

# **The NCAR-AFWA Tropical Cyclone Bogussing Scheme**

*A Report Prepared for the Air Force Weather Agency (AFWA)*

by

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## Introduction

Contained in this document is a summary of a simple scheme for bogussing tropical cyclones into the initial condition of MM5. The scheme is designed to be robust and provide a significant enhancement of initial tropical storm strength and positioning relative to what is available in the background gridded information obtained from global models. Typically, these background data come from the Navy Operational Global Analysis and Prediction System (NOGAPS), but NCAR-AFWA bogussing scheme is technically independent of the source of the first guess. The scheme can be broken into two primary components:

- (1) Detection and extraction of tropical cyclone from the first-guess.
- (2) Computation of bogus vortex and blending with a modified background field.

A flow diagram of the bogussing scheme appears in Fig. 1. In the remainder of this document, each component of the bogussing scheme will be discussed in detail. Two examples of the scheme's performance, and the performance of the forecast resulting from using this initialization, will be presented.

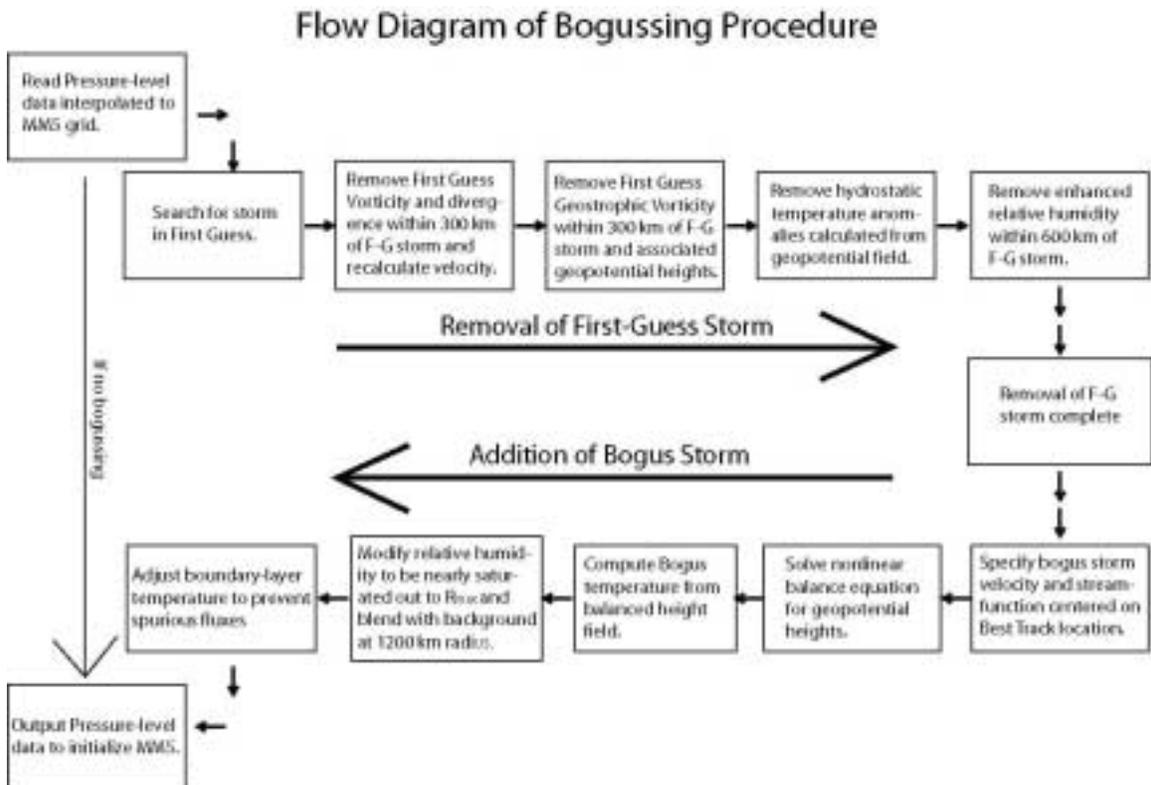


Figure 1. Flow diagram of bogussing calculations.

## ***Removal of Vortex from Background***

Because most of the first guess information that is available (and the models producing the information) are integrated on domains with relatively coarse effective resolution, the vortices contained in gridded analyses are too broad and too weak. Initialization of a higher-resolution model from these analyses results in a storm that typically maintains its physical characteristics from the initial time. If the storm starts out with a radius of maximum wind (RMW) of, say, 200 km, the RMW tends to remain near this value for an extended period during the forecast until the model is able to produce a scale contraction and associated intensification of the vortex. This often requires 1-2 days of integration.

