The Role of Statistical Models in the Prediction of Tropical Cyclone Motion

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Tropical cyclones (tropical storms, hurricanes, typhoons, etc.) occur over many of the earth's tropical marine areas. Responsibility for tracking and predicting the future course of these storms is assigned to one or more domestic or foreign meteorological services. These services routinely activate a number of statistical and dynamical prediction models as objective guidance preparatory to issuing official forecasts on these storms. In this article, the role of the statistical models in this process is examined.

KEY WORDS: Hurricanes; Hurricane forecasting; Hurricane prediction.

1. INTRODUCTION

In six regions of the globe, the combination of a moist, tropical, marine environment and other supporting atmospheric conditions leads to the genesis of storms referred to as tropical cyclones. These regions, including the areas affected after storms develop and move, are known as *tropical cyclone basins*. Collectively, they produce an average of 83 major storms per year. The Western North Pacific Basin is the most active (26 storms per year). The remaining basins, in order of decreasing activity, are the Eastern North Pacific (15 storms per year), the Southwest Pacific/Australian area (15), the Southwest Indian Ocean (11), the North Atlantic (10), and the North Indian Ocean (6). Further details on worldwide tropical cyclone climatology are given by Crutcher and Quayle (1974). Neumann et al. (1981) treat the North Atlantic Basin in additional detail.

Tropical cyclones are classified according to their intensity. Storms with maximum surface winds of less than 34 knots are defined as *tropical depressions*; those with maximum winds of 34 to less than 64 knots, *tropical storms*; and those of still higher intensity, *hurricanes* (*typhoons* in the Western Pacific). In this study, the weaker tropical depressions are not considered; the collective term *tropical cyclones* refers only to tropical storms and hurricanes or typhoons.

Responsibility for detecting, tracking, forecasting, and issuing advisories on tropical cyclones is shared by a number of international meteorological services. In the United States, the National Oceanographic and Atmospheric Administration's (NOAA) National Hurricane Center (NHC) (Coral Gables, FL), Eastern Pacific Hurricane Center (Redwood City, CA), and Central Pacific Hurricane Center (Honolulu, HI) are responsible for the North Atlantic, the Eastern North Pacific, and the Central North Pacific, respectively. Military interests also rely on these advisories. U.S. military interests in the remaining basins rely on information issued by the Joint U.S. Navy/U.S. Air Force Typhoon Warning Center (JTWC) on Guam.

Forecasts (projections) on tropical cyclone motion and intensity are typically issued every 6 hours for periods through 72 hours. In determining these projections, weather services consult diagnostic and prognostic aids for forecast guidance. General guidance, mostly analyzed maps and charts, depicts large-scale current and future atmospheric circulation patterns in which the storm is or will be embedded. The often limited data on which many of these analyses are based are discussed in the companion article on the hurricane data problem (Pike 1985).

Specific additional guidance is provided by prediction models. These models focus on the storm itself, whereas the general guidance treats the large-scale patterns within which storms are embedded. Tropical cyclone forecasts are seldom, if ever, based on a unique piece of guidance. The forecaster considers all of the information at his or her disposal, resolves conflicts, and coordinates with other agencies before constructing the final forecast package. In practice, even though a large amount of objective information is available, the final forecast is rather subjectively formulated. The forecaster's experience, heuristic reasoning, the forecast problem itself, and the guidance material have bearing on the final product.

In this article, the role of the statistical models in suggesting the future track of tropical cyclones is examined. A survey of worldwide operational models (Hope and Neumann 1977) showed that most operational models are indeed statistical. Purely dynamical models are, however, becoming increasingly important, and in the area of adequate data for their initialization, dynamical models generally outperform statistical models beyond the 36-hour projection. Statistical models have always enjoyed the advantage of requiring only minimal computer resources, compared to the dynamical models. With the operational availability of the newer, extremely fast computers, this is no longer a distinct advantage, at least in the United States. Many countries do not have the computer resources, however, nor the analyzed environmental fields needed by the purely dynamical models, and statistical models continue to play a dominant role.

There are several types of statistical models, and the choice of model depends on the nature of the forecast problem; some of the factors involved here are discussed in Section 2. The models are discussed in Section 3, and Sections 4 and 5 discuss related issues.

2. THE FORECAST PROBLEM

Statistical models use three information sources to reduce the variance of tropical cyclone motion—motion climatol-

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ogy, motion persistence (the tendency for successive storm motion vectors to be serially correlated), and environmental data (winds and pressures). The latter are often referred to as environmental *steering forces*. These sources, discussed in Section 2.3, are not independent. Accordingly, intercorrelations and partial correlations must be carefully considered in structuring statistical models.

2.1 Motion Climatology

Over the Atlantic Basin, as elsewhere, the motion of a tropical cyclone is highly correlated with latitude. Storms on the equatorward side of the basin typically display a strong westward component of motion, that is, a component directed from east to west, whereas those on the poleward side of the basin display a strong eastward component of motion. This motion is in accordance with the large-scale environmental steering forces in which storms are embedded.

The dependence of storm motion on latitude is illustrated in Figure 1. The change with latitude in the east/west (zonal, or u) component of average storm motion is clearly evident with a change in sign (easterly component to westerly component) taking place near 28.5N. Meteorologists refer to this process as recurvature into the westerlies, or simply recurvature. The terms *westerlies* and *easterlies* refer to the large-scale broad bands of winds having, respectively, a west-to-east component poleward from about 28.5N and an east-to-west component equatorward from that latitude over the Atlantic. On the surface, the latter winds are also referred to as tradewinds.

Figure 1 also illustrates the gradual poleward increase to about 50N in the north/south (meridional, or v) component of average storm motion. Finally, the figure shows the latitudinal variation in the magnitude of the total storm motion vector. Since the algebraic sign is ignored, the magnitude of the average total storm vector always exceeds the component speeds. Minimum storm forward speeds are seen to occur just before the recurvature zone, and maximum forward speeds tend to occur near 50N.

Certain models excel in predictions of storms that are south of the recurvature zone (storms having a westward component of motion). Others excel for storms north of the recurvature zone (storms having an eastward component of motion). A given statistical model typically does not exhibit optimum performance throughout all portions of a tropical cyclone basin.

Tropical cyclone motion variance, an important consideration insofar as the statistical models are concerned, also varies significantly with latitude. This variance is addressed in Figure 2, as well as in subsequent figures. Figure 2a displays the distribution of the magnitude of the observed 24-hour motion vectors for storms having an initial westward component of motion. Displacement exceeding 500 nautical miles (n.mi.; as obtained from the gamma fit) can be expected only about 1% of the time. This distribution can be contrasted with Figure 2b, which shows the distribution of observed 24-hour motion vectors for storms having an initial eastward component of motion. Here displacements over 500 n.mi. can be expected about 19% of the time and extreme right-skewness is in evidence. Indeed, the variance of Figure 2b storm motion is four to five times that of Figure 2a storms. In both distributions, however, the modal value of the motion vector magnitude is near 200 n.mi.

A better perspective on the increase in variance of tropical cyclone motion with increasing latitude can be obtained by considering the problem in its proper bivariate sense. As documented by Crutcher (1971), tropical cyclone motion is described by the bivariate normal distribution. Care must be exercised, however, in ascertaining that one is not dealing

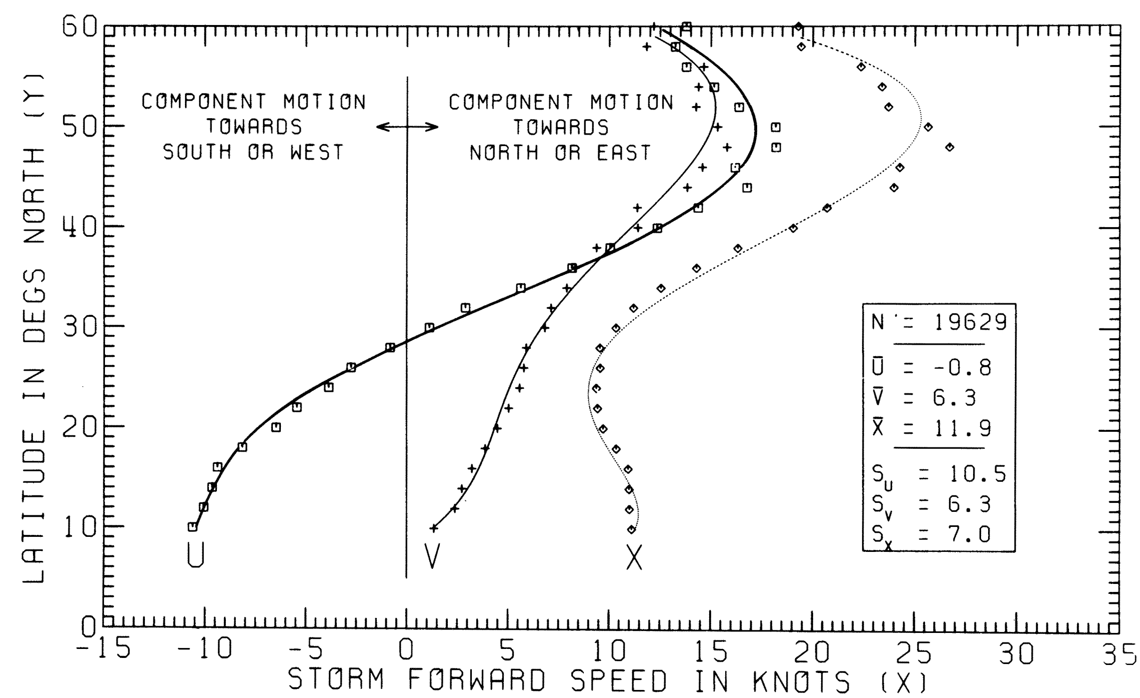

Figure 1. Latitudinal Variation of North Atlantic Tropical Cyclone Motion Averaged Over the 98-Year Period (1886–1983). Solid curves on left represent component speeds, where u is the east/west (zonal) component and v is the north/south (meridional) component. Dotted curve on right is total speed. Inset gives sample size, mean, and standard deviation of the three speed parameters.

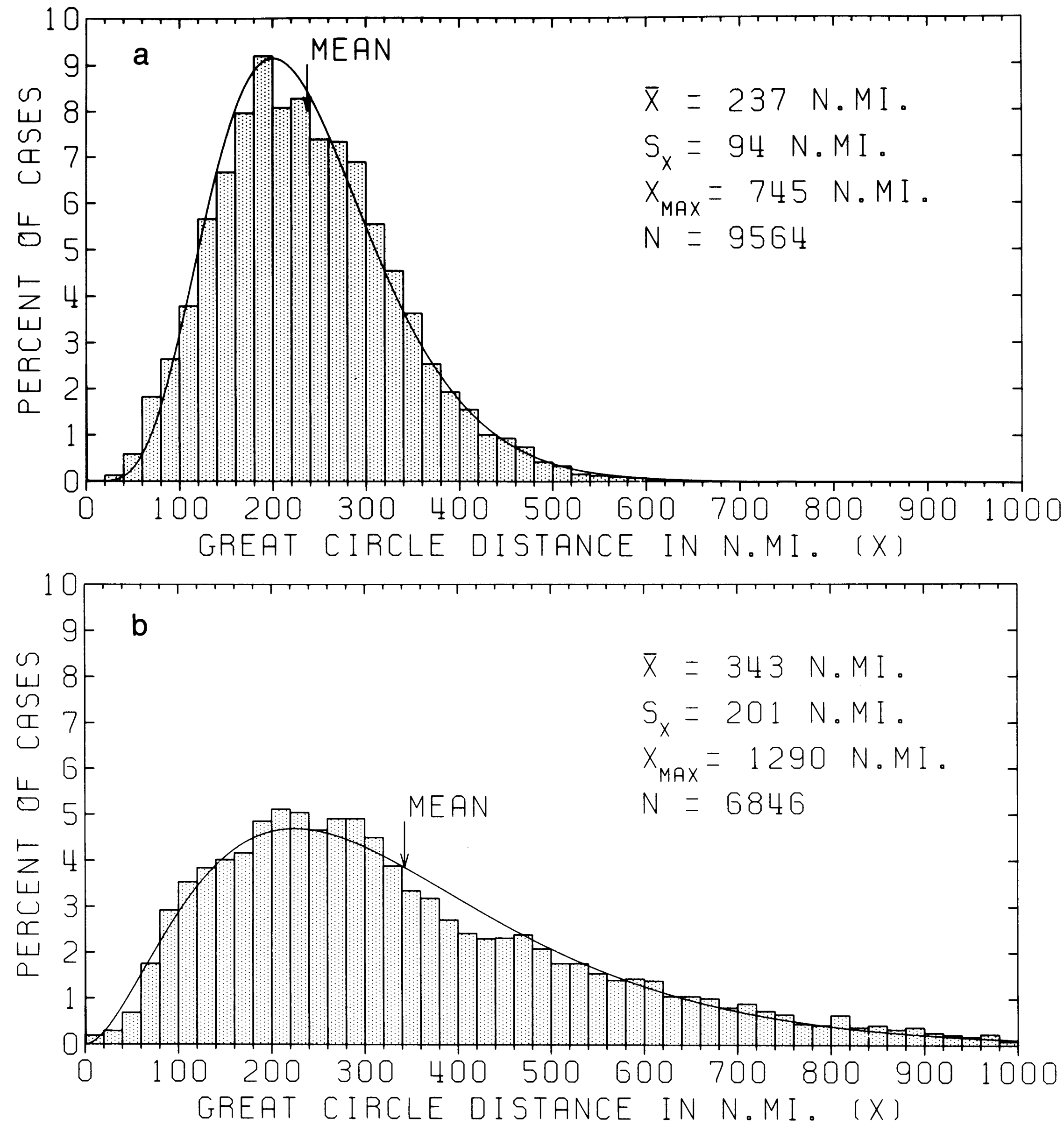

Figure 2. (a) Distribution of 24-Hour Tropical Cyclone Movement in Class Intervals of 20 n.mi. and With Fitted Gamma Distribution. Display includes Atlantic tropical storms and hurricanes with 24-hour motion vector having east-to-west component of motion. Period of record is 1886–1983. High-latitude storms have been excluded. (b) Same as (a) Except West-to-East Component.

