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Hurricane Prediction: Progress and Problem Areas

Avoidance of a serious hurricane disaster hinges on our ability to pinpoint the landfall of the center.

R. H. Simpson

Hurricane warnings and protective measures depend on an interlocking chain of weather and oceanographic prediction. The prediction skill for individual links in the chain varies widely and the effectiveness of warnings is largely limited by the weakest link. Prediction begins with the detection and tracking of the hurricane seedling or rain cloud cluster from which damaging wind storms grow (*1*). Next is the prediction of seedling development into a storm with sustained winds of gale force. Then one must predict the growth and strengthening of the circular wind system commonly referred to as the hurricane vortex, the movement and landfall of the hurricane center as it approaches a coastline, and finally the storm surge, an oceanographic phenomenon, which often inundates the coastline as the hurricane moves inland.

About nine out of ten lives lost in hurricanes result from drownings, and most drownings result from the coastal inundation caused by the storm surge. In most instances the greatest property losses are also caused by the storm surge and related effects. The inundation undermines the foundations of exposed residential property and weakens structural members, and heavy wave action propels the remnants of weaker structures as battering rams, which damage or destroy stronger structures. Nevertheless, one cannot conclude from this that the most critical link in the chain of predictions is that of storm surge. Actually it is the strongest link in most instances. The generation of storm surge, and the water profile that a hurricane can be expected to present along an open coastline, can be simulated far more accurately than any other aspect of the hurricane. It is ironic, however, that this skill is largely vitiated due to the lower skill in predicting the landfall and the changes in strength of maximum winds.

Figure 1 is a machine printout of the profile of storm surge heights based on a sophisticated numerical model (*2*) which employs a careful mapping of water depths seaward from the shorelines (these values are stored on tape), and incorporates the characteristics of the current hurricane—size, strength, movement, and angle of approach to the coast. The program even provides the forecaster with specific incremental corrections to this profile in the event that he errs in such other aspects of prediction as the landfall or strength of the storm. This model, the special program to list amplitudes of surges from hurricanes (SPLASH), predicted a peak inundation depth of approximately 25 feet in Hurricane Camille in 1969, which compares favorably with the observed maximum of 24.5 feet (*3*). While SPLASH, as we shall see, has not solved all the problems of predicting inundation, especially in estuaries and along irregular coastlines, it is the link in which the forecaster has the most confidence. His greatest worries center around the prediction of landfall. A miss of 100 miles—not a large error for a 24-hour forecast—can result not only in a vastly different inundation potential, as shown in Fig. 1, but in entirely different plans and measures for evacuation and preparedness.

In this article, therefore, I shall devote most of my attention to the task of predicting the hurricane track and landfall. However, since all predictions must begin by describing a baseline of initial conditions, we shall first look at the problem of detecting, tracking, and describing tropical cyclones, and then proceed to the other links in the chain of predictions, examining the progress that has been made during the last several decades and flagging problems which continue to complicate the matter of warning and evacuating coastal residents.

Detection and Description

The most important meteorological tool for detecting and tracking storm systems is the weather satellite. Figure 2, a typical view of a series of hurricane seedlings and one hurricane in the tropical Atlantic, demonstrates how important a tool of observation the satellite is in regions where other sources of observations are few and far between. The polar orbiting satellite, such as NOAA-II and ESSA-VIII, provides successive sightings of seedlings or storm systems, which makes it possible to track and to some extent estimate the growth of the systems. The geostationary satellite, a much more powerful tool in the tropics, looks down continuously on the same geography from a position 22,300 miles above the equator. It can provide storm surveillance pictures as often as once every 11 minutes, from which a movie loop may be compiled showing the motion of clouds and often the precise move-

The author is director of the National Hurricane Center, National Oceanic and Atmospheric Administration, Miami, Florida 33124.

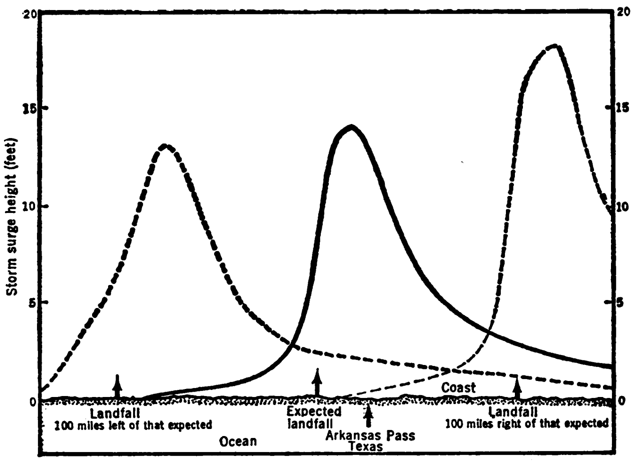


Fig. 1. Profile of storm surge heights along the Gulf coast of Texas from a severe hurricane, for an expected landfall on Padre Island, for an actual landfall 100 miles south of the expected position, and for an actual landfall 100 miles north of the expected position.

ment of the storm center. Moreover, from the displacements of small clouds in both lower and upper levels of a storm system for known periods of time, wind direction and speed can be measured, so that inflow in lower levels and outflow at the top of the system can be more accurately described, as well as the circulation of air in the nurturing environment which propels the seedling or storm system along its way.

This observing capability is in sharp contrast to circumstances several decades ago when often days would pass without an observation from ship or aircraft within a thousand miles of an advancing tropical cyclone in mid-Atlantic. Moreover, on such occasions reconnaissance aircraft often were dispatched to "areas of suspicion" on missions which ended up as wild-goose chases. Whatever other advantages accrue from the weather satellite, it unquestionably demonstrates to the forecaster that he has more problems than his weather charts would otherwise have revealed.

The weather satellite view of a full-blown hurricane is a magnificent sight (Fig. 3). When it is not possible to view and track the storm center or eye from a succession of satellite pictures or a movie loop of black-and-white pictures, the forecaster can use a color densitometer to delineate the stratiform clouds, which are poorer reflectors of sunlight, from the convective rainbands, which spiral in nebula fashion around the center (Fig. 4). From the rainband configurations the storm center can usually be accurately inferred.

Much progress has been made in the application of satellite meteorology to the hurricane warning problem, and more is being learned empirically each year about the relationship between the shape and appearance of the hurricane cloud system and the maximum winds which it sustains. Figure 5 shows some elements of a classification system recently developed by Dvorak (*4*), which has given very encouraging results during its use in both the Atlantic and the Pacific.

