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USING 4D-VAR TO MOVE A SIMULATED TROPICAL CYCLONE IN A MESOSCALE MODEL

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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, by demonstrating 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.

Central Pacific Hurricane Iniki (1992) had a tremendous impact on parts of the Hawaiian Islands, causing extensive damage to property and vegetation and killing six people (CPHC 1992). The storm made landfall on Kauai at 0130 UTC 12 September 1992, with a central pressure of 945 hPa. Maximum sustained winds over land were estimated at 60 ms^{-1} with gusts as high as 80 ms^{-1}. Iniki is a fine example of a storm which would have had less impact, in terms of wind damage, on the Hawaiian Islands if the track had been displaced farther west by as little as 100 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 Iniki farther to the west. 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.

2 MESOSCALE MODEL AND DATASETS

The MM5 used in our experiments is described by Grell et al. (1994). In our experiments, the MM5 computational grid is a 97 × 79 40-km horizontal mesh 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: bulk surface fluxes, Kuo cumulus convection, and simple radiative transfer. To maintain a vortex of hurricane intensity using these simple parameterizations, we increase the observed sea surface temperature by 5° C in our simulations.

We run two sets of simulations. The first set consists of two 48-h simulations with initial conditions valid at 0600 UTC 10 September 1992 (hereafter, "case 1"), while the second set consists of two 30-h simulations with initial conditions valid at 0600 UTC 11 September 1992 (hereafter, "case 2"). All simulations cover Iniki's northward translation towards Hawaii. The first simulation of each case study is initialized from unmodified initial conditions (hereafter, "unperturbed"), while the second uses initial conditions modified by 4d-VAR (hereafter, "controlled"). The case 1 boundary conditions and unmodified initial conditions are provided by the inner domain of a cycling data assimilation experiment described by Louis et al. (2002). The experiments of Louis et al. made use of the MM5 model, a version of optimal interpolation, the best track data, and NCEP-NCAR reanalysis project gridded data fields (Kalnay et al. 1996) for boundary conditions. The case 2 boundary conditions and unmodified initial conditions are provided by 6-hourly NCEP-NCAR reanalysis fields. Due to the coarse resolution and simple parameterized physics used here, our simulations are only crude representations of Iniki's observed track and intensity. They are presented to demonstrate the ability of 4d-VAR to reposition a hurricane.

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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, making use of the adjoint of a linearized version of the model.

The basic experiment reported here is a variation on 4d-VAR. Consider the unperturbed simulation as reality. We seek a controlled state close to the observed state at the initial time ($t = 0$), such that at a later time ($t = T$), the controlled simulation is close to a target state. Then, if we perturb the atmosphere to match our calculations, the atmosphere will evolve to be close to the target. We define the unperturbed simulation U, from time 0 to T, with corresponding states $U(0)$ and $U(T)$. For each of cases 1 and 2, the target state $G(T)$ has the tropical cyclone positioned approximately 100 km west of the position in $U(T)$. We then use 4d-VAR to find an optimal controlled simulation C by simultaneously minimizing the difference from the target (i.e., $C(T) - G(T)$) and the initial state (i.e., $C(0) - U(0)$). In other words, $C(0) - U(0)$ is the minimal perturbation to get within $C(T) - G(T)$ of the target.

In these preliminary experiments, both the target mismatch and the size of the initial perturbation are represented in the cost function by a simple quadratic norm:

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

Here x defines the three control vector variables (temperature and the horizontal wind components), i, j, and k index the grid points in the three spatial dimensions, and t denotes time (either 0 or T). For convenience in writing (1), we define $G(0) = U(0)$, i.e., the goal at $t = 0$ is to stay close to the unperturbed initial conditions.

The controlled initial conditions reported here are calculated by applying 4d-VAR during the first six hours of the simulation to best match a target state in which the cyclone has been repositioned to the west. Ten iterations of the 4d-VAR minimizer were sufficient.

The scaling S_{xk} depends only on variable and layer and is used to equalize the contributions of variables of different magnitudes. S_{xk} is calculated as the maximum absolute difference between $U(0)$ and $U(\delta t)$ for each variable at each layer; δt is taken to be 40 minutes.

