

Joint Hurricane Testbed: Mid-year Progress Report, Year 1

Dynamic Initialization to Improve Tropical Cyclone Intensity and Structure Forecasts

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1. Background

Because of recent improvement in data assimilation, initialization becomes a less important component in general Numerical Weather Prediction (NWP) applications. With balance conditions included as constraints in analysis methods and high quality first guesses from previous forecasts, the analysis fields from 3-dimension variational (3D-Var) analysis are quite balanced for synoptic weather systems. However, for tropical cyclones, the analysis fields from 3D-Var may be significantly unbalanced due to (1) inadequate balance conditions included in the analysis method and (2) large analysis increments by poor first guesses. The goal of this project is to develop and implement a dynamic initialization procedure for hurricane Weather Research and Forecasting (WRF) model and Coupled Ocean-Atmosphere Mesoscale Prediction System (COAMPS^{®1}), using diabatic digital filtering, to improve tropical cyclone intensity and structure forecasts.

Digital filter is a very selective low-pass filter. It filters out unbalanced high-frequency components from initial conditions through weighted inverse Fourier transform

$$\tilde{f}_n = \sum_{k=-N}^{k=N} h_k w_k f_{n-k}, \quad (1)$$

where \tilde{f}_n is the filtered field, f_{n-k} is the original field, $h_k = \frac{\sin k\theta_c}{k\pi}$ is the filtering weight with cutoff frequency θ_c , and w_k is the window function to reduce Gibbs oscillations. The field f_{n-k} is obtained by forward and backward time integrations for the dynamic initialization. Diabatic digital filtering initialization includes diabatic processes in the forward time integration for f_{n-k} . We use COAMPS as a tool to develop the diabatic digital filtering initialization in the first year and then adapt the initialization procedure to hurricane WRF in the second year.

2. Tasks Completed and Work in Progress

(a) Task 1: *Test and evaluate different window filters and time integration strategies for diabatic digital filtering initialization*

The cost of the diabatic digital filtering initialization depends entirely upon the length of the initialization time integration. The length of the integration is, however, controlled by (1) cutoff frequency and (2) efficiency of the window filter in reducing the width of the transition band and ripples of the stop band. The longer the cutoff period and wider the transition band, the more expensive the initialization will be. A window with a wide

¹ COAMPS[®] is a trademark of Naval Research Laboratory

transition band leaks large weights to components with a frequency higher than the cutoff frequency so that a longer cutoff period is necessary.

We have tested 5 different windows: Hamming, Lanczos, Riesz, Kaiser, and Dolph for diabatic digital filtering initialization. The former 3 are fixed windows with fixed formulas, while the latter 2 are adjustable windows with a selectable parameter to control its output response. The consideration factors to choose a proper window are (1) complexity of the calculation, (2) width of transition band, and (3) ripple size of stop band. Since the window filter is calculated only once in the initialization procedure, the complexity of the window calculation is not an issue of the diabatic digital filtering initialization. Since very high frequency components of the atmosphere circulation have very small magnitudes anyway, the very high frequency ripples of the stop band have limited impacts on the digital filtering initialization. Therefore, a desired window filter for tropical cyclone initialization should have a narrow transition band and small ripples at the low frequency part of the stop band. For the 2 adjustable windows, we choose the control parameters to give the maximum ripple of the stop band no more than 1% of input signals. Among the 5 windows, the Riesz window shows smallest improvement in reducing the Gibbs oscillations; it reduces the maximum ripples of the stop band by $\frac{1}{2}$ only. The other 4 windows have similar ripples in the stop band, while the Dolph window provides with the narrowest transition band (Fig.1). We therefore, choose the Dolph window for the diabatic digital filtering initialization.

The cutoff period is usually chosen to be 6-hour for NWP applications. However, for tropical cyclone initialization, we may choose a shorter cutoff period. If we consider the unbalanced components of tropical cyclone initial conditions are in a form of gravity waves with wavelength shorter than 1200 km, using a phase speed of 200 m/s, we can estimate the lowest frequency for those gravity waves to be $1.67 \times 10^{-4} \text{ s}^{-1}$. Therefore, a 2-hour cutoff period will be sufficient to remove the unbalanced components for tropical cyclone initialization. As a consequence, the diabatic forward time integration from -1 hour to +1 hour will be sufficient to initialