USING 4D-VAR TO MINIMIZE PROPERTY DAMAGE IN AN MM5-SIMULATED HURRICANE

R. N. Hoffman,* J. M. Henderson, and S. M. Leidner
Atmospheric and Environmental Research, Inc.

1 INTRODUCTION

Hoffman (2002) has discussed the possibility of controlling the global weather by introducing a series of small, precisely calculated perturbations. In the preliminary work reported here, we take a small component of the global weather control system of Hoffman (2002) and put it into practice, in an admittedly crude manner. We demonstrate the ability of a currently available data assimilation technique, four-dimensional variational analysis (4d-VAR), to estimate the perturbations needed to locally "control" the weather.

The motivation to modify the weather is especially strong in the case of tropical cyclones. The AMS policy statement "Hurricane Research and Forecasting" (AMS 2000) summarizes the hazards of tropical cyclones over land: loss of life and nearly $5 billion (in 1998 dollars) annually in damage due to the storm surge, high winds, and flooding. The economic cost continues to rise due to growing population and wealth in coastal regions.

According to the Hurricane Andrew Reanalysis Project (HRD 2002), Hurricane Andrew (1992) is only the third Category 5 (Simpson 1974) hurricane to make landfall in the US since records began. Damage of approximately $26 billion was inflicted on southern Florida and Lousiana, and 23 people were killed. The storm first made landfall on the US mainland near Homestead at 0905 UTC 24 August with a central pressure of 922 hPa. Maximum sustained winds at landfall were estimated at 75 ms^{-1}. Andrew is a fine example of a storm that would have had less impact, in terms of wind damage, on the US coastline if the track had been displaced farther south by as little as 150 km.

To this end, we apply the Penn State/NCAR Mesoscale Model 5 (MM5) 4d-VAR-system with the goal of repositioning a simulation of Hurricane Andrew farther to the south. MM5 produces very detailed and accurate simulations of tropical cyclones when high resolution and advanced physical parameterizations are used (*e.g.*, Liu et al. 1999). However, in the current experiments, coarse resolution is used for computational efficiency. For the purpose of our demonstration, the unperturbed MM5 simulation is taken to be reality.

*Corresponding author: R. N. Hoffman, Atmospheric and Environmental Research, Inc., 131 Hartwell Avenue, Lexington, MA 02421. e-mail: rhoffman@aer.com

2 MESOSCALE MODEL AND DATASETS

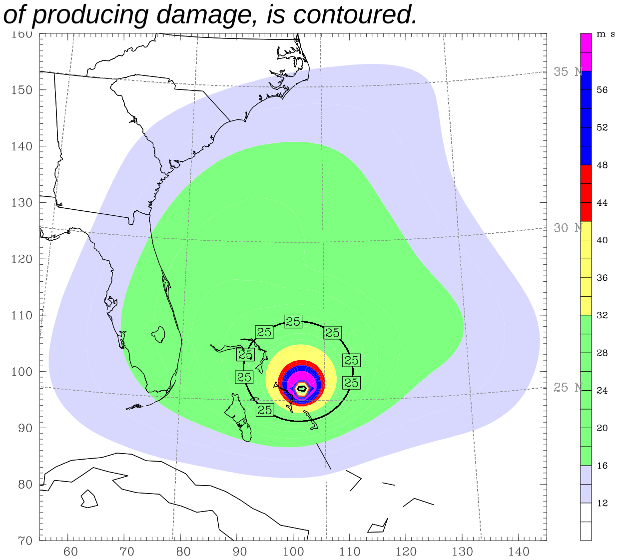
The MM5 is described in detail by Grell et al. (1994). In our experiments, the dimensions of the MM5 computational grid are 200 $\times$ 200. The horizontal resolution is 20 km with ten sigma layers in the vertical from the surface to 50 hPa. Only basic physical parameterizations are currently available in the MM5 4d-VAR system: MRF PBL scheme, Kuo cumulus convection, stable explicit moisture, and simple radiative transfer.

The first simulation we present is a 24-h integration with initial and boundary conditions provided by the 6-hourly NCEP-NCAR reanalysis fields (Kalnay et al. 1996); the inital time of this "unperturbed" run is 1800 UTC 23 August 1992. A vortex of intensity equal to the observed was bogussed into the initial conditions using the NCAR/AFWA MM5 tropical cyclone bogussing system (Davis and Low-Nam 2001). At the initial time (Fig. 1), Andrew is a Category 4 storm. The second simulation (hereafter, "controlled"), with an initial time of 0000 UTC 24 August 1992, is an 18-h integration using initial conditions modified by 4d-VAR. The 6-h forecast fields from the unperturbed simulation provided input to 4d-VAR. The simulations cover Andrew's westward translation towards south Florida.

3 CALCULATION OF PERTURBATIONS

The MM5 implementation of 4d-VAR is described by Zou et al. (1997). 4d-VAR can be used to find the smallest global perturbation, as measured by the *a priori*, or background, error covariances, at the start of each data assimilation period so that the solution best fits all the available data. 4d-VAR solves this complex nonlinear minimization problem iteratively (we permit 10 iterations), making use of the

Figure 1: *Surface (lowest sigma layer) wind speed (ms^{-1}), shaded by Saffir-Simpson category, valid at 1800 UTC 23 August 1992. The 25-ms^{-1} isotach, representing the lowest wind speed capable of producing damage, is contoured.*



adjoint of a linearized version of the model.

In our experiments, 4d-VAR determines the optimal atmospheric state trajectory $C_{xijk}(t)$ which simultaneously minimizes the size of the initial perturbation (using a quadratic norm) and a penalty function, based on surface wind speed, that is evaluated at a later time when damaging winds are over land. The total cost function, therefore, is given by $J = J_0 + \lambda J_d$, where the subscript d stands for damage and λ is a weighting factor. In the above equation, J_0 represents the size of the initial perturbation and is represented in the cost function by a simple quadratic norm:

$$J_o = \sum_{xtk} \frac{1}{S_{xk}^2} \left[\sum_{i,j} \{C_{xijk}(t) - G_{xijk}(t)\}^2 \right]. \quad (1)$$

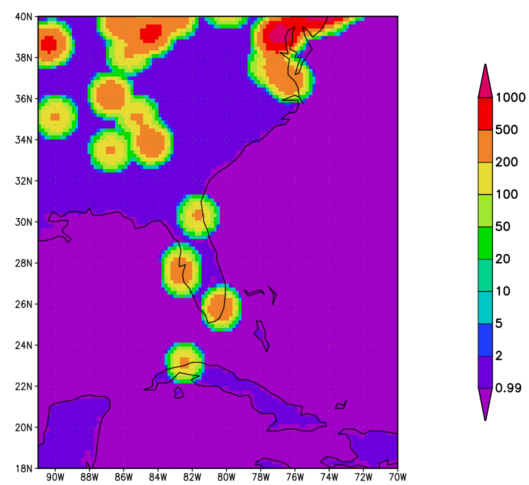
Here x represents the one control vector variable, temperature; i, j, and k index the grid points in the three spatial dimensions; t denotes time; and the scaling S_{xk} depends only on variable and layer and represents the maximum absolute difference between the unperturbed model trajectories $U(t = 0)$ and $U(t = 40min)$ for each variable at each layer. We define $G(0)$ to be the unperturbed initial conditions.

The damage cost function J_d is written in terms of physical damage estimates based on an empirical relationship between surface wind speeds and economic damage. The contribution to the cost function at each grid point is the product of the fractional wind damage D_{ij} and the property value P_{ij}. Thus, $J_d = \sum_{i,j} D_{ij} P_{ij}$. The fractional damage (Unanwa et al. 2000) depends upon two threshold wind speeds; the lower threshold v_0 is the wind speed at which damage to property first occurs, while the second v_1 is the wind speed at which complete destruction occurs. Between these two threshold values, we model the increase in damage using a cosine curve:

$$D_{ij} = 0.5 * (1. + cos(\pi(v_1 - V_{ij})/(v_1 - v_0)),$$

where V_{ij} is the horizontal wind speed. The thresholds v_0 and v_1 could vary depending on property type at each grid point, but here are fixed at 25 and 90 ms^{-1}, respectively. A basic two-dimensional property value field was generated by applying a smoother to the MM5's representation of urban grid points (Fig. 2). By smoothing the urban grid points, we penalize damaging winds near, as well as over, land.

Figure 2: *The relative property value field based on a smoothed 20-km land use field.*



The wind damage cost function is evaluated every 15 min between hours 4 and 6 during the 6-h assimilation window that ends 0600 UTC 24 August 1992. The high frequency of evaluations prevents the storm from regenerating during the 2-h window.

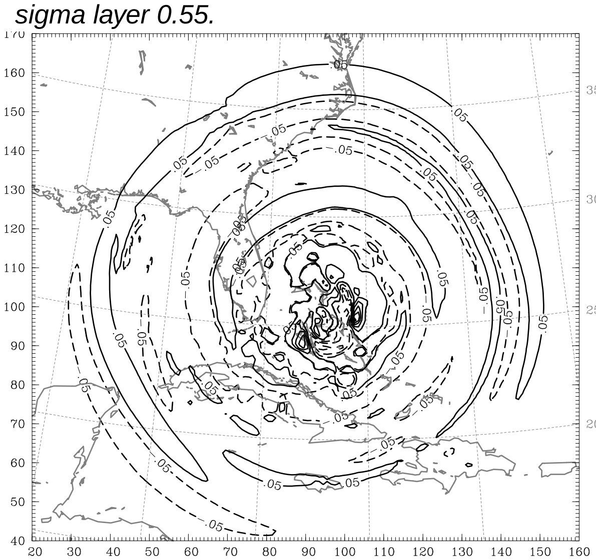
We permit changes in the initial conditions to the temperature field only. Note that the other model variables—horizontal winds, specific humidity, vertical velocity, and pressure relative to the reference state—are not included in the definition of J_o, and are not allowed to vary.

4 RESULTS

a. 4d-VAR increments

The initial-time temperature increments (Fig. 3), which are constrained by the unmodified background field, are relatively small. Of note is a fairly chaotic region (maximized in mid and upper levels) of positive and negative increments (magnitudes in isolated areas of 5 K) near the center of the vortex. At larger radial distances, concentric rings (magnitudes $<$ 1 K) of alternating positive and negative increments move radially outward during the 6 h of the assimilation window.

