Technical Memorandum NWS NMC 70

THE BETA AND ADVECTION MODEL FOR HURRICANE TRACK FORECASTING

National Meteorological Center
Washington, D. C.
JANUARY 1992

U.S. DEPARTMENT OF COMMERCE / National Oceanic and Atmospheric Administration / National Weather Service

NOAA TECHNICAL MEMORANDUMS

National Meteorological Center
Weather Service, National Meteorological Center Series

rological Center (NMC) of the National Weather Service (NWS) produces weather or the Northern Hemisphere. Areal coverage is being expanded to include the er conducts research and development to improve the accuracy of forecasts, to e most useful form, and to present data as automatically as practicable.

NOAA Technical Memorandums in the NWS NMC series facilitate rapid dissemination of material of general interest which may be preliminary in nature and which may be published formally elsewhere at a later date. Publications 34 through 37 are in the former series, Weather Bureau Technical Notes (TN), National Meteorological Center Technical Memoranda; publications 38 through 48 are in the former series ESSA Technical Memoranda, Weather Bureau Technical Memoranda (WBTM). Beginning with 49, publications are now part of the series, NOAA Technical Memorandums NWS.

Publications listed below are available from the National Technical Information Service (NTIS), U.S. Department of Commerce, Sills Bldg., 5285 Port Royal Road, Springfield, VA 22161. Prices on request. Order by accession number, (given in parentheses).

Weather Bureau Technical Notes

TN 22 NMC 34 Tropospheric Heating and Cooling for Selected Days and Locations over the United States During Winter 1960 and Spring 1962. Philip F. Clapp and Francis J. Winninghoff, 1965, 18 pp. (PB-170-584)

TN 30 NMC 35 Saturation Thickness Tables for the Dry Adiabatic, Pseudo-adiabatic, and Standard Atmospheres. Jerrold A. LaRue and Russell J. Younkin, January 1966, 18 pp. (PB-169-382)

TN 37 NMC 36 Summary of Verification of Numerical Operational Tropical Cyclone Forecast Tracks for 1965. March 1966, 6 pp. (PB-170-410)

TN 40 NMC 37 Catalog of 5-Day Mean 700-mb. Height Anomaly Centers 1947-1963 and Suggested Applications. J. F. O'Conner, April 1966, 63 pp. (PB-170-376)

ESSA Technical Memoranda

WBTM NMC 38 A Summary of the First-Guess Fields Used for Operational Analyses. J. E. McDonell, February 1967, 17 pp. (AD-810-279)

WBTM NMC 39 Objective Numerical Prediction Out to Six Days Using the Primitive Equation Model--A Test Case. A. J. Wagner, May 1967, 19 pp. (PB-174-920)

WBTM NMC 40 A Snow Index. R. J. Younkin, June 1967, 7 pp. (PB-175-641)

WBTM NMC 41 Detailed Sounding Analysis and Computer Forecasts of the Lifted Index. John D. Stackpole, August 1967, 8 pp. (PB-175-928)

WBTM NMC 42 On Analysis and Initialization for the Primitive Forecast Equations. Takashi Nitta and John B. Hovermale, October 1967, 24 pp. (PB-176-510)

WBTM NMC 43 The Air Pollution Potential Forecast Program. John D. Stackpole, November 1967, 8 pp. (PB-176-949)

WBTM NMC 44 Northern Hemisphere Cloud Cover for Selected Late Fall Seasons Using TIROS Nephanalyses. Philip F. Clapp, December 1968, 11 pp. (PB-186-392)

WBTM NMC 45 On a Certain Type of Integration Error in Numerical Weather Prediction Models. Hans Okland, September 1969, 23 pp. (PB-187-795)

WBTM NMC 46 Noise Analysis of a Limited-Area Fine-Mesh Prediction Model. Joseph P. Gerrity, Jr., and Ronald D. McPherson, February 1970, 81 pp. (PB-191-188)

WBTM NMC 47 The National Air Pollution Potential Forecast Program. Edward Gross, May 1970, 28 pp. (PB-192-324)

WBTM NMC 48 Recent Studies of Computational Stability. Joseph P. Gerrity, Jr., and Ronald D. McPherson, May 1970, 24 pp. (PB-192-979)

(continued on inside back cover)

NOAA Technical Memorandum NWS NMC 70

THE BETA AND ADVECTION MODEL FOR HURRICANE TRACK FORECASTING

Donald G. Marks

Washington, D.C.
January 1992

UNITED STATES DEPARTMENT OF COMMERCE
Rockwell A. Schnabel
Acting Secretary

National Oceanic and Atmospheric Administration
John A. Knauss
Under Secretary

National Weather Service
Elbert W. Friday, Jr.
Assistant Administrator

The Beta and Advection Model for Hurricane Track Forecasting

Donald G. Marks
National Meteorological Center

Contents

Figures

Tables

Part I. Model Development

1. Introduction

Since G. Holland's 1983 paper, the subject of forecasting hurricane motion has taken on a somewhat more controversial tone than in the past. This is due to the changing perception of the requirements necessary to actually produce useful forecasts from dynamical concepts. Until this time, it was generally assumed that the mechanisms producing the storm motion and structure were so poorly understood as to make forecasting very difficult. Much of the work was therefore directed toward understanding not only the storm's motion, but also the structure and dynamics. One of Holland's implicit assertions was that the motion can be forecast without detailed knowledge of the structure. At the National Meteorological Center (NMC) the basic concepts in Holland's work were greatly expanded and a forecasting technique derived that utilizes the large-scale flow from a global model and applies only a modest deviation to this advection. Some details of this technique (which will be greatly expanded upon in this paper), called the "Beta and Advection Model" (BAM) are contained in Marks, (1989a).

The results from the BAM are competitive with other techniques. This is remarkable since these results are obtained while the forecast is tightly tied to the large scale flow field, in this case the NMC Spectral Model (Sela, 1980). That is, both the strengths and weaknesses of the global model will be reflected in the hurricane forecast. On the other hand, the accuracy of the spectral model is also reflected in the BAM's forecast. This paper explains some of the theory resulting in these forecasts. The model results may then be viewed as the verification of that theory. The essence of this theory is that the most important component of tropical storm motion is the large-scale advection. Of secondary importance is a flow induced by the variation in the coriolis force (i.e. the beta effect). The beta effect will add a northward motion to the storm as the storm affects the environment. The circular component of the storm rotation will add a westward motion to the storm. The storm will thus be deflected from the advecting flow towards the NW at a speed averaging around 1.5 m/s faster than the environmental flow. This merely explains conventional practice, since for many years forecasters have assumed that these storms would drift NW if they were in an area with no steering current. The reader is cautioned against a wholesale application of this observation, however. While this deviation usually determines the storm's general direction, other effects, developed later, affect the storm's speed and exact direction.

The solution of the equations necessary to forecast the storm motion is straightforward. Much of the integration is contained in the theory, so small finite difference time steps are not necessary. The equations can be analytically solved and the direction and speed of the storm motion are unchanged until the large-scale wind field changes. It is assumed here that the large-scale wind changes very little in the space of one hour and so the "time step" is one hour. The deviation is therefore recalculated only every hour, resulting in an extremely fast run time. In fact, this technique can be used in an interactive mode, with the meteorologist entering the data and looking at the forecast within a few seconds. A skilled forecaster may then run several forecasts and investigate the track sensitivity to various factors.

The results of the technique give overall average forecasts that indicate that the model has considerable skill. Comparisons will be made later, but it is safe to say that the BAM is competitive with most current operational models. It is not always the best guidance for an individual storm, or even over an entire season, but it is consistently good. It must be remembered that the BAM errors are due to a combination of both errors from the theory and errors in the large-scale model forecast. The large scale model will forecast all convection, sea surface temperatures, the land-sea boundary, any intensification/decay, and large scale divergence and vorticity. The model storm contains asymmetries that are always oriented the same direction and depend solely upon how the storm deviates from the initial, analyzed environment. These are all terms which, at one time or another, have been thought to greatly influence the storm motion at the small scale level. The fact that accurate forecasts may be obtained using these terms directly from the large-scale model does not eliminate them from future consideration, but it does help point out their relative importance. In fact, this is justification for saying that the most crucial term in hurricane forecasting is the large-scale flow. If a model does not correctly forecast this flow, it cannot consistently produce good forecasts. This is where the BAM technique excels, since it uses the NMC model specifically designed to accurately forecast this large-scale motion. The increase in accuracy in the long waves more than compensates for neglecting several smaller terms.

This report will both explain the technique, and explore the sensitivity of the model to changes in the method of calculation. The theory reveals significant insight into the motion of tropical storms. By varying the parameters in the model, the importance of several factors may be investigated. Some of these experiments will show characteristics of the spectral model, some will show behavioral characteristics of the atmosphere, and some will show areas where further research is needed in order to explain the results.

2. The Pocket Hurricane Model

A discussion of this topic would not be complete without at least a rudimentary discussion of its ancestor, the Pocket Hurricane Model (PHM). This technique was proposed by Holland (1983) but acquired its name at NMC. The technique assumes that a hurricane may be described by a modified Rankine Vortex ($V_s = CR^{-x}$, an assumption maintained in the BAM and examined further in section 5). The rate of change of the storm's vorticity is described analytically by equation (1) and the maximum rate of change defines the direction of storm motion. Storm motion is due to advection (A), the change of relative vorticity due to the beta effect (B), and some terms relating to the large scale vorticity and divergence (C). Further explanation of the terms is given in Figure 1.

$$\frac{\partial \zeta}{\partial t} = |V_B| \cos(\theta-\alpha) \frac{V_s}{R^2}(1-x^2) \qquad \text{(A)}$$

$$+\beta\{V_s(\gamma(2-x)\cos\theta+\sin\theta) \qquad \text{(B)} \qquad (1)$$

$$+R(\zeta_1\sin\theta-(2\delta_0+\delta_1)\cos\theta)\} \qquad \text{(C)}$$

where

V_s = tangential (cyclonic) wind speed (m/s)

V_B = basic (large-scale) wind speed

R = effective radius of the model

α = angle of the basic (large-scale) wind flow (counter-clockwise from north)

γ = tangent of the inflow angle

x = "shape parameter" (see section 5)

θ = angle of the storm movement

ζ_1 = large-scale zonal component of vorticity

δ_0 = large-scale meridional component of divergence

δ_1 = large-scale zonal component of divergence

If we ignore term (C) for the moment, then equation (1) defines the storm direction of motion to be due to advection, plus a small northwest deviation (westward due to the beta effect, northward due to inflow into the storm). While the BAM arrives at the terms in a different manner, the idea of advection plus a NW deviation remains the same. In a sense, both the BAM and the PHM are parameterized models, utilizing terms which cannot be directly measured, but must be inferred from the storm motion. Although the results are similar, the PHM and the BAM rely upon different philosophies of forecasting. The PHM attempts to analyze the motion that would occur if a vortex were superimposed upon a known flow field. The BAM attempts to derive a steady state balance between the vortex and the environment and then extrapolate this motion.

For either the PHM or the BAM it is necessary to analyze what effects are present in the large-scale model and what effects have to be added. This analysis is required in order to make the transition between a theoretical development and an operational product which gets information from different sources. Only certain of the meteorological terms need to be added along with the vortex. Questions raised in attempting to explain a steady state situation, while utilizing the NMC global fields, eventually lead to revisions of significant enough magnitude to justify the change of name.

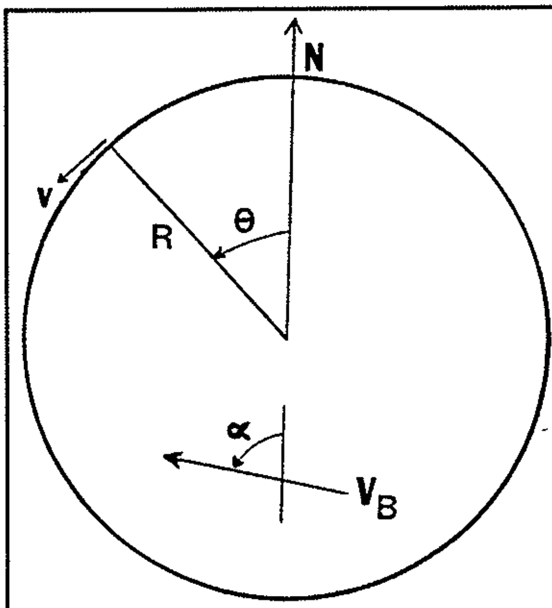

Figure 1. Coordinate system used in this paper (after Holland, 1983).
V_B = Basic (large-scale) wind

3. Beta and Advection Model

3.1 Model Equations

The equations governing the BAM forecast will first be given with only a general explanation of the terms. Later sections will provide a more detailed development of their formulation. The first assumption in the BAM system is that the storm is of a finite size and its motion is basically determined by the interactions that occur at the boundary between the storm and the environment. These interactions are shown schematically in Figure 2.

