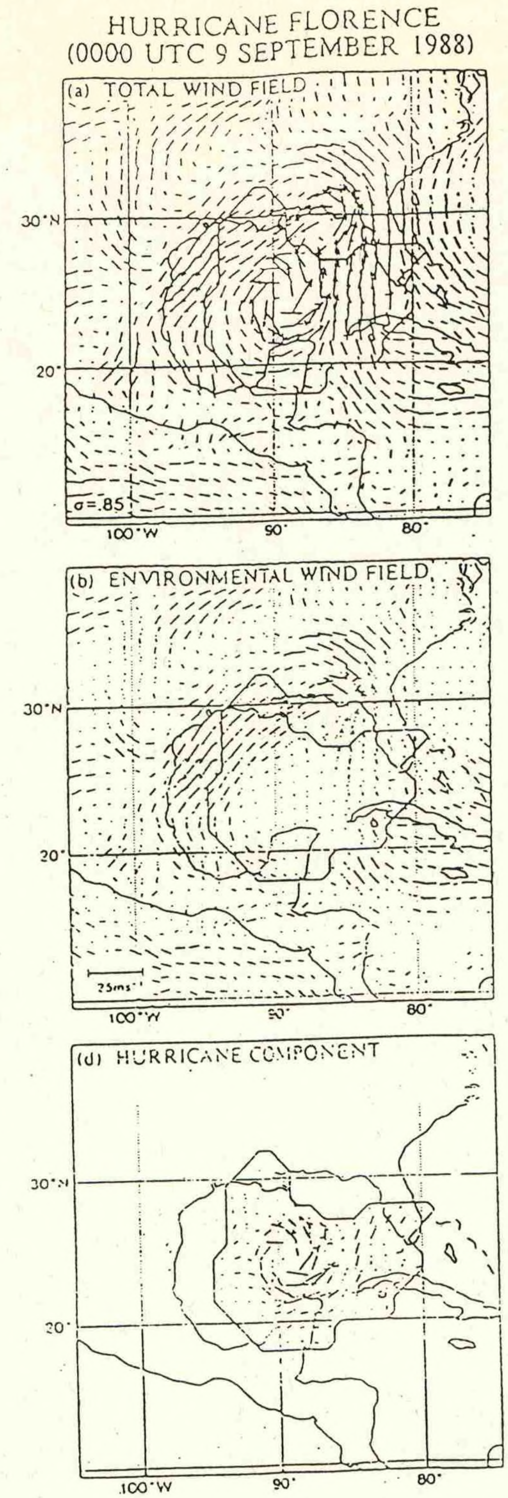


Figure 2. (a) The original total low-level (σ = .85) wind field of Hurricane Florence at 0000 UTC 9 September 1988. This field (a) is split into (b) the environmental wind field obtained using the new initialization method and (c) hurricane component. The scale of wind vector arrows shown in (b) applies to all panels. The filter domain is indicated in each panel by a thick solid line.

