Physical Initialization and Hurricane Ensemble Forecasts

T. N. KRISHNAMURTI, RICARDO CORREA-TORRES, GREG ROHALY, AND DARLENE OOSTERHOF

Department of Meteorology, The Florida State University, Tallahassee, Florida

NAOMI SURGI

Tropical Prediction Center, Miami, Florida

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ABSTRACT

Ensemble forecasting of hurricane tracks is an emerging area in numerical weather prediction. In this paper, the spread of the ensemble of forecast tracks from a family of different First Global GARP (Global Atmospheric Research Program) Experiment analyses is illustrated. All forecasts start at the same date and use the same global prediction model. The authors have examined ensemble forecasts for three different hurricanes/typhoons of the year 1979. The authors have used eight different initial analyses to examine the spread of ensemble forecasts through 6 days from the initial state. A total of 16 forecasts were made, of which 8 of them invoked physical initialization. Physical initialization is a procedure for improving the initial rainfall rates consistent with satellite/rain gauge based measures of rainfall. The main results of this study are that useful track forecasts are obtained from physical initialization, which is shown to suppress the spread of the ensemble of track forecasts. The spread of the tracks is quite large if the rain rates are not initialized. The major issue here is how one could make use of this information on ensemble forecasts for providing guidance. Toward that end, a statistical framework that makes use of the spread of forecast tracks to provide such guidance is presented.

1. Introduction

In this paper we use the analyses from various global modeling centers to carry out medium-range prediction experiments starting from the same initial date. Using a single multilevel global forecast model, an ensemble of hurricane forecast tracks is obtained. We then ask the question if such an ensemble can provide useful information.

Currently at the Tropical Prediction Center (TPC, a list of acronyms appears in the appendix), a mix of forecasts from various dynamical models of the NCEP, HRD, and various statistical models of TPC are being used to obtain a consensus forecast. The consensus is based on skillful decisions of experienced forecasters. In some sense this operational approach is an ensemble forecast that shall perhaps remain in the forefront of real-time decision making for some time. Figure 1 illustrates a diverse suite of forecast tracks for Hurricane Felix of 1995: This includes the results of 3-day forecasts starting at 0600 UTC 14 September 1995 for the following models: NCEP's global spectral model (AVNI); GFDL, Princeton's high-resolution nested grid model; beta advection models of the HRD for a shallow layer (BAMS), a medium layer (BAMM), and a deep layer (BAMD); VICBAR shallow-water steering model (VBAR); a statistical regression model of the TPC (A90E); the forecast based on persistence and climatology (CLIP); the official forecast of TPC (OFCI); and the observed best track (OBS).

It is apparent that, in this instance, a diverse array of predicted tracks was available to the operational forecasters. The official forecast, labeled as OFCI, made use of this suite of forecasts plus operational experience. We shall not address the details of the operational decision-making process here since that does vary from storm to storm. It is apparent that the task of operational hurricane forecasting would require a complex decision process. It is well known that the skill of real-time dynamical forecasts varies from day to day, as illustrated by a sequence of the daily skill of the 500-mb geopotential height based on Kalnay and Dalcher (1987) (Fig. 2). It is apparent that one cannot maintain a high degree of forecast skill each day given the uncertainties in the data coverage plus the model deficiencies. The same problem exists in hurricane forecasting by almost any of the current methods; that is, we must anticipate some degree of variation of skill on a day by day basis. This is one of the reasons that one finds the notion of ensemble forecasts quite appealing. Ensemble techniques also provide information about the uncertainty in a spe-

Corresponding author address: Dr. T. N. Krishnamurti, Dept. of Meteorology 3034, The Florida State University, 430 Love Building, Tallahassee, FL 32304-3034.
E-mail: tnk@io.Met.fsu.edu

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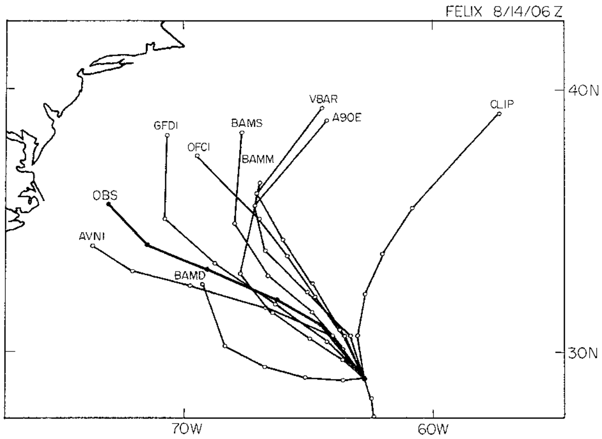

FIG. 1. Forecast tracks for Hurricane Felix starting at 0600 UTC 14 August 1995. This suite of tracks was provided by the Tropical Prediction Center. The various models of the suite are defined in the appendix. The start time is the third dot from the bottom from where the predicted tracks diverge. The first two dots at the bottom denote true storm positions at hours −12 and −24. The other dots are at 12-h intervals for a 60-h forecast. OBS denotes the observed best track of Hurricane Felix.

cific forecast, while identifying what might be uncommon events.

Currently there are two somewhat different ensemble initialization methods that are being used in operational practice. The ECMWF method, called the singular perturbation method, explores the instability of the baroclinic state at middle latitude. These perturbations are defined using the linearized version of a global model at coarse resolution (triangular truncation, 63 waves, i.e., T63). The linear adjoint algorithm determines the optimal perturbations. These perturbations are introduced in the operational ensemble forecast model at the resolution T63 (Palmer 1988). That is a lower resolution than the ECMWF's current operational medium-range prediction model. Sixteen forecasts are made on a daily basis. Figure 3 illustrates a 7.5-day forecast from an ensemble of eight such initial states. These forecasts do exhibit a degree of diversity. In this instance the central Mediterranean coast of Libya experienced a surface air temperature drop of 8°C. The best forecast shown by Fig. 3 n illustrates the extension of the upper trough toward the west-central Mediterranean. That was critical for the temperature forecast.

The operational effort of NCEP on ensemble forecasting is described in two recent papers (Toth and Kalnay 1993; Tracton and Kalnay 1993). Perturbations are generated using the breeding method. Here one introduces scaled perturbations within a data assimilation phase. Two types of perturbations with opposite signs are introduced initially within a 6-h assimilation cycle. A control run, carried out in parallel without such perturbations, is used to measure the amplitude for the two breeding runs. The perturbations are scaled down to the initial amplitudes at the end of each 6-h assimilation cycle. These perturbations are permitted to breed for roughly 5 days prior to the execution of a medium-range forecast. Here the resolution of the ensemble forecasts are similar to those of the ECMWF. This method has been shown to hold considerable promise in the middle-latitude medium-range forecasts.

The purpose of this article is to illustrate the possible potential of ensemble forecasts for the hurricane track issue. This was motivated by the success of our storm forecast experimentation with physical initialization (Krishnamurti et al. 1993, 1994). Physical initialization is defined in the next section. One of the forecasts was started at 0000 UTC 1 September 1979. This includes two hurricanes: David and Frederic. The analysis based on observations of the 850-mb flow is shown in Fig. 4. Figure 5 shows the corresponding fields from a forecast made with the global model using the ECMWF initial analysis. Here we note a remarkable success is the prediction of the Hurricanes David and Frederic on the medium-range timescale. These results are from one member of the ensemble forecast, arbitrarily chosen before the forecasts were computed. We shall not display all of the forecasts here.