Since the conventional 4d-VAR setup that we use allows changes to the entire control vector, there are changes to other variables at all layers and at large distances from the center of the tropical cyclone. Note that the other model variables—specific humidity, vertical velocity, and pressure relative to the reference state—are not included in the definition of J, but are allowed to vary.

Also, to create the target state, we did not simply move the entire grid since this would have created discontinuities at the lateral boundaries. Instead, we used a smoothly varying vector field of displacements to adjust the unperturbed forecast. The methodology is analogous to the feature calibration and alignment technique described by Hoffman and Grassotti (1996), except that here the adjustment is found by fitting a number of prescribed displacement vectors.

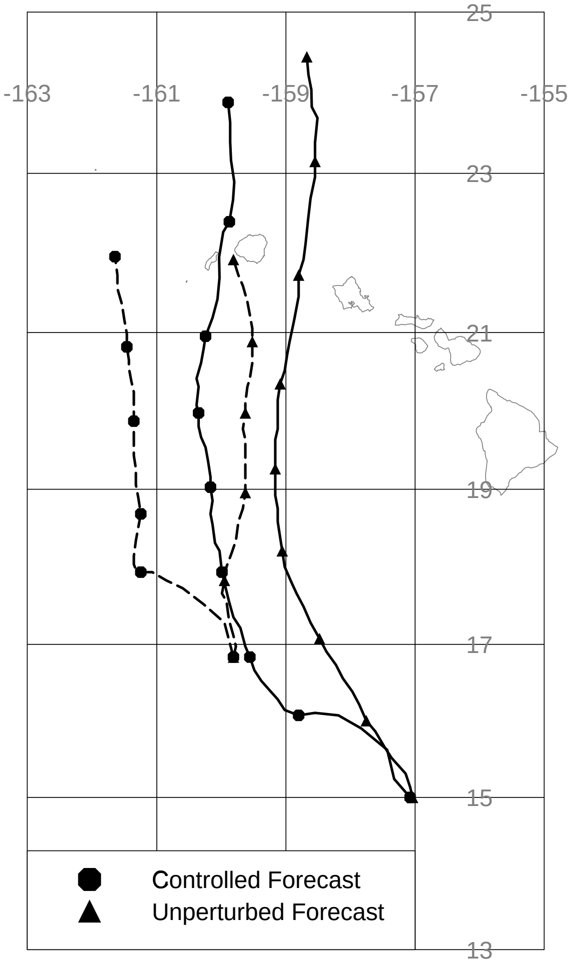
4 RESULTS

The unperturbed and controlled forecast tracks are plotted for both cases in Fig. 1. The Hawaiian islands are included to provide context for our attempt at steering the hurricane away from the islands. For both case studies, the exercise in 4d-VAR has successfully repositioned Hurricane Iniki to the west by the desired amount. The strongest winds remain offshore in case 2. In case 1, however, the unperturbed track reflects a poor model simulation, emphasizing the need for realistic unperturbed simulations using a well-positioned storm in the initial conditions and more complex physical parameterizations in the MM5.

In the unperturbed simulations, the tropical cyclone travels north-northwest ∼100 km during the first 6-h period. The application of 4d-VAR in the controlled simulations weakens the tropical cyclone during most of the forecast periods. At 6 h (i.e., at $t = T$), the MM5 4d-VAR system positions the controlled tropical cyclones (Fig. 1) very close to the position of the storms in the target fields. Note that the distance between the unperturbed and controlled storm centers appears to grow exponentially during the first 6 h of the forecasts.

The value of the cost function J (not shown) for hours 0 (J_0) and 6 (J_6), at each iteration, asymptotes at the end of the minimization. Because of the sensitivity of the model atmosphere to changes in initial conditions, a large decrease in J at hour 6 requires only a small increase in J at hour 0. There

