Hurricane Development and Movement

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Introduction

Economic losses due to hurricanes in the United States currently averages more than $800 million a year[1] and the trend over the last three decades (see Fig. 1 next page) is exponentially upward.[2] This reflects the enormous increases in construction along the hurricane-vulnerable coastlines as Americans migrate to the seashore. Over the same period the annual loss of life in hurricanes has steadily diminished. If this is a measure of increasing effectiveness of the hurricane warning service, it is also a frail statistic. There are at least three reasons: first is the increasing numbers of people directly exposed to hurricanes, many of whom have never experienced one (N. L. Frank, 1974); second, the near-plateau reached some years ago in prediction skill (R. H. Simpson, 1973) which persists despite the progress which continues to be made in understanding hurricane structure and the energy transformations which drive it (J. Malkus and H. Riehl, 1960; LaSeur and Hawkins, 1963). Finally, the great killer hurricanes are rare and comprise not only a critical challenge to the experience and wits of the forecaster (R. Simpson, 1971), but also to the formulation of the dynamic prediction models upon which he is ever more dependent each year; models which, because of a number of limiting factors described in this paper, are better able to predict the run-of-the-mill hurricane than the extreme event.

The hurricane poses a more difficult problem of modeling and of warning than do storms of temperate latitudes because most of the hurricane's destructive forces are concentrated within 20-50 miles of its center, whereas the extratropical wave cyclone has a broader more homogeneous swath of damaging winds. A small change in the hurricane track may cause a major shift in the coastal threat (see e.g., Brand and Blelloch, 1975). Thus, one of the greatest challenges in hurricane forecasting is the prediction of landfall, and most of the forecast improvement resources have been devoted to the problems of movement and landfall.

Hurricane forecasting comprises three closely related but (at present) independent prediction tasks, the failure of any one of which may vitiate the success of the others. These tasks are: (1) the prediction of movement and landfall; (2) the simulation of the storm surge[3] including inland and riverine flooding; and (3) the prediction of extreme winds and areal extent of damaging winds. Of these three, the greatest progress has been made in the simulation of storm surge profiles (Jelesnianski, 1968, 1972). The least progress has been made in predicting development or change in circulation strength. In fact, the modeling of development has been so ponderous and the initial value problem so intractable that nearly all prediction models designed for operational use seek only to forecast movement.

In the sections which follow we shall trace the progress in developing prediction techniques primarily for movement and landfall. We will examine the reasons why forecast skills have plateaued and what roadblocks must be removed before significant new improvements can be expected. However, the related oceanographic problems relating to the sea-air interface, and the hydrologic problems of flash and riverine flooding due to excessive rains are beyond the scope of this paper and are treated only inferentially.

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[1] National Weather Service, 1975: Hurricane preparedness briefing documents (slides).

[2] For a summary of the 1975 hurricane season with an illustration of storm tracks see *Mon. Wea. Rev.*, April 1976, Vol. **104** (Dollar amounts are adjusted to 1957-59 values).

[3] An abnormal rise in sea level due to the influence of hurricane pressure gradients and wind stresses on the sea.

Similar terms which are common to the vocabularies of fluid dynamicists and are essential to the discussion in this text are defined in "Glossary of Meteorology," 1959: Amer. Met. Soc., Boston, Mass.