In the terminology of Holland (1983), this boundary is called the "effective radius". This is an especially appropriate description, since this parameter is not related to any real radius, as will be discussed later. The storm moves as a unit, maintaining its internal structure. It will move in that direction where the relative vorticity is increasing the fastest (on the average, for the entire storm). The storm is assumed to be in a steady state condition, with no changes of intensity. The steady state assumption allows us to define a constant secondary flow, toward the northwest, which is added to the large-scale advecting flow. It is assumed that the absolute vorticity is symmetric, but the relative vorticity and wind fields are asymmetric. These asymmetries affect the storm direction and speed. Using all these conditions, which will be explained later, the equations to be solved become:

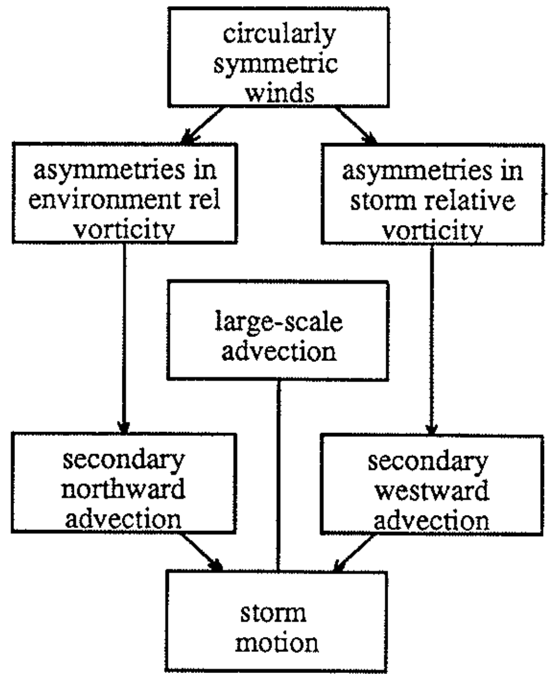

Figure 2. Schematic diagram showing influences upon the storm.

$$\frac{\partial \zeta}{\partial t} = (|V_B| \cos(\theta - \alpha) + |V_N| \cos(\theta + \gamma') \qquad (2)$$

the angle of the storm motion (θ) is where ($\partial\zeta/\partial t$) is a maximum.

and speed $= -(\partial\zeta/\partial t)((\overline{\partial\zeta}_B + \overline{\partial\zeta}_A)/\partial R)^{-1}$ (3)

where

γ' is the inflow angle

V_N is the secondary flow to the north

V_W is the secondary flow to the west

$\overline{\frac{\partial \zeta_S}{\partial R}}$ is the average change in relative vorticity of the symmetric part of the storm

$\overline{\frac{\partial \zeta_A}{\partial R}}$ is the average change in relative vorticity of the asymmetric part of the storm

Essentially the same deviations may be obtained by setting $\gamma = \tan(25^0)$ in equation (1), although the radius changes considerably. The values of V_N and V_W are explained in the next sections. These components typically are 20% of the advecting wind and advect the entire storm in the same way as the global wind. The exact magnitudes of V_N and V_W are not as important as the relative magnitude and hence the angle of the deviation. Reasonable assumptions lead to deviations between 295^0 and 315^0, a range of values that will take on added meaning in sections 7-10. These equations have evolved over several years and it is worthwhile to investigate just how some of the variables affect the forecasts.

3.2 Comparison with the Pocket Hurricane Model

The BAM and the PHM share a common heritage and have very similar results. In the BAM model, the advection term from the PHM is retained (term A of equation 1), the beta effect (term B) is evaluated assuming a steady-state condition (and hence can be incorporated into advection), and the large-scale effects (term C) are assumed to be present in the global model forecasts and so are not reproduced explicitly. Some comparisons between the PHM and the BAM are shown in Table 1.

TABLE 1

Pocket Hurricane Model results. The PHM results obtained at NMC, and the BAM forecast for the identical cases. (number of cases in parentheses, mean vector errors in nautical miles).

forecast hours	PHM	BAM
12	50	47(95)
24	91	84(91)
36	128	119(78)
48	174	162(67)
60	241	204(57)
72	271	229(25)

It is evident from the table that the BAM formulation enjoys a considerable edge as far as forecast accuracy is concerned. Since the BAM's most important terms are very similar to the first two terms of the PHM, it appears that the large-scale divergence and vorticity terms would not improve the BAM forecast accuracy. This does not mean that the original analysis was erroneous, rather that the terms are already included in the NMC global forecast. This insensitivity of storm motion to large-scale divergence was noted by Shapiro and Ooyama (1990). Including term (C) of equation (1) in either the PHM or the BAM does not impact the forecast to any significant degree.

It was also necessary to provide a more satisfactory technique of turning the storm northward than was explained in the Pocket Hurricane Model. In a quiet atmosphere a non-divergent storm would move straight west according to equation (1). Yet Anthes (1982), Adem(1956) and Fiorino (1987) have all postulated that the storm would turn north as a result of the beta effect. These authors all deal with the non-linear aspects of the beta effect, an aspect that is not covered in either equation (1) or equation (2). At best, the BAM and PHM can be regarded as obtaining a linear approximation to these non-linear effects. Holland properly states that the northward motion is due to an additional effect that is developed in the large-scale flow. Usually, however, the NMC model does not have high enough resolution to develop this northward flow. Indeed, because the northward drift is due to the effect of the storm upon the environment, if the model could forecast this effect, it could also forecast the storm movement. The PHM compensates for this problem by using large inflow values (γ). The BAM, however, estimates the value of the northward flow that should be in the model and adds it to the forecasted large scale flow.

3.3 The Beta Drift

The treatment of the so-called "beta drift" or "beta effect" requires a refinement of our perception of storm motion. There are different points of view regarding the dynamics of hurricane motion. One view is that the storm is an entity, and maintains its integrity throughout the motion. The other view, expressed by Willoughby (1987), is that it is a wave structure, and the storm moves as the energy center moves. These viewpoints are variations of the barotropic/baroclinic debate, and tropical storms contain aspects of both mechanisms. The view taken here is a combination of the two. There seems to be an actual, physical storm that is advected "as a cork in a stream", but there is also a mechanism that modifies this motion. That is, once the storm has formed, it is a physical entity that cannot be ignored, but there also is a disturbance that exists along with the storm, but not necessarily coincident with it, that affects the environment. Hurricane Gilbert in 1988 showed both effects. There were reports of African insects falling on Caribbean islands (confirming the "cork in a stream" theory). However, the storm was moving faster than the environmental flow (requiring a "wave" treatment). The treatment of the northward drift requires a wave viewpoint. One can imagine that a storm circulation suddenly is superimposed upon the environment. This causes somewhat different reactions than simple advection would produce. This can be thought of as being due to baroclinicity, the twisting term, stretching term, or differential vertical advection. Virtually any situation where the storm is moving faster, slower, or in a different direction than the advecting wind will result in a northward "Beta Drift" effect.

3.4 Northward Motion

It has been shown by Fiorino (1987) that the superposition of a vortex upon an otherwise balanced atmosphere quickly leads to northward motion of the vortex. As the storm moves into an area previously unaffected by it, it advects environment air from the north side of the storm over to the west side (see also Anthes, 1982). This is represented in term (B) of equation (1) as: $V_s \sin\theta$. There is thus a build up of cyclonic vorticity to the west and a concomitant buildup of anti-cyclonic vorticity to the east of the center (Figure 3). These two vorticity maxima then induce a wind which advects the storm center northward. This flow is not represented by the large scale flow and needs to be added to the formulation to properly forecast the movement.

This discussion is, strictly speaking, only valid for the air that is entrained by the storm. This air will initially have relative vorticity only from the large scale flow, and any change in wind flow due to large scale vorticity advection will have been taken care of by the large scale model. The storm, not being in the large-scale flow, and the resultant secondary circulation both need to be added to the large-scale flow.

If we assume a non-divergent, quiet atmosphere, any change in relative vorticity is entirely due to the beta effect. However, it is evident that, over a long period of time, $\frac{\partial \zeta}{\partial t} = \beta V_s \sin\theta$ would lead to an inordinately large increase in vorticity. A more realistic interpretation is that this is a manifestation of the conservation of absolute vorticity, a concept going back at least as far as Rossby (1940). As such, the relative vorticity will increase only until the absolute vorticity is constant along the streamline. So this portion of equation (1) will be zero when:

$$\frac{\partial}{\partial y}(\zeta_E + f)V_s\sin\theta = 0$$

or,

$$\zeta_E = \beta R(1-|\cos\theta|) \quad \text{for} \quad 0<\theta<\pi \qquad (4)$$

where ζ_E is the increase in relative vorticity traveling from point B to point C of figure 3. Figure 3 shows a model of these vorticity and wind changes. The wind circulation pattern corresponding to this vorticity has a net northward component over the area of the storm. There are thus two "gyres" developed which will tend to move the storm northward.

The average northward "wind" exerted upon the storm is going to depend on the integral of the northward components over the area of the storm. At this point, we are only dealing with the environment vorticity, outside the storm. The vorticity inside the storm is described later.

If the induced wind is assumed to depend linearly on the distance across the storm, (R sin θ) then the average northward wind in a horizontal cross section of width dy, (0<θ<90°) will be:

$$\overline{V_{x'}} = 2\int_0^{R\sin\theta}\beta R(1-\cos\theta)\,dx/2R\sin\theta = \beta R(1-\cos\theta)$$

and the magnitude of the average over the entire storm will be

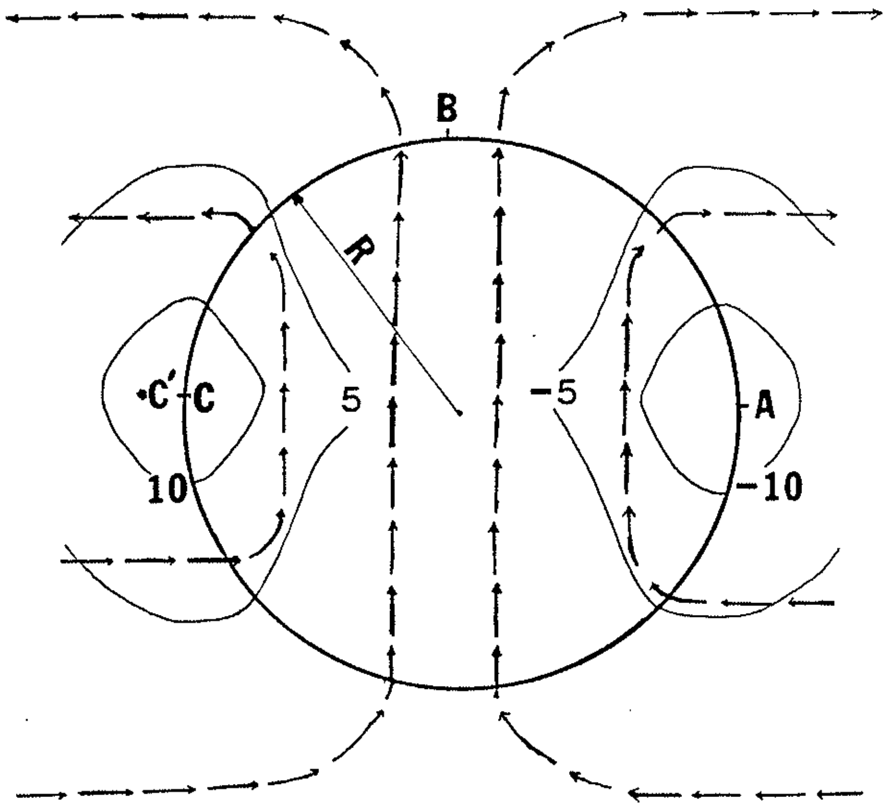

Figure 3. Background asymmetries. Schematic of the asymmetric changes to the background model's relative vorticity field due to the addition of a circularly symmetric vortex (in arbitrary units, solid lines). Circulation (dashed lines) induced by such a vorticity pattern. Vorticity values are calculated inside R only for consistency, wind fields do not depend upon R.

$$|V_x| = \left(\frac{1}{\pi}\right) 2\int_0^{\pi/2} \overline{V_{x'}} R \sin\theta \, d\theta = \beta R^2 \left(\frac{2}{\pi}\right) \tag{5}$$

The wind in equation (5) is a new circulation acting on the storm that was not developed in previous formulations. Of course, the effect of the storm's inflow (outflow) will change the direction of this wind and the resultant wind will have both a northward and a westward component, vis,

$$\vec{V}_A = |V_x| \sin(\gamma') \vec{i} + |V_x| \cos(\gamma') \vec{j} \qquad (6)$$

where $\gamma' = \arctan \gamma$

A discussion of the effect of inflow in changing the orientation of these gyres is contained in Holland's paper.

3.5 Westward Motion

Real tropical storms move westward faster than the advecting flow (see Section 9 for further evidence). This is actually a larger effect than the northward drift and is due to steady state asymmetries forced by the variable coriolis force.