To improve the intensity prediction, it is necessary to insert an initial vortex that is closer to the observed storm intensity than is the vortex in the background. In order to do this, the erroneously large vortex in the background must be first removed. Otherwise, the initial state for MM5 would contain two vortices which may be at different spatial locations.

The first step of the removal process is to identify the vortex corresponding to the storm of interest in the first guess field. This is accomplished by searching for the maximum vorticity on the analysis pressure-level nearest the surface (either 1013 hPa or 1000 hPa) within a prescribed radial distance from the Best Track location of the tropical cyclone. Currently the search radius is set to 400 km (Fig. 2). The point of maximum vorticity then

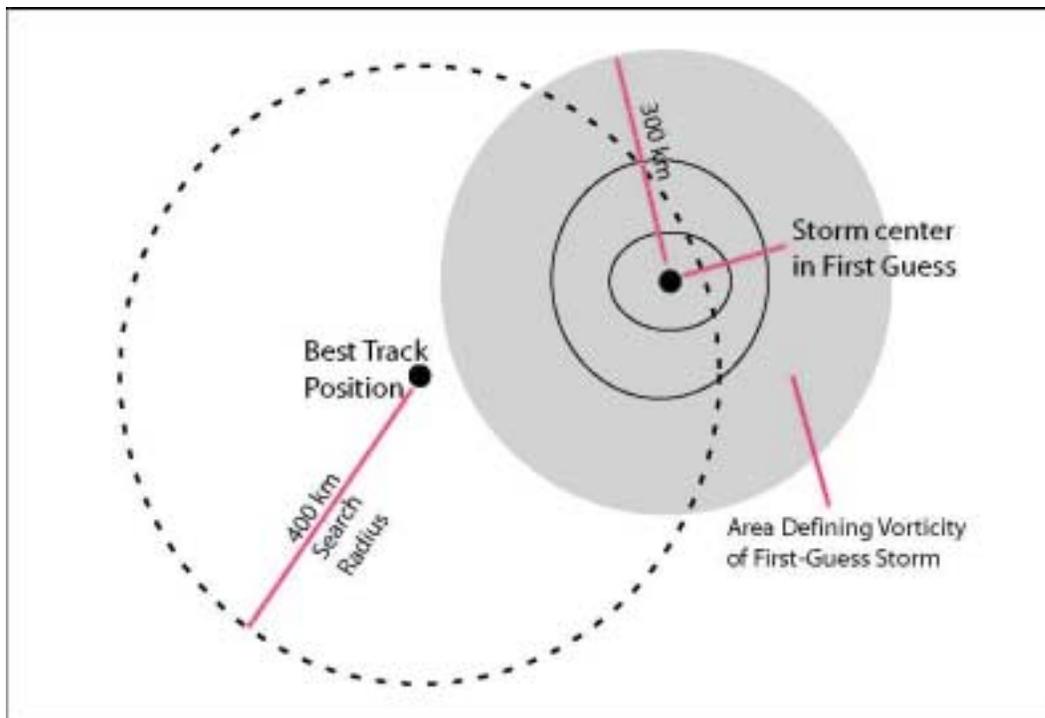


Figure 2. Schematic of search for vortex in first guess. Solid black contours are near-surface vorticity. Black filled circles indicate positions of the observed storm and of the vortex center in the first guess.

serves as the center of the vortex to be removed. Because the first guess has a coarse grid increment, the vorticity field on the MM5 grid has no small-scale variations that might complicate locating the center.

Once the first-guess vortex is located, there are many ways one might consider for removing it. For example, a scale-selective smoothing might be imposed to try to damp out the incorrect circulation. In the GFDL bogussing scheme (Kurihara 1993) a sophisticated filtering is used. However, smoothing can have adverse effects on the far field, and may not remove the entire storm from the first guess, or will likely leave significant imbalances in the modified background field. The general approach we adopt is to modify the vorticity, geostrophic vorticity, and divergence, then solve for the change in the non-divergent stream function, geopotential and velocity potential, respectively, and compute a modified velocity field.

The general approach to modifying the flow can be illustrated in the context of vorticity and non-divergent wind. The relationship between wind, stream function and vorticity is:

$$\nabla^2 \psi = \zeta , \quad (1)$$

$$v_\psi = \hat{k} \times \nabla \psi , \quad (2)$$

where  $\psi$  is the stream function for the non-divergent wind,  $\zeta$  is the relative vorticity and  $v_\psi$  is the non-divergent wind. To define the non-divergent wind associated with the first-guess storm, we set vorticity equal to zero outside a radius ' $r_m$ ', specify  $\psi=0$  on the lateral boundaries of the domain and solve (1) for a perturbation stream function  $\psi'$  on all pressure surfaces. From (2)  $v_\psi'$  is calculated and subtracted from the first-guess wind field.

Removal of divergent wind and pressure anomalies associated with the first-guess storm follows (1) and (2), except in the case of divergence, (1) and (2) are replaced by

$$\nabla^2 \chi = \delta , \quad (3)$$

$$v_\chi = \nabla \chi , \quad (4)$$

where  $\chi$  is the velocity potential,  $\delta$  the divergence and  $v_\chi$  the velocity potential. To remove the geopotential height anomaly (1) and (2) become

$$\nabla^2 \phi = \zeta_g f_0 , \quad (5)$$

$$v_g = \hat{k} \times \nabla \phi , \quad (6)$$

and we similarly set the geostrophic vorticity (subscript 'g') equal to zero outside  $r=r_m$  and solve for a geopotential anomaly  $\phi'$  to be subtracted from the background.

To remove the temperature anomaly field due to the first-guess storm, we use the hydrostatic relation,

$$\frac{\partial \phi'}{\partial \ln(p)} = -RT' \quad (7)$$

where  $R$  is the gas constant and  $p$  is the pressure. The temperature anomaly field is also removed, leaving a first-guess field with only a background wind and temperature where the first-guess storm was located (Fig. 3). Although in the current version of the scheme the background flow is unmodified, deviations between the background steering flow and storm track could be identified at this stage. The background flow could be altered by adding a vortex dipole whose associated wind field corrects the initial storm motion. Note that the bogus storm to be added is axisymmetric in the current version of the scheme and hence, will not affect the storm motion, at least close to the initial time.

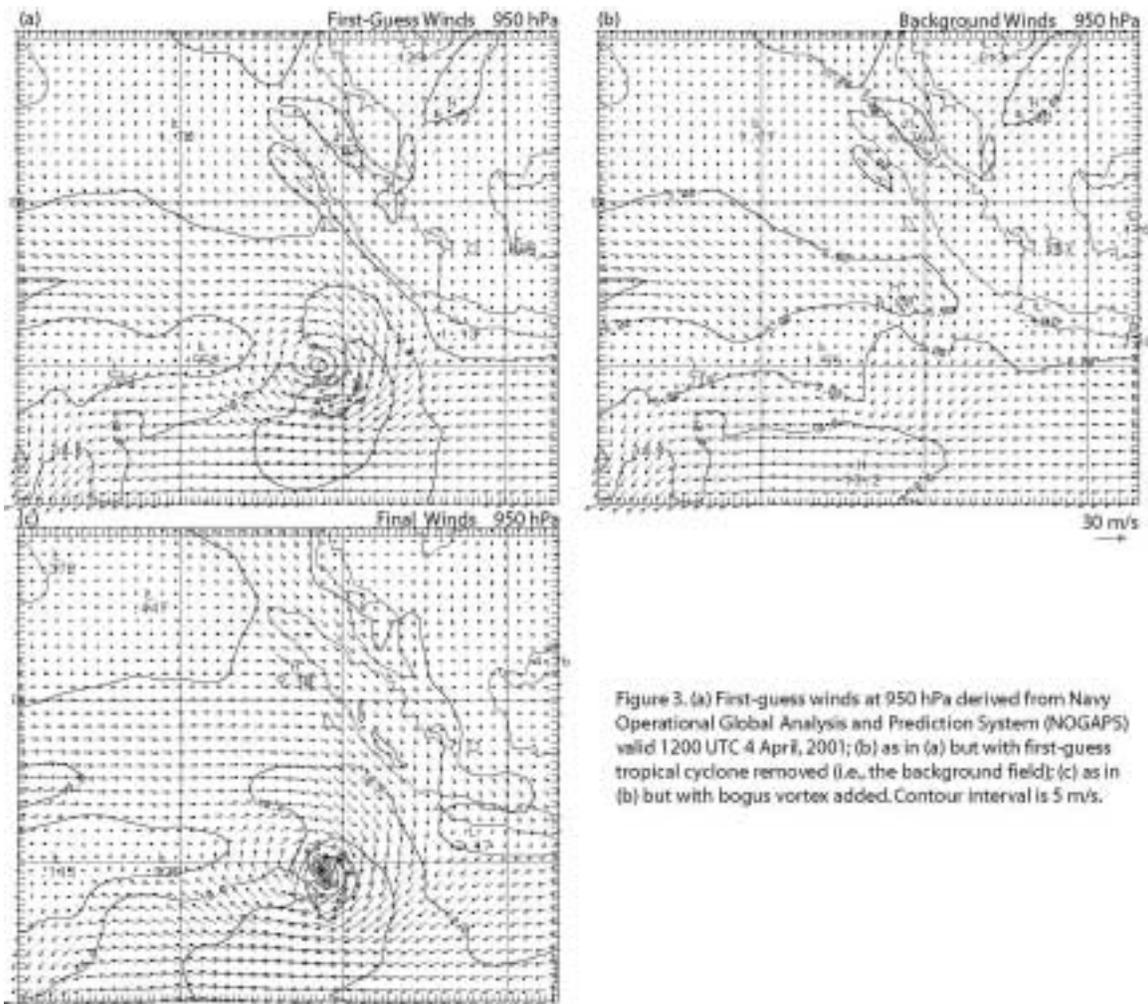


Figure 3. (a) First-guess winds at 950 hPa derived from Navy Operational Global Analysis and Prediction System (NOGAPS) valid 1200 UTC 4 April, 2001; (b) as in (a) but with first-guess tropical cyclone removed (i.e., the background field); (c) as in (b) but with bogus vortex added. Contour interval is 5 m/s.

## ***Addition of Bogus Vortex***

Because the input data to the NCAR-AFWA scheme is limited, consisting mainly of storm location and estimated maximum winds, the specification of a three-dimensional vortex structure is arbitrary, to some extent. The need for rapid integration of the model initialization scheme precludes the use of sophisticated schemes such as developed by Zou et al. (1999) based on four-dimensional, variational data assimilation (4D-VAR). The bogus storm profile chosen here is based on the following assumptions:

- (1) Axisymmetry.
- (2) Radius of maximum wind (RMW) fixed (90 km on 45-km grid).
- (3) Mass and wind fields in nonlinear balance.
- (4) Nearly saturated (w.r.t. water or ice) core; no eye (on 45-km grid).
- (5) Maximum winds of bogus storm are a pre-determined fraction of maximum winds observed.

Item (1) results from a lack of observations of asymmetries for many storms worldwide. The RMW (item 2) is specified to be two grid lengths on the 45-km grid, but on a 15-km grid, would be set to a value of 50-60 km. Tests integrating MM5 on a 45-km grid from initial conditions in which a storm with a radius of about 50 km was inserted suggest that the model is unable to resolve the velocity variation and quickly re-establishes the RMW near 90 km, where it remains. Regarding item (3), use of nonlinear balance, we recognize that this balance does not hold within the planetary boundary layer, where friction, and thermally-driven turbulence disrupt the state prescribed by nonlinear balance. Our approach is to let the model adjust the structure as it integrates, which appears to occur mainly with the first 1-2 h of integration. Item (5) is related to item (1). Because we specify a symmetric circulation, the maximum winds should be somewhat lower than the maximum wind reported, which may involve significant asymmetries. In general, we expect a greater relative difference between the two quantities for weaker tropical cyclones, but this is not taken into account.

The vortex wind profile is given by the simple Rankine vortex:

$$v = A(z)F(r) \quad (8)$$

$$F(r) = \frac{v_m}{r_m} r; (r \leq r_m)$$

$$F(r) = \frac{v_m}{r_m^\alpha} r^\alpha; (r > r_m)$$

for which we choose  $\alpha = -0.75$ . Other studies suggest slightly different values of  $\alpha$  typically around -0.5 (Riehl 1963). However, these profiles tend to be measured only within 150 km or so of the storm center. Such a profile yields velocities that are demonstrably too large at large radii (of order 500-1000 km) where the influence of the hurricane flow is often hard to deduce given the presence of other disturbances. The choice of  $\alpha = -0.75$  is a compromise to yield an approximately correct functional relationship near the storm and reduce the influence of the storm at large radii. We

discuss the possible future inclusion of more realistic wind profiles, based on the profiles produced by MM5 itself, later.

The amplitude and height dependence are contained in  $A(z)$ . We assume that the maximum azimuthally averaged wind is  $0.75V$ , where  $V$  is the reported maximum wind from the Best Track data. The coefficient 0.75 is based on several MM5 simulations of tropical cyclones of varying intensity with varying grid increments. The vertical weight function is specified to be unity from the surface through 850 hPa, 0.95 at 700 hPa, 0.9 at 500 hPa, 0.7 at 300 hPa, 0.6 at 200 hPa and 0.1 at 100 hPa.

## Results

An example of the effect of the bogussing on the model initial conditions and on the subsequent forecast is shown in Fig. 4. The example is tropical cyclone 19 (TC19) from the southern Indian Ocean. The model was initialized at 1200 UTC 4 April, 2001 using initial conditions obtained from the NOGAPS model through AFWA. Two forecasts were run, with and without bogussing. The microphysics used was the simple ice scheme of Dudhia (1989), and a resolution of 31 layers was used. These differed from the AFWA operational version, which used the Reisner et al. (1998) level I scheme and 41 layers, but the differences were not found to be significant. Two sets of bogus cyclone parameters were used. The first prescribes the radius of maximum wind to be 50 km and assumes that the maximum wind reported by the Best Track data represents the azimuthal mean maximum wind. Clearly, the bogus storm projects heavily onto 2-grid-point variation in this case and we expect significant smoothing of the structure as the model integrates. Such smoothing will limit the overall intensity.

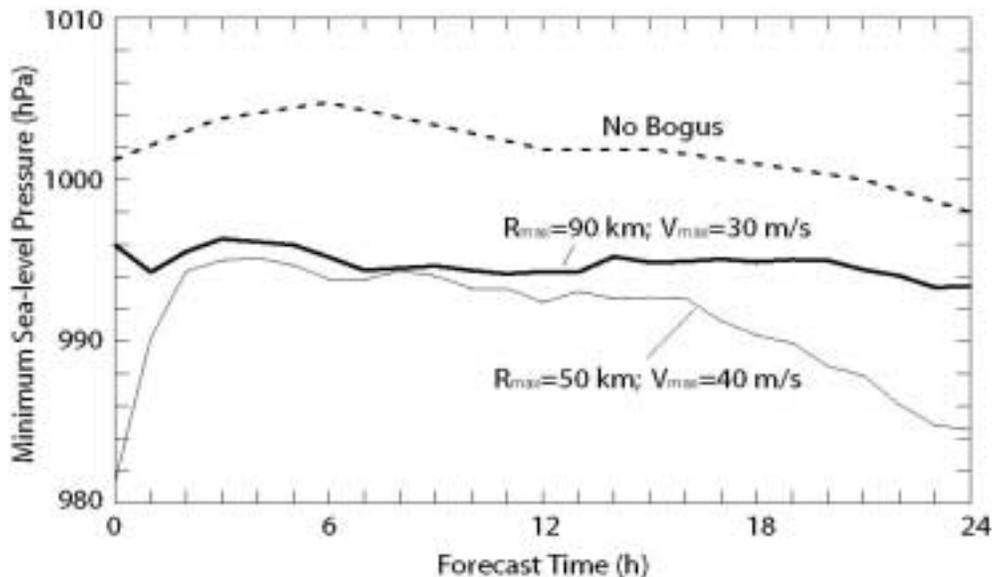


Figure 4. Time series of minimum sea-level pressure for 24 h forecasts for TC19 in the Indian Ocean (initialized 1200 UTC 4 April, 2001).

Furthermore, the maximum winds observed are often significantly higher than the maximum azimuthal mean wind, particularly for weaker storms or storms which are translating rapidly. Therefore, the second (and default) set of parameters specifies the RMW to be 90 km (for the 45-km grid) and the maximum azimuthal mean wind to be  $\frac{3}{4}$  of the reported maximum wind. These parameters were derived from two MM5 simulations, one from the present case, the other from Hurricane Floyd (1999) in the north Atlantic, during a time when the storm intensity was nearly constant.