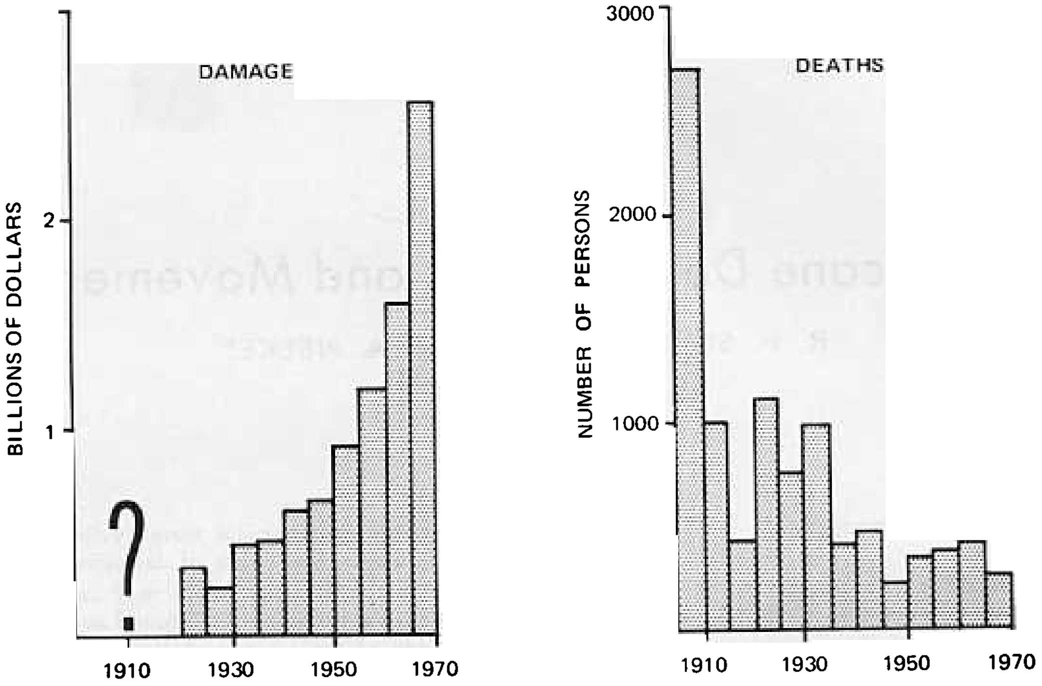

FIG. 1 TRENDS IN HURRICANE RELATED DAMAGE AND DEATHS IN THE U.S. (5-YEAR AVERAGES)

The Conceptual Problem in Predicting Movement

Before the advent of dynamic prediction models, hurricane movement was regarded conceptually as a response to a "steering current" in the environment, and the development of prediction methods sought to identify and relate the properties of a *steering level* or layer to the direction and speed of movement of the hurricane center. For example, Norton (1948) used the prevailing wind direction and speed "at the top of the hurricane" as an index to movement of the vortex. Dynamically, however, the hurricane moves as a complex response to the net forces imposed by environmental circulations interacting with the entire vortex (Beebe and Simpson, 1976). An unresolved problem is the degree to which the vortex circulation may influence its own movement.

The evidence suggests that when a hurricane circulation approaches steady state, its movement is almost wholly determined by the dynamics of environmental circulations.[4] Hovermale (1975), in his development of a new hurricane prediction model for use at the National Meteorological Center draws upon this evidence to solve the very difficult problem of initializing his model. He first removes the vortex and replaces it with one which is artificially spun up.

While further details of this procedure will be discussed in a later section, we remark here that the justification of this procedure will be severely tested in the performance of the model with hurricanes which are rapidly intensifying as they approach the coast, as in Celia (1970), Carmen (1974), Eloise (1975), and the Florida hurricane of September, 1947. In such cases the influence of the developing vortex on its own movement may turn out to be significant. If so, another means must be found to deal with the initial value problem if such sophisticated primitive equation models are to cope with anomalous movement of the "bad actor," high-risk hurricanes more effectively than the simpler barotropic or statistically founded models which can, at best, provide results of uncertain value in such cases.

The earliest conceptual model to provide objective predictions of hurricane movement was developed by H. Riehl, et al. (1956). Riehl considered that the best index to steering of the hurricane was the geostrophic flow of the environment at the level of nondivergence. Zonal and meridional components of geostrophic motion were calculated for the 500 mb surface (~5.5 km) using a large rectangular grid which enclosed the vortex. This was used as input to a regression relation based upon historic data to obtain the westward and northward displacements of the vortex for the succeeding 24-hour period. The method worked surprisingly well in a research environment but, operationally, suffered from the subjectivity of hurried hand analyses of the 500 mb geopotential fields.

