USE OF RADAR DATA FOR TC INITIALIZATION AND PREDICTIONS

J.-L. Lee[1] and A.E. MacDonald[1]

[1]NOAA Research-Forecast Systems Laboratory, Boulder, Colorado

1. INTRODUCTION[1]

Hurricane track forecasts improve steadily over the last several decades primarily due to the increasing use of satellite observations in operational centers to improve large-scale environmental flow over ocean. However, intensity forecasts show very little improvement over the last decade because small-scale inner-core circulation can not be properly resolved by satellite observations. To improve intensity forecasts, it is important to use high-resolution Doppler radar data to properly initialize inner-core circulation for high-resolution numerical models. A technique is developed for initialization of a hurricane vortex using horizontal velocities through a deep layer of the atmosphere obtained from Doppler radar. The technique uses two new innovations. The first is the use of the mesoscale vorticity method (Lee et al. 2003) to diagnose the vertical velocity and divergent wind based on the vorticity equation including the tilting terms. The second is the use of mesoscale Bounded Derivative Initialization (Lee and MacDonald, 2000) to obtain two dynamic constraints, one each for gravity and sound waves. With the fast waves controlled, a nonhydrostatic model can be initialized to allow a smooth and balanced start. In this study, the mesoscale vorticity method is used to derive hurricane Danny's divergent wind/vertical velocity from the high temporal and spatial vorticity variations retrieved from the ground-based velocity track display (GBVTD) (Lee et al. 1999) technique based on single Doppler radar data. A four-dimensional data assimilation system (FDDA) (Stauffer and Seaman, 1990) based on Newtonian relaxation/nudging is used to generate the dynamically consistent datasets for unobserved fields such as heating and cloud fields.

2. NUMERICAL METHODS

Numerical methods used to derive the initial field for a tropical cyclone include the vorticity method, BDI, GBVTD, and FDDA. These methods are described in detail by Lee et al. (2003) for the vorticity method, Lee and MacDonald (2000) for the mesoscale BDI, Lee et al. (1999) for GBVTD, and Stauffer and Seaman (1990) for FDDA. Following is a brief summary of the mesoscale vorticity method and BDI.

2.1 The Mesoscale Vorticity Method

The variation of vorticity in time and space can be used to derive the vertical velocity through the vorticity equation. The dimensionless vorticity equation can be written in terms of the parameter $\varepsilon = 10^{-1}$ as follows:

$$[\frac{\partial \zeta}{\partial t} + V_h \cdot \nabla_h(\zeta + f) + \varepsilon^n w \frac{\partial \zeta}{\partial z}] =$$

$$-(f + \varepsilon^n \zeta)\, \nabla_h \cdot V_h - \varepsilon^n \vec{k} \cdot \nabla_h w \times \frac{\partial V_h}{\partial z}$$

$$-\varepsilon^{3-2n} \frac{1}{\rho_s^2} \vec{k} \cdot \nabla_h p \times \nabla_h \rho \ , \qquad (1)$$

where

$$n = \begin{cases} 1 & \text{for } L \sim 10^6 \quad \text{m} \\ 0 & \text{for } L \sim 10^5 \quad \text{m} \end{cases} .$$

The horizontal and vertical components of wind are $V_h = (u, v)$ and w; the vorticity ζ is defined as $\zeta \equiv \partial v/\partial x$ - $\partial u/\partial y$, and f is the Coriolis parameter. The horizontal gradient operator is defined as $\nabla_h = (\frac{\partial}{\partial x}, \frac{\partial}{\partial y}, 0)$. In addition, p and ρ denote pressure and density, respectively.