with mixed distributions (Crutcher et al. 1982). In Figure 3, initial motion vectors on three groups of storms have been fitted to a bivariate normal distribution; depicted is the 50% probability elliptical envelope. The groups of storms are (a) low-latitude storms (10–15N), well embedded in the atmospheric east-to-west steering flow; (b) mid-latitude storms (25–30N), near the recurvature zone; and (c) high-latitude storms (40–45N), well embedded in the atmospheric west to east steering zone. In Figure 3, the contrast in the size of the elliptical envelopes is quite striking. This difference clearly illustrates the large variance that must be explained by the models in the case of high-latitude storms compared with low-latitude storms.

In addition to size, the orientation of the ellipses also provides information on the nature of the forecast situation. To visualize these situations better, the elliptical envelopes in Figure 3 have been transferred to the geographical framework shown in Figure 4.

Figure 4 illustrates three common forecast scenarios. Consider a storm moving into the Caribbean Sea (ellipse A). Here the storm direction of motion is oriented more or less along the major elliptical axis. Thus the forecast problem is apt to be one of speed rather than direction, that is, along rather than across the track. In tropical cyclone forecasting, a speed problem is considered less serious than a direction problem, since more credibility is lost if a storm completely misses an area than if arrival time is earlier or later than expected. Regardless of the forecast outcome, the relatively small motion variance suggests that the forecast error, measured as the distance between a forecast and a later observed point, will also be relatively small. This small variance further suggests the use of rather simple climatological models in this geographical area.

Now consider the scenario of a storm that is off the northern Bahamas and moving slowly toward the north-northwest, as illustrated by ellipse B. Here it can be noted

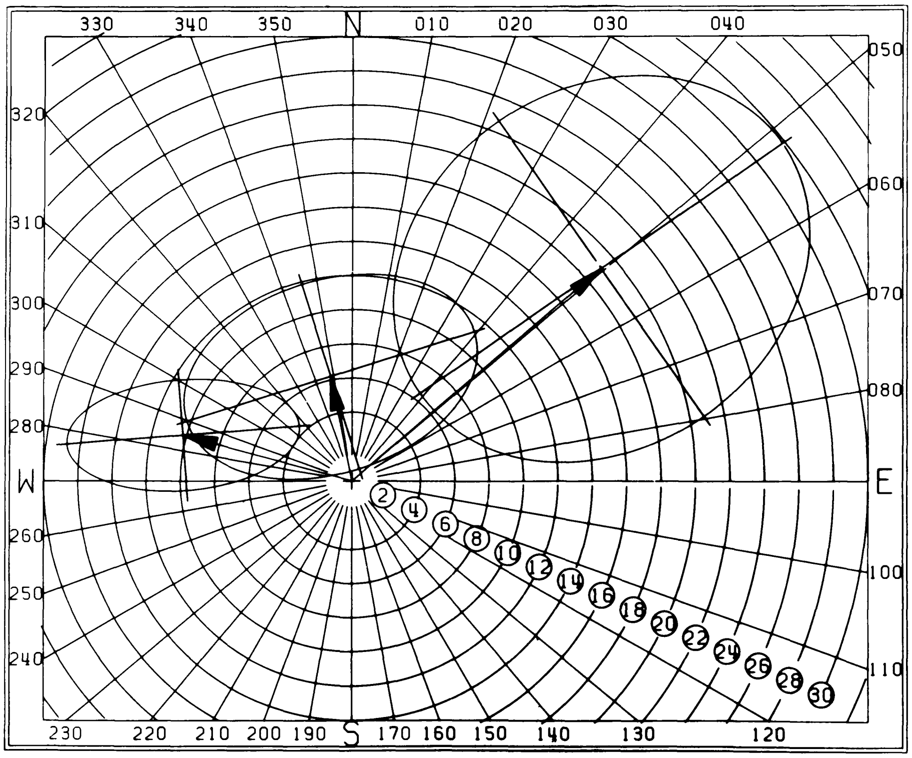

Figure 3. Latitudinal Variation of Tropical Cyclone Average Speed and Speed Variance. Shown are the 50% probability ellipse envelopes of initial storm motion vectors averaged over the 98-year period 1886–1983. From left to right, ellipses are for 5° latitude bands, zonally across the Atlantic Basin, 10–15N, 25–30N, and 40–45N, respectively. Storm translational speeds (circled) are in knots.