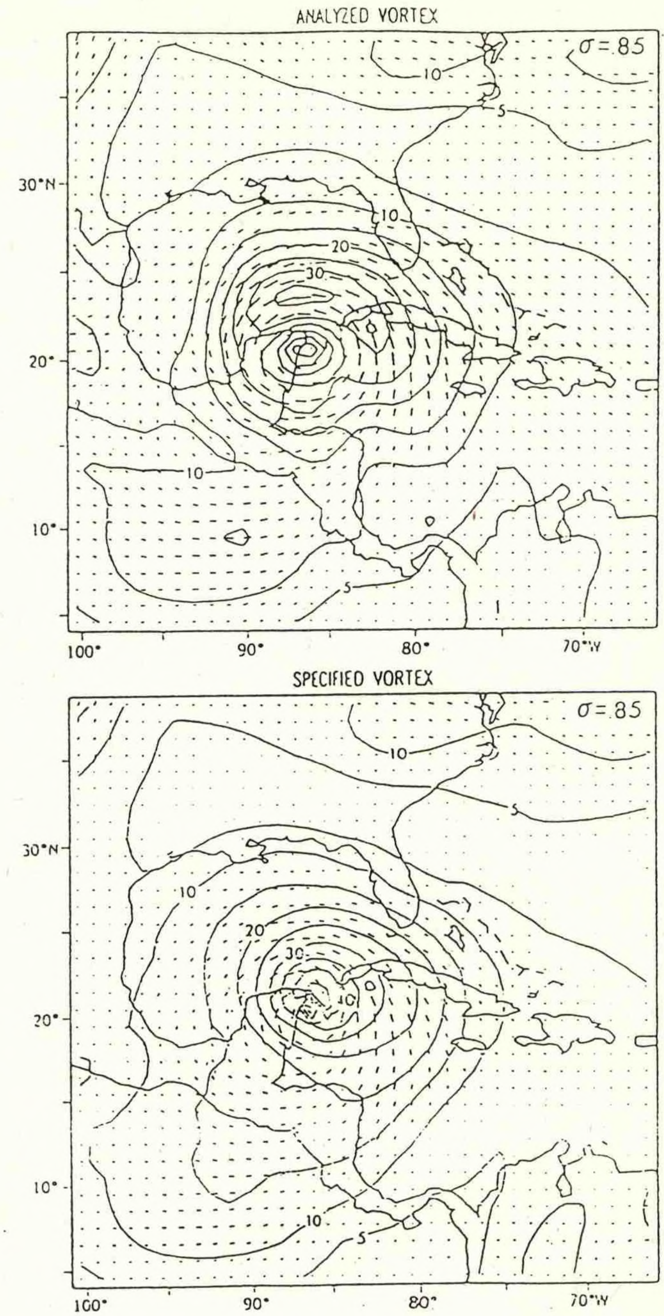


Figure 3. Distribution of horizontal wind vectors and wind speed ($m\ s^{-1}$) at 1200 UTC 14 September 1988 (Hurricane Gilbert) at model level 14 (σ = .856), for both the global analysis (top) and the specified vortex (bottom). The region shown is for a portion of the integration domain surrounding the storm region. The wind distribution shown, plotted with a 5-$m\ s^{-1}$ contour interval, is for the wind field resolved by the 1° resolution.