The storm cannot be represented by a structure that is symmetric in both the wind field and the vorticity field. This is also due to the principle of conservation of absolute vorticity. Using a barotropic model, Shapiro and Ooyama (1990) showed that absolute vorticity was nearly constant in the innermost 350km around the storm (a typical value for the effective radius). The cyclonic relative vorticity will therefore increase to the south and anticyclonic relative vorticity will increase to the north of the center. This construction of the storm comes from the "entity" viewpoint, not the "wave" viewpoint. So in this section it is convenient to visualize the storm as a fluid in constant rotation, not affecting the environment. The storm vorticity will therefore be of the form

$$\zeta_A = -\beta R\cos\theta$$

This is the asymmetric part of the storm itself whereas equation (4) describes an asymmetry induced by the storm on the large-scale flow. A storm of this structure will have constant absolute vorticity at all points of a constant radius (see Figure 4). The reader is referred to Willoughby (1987) for a further discussion of this structure. This relative vorticity dipole (or gyre) will induce a large-scale wind field in an analogous way that the northward wind was produced. This wind, however, will be toward the west. Developing the equation analogous to equation (5) for the E-W wind reveals that the wind is equal in magnitude to the N-S wind. So

$$\vec{V}_c = -|V_x|\cos(\gamma')\,\vec{i} + |V_x|\sin(\gamma')\,\vec{j}$$

Thus the secondary circulation, induced by symmetric rotation on a spherical earth, will be toward the Northwest

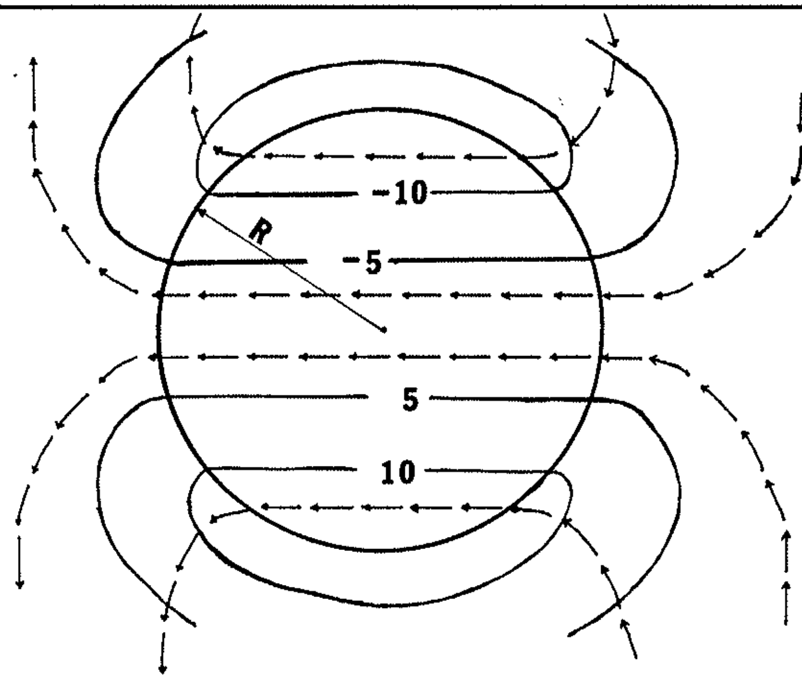

Figure 4. Storm asymmetries. This figure shows the asymmetric portion of the relative vorticity field (inside the effective radius) produced by the beta effect for circularly symmetric rotation. Also shows schematic representation of the wind field induced by such asymmetries (all values in arbitrary units). Vorticity values are calculated outside R only to avoid a discontinuity, wind fields do not depend upon R.

(315°) at an amplitude of:

$$| V_I | = \sqrt{2} |V_x|$$

This direction is modified only slightly by convergence (divergence) into (out of) the storm, since γ is small. Section 7 shows the effect of varying this development. This is the induced secondary circulation which must be added to the large-scale flow to properly predict the storm motion.

The direction of the secondary circulation after allowing for inflow is $(\pi/4-\gamma')$. The projection of this influence in the direction θ is therefore $|V_I|\cos(\theta-\pi/4+\gamma')$ in a manner exactly equivalent to the large-scale advection. This is, after all, a component of the large scale advection, and it differs solely due to its direction.

The existence of these "steering gyres" has been noted by several other authors, most recently Shapiro and Ooyama (1990), who use a barotropic model to generate asymmetric effects. The circulation developed is remarkably similar in orientation to a combination of Figures 3 and 4. The gyres reach a maximum at 600km, a value that is also reasonable from the BAM development. As in the BAM development, these gyres are independent of direction of motion. Herein lies the power of the BAM technique, much of the deviation from advection is constant for all storms. Fiorino and Elsberry (1989), also develop gyres, but they are oriented East and West of the storm, yielding a more northward deviation to the motion. This seems to contradict previous observational studies (Holland, 1984) as well as the results of this study (see Part II, Section 8, Table 12) that show a more substantial westward motion.

4.0 Implications for Numerical Model Spinups

Many numerical models such as the MFM (Hovermale et. al., 1977), and the QLM (Mathur and Facey, 1985) use the technique of a "spinup" to get the model started. In most cases, there is not enough data available to analyze a tropical storm properly, so a numerically generated vortex (with a symmetric wind field) is superimposed upon the analyzed, or forecast, environment. Once such a well defined vortex is implanted, the fine mesh, primitive equation model can then forecast the motion of the storm.

This section analyses some of the impact such a spinup has upon the model prediction. The questions addressed are basically ones concerning the initialization technique, not the atmosphere or even the model behavior. The intention is to show that the structures developed in Section 3 should be included at initialization time for numerical models. Some of the development from Section 3 is repeated for clarity. The arguments are admittedly linear estimates to highly complex processes. The implicit assumption is that, at the very least, the linear effects must be modeled correctly in order to achieve proper performance.

A wind-symmetric vortex is usually created by running the model in a 2-dimensional (x-z) plane, and then "rotating" the resulting fields about the z-axis. Both the MFM and the QLM initially suffered from an anomalous northward motion whenever such a symmetric spinup was used. The MFM changed its initialization technique to deal with this problem, using an asymmetric vortex, formed by running the model for 24 hours (forecast time), in a quiet atmosphere so as to develop the asymmetries. Since generating such a 3-D spinup required considerable computer resources, a library of these spinups were generated, one for each five degrees of latitude. The MFM then interpolated to the desired latitude. Some improvement was noticed with this technique. However, this meant that the spinup storm did not resemble the real storm, indeed, all MFM spinups differed only by the beta effect due to latitude. The QLM, on the other hand, returned to the symmetric storm formulation in order to match the spinup with the actual storm size and structure, and to avoid interpolating to the latitude. The QLM thus avoids some problems, but encounters others.

The technique presented here attempts to retain the benefits of linking the model storm with the real storm, while avoiding the inconsistencies in the MFM method. That is, the model spinup should be derived from the real atmospheric storm, but it should also contain asymmetries consistent with a variable coriolis force as were developed in Section 3. The use of a wind-symmetric vortex is equivalent to accepting the "wave" viewpoint for 100% of the motion during the first few hours of the forecast. Even an elementary linear examination indicates that the beta effect acts on a wind-symmetric spinup to cause a hurricane forecast model to forecast an erroneous northward movement during the first 12 hours of the model forecast, followed by a turn to the west. The substitution of a vortex that has a symmetric absolute vorticity field (but an asymmetric wind field) dramatically improves the forecast for typical cases.

4.2 Description of the effect

To describe what is happening, we will assume that a vortex with a circularly symmetric wind field is added to a flow field where there is currently no indication of such a circulation. We will eliminate from consideration all those variables except the one suspected of causing this northward bias. Under such idealized conditions, it may be possible to determine the cause and extent of this phenomena.

As in previous sections, we assume that the storm motion can be described by the divergent barotropic vorticity equation.

$$\frac{\partial \zeta}{\partial t} = -\vec{V}\cdot\nabla(\zeta+f) - \omega\frac{\partial \zeta}{\partial p} - (\zeta+f)\nabla\cdot\vec{V} + \vec{K}\cdot\left(\frac{\partial V}{\partial p} X \nabla\omega\right) + \vec{K}\cdot(\nabla XF) \qquad (7)$$

The storm will go in that direction where the change in vorticity is a maximum.

Now, assume we are dealing with a quiet, non-divergent, frictionless atmosphere. Onto this quiet atmosphere, we superimpose a symmetric vortex described by: $V_s = C/\sqrt{r}$ where V_s is the tangential wind, r is the distance from the center, and C is a constant. We also ignore the tilting term and the azimuthally symmetric terms ($\partial\zeta/\partial x$, $\partial\zeta/\partial y$) which, as Holland (1983) states, "may cause an expansion or contraction of the vortex rings surrounding the cyclone but cannot contribute to their net translation". These assumptions basically reduce the motion to that due to the variation of the coriolis force (the beta effect). Then the direction of motion of the storm reduces to:

$$\frac{\partial \zeta}{\partial t} = -\vec{V}\cdot\nabla(\zeta+f) = -v\beta = \beta V_s(\sin\theta) \qquad (8)$$

where θ is the angle of motion, measured counterclockwise from north. Since the maximum for equation (8) occurs at θ=90°, the storm moves straight west. The speed of the storm is obtained by dividing by the rate of change of vorticity in the direction of motion, or:

$$speed = -\frac{\partial\zeta/\partial t}{\partial\zeta/\partial r} \tag{9}$$

The wind structure and the definition of vorticity, yields,

$$\frac{\partial\zeta}{\partial r} = -\left(\frac{3}{4}\right)\left(\frac{V_s}{R^2}\right) \tag{10}$$

We can substitute equations (8) and (10) into (9) to get the speed of the westward motion. A typical case has V_s=17 m/s at R=200km, giving:

$$Speed = -\frac{4}{3}\beta R^2 \sin\theta = 1.15 m/s \tag{11}$$

So the storm moves west and, under the assumptions outlined, this motion is a constant, independent of time.

Now, let's examine the relative vorticity at a point 200km west of the storm center after 6 hours (called point C in Figure 3). Assume that beta = $2.15X10^{-11}$. Since the storm has moved 25km during that six hours (1.15m/s for 6 hours), at the initial time, point C was 225km away from the center (point C' in Figure 3) and had a tangential wind of 16m/s. If we calculate the change in relative vorticity due to beta for the average wind at the point C ((16m/s + 17m/s)/2) then

$$\delta\zeta = \int_0^{6\ hours} \frac{\partial\zeta}{\partial t}\,dt = \int_0^{21600sec} (16.5)(2.15x10^{-11})\,dt = 7.66x10^{-6}$$

and similarly for the point to the east of the center. The vorticity and wind are related by:

$$\zeta_r = -\partial u/\partial y + \partial v/\partial x$$

So, if we consider a horizontal line through the center of the storm, $\partial u/\partial y = 0$ and the average relative vorticity between the center and the easternmost point is approximately $(7.66x10^{-6})/2$. The wind appropriate to this vorticity pattern (as shown in Figure 3) may be found by integrating the vorticity in the x-direction:

$$\delta v = 2\int_0^{200km} \delta\zeta dx = 1.5M/S \qquad (12)$$

which is a northward motion.

This approximates the average northward wind over the area of the storm, which would be generated by the model. The northward motion generated by the beta effect is therefore larger than the westward motion after only 6 hours. The northward motion will continue to increase indefinitely since it is a function of time. Thus, the "beta effect", if handled in this way, can impart an infinitely strong northward motion to the storm. Obviously, neither the real atmosphere nor the model allows this type of unlimited acceleration. This effect seems to take place during the first 12 hours of the model forecast, until compensating forces are established. It appears that a symmetric spinup does not (at least initially) have the proper compensating forces. It is possible, however, to evaluate those forces and include them in the initial conditions.

4.3 The Westward Motion

The above effect is not real, but is an initialization problem caused by using a wind-symmetric vortex in the spinup. The error in the analysis becomes clear if we remember that absolute vorticity should be conserved, not earth vorticity. At the initial time, the relative vorticity is symmetric and therefore drops out of equation (7). However, within a short time the relative vorticity is no longer symmetric and must be included in both equations (7) and (8). Thus the relative vorticity at any point can only increase until the change in relative vorticity in the N-S direction is equal and opposite the change in earth vorticity, i.e. if,

$$\frac{\partial \zeta_r}{\partial n} = -\beta$$

then,

$$\frac{\partial \zeta_r}{\partial t} = 0$$

This means that the relative vorticity reaches a steady state when:

$$\zeta_r = -r\beta\cos\theta$$

This is the pattern shown in Figure 4.

The average relative vorticity along a vertical line through the center is then:

$$\overline{\zeta_r} = -R\beta/2$$

and a westward wind may be calculated by integrating vorticity in the y-direction:

$$\delta u = -2\int_0^{200km} \delta\zeta dy = -0.86m/s \qquad (13)$$

This is the correct formulation and should be included in the spinup. Since the effect is caused by actually moving air around in a circle, the time necessary to reach this steady state can be approximated by the time it takes a parcel of air, in the storm, to traverse the distance from the northernmost point to the southernmost point. Again taking the radius to be 200km, and the wind speed to be 17m/s, this time is 10.3 hours.

In a numerical model, the net result is even more pronounced than indicated here. The change in vorticity for point C will occur at the rate, $\frac{\partial \zeta}{\partial t} = V_s \beta$ and hence the maximum value will be obtained rather quickly. This result is documented by Fiorino (1987), and by Chan and Williams (1987) who noted that this term was capable of only slightly moving the center of the storm. As the maximum is approached, the rate of change goes to zero and the westward motion of equation (11) is reduced, the westward motion shown in Figure (4) and equation (13) has not developed yet, leaving only the northward motion of equation (12). The model will move the storm north initially, followed by a gradual turning to the west. The model is handling the beta effect properly, it is simply the unbalanced initial vortex that generates the northward motion until a balance is obtained.

4.4 Proposed Changes

The question now arises as to how to rectify this situation. The answer, of course, is to add the vorticity pattern shown in Figure 4, with a west wind over the area of the storm to the symmetric wind pattern currently used. This is the pattern that would be generated if a three dimensional spinup were used instead of a symmetric (2-dimensional) one. The asymmetric relative vorticity at point (r,θ) can be described by:

$$\begin{aligned} \zeta_r &= -r\beta\cos\theta && \textit{for } 0<r\leq R \\ \zeta_r &= -r\beta\cos\theta(2.0-r/R) && \textit{for } R<r\leq 2R \\ \zeta_r &= 0 && \textit{elsewhere} \end{aligned} \tag{14}$$

Since relative vorticity cannot be added directly to the initial fields, it is necessary to generate wind fields that yield an equivalent relative vorticity change. If the large-scale fields contain no circulation, equation (14) should be applied over the entire area influenced by the spinup. The specification of the relative vorticity outside the area of influence only provides a smooth transition back to the background flow. The winds that correspond to this vorticity pattern can be calculated by relaxation, setting the winds at the boundaries to zero, in exactly the same way that heights are calculated from winds. This wind field is then added to the symmetric wind field to get the initial vortex. This change should be applied to all layers showing cyclonic circulation. Air parcels on circular trajectories will then experience relatively little change in absolute vorticity and erroneous motions will not be generated. The determination of R is straight-forward. It is the radius of the spinup used.