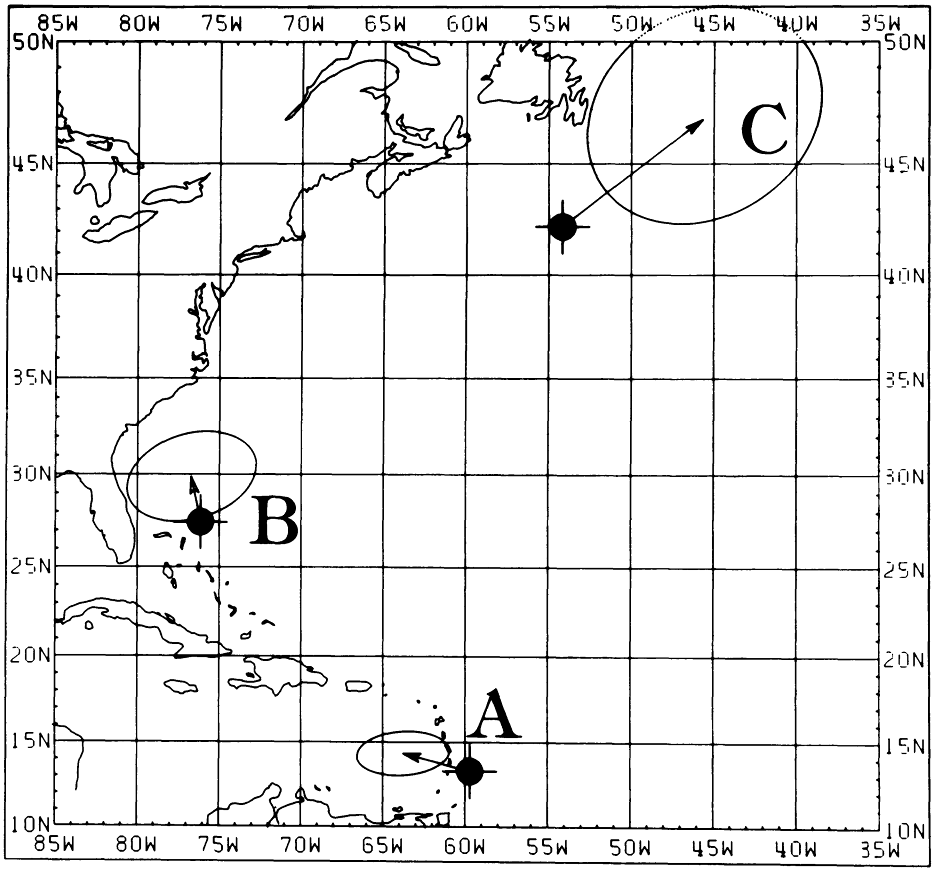

Figure 4. Similar to Figure 3 except ellipses have been scaled to contain displacement vectors that would be obtained if motion in Figure 3 remained constant for 24 hours. Large circles represent initial composite location of all storms in the 5° latitude bands.

that the major elliptical axis is perpendicular to the initial storm motion vector, and errors are apt to be more in direction than in speed. Indeed, there is about an equal climatological chance that the storm will take on a heading toward anywhere from Central Florida northward along the entire East Coast of the United States or, perhaps, the storm will continue to recurve and miss the United States. This is obviously a critical forecast area, since warnings may have to be posted for some portion of the coastline. A prediction model that excels in direction is needed.

Finally, elliptical envelope C depicts a scenario important mainly to ships at sea. Here the forecast problem is apt to manifest itself in both speed and direction, although even with a reasonably good forecast of storm speed and direction, it would be difficult to realize a small forecast error because at these speeds, the motion vector of the actual storm track and the forecast storm track can diverge quite rapidly. In zones A and B, ships can usually outmaneuver storms, even with a relatively poor forecast. In situation C, however, outmaneuvering becomes difficult because of the rapid translational speeds of storms at these latitudes. In zone C, a forecast model must be capable of reducing large zonal and meridional variances.

In actual practice, a given forecast situation is apt to be somewhere among the three examples cited. In the Gulf of Mexico, for example, forecast scenarios somewhere between types A and B are typical.

2.2 Motion Persistence

An important ingredient in all statistical models for the prediction of tropical cyclone motion is the storm's present and past motion. Tropical cyclone motion changes very slowly with time, such that if current and past motion are precisely known, they can be extrapolated into the future. Alternatively, present and past motion can be used as statistical predictors. The actual linear correlations between current and future motion for a large sample of storms are high—.95 and .88 for 12-hour zonal and meridional motion, respectively. These correlations decay with time, but even at the 72-hour projection, they are significant—.65 and .34, respectively (Neumann 1972).

These correlation coefficients were obtained in a research mode in which current and past storm motion are "perfectly" known. However, the center (eye) of the storm, a convenient tracking entity, typically exhibits small-scale motions (about 5–20 n.mi. across the mean path) that mask the larger scale motion that needs to be determined. It is difficult to distinguish between these two scales of motion in an operational mode, and some of this potential variance reduction is lost. It is obviously impossible to obtain research mode motion vectors in an operational environment, since a perfect knowledge of future storm position is required. Even a small improvement in current ability to assess initial motion vectors can, however, be shown to yield relatively large reductions in short-term forecast error. The problem is discussed more fully in the companion article on the hurricane data problem (Pike 1985).

2.3 Environmental Steering Forces

Tropical cyclones move in relation to the integrated, deep-layer (surface to 55,000 ft or about 17 km) environmental flow in which they are embedded. Often, the flow patterns at the midtropospheric levels (10,000–25,000 ft or about 3–7.6 km) are used as approximations to this deep-layer flow. Figure 5 shows the average atmospheric flow patterns at the 700-millibar (mb; near 10,000 ft or 3 km) level during

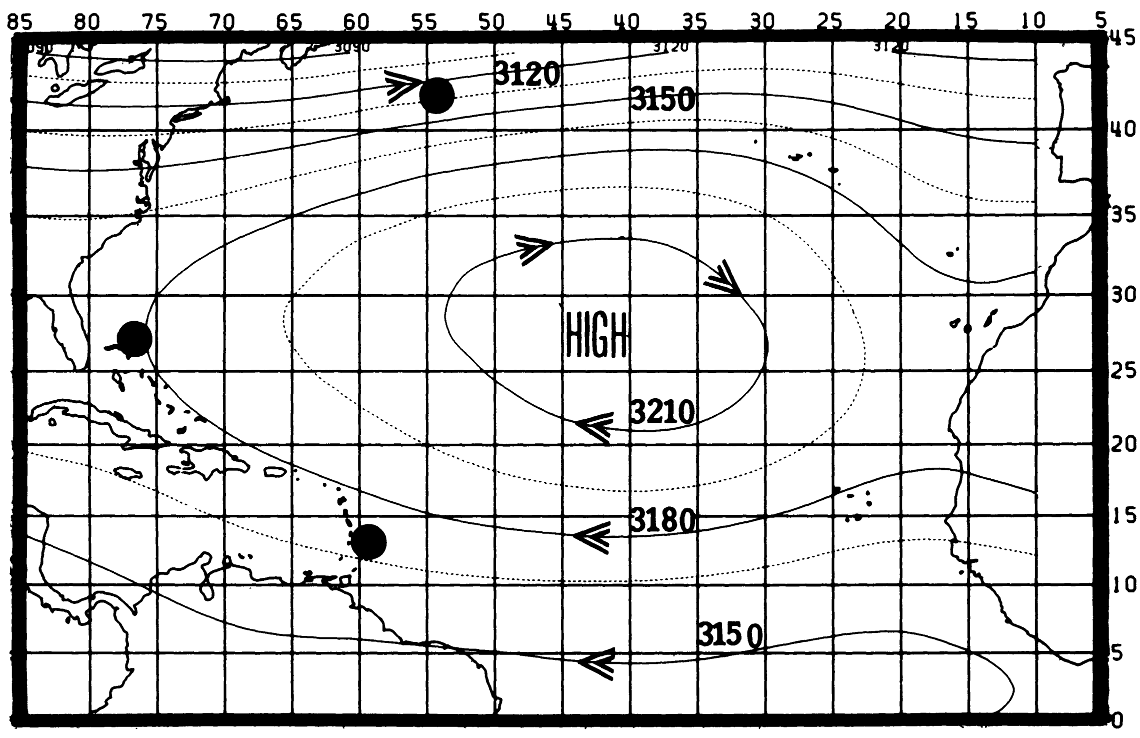

Figure 5. Mean Height (meters) of the 700-mb Level During September. Arrows show direction of accompanying winds. Large darkened circles give locations of ellipse origins depicted in Figures 3 and 4.

the principal Atlantic tropical cyclone month of September. Atmospheric circulation (wind) is clockwise around the large high-pressure area (anticyclone) centered near the mid-Atlantic. In addition, the speed of the circulation is proportional to the spacing between the contours. Thus the strongest winds, from a westerly direction, can be expected north of 35N, whereas light winds from a generally southerly direction can be expected off Central Florida and moderately strong easterly winds can be expected at low latitudes in the mid-Atlantic.

