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Partners or Cooperative Project: Development of a Forward Model for Hurricane Initialization
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SECTION 1: PROJECT OBJECTIVES AND ACCOMPLISHMENTS
1.1

The objective of this research was to formulate forward and adjoint models that could be used for hurricane initialization in the NCEP operational modeling system (AVN/GFS). The cost functions associated with the forward model are designed to perturb the AVN/GFS fields towards operational observed parameters from the Tropical Prediction Center (TPC).

Our first accomplishment was the formulation of the Eliassen balanced vortex model in a generalized vertical coordinate $\eta(p, p_s, \theta)$,

$$\frac{\partial}{\partial r}\left(A\frac{\partial(r\psi)}{r\partial r}+B\frac{\partial\psi}{\partial\eta}\right)+\frac{\partial}{\partial\eta}\left(B\frac{\partial(r\psi)}{r\partial r}+C\frac{\partial\psi}{\partial\eta}\right)=\frac{\partial(\dot{\theta},\Pi)}{\partial(r,\eta)}, \tag{1}$$

where

$$A=-\frac{\alpha}{\theta}\frac{\partial\theta}{\partial\eta},$$

$$B=\frac{\alpha}{\theta}\frac{\partial\theta}{\partial r},$$

$$C=\frac{1}{m}\left(f+\frac{2v}{r}\right)\left(f+\frac{\partial(rv)}{r\partial r}\right)-\frac{1}{m}\frac{\partial\Pi}{\partial r}\frac{\partial\theta}{\partial r},$$

and $m=\partial p/\partial\eta$ is the pseudodensity, $\alpha=RT/p$ the specific volume, $\Pi=c_p(p/p_0)^\kappa$ the Exner function, and where the partial derivative $\partial/\partial r$ is understood to be at fixed η. For the particular case $\eta=\sigma$, i.e. for application in the NCEP operational model, the transverse circulation equation is

$$\frac{\partial}{\partial r}\left(A\frac{\partial(r\psi)}{r\partial r}+B\frac{\partial\psi}{\partial\sigma}\right)+\frac{\partial}{\partial\sigma}\left(B\frac{\partial(r\psi)}{r\partial r}+C\frac{\partial\psi}{\partial\sigma}\right)=\frac{\partial(\dot{\theta},\Pi)}{\partial(r,\sigma)}, \tag{2}$$

where

$$A=-\frac{\alpha}{\theta}\frac{\partial\theta}{\partial\sigma},$$

$$B=\frac{\alpha}{\theta}\frac{\partial\theta}{\partial r},$$

$$C=\frac{1}{p_s}\left(f+\frac{2v}{r}\right)\left(f+\frac{\partial(rv)}{r\partial r}\right)-\sigma\alpha\frac{\partial\ln p_s}{\partial r}\frac{\partial\ln\theta}{\partial r}.$$

The relationship given by (1) [and (2)] does not appear to be given anywhere in the literature and is thus a new result.

Our original goal was to use (2), initialized using AVN/GFS winds, as our forward model. After further consideration of the problem, however, it seemed more feasible to first take a simpler approach that does not require compatibility with the AVN/GFS's parameterized nonconservative physics. Our current thinking has been to simplify the forward model as much as possible, and possibly return to the more complicated forward model at a later date. Following this philosophy, we describe our simplest forward model here:

1. Start with the AVN/GFS wind field around a tropical cyclone (TC) at the surface $[u^{\mathrm{GFS}}(x,y,\sigma_{\max}), v^{\mathrm{GFS}}(x,y,\sigma_{\max})]$, and observational values for the maximum tangential wind (v_0^{obs}), the radius of maximum tangential wind (r_0^{obs}), and the radius of 34 knot wind (r_{34}^{obs}) from the Tropical Prediction Center (TPC).

2. With knowledge of the position of the TC center (from TPC), use $(u^{\mathrm{GFS}}, v^{\mathrm{GFS}})$ to extract the azimuthally averaged tangential wind $v_\lambda(r)$.

3. Fit $v_\lambda(r)$ to the parametric axisymmetric wind field given by the modified Rankine profile,
$$v(r) = v_0 \begin{cases} r/r_0 & 0 \le r \le r_0, \\ (r_0/r)^x & r_0 \le r < \infty, \end{cases} , \tag{3}$$
where $x > 0$ is a dimensionless parameter. Fitting was accomplished by varying the parameters (v_0, r_0, x) in a downhill simplex algorithm.

4. Construct cost functions for each TPC parameter, $C_1 = \frac{1}{2}(v_0 - v_0^{\mathrm{obs}})^2$, $C_2 = \frac{1}{2}(r_0 - r_0^{\mathrm{obs}})^2$, and $C_3 = \frac{1}{2}(r_{34} - r_{34}^{\mathrm{obs}})^2$, and form their gradients,

$$\frac{\partial C_1}{\partial v} = (v_0 - v_0^{\mathrm{obs}}) \begin{cases} r_0/r & 0 \le r \le r_0, \\ (r/r_0)^x & r_0 \le r < \infty, \end{cases} , \tag{4}$$

$$\frac{\partial C_2}{\partial v} = (r_0 - r_0^{\mathrm{obs}}) \begin{cases} -r v_0/v^2 & 0 \le r \le r_0, \\ (r/(x v_0))(v/v_0)^{(1-x)/x} & r_0 \le r < \infty, \end{cases} , \tag{5}$$

$$\frac{\partial C_3}{\partial v} = (r_{34} - r_{34}^{\mathrm{obs}}) \frac{\partial r_{34}}{\partial v}, \tag{6}$$