Several tests have been run using this technique at NMC. As an example, Figure 5 shows the forecast track, for a case using both a symmetric and an asymmetric spinup. The model used was the QLM. The improvement in the first 12 hours is dramatic. The model behaved exactly as the theory predicted. With the asymmetric vortex, the storm immediately moves west along with the large-scale flow. The 12h forecast error is reduced from 142 nautical miles to 30 nautical miles, the 72h forecast is reduced from 257 nautical miles to 114 nautical miles. It is interesting to note that the vorticity pattern of Figure 4 does not simply increase the westward motion, it decreases the northward motion. This reduction of northward motion and increase in westward motion was evident in all cases. For those cases where the QLM initially started the storm moving in the right direction and speed, it is theorized that the large scale flow already contained a circular flow.

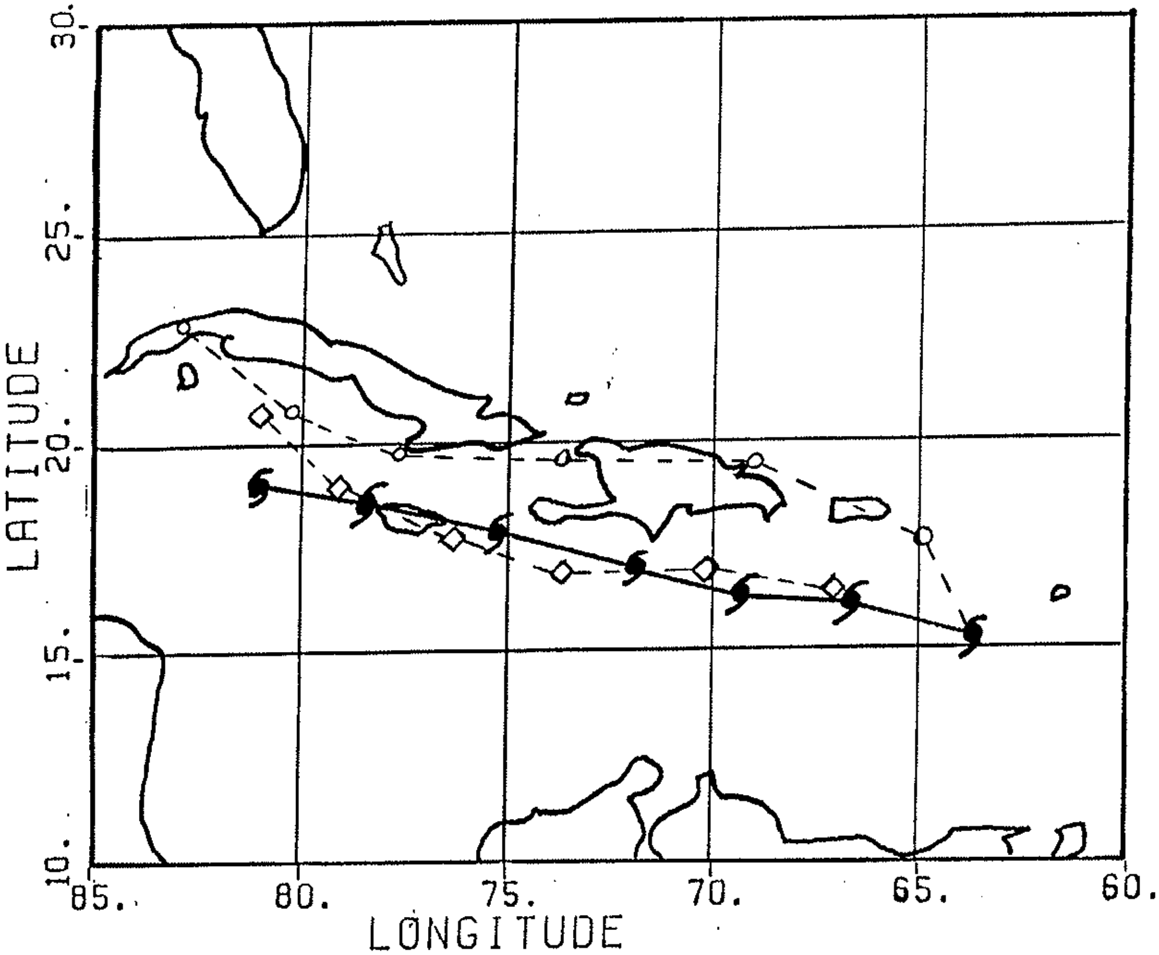

Figure 5. Gilbert 88/9/10/00z.
- Observed track
- QLM forecast with symmetric spinup
- QLM forecast with asymmetric spinup

Note that, if the large scale model already represents the circulation, it will also have generated the vorticity asymmetries. In these cases, the spinup storm adds to an already existing structure and may actually move south until the proper magnitudes are restored. Additional experiments are necessary to explicitly define when additional asymmetries are required or are already present.

It was not expected that the longer forecasts would be affected, but they also have been improved substantially. The problems in the model or the large-scale flow field that eventually turned the forecast northward are still evident. They are not as serious since the initial error has been reduced, however. This may have been a fortuitous case, of course. In fact, since this case did not have a "quiet atmosphere", other factors may have caused the errors evident in the symmetric case. However, the only difference between the two forecasts was the added asymmetries in the spinup. It is thus evident that asymmetric spinups may produce significantly different forecasts than symmetric ones.

4.5 Summary

The analysis of the impact of using a wind-symmetric spinup to initialize a hurricane model indicates that, in the absence of other factors, 1) the model storm initially moves slowly west for perhaps 1 hour, 2) the storm rapidly turns north and picks up speed, and 3) finally, at about 12 hours, the motion stabilizes in a westward direction. The theorized reason for the stable westward motion is the development of asymmetric gyres caused by the beta effect. The solution to the spurious northward motion is therefore to add these gyres to the initial symmetric vortex.

It is always difficult to draw conclusions from a theory and a few cases, and modifications to the technique may have to be made for northward moving storms and for storms already represented in the large scale flow. However, the technique holds promise for significant improvements to other numerical models that use similar methods. A more thorough understanding of this effect may enable us to define situations where this is appropriate and also lead to better understanding of hurricane dynamics in general.

PART II. Test Results

As with any new model or theory, it is necessary to perform enough tests to establish feasibility. To do this, the global wind fields for a number of cases have been saved at NMC to test new formulations of the model. Since NMC is primarily an operational center, it is difficult to archive enough cases in a short period of time to make extensive tests. The test cases used in this study were selected over the years 1984-1988. They were designed to be independent cases, with no two cases being within 36 hours of each other. Naturally, the most interesting cases tended to be selected (Elena, Kate, Gilbert, etc.) along with cases where the storm was still viable after 72 hours. The data set containing the cases may, therefore, not be entirely random, although cases from all oceans were included both in their own right and because they happened to occur on the same day as another storm. Since the entire global wind fields are saved, some days were selected to give several cases with only one archive. There are now over a hundred and fifty separate storms, of all descriptions, available for testing. Some of these are only valid for short forecasts, however. The speed of the model allows changes to be made, a job submitted to the computer, and the 120 forecasts (each out to 72 hours) to be made and verified, all in the space of about 2 hours (less on evenings and weekends). It is unfortunately true that not enough data was saved for some of the cases, (i.e. not all the levels were saved) thus limiting the scope of some of the experiments. However, to save everything would have meant many fewer cases.

In the following discussions, comparisons on the same table or graph have only one difference between the forecasts, namely that parameter being investigated. However, this is an operational, dynamically changing model and not all experiments are relative to the same initial set of parameters. Once some parameter has shown itself to improve the average forecast, then that parameter tends to be used in the model from then on, and future experiments must show an improvement from this new configuration. Thus comparisons on a single graph are valid, but comparisons between different graphs are not necessarily justified.

5. Storm Structure

One of the first things to investigate is how the storm structure affects the storm movement. The initial description of the storm structure, from Holland (1983) was that of a modified Rankine vortex,
where

$$V_s = C/R^x$$
$$U_s = -\gamma V_s \qquad (15)$$

C = a "strength parameter"

x = a "shape parameter"

V_s = the (symmetric) tangential wind velocity

U_s = the radial velocity

γ = the tangent of the inflow angle

The structure of the storm inside the radius of maximum winds is not defined or used by the model. In fact, equation 14 only really needs to hold at the effective radius. Given two winds at two known radii, it is possible to solve equation (15) for both x and C. If the radius of the 25 m/s wind is 200km, and the radius of 17 m/s wind is 400km, then C=20583 and x=0.55.

It was discovered, however, that choosing x=0.5 actually gave better forecasts than could be obtained by solving for x from the observation. So,

$$V_s = C/\sqrt{R} \tag{16}$$

The results of a comparison between the calculated value of x, and the constant x=0.5 are shown in Table 2. Overall, the choice x=0.5 is slightly superior to the calculated value. This requirement that x=0.5 is an altogether reasonable one. In fact, Riehl (1963) derives this relationship based upon the conservation of potential vorticity and the usual assumption that the surface stress is proportional to V^2. In addition, since hurricane flow is usually cyclostrophic, we know:

$$\frac{V^2}{R} = -\frac{1}{\rho}\frac{\partial P}{\partial R} \tag{17}$$

but if $V^2 = C^2/R$

then $P = \frac{constant}{R} + k$

Such a hyperbolic pressure-radius distribution is similar to several used over the years by various researchers including

TABLE 2
Results of running the BAM model, calculating the variable x from the observed radius of gale force winds versus using a constant. Mean vector errors in nautical miles.

forecast hour	Calculated x	x=0.5	number of cases
12	50	49	94
24	94	90	89
36	139	133	78
48	182	184	67
60	239	239	57
72	322	304	25

Kurihara and Tuleya (1974). For such a field, the only possible path which conserves angular momentum is a circular one.

These results lend additional credence to the technique of considering the flow as two components, one radial, one tangential. Some implications of this circular path have already been investigated in Section 3.4. Any inflow (outflow) is due to the superposition of another force (i.e. friction), not the pressure force. It should be remembered, of course, that x=0.5 is an empirically "discovered" value, as well as a theoretically derived one. It is very gratifying that this value is consistent with so many observations and hurricane principles.

In addition to the theoretical reasons for choosing x=0.5, a basic reason for the result is that the observations in the vicinity of a hurricane are far too sensitive to transient fluctuations to be used to solve for parameters used in a steady state type of model such as the BAM. Utilizing calculated values of x accepts one of these transient values and then fixes it throughout the length of the forecast. This is more likely to cause harm than good. This is pointed out even better in Table 3, where the calculation of both x and C leads to disastrous results, worse than is obtained by calculating each while holding the other constant. Thus errors introduced by calculating poor values for x are made even worse by calculating poor values for C.

TABLE 3

Influence of the Strength Parameter "C". Comparison using an average value of C (C=7460) vs. calculating C from observations, (5500<C<9000, x=0.5). (Use of C=7360 produces same average statistics as C=7460). The forth column shows results of calculating both C and x, with 0.2<X<0.8. (mean vector error in nautical miles)

forecast hour	C=7460	Calculated C	Unrestricted C and X	number of cases
12	49	49	70	119
24	88	89	141	116
36	121	121	191	99
48	168	168	257	88
60	210	210	311	75
72	244	247	386	43

A more unexpected result was the fact that C can also be fixed, irrespective of the storm observations. Once x is assumed to be constant, only the radius of the outermost winds are necessary to calculate C, and it was expected that these would be quite accurate. However, using a mean value for C actually produces better overall forecasts. These results are also shown in Table 3. The best average value for C discovered so far is C=7460. This gives a value for the wind of almost 34 knots at 100 nautical miles from the center, in effect, using a climatological storm size. Small changes in the value of C do not have a big effect upon the forecasts. One possible explanation for this behavior is the fact that, in the model, C must remain constant throughout the 72h forecast whereas in the atmosphere C changes with the storm size and intensity during this time.

This is a significant observation, since it has become conventional wisdom that the size of the storm impacts its motion. Several studies, including this one (see also DeMaria 1985) have concluded that model response is sensitive to storm size. The connection between a model and a real storm is a tenuous one, however. The author knows of no study showing such a relationship to real atmospheric storms. In fact, none of the statistical models developed at NHC use the storm size as a predictor (Neumann, 1979). These results indicate that the outermost radius of strong winds has very little real impact on the real storm motion. This topic will be examined further in Section 10, where real data, (not from the model) are examined. At this point it is sufficient to note that: for the Beta and Advection Model, the forecast error is not a function of the size of the real storm. As long as the value of C is reasonable, the forecast is affected very little. Larger atmospheric storms do not necessarily lead to larger model storms, and larger atmospheric storms are neither easier nor harder for the model to forecast. In the model, the size, or effective radius, is indeed the most important parameter of forecast motion. However, this is a function of the storm movement, not the storm size. It is not clear at this time exactly what the effective radius means in terms of real storms.

These results are potentially of great importance for numerical modelers. If forecasts of this accuracy are possible using such a simple, analytic description of the wind field, why spend great amounts of time initializing a vortex for a numerical model? Both the asymmetric effects discussed in Section 4, and the symmetric portion (equation 16) could be combined to analytically define the spinup vortex. Some results for the MFM initialization have been presented by Marks (1987). In these experiments the symmetric wind structure (equation 16) was blended with other, 3-D, data to define the initial spinup vortex. Results using this older MFM model showed that some improvement in the short range forecasts (12h-24h) was definitely possible, without degrading the longer range forecasts. The incorporation of both symmetric and asymmetric structures into the initial flow field for an active complex numerical model is still being researched at NMC.

6. Steering Flow

When the BAM was first run at NMC, a particular steering level, such as 500mb, was selected, which remained constant throughout the forecast period. Studies at NHC (i.e., Pike, 1987), however, have shown that a deep layer mean flow is usually a better steering flow. The BAM was therefore converted to use the 500-700mb average before 1987, and in 1988 and later years the flow from 850-200mb was used. Statistics for the single layer steering are not available, but Table 4 shows the 500-700mb layer, and the 400-700mb layer. Since so few cases are available containing the complete 850-200mb layer those statistics are not shown here. The deep layer mean is calculated in a similar fashion to the technique given by Neumann (1979). That is, each level is weighted according to the depth of the layer it represents. The 250mb level is not used, in order to conserve archive space. Since Neumann's study showed that lower levels had limited value as steering levels, the 850mb level is given 1/2 its normal weight. Also, the upper levels are only used if the vertical wind shear between the upper layer and the lower layer average does not exceed 8 m/s. This figure is a generalization from the Australian Weather Service

TABLE 4

Comparison of differing steering flows. The first case consists of the average of the 500mb and 700mb flow, the next case adds the 400mb flow. (mean vector error in nautical miles).

forecast hour	500-700mb	400-700mb	number of cases
12	50	49	119
24	89	88	116
36	124	121	99
48	174	168	88
60	213	210	75
72	256	244	43

Table 5

Vertical Shear Test. Mean vector error (nautical miles), for storms in 1988, using a deep layer mean (850mb-200mb) versus not using the 300-200mb layers if the vertical wind shear is excessive.

forecast hour	Deep-Layer Mean	DLM with test	cases
12	48	39	35
24	N/A	N/A	N/A
36	157	137	34
48	215	199	32
60	276	254	28
72	311	279	23

techniques as reported by McBride and Holland (1987). Results of using all levels versus eliminating those with high vertical shear are shown in Table 5. Even though all of these cases (in Table 5) come from 1988, it does show that eliminating the high-shear upper layers improves the forecast average.

The large scale flow for these forecasts comes from NMC's 80-wave spectral model (Sela, 1980). The model utilized fewer waves prior to 1987 and hence had somewhat poorer resolution. Only the wind components are utilized from the model. Since it is possible for some trace of the hurricane to be present in the spectral forecast, some smoothing is necessary. Conventional smoothing, however, is not the method chosen. Two techniques are utilized to extract only the large scale model flow instead of any influence due to the storm itself. On the basis of previous findings (i.e. Chan and Gray, 1982) and experimentation at NMC, the large scale flow is calculated at some distance from the center of the storm. The spectral coefficients are summed at each of 4 points, 400km from the center. The average then defines the flow at the center.

The second method of "smoothing" involves not utilizing short waves in defining the steering flow. Because the hurricane pressure structure along a diameter can be represented by a half wavelength, only waves of wavelength longer than four times the storm's radius need to be recombined to form the large scale flow field. Since the spectral model produces coefficients for 80 waves, many of these are not needed to define the "large-scale" flow. Thus, if the model storm radius is 400 km, then the flow for the Beta and Advection Model uses a triangular truncation of about 25 waves (wave 25 has a wave length of about 1600 km). Table 6 shows the impact of deleting these short waves, which was not as great as originally assumed. A much more drastic truncation, also shown in Table 6, does show some positive impact from eliminating even shorter waves. Here, the observed radius of 34-knot winds was assumed to be one-half the radius of the storm. As the global model has achieved higher resolution, more storms are able to be represented. In data-poor regions, these are frequently mis-located and need to be removed. The calculation of the background flow is the only place where the BAM uses the real storm size. While this usually did not have a great impact on the calculation, for extreme cases (i.e. very large storms), as few as 12 waves were recombined to form the large scale flow. The results indicate that there is a definite, though fairly small improvement in eliminating the small scale waves from the background flows. The objective here is to eliminate the

TABLE 6

Effects of Large-scale smoothing. Results of running the BAM model using 30 waves (rhomboidal) from the NMC spectral model (on storms from 1984-85) and using a triangular truncation determined by the effective radius (R-based), approximately 26 waves. Second comparison uses truncation determined from observed radius of gale force winds for storms in 1988 (mean vector error in nautical miles).

fcst hour	30 waves	R-based trunc.	cases	:	R-based	obs-based	cases
12	49	48	96	:	39	39	35
24	90	88	92	:	74	73	33
36	128	126	80	:	124	121	34
48	176	174	68	:	183	174	32
60	226	223	58	:	230	221	28
72	258	251	26	:	246	238	23

circulation caused by the storm while retaining all the larger scale flows represented in the model.

Since the impact of deleting these short waves is not as great as originally assumed, the BAM could be utilized from gridded fields as are provided to the meteorological community either in real time or via various archives. Only modest smoothing of these fields would be required. This result also makes it possible to predict that the accuracy would not suffer greatly by running the BAM using a fine mesh model such as the LFM, or NGM (Gerrity, 1977; Hoke et. al, 1989). These models only cover the data rich region around the U.S., so storms are usually faithfully represented if they are contained in the area. Although there have not been enough cases run to publish any valid comparisons, this capability does exist at NMC and is used routinely in order to get an early look at a forecast (the LFM and NGM output is available substantially earlier than the global model forecast).

The BAM is dealing with a deviation to the steering flow. It seems clear, therefore, that the "observed" direction and speed must be fairly close to that flow. Indeed, one of the sources of error for the BAM comes from the observed direction and speed. For well defined, mature hurricanes, this may not be a big problem, but for many storms, the current direction and speed of motion are not well defined. Such things as an ill-defined eye or a sudden change in direction can lead to substantial error in these observations. These storms also occasionally oscillate about their "true" track and short term motion may be mis-leading.

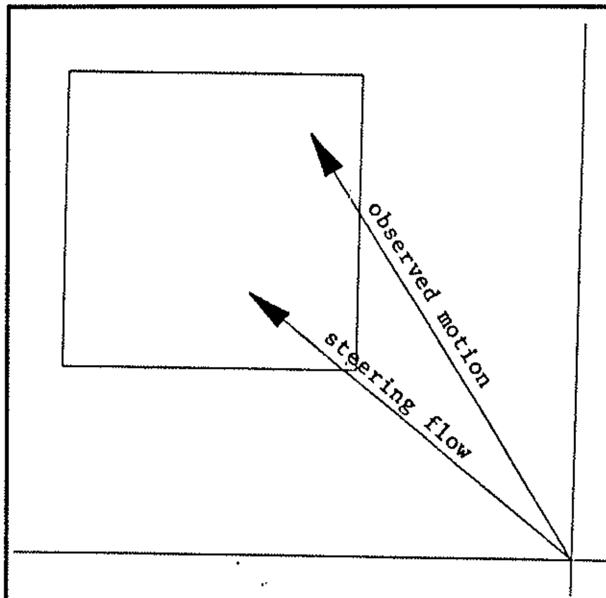

Figure 6. Diagram showing allowable direction and magnitude of observed motion relative to the steering flow. The observed motion vector must terminate within the box, thus limiting the storms deviation from the steering current.

Since the effective radius is determined from these observations, it is necessary to reconcile the observations and the steering flow. The theory behind the BAM requires that the direction and speed of motion be close to the steering flow, and if there is a large deviation from this flow, the observation is assumed to be in error and is adjusted. That is, the storm may move north faster than the steering flow only by 1.5 m/s, and must be at least as large as 80% of that northward steering flow. Similarly, the westward motion may exceed the large-scale flow by no more than 2 m/s, and must be no less than 70% of the westward flow. If the observations exceed these limits, they are changed to the closest value which is allowed. Figure 6 shows graphically the relation between the steering flow vector and the observed motion vector. The observed motion vector must terminate at a point within the box about the steering flow vector. If it does not, then the observation is changed to correspond to the closest point on the box. The average change in the components is less than 0.25m/s but is crucial in a few cases.

7. Storm Speed/Direction

The motion of the storm is affected by a secondary circulation induced on the large-scale flow by the storm's rotation on a beta plane as has been discussed in section 3. In order for the storm to maintain constant absolute vorticity for its circular motion, a relative vorticity field must be set up as shown in Figure 4. Since the earth vorticity is greater for the northern portion of the storm, the relative vorticity must be less in that northward portion. This relative vorticity field will induce a westward wind as shown in the figure.

A different effect is shown in Figure 3; the vorticity field created by the storm on the environment. If we assume that the environmental air has no relative vorticity, as it comes under the influence of the storm, through entrainment or storm motion, a relative vorticity field will be generated as shown in Figure 3 and will generate northward winds as shown.

These vorticity changes are not part of the storm, and the winds caused by these patterns rightly belong in the realm of the large scale environment. The two effects together, therefore, will add a NW wind of small magnitude to the environmental flow. This is in keeping with numerous observational studies.

The magnitude of these wind components may be determined by integrating the vorticity in a N-S or W-E direction and taking the average over the storm as was done in Section 3.4. However, several variations of this technique are reasonable. It is possible to assume that the vorticity varies linearly between points on the circle. While this is appropriate for the E-W wind, figure 3 shows that the northward wind should more properly be expressed as a trigonometric function of vorticity. That is, the relative vorticity may be expressed as $\zeta_p = \beta(r)\sin\theta(1-|\cos\theta|)$. If only the winds out to a distance R are assumed to be changed, then the resulting wind components (as used in equation 2) are:

$$V_N = 0.46\ \beta\ R^2$$
$$V_W = 0.64\ \beta\ R^2 \qquad (18)$$

This gives a direction of about 305° to the deviation. Therefore, a storm of radius 200km, in a quiet environment, would move at an angle of 305° and a speed of 1.3 m/s due solely to this induced flow. If the northward deviation equals the westward deviation then the angle would be 315°. Table 7 shows a comparison of these two assumptions along with the results obtainable using an angle of 295°, which would be a preferred angle if Holland's (1983) assumptions were used. The angle of 295° is also obtainable if it is assumed that the vorticity and the winds are in balance only to the center of the storm, rather than for a distance R. The difference in the mean forecast is extremely small, and may actually favor the angle of 315°. However, looking at the average east-west and north-south error shows that the 305° or 295° direction is frequently better. In fact, the advantage of using 315° can be traced to a couple of forecasts that predicted recurvatures that were missed by the more southerly track. Since the storm got caught in the westerlies, errors from missing recurvature were very large, which more then compensated for the numerous times that the 315° angle drifted

TABLE 7

Impact of different deviations. Results of running the BAM model using a deviation to the large-scale wind of 315°, 305°, and 295°. Vector errors (naut. miles). DW and DN denote average westward and northward error (in degrees).

fcst hour	315	DW	DN	305	DW	DN	295	DW	DN	number of cases
12	49	.0	.2	49	.0	.1	50	.0	.0	119
24	89	.0	.2	89	-.1	.1	90	-.1	-.1	116
36	121	.1	.3	122	.0	.2	124	-.1	-.1	99
48	168	.2	.5	169	.2	.3	171	.1	.0	88
60	210	.1	.6	210	.0	.4	214	-.1	.0	75
72	246	.3	-.1	244	.2	-.3	248	-.1	-1.0	43

a little too far north but encountered no strong winds. Using the 305° or 295° angle will generally lead to fewer "false alarms" for recurvature but will occasionally miss a recurvature, whereas 315° will virtually never miss a recurvature, but will also forecast a few more than actually occur. Since the 305° deviation is the most consistent theoretical value along with providing excellent forecasts, it is used as the operational value.

One of the more surprising results is the derivation of a term which tends to slow the storm's motion to the west and speed it up when going east. The derivation of this term is explained more completely in Appendix A. Basically, the change is due to the storm's asymmetries (negative relative vorticity to the north, positive relative vorticity to the south), and the fact that the storm must move as a unit. Taking the projections of the radial and tangential changes of vorticity around the entire circumference of the storm, and then using the average value leads to the following equation for the rate of change of relative vorticity.

$$\frac{(\partial\zeta_S+\partial\zeta_A)}{\partial R} = \underbrace{\frac{V_S}{R^2}(1-x^2)}_{(A)} - \underbrace{\frac{8}{2\pi}\beta\sin\theta}_{(B)} \qquad (19)$$

where:

$$\frac{\partial \zeta_S}{\partial R} \text{ = the change in symmetric relative vorticity}$$

$$\frac{\partial \zeta_A}{\partial R} \text{ = the change in asymmetric relative vorticity}$$

The importance of term (B) is shown in Table 8. Again, the change here is not large, but it does show an improvement. This term is in the denominator of equation (3) and hence changes the magnitude of the entire motion, due to both the

TABLE 8

Effect of asymmetries. Results of running the BAM model using equation 19 (Case 1), vs. not accounting for the change in speed due to asymmetries (Case 2). (mean vector errors in nautical miles)

forecast hour	Case 1	Case 2	number of cases
12	49	52	119
24	89	90	116
36	122	124	99
48	171	177	88
60	211	216	75
72	250	273	43

steering current and the deviation. It tends to obfuscate The effect of the NW deviation developed previously.

The beta effect shows up in an additional way related to the storm speed. As the storm moves north, the asymmetric portion of the storm changes slightly. Air moving on a circular path around the (moving) storm center will now have a longer path to reach the top of the storm (i.e. a larger negative relative vorticity adjustment) than will be required in order to reach the bottom portion of the storm. Thus, that area of the storm will experience a modest decline in (positive) relative vorticity. But, the storm is defined to be centered at the area of largest positive relative vorticity. Therefore, the speed of the storm must slow up slightly in order to overcome the effects of the increasing coriolis force. The East-West pattern also changes for a storm moving north. In this case, the storm speed to the west is increased slightly as the storm moves north.