However, the satellite view of the more violent portions of the hurricane unfortunately is mainly that of the exhaust product from the heat engine rather than the convective elements which control the growth and hold the key to the future potential of the storm system. To simulate hurricane movement and behavior with numerical models, or to properly diagnose the trends in development and movement, most meteorologists agree that more information is needed than can presently be provided by the weather satellite. The only means of supplying this information is by directly probing the vortex with reconnaissance aircraft.

Because of the stringent requirement anticipated for data from the storm core or vortex to initiate future numer-

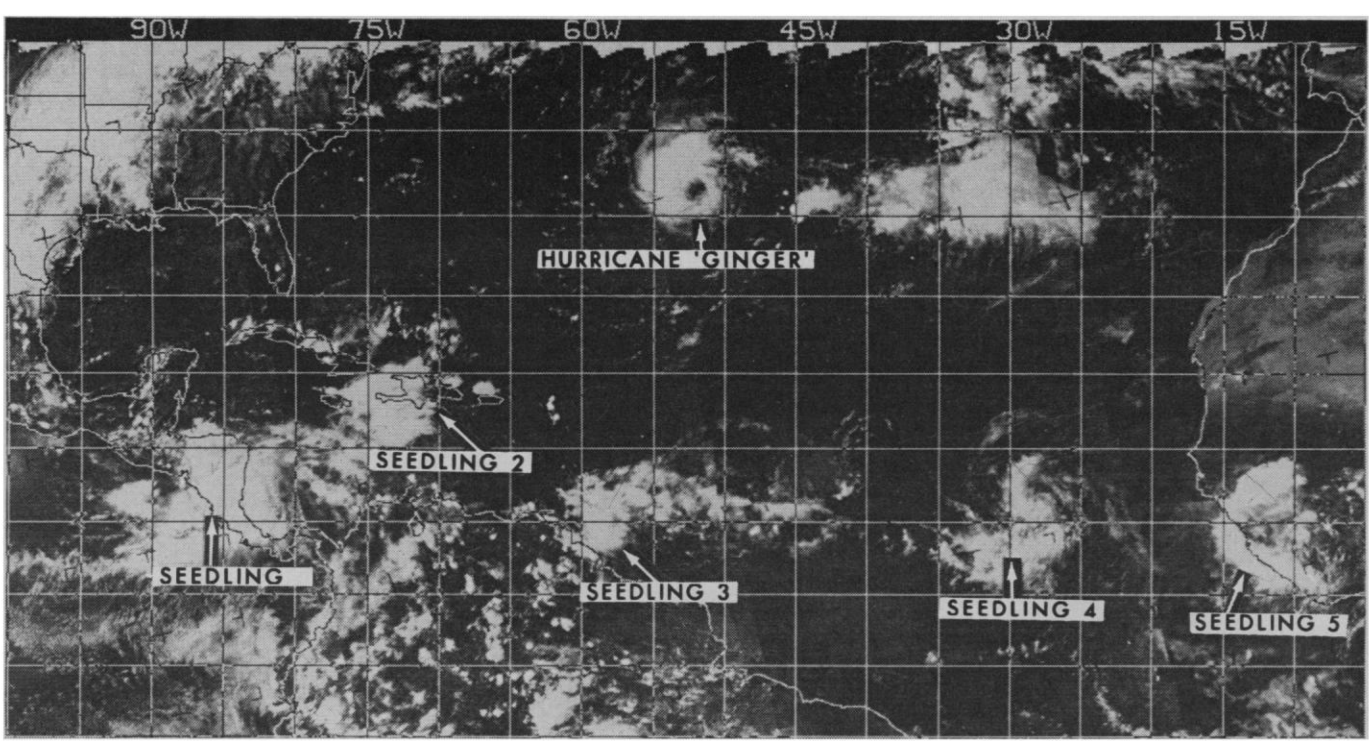


Fig. 2. Satellite view of five hurricane seedlings and one mature hurricane (Ginger) on 19 September 1971.

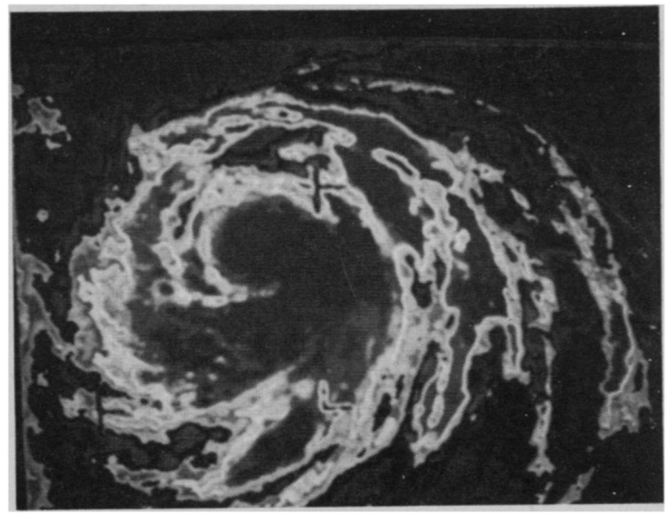


Fig. 3 (left). Satellite view of Hurricane Beulah (1967) approaching the Texas coast. Fig. 4 (right). Color densitometer analysis of the black and white photograph of Beulah in Fig. 3, shown here in black and white. The configuration of the more highly reflective spiral rainbands helps identify the hurricane center when no eye is visible.

ical prediction models of the hurricane, the Department of Defense several years ago was requested to acquire data from the hurricane vortex by flying reconnaissance aircraft along a standard track similar to that shown in Fig. 6. The aircraft always enters the storm from the left rear quadrant and moves diametrically across the center from 80 miles on one side to 80 miles on the other side of the eye. It then proceeds downstream to a similar position in the left front quadrant and passes diametrically through the center to the right rear quadrant. Subsequently, a foray is made into the environment to measure circulation conditions and sea surface temperatures which might influence the strength and development of the hurricane in the hours ahead. These data presently are used diagnostically to determine the asymmetries and state of development of the storm system and the environmental influences which may reflect what is about to happen in the life cycle of the storm.

Growth of the Hurricane Seedling

The cluster of rain clouds which we have identified as the hurricane seedling, often covering an area several hundred miles wide, comprises a number of thunderstorm-type cells, each of which attempts to lead an independent way of life with regard to energy release, convergent inflow, entrainment of air from the environment, and divergent outflow at cloud tops.