Figure 3: *4d-VAR temperature increments (K) at sigma layer 0.55.*

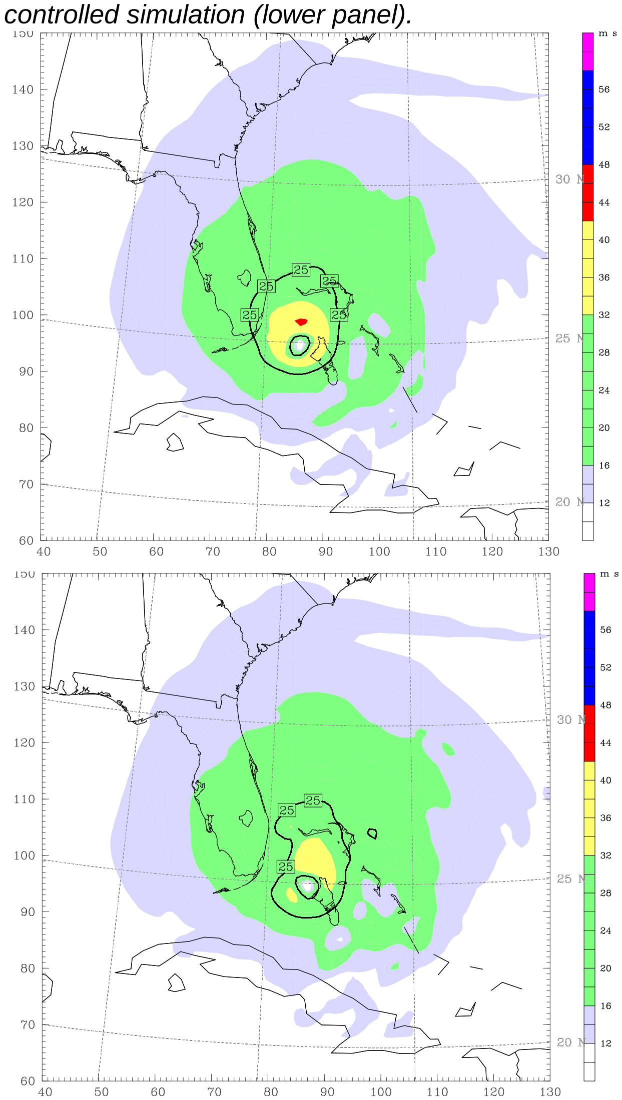


b. unperturbed and controlled simulations

Andrew, in the unperturbed simulation, weakens steadily from a strong Category 4 storm as it approaches Florida. During the evaluation period of the wind damage cost function (0400-0600 UTC), damaging winds are extensive over southeastern Florida; see the upper panel of Fig. 4, valid at 0600 UTC. The storm then passes south of the mainland; intensification back to Category 3 strength occurs in the Florida Keys.

In the controlled simulation, the 4d-VAR increments act to restrict the magnitude and extent of surface winds at the evaluation times of the wind damage cost function. Comparing the upper and lower panels of Fig. 4 shows the reduced area of damaging winds (winds $>$ 25 ms^{-1}) over, and near, Miami, and the nearshore waters. The relatively high property values of Miami penalize damaging winds in these regions. However, the controlled storm's surface winds regenerate after the final evaluation of the cost function at hour 6, though not during the two hour window of evaluation. The storm then also passes south of the mainland. Unfortunately, this application of 4d-VAR does not result in a substantial shift in the track of Hurricane Andrew, even though we present 4d-VAR with a property damage field that would facilitate passage between Key West and Cuba.

Figure 4: *As in Fig. 1, except for 0600 UTC 24 August 1992 for the unperturbed (upper panel) and the controlled simulation (lower panel).*



5 DISCUSSION

The study described here shows that 4d-VAR can be used to calculate "optimal" perturbations to control the intensity of a simulated tropical cyclone.

Results show that, while we were able to lower the wind speeds during the cost function evaluation period, the surface winds increased soon afterward. This observation is consistent with previous attempts with Hurricane Andrew and 1992 Pacific Hurricane Iniki. Those experiments used the wind damage cost function evaluated at a single time level and with a simple property value field based only on the MM5 terrain field. Apparently, it is easier to weaken the storm along its original path than fight the steering flow winds, which were robust in an extensive area surrounding the two storms. However, preliminary experiments for Iniki which used a displaced "target" hurricane were successful in moving the controlled storm to the target location (Hoffman et al. 2002).

The amount of energy contained in the 4d-VAR increments is enormous. For a similar experiment using Hurricane Iniki, the energy requirement was 10^{16} J, which is approximately 3% of the total annual US energy output from nuclear power (NUREG 2002).

Further progress on some of the technical issues, which made lead to reductions in the energy requirements, may be made by refining the 4d-VAR study presented here. In future experiments, we could:

-Use higher resolution for the MM5 grids and improved physical parameterizations in the 4d-VAR system.

-Increase the lead time in an attempt to decrease the size of the perturbations.

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