During the late 1950's and early 1960's the search for methods less sensitive to subjective circulation

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[4] e.g., NOAA, 1975: "NHEML Field Program Plans—1975 (Hurricane)," p. 50.

analyses led to the use of statistical screening to identify predictors from surface charts. Veigas, et al. (1959) and R. G. Miller (1958) used a large storm-centered grid to screen for predictors of 24-hour displacements. This research produced an operational model known as T-60 (Veigas, 1961, 1962) which, despite the fact that it took no cognizance of upper-level circulations, displayed good skill with westward-moving hurricanes, and blazed the trail for development of a heirarchy of the more powerful models that followed. These included one by B. I. Miller and Paul Moore (1960), and the NHC-64 model by B. I. Miller and P. Chase (1966). The latter attempted to incorporate the better features of the work of Riehl and of Veigas, and is the foundation upon which the subsequent statistically founded methods, described in the next section, have evolved. The application of these models was primarily responsible for a significant increase in forecast skills at the National Hurricane Center in the early 1960's. (Dunn, et al., 1968).

The problem of predicting hurricane development, from tropical cyclogenesis to the extreme event with winds up to 100 mps, remains one of the most difficult and intractable problems in meteorology. As such, it is usually treated operationally as a separate problem, presently handled only through diagnostic, subjective reasoning. This deserves at least brief attention here.

Conceptually, organized tropical rain disturbances, releasing abundant supplies of latent heat, develop dangerous winds and become tropical storms only when the vertical circulation of mass succeeds in systematically storing latent heat through a deep tropospheric column. The most obvious inhibiting factor is a pronounced vertical shear of the horizontal wind which disperses the latent heat laterally (W. Gray, 1967; R. and J. Simpson, 1976).

While more than 100 tropical disturbances, sometimes called hurricane "seedlings," move westward across the tropical Atlantic each year, less than 10 percent develop sustained winds of gale force and acquire names (Frank, 1973). The numerical simulation of this process encounters difficulty in parameterizing the effect of cumulus convection, both in the disturbance and in the developed hurricane. This is largely due to the fact, demonstrated by Gray and Shea (1973), that the warm core, the heart of the hurricane "heat engine" is not generated by a simple redistribution of latent heat released by convection, but rather by a combination of adiabatic heating from downward motions associated with the convection and the release of latent heat (Shea and Gray, 1973). This combination is a much more difficult process to parameterize.

A further complication in modeling the initial growth of disturbances is currently unfolding from the results of field experiments in the BOMEX[5] and GATE[6] expeditions (Garstang and Betts, 1974; Garstang, 1975), which imply that dynamic interactions between cumulus-scale circulations and those of much larger scale in the environment supply a brake to the growth of disturbances.

The explosive development of disturbances, and the rapid growth of hurricanes into extreme events—presently beyond the reach of operational models—comprise serious problems in hurricane prediction and warning: first, because the skills of most models are at lowest ebb in cases where there are development extremes, and second, because significant changes in strength and size of the hurricane strongly influence the distribution of storm surge and tidal flooding at landfall, and hence, the need for evacuating coastal residents.

Progress with Statistically Founded Prediction Models

Statistically founded methods for predicting movement are of two types, one employing historical information whose application depends upon current observations only as regards the location of storm center and of its instantaneous movement. The second uses statistical analogs or screening techniques to obtain predictors related to circulation characteristics, usually over a scale much larger than the hurricane environment. The multivariate results are then applied to current analyses or to short-period circulation prognoses to determine hurricane displacements for successive 12-hour periods up to 72 hours.

It is interesting to note that, historically, such methods seem to begin with bold attempts to apply purely kinematic or dynamic concepts to current data to obtain a prediction, the operational weaknesses of which lead to modifications which incorporate statistical constraints. Then, as more is learned of hurricane structure and energetics, in the next generation of methods the researcher once more patronizes his urge to employ purely dynamical procedures to current analyses, only to find once again a need to apply statistical constraints or statistical processing of the dynamical data. It is interesting to contemplate whether, in connection with the development of the more sophisticated dynamical models to be discussed in the section below, this cyclical process in the sequence of prediction methodologies may now have ended.