From Fig. 4, it is apparent that the bogussing scheme which specifies a 50-km RMW (B50) leads to a rapid weakening of the storm in the first two hours. By 24 h, the storm has nearly reached its initial intensity, though the RMW is nearly 90 km. The observed central pressure is not known, but the maximum winds in TC19 show no net change over the 24 h period, beginning and ending at 40 m/s. The observed intensity peaks at 45 m/s at 0000 UTC and 0600 UTC 5 April. The maximum winds in B50 begin at 44 m/s, weaken to 32 m/s in the first hour, then increase gradually to 42 m/s by 24 h (1200 UTC 5 April). Thus, the intensity change in B50 has the wrong sign during most of the simulation. Furthermore, when the storm in B50 reintensifies, its RMW is 100 km. This reinforces the point that a smaller RMW is not sustainable on with a grid spacing of 45 km.

Using an RMW = 90 km and maximum wind of 30 m/s, simulation B90 exhibits nearly constant intensity for the 24-h period. The lack of a large adjustment in the first hour suggests that the structure imposed is much closer to that preferred by MM5. Note, too, that the storm in B90 is 5-10 hPa deeper than the simulation without bogussing, with maximum winds averaging about 33 m/s as opposed to 20-25 m/s without bogussing. Furthermore, the intensity change in the simulation without bogussing is out of phase with the observed change.

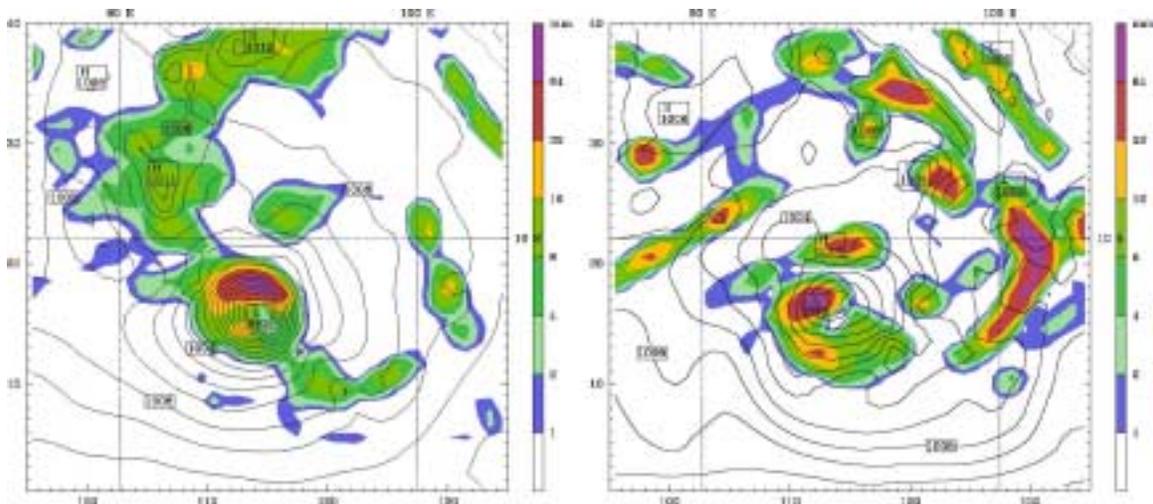


Figure 5. Comparison of 24 h forecasts of sea-level pressure and three-hourly precipitation valid 1200 UTC 5 April, 2001. At left is simulation with NCAR-AFWA bogussing scheme; at right is simulation with identical physics but no bogussing.

The sea-level pressure and precipitation fields from B90 and the no-bogussing simulation are shown in Fig. 5. The greater degree of axial symmetry in the B90 storm is apparent, as well as more overall organization in the precipitation pattern. In view of all these differences, we conclude that B90 yields the best simulation.

Considerable testing of the bogussing algorithm was also performed on a grid of 15-km spacing. On this grid, it is more reasonable to prescribe the radius of maximum wind to be 50 km (or smaller if there are observations that support it). In addition, the ratio of maximum azimuthal mean wind to maximum sustained observed wind may be higher than 0.75 (used for the 45-km grid) because the storm core should be resolved well enough that the simulation captures nearly the full intensity of the cyclone. We therefore recommend values between 0.85 and 0.9.

### ***Potential Improvements***

One of the shortcomings of the NCAR-AFWA bogussing scheme as it currently exists is that the storm imposed is symmetric and follows a Rankine-like wind profile. The vortex is assumed balanced and no adjustment is made for realistic structure in the boundary layer. In an effort to further reduce spinup problems, and as possibly a prelude to developing a scheme to use within an analysis-forecast cycle wherein the MM5 is used as a first guess, we suggest a method for prescribing a storm structure that is more in agreement with what the model produces.