2. Physical initialization

Physical initialization was introduced by Krishnamurti et al. (1991). It entails the assimilation of observed rain rates in a numerical prediction model. During this process the vertical profiles of the humidity variable, the vertical velocity, the horizontal divergence, the convective heating, and the surface pressure undergo an adjustment. A final product of this process is the model's initialized rainfall, which closely matches the ''observed'' rain rates for a prescribed resolution.

Three algorithms were used to restructure the humidity variable. These include a reverse cumulus parameterization, a reverse surface similarity, and an OLR matching algorithm. The reverse cumulus algorithm restructures the humidity variable such that the model-based rainfall would match the observed rainfall provided to it. The reverse similarity algorithm determines the surface flux of moisture that satisfies an expression for the vertically integrated apparent moisture flux and the prescribed observed rain rates. This algorithm provides a robust coupling of the ocean and the atmosphere. The OLR matching is accomplished from the use of the bisection method that restructures the humidity of the upper troposphere such that the model matches the satellite-based OLR closely. The above algorithms are assimilated in the global model to define an initial state where the distribution of the improved humidity variable, the vertical distribution of heating and divergence, the vorticity field for high wavenumbers, and surface pressure undergo a spinup.

Here we have used a mix of FGGE rain gauge data, OLR rain based on the Krishnamurti et al. (1983) al-

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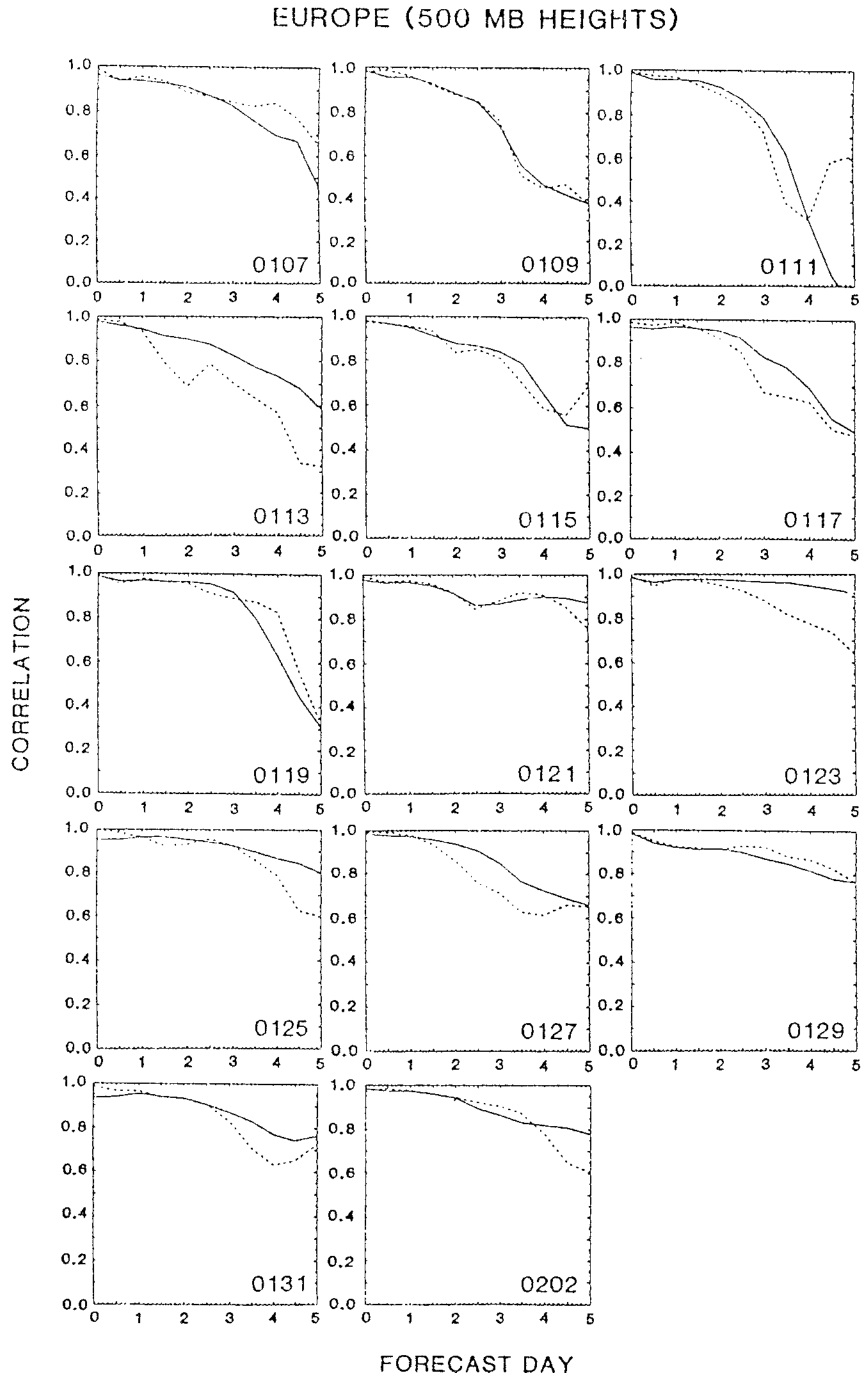

FIG. 2. Comparison of the 500-mb geopotential observed (dashed) and predicted (solid) anomaly correlation for each of the 14 5-day forecasts verified over Europe. The abscissa is forecast time, the ordinate is correlation, and the month and date of the initial conditions are indicated by the four digits inside each panel (Kalnay and Dalcher 1987).

gorithm and MSU-based rainfall over the oceans based on Spencer (1993). The OLR-based rainfall is used as a first-guess field. The MSU-based rain and rain gauge data are objectively analyzed. Here the observed rain rates are defined on space–time bins of 6 h (time averaged) and over a transform grid square (at the resolution T63, i.e., roughly 1.875° lat–long). An example of the observed and the initialized rainfall (24-h assimilations) is shown in Fig. 6. Here we note that mesoscale rainfall elements are being initialized individually over the entire Tropics. Further details on the physical initialization may be found in Krishnamurti et al. (1991,

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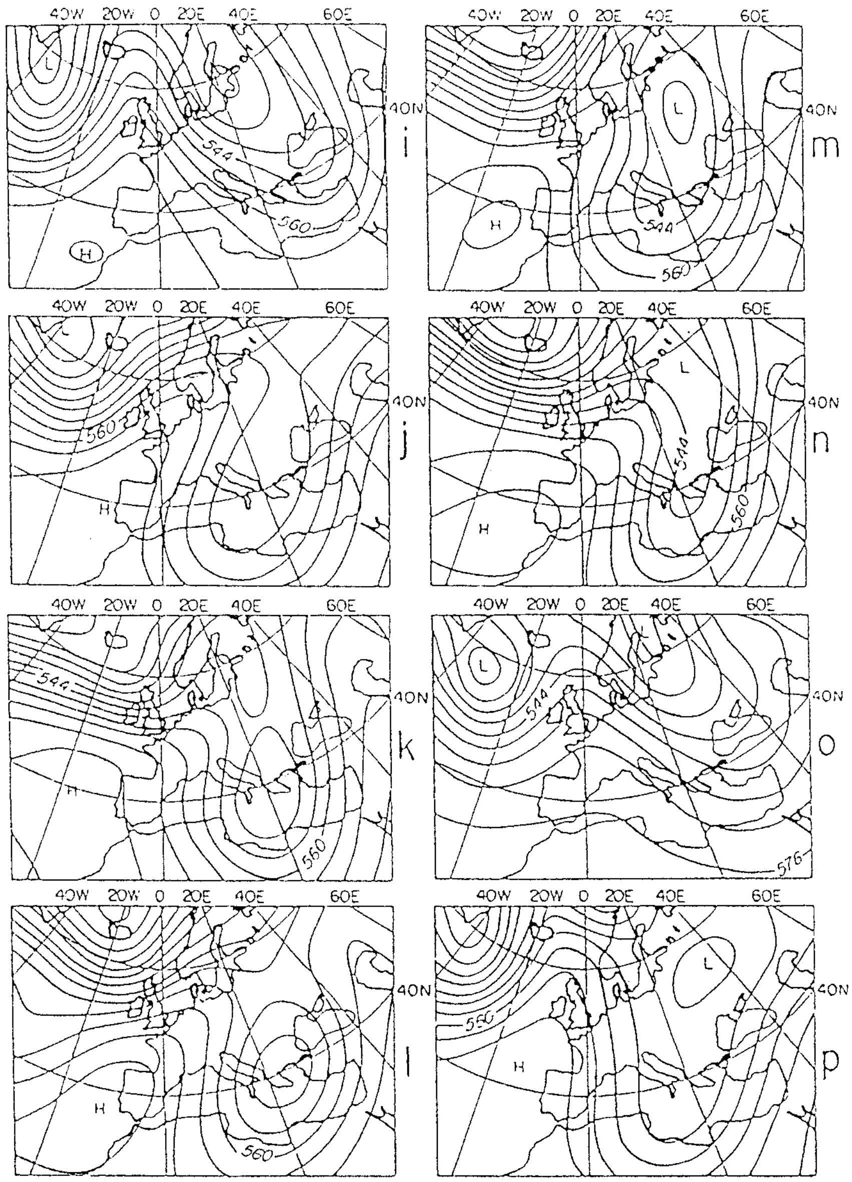

FIG. 3. (i)–(p) Initial contours of 500-mb surface (units = tens of meters) forecasts at day 7.5 for respective eight members. Adapted from Palmer (1988).

1993, 1994). We shall next provide an outline of the global model used in the present study.

3. An outline of the FSU global spectral model

The global model used in this study is identical in all respects to that used in Krishnamurti et al. (1991). The following is an outline of the global model:

1) Independent variables: (x, y, σ, t)
2) Dependent variables: vorticity, divergence, surface pressure, vertical velocity, temperature, and humidity
3) Horizontal resolution: triangular truncation, 63 waves
4) Vertical resolution: 15 layers between roughly 50 and 1000 mb
5) Semi-implicit time differencing scheme
6) Envelope orography (Wallace et al. 1983)
7) Centered differences in the vertical for all variables except humidity, which is handled by an upstream differencing scheme
8) Fourth-order horizontal diffusion (Kanamitsu et al. 1983)
9) Kuo-type cumulus parameterization (Krishnamurti et al. 1983)
10) Shallow convection (Tiedke 1984)
11) Dry convective adjustment
12) Large-scale condensation (Kanamitsu 1975)

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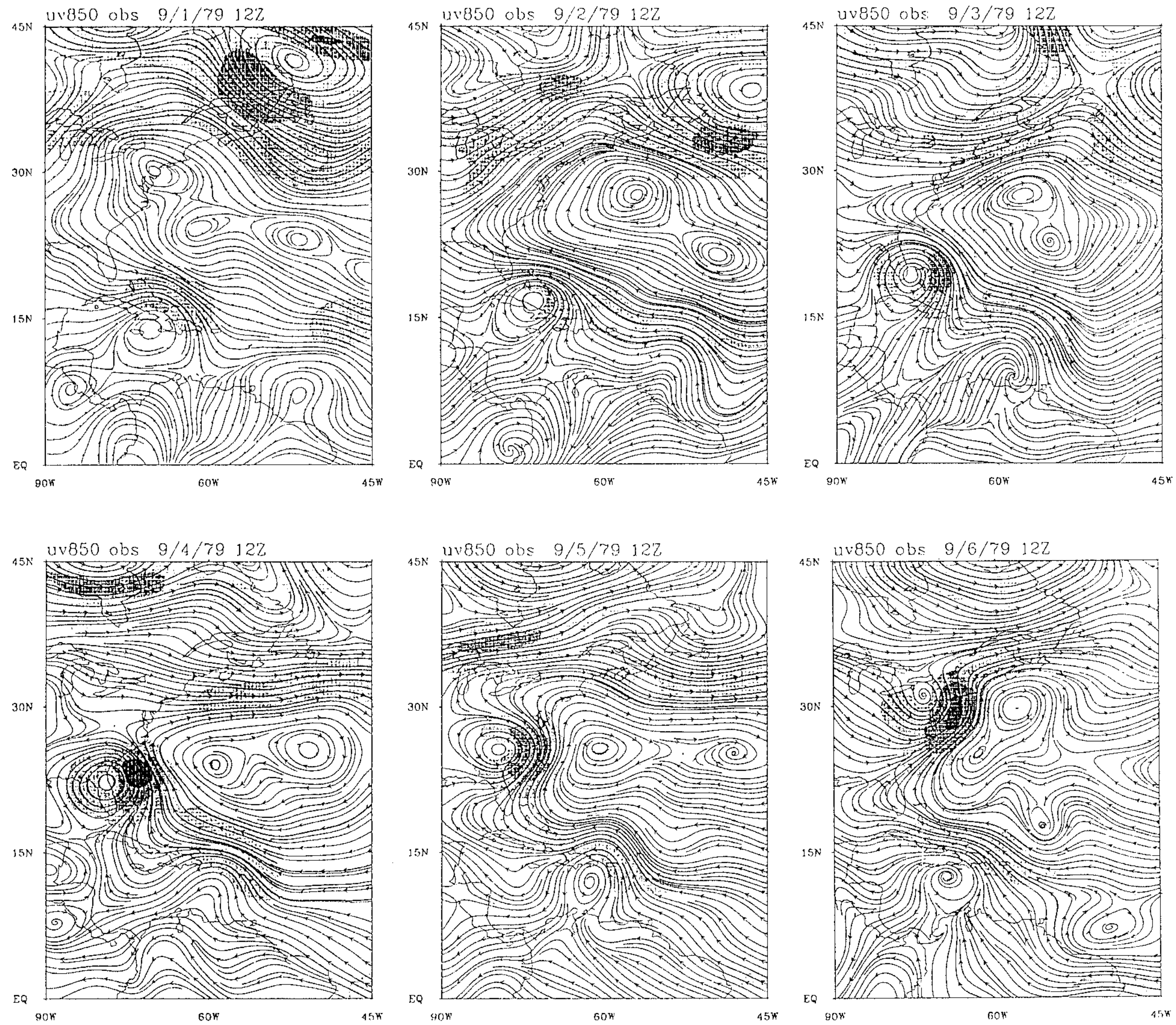

FIG. 4. "Observed" 850-mb flow fields illustrating the passage of Hurricanes Frederic and David of 1979. (all times 0000 UTC): (a) 1 September, (b) 2 September, (c) 3 September, (d) 4 September, (e) 5 September, and (f) 6 September.

13) Surface fluxes via similarity theory (Businger et al. 1971)
14) Vertical distribution of fluxes utilizing diffusive formulation where the exchange coefficients are functions of the Richardson number (Louis 1979)
15) Long- and shortwave radiative fluxes based on a band model (Harshvardan and Corsetti 1984; Lacis and Hansen 1974)
16) Diurnal cycle
17) Parameterization of low, middle, and high clouds based on threshold relative humidity for radiative transfer calculations
18) Surface energy balance coupled to the similarity theory (Krishnamurti et al. 1991)
19) (s) Nonlinear normal mode initialization for five vertical modes (Kitade 1983)
20) Physical initialization (Krishnamurti et al. 1991)

4. An ensemble of hurricane forecasts using different analyses

The procedure adopted here is to use eight analyses during the FGGE period. Of these, four were at 0000 UTC, and the other four were at 1200 UTC. The analyses were produced as part of the FGGE analysis by different global modeling groups: NCEP, ECMWF, GFDL, and NASA/Goddard. Here we make use of the analyses from these various groups at two adjacent map times, the maximum time difference among the analyses being only 12 h. These eight analyses provide the candidates for "an ensemble of eight" medium-range forecasts. There are a couple of cautionary notes that must be considered. First, only a single (one initial date) case study is examined. Also, dynamically constrained perturbations (e.g., singular perturbation method and breed-

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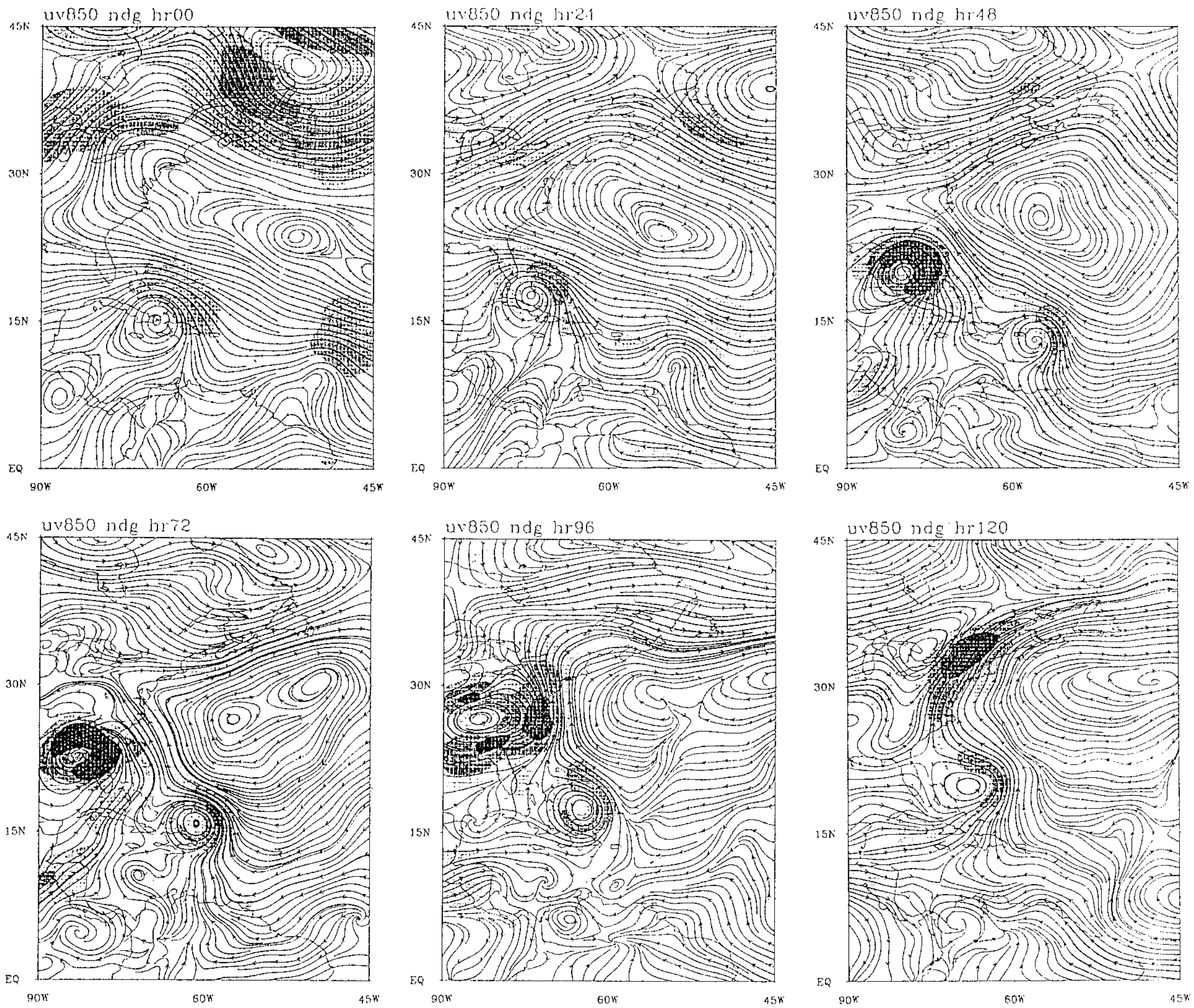

FIG. 5. Predicted 850-mb flow fields using physical initialization illustrating the passage of Hurricanes Frederic and David of 1979 (all times 0000 UTC): (a) 1 September, (b) 2 September, (c) 3 September, (d) 4 September, (e) 5 September, and (f) 6 September.

ing method) are the most efficient and effective approach for obtaining ensemble members. However, the method outlined here should provide a good demonstration of the potential for ensemble prediction.

Four tropical cyclones were present during this initial date, that is, 1 September 1979. The storms over the Atlantic were Hurricanes David and Frederic. The storms over the Pacific included Tropical Storm Ken and Typhoon Lola. The three strongest tropical cyclones (David, Frederic, and Lola) will be discussed. A set of eight medium-range forecasts were first made with these datasets after subjecting the initial analyses to normal mode initialization, following Kitade (1983), and retaining five vertical modes. We shall call these the control experiments. A second set of eight forecasts were made after subjecting these datasets to physical initialization. That required the use of rain rates and their assimilation for the respective experiments during a 24-h period prior to the initial state.