The process by which these cells are persuaded to join together and form the gigantic atmospheric heat pump which is the hurricane system is one of the great puzzling problems in meterology today. The pump consists of a spiraling influx of warm moist air at its intake in the lower boundary layer, and an equally large-scale spiraling efflux at the exhaust end or top of the storm system. Many of the necessary conditions for this merging process are known, but no one has been able to specify a suf-

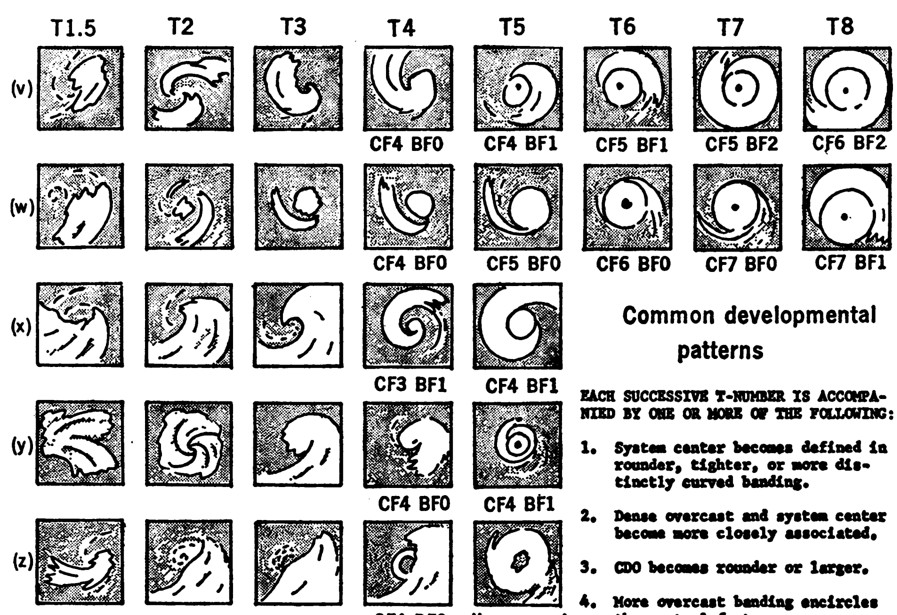


Fig. 5. Model set of hurricane cloud configurations used in the Dvorak system (*4*) to relate empirically the strength of maximum winds to patterns of cloudiness viewed by satellite. In the inset, CDO means central dense overcast.

ficient set of conditions which, when observed in the real atmosphere, will invariably lead to hurricane formation (*5*). Approximately 100 hurricane seedlings per year originate in and traverse the Atlantic Ocean, of which about 10 percent succeed in developing into tropical cyclones of gale or hurricane strength (*6*). As has often been said, the great question about hurricanes is not why or how they form, but why so few seedlings manage to become hurricanes.

There are various brakes to the growth of circular wind systems which can be defined with reference to the larger-scale circulation in the environment (*7*). A few others involve transport within the individual cloud cells themselves (*8*). It is clear that three basic conditions must prevail before the seedling can grow into a hurricane. First, there must be a basic mechanism to provide pressure falls near the surface. In the barotropic atmosphere this can occur only by concentrating the latent heat of condensation released by a cloud cluster throughout a major portion of the tropospheric column, reducing the air density and thus the surface pressure (*9*). Latent heat released by cloud clusters cannot be concentrated in such a vertical column unless there is very little vertical shear of the horizontal wind. In the case where strong westerlies overlay a shallow layer of trade wind easterlies the heat released by the cloud clusters cannot be conserved in a single tropospheric column.

Second, the dynamical structure of circulation in the planetary boundary layer must favor frictional transport of mass toward the center of falling pressure. This is considered by many meteorologists to be a function of the vorticity of circulation in the lower boundary layer. Third, in the efflux area at the top of the cloud system the circulation must favor the conduction of the effluent away from the storm center in a systematic large-scale divergent movement. If environmental air currents tend to constrain the efflux from the hurricane or seedling system, then the heat pump will not operate efficiently, if at all. A good example of this kind of constraint occurred as Hurricane Beulah swept westward across the Caribbean Sea toward Jamaica in 1967. As it left the Barahona Peninsula of the Dominican Republic it was a hurricane of moderate strength. However, before it reached the longitude of Jamaica it had diminished to a weak, poorly organized wind system. This change was brought about suddenly by the intrusion of a pressure trough from the environment at the level of efflux, which stifled the outflow from the hurricane.

Recently Garstang and his colleagues at the University of Virginia (*8*) demonstrated that the growth of massive convection has other built-in constraints; the individual rain cells tend to increase the thermal stability and decrease the buoyancy of convective elements while bringing down momentum from aloft. This reduces the amount of free energy released in the system, and poses a complicated interaction between the large-scale inflow of moist air into the heat pump and the circulations of individual convective cells which are the motive forces for the pump.

To summarize, the intricate interaction between the individual convective cells and the larger-scale environment has not yet been effectively modeled or simulated. Many numerical models have been developed, but the release of latent heat has necessarily been employed only through various parametrizations. The most encouraging progress made in recent years in attempting to incorporate cloud microphysics into a hurricane model has been the work of Rosenthal (*10*).

Thus, the task of predicting development of the seedling and growth of the vortex, once a storm has formed, is presently a matter of diagnostic rather than prognostic reasoning; the forecaster examines the circulation environment to determine whether the neces-