where

$$\frac{\partial r_{34}}{\partial v} = r_0 (v_0/34)^{1/x} [(1/r_0)(\partial r_0/\partial v) + (1/x v_0)(\partial v_0/\partial v) + (1/x^2)\ln(34/v_0)(\partial x/\partial v)], \tag{7}$$

and

$$\frac{\partial x}{\partial v} = (v_0 (r_0/r)^x \ln(r_0/r))^{-1} \tag{8}$$

If deemed appropriate, the next step is the inclusion of vertical structure, but still under the assumption of axisymmetry. The mass field is calculated using hydrostatic and gradient balance. The surface tangential wind of the simple vortex is given by (3), and the vertical structure of the wind is specified as

$$\Gamma(r,\sigma) = \cos\left\{\frac{\pi}{2}\left[(1-\sigma)/(1-\sigma_0(r))\right]\right\}, \tag{9}$$

where

$$\sigma_0(r) = \sigma_1 + \left\{1 - \exp\left[-(r/a)^b\right]\right\}(\sigma_2 - \sigma_1).$$

This allows a realistic decay with decreasing σ and a realistic upper-level anticyclone positioned outside of the eyewall region. Multiplication of (3) and (8) describes an axisymmetric 2D wind field $v(r,\sigma)$ that depends on seven parameters $v_0, r_0, x, \sigma_1, \sigma_2, a, b$. The seven parameters are fit to the background AVN/GFS model winds using a downhill simplex algorithm. The 2D mass field is then iteratively deduced from $v(r,\sigma)$ by forcing gradient and hydrostatic balance at each level (with appropriate boundary conditions deduced from the AVN/GFS fields).

With knowledge of the 2D wind and mass fields, the forward model representation of the TPC parameters can be calculated. The gradients of the squared difference between the observed TPC parameters and the forward model representation of the TPC parameters can then be calculated. A subroutine where the input is the TPC parameters and AVN/GFS model fields and the output is the gradient of the TPC parameter difference with respect to the AVN/GFS model fields can be provided to NCEP, to be included as a component of their global data assimilation system. For possible future expansion of our results, coordination with NCEP will be required to customize this routine to the form required by their assimilation system.

SECTION 2: SUMMARY OF UNIVERSITY/NWS/AFWA/NAVY EXCHANGES

2.1

During the course of this research, the NESDIS PI (Mark DeMaria) had three informal meetings with NCEP/EMC personnel, while in Camp Springs on other business. The first two meetings were with John Derber and Naomi Surgi, to help clarify the relationship between the constrained vortex model described above in section 1, and the operational NCEP global data assimilation system (GDAS). During these meetings, the need to add terms related to wind increments for use in the GDAS system was clarified. In principle, these terms would be determined from a scaled version of the gradients defined by (4)–(6) above. These terms would drive the wind analysis so that the global model wind fields would contain better representations of the wind parameters estimated by the National Hurricane Center (observed maximum wind, radius of maximum wind and average radius of 34 knot wind), when fitted to the assumed vortex model. The changes in the global model wind field determined by these gradients would have to appropriately weighted against other factors in the GDAS, such as the difference between the analysis and other observations, and the analysis background fields.

The third meeting was with Qing-Fu Liu (an NCEP/EMC contractor), who was developing a "vortex relocation method" for tropical cyclone initialization in the NCEP global model.

In this method, the symmetric part of the storm circulation in the background field (a short-term global model forecast) is re-located to the observed position, but otherwise is not modified. During this meeting, the similarities between the "vortex relocation" and the "forward model" methods were discussed. Both methods would provide a symmetric circulation in the proper location, but the horizontal and vertical structure would differ. In the "forward model" method, this structure would be constrained by the assumed structure of the parametric vortex. In the "vortex relocation" method, it would be determined by the global model forecast.

Further correspondence with NCEP indicated that the method proposed in this research provided a vortex structure that was too constrained. Although the method described in section 1 above has some merit, the determination of the vortex circulation from the model forecast is more general, especially if ancillary data such as aircraft reconnaissance observations are available. Thus, their decision was to document the method outlined in section 1, but to stop short of doing the continuing work that would be required to test this idea in the NCEP operational model.

SECTION 3: PRESENTATIONS AND PUBLICATIONS

3.1

There have been no publications thus far related to this work. A brief description of this project was provided on 18 March 2002 in a presentation by Mark DeMaria to NESDIS/ORA management on data assimilation activities at CIRA.

SECTION 4: SUMMARY OF BENEFITS AND PROBLEMS ENCOUNTERED

4.1

This research explored the basic framework for developing a "forward model" to map the NCEP global model analysis to the tropical cyclone parameters that are determined by NHC (radius of maximum winds, gale force winds, etc), as described in the original research announcement. The balance equations in sigma coordinates were developed, and a highly simplified version of this method was explored further. This exploration helped to clarify the assumptions and constraints necessary to apply this type of method in the GDAS. Once these were clarified, the utility of this method became less attractive, except perhaps in highly data-void regions. The assumptions that are necessary to map the NCEP fields to the NHC parameters required a highly constrained vortex structure.

4.2 (To be completed by forecaster partner)

We (NCEP) originally requested this research as an exploratory effort to determine if better use could be made of the tropical cyclone parameters estimated by NHC from satellite and other means. After obtaining a better understanding of what is needed in this method, we chose not to implement this procedure in our operational model. The vortex relocation method we are currently using is more general, and has shown very positive results in the past few years. The forward model method has some characteristics in common with "vortex bogussing" which we abandoned in the GDAS in favor of the vortex relocation. This research accomplished our goal of clarifying our options with regard to inclusion of the NHC tropical cyclone parameters in our GDAS.