In the case of the GFDL scheme, the radial profile of wind is taken from a barotropic model integration. This obviously fails to account for the full three-dimensional structure of the storm. From simulation B90, we can construct profiles at all levels by computing the radial profile of vorticity and velocity at many levels from the model solution and using this profile to specify the initial vortex structure. No balance need be assumed, but by using a time average to define the structure, some type of near balance is implicit. In Fig. 6, we see that a typical radial profile, this one from about 950 hPa, is smoother than the Rankine profile in which vorticity is a step function. The relatively greater variance of velocity at radii greater than 700 km indicates the radial distance intersects the boundary in some quadrant of the storm, in this case, toward the south. The disagreement between actual and integrated velocity is a function of poor definition of vorticity near the storm center, resulting from finite differencing the velocity field on the original model grid.

Instead of an analytical profile, use of data such as in Fig. 6 would be done with a lookup table for each level in the vertical. This method would allow better specification of the moisture field, boundary-layer structure, divergent wind profile and the anticyclone in the upper troposphere.

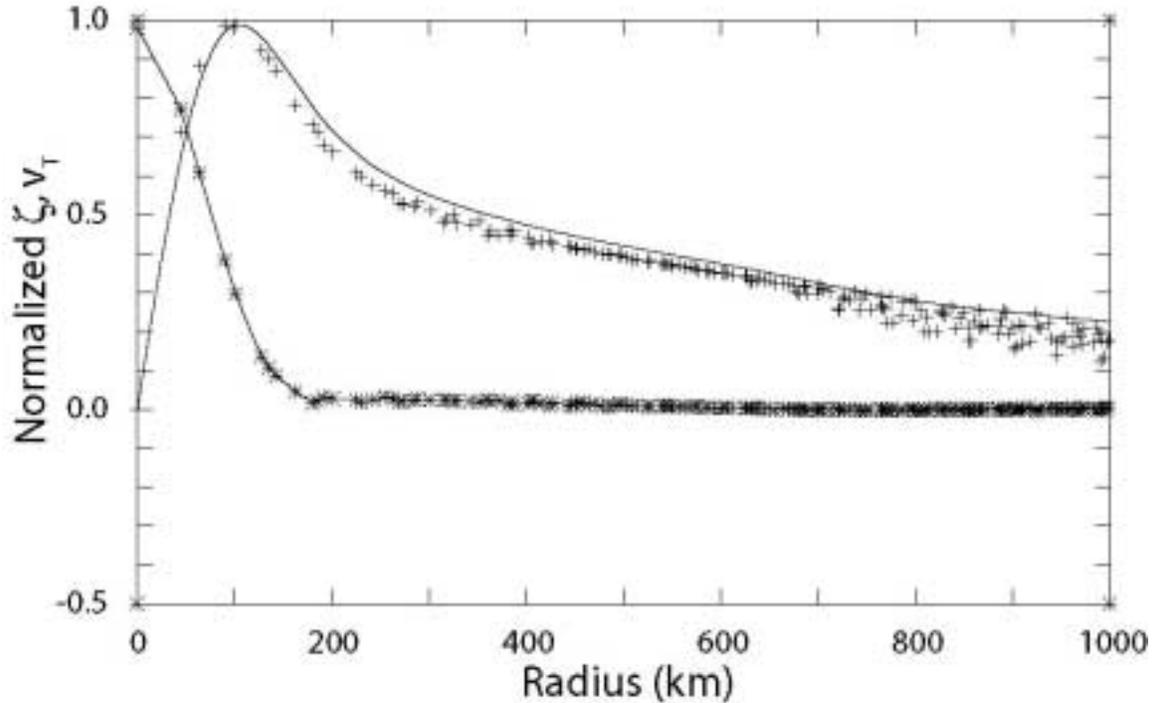


Figure 6. Radial profiles azimuthal mean relative vorticity and velocity, normalized by maximum value at any level. Asterisk symbols denote vorticity, corresponding solid line is a smoothed interpolation to 1 km resolution. Plusses denote velocity; corresponding line is obtained by integrating the vorticity outward from  $r=0$ .

## Conclusions

The NCAR-AFWA tropical cyclone bogussing scheme has been implemented into the preprocessing software of the MM5 model, thereby allowing the specification of more realistic tropical cyclone intensity with a dynamically balanced structure in the initial condition. The scheme appears to improve significantly upon the intensity of tropical cyclones present in first guess first from global models. The evolution of storm intensity during the first few hours of model integration does not feature rapid adjustment as can occur if the initial conditions are not balanced or if the initial structure is not resolvable on the model grid.