The NHC-64 method, by far the most skillful and objective operational method used prior to 1957, was revised by B. I. Miller, et al. (1968), and became known as NHC-67. This employs predictors from the 1000- , 700- , and 500-mb surfaces and produces center positions for successive 12-hour intervals up to 72 hours. NHC-67 is still in use at the hurricane center in Miami, mainly because its predictions of northward displacement during recurvatures are more dependably skillful than from any other technique presently available. This method has been adapted for use in the Pacific by both the Japanese and the People's Republic of China.

In the late 1960's Renard, et al. (1968, 1973) developed a statistically constrained dynamical method

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[5] Barbados Oceanographic and Meteorological Experiment.

[6] Atlantic Tropical Experiment of the Global Atmospheric Research Program.

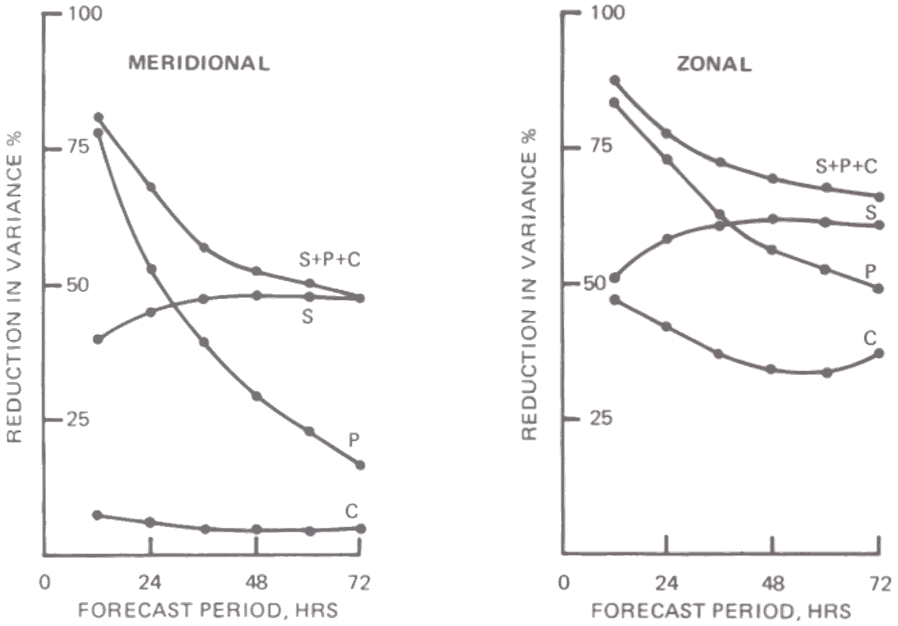

FIG. 2 REDUCTION IN VARIANCE, AFTER NEUMANN, 1975

which returned to the concept of a steering level. This method uses digital computer procedures for the analysis of standard geopotential surfaces (850- , 700- , 500- , 300-mbs) and for objectively filtering out perturbations with a scale size of 100s of km including the hurricane vortex, which is reduced to a point entity. It then moves the point vortex geostrophically in the large scale flow for a 72-96 hour period. The observed vector error in position after 12 hours of such movement is subtracted from the computed position at subsequent 12-hour intervals to obtain a track up to 80 hours in advance.

This method, which of course assumes persistence of large scale circulations, tends to work well where persistence is a good predictor, and when the correct steering level can be selected. However, because the method predicts a hierarchy of tracks—one for each standard geopotential surface—and leaves the choice to the judgment of the forecaster, and because the more difficult predictions occur when persistence is *not* a good predictor, the method has not gained wide operational use although it is still used experimentally or as forecaster guidance in some areas.

Until 1967, nearly all objective prediction models provided outputs which were essentially deterministic and offered no means for the user to evaluate the uncertainties of predicted positions. In response to a requirement of NASA for probabilistic information on hurricane tracks, Hope and Neumann (1970) developed an analog model known as HURRAN. The only current information used by this model is the direction and speed of movement the preceding 12 hours. With this initial constraint, the model computes the most probable track for a 72-hour movement using as analogs the historic tracks of hurricanes which had passed near the current position with about the same movement vector and at about the same calender date. As an additional output, it computes and constructs a family of ellipses enclosing areas in which the storm center has a 50 percent probability of residing after 12, 24, 36, 48, and 72 hours.

The remarkable skill of this purely statistical model, despite the fact it ignores the current and predicted circulations in the path of the hurricane as well as its size and strength, has encouraged its adoption as an objective tool for identifying coastal sectors which require hurricane watches. The "watch" sector is the coastal segment located between the two tangents connecting the 50 percent probability ellipses for 24 and 48 hours, respectively, as the latter ellipse passes inland. Similar analog methods have been developed by Jarrill and Wagoner (1973) for use in the Pacific and Indian Oceans.

The principal shortcoming of HURRAN and other analog methods is the limited usefulness in cases of highly anomalous movements. To alleviate this constraint, Neumann (1972) developed an auxillary method known as CLIPER which drew its predictors solely from CLImatology, and PERsistence (of past motion). The output similar to HURRAN, is a most probable track for the following 72 hours accompanied by a family of probability ellipses. In operational use it soon became clear that the combined use of HURRAN and CLIPER provided more reliable predictions of zonal movement than did any of the alternate prediction methods, while NHC-67 provided more reliable predictions of meridional movement.

Logically, the next step in procedure development was to forge a marriage of the three methods. Neumann, et al. (1972) accomplished this task, which culminated in the astonishing result illustrated in Fig. 2 (after Neumann, 1975a). This shows the reduction in variance by the predictors from *persistence* (P), from *climatology* (C), and from *circulation dynamics* (S). Predictors from persistence both for zonal and meridional movement account for larger reductions of variance than from either *climatology* or *circulation dynamics,* but the three together account for almost an 80 percent reduction for zonal movement and 70 percent for meridional movement for a 24-hour forecast. (The curious increase in variance reduction with time in curve (S) is due to several problems of initialization, including the exact location of the hurricane center).

The most recent improvement in statistical dynamical models has been the incorporation of predictors by Neumann and Lawrence (1975) (and subsequently by Neumann and Randrianarison (1976) for the Indian Ocean) from prognostic charts of 500 mb circulation for 24, 36, and 48 hours in advance of forecast time. This procedure was attempted by Veigas (1966) without success due to the poorer quality of machine prognostic charts during the early 1960's.

With the skills presently achievable with statistically founded models, especially for hurricanes with regular tracks, and with results presented in probabilistic format, *the principal challenge for the more sophisticated purely dynamical models is to predict dependably the more anomalous movements and explosive developments, and the heavy precipitation after a hurricane passes inland* which frequently generates riverine and flash flooding.

Progress with Dynamically Founded Numerical Prediction Models

As opposed to the statistical prediction models, the dynamic models of hurricane movement are developed directly from basic physical principles. These include Newton's second law of motion for a rotating earth, the first law of thermodynamics, and the ideal gas law, as well as conservation relations for mass and for water substance in its three phases. Unfortunately, since these differential relationships are valid only on a scale in the atmosphere of a few centimeters at most,[7] and because they are a set of nonlinear partial differential equations which cannot be solved by standard analytic techniques, they must be averaged over a volume corresponding to the space-time grid mesh in a numerical model. Averaging of nonlinear equations, however, introduces terms in the equations which represent the influence of the subgrid scale on the resolvable scale. In order to close the system of equations it is necessary to parameterize these terms, which is generally done by assuming the subgrid scale contributions are functions of the resolvable variables.