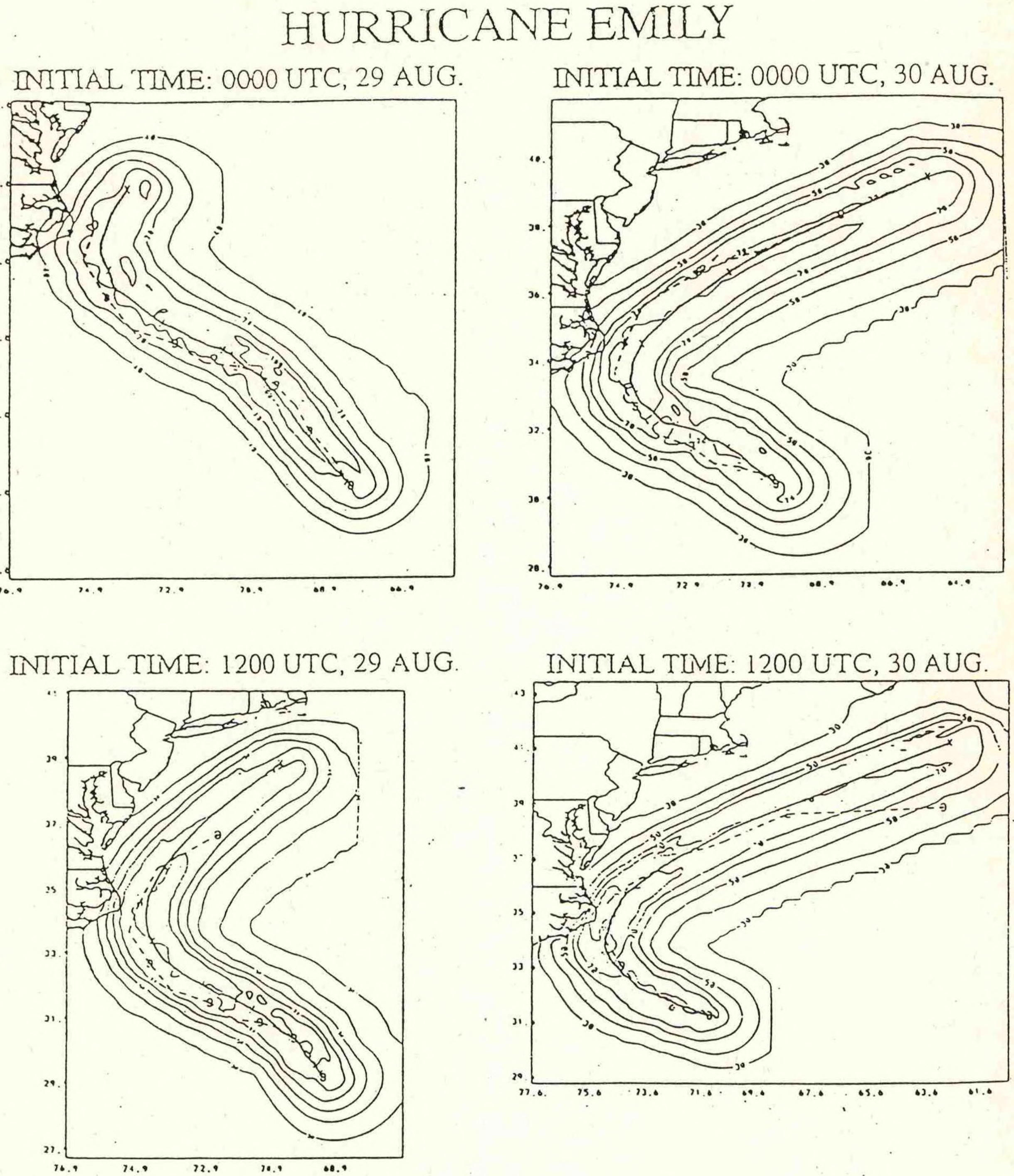


Figure 4. Distribution of maximum surface wind during the passage of Hurricane Emily for four forecasts (29 & 30 Aug., 0000 &1200 UTC) of the GHM. Solid and dashed lines indicate forecast and observed tracks respectively. Isopleths are in knots.