The procedure for the combined satellite–rain gauge algorithm is described in Goirala and Krishnamurti (1992). Here we use a sharpened OLR-based rainfall as a first-guess field. An objective analysis uses the rain-gauge and SSM/I-based rainfall as datasets. The model-based rain rates for the control experiments are not identical even for each of the 0000 UTC (or for each of the 1200 UTC) start experiments. However, the physical initialization is so robust that these model-based rain rates in fact become very close to each other for the 0000 UTC (or for the 1200 UTC) start experiments. Figure 6 illustrates the observed and the physically initialized 24-h rain rates between hours -24 and hour 0 for one of the experiments, where the correlation between the observed and the respective physically initialized rainfall totals is around 0.93. That is a correlation measured over transformed grid squares and 6 h in time (hours 0 to -6) for the modeled and the observed rain. It was apparent that the physical initialization re-

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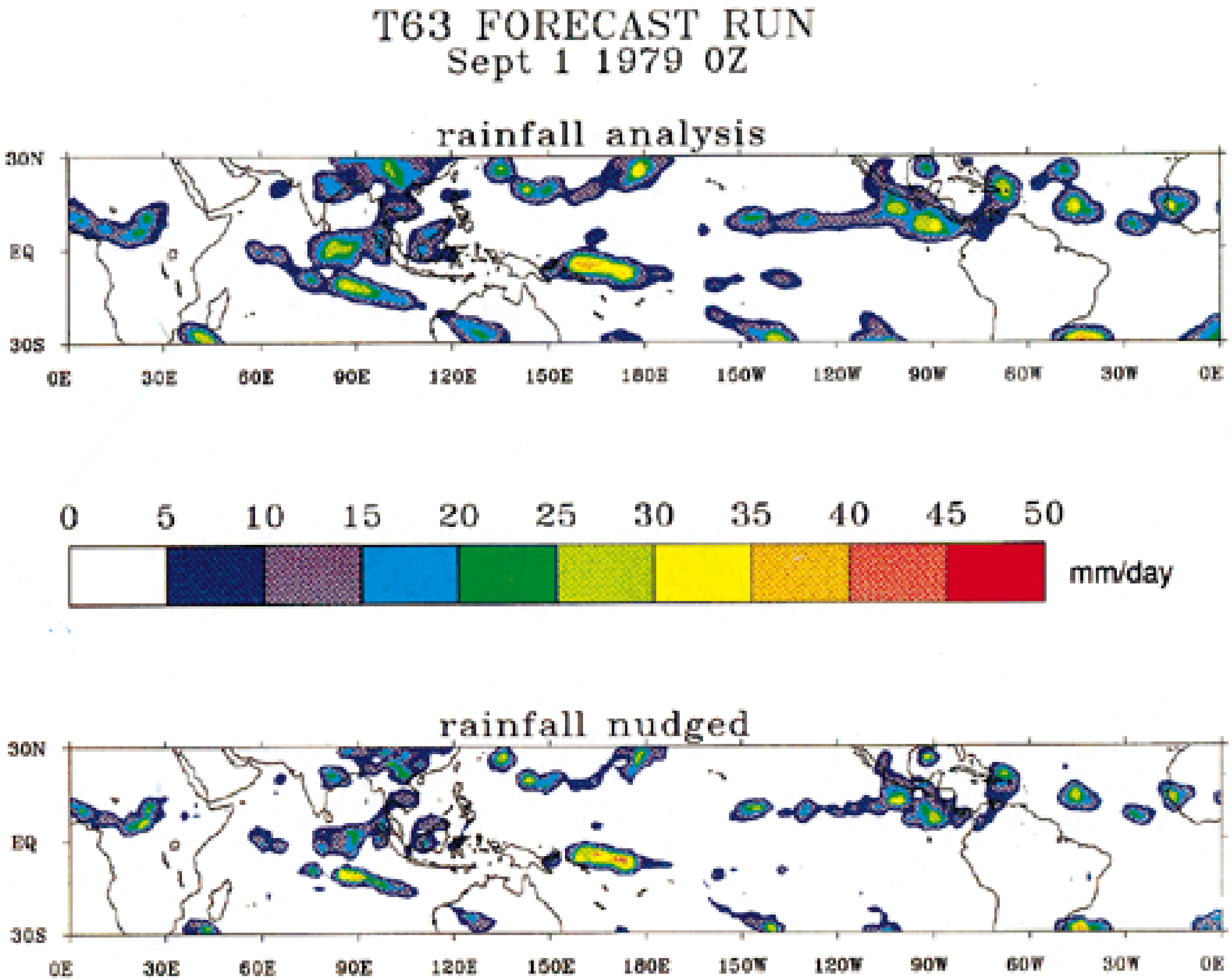

FIG. 6. The 24-h rainfall totals over the Tropics: (a) obtained from satellite and rain gauge observation between 31 Aug 1979 and 1 Sep 1979 (0000 UTC) (units: mm day^{-1}) and (b) physically initialized rainfall for the same period.

covers most of the observed rain for each of these experiments (Krishnamurti et al. 1994).

Figure 7 illustrates the results of ensemble forecasts for Hurricane David of 1979 that made its traverse along the east coast of Florida. The top-left panel illustrates the best track of the ensemble mean of all of the *control forecasts,* that is, of the eight tracks; this also includes the modified mean of selected tracks where the outliers were disregarded. Outliers were identified as individual forecasts that were more than one-and-a-half standard deviations away from the mean forecast. The rationale for obtaining outliers is due to possible inequities in the initial analyses. The various modeling groups used different methods for obtaining their analyses, with different degrees of accuracy or skill. Unlike an ensemble made with dynamically constrained perturbations, the ensemble members here may not necessarily be of equal value. Of course, the outlier removal method proposed here is only a suggestion for addressing this problem and not the final word. In Fig. 7 we find that the modified mean of these selected tracks almost coincide with the best track through day 5 of the forecast. The top-right panel illustrates the spread of all predicted tracks for the *control experiments.* The bottom-left and -right panels illustrate the corresponding results for the physical initialization experiment. Here we note that the mean track, which includes all of the storms, is very close to the best track. The other track in this panel illustrates the modified mean track. In the bottom-right panel, we see less of a spread for all storms that originated at either 0000 or 1200 UTC start times as compared to corresponding tracks for the control experiment that did not include a rain-rate initialization. The best results were obtained for those that used a 0000 UTC start time. In both the control and physical initialization cases, all of the various mean tracks were close to the best track.