The vorticity equation, valid for the large-scale and mesoscale motion, is obtained by retaining $O(1)$ terms with $n = 1$ or $n = 0$, respectively. Because $\varepsilon^{3-2n} \ll 1$ for both the large

---

[1] *Corresponding author address:* Jin-Luen Lee, NOAA Forecast Systems Laboratory, FSL, 325 Broadway, Boulder, CO 80305-3328, e-mail:jin.lee@noaa.gov

scale and mesoscale, the solenoidal term is negligible to a first approximation in both scales. The vorticity equation with $n = 1$, i.e., the quasi-geostrophic (Q-G) vorticity equation, has been used by Sawyer (1949), Sardeshmukh and Hoskins (1987), Lee and Browning (1994) and Lee et al. (1995) to derive the large-scale vertical velocity. The use of Q-G vorticity equation in previous studies may be justified by the limitation of data resolution (e.g., Lee et al. 1995). However, with high resolution Doppler radar data, the vorticity method has to be applied based on the mesoscale vorticity equation including the tilting terms. Unfortunately, it's not possible for the mesoscale vorticity method to separate w from other terms in Eq.(1) formulated on the Eulerian coordinate.

In order to achieve the separation of variables, the mesoscale vorticity equation, Eq. (1), is rearranged into the following equation for w in terms of the characteristic line as follows:

$$\begin{aligned}\frac{dw}{ds} &= aw_x + bw_y + cw_z \\ &= w\left(\frac{\partial \eta}{\partial z} - \frac{\eta}{\rho_0(z)}\frac{d\rho_0(z)}{dz}\right) + \frac{d_h \eta}{dt}\end{aligned}$$

where,

$$\begin{aligned}a &= \frac{dX}{ds} = -\frac{\partial v}{\partial z} \\ b &= \frac{dY}{ds} = \frac{\partial u}{\partial z} \\ c &= \frac{dZ}{ds} = \eta\end{aligned}$$

The above equation is an ordinary differential equation (ODE) for w formulated on the characteristic line s, and s denotes the arc length along which the solution is to be solved. A step-by-step numerical procedure for solving the characteristic equation is given in Lee et al. (2003).

2.2 Mesoscale BDI

Bounded derivative initialization (BDI) is based on the bounded derivative principle (Kreiss, 1989) which states that if the solution of a symmetric hyperbolic system is to vary smoothly, then a number of time derivatives must be of the order unity at the initial time. BDI (Browning et al. ,1980, Kasahara, 1982) derives initial data so that a number of time derivatives of the dependent variables at initial time are of order one. In the context of large-scale baroclinic primitive equation model, Kasahara (1982) demonstrated in theory that BDI and NMI are identical to the degree of approximations expected from quasi-geostrophic assumption employed in the study. This theoretical conclusion was reinforced by Semazzi and Navon (1986), Bijlsma and Hafkenscheid (1986) in real data large-scale simulations. In a recent study, Lee and MacDonald (2000) further extended large-scale BDI to include mesoscale variations with formulation over complex terrain.

3. NUMERICAL RESULTS

Hurricane Danny (1997) approached the data-rich Alabama coast area on 18 July 1997. In this study, the GBVTD technique has been applied to the Slidell (KLIX) single-Doppler data to derive high temporal resolution of horizontal wind and vorticity fields. The spatial resolution of the wind data is 1 km in the horizontal and vertical from a minimum height of 1 km above the ground level (AGL) to a maximum height of 10 km AGL. These high temporal and spatial wind/vorticity fields are used to derive the vertical velocity using the vorticity method. Figure 1 shows the vertical crossection of Danny's inner-core wind vectors derived from the mesoscale vorticity method based on single-Doppler radar wind measurements obtained from GBVTD. The vertical crossection extends vertical from 1-km to 10-km above the ground. It is oriented longitudinally across the center of hurricane Danny with the eye located near the center of the figure. Figure 1 clearly show Danny's inner-core circulation. For example, a deep layer of downward motions can be found over the region of the eye. These downward motions break into two branches, one moves outward to the east and the other to the west of the eye. These outflows converge with the strong inflows and result in narrow bands of strong upward motions over the eye wall region located at approximately 15-20 km around the center of the eye. These strong upward motions tilt outward vertically and correspond very well with the strong echoes in the eye wall. We have derived the detailed inner-structure of Danny's kinematic wind fields every six minutes from single Doppler radar wind measurements. The inner-core mass fields can be derived from these high resolution kinematic wind fields. These inner-core kinematic and mass fields were inserted into the 1.5-km resolution MM5 model with MM5 FDDA for the balanced heating and cloud fields. These balanced initial fields were numerically integrated with 1.5-km resolution MM5 model for the 16-hour forecast of hurricane Danny until its landfall at Mobil Bay, Louisiana. Figure 2 shows the intensity forecast of wind at the inner core of hurricane Danny. The curve in figure shows the root mean square error (RMSE) in the horizontal wind verified against the GBVTD radar analysis wind field. Each point in the RMSE curve represents the differences in the horizontal wind between the forecast and GBVTD analysis over the inner-core area from 1 km to 5 km above the sea level. It shows the forecast wind RMSE is approximately on the order of 5 m/s over the 16-hour forecast period before the land fall.