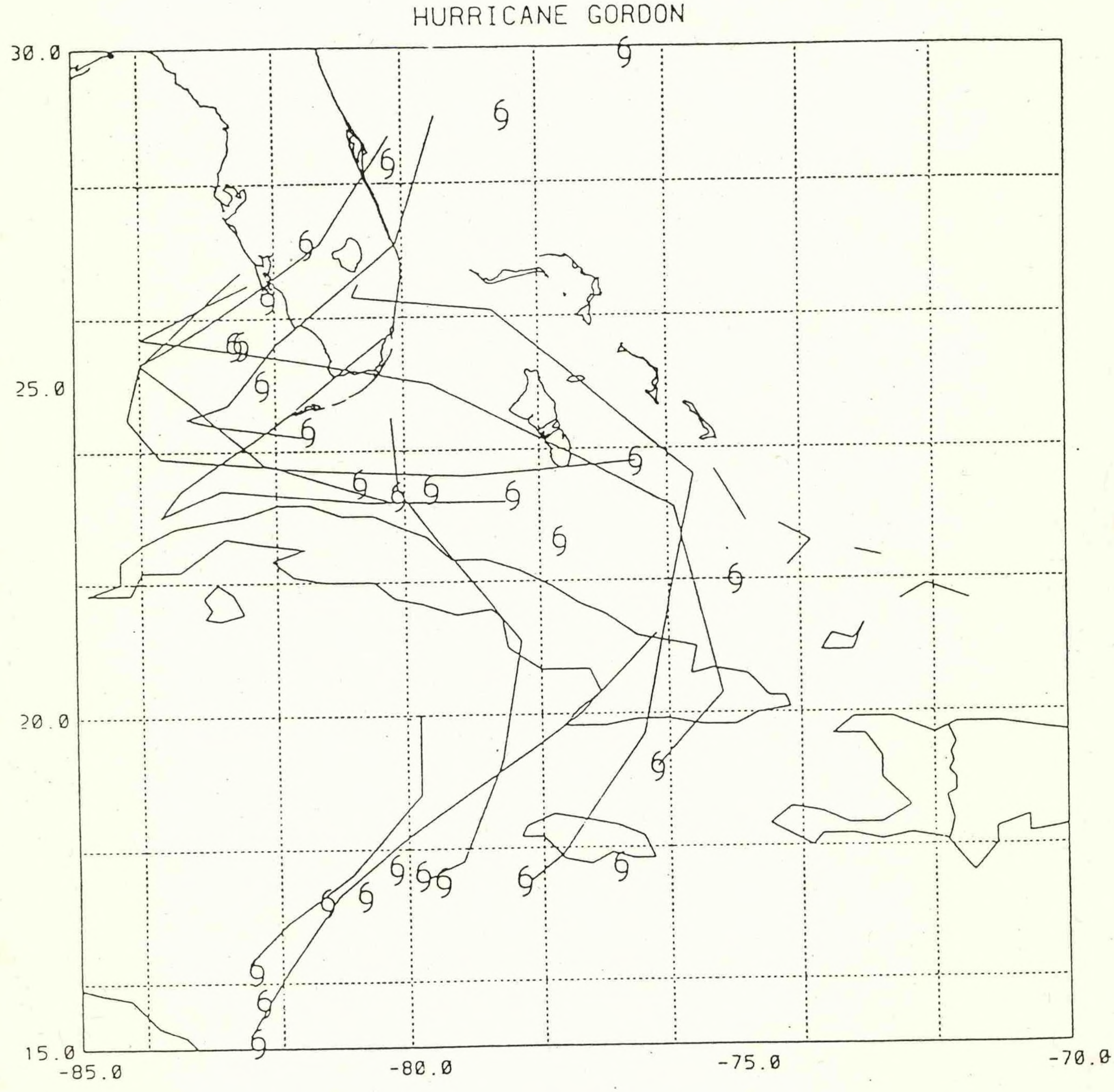


Figure 5. Composite of track forecasts for Hurricane Gordon. Only the forecasts made prior to landfall over Florida are shown. Also plotted are the observed positions every 6 hours from 0000 UTC 11 Nov. to 1200 UTC 17 Nov. 1994.