The scheme consists of an extraction of any storm that may be present near (within 400 km) the observed storm in the first guess. The methodology for the extraction departs significantly from the filtering method used by the Geophysical Fluid Dynamics Laboratory (GFDL). In the NCAR-AFWA scheme a series of Poisson-type equations are solved to calculate nondivergent, irrotational and geostrophic wind fields with the vortex to be removed. Temperature anomalies are calculated from the hydrostatic equation.

The bogus vortex is added to the background field obtained by removing the first-guess storm. In the current version of the scheme, a Rankine profile of bogus-storm tangential

wind is assumed, but more realistic profiles, based on profiles produced by the MM5, have been investigated and a plan for their incorporation has been developed.

The scheme is designed to improve the first guess conditions from which the MM5 initial conditions are derived. It is not intended for use with subsequent analysis packages because the imposed structure may be significantly distorted especially in the case of sparsely distributed observations. We are currently investigating methods of coupling the bogussing technique described in this report to more sophisticated initialization schemes wherein cycling of model forecasts and multivariate incorporation of observations is performed.

### ***Appendix: Choice of physical parameterizations and model configuration for tropical cyclone prediction***

While there is probably no single configuration of MM5 that is appropriate for all tropical cyclone predictions, work in recent years has led to a number of recommendations and the emergence of some systematic behavior when using particular schemes. These are listed below.

- (1) The MRF PBL scheme (Hong and Pan 1996) tends to produce boundary layers that are too deep and too dry outside the eye wall of mature hurricanes. This derives from excessive vertical mixing. For tropical storms and depressions, this bias is less of a concern. Experience suggests that when wind speeds approach 30 m/s, the PBL structure becomes unrealistic. The Burk-Thompson scheme (Burk and Thompson 1989) tends to produce the strongest storms. Braun and Tao (2000) compare PBL performance for hurricane Bob (1991). With grid spacings too large to resolve the core, the choice of PBL is probably less important than in high-resolution simulations.
- (2) A grid spacing of about 10-15 km is necessary to begin resolving the eye-wall structure. At coarser resolution, the maximum winds will typically underestimate storm intensity. At 45 km, the core of the storm typically has a diameter of about 2 grid points and cannot be resolved.
- (3) Reasonable predictions of tropical cyclones can be obtained for as few as 25-30 vertical levels. More levels may be needed when using finer horizontal grid spacing.
- (4) Large differences result from different choices of cumulus parameterizations. The Betts-Miller (Betts and Miller 1993) scheme is the most popular for tropical systems, but the reference profile must be carefully chosen. The default profile in MM5 is probably not adequate. Betts-Miller produces few downdrafts and has a tendency to spinup vortices too easily. The Kain-Fritsch scheme (Kain and Fritsch 1993) has not been run extensively in the tropics. As configured in the standard MM5, it tends to produce too much precipitation distributed over too wide an area. The Grell scheme (Grell 1993) tends to be relatively inactive and allow more grid-resolved precipitation. With weak tropical cyclones there can be numerous

small-scale cyclonic spinups away from the storm center. Grell is the only MM5 scheme that is routinely run near 10 km grid spacing.

- (5) At coarse resolution (>15 km grid spacing), cloud microphysics may be less important than the choice of PBL and cumulus schemes. Below 10 km grid spacing, and especially below 5 km, vertical velocities begin to approach particle fall speeds and microphysics becomes increasingly important. The scheme of Tao and Simpson (1993) is computationally expensive but has been tested more in the tropics than the other 3-category schemes used in MM5.
- (6) Coupling with the ocean so as to capture upwelling is probably critical for reasonably accurate intensity prediction. This is not currently available within the community version of MM5.

In summary, here are some recommendations for model physics.

45-km grid spacing:

Blackadar or Eta PBL (MRF may be adequate if storms are weak)  
 Reisner I or simple ice physics  
 Betts-Miller cumulus (tuned for tropics) or Grell cumulus

15-km grid spacing:

Blackadar or Eta PBL  
 Reisner I or simple ice physics  
 Grell cumulus

5-km grid spacing:

Blackadar or Eta PBL  
 Tao and Simpson or Reisner II  
 No cumulus scheme

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