Current computer storage and speed restrict the minimum mesh size for a particular problem. In the case of a hurricane, the domain of the model must be several thousand kilometers on a lateral side and extend vertically at least to the tropopause in order to include sufficient coverage of the hurricane and its environment. To eliminate the need for averaging the equations one would need to describe the field of motion with a *resolution of about one centimeter*! This need grows from the reality that the atmosphere in motion cannot be described dynamically in terms of a single scale of motion. It comprises a hierarchy of motion scales ranging from the small viscous to that of the large planetary waves. Of course a resolution of one centimeter is unachievable. It would require approximately 1.4×10^{23} data points for a minimal domain of $3000 \times 3000 \times 15$ km and a computer capability that is inconceivable within current technology, not to mention the problems of initializing such a model. Even with resolutions of 10 km (horizontal) and 1 km (vertical), a hurricane model would need approximately 1.35×10^6 grid points to resolve the entire domain uniformly, again well beyond present computer capabilities.[8]

Because of this limitation, hurricane simulation has taken one of the three following approaches: (1) resolve the hurricane in detail in an idealized larger scale environment, (2) resolve the dynamics of the environmental flow and treat the hurricane as an idealized vortex, or (3) a combination of 1 and 2, where the spatial and temporal asymmetrics of the large scale flow are treated, with hurricane dynamics expressed rather crudely.

In the first category, two forms of models have been utilized—asymmetric and axisymmetric representations. In the axisymmetric model, variations in the azimuthal direction are neglected, permitting much more economical calculations as opposed to the more complete three-dimensional asymmetric simulations. As shown by Anthes, et al. (1971) and Kurihara (1975), axisymmetric versions are valid tools to investigate many aspects of mature hurricanes for a uniform large scale environment. For instance, Rosenthal's (1970) axisymmetric model demonstrated that the use of a 10 km horizontal grid provides a significantly better simulation of hurricane dynamics than a 20 km grid. Anthes (1974a) has used an axisymmetric model to demonstrate the advantages of dynamic initialization and to

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[7] A scale much larger than the molecular scale but small enough that higher order Taylor series terms in the differential relations are insignificant.

[8] Up to eight variables are needed for at least two time levels at each grid point in the numerical solution of the time dependent equations which corresponds to 2.16×10^7 computer storage locations. The time levels are determined by the incremental time steps used in the marching solution of the prognostic equation.

show that, for the idealized storm without azimuthal inhomogeneities, observations of winds and temperature near the center of the storm at low levels provide the most valuable initial data for hurricane models.

On the other hand, the asymmetric version allows the development of azimuthal variations in the hurricane flow fields. As found by Anthes (1972), features apparently related to the spiral rainbands in actual hurricanes develop due to dynamic instability in the outflow layer, and rotate cyclonically as they propagate outward from the center. Kurihara and Tuleya (1974) found a similar feature in their asymmetric model which developed near the center of the storm and propagated outward with diminishing amplitude, which they attribute to the movement of internal gravity waves. Anthes, et al. (1971) found that the development of asymmetries in the hurricane outflow is correlated with hurricane intensification.

In all of these models, the influences of subgrid-scale motions due to deep cumulus activity was found to be essential for the realistic development and sustenance of hurricanes. Anthes (1974b) presents an excellent summary of this topic as well as other aspects of the dynamics and energetics of hurricanes in idealized environments. Hurricane models in this format have been used as research tools to improve the physical understanding of hurricanes and to investigate means to mitigate their intensity (Rosenthal, 1974).

Kasahara (1959) and Birchfield (1960), developed the first models under the second category listed above. Kasahara's model assumed barotropic nondivergent motion where the hurricane vortex was subtracted from his analyzed fields, and the dynamic equations integrated forward in time. After the evolution of the steering flow, the tropical system was advected as a point trajectory. Forecasts from his model tended to deflect storms to the right of their actual paths and to slow them excessively, particularly after recurvature. Hubert (1959) attributed this error to the unrealistic flat gradients which remained after subtracting the vortex, particularly in cases where the vortex was in an area of dilatory flow. Birchfield developed a similar barotropic model, but employed a fine grid over the hurricane circulation in order to resolve some of the vortex-environment interaction. He found that truncation errors contribute significantly to the errors of predicted movement of the hurricane.

More recently, Sanders and Burpee (1968), and Sanders, et al. (1975) have developed a barotropic prediction model for operational application at the National Hurricane Center (NHC). The procedure begins by computing pressure weighted mean winds for the layer 1,000-100 mb and analyzes stream functions over a large fixed domain as input to the prediction model. The initial wind field in the vicinity of the hurricane is determined as the sum of the steering flow, derived from the best estimate of storm motion, and winds due to an idealized vortex. A horizontal grid resolution of 165 km is used. Sanders, et al., felt that this approach has a maximum achievable accuracy in storm position forecasts of 125 km at 24h and 500 km at 72h.

As contrasted with the first category, these models have been developed for operational use in predicting storm track alone. Without incorporating synoptic scale baroclinic effects and, more importantly, an effective resolution of the hurricane vortex, the crucial determination of explosive intensification and of radial alterations in storm tracks is not possible.

The third category represents the initial attempts to adequately resolve hurricane dynamics, yet retain a dynamic asymmetrical large scale flow field. The model of B. I. Miller, et al. (1972) used horizontal resolutions as small as 75 hm to predict the movement and strengthening of Hurricane Celia in 1970 and Hurricane Alma in 1962, as well as a nondeveloping tropical system. Miller found that the model was able to predict deepending (as in Alma), but not the explosive intensification observed in Celia. He attributed the error to lack of adequate resolution. Both track and intensity of Alma were well predicted. Mathur (1974, 1975) incorporated a fine mesh grid (horizontal resolution of 37 km) inside a coarser mesh (horizontal resolution. 74 km) in order to simulate the development of Hurricane Isbell in 1964. The fine mesh was centered over the storm and its vicinity, while the coarser mesh was used to represent the larger scale environment. The predicted movement and rate of intensification of the initial disturbance agreed favorably with the observations.

Krishnamurti and Kanamitsu (1973) have used the Florida State University's tropical prediction model (Krishnamurti, et al., 1973) to simulate the movement and intensity of a nondeveloping easterly wave with a horizontal resolution of 2 × 2 degrees of latitude. The solution agreed favorably with observations up to periods of 72 hours. Ceselski (1974) applied this model to the development of Hurricane Alma (1962) and, like Miller, et al. (1972), obtained excellent agreement with the observed movement and intensity. Ceselski emphasized the importance of the upper-level outflow in intensifying the system.

Hovermale (1975) is developing a model at the National Meteorological Center for operational use, which predicts dynamic changes in the synoptic environment and allows intensification of an arbitrarily specified vortex. The model domain moves relative to the earth's surface and has a horizontal grid resolution of 60 km. In the first season of testing (1975), the model predicted storm path more accurately than speed. The model appears to have a distinct advantage over the statistical models because of its finer resolution, which enables it to predict much of the observed mesoscale variations when the calculations are performed over land in a region of denser data coverage.

Jones (1976), as reported by Rosenthal,[9] is testing a meshed hurricane model with two inner grids having

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[9] Personal communication.

resolutions of 10 km and 30 km, respectively, and moving with the hurricane center, together with an outer grid of 90 km resolution which moves at a uniform speed relative to the earth. The nested grids are fully interactive and permit high resolution near the storm core, where previous work by Rosenthal (1970) demonstrated it is most needed, but retain a large domain by use of the coarser grid beyond the storm. The model has not been applied to actual situations; however, results with ideal initial conditions have been very encouraging.

Assessment of the Modeling Problems

The models in the third category represent attempts to synthesize advancements in the first two. It is in this category that improved forecasts of the anomalous hurricane and the extreme event are possible. But, as evident from the above work, both the details of the hurricane dynamics and of the larger scale flow are essential for accurate predictions. Successful accomplishment of this goal will necessitate the following improvements to the models:

1. Observational data are required with improved spatial resolution over the oceans in the vicinity of the tropical system, and at low levels near the center of storm. For the significantly asymmetric tropical system and for the developing distrubance, representative measurements at all regions in the disturbed environment may be necessary. Horizontal winds and temperatures, based on Anthes' (1974) results, appear to be of vital importance. Sea surface-temperature distributions must also be available. It is the concensus of hurricane modelers that the acquisition of these data to initialize the models is a necessary ingredient to improved hurricane predictions.
2. A more realistic means must be found to represent cumulus activity in the model-simulated hurricane and its environment. This parameterization must include dynamic as well as thermodynamic interactions if the case of explosive intensification is to be properly handled in a synoptic baroclinic atmosphere. Horizontal fluxes of heat, moisture, and momentum, not only associated with cumuli but also in the clear air, must be represented realistically in the eye-wall area.
3. The entire planetary boundary layer must be parameterized accurately for horizontal nonhomogeneous nonsteady conditions and must be coupled with the ocean. The influence of sea spray, in the region of strong winds, for instance, must be included in the boundary-layer formulations of moisture flux. Realistic topography and land-air interactions and their influence on the boundary layer must be included in order to simulate extreme events such as flooding and severe thunderstorms, which may occur after landfall (as in Camille (1969), Beulah (1967), and Agnes (1971).
4. The influence of radiational flux divergence on the dynamics and thermodynamics of the hurricane must be considered. Recent day and night infrared satellite imagery from the Synchronous Meteorological Satellite (SMS-1), for example, indicates a diurnal variation of cirrus cloud cover in a hurricane.[10]

The successful incorporation of the above physical processes into a hurricane track and development model is a many-year task, and will require contributions from the entire spectrum of the meteorological community as well as collaboration with oceanographers. Nonetheless, the pay-off in improved forecasts of occurrence, and of landfall alone for the extreme event, will make the task worth pursuing. In the near future, however, the principal use of dynamic models will be to forecast track (particularly recurvature) and the flood-producing rains which occur after landfall, where the results will be most accurate—north of about the 20th parallel in regions of denser observational data.

Summary and Outlook

The ability to achieve greater skill from statistically founded prediction models appears to hinge large upon improvements in the initial center location data. Neumann (1975a,b), in a study of errors in the probabilistic prediction methods, identified as the most important source of error the mislocation of the initial position of the hurricane (average error 38 km). This problem can apparently be overcome only by using reconnaissance aircraft with more sophisticated equipment and flight procedures than are presently available. The benefits, however, are large and he makes a convincing case for an annual potential savings of at least $5.5 million in preparedness costs alone!

Further reductions in variance for the present methods will depend upon enlarging the existing body of dependent data, or upon the acquisition of predictors which relate more explicitly to the interaction between the vortex and its environment. The latter may become possible as better means are found to apply information from satellites to this problem. The satellite is one of the few tools by which changes in hurricane strength can be frequently and effectively monitored qualitatively. However, it provides, at present, little information of prognostic worth for input to numerical prediction models, either statistically or dynamically founded.

The most important problems which must be faced in the further development of dynamical prediction models are, in our opinion: (1) the initial value problem, and (2) more accurate physical representations of the planetary boundary layer, including sea-air interaction, and of cumulus-cloud interactions with the larger-scale environment. The replacement of the real vortex with a spun-up artifice may produce realistic

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[10] Personal communication from W. Woodley. Publication in press.

track prediction under conditions of near steady state, but is unlikely to do so under conditions of anomalous movement or explosive development, *the two conditions which most need to be handled skillfully by the more sophisticated physical models.* These conditions are associated with the most dangerous warning cases and are unlikely to be handled with dependable skill, even by later generations of statistically founded models.

On the brighter side, dynamical models, which may in the future use a system of nested grids moving with the hurricane, may possibly provide sufficient resolution to represent realistically the hurricane and its environment. If so, they could show significant skill in predicting well in advance the excessive hurricane rains which occur after landfall, rains which depend mainly upon orographic and baroclinic processes and sometimes lead to heavy losses of life and property from such floods as occurred in hurricanes Diane (1955), Agnes (1972), and Camille (1969). Within reach ultimately, if appropriate means can be found to initialize the model, should be the prediction of such dangerous explosive intensifications as were observed in Camille (1969), Celia (1970), and Eloise (1975).

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