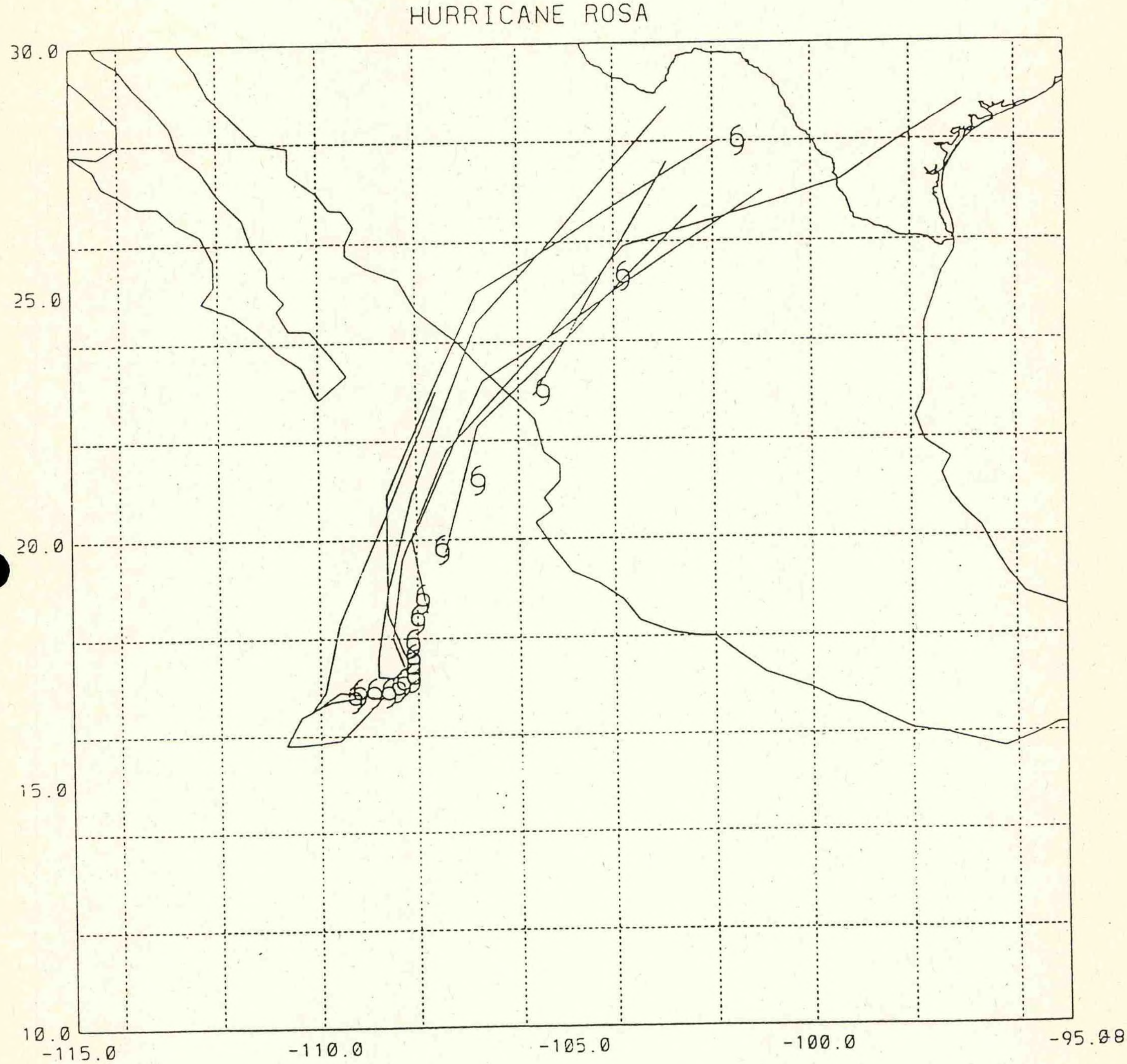
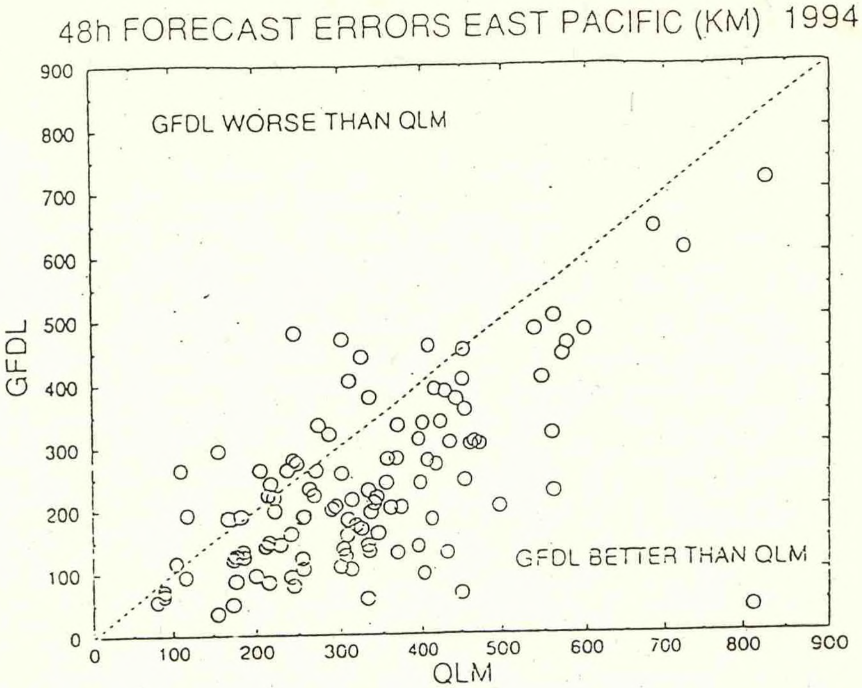


Figure 6. Composite of all track forecasts for Hurricane Rosa. Also plotted are the observed positions every 6 hours from 0000 UTC Oct. 11 to 0000 UTC 15 Oct. 1994.