The three darkened circles in Figure 5 have been positioned at the same location as the ellipse origins depicted in Figure 4. Here it can be noted that the average motion of the three types of tropical cyclone forecast situations is very close to the average motion suggested by the 700-mb contour patterns. In reference to Figure 4, it can also be noted that storm motion tends to be somewhat to the left of the direction suggested by the contours and that this deviation, very small at low latitudes, increases at high latitudes. Even though Figure 5 includes other than tropical cyclone situations, the suggested relationship between storm motion and environmental forces is similar to that found by others (George and Gray 1976; Brand et al. 1981).

The standard deviations of the 700-mb-height data depicted in Figure 5, and given in Table 1, are also of statistical interest. The increase from north to south across the Atlantic tropical cyclone basin is seen to be substantial. This increase is in accordance with the increased dispersion of tropical cyclone motion with latitude, as depicted in Figures 3 and 4.

In summary, the average motion of Atlantic tropical cyclones shows wide variation from one portion of the basin to another, with the main gradients occurring in the north/south (meridional) direction. Storms tend to be steered by the larger scale atmospheric forces in which they are embedded. Excellent agreement between average storm motion and average environmental forces has been demonstrated. This relationship provides the rationale for the development

Table 1. Standard Deviation (meters) in Height of 700-mb Surface for September Along Longitude 65W, 1980–1983

Latitude (° North)	Standard Deviation
0	8
5	9
10	9
15	11
20	17
25	23
30	31
35	37
40	43
45	61
50	79
55	79
60	74

NOTE: The number of observations, taken at 12 hourly intervals from National Meteorological Center objective analysis, is 240.

of statistical models relating tropical cyclone motion to observed atmospheric circulation patterns, as well as to climatology and persistence. The latter can be considered "fallbacks," when environmental steering forces are not known with sufficient precision.

3. THE MODELS

In the broadest sense, models for the prediction of tropical cyclone motion are either statistically or dynamically founded, the latter referring to those models that use purely mathematical, thermodynamical, and physical formulations to arrive at a forecast given a set of initial atmospheric conditions. There are six model subdivisions within the two basic types. Schematically, these models are shown in Figure 6. In this article, discussion is limited to the purely statistical models (types 1–3) and statistical models that use dynamical forecast data in a statistical prediction framework (type 4). Purely dynamical models are sometimes subject to statistical adjustments and have been referred to as *dynamical-statistical*

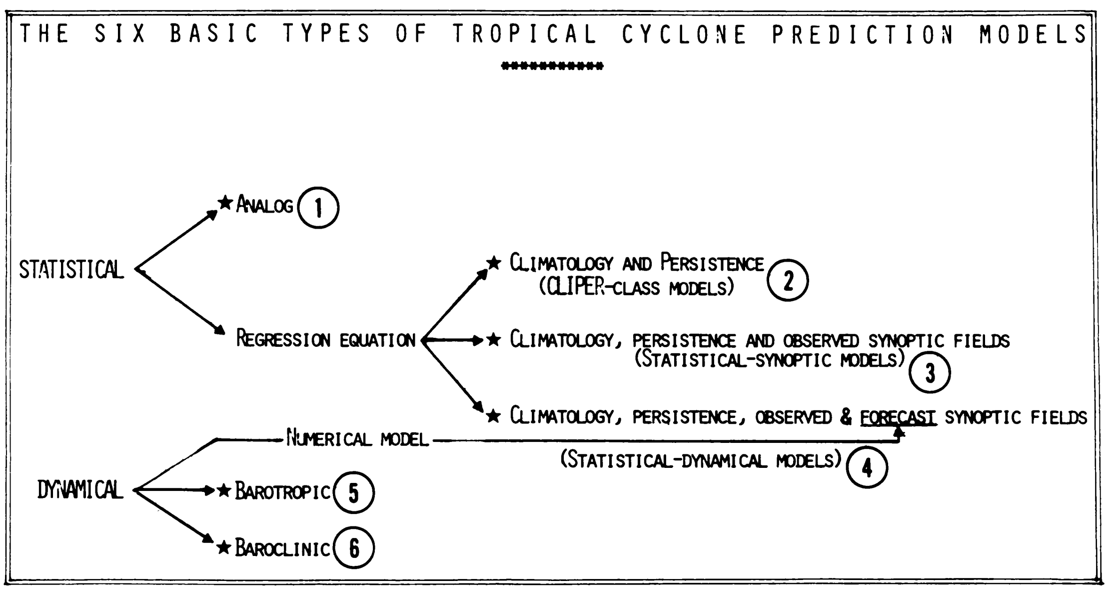

Figure 6. The Six Basic Tropical Cyclone Prediction Models. The term "synoptic" refers to analyzed fields of environmental data observed at a given time.

models (Peak and Elsberry 1984). Further information on dynamical models and other aspects of tropical cyclones are discussed by Anthes (1982) and Simpson and Riehl (1980).

3.1 Analog Models

Much of the variance of tropical cyclone motion is explained by seasonal considerations. For example, Figure 7 shows the June and August tropical cyclone track patterns over the Atlantic Basin. The patterns are clearly seasonally dependent. Analog models, in use at all tropical cyclone forecasting centers (Hope and Neumann 1970), are based on the premise that there are families (distributions) of tropical cyclone tracks associated with repetitive and recognizable large-scale weather patterns. These families are identified by computer algorithms that search historical records for storms having characteristics similar to a current storm.

A somewhat simplified analog process is illustrated in Figure 8. Here a 72-hour forecast is needed for a storm initially at 14.9N, 69.5W in the Caribbean Sea on August 15 and moving toward the west-northwest at 12 knots. A computer algorithm scans the 815 storm tracks since 1886 and identifies 16 storms (Fig. 8, top) as having spatial, temporal, and motion characteristics similar to the current storm. Next (Fig 8, middle), the 16 storms are moved to a common origin, and the recorded downstream positions are fitted to a bivariate normal distribution (Fig. 8, bottom). The centroids of the distributions are connected and yield the desired forecast track.

Most analog models consider persistence (the tendency for current storm motion to persist in time) and other innovations in the algorithm, but the basic scheme is much like that depicted in Figure 8. It is also feasible to integrate the bivariate normal density function over space and time to obtain the probability of the given storm's passing within a given point within a given time interval. This methodology is being used in the recently inaugurated National Weather Service Hurricane Probability Program (Sheets 1984), although in that program, the distributions are based on the known bivariate error statistics of the "official forecasts" rather than being obtained from a given model.