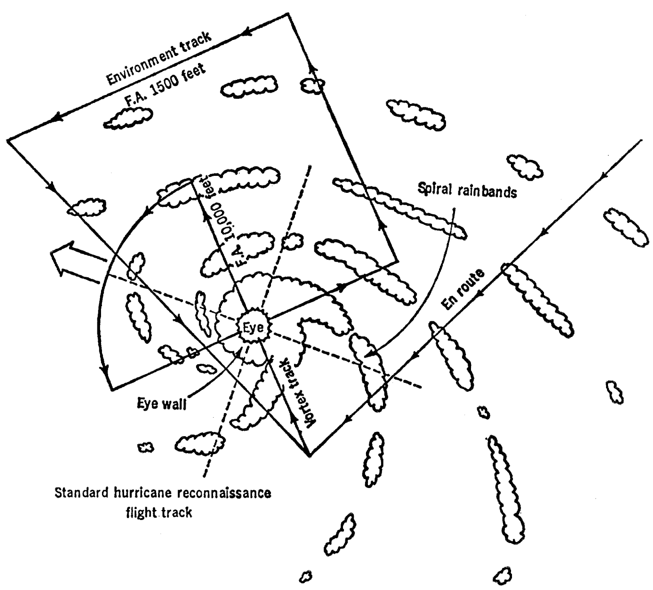
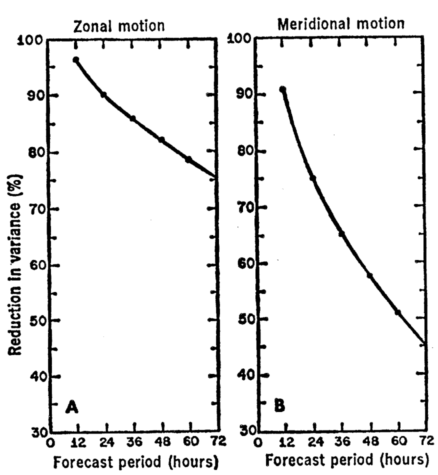


Fig. 6. Standard track flown by hurricane reconnaissance aircraft to obtain data from the storm core or vortex. The arrow indicates the track of the hurricane; quadrants, indicated by dashed lines, are defined with respect to the arrow; F.A. denotes flight altitude.



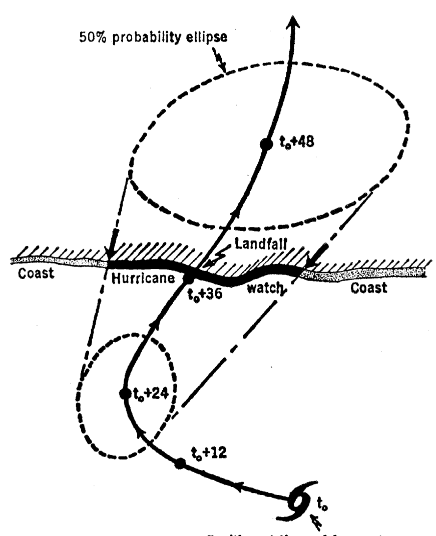


Fig. 7 (left). Variance-reducing potential of the CLIPER system at forecast intervals of 12 hours, out to 72 hours. (A) Westward motion; (B) northward motion. [After Neumann (*11*)] Fig. 8 (right). Objective determination of the coastal area to be placed under a hurricane watch 36 hours before the expected arrival of the center. The time of the forecast is t_0.

sary conditions for development are present and whether the trends in these conditions favor or discourage vortex growth.

Predicting the Hurricane Track

The prediction of movement in about seven out of ten hurricanes can be accomplished adequately by systematic extrapolation of the observed movement during the preceding 24 to 36 hours. It is the deceptive movement in three out of ten hurricanes that tests the skill and the mettle of the forecaster, and the effectiveness of the objective tools which he uses to guide his forecast decisions.

At the National Hurricane Center, Miami, Florida, there are at present four track prediction models which are used as guidance in preparing the official track. Only one of these involves purely dynamical procedures. The other three use various statistically founded procedures to identify the probable movement of the storm based on historical or analog data, or on statistical screening procedures which relate the expected movement to conditions prevailing in the large-scale environment at the time the forecast is initiated. One method uses a combination of the latter two approaches. No one of the four methods is uniquely superior for a majority of forecasts, and the reason that four different guidance solutions are furnished the forecaster is that each has identifiable strengths and weaknesses which vary from one storm setting to another. The forecaster can identify the method whose expected skills on any one occasion will be highest and lean more heavily on that guidance.

It is remarkable and at the same time discouraging to the forecaster to learn that under many conditions nearly 90 percent of the variance of the storm movement can be explained by a simple combination of data on climatology and persistence of movement without any consideration of environmental influences at the time of the forecast. Figure 7 pertains to the first of the four methods, which was developed by Neumann (*11*) and is known as CLIPER—a combination of climatology and persistence. For most storms a high percentage of the variance in the westward motion can be explained with this method (Fig. 7A); however, it is not so reliable in predicting the northward component of motion (Fig. 7B). Nevertheless, under certain identifiable conditions the most probable track generated with this method is the best forecast available. The second method, known as HURRAN (for hurricane analog), contains additional information based on a sophisticated compositing of the movement of all hurricanes of record which closely resemble the present hurricane in position, movement, and time of occurrence. This again gives a most probable track up to 72 hours in advance and a family of 50 percent probability ellipses which