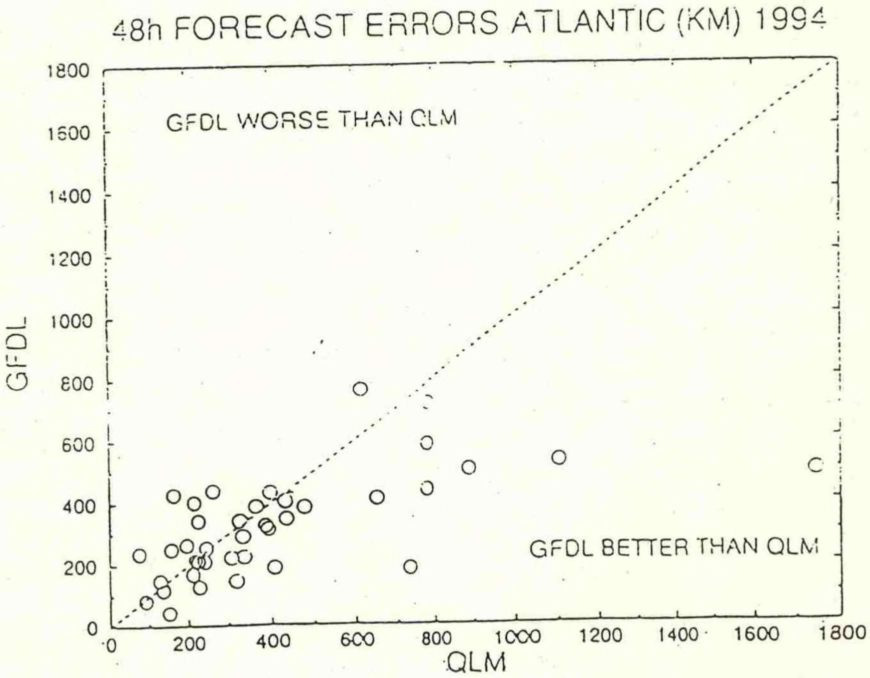
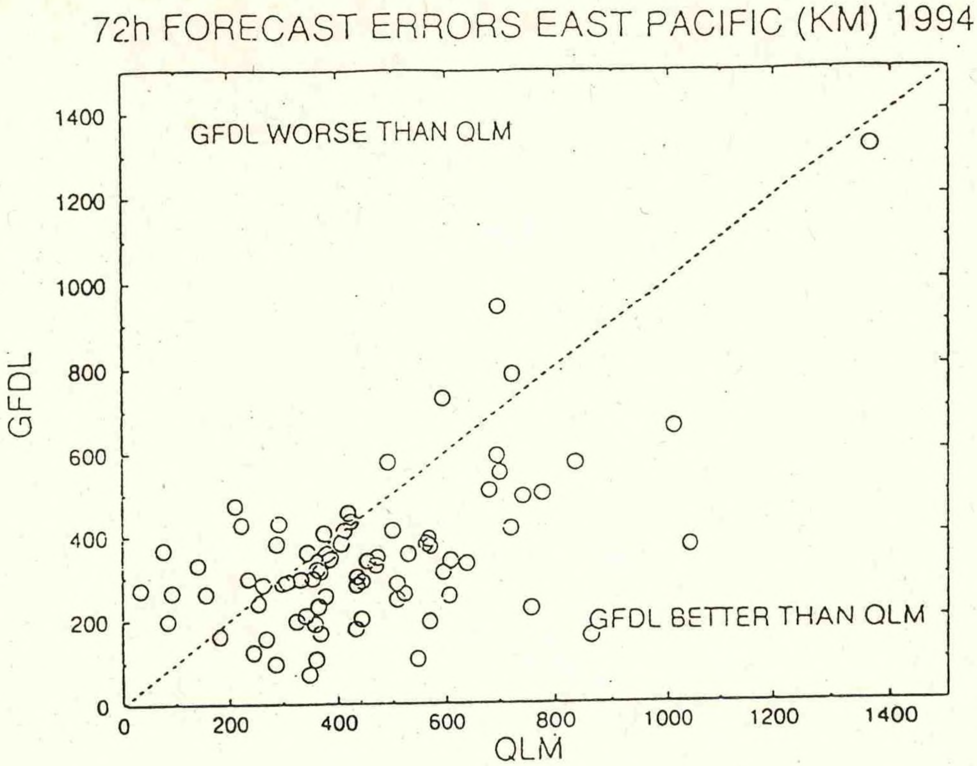


Figure 7. Forecast track errors (km) at 48 hours for all cases in the East Pacific (top) and the Atlantic (bottom) for the GHM compared to the QLM model. All circles below the dotted line indicate forecasts in which the GHM forecast errors were less than the QLM. All circle above the line indicate forecasts in which the QLM errors were less than the GHM.



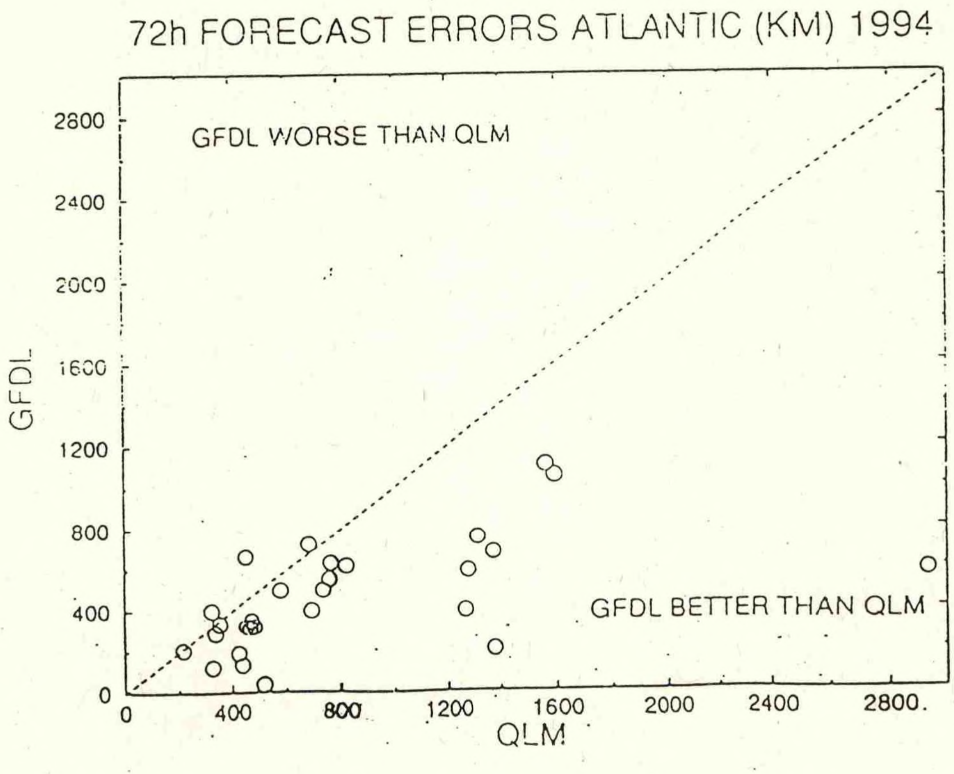


Figure 8. Same as Figure 7, but for forecast errors at 72 hours.