4. DISCUSSION

We have developed a tropical storm initialization scheme that utilizes the mesoscale vorticity method, BDI and FDDA to derive a balanced hurricane inner-core vortex from single Doppler radar wind measurements. This initialization scheme is tested using the 1.5-km resolution MM5 model with real radar data from Hurricane Danny as it approached the Gulf Coast. Numerical results show positive radar data impacts on track and intensity forecasts. The initialization scheme correctly inserts the observed storm derived from radar data in the right location, and the forecast storm track closely follows the actual storm track after the initialization. Comparisons of forecast winds and radar wind measurements show the use of radar data substantially improves the intensity and horizontal structure of forecast wind fields.

5. REFERENCES

Bijlsma, S.J., and L.M. Hafkenscheid, 1986: Initialization of a limited area model: A comparison between the nonlinear normal mode and bounded derivative methods. *Mon. Wea. Rev.*, **114**, 1445-1455.

Browning G.L., A. Kasahara, and H.-O. Kreiss, 1980: Initialization of the primitive equations by the bounded derivative method. *J. Atmos. Sci.*, **37**, 1424-1436.

Kasahara, A., 1982: Nonlinear normal mode initialization and the bounded derivative method. *Rev. Geophys. Space Phys.*, **20**, 385-397. Kreiss, H.-O. and J. Lorenz, 1989: *Initial Boundary Value Problems and the Navier-Stokes Equations.* Academic Press, 402 pp.

Lee, J.L. and G.L. Browning, 1994: Analysis of errors in the horizontal divergence derived from high temporal resolution of the wind. *Mon. Wea. Rev.*, **122**, 851-863.

Lee, J.L., G.L. Browning, and Y.F. Xie, 1995: Estimating divergence and vorticity from the wind profiler network hourly wind measurements. *Tellus*, **47A**, 892-910.

Lee, J.L. and A.E. MacDonald, 2000: QNH: Mesoscale bounded derivative initialization and winter storm test over complex terrain. *Mon. Wea. Rev.*, **128**, 1037-1051.

Lee, J.L., Y.-H. Kuo, and A.E. MacDonald, 2003: The vorticity method: Extension to mesoscale vertical velocity and validation for tropical storms. *Quart. J. Roy. Meteor. Soc.*, **129**, 1029-1050.

Lee, W.-C., B. J.-D. Jou, P.-L. Chang, and S.-M. Deng, 1999: Tropical cyclone kinematic structure retrieved from single-Doppler radar observations. Part I: Interpretation of Doppler velocity patterns and the GBVTD technique. *Mon. Wea. Rev.*, **127**, 2419-2439.

Sardeshmukh, P.D. and B.J. Hoskins, 1987: On the derivation of the divergent flow from the rotational flow: The chi problem. *Quart. J. Roy. Meteor. Soc.*, **113**, 339-360.

Semazzi, F.H.M. and I.M. Navon, 1986: A comparison of the bounded derivative and the normal-mode initialization methods using real data. *Mon. Wea. Rev.*, **114**, 2106-2121. Sawyer, J.S., 1949: Large scale vertical motion in the atmosphere. *Quart. J. Roy. Meteor. Soc.*, **75**, 185-188.