It should be noted that this effect is very small. The ratio of the vorticities (rate of change in coriolis/rate of change of symmetric vorticity) is approximately,

$$\frac{(\beta V_N)}{((1-x^2)\,V_S V_N/R^2)} = \frac{\beta R^2}{(1-x^2)\,V_S} = A_F \qquad (20)$$

If this is then weighted according to the winds that apply to each vorticity, (north motion divided by outermost winds), then the resultant northward and westward components are:

$$V_{tn} = V_{mn}/(1 + A_F*V_{mn}/V_s)$$

$$V_{tw} = V_{mw} + V_{mn}*A_F*(V_{mn}/V_s)$$

where V_{mn}, V_{mw} are the (large-scale) model forecast motions to the north and west, respectively. V_{tn}, V_{tw} are the total, final components, after adjustment.

The results of using this as a correction factor are given in Table 9. The improvement is very slight, as indeed the correction is small and it is questionable whether the calculation is worthwhile. When the term was first developed, the improvement was much more dramatic, but as the real causes of the erroneous forecasts (this was early in the development of the theory) were discovered, the importance of this correction has diminished. Presentation of the results will perhaps prevent a re-evaluation of this effect by some other researcher.

TABLE 9

Effect of asymmetric distortion. The effect on the BAM average track errors due to the distortion of the asymmetric component by the northward motion.

forecast hour	no change	asymmetric distortion	number of cases
12	50	49	119
24	90	89	116
36	124	122	99
48	169	169	88
60	220	210	75
72	242	244	43

8. Vertical Motion/Moisture

It was noted by Dong and Neumann (1986) that storm intensity seemed to affect the motion. This may be due to the strong vertical motion in low latitude regions, causing some of the usual geostrophic assumptions to no longer hold. An approximation of the effect of the storm's vertical motion upon its own horizontal motion can be developed as follows: Start with the equations of relative motion:

$$\frac{du}{dt} = -\alpha\frac{\partial P}{\partial x} + 2V\Omega\sin\phi - 2w\Omega\cos\phi$$
$$\frac{dv}{dt} = -\alpha\frac{\partial P}{\partial y} - 2U\Omega\sin\phi \qquad (21)$$

(For a more complete discussion of these equations see Haltiner and Martin 1957, p164-166). If geostropic balance and a quiet atmosphere are initially assumed, only the vertical motion will be left. The vertical motion will cause the westward wind to increase, which will in turn increase the northward wind. Since we are dealing with mean flows, both horizontally and vertically, a steady state condition means that:

$$\frac{du}{dt} = \frac{\partial u}{\partial t} = 0$$

Substituting this into part one of equation (21) gives V_f.

$$V_f = w \cot an\phi \qquad (22)$$

Then integrate, using V_f and t as upper limits, to find an expression for U_f, getting,

$$U_f = \Omega \cos \phi \, (w^2 \; \cot an\phi \; - 2wt)$$

where U_f, V_f are the final eastward and northward components of the storm motion caused by the upward motion in the storm (the time used for U_f cannot exceed the time necessary to attain V_f).

This is only a (linear) approximation to the effect caused by a single phenomena - namely the vertical motion. However, this relationship does tie together the storm's intensity and its motion. It also helps to explain why these storms never cross the equator since the V_f term gets very strong at extremely low latitudes. The time necessary to reach V_f is found from the second part of equation (21), $| t = (\sqrt{2}\Omega \sin\theta)^{-1}$. Since the time necessary to reach this steady state is large, ($t > 54000$ sec at 10°N),

$$U_f = -2\Omega w \cos\phi\, t \tag{23}$$

is a good approximation. Then,

$$\frac{U_f}{V_f} = -\frac{2}{\sqrt{2}} = -1.414$$

So the relationship of the westward and the northward deviations is again at that mystical angle of 305 degrees. Since this was already the chosen deviation, including this term resulted in virtually no change in the forecast statistics.

The average vertical velocity in a hurricane, as reported by Frank (1977) is (a quite small) 6cm/sec. Hurricanes certainly have much greater vertical velocities at the center, but over a large area, and for a deep layer, downdrafts and updrafts tend to cancel out. At this rate, air would require over two days to travel the distance between the surface of a storm and the outflow layer.

This helps explain the following curious result obtained at NMC. The MFM (Hovermale, et. al. 1977) was used, experimentally, to produce a forecast of storm movement using both air-sea interaction and no air-sea interaction. The results indicated that the air-sea interaction was not significant in determining the model's forecast. Since the model starts with a (almost) saturated atmosphere (as is found in the vicinity of hurricanes) and only forecasts out to 3 days, the initially available moisture was sufficient to maintain the structure of the storm. Thus air-sea interaction seems to be vital for setting up a storm and for the (very) long term maintenance of its structure, but not for short term effects. The fact that the BAM can produce good 3-day forecasts without any consideration of moisture or convection also reinforces this observation. No model could, of course, survive without this interaction if it started with a dry atmosphere or if it allowed moisture to be removed but not replaced. It is not unreasonable, however, to visualize a hurricane as a steady state system, where evaporation from the ocean is matched by rain falling back into the ocean, so that the entire system experiences no net gain or loss of moisture. That is, if one assumes that the moisture supplies exactly enough energy to balance friction, then both may be ignored. Moisture is the fuel for the maintenance of the storm, but it may not affect the motion. Under these conditions, moisture may be ignored.

9. Observations from the Data

Since a large number of storm tracks have now been archived, along with the same day forecast wind fields, some additional observations are worthwhile. While the data set may not be rigorously enough defined to make definite conclusions, several characteristics are worth mentioning. Here, the observations are from the collection of tropical cyclones that were used as test cases for the BAM. The test cases are at least 36 hr. apart and in different oceans, so they are considered to be independent. Hence, characteristics relevant to tropical cyclone motion may be inferred without reference to the particular model being used to forecast the movement. However, the BAM forecasts can be referenced to point out differences or verifications of the theory developed here.

One of the major sources of error in the BAM may be the reported initial direction and speed. If we compare the actual motion with the reported initial direction and speed, (see Table 10) we see that the reported direction (in the average) is very close to the actual motion of the storm. The reported speed, however, tends to be too slow. If this 0.6m/s error is retained throughout the 72h forecast, the resultant error would amount to 84 nautical miles. This is not insignificant and re-enforces the necessity for checking those values as discussed in Section 6. In all fairness, since speed is reported in integer knots, an error of under 1 knot is really all that can be expected. Much of this error is undoubtedly due to a few eastward moving storms that experienced rapid acceleration, and since rapidly moving storms rarely decelerate as fast, the averages may be biased toward faster storms.

Table 10 also indicates that the storms move at the same or slower speed as the steering flow. If the components are analyzed, however, instead of the direction and speed, then the storm actually moves west of the steering flow, an average of 1.7 m/s, and 0.2 m/s more to the north. The westward speed

TABLE 10

Comparison of the reported storm motion (from the warning bulletins) actual storm motion from subsequently observed positions, and the model steering flow acting on storm, during the first 12 hours of movement. (Angle refers to the direction, in degrees, clockwise from north, speed is in m/s)

Actual angle	Reported angle	Steering flow angle	Actual speed	Reported speed	Steering flow speed
321	322	343	5.3	4.7	5.6

increase is consistent with the observed deviation from the steering. The northward increase implies a more complicated relationship with westward steering producing stronger northward deviations than northward steering. This phenomena is not adequately explained by the BAM, although sections 3, 7 and 9 contain some hint of explanations.

These deviations show up as reducing the speed for eastward and southward moving storms, and hence allow the average actual movement to be essentially the same as the average speed of the steering flow. The motion for any one storm, however, will be faster or slower than the steering current, depending on the relative magnitude of the factors developed earlier. The original development by Holland (1983) has been criticized for not having a way for the storm to move north (as everyone knows they do), but only allows a westward deviation. The BAM also requires a northward motion to satisfy the theory and to produce better results (note that assuming that the northward deviation equals the westward deviation produces the lowest average error -- Table 7). However, looking at Table 7 we see that this northward deviation is a little too strong (by an average of about 0.2 m/s over a 72 hour forecast). Table 11 shows the average latitude-longitude errors when only advection is considered. That is, by 48 hours, using only large scale advection, the forecast position averages 1.3° too far east and only 0.1° too far north. The indication, therefore, is that the storm has a much smaller northward drift than is commonly believed. This also lends credence to the previous decision to use a deviation toward 305° instead of 315°.

If the storm direction is plotted as a deviation to the steering flow, as in Figure 7, some additional justification for the BAM technique is evident. Here, it is easy to see that for steering direction from 320° to 90°, the deviation is to the left. For steering direction from 140° to 270°, the storm track deviates to the right of the flow. A linear regression analysis reveals that a steering angle of 295° is the preferred angle of no deviation to the motion, whereas for other choices of steering flow there is a tendency to deviate toward the WNW. In other words, storms do not deviate so much

---

TABLE 11

Forecasts made with advection only compared to BAM forecasts. Vector errors in nautical miles, DW indicates westward error, in degrees, and DN indicates northward error (in degrees).

fcst hour	advection only	DW	DN	cases	BAM
12	59	-0.4	-0.1	119	49
24	107	-0.9	-0.1	116	88
36	149	-1.2	-0.0	99	120
48	208	-1.3	+0.1	88	167
60	264	-1.7	+0.2	75	209
72	325	-2.2	-0.9	43	241

to the right or left of the motion as they deviate toward an angle of 295°. This differs only slightly from the theory developed in this paper which forecasts a deviation toward 305°. In fact, for the set of storms studied here, the actual storm track averages a deviation of 20° from the steering flow, toward the direction of 305°. If the storm is already moving at about 305° (or opposite to 305°) then the deviation is unreliable since small errors in forecast wind or observation can lead to a change in sign of the deviation. The exact "preferred direction" of these storms is still open to some investigation, but it seems clear that an angle between 275° and 315° is justified. Storms in an area containing no large scale wind would move in this direction. Storms in an area with steering flow to the WNW would speed up but deviate little from that direction. Other choices of steering flow would result in changes toward the WNW, but the magnitude would be determined by other factors. This is in agreement with several recently published studies, such as Dong and Neumann (1986), where it was noted that storms in the easterlies tended to deviate to the right, while storms in the westerlies deviated to the left. This is easily explained by a single deviation to the NW. Several other studies have shown similar results, virtually all of which seem to be explainable by this NW deviation.

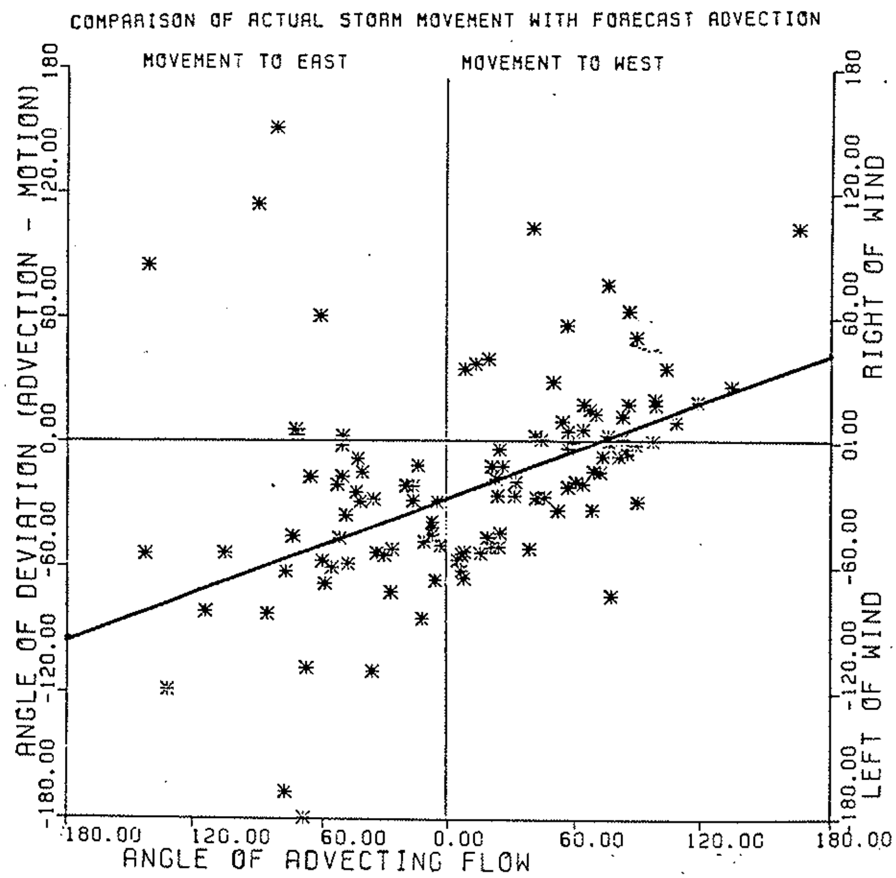

Figure 7.

One of the most interesting observations to come out of this study involves the influence of the storm size upon the storm motion. As noted before, it is sometimes assumed that larger storms will deviate more from the steering current than will small storms. However, this conclusion is based almost entirely upon theoretical reasoning. Here is an opportunity to test the theory against real, observed, data. This was done very simply. First, the average deviation of the storm motion from the steering current was calculated for the initial 12 hour interval. Then these values were compared to the observed storm size via a linear regression technique. The correlation between the observed radius of 34 knot winds and the northward deviation was -0.03, the correlation to the westward deviation was +0.03. These correlations are so small as to be meaningless. Thus it appears that there is NO relationship between the storm size and the deviation to the environmental flow. This is in keeping with the previously disclosed result that the storm structure may be fixed in the model and is not related to the actual, observed storm size or structure. This means that the "effective radius" referred to in the discussion is simply a parameter, not a real measurement of the storm's linear extent. Referring to it as a radius is a reflection of our perception of the atmosphere, and is not due to the real structure of the interactions. The author suspects (but has not investigated) that the effective radius is a much broader measure of a storm's size and is a function of the intensity, shape, and magnitude of convection as well as the circulation radius.