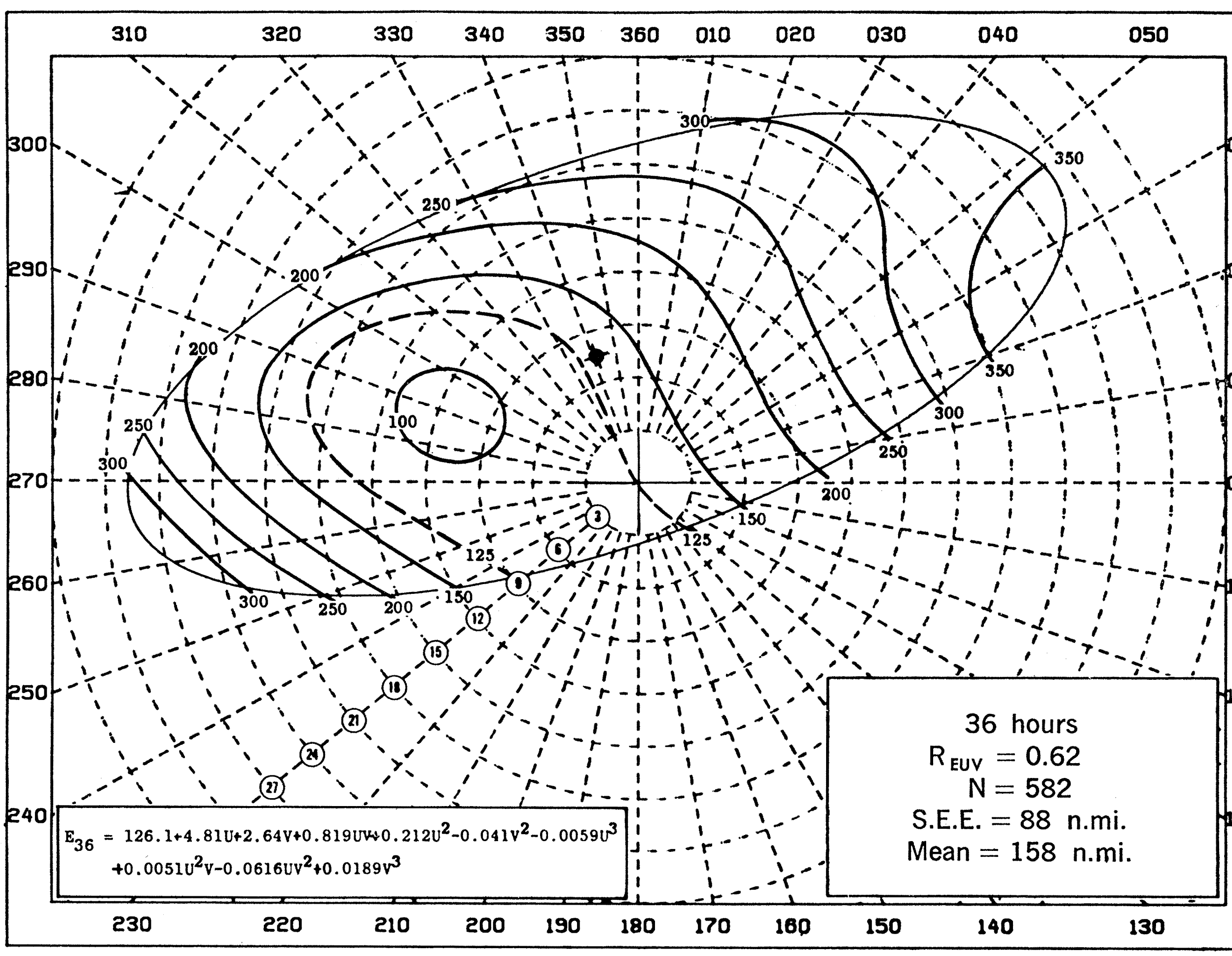
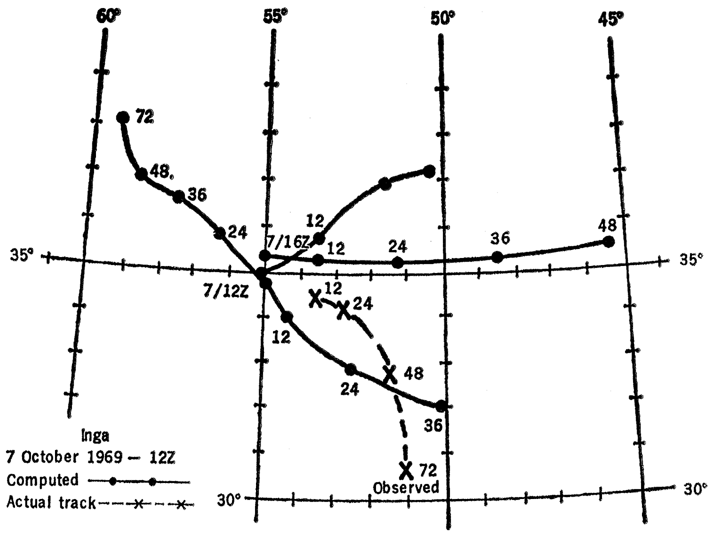


Fig. 9. Expected errors after 36 hours for the HURRAN track prediction method, presented as a function of the direction in which the center is moving and the speed of movement (3-knot increments). The abbreviations are: *E*, 36-hour expected error; *U* and *V*, westerly and northerly components of motion; R_{EUV}, correlation coefficient of the expected error of the vector of motion; *N*, number of cases of dependent data; *S.E.E.*, standard error of the estimate; *n.mi.*, nautical miles. [After Hope and Neumann (*12*)]



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ALICE INPUT DATA FOR ERROR ANALYSIS

LATITUDE	LONGITUDE	DIRECTION	SPEED	U COMP.	V COMP.
35.3	65.1	360	9	0.0	9.0

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WARNING...YOUR LATITUDE DEVIATES BY MORE THAN
2*SIGMA FROM THE MEAN OF THE FOLLOWING DATA SET

.....HURRAN.....

FORECAST TECHNIQUE

	CLIPER			HURRAN		
COMPONENT	N/S	E/W	TOTAL	N/S	E/W	TOTAL
FORECAST PERIOD	EXPECTED ERRORS IN NAUTICAL MILES					
12 HR	37.2	18.7	29.0	22.0	20.3	32.5
24 HR	64.0	67.8	103.1	68.5	66.5	102.1
36 HR	120.6	127.3	193.2	142.8	142.7	217.8
48 HR	184.7	205.2	303.4	166.8	243.6	335.9
72 HR	321.1	384.2	545.9	209.4	404.4	491.4
	NHC72			NHC67		
12 HR	17.7	14.9	26.2	36.1	33.1	53.7
24 HR	38.5	44.8	66.0	38.1	67.4	104.3
36 HR	64.2	84.4	118.0	120.5	113.3	182.5
48 HR	102.5	118.6	174.8	186.0	176.7	280.2
72 HR	161.4	195.5	280.6	297.7	386.2	525.1

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Fig. 10 (left). Widely differing tracks for Hurricane Inga (1969) generated by four separate prediction methods. Greenwich meridional time is denoted by Z. Fig. 11 (right). Diagnostic analysis of expected track prediction errors for each of four methods.

accompany each 24-hour displacement. This method, developed by Hope and Neumann (*12*), gives sufficiently stable results that it has become the primary basis for posting a preliminary alert, known as a hurricane watch, as a hurricane approaches the coast. The watch is a notice to residents located along a broad stretch of coastline that they should consider the fast actions they might need to take if the hurricane were to zero in on their locality, and stand by for specific hurricane warnings which might follow. A watch is posted at a coastline as soon as the 48-hour probability ellipse associated with the HURRAN track moves inland. The sector of coast which is subject to the watch is that intercepted by the two tangents joining the extremities of the 24- and 48-hour probability ellipses, as shown in Fig. 8. One handicap in applying the HURRAN method is that on some occasions, especially in hurricanes of an unusual type, there are not sufficient analog cases to provide a statistically significant analysis and most probable track. Figure 9 shows the variation in skill to be expected from the HURRAN method in terms of the hurricane's instantaneous direction and speed of motion. For a 36-hour forecast, maximum skill occurs when a storm is moving westward at a speed of about 12 knots. A much larger expected error is encountered for storms moving northward.