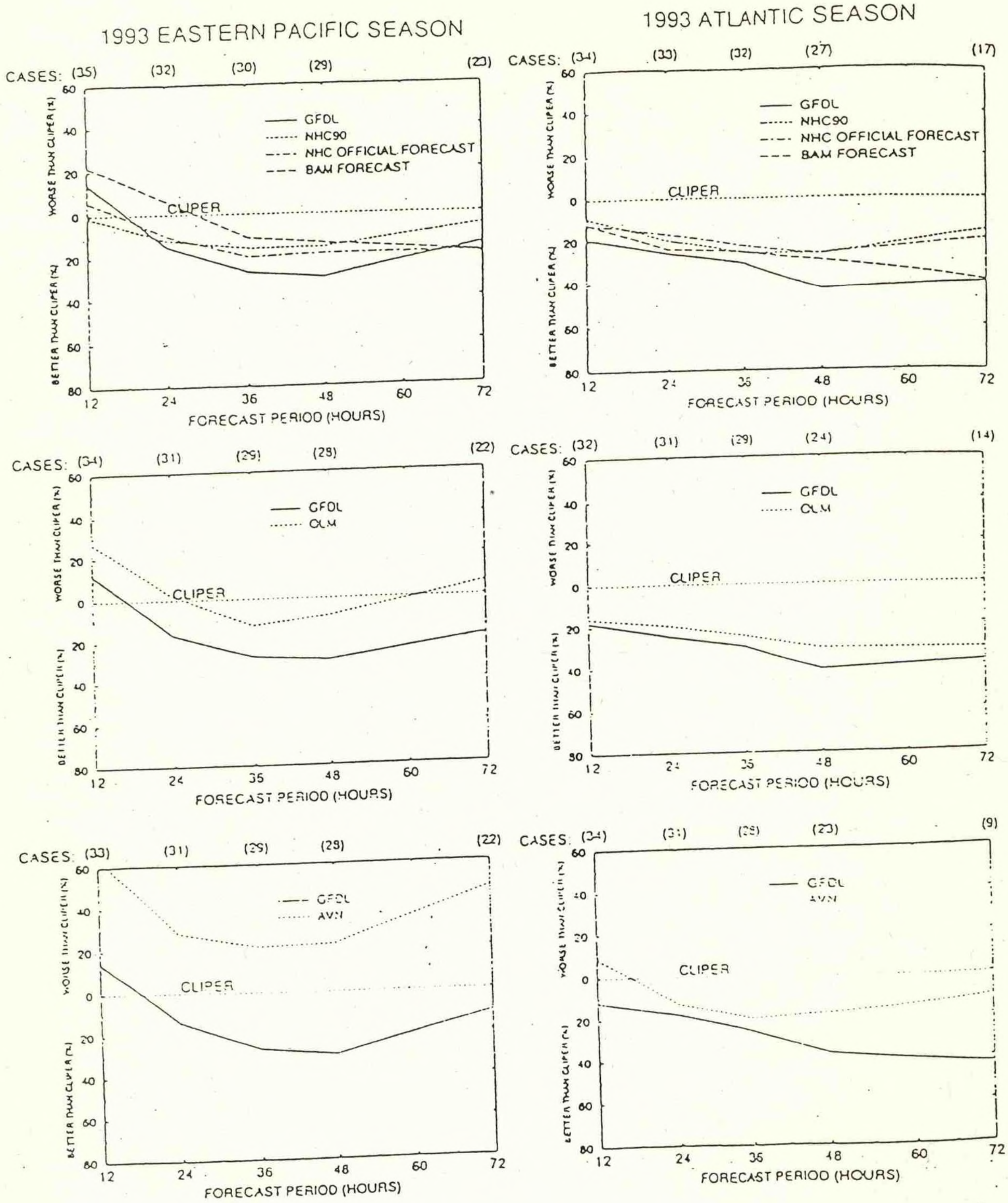


Figure 9. Summary of GHM track errors relative to Cliper for the Eastern Pacific (left) and Atlantic (right) for the 12- to 72-h forecast period. GHM results are indicated by solid lines whereas other model forecasts are indicated by dotted or dashed lines. Forecast error percentages indicate skill relative to climatology and persistence.