10.0 Results

The results obtained from running the BAM model are competitive with most other techniques. Indeed, the fact that good forecasts can be obtained in this rather simple fashion is one of the most compelling reasons to believe the theory previously developed. Tables 12, 13 and 14 show some of the comparisons available with other models. The BAM model was not routinely compared with other models until the 1987 season. The comparisons in the tables include three models developed and run by the National Hurricane Center, CLIPER, SANBAR, and NHC83 (Neumann, 1979, 1988), one high resolution primitive equation model developed and run at NMC, the QLM, and one model developed and run by the U.S. Navy, the OTCM. In choosing the models to be compared, an attempt was made to choose those models which were the best, or most representative of that type of operational model. Other operational models can be expected to behave similarly, or worse. Research models were not considered for these comparisons.

The BAM is clearly competitive with most, if not all of these models. The only model which seems to be superior to the BAM is NHC83 (Neumann, 1988). Several other models are either very close in overall statistics (OTCM, CLIPER-1988), or are better at some time periods and worse at others (QLM-1987, SANBAR). Some of this variation is explainable by the type of storms prevalent in a given year. In comparing the years 1987-1988, for example, the straight moving storms of 1988 were perfect for CLIPER, but the northerly erratic storms of 1987 required the dynamics in the QLM. The BAM was in about the same relative position in both years.

Of particular interest are the figures labeled "average". These are formed by taking the points midway between the two forecasts. In many instances, the average forecast is better than either of the component forecasts. Thus, if a storm moves straight west while one model forecasts a northwestward motion, and the other model forecasts a southwestward motion, the average is better than either. This is especially noticeable when using the average of the BAM and a model from a different center (not the QLM). Models from different centers have independent data bases, analyses, and methods. The errors made at each center will thus also tend to be independent, and are more likely to "cancel out" when added together. The most dramatic examples of this come from adding the BAM to the SANBAR or the OTCM. The BAM can thus be thought of as adding new information even when it is not the most accurate single model. The BAM's assumptions, even if not exactly correct, are substantially different from other models and thus add a new perspective on the storm motion than was considered before. This trait makes a strong argument in favor of including the BAM in any set of forecast models being considered.

Finally, it should be remembered that the BAM can run anywhere in the world. Table 15 shows the results of a sample of storms in the southern hemisphere. Converting the BAM to run in the southern hemisphere requires replacing "northward" terms with equivalent "poleward" terms. It was not possible to obtain the forecasts from equivalent models but the results are indicative of the general level of forecasting ability in the southern hemisphere.

Table 12.
Model comparisons. Mean vector error (nt. mi.) for models, storms in 1988 (homogeneous sets). CLIPER is NHC's climatology-persistence model, NHC83 is NHC's statistical-dynamical model, QLM refers to NMC's Quasi-Lagrangian model, and OTCM is the One-way Tropical Cyclone Model of the U.S. Navy.

	forecast period				
model	12	24	36	48	72
BAM	46	76	116	163	237
CLIPER	45	85	132	174	254
Average	42	71	109	150	212
cases	69	65	60	54	45
BAM	43	74	110	147	227
NHC83	42	70	98	132	188
Average	39	66	96	130	191
cases	67	61	56	51	42
BAM	36	70	115	157	220
SANBAR	66	69	106	130	230
Average	46	56	89	113	186
Cases	49	44	42	37	30
BAM	47	82	121	160	238
QLM	78	128	176	224	332
Average	56	95	133	172	252
cases	115	111	103	95	79
BAM		98		197	284
OTCM		110		215	298
Average		91		181	242
cases		100		75	63

Table 13.

(same as Table 12, but for 1987)

model	forecast period 12	24	36	48	72
BAM	64	119		234	416
CLIPER	65	133		291	523
Average	59	114		225	395
cases	57	55		43	30
BAM	63	118		235	414
NHC83	63	102		212	374
Average	58	98		189	347
cases	58	56		43	33
BAM	58	120		254	436
SANBAR	70	143		303	312
Average	58	109		224	311
cases	38	35		25	14
BAM	67	132	214	268	498
QLM	84	144	251	273	405
Average	71	129	221	259	423
cases	27	24	21	18	13
BAM		107		185	278
OTCM		103		196	308
Average		89		150	236
cases		162		139	107

Table 14.

Model comparisons for 1989, homogeneous cases, courtesy of the National Hurricane Center. (models are the same as in Table 12)

	forecast period				
model	12	24	36	48	72
BAM	59	92	132	161	256
CLIPER	36	89	154	211	341
NHC83	33	66	105	132	256
QLM	63	89	130	190	266
SANBAR	35	76	116	155	311
OFFICIAL	29	73	123	172	301
CASES	46	41	37	32	23

Table 15.

BAM in the Southern Hemisphere. Mean vector error (nt. mi.) for the years 1988-1989.

	forecast period				
	12	24	36	48	72
BAM	86	132	191	239	310
cases	90	78	70	60	37

11.0 Conclusions and Implications

The accuracy of the BAM is substantially better than was originally expected. The basic idea of analyzing steady-state forces seems to be appropriate to these storms. By far the greatest such force is the external advection. To this is added a small northwestward motion due to a secondary circulation induced by the beta effect. These two forces determine, to a very great extent, the direction and speed of the storm motion. Small changes to the northwestward motion are possible due to the size and divergence of the storm.

It should be remembered that alternate explanations for some of these effects are possible. For example, both the PHM and the BAM add a NW motion to the storm, but for different reasons. The facts presented in this paper are believed to be accurate and the reasons given to explain those facts are based upon observation and scientific reasoning, but a great deal is unknown about tropical storms. Even the basic asymmetric steering patterns shown in Figures 3 and 4 cannot be observed since they are a very small perturbation in the fields of the actual observed winds.

The fact that the Beta and Advection Model is among the most accurate track forecasting models in existence implies two requirements for future numerical modeling efforts. First, it is crucial that the large-scale flow be modeled accurately, at least as well as the NMC Spectral Model. Second, the variation of the coriolis force must be properly accounted for and its effects meticulously modeled. If a model meets these two requirements, any improvement over the BAM will depend on its ability to predict non-linear interactions, intensity changes, reactions due to surface changes, etc. For the most part, however, these are substantially smaller forces than the beta effect and therefore are more difficult to model. The BAM model will, however, automatically take advantage of any improvements made to the large-scale model it is derived from. As the large-scale models improve their forecasts in the tropical regions, we may discover that forces not associated with advection or the coriolis force are very small indeed. At this point it is not clear whether the BAM errors are due to defects in the formulation or problems in the large-scale forecast.

The specifics of the BAM model should not be overlooked, either. The simple wind-radius relationship (eq. 14) and the technique used to derive the northwest deviation should find wide application in other numerical models. The induced secondary circulation could be utilized to initialize other models. Both the symmetric and the asymmetric circulations could be added to the large-scale analysis as a way to ensure proper placement and structure in the large-scale model. The proper placement of the asymmetries could also help the large scale model to forecast the direction and speed correctly. Since the storm direction and speed may be observed from satellites, an inverse relationship may be derived and an estimate of the large-scale wind field may be made from the storm motion. This can be inserted into the analysis at the appropriate point. This is especially appropriate in the data-sparse areas of the Pacific and Indian Oceans.

Apart from the model, the data itself has revealed some interesting results. Namely, that storms tend to move to the west of the steering flow, and only slightly north, with a preferred direction of about 295°. It is thus more realistic to visualize storms as deviating to the WNW, rather than to the right or left of the steering flow. The observed data also indicates that the size of the storm's circulation does not affect this deviation. This observation challenges such long established concepts that additional studies and research are well worthwhile. These particular conclusions stem from the observed data, not the BAM, although the observations and the model reinforce each other. That is, the BAM could not produce results of this quality, with a constant storm size and shape, if the size and shape were crucial to the storm motion. Similarly, the NW deviation predicted by the BAM must imitate such a deviation in the real world.

Finally, since the entire forecast process only takes about 3 seconds of CPU time on a NAS9050 computer, a Monte Carlo approach could be used to generate a probability forecast. With some optimization, and on a faster, vector machine, a thousand forecasts, each with slightly different input variables, could be produced. As DeMaria (1985) has shown, some storms will be very sensitive to small perturbations, while others will show almost no such sensitivity. An example of this capability is shown in Figure 8 for a Hurricane Gilbert case. The parameters varied in this example were effective radius and steering levels. Each different selection produces a slightly different forecast. While this storm did not produce a lot of variation, the best forecasts come from choosing high steering levels (300mb). This is not surprising since the storm was very large and strong at this time. This technique could be used to produce a numerical probability forecast to supplement the currently available climatological probabilities and improve both the forecasts and the planning abilities of the coastal communities.

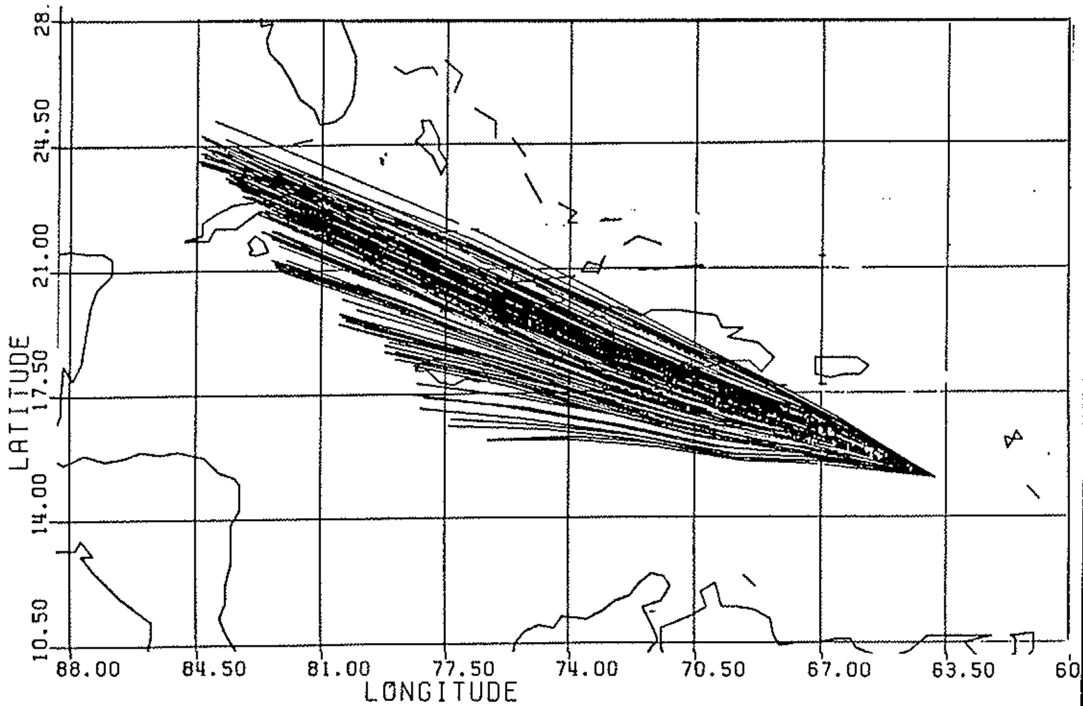

Figure 8. BAM forecasts for hurricane Gilbert (12z/9/10/88), made with various steering levels, and storm sizes.

12.0 Acknowledgements

The author wishes to thank all those people at NMC who have patiently listened to his theories, read his drafts and offered constructive responses, especially James Hoke, Ralph Jones and Alan Shapiro. He would also like to thank John Stackpole and James Howcroft for their encouragement of this work, without which it could not have been accomplished.

Appendix A

Derivation of the Average Rate of Change of Asymmetric Relative Vorticity in the Direction of Motion

The second term in the denominator of equation (3) deserves some attention. The proper method of calculating speed is to divide the time rate of change by the spacial rate of change of vorticity in the direction of motion. Here, however, the entire storm must move as a unit, and the average change of relative vorticity over the entire effective radius must be used. The symmetric portion of the storm poses no problems, but the asymmetries shown in Figure 4 require an expanded treatment.

As Figure A.1 shows, both the radial change of vorticity and the tangential change of vorticity of the asymmetric portion of the storm will have a positive

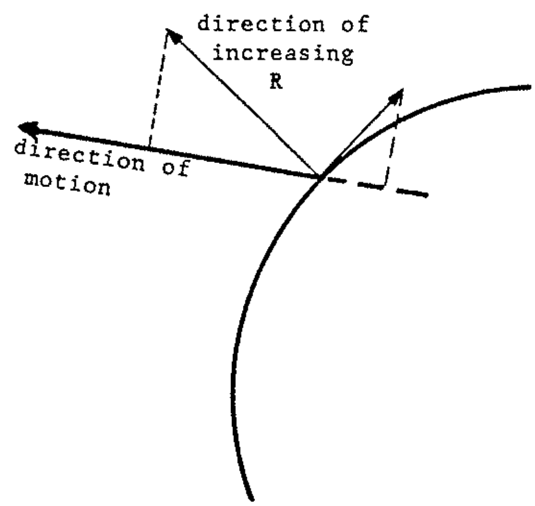

Figure A.1. Projections, in the direction of motion, of the rate of change of the asymmetrical components of the relative vorticity.

projection in the direction of motion.

Let us pick a point at (R,θ), and assume that the storm moves in direction θ_1.