The third method, known as NHC-72 (for National Hurricane Center), employs a statistical screening procedure for relating the circulation features within several thousand miles of the hurricane center to the probable displacement of the hurricane center for successive 12-hour periods up to 72 hours, then combines this with the analog information obtained from the HURRAN method to constrain the direction and speed of motion for each period. The output again is in the form of a most probable track with 50 percent probability ellipses. This method supplies a far more skillful simulation of the northward component of motion than does either HURRAN or CLIPER but tends to be weakest for very low latitudes, the westernmost parts of the Caribbean Sea, and the Gulf of Mexico.

The fourth method, known as SANBAR (for Sanders barotropic), was developed at Massachusetts Institute of Technology by Sanders and his colleagues (*13*). This method makes a dynamical prediction of changes in the deep-layer barotropic atmosphere which encompasses and steers the hurricane vortex. It begins by computing mean winds for the deep layer from the surface to about 55,000 feet, analyzes the wind circulation in terms of stream functions, and predicts the displacement of the particular point where the stream function has its minimum value and the vorticity its maximum value, which identifies the hurricane center. This method is unconstrained by statistical or analog data but accounts for the interaction between the vortex and the environment only through insertion of a synthetic vortex. It also suffers the constraint that it must conserve the total kinetic energy of the analyzed circulations, although this appears to be of little consequence in predicting movement on most occasions. Excellent results have been obtained with this model, particularly for prediction periods longer than 36 hours. In the past 2 years, strangely enough, this method, while showing very low skill relative to the other methods in the predictions for the first 24 hours, has shown a distinctly better track record than any other method for 48- and 72-hour positions. At this time the main application of this method is to constrain the final track configuration in terms of the SANBAR track for the last 2 days of a 3-day prediction.

On some occasions forecasters are confronted with the kind of dilemma represented in Fig. 10. This series of tracks, generated during Hurricane Inga in 1969, yielded confusing results. In such cases, careful application of diagnostic machine programs must be made to identify the method on which greatest reliance can be placed. Such a program has recently been developed, and Fig. 11 shows an example of the computed expected skills for each of four guidance methods. This is a quick guide to the method which is most likely to be telling the truth. On some occasions one method may be expected to show greatest skill in predicting the westward component of motion, while another will have the highest skill in predicting the northward component. This program has been developed by a rescreening of the dependent data which were used to develop each prediction method. Of course, this cannot be applied to the SANBAR method, whose frailties usually are associated with either a faulty initial analysis or boundary conditions that are unsatisfactory for the circulation existing at the time of the prediction.

Another machine program for analyzing the skills of the various guidance methods is a program which uses a Bayesian analysis of the performance of each track prediction procedure for successive forecasts during the life cycle of a tropical cyclone. This method (*14*), called LANDFALL, analyzes the errors in predicting landfall at a virtual coastline after periods of 18 and 30 hours for each of the guidance method tracks, the bias (left or right of the track), and the evidence in support of each.

After assessing each of the track prediction methods and selecting the one likely to be closest to the truth, the forecaster turns to the prognostic charts of hemispheric circulation produced by the National Meteorological Center in Suitland, Maryland, and examines the implied influence of these larger circulation features on the steering of the hurricane with particular reference to the differences between these implications and the track computed by the favored guidance method. At this point the skill and experience of the forecaster is brought to bear in the heuristic dynamical reasoning concerning the impact of larger-scale circulations, adjustments (usually small) are made in the favored guidance track, and a final official track is derived which forms the basis for warnings and preparedness measures.

A machine plot of the final track and the latitude and longitude of hourly positions is printed together with the family of probability ellipses from the NHC-72 prediction method. The frailty of the final prediction is in part reflected by the displacement of the adjusted track from the centroids of the probability ellipses. Figure 12 is an example of a final machine-constructed track of the hurricane.

Progress in Predicting the Hurricane Track

Before digital computers ushered in a new age of numerical modeling and simulation, and made possible numerous diagnostic as well as prognostic calculations, hurricane track predictions made use of various steering concepts. Some sought a level near the top of the cloud system at which winds were suspected to flow out from the position of the hurricane in the direction in which the center would subsequently move. Other methods computed the steering of the hurricane in terms of the instantaneous resultant pressure forces in the environment acting on the circular wind system or vortex. All such methods had one serious problem in common—the charts on which estimates or calculations were based had few observation points over the oceans, and all charts had to be analyzed subjectively by hand. For this reason it was difficult for two analysts working independently to come up with the same prediction.

Whatever progress has been made, most circulation analyses are now objectively constructed by machine methods. These have the advantage of having copious wind observations from the weather satellite data.

However, while our knowledge of the hurricane, its structure, its sources of energy, and its energy transformations has expanded enormously in the last two decades as a result of intensive research and field investigations, and we now apply sounder and more objective scientific reasoning to the task of prediction, the improvement in forecast skill, certainly for periods longer than 24 hours, does not seem to reflect the dividends that all this newfound knowledge might suggest. Some meteorologists believe the reason for this is that nearly all operational prediction models fail to account for the interaction between the circular wind system of the hurricane and the impinging environment. Whether this is generally true or not, the most significant improvements to date have come from the sophisticated application of statistical procedures to evaluate the probable displacement of the hurricane center in terms of the observed circulation features of the environment at the time of the forecast. Perhaps the most important benefit to forecasting from all the research on hurricanes has been the detailed understanding of how a hurricane works. This equips the forecaster with a keener ability to sense when