Analog models work well in areas where the variance of tropical cyclone motion is small and in other climatologically normal situations. Such models often fail in anomalous forecast situations, because not enough analog storms are identified.

3.2 Regression Equation Models

Another type of statistical model depicted in Figure 6 is based on regression equations. This type is further subdivided, depending upon the type of predictors entering the equations. The simplest regression equation models are those that use predictors derived only from climatology and persistence (CLIPER-class models). In this respect, they are conceptually similar to analog models, except that continuous functional relationships are used in place of the sometimes discontinuous analog process. Predictors entering the model are present storm motion, past storm motion, current storm location, intensity, and time of year (Julian day number). These eight predictors are fitted to general cubic polynomials, using classical least-squares methods or stepwise screening regression.

Being based only on climatology and persistence of storm motion, CLIPER-class models provide a convenient frame of reference on which the skill of more sophisticated models can be assessed. They also provide a type of "forecast difficulty index" (Neumann 1981) that can be used to normalize interbasin or intrabasin forecasts from other models. CLIPER-class models appear to make better use of climatology than do the analog models. They make explicit use, however, of the present and the past storm motion vectors. If these predictors are imperfectly known, the forecast can be substantially degraded.

The next echelon of regression equation models (Fig. 6) is the statistical-synoptic models. In addition to climatology and persistence, these models use predictors selected by stepwise screening regression or empirical orthogonal function (Shaffer and Elsberry 1982) methods from current analyzed fields of upper-level pressure-height data. These data are represented on a large grid system, the domain of which is illustrated in Figure 9. Because such a grid offers a large number of potential predictors (in this case, 165) and only a few are selected, care must be taken in assessing statistical significance. Monte Carlo methods (Neumann et al. 1977; Shapiro 1984) are used for this purpose.

Since statistical-synoptic models include predictors that are representative of current environmental forcing, they would be expected to outperform the lower-echelon CLIPER-class models. Long records of operational performance show, however, that this is true only for storms in categories B and C of Figure 4. The inclusion of environmental data actually degrades the performance of the CLIPER-class models on category A storms, that is, storms embedded in the tropical east-to-west general circulation. This result is attributable to (a) the low standard deviation of environmental predictors in the tropics, (b) large data-void areas and resultant analysis uncertainties, and (c) failure to keep model sophistication commensurate with analysis deficiencies. These factors are related to difficulties in assessing statistical significance in the tropics. The problem is further discussed by Pike (1985).

In current operational practice, the models employ a grid system oriented with respect to a traditional zonal and meridional orthogonal system. Based on the findings of Shapiro and Neumann (1983), however, improvements in the important short-range projections can be effected by using a grid system oriented with respect to the storm heading, rather than in the traditional sense. The rationale, being tested operationally, is based on components along the storm-oriented system's being nearly uncorrelated, permitting them to be combined vectorially without the introduction of distortion. In the traditional coordinate system, correlation between the components apparently leads to a slow speed bias, common to all National Hurricane Center models (Neumann and Pelissier 1981).

The upper echelon of statistical models in tropical cyclone prediction are those designated statistical-dynamical (type 4 in Fig. 6). These models use the same predictors as those used by the lower-echelon statistical-synoptic models (type 3 in Fig. 6) but make additional use of predictors generated a

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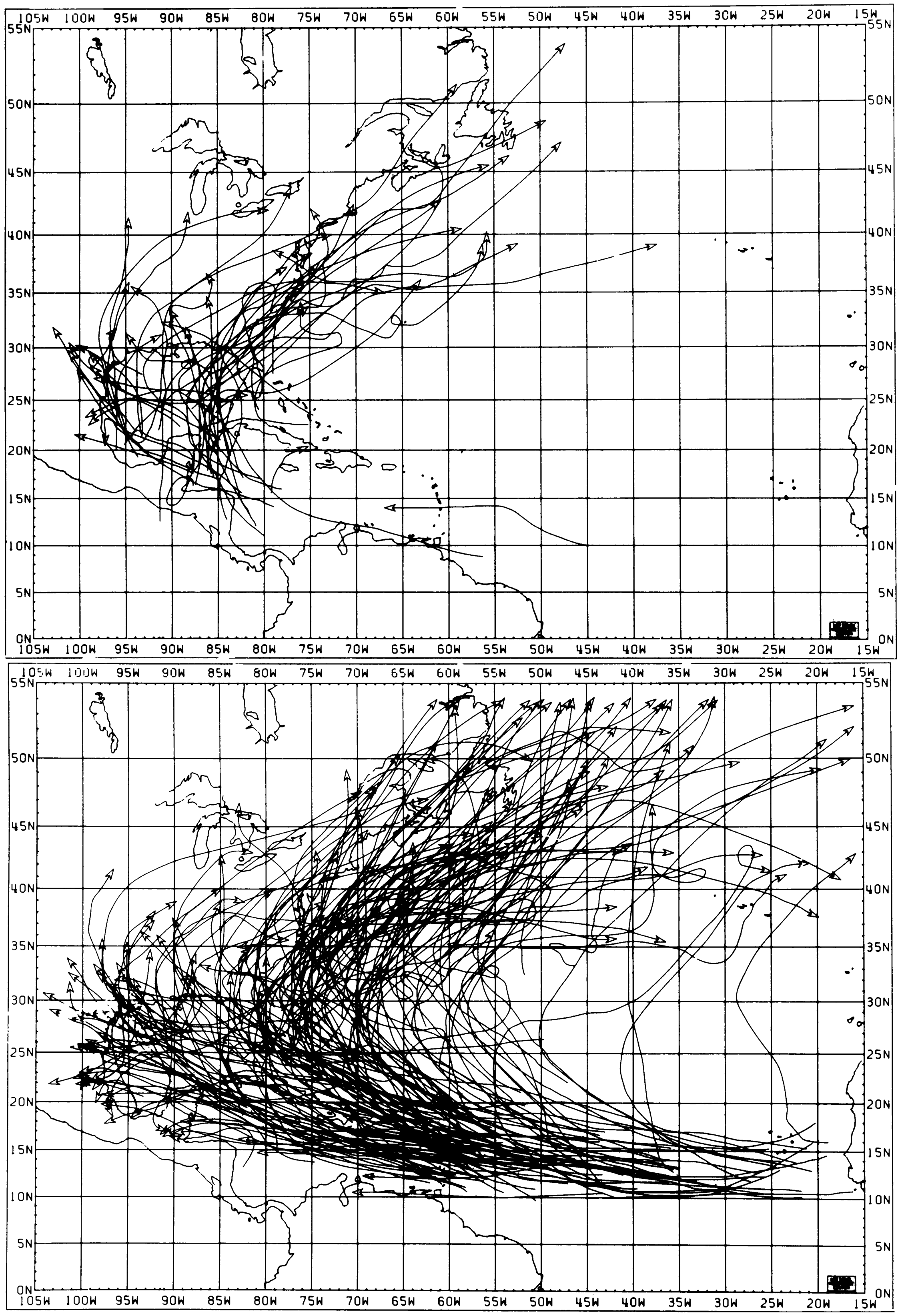

Figure 7. (a) North Atlantic Tropical Cyclone Tracks Beginning in June 1886–1983 (53 storms). (b) North Atlantic Tropical Cyclone Tracks Beginning in August 1886–1983 (191 storms).

by a dynamical model. The National Hurricane Center's NHC73 model (Neumann and Lawrence 1975), for example, uses output from global dynamical models that are run twice daily at the NOAA National Weather Service, National Meteorological Center.