The corresponding four panel charts for Hurricane Frederic of September 1979 are shown in Fig. 8. Here

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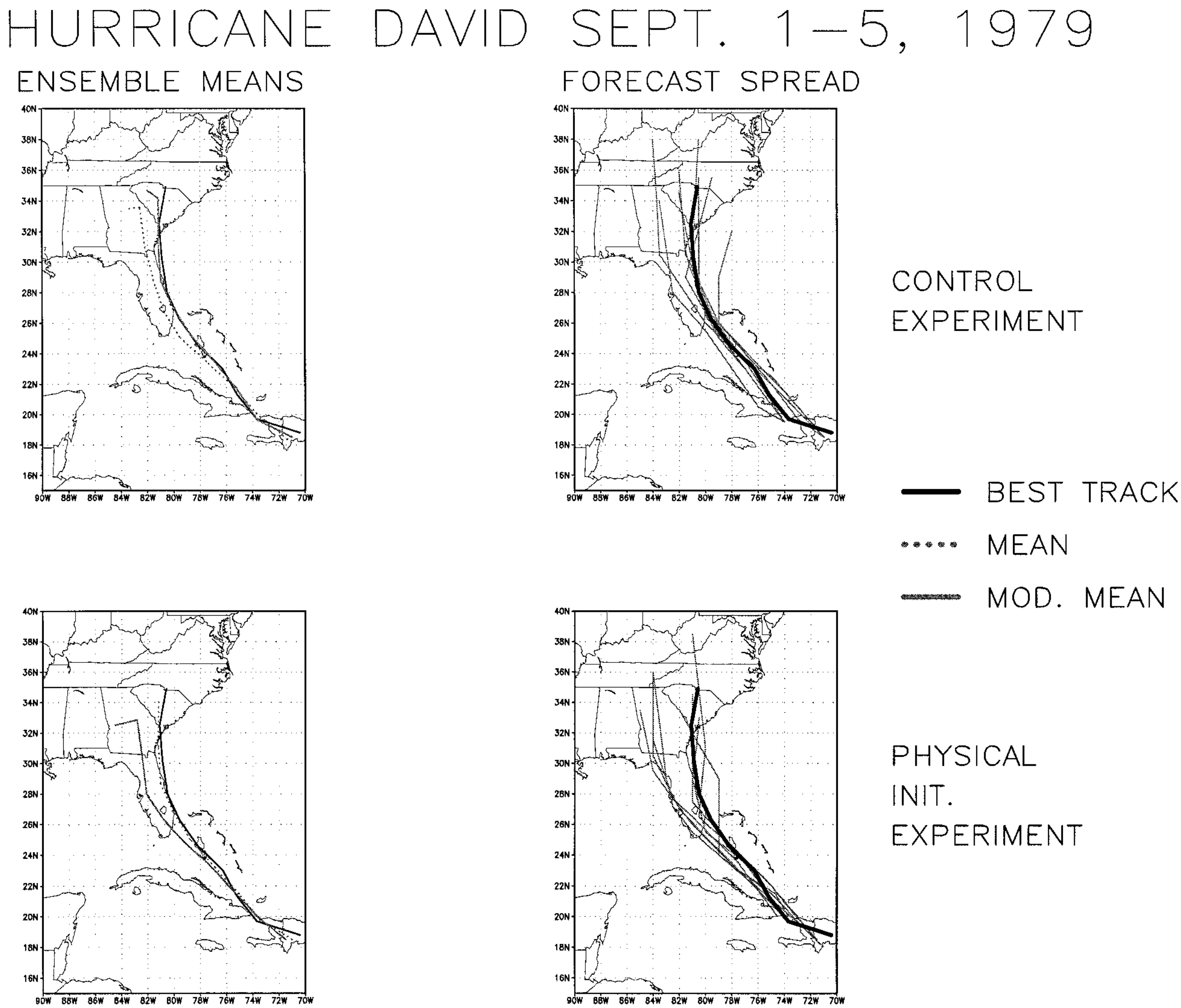

FIG. 7. Hurricane David: The two top panels show results for the control experiment, whereas the two bottom panels show results for the experiment that includes physical initialization. The left panels show the observed track, the ensemble mean track, and the ensemble mean track with outliers removed. The right panels show the observed best track and the array of tracks for the entire ensemble.

we find that the ensemble mean track and the modified mean track (excluding outliers) both have small position errors through day 4 of the forecast. The spread of the forecast tracks for the control experiment (without rain-rate initialization) is quite large whereas the spread of tracks is substantially reduced for the forecasts with the rain-rate initialization. The results suggest that a cluster analysis may be appropriate. We will examine the results of this analysis in future studies.

The corresponding results for Typhoon Lola are shown in Fig. 9. Although the 6-day motion of Typhoon Lola was very slow, the results from the inclusion of physical initialization markedly improved the ensemble mean track over those of the control experiment.

The other relevant question for this study is the assessment of the most useful information from the physically initialized ensemble forecasts. Given that the ensemble forecasts, including the physical initialization, have a smaller spread of forecast tracks, we asked the question of what useful information could be extracted from it.

Table 1 illustrates the day by day error statistics for all eight members of the ensemble for David. Here the position errors are tabulated. The last three columns show, respectively, the error from the ensemble means with outlier tracks removed for the physical initialization case, excluding tracks that have large initial errors for the physical initialization case, and with outlier tracks removed for the control case. The ensemble mean excluding tracks that have large inital errors is obtained by comparing the 12-h forecast positions from the individual ensemble members with the best track position at that time. Those ensemble members whose position error at 12 h is greater than an arbitrary threshold are

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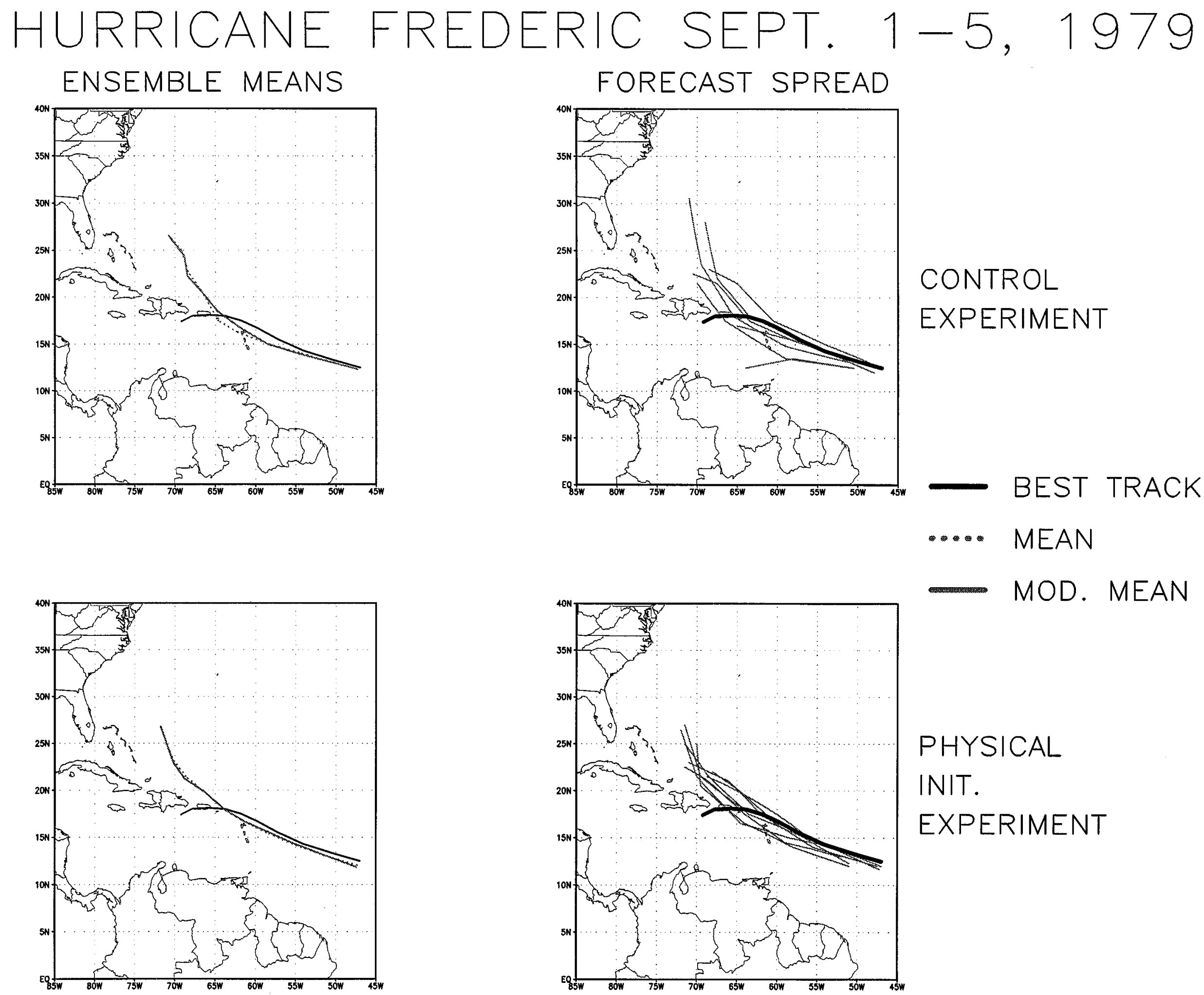

FIG. 8. Hurricane Frederic: The two top panels show results for the control experiment, whereas the two bottom panels show results for the experiment that includes physical initialization. The left panels show the observed track, the ensemble mean track, and the ensemble mean track with outliers removed. The right panels show the observed best track and the array of tracks for the entire ensemble.

removed and a mean is calculated with the remaining members. The daily position errors at the end of 24, 48, 72, and 96 h of forecasts for each member of the physical initialization ensemble (1 through 8) are also shown in Table 1. Storm positions were identified by the minimum sea level pressure in these tabulations.

Tables 1 and 2 (the corresponding table for Hurricane Frederic) show that these ensemble means, shown in the last few columns, carry useful information. Errors for Hurricane Frederic were considerably larger than those for David at day 4 of the forecast. Ensemble forecasts for David, using the physical initialization procedure, produced results that were superior to recent average operational forecast performances. Between 1984 and 1993, the Tropical Prediction Center's average forecast errors for 24, 48, and 72 h were 187, 369, and 560 km, respectively (Avila and Rappaport 1996). The ensemble means for Hurricane David are well below these values, particularly at 48 and 72 h. The ensemble means for Hurricane Frederic are also below these values. Caution should be exercised when comparing individual tropical cyclone forecast errors with long-term averages, since forecast difficulty varies widely from cyclone to cyclone. It is possible that Hurricanes David and Frederic are comparatively easy forecast cases. However, the results are still very encouraging. The results for Typhoon Lola of the Pacific Ocean, shown in Table 3, were most impressive.

The members of the ensemble exhibited rather diverse forecasts for typhoon Lola (Table 3). The efforts of the 4-day forecasts, made from different analyses, had track errors ranging from 170 to 1010 km. The ensemble mean, where we excluded those members that had the largest errors in the first 12 h of forecast (mean B column of Table 3), ranks near the top when compared to the individual ensemble members. Furthermore, its error stability, in comparison to the individual ensemble members is clearly preferable. For example, although

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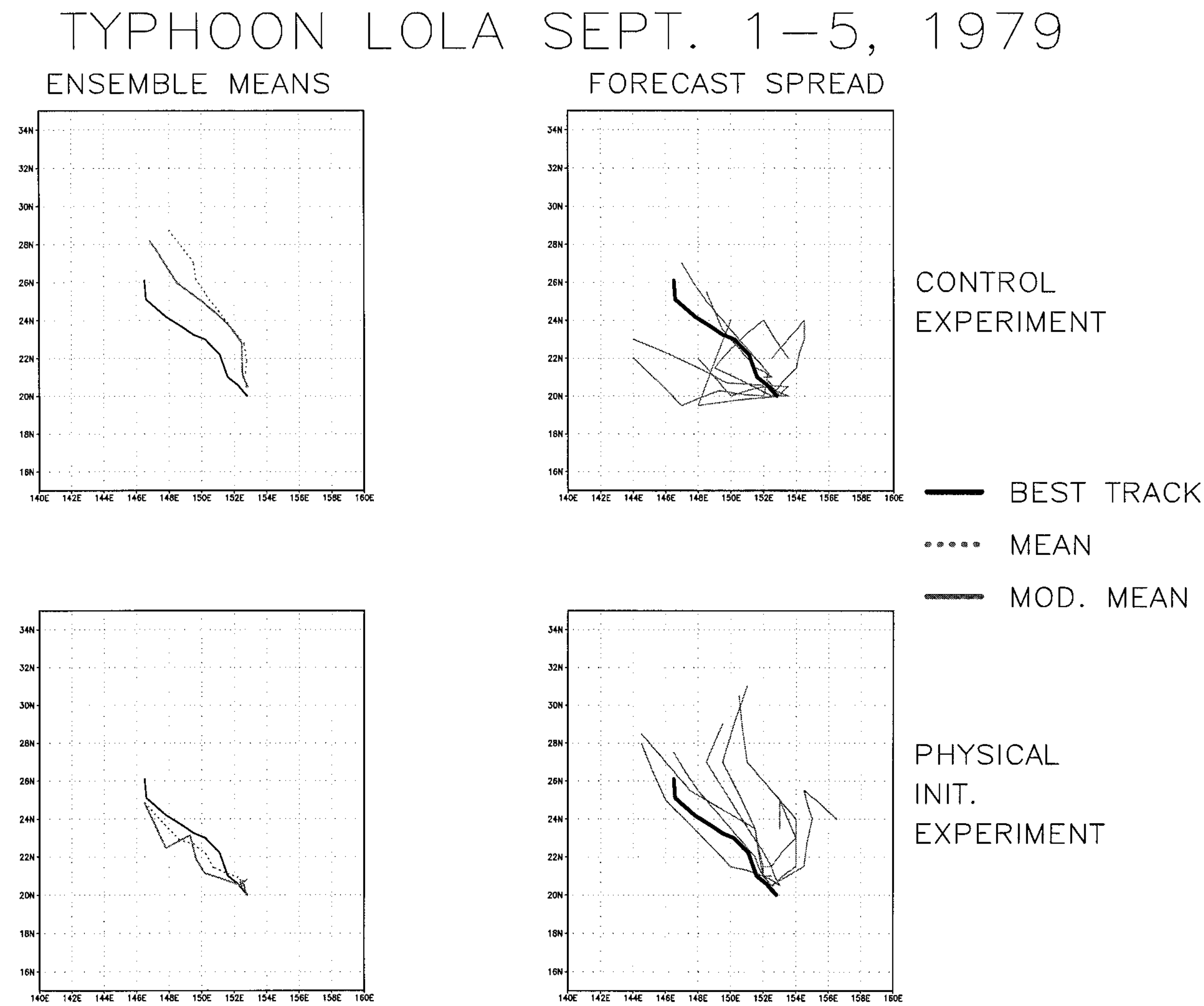