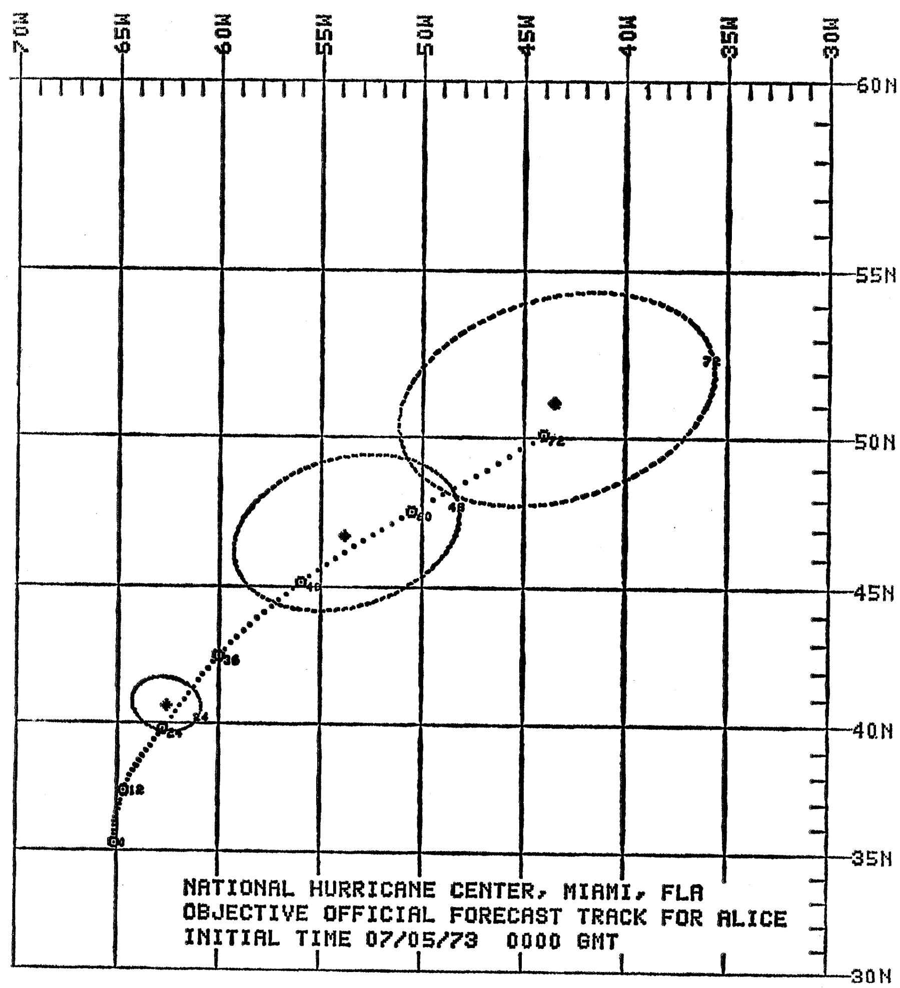

Fig. 12. Machine construction of forecaster's final adjusted hurricane track with 50 percent probability ellipses derived from the NHC-72 method. Part of the printout, the exact latitude and longitude for each hour of movement, is not shown here.

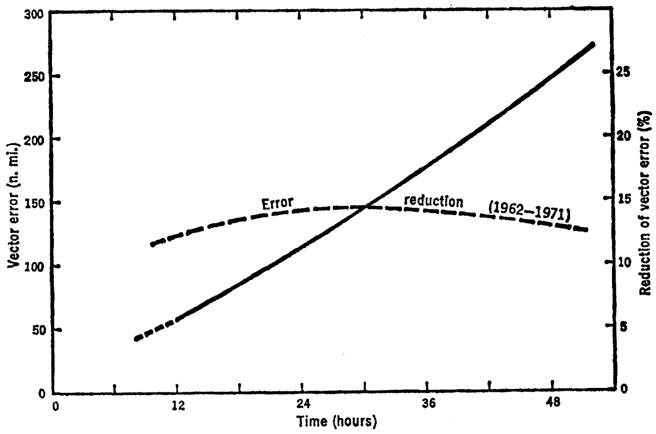

Fig. 13. (Solid line) Growth of the absolute magnitude of the vector error with length of the forecast (3-year running averages); (broken line) percentage reduction in this error during the period 1962 to 1971. Verifications until 1967 were made somewhat differently than at present. For example, in the early 1960's a 24-hour forecast based on observations at 1200 G.M.T. was regarded as the 24-hour period beyond the advisory time at 1600 G.M.T. At present, a 24-hour forecast is measured from the observation time 1200 G.M.T. for which all guidance computations are made. The percentage reduction has been computed by assuming that in the period 1961 to 1963 errors were for a 4-hour-longer period (that is, 28 and 52 hours rather than 24 and 48 hours). The recorded "24-hour" average error for 1961 to 1963 was 153 nautical miles (*n. mi.*); for 1970 to 1972 it was 114 nautical miles.

something goes awry and a hurricane turns into a bad actor. Thus, the forecaster is less likely to be deceived by the numbers thrust before him by the computer when computational failure is occurring.

Figure 13 compares the track error and its growth with time during the early 1960's with that of the last 3 years. These curves tell a significant story which bears directly on problems of hurricane preparedness and plans for evacuation of coastal residents. While there has been a significant increase in skill for 24-hour predictions, the improvement in forecasts for longer periods has been slow. The reason for this is a complex problem of practicability and credibility. With an expected vector error of approximately 100 miles for a 24-hour prediction, the forecaster must walk a tightrope in posting hurricane warnings which will become the basis for evacuating thousands of people and making expensive preparations for high winds and inundations. It is estimated, for example, that Dade County, Florida, spends as much as $2 million in programmed preparedness measures every time a hurricane warning is issued for that area. If hurricane warnings are spread over too large a sector of the coastline, it becomes an economic impracticability to initiate all-out preparedness measures everywhere, especially if half or more of the area ends up without reason for having taken these measures. Likewise, if two out of three people evacuated from an exposed coastline return home to find no obvious reason for having left, the credibility of warnings rapidly diminishes and public responsiveness to subsequent warnings will drop to a dangerously low level.

Because of these factors, specific hurricane warnings are rarely issued more than 12 to 18 hours before the hurricane center reaches the coast, at which time it is possible with continuous tracking by radar and frequent reports from coastal stations to zero in on landfall with much greater accuracy. From the progress presently being made and the outlook ahead, it is unlikely, barring a breakthrough, that hurricane warnings can be issued much farther in advance in the foreseeable future than has been the case in the past, although it may be possible to restrict the length of the coastline which does receive these warnings. This poses another kind of problem. With rapid increases in population at the shoreline, the relocation of residents during hurricane emergencies, with no increase in warnings, may require an entirely different approach to evacuation (*15*) and different planning by many communities if disaster is to be avoided when road systems fail to allow all who must leave home to reach points of safety before high winds and rising water cut off the escape.