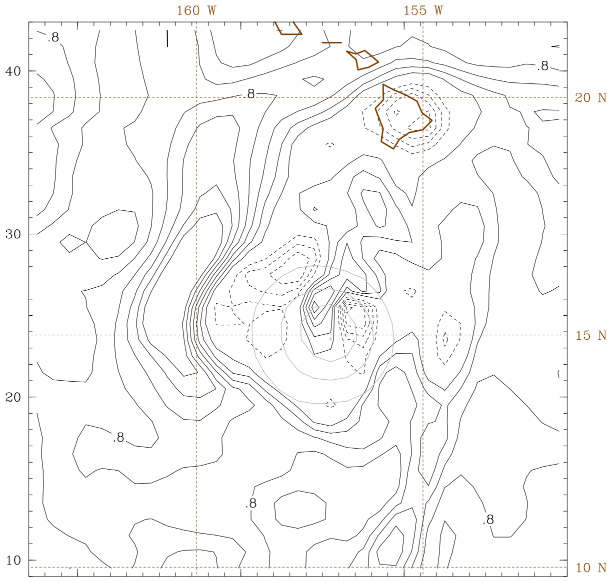
Figure 1: The hourly case 1 (solid, from 0600 UTC 920910) and case 2 (dashed, from 0600 UTC 920911) unperturbed and controlled forecast tracks. Symbols represent 6-hourly positions.



are large decreases (by a factor of ∼2) in rms differences at 6 h after the minimization in both wind and temperature.

The lowest layer temperature perturbations are presented for case 1 in Fig. 2. The temperature perturbations correspond to a widespread warming to the west of the tropical cyclone (i.e., in the direction of the target) and smaller-scale regions of slight cooling and warming in the vicinity of the tropical cyclone. At other levels in the lower troposphere (not shown), temperature increments are smaller in scale and are generally negative with magnitudes less than 1° C. Based on the sea-level pressure and the perturbation wind fields (not shown), 4d-VAR has only a small effect on the position of the tropical cyclone at the initial time. Of interest is a region of spatially coherent wind perturbations around 200 hPa (not shown), perhaps associated with the storm's upper-level outflow, which acts to enhance the anticyclonic shear side of an existing jet stream positioned to the north and northeast of the storm.

Figure 2: Initial-time lowest-layer temperature perturbations for case 1, contoured every 0.2° C; negative values are dashed and the zero contour has been omitted. Circular mean sea-level pressure contours denote the position of Iniki.



In case 2 (Fig. 3), maximum surface temperature increments are of similar magnitude to those of case 1, but are largest to the immediate *southeast* of the storm center and exhibit $2\Delta x$ noise.

In both cases, convection is redistributed around Iniki's center (not shown). This redistribution may play a role in repositioning the controlled vortex towards the west in the controlled forecasts.

5 DISCUSSION

The preliminary study described here shows that 4d-VAR can be used to calculate "optimal" perturbations to control the track of a simulated tropical cyclone. A necessary prerequisite is the ability to forecast tropical cyclones accurately.

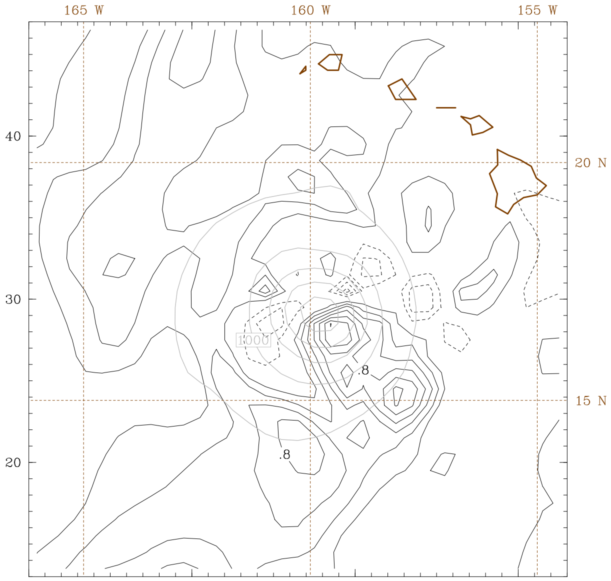
Further progress on some of the technical issues may be made by refining the 4d-VAR study presented here. In future experiments, we could:

-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.

-Modify the cost function to estimate the prop-

Figure 3: As in Fig. 2, but for case 2.



erty loss (in dollars) as a function of forecast wind speed, or, to require only that the modeled tropical cyclone avoids certain geographical areas, which may result in more localized and smaller perturbations.

-Restrict the control vector to specific fields, such as temperature, and so that only certain types of "feasible" perturbations, which are continuous in time, are allowed.

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