Conceptually, statistical-dynamical models should provide the best overall guidance in the statistical model category, and indeed, in the overall sense, performance records bear this out. In the deep tropics, however, the model in its present configuration is oversophisticated in that the dy-

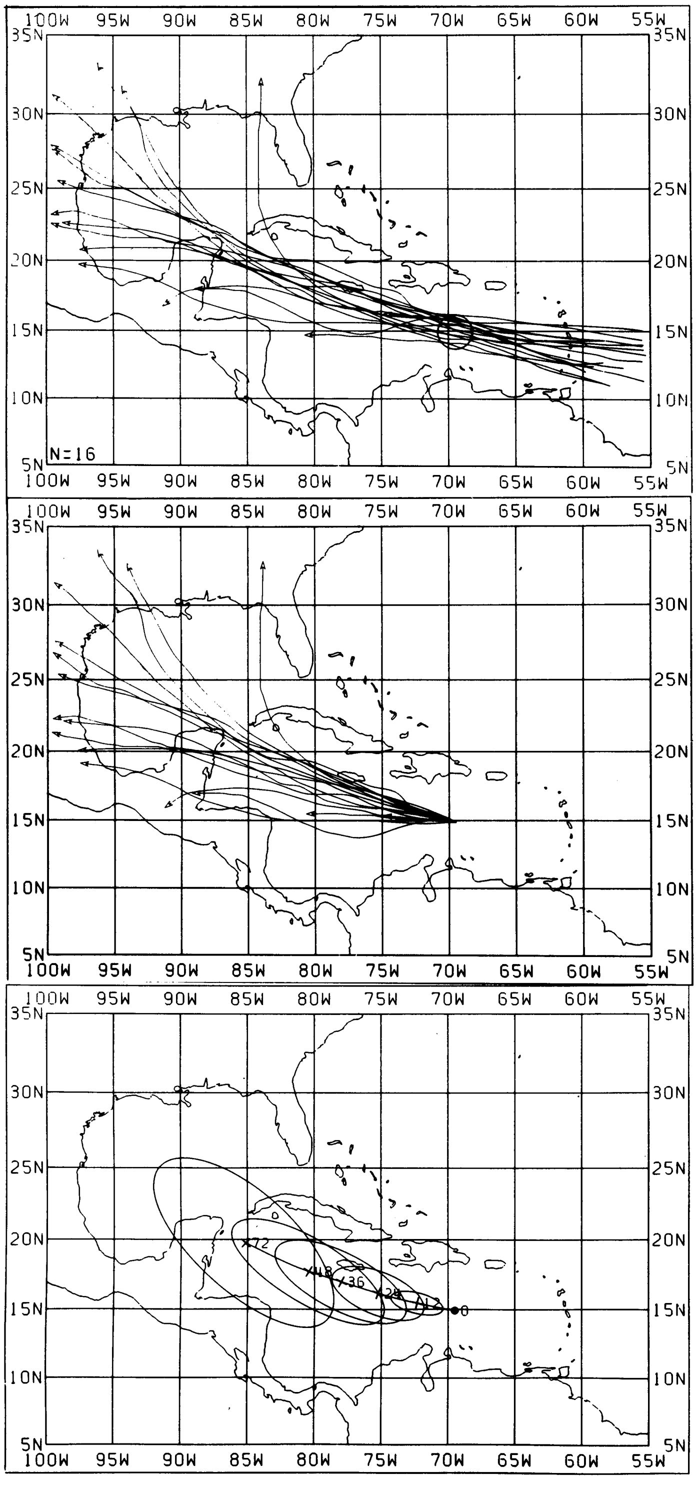

Figure 8. (Top) The Tracks of the 16 Atlantic Basin Tropical Cyclones Passing Within 75 n.mi. of 14.9N, 69.5W, August 1886–1983. (Middle) Tracks in Top Panel Moved to a Common Origin. (Bottom) Seventy-Two-Hour Forecast Tracks With 75% Probability Ellipse for Specified Projection in Hours From Time Zero.

namical models have had difficulty improving over simple persistence in that area. The NHC73 model is being restructured to correct this deficiency. On a global scale, the potential of this type of model has not been fully explored because many meteorological services do not possess the resources to provide the dynamical input required of the model.

4. THE FORECASTER'S DILEMMA

One of the main problems facing the operational forecaster is the evaluation of the forecasts from the different models. At the National Hurricane Center, the forecaster routinely receives guidance from seven prediction models. Even though in many instances the models are in reasonably good agreement, there are other instances when they disagree completely.

Contrasting scenarios are shown in Figure 10. Here 72-hour forecast tracks from six of the seven NHC models are presented for two situations, as well as the verifying tracks. In the DAVID forecast, the tracks are in reasonably good agreement. In fact, this is about as good agreement as can be hoped for. The forecaster would probably select a 72-hour position over South Florida or the Florida Keys. As it turned out, none of the tracks verified particularly well, the observed track being to the right of all of the guidance.

Now consider the DEBBY forecast in Figure 10. Here the tracks vary widely. This is a common situation confronting the forecaster, and an evaluation must be made based on the known characteristics of each model for the given area and forecast situation. Such an evaluation, however, is very time consuming and cannot be fully accomplished (except in general terms) in an operational environment. Much of the evaluation depends, for example, on the adequacy of the raw data and the analyses of the raw data that are used in initializing the various models. This information is not known until after the fact. Figure 10 points out just one of the many reasons why tropical cyclone forecasting contains a high degree of subjectivity.

5. CONCLUSION

In this article, the models for the operational prediction of tropical cyclone motion and their rationales have been briefly reviewed. Experience has shown that no single model can serve the needs of an entire forecast basin, hence the need for a number of models, each with its own spatial or temporal characteristics.

The performance of the models is often disappointing. Until improvements can be effected, their role must be considered as advisory rather than absolute. In this connection, there is a need to further our ability to "decode" the messages provided by the models. Collectively, they provide a large amount of diagnostic and prognostic information that is often masked by the diversity of tracks. Attempts to automate this decision process have been unsuccessful.