FIG. 9. Typhoon Lola: The two top panels show results for the control experiments, whereas the two bottom panels show results for the experiment that includes physical initialization. The left panels show the observed track, the ensemble mean track, and the ensemble mean track with outliers removed. The right panels show the observed best track and the array of tracks for the entire ensemble.

ensemble member 3 has slightly better errors at hours 24 and 48, it has much larger errors at hours 72 and 96. Likewise, ensemble member eight has better errors at hours 72 and 96 but has an hour 48 error that ranks in the lower half of the ensemble. The previous column (mean of A) shows the results from the ensemble mean of the track forecasts where the outliers have been excluded. This forecast also appears superior to most of the eight member ensemble forecasts at hours 72 and 96, although not at hours 24 and 48. The results for Hurricane Frederic, Hurricane David, and Typhoon Lola appear to suggest the usefulness of the ensemble means suggested here as additional approaches for analyzing ensemble forecast. Tables 1, 2, and 3 show that the physical initialization ensemble means (means A and B) are in general superior to the control, nonphysical

TABLE 1. Hurricane David 1979 (error in kilometers).

Hour	1	2	3	4	5	6	7	8	Mean of A	Mean of B	Mean of C
24	40	140	80	30	90	60	90	50	50	20	50
48	300	310	130	100	190	110	120	30	100	130	80
72	270	340	70	180	260	200	200	90	160	110	90
96	470	670	220	140	280	340	340	170	160	160	180

A—mean track excluding outliers. B—mean track excluding tracks with poor initial skill. C—mean track excluding outliers for control forecasts.

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TABLE 2. Hurricane Frederic 1979 (error in kilometers).

Hour	1	2	3	4	5	6	7	8	Mean of A	Mean of B	Mean of C
24	150	270	220	220	160	80	40	150	140	110	60
48	250	400	90	100	200	220	210	200	180	170	230
72	410	630	260	240	300	430	390	320	340	330	430
96	650	870	400	440	480	750	740	570	600	620	710

A—mean track excluding outliers. B—mean track excluding tracks with poor initial skill. C—mean track excluding outliers for Control forecasts.

initialization ensemble means (mean C). Means A and B are both better than mean C in eight out of the 12-h forecast hours. Of course, caution must be exercised with this last point, as there are only three cases examined here. However, as mentioned previously, physical initialization has been shown to improve tropical cyclone forecasts (Krishnamurti et al. 1993, 1994).

The position of the storm 12 h into the future is generally available because of the delays in the data collection and the time required for the execution of the ensemble forecasts. Thus +12 h can be regarded as within the available real-time datasets. In conclusion, given several global analyses, it appears that physically initialized ensemble forecasts can provide useful guidance for medium-range forecasts of storm tracks.

5. Concluding remarks

The important message from this study is that physical initialization reduces the spread of an ensemble forecast. That was quite a consistent result for each of the three storms studied here. This reduction of spread occurs even though the rotational parts of the flows were essentially unaltered by the physical initialization for the eight members of the ensemble. The reduction of spread is evidently related to the better control of the storms steering over the medium range. By invoking physical initialization, we are defining the heat sources and sinks over the entire Tropics in a uniform way for all of the members of the ensemble. During the spin up of the model, from physical initialization, the divergence heating, surface pressure, and the humidity variable are brought closer for all of the members of the ensemble. These tend to dictate a similar evolution for the rotational flows in the medium range, thus providing a similar steering for the storm motion. In the absence of physical initialization, the storm tracks of the ensemble exhibit a great degree of diversity. This is evidently related to the diversity of the heat sources and sinks, which contribute to the diverse evolution of the steering flows.

In this study, the reduced variance produced by physical initialization represented an improvement, in general. In Tables 1–3, the reduced variance physical initialization case (mean of A) has less error than the control case (mean of C) in 8 out of the 11 times, with one tie. The Hurricane David case is the source of two of the three exceptions. However, both sets of errors for David are quite small in comparison to the corresponding errors for Frederic and Lola. This suggests that the David case may have been an easier forecast for the model than either Frederic of Lola. One of the strengths of the physical initialization procedure is that it improves the initial global analysis over data-sparse oceanic regions, thereby improving the tropical cyclone representation and the steering flow. This improvement should logically be less defined for David (whose initial position and environment are nearer to land areas and correspondingly greater data coverage) than for Frederic or Lola (whose initial positions and environments are over open oceanic regions). Based upon the above discussion, the reduced variance produced by phsyical initialization appears to decrease a false variance (related to significant errors in the initial analyses) present in the control ensemble, rather than any actual variance (related to inherent analyses uncertainty). We do not feel that the reduced variance represents inadequate sampling of the intrinsic diversity of solutions. Of course, these results must be interpreted with some caution, because of the limited sample size.

We defined two types of ensemble means: one that excludes some outlier tracks, and the other that excludes those that have the largest forecast errors in the first 12 h. Although the sample of ensemble forecasts presented here is small, it appears that the suggested ensemble mean tracks do carry additional useful information for

TABLE 3. Typhoon Lola 1979 (error in kilometers).

Hour	1	2	3	4	5	6	7	8	Mean of A	Mean of B	Mean of C
24	110	310	40	250	50	80	70	60	100	50	120
48	390	500	140	400	160	190	210	230	230	160	240
72	440	600	250	430	250	200	100	80	190	100	210
96	670	1010	430	710	560	400	210	170	300	280	320

A—mean track excluding outliers. B—mean track excluding tracks with poor initial skill. C—mean track excluding outliers for control forecasts.

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storm guidance. These modified ensemble means, in conjunction with the individual ensemble members, provide a strong platform for probability analyses of ensemble forecasts.

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APPENDIX

List of Acronyms

AVNI	The global model of the National Weather Service (called the aviation model)
BAMD	Beta advection model (deep layer)
BAMM	Beta advection model (medium layer)
BAMS	Beta advection model (shallow layer)
CLIP	Climatology and persistence model
ECMWF	European Centre for Medium-Range Weather Forecasts
FGGE	First Global GARP Experiment
FSU	The Florida State University
GARP	Global Atmospheric Research Program
GFDL	Geophysical Fluid Dynamics Laboratory
HRD	Hurricane Research Division
MSU	Microwave sensing unit
NASA	National Aeronautics and Space Administration
NCEP	National Centers for Environment Prediction
OBS	Observed (best fit) hurricane track
OLR	Outgoing longwave radiation
SSM/I	Special Sensor Microwave/Imager
TPC	Tropical Prediction Center
TPC (A9OE)	Tropical Prediction Center's statistical model
TPC (OFCI)	Official track forecast of the Tropical Prediction Center
UTC	Universal time coordinated
VBAR	Same as VICBAR (used in Fig. 1)
VICBAR	Vic Ooyama's barotropic model

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