Stauffer, D.R., and N.L. Seaman, 1990: Use of four-dimensional data assimilation in a limited-area mesoscale model. Part I: Experiments with synoptic data. *Mon. Wea. Rev.*, **118**, 1250-1277.

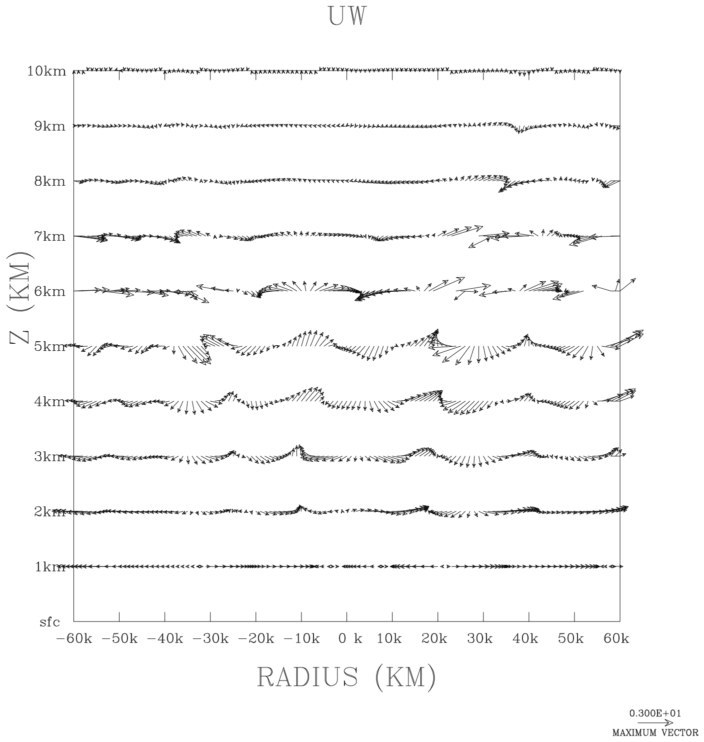

Figure 1: The vertical crossection of inner-core wind vectors derived from Doppler radar wind measurements using the vorticity method.

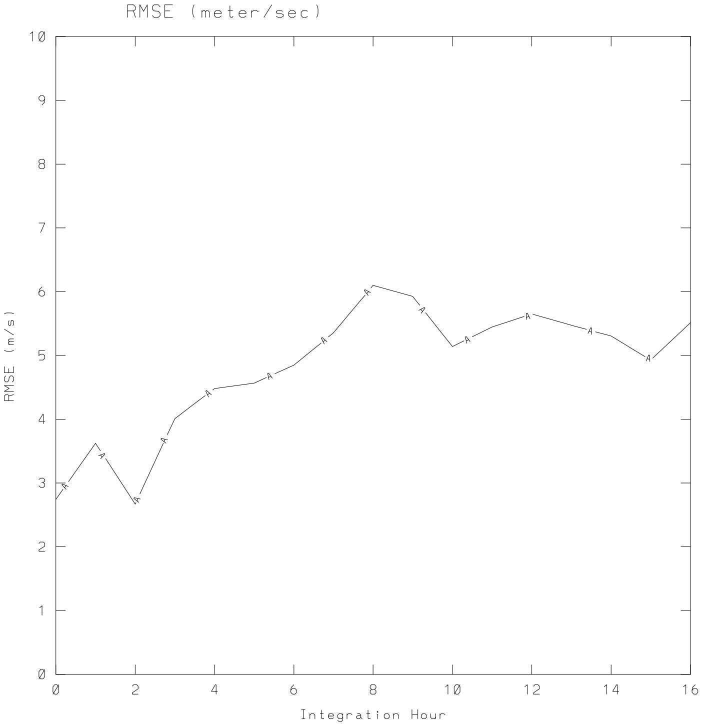

Figure 2: The forecast RMSE in wind field averaged over the inner core area extending from the height of 1-km to 5-km above the sea level.