Within the realm of an unknown limit of predictability, some of the problems with the models probably relate to the quality and quantity of meteorological data in and around the storm area. These factors lead to uncertainties in the analyses with which the models are initialized. Dynamical models are particularly vulnerable. It has been demonstrated that the performance of these models (and statistical-dynamical models) improves as the quality of the initial data improves. The meteorological community is aware of this problem, and data improvements are being sought through advanced satellite technology, improved aircraft atmospheric sampling methods, and improved temporal and spatial analysis techniques. Improvements are also being sought

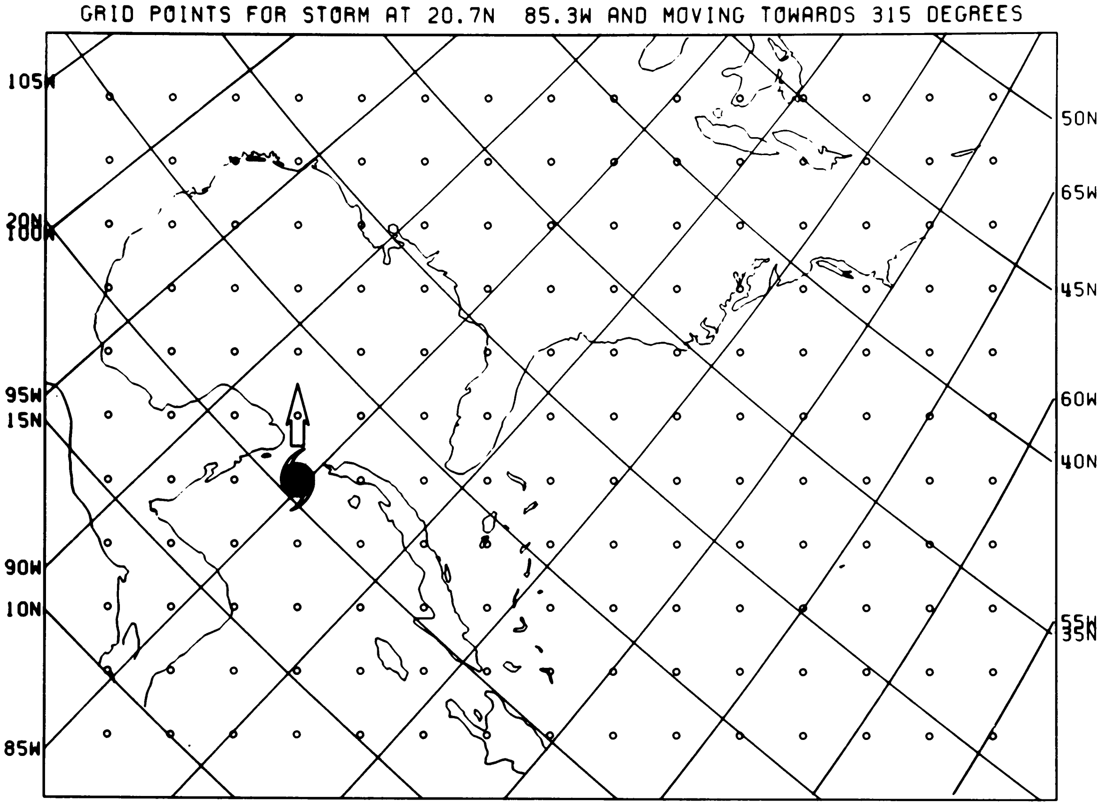

Figure 9. Example of the 15 × 11 Grid System Used by Experimental National Hurricane Center Statistical Prediction Model. Hurricane symbol depicts location of storm in grid system. Grid spacing is approximately 278 km.

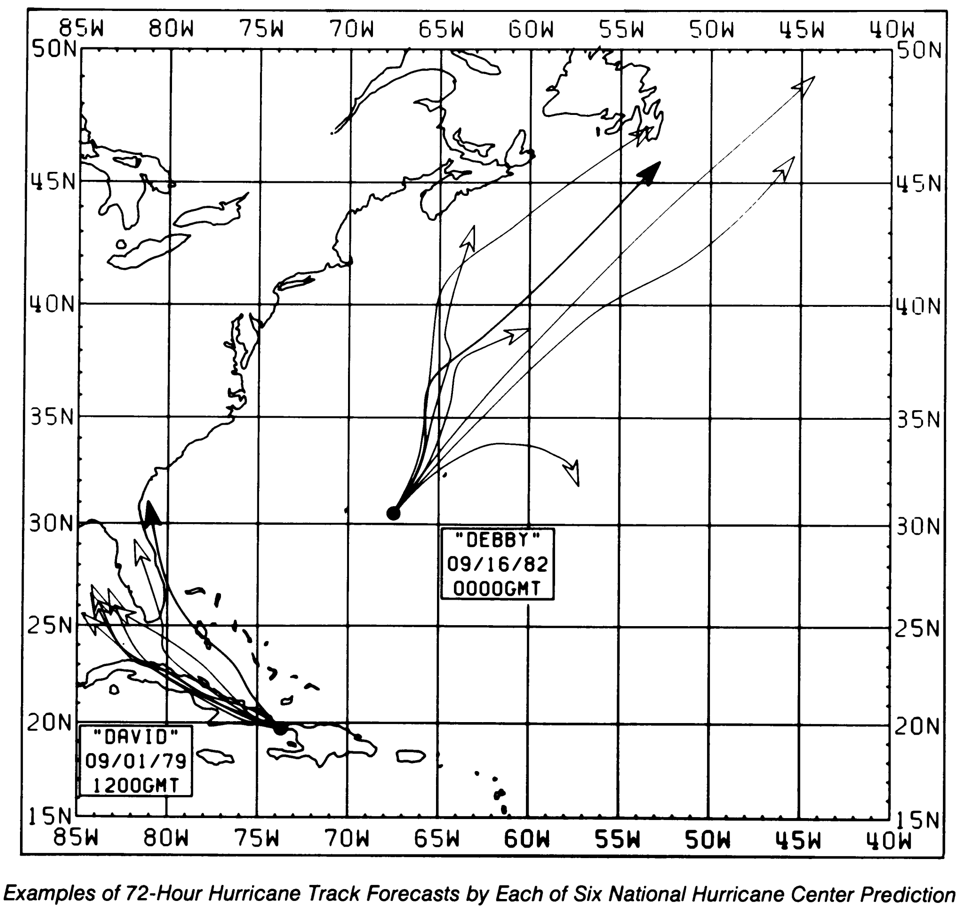

Figure 10. Two Examples of 72-Hour Hurricane Track Forecasts by Each of Six National Hurricane Center Prediction Models. Heavy track with darkened arrow is observed track.

in the structure of the models, by tuning their sophistication to the quality of the input data. Finally, much of the variance-reducing potential of persistence is lost by our not being able to determine representative initial storm motion vectors; improvements are also being sought in this area.

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