For the tangential component,

$$\frac{\partial \zeta_A}{\partial R} = -\beta \cos\theta$$

the projection in the direction of motion is:

$$\frac{\partial \zeta_A}{\partial R}\cos(\theta_1 - \theta)$$

and the average value around the entire radius is:

$$\frac{\int_0^{2\pi} (\partial \zeta_A/\partial R)\cos(\theta_1 - \theta)\, d\theta}{\int_0^{2\pi} d\theta} = -\frac{\beta}{2\pi}(\pi\cos\theta_1 + 4\sin\theta_1)$$

Similarly, for the radial component,

$$\frac{1}{R}\frac{\partial \zeta_A}{\partial \theta} = \beta \sin\theta$$

and its average value is:

$$\frac{\int_0^{2\pi} \frac{1}{R}\frac{\partial\zeta_A}{\partial\theta}\cos(\theta-\theta_1+\frac{\pi}{2})\,d\theta}{\int_0^{2\pi} d\theta} = \frac{\beta}{2\pi}(\pi\cos\theta_1 - 4\sin\theta_1)$$

So, the total change in relative vorticity in the direction of motion, due to the asymmetric component is:

$$\overline{\frac{\partial\zeta_A}{\partial R}} = -\frac{8}{2\pi}\beta\sin\theta_1$$

which must be added to the change due to the symmetric component.

Other intuitive possibilities, such as using only the symmetric component, or including the large-scale asymmetric component were tried, but lead to poorer results. The form of equation (3) will slow up storm movement toward the west, and speed up motion to the east. In this sense, it opposes the second term of the RHS of equation (1). The eastward preference is a direct result of the fact that the relative vorticity distribution in the steady state storm is opposite the earth vorticity distribution.

REFERENCES

Adem, J.,1956: A series solution for the barotropic vorticity equation and its application in the study of atmospheric vorticities. Tellus,8,364-372.

Anthes, R.A., 1982: Tropical Cyclones: Their Evolution, Structure and Effects. Meteor. Monogr. No. 41, AMS, 208pp.

......., and J.E. Hoke, 1975: the effect of horizontal divergence and latitudinal variation of the Coriolis parameter on the drift of a model hurricane. Mon. Wea. Rev., 103,757-763.

Carr and Williams: 1989: Barotropic vortex stability to perturbations from axisymmetry. J. Atmos. Sci.,47,3177-3191.

Chan, J.C.L., and W.M. Gray, 1982: tropical cyclone movement and surrounding flow relationships. Mon. Wea. Rev., 110, 1354-1374.

..........and R.T. Williams, 1987: Analytical and numerical studies of the beta-effect in tropical cyclone motion. Part I: zero mean flow. J. Atmos. Sci.,44,1257-1265.

Dong, K. and C. J. Neumann,1986: The relationship between tropical cyclone motion and environmental geostrophic flows. Mon. Wea. Rev.,114,115-122.

DeMaria, M., 1985: Sensitivity of dynamical hurricane track forecasts to properties of the large-scale flow. Extended Abstracts Volume: 16th Conf. on Hurricanes and Tropical Meteorology. AMS, Boston, Ma.,83-84

Fiorino, M., 1987: The role of vortex motion in tropical cyclone motion. Ph.D. dissertation, Department of Meteorology, Naval Postgraduate School, Monterey, Ca. 371 pp.

........, and R. L. Elsberry, 1987: the role of vortex structure in barotropic tropical cyclone motion. Extended Abstracts: 17th Conference on Hurricanes and Tropical Meteorology. AMS, Boston, Ma.,55-59.

.............................., 1989: Some aspects of vortex structure related to tropical cyclone motion. J. Atmos. Sci., 46, 975-990.

Frank, W.M., 1977: The structure and energetics of the tropical cyclone, paper I: storm structure. Mon. Wea. Rev., 105, 1119-1135.

Gerrity, J., 1977: The LFM model--1976: A documentation. NOAA Tech. Memo. NWS NMC 60, 68pp.

Haltiner, G. J., and F. L. Martin, 1957: Dynamical and Physical Meteorology, McGraw-Hill, N.Y.

Hoke, J. E., N. A. Phillips, G. J. DiMego, J. J. Tuccillo, and J. G. Sela, 1989: The regional analysis and forecast system of the National Meteorological Center. Weather and Forecasting, 4.,323-334.

Holland, G. J., 1983: Tropical cyclone motion: environmental interaction plus a beta effect. J. Atmos. Sci., 40, 328-342.

..........1984: Tropical cyclone motion: A comparison of theory and observation. J. Atmos. Sci.,34,1518-1527.

Hovermale, J. B., D. G. Marks, and S. H. Scolnik, 1977: Operational analysis and prediction with a Moveable Fine Mesh system at the National Meteorological Center. Proceedings: AMS 7th Technical Exchange Conference, El Paso, Tx., AMS, Boston, Ma.

.... and R.E. Livezey, 1977: Three-year performance characteristics of the NMC hurricane model. Proceedings, Eleventh AMS Technical Conference on Hurricanes and Tropical Meteorology, 122-125.

Mathur, M.B., 1983: A quasi-Lagrangian regional model designed for operational weather prediction. Mon. Wea. Rev., 111, 2087-2098.

.............., and W. B. Facey, 1985: Simulation of hurricanes with a fine-mesh quasi-lagrangian primitive equation model. Extended Abstracts: 16th Conference on Hurricanes and Tropical Meteorology, p144-145, AMS, Boston, Ma.

Marks, D.G., 1987: A technique to improve the MFM 12 hour forecasts by modifying the spinup. Extended Abstracts: 17th Conference on Hurricanes and Tropical Meteorology, AMS, Boston, Ma.,64-66.

.... 1989a: The beta and advection model for hurricane track forecasting. Extended Abstracts: 18th Conference on Hurricanes and Tropical Meteorology. AMS, Boston, Ma.

............, 1989b: Cause and Cure of the spurious northward bias induced by hurricane model spinup techniques. NMC Office Note No. 357. National Meteorological Center, Washington, D.C.

McBride, J.L. and G. J. Holland, 1987: Tropical-cyclone forecasting: a worldwide summary of techniques and verification statistics. Bull. of the AMS, 68, 1230-1238

Neumann, C. J., 1979: A guide to Atlantic and eastern Pacific models for the prediction of tropical cyclone motion. NOAA Tech. Memo, NWS NHC-11, 26pp.

............., 1988: The National Hurricane Center NHC83 Model. NOAA Tech. Memo, NWS NHC-41, 44p.

Pike, A. C., 1987: A comparison of wind components and geopotential heights as statistical predictors of tropical cyclone motion. Extended Abstracts: 17th Conference on Hurricanes and Tropical Meteorology,101-103. AMS, Boston, Ma.

Riehl, H., 1963: Some relations between the wind and thermal structure of steady-state hurricanes. J. Atmos. Sci., 20, 276-287.

Rossby, C.G, 1940: Suppl. Quart. J. Royal Meteorol. Soc.,66.

Sela, J. G., 1980: Spectral modeling at the National Meteorological Center. Mon. Wea. Rev., 108, 1279-1292.

Shapiro, J., and K.V. Ooyama, 1990: barotropic vortex evolution on a beta plane. J. Atmos. Sci.,48,170-187.

Smith, R.K., and W. Ulrich, 1990: An analytical study of tropical cyclone motion using a barotropic model. J. Atmos. Sci.,in press.

.... and Dietachmayer, 1990: A numerical study of tropical cyclone motion using a barotropic model. Part I. The role of vortex asymmetries. Quart. J. Roy. Meteor. Soc.,337-362

Tuleya, R. E., and Yoshio Kurihara, 1975: The energy and angular momentum budgets of a three-dimensional tropical cyclone model. J. Atmos. Sci., 32,287-301.

Willoughby, H. E., 1987: tropical cyclone track prediction: some theoretical aspects. Extended Abstracts: 17th Conference on Hurricanes and Tropical Meteorology, 262-265. AMS. Boston, Ma.

(continued from inside front cover)

NOAA Technical Memorandums

NWS NMC 49 A Study of Non-Linear Computational Instability for a Two-Dimensional Model. Paul D. Polger, February 1971, 22 pp. (COM-71-00246)
NWS NMC 50 Recent Research in Numerical Methods at the National Meteorological Center. Ronald D. McPherson, April 1971, 35 pp. (COM-71-00595)
NWS NMC 51 Updating Asynoptic Data for Use in Objective Analysis. Armand J. Desmarais, December 1972, 19 pp. (COM-73-10078)

NOAA Technical Memorandums

NWS NMC 52 Toward Developing a Quality Control System for Rawinsonde Reports. Frederick G. Finger and Arthur R. Thomas, February 1973, 28 pp. (COM-73-10673)

NWS NMC 53 A Semi-Implicit Version of the Shuman-Hovermale Model. Joseph P. Gerrity, Jr., Ronald D. McPherson, and Stephen Scolnik, July 1973, 44 pp. (COM-73-11323)
NWS NMC 54 Status Report on a Semi-Implicit Version of the Shuman-Hovermale Model. Kenneth Campana, March 1974, 22 pp. (COM-74-11096/AS)
NWS NMC 55 An Evaluation of the National Meteorological Center's Experimental Boundary Layer Model. Paul D. Polger, December 1974, 16 pp. (COM-75-10267/AS)
NWS NMC 56 Theoretical and Experimental Comparison of Selected Time Integration Methods Applied to Four-Dimensional Data Assimilation. Ronald D. McPherson and Robert E. Kistler, April 1975, 62 pp. (COM-75-10882/AS)
NWS NMC 57 A Test of the Impact of NOAA-2 VTPR Soundings on Operational Analyses and Forecasts. William D. Bonner, Paul L. Lemar, Robert J. Van Haaren, Armand J. Desmarais, and Hugh M. O'Neil, February 1976, 43 pp. (PB-256-075)
NWS NMC 58 Operational-Type Analyses Derived Without Radiosonde Data from NIMBUS 5 and NOAA 2 Temperature Soundings. William D. Bonner, Robert Van Haaren, and Christopher M. Hayden, March 1976, 17 pp. (PB-256-099)
NWS NMC 59 Decomposition of a Wind Field on the Sphere. Clifford H. Dey and John A. Brown, Jr. April 1976, 13 pp. (PB-265-422)
NWS NMC 60 The LFM Model 1976: A Documentation. Joseph P. Gerrity, Jr., December 1977, 68 pp. (PB-279-419)
NWS NMC 61 Semi-Implicit Higher Order Version of the Shuman-Hovermale Model. Kenneth A. Campana, April 1978, 55 pp. (PB-286-012)
NWS NMC 62 Addition of Orography to the Semi-Implicit Version of the Shuman-Hovermale Model. Kenneth A. Campana, April 1978, 17 pp. (PB-286-009)
NWS NMC 63 Day-Night Differences in Radiosonde Observations in the Stratosphere and Troposhere. Raymond M. McInturff, Frederick G. Finger, Keith W. Johnson, and James D. Laver, September 1979, 54 pp. (PB80 117989)
NWS NMC 64 The Use of Drifting Buoy Data at NMC. David Wright, June 1980, 23 pp. (PB80 220791)
NWS NMC 65 Evaluation of TIROS-N Data, January-June 1979. David Wright, June 1980, 21 pp. (PB80 220494)
NWS NMC 66 The LFM II Model--1980. John E. Newell and Dennis G. Deaven, August 1981, 20 pp. (PB82 156845)
NWS NMC 67 Gulf Stream System Landward Surface Edge Statistics. Stephen J. Auer, October 1983, 20 pp. (PB84 104314)
NWS NMC 68 Compendium of Marine Meteorological and Oceanographic Products of the Ocean Products Center. David M. Feit, September 1986, 93 pp. (PB87 101812/AS)
NWS NMC 68 (Rev. 1) Compendium of Marine Meteorological and Oceanographic Products of the Ocean Products Center. (Revision 1) David M. Feit, June 1989, 78 pp. (PB89 230684)
NWS NMC 69 An Evaluation of NESDIS TOVS Physical Retrievals Using Data Impact Studies. Clifford H.Dey, Ralph A. Petersen, Bradley A. Ballish, Peter M. Caplan, Lauren L. Morone, H. Jean Thiebaux, and Glenn H. White, National Meteorological Center, Henry E. Fleming, Anthony L. Reale, and Donald G. Gray, Office of Research and Applications, NESDIS, and Mitchell D. Goldberg and Jamie M. Daniels, ST Systems Corporation, Lanham, Maryland, June 1989, 53 pp. (PB90 185091/AS)

NOAA SCIENTIFIC AND TECHNICAL PUBLICATIONS

The National Oceanic and Atmospheric Administration was established as part of the Department of Commerce on October 3, 1970. The mission responsibilities of NOAA are to assess the socioeconomic impact of natural and technological changes in the environment and to monitor and predict the state of the solid Earth, the oceans and their living resources, the atmosphere, and the space environment of the Earth.

The major components of NOAA regularly produce various types of scientific and technical information in the following kinds of publications:

PROFESSIONAL PAPERS — Important definitive research results, major techniques, and special investigations.

CONTRACT AND GRANT REPORTS — Reports prepared by contractors or grantees under NOAA sponsorship.

ATLAS — Presentation of analyzed data generally in the form of maps showing distribution of rainfall, chemical and physical conditions of oceans and atmosphere, distribution of fishes and marine mammals, ionospheric conditions, etc.

TECHNICAL SERVICE PUBLICATIONS — Reports containing data, observations, instructions, etc. A partial listing includes data serials; prediction and outlook periodicals; technical manuals, training papers, planning reports, and information serials; and miscellaneous technical publications.

TECHNICAL REPORTS — Journal quality with extensive details, mathematical developments, or data listings.

TECHNICAL MEMORANDUMS — Reports of preliminary, partial, or negative research or technology results, interim instructions, and the like.

NATIONAL OCEANIC AND ATMOSPHERIC ADMINISTRATION
NOAA
U.S. DEPARTMENT OF COMMERCE

Information on availability of NOAA publications can be obtained from:

NATIONAL TECHNICAL INFORMATION SERVICE
U. S. DEPARTMENT OF COMMERCE
5285 PORT ROYAL ROAD
SPRINGFIELD, VA 22161