Predicting the Storm Surge and Coastal Inundation

Jelesnianski's (*2*) storm surge simulation model known as SPLASH needs further comment at this point. SPLASH is a physical model from which it can be demonstrated that the rise of sea level from storm surge depends on (i) the radial distance from the storm center to the point of maximum winds, (ii) the barometric pressure at the storm core, (iii) the rate of movement of the center, (iv) the angle at which the storm crosses the coastline, and (v) the profile of water depths seaward from the coastline. For the greatest storm surge heights shoal water must extend seaward from the coast a distance at least equal to the radius at which the maximum winds occur. While SPLASH accurately computes the expected water levels at an open coastline, it does not specify the distribution of water inland, especially in complex estuarine areas. Each complex coastal sector of this kind must be modeled individually based upon two-dimensional bathymetry of varying water depths of each basin.

Another factor, much less commonplace than storm surge and far more difficult to predict, sometimes causes serious coastal inundations separate from the storm surge itself. That is the phenomenon known as the seiche. A severe hurricane moving across some shallow bay and estuarine areas at a critical speed which relates resonantly to the mean depth of water in the basin can excite or generate a series of tsunami-type waves; these break at considerable heights and with great suddenness along the seashore, cascading across the coastal plain. It was this type of phenomenon in all likelihood which swept across Galveston Bay in 1900 and drowned nearly 6000 people, and which was responsible for similar sudden inundations in Corpus Christi, Texas, in 1919, in Lake Okeechobee, Florida, in 1928, and possibly on a number of other occasions where less complete information on the rate of water rise has been available.

Seiche can occur in open basins as well as closed ones. A storm moving parallel to a coastline at a critical speed in relation to the slope of the continental shelf can generate seiche and cascade water rapidly across shorelines which are never crossed by the storm center. While the SPLASH model does predict seiche in open basins, much more work will have to be done to predict this for individual closed basins, and for distribution of storm heights inland over bays and estuaries.

Outlook for the Future

This year for the first time a sophisticated model for hurricane prediction based on the primitive equations will be used experimentally in real time. This model, developed by Miller *et al.* (*16*) of the National Hurricane Center, involves an objective analysis of seven layers of the atmosphere over a large domain including the hurricane and its environment. The model predicts both movement of the hurricane center and changes in strength of the winds. The grid system over which the computations are made has a mesh length for this analysis of approximately 100 kilometers. In a research environment the model has shown encouraging results, and the real-time experiment this season will be watched with great interest.

Work on a new and even larger model is beginning at this time. It will comprise a cooperative effort of four research centers of the National Oceanic and Atmospheric Administration: the National Hurricane Research Laboratory, Coral Gables, Florida; the Geophysical Fluid Dynamics Laboratory at Princeton University; the National Hurricane Center; and the National Meteorological Center, the latter serving as the focal point for the testing. The new model will involve several additional sophistications, will compute changes for approximately 20 layers of the atmosphere, and will use a mesh length as small as 30 kilometers. Such a model has not been operationally feasible in the past because no computers of sufficient size and speed have existed to carry out the computations in real time.

One of the principal questions about the application of such a model is the initialization process, that is, the detailed description of conditions at the time the forecast begins. Anthes (*17*) of Pennsylvania State University has shown that such a model would require information from at least one level in the atmosphere in much greater detail than is presently available from any source. It could be obtained only by reconnaissance aircraft with more sophisticated probe and recorder systems and a more exacting and intricate reconnaissance flight plan through the hurricane vortex.

Summary and Conclusions

The subjective approach to hurricane prediction of yesteryear has given way to the automation of many facets of prediction, leaving the forecaster with more time to reason dynamically in making the final adjustments to the official track derived from a hierarchy of computer-generated guidances. The most important task immediately ahead is to develop and apply better diagnostic procedures to help the forecaster identify the guidance sources which are most likely to contain the truth, and to help assure that his final decision will either succeed or fail safely.

The ultimate prediction method for both hurricane development and movement will probably need to simulate not only the circulation of the hurricane but the interaction of the cloud clusters in its vortex with the large-scale environment. Assuming that this can be effectively done, the most important further handicap will be the problem of describing the initial conditions.

The development of a model which will dependably simulate the behavior of the three hurricanes in ten that turn out to be bad actors will not likely become operational in the near future. The most troubling problem in applying such a model—and it would have to be tested for years over a range of many storm types and conditions before becoming fully operational—is that the more complex the model is the more inscrutable the results are and the more difficult it becomes to identify the condition in which computational failure is probable. It would appear, therefore, that engineering approaches to prediction and diagnostic procedures of evaluation will dominate the methodology of hurricane forecasting for a number of years to come.

References and Notes

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3. Conversion factors for units used in this article are: 1 foot = 0.3048 meter; 1 mile = 1.609 kilometers; 1 nautical mile = 1.852 kilometers; 1 knot = 1 nautical mile per hour.
4. V. F. Dvorak, *NOAA Tech. Memo. NESS-45* (1973).
5. Here we distinguish between conditions that can be identified in the real atmosphere and parametrizations of numerical modelers. Almost every diagnostic model of a hurricane has no difficulty in moving rapidly to hurricane strength, whereas only one in ten disturbances in the real atmosphere develop dangerous wind systems.
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7. R. H. Simpson, *NOAA Tech. Memo. NWS-53* (1971).
8. S. L. Ulanski, R. K. Hadlock, M. Garstang, in preparation.
9. This assumes that the height of the tropopause is conserved. If for any reason the tropopause should lower and be replaced by warm stratospheric air, the pressure would also fall. However, observations from aircraft and sounding balloons indicate that this does not occur during the development process.
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12. J. R. Hope and C. J. Neumann, *Mon. Weather Rev.* **98**, 925 (1970).
13. F. Sanders and R. W. Burpee, *J. Appl. Meteorol.* **7**, 313 (1968).
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15. The Federal Executive Board of Miami has just completed a pilot study of hurricane evacuation problems in Dade County, Florida, which recommends the use of "vertical evacuation" wherever practicable. This calls for the relocation of displaced persons into the common use areas of high-rise structures above the third-floor level for the limited period when protection is required against high winds and coastal flooding. This reduces the need for highway travel to uncertain points of safety far inland.
16. B. I. Miller, P. P. Chase, B. R. Jarvinen, *Mon. Weather Rev.* **100**, 825 (1972).
17. R. Anthes, paper presented at the eighth Hurricane Technical Conference of the American Meteorological Society, Key Biscayne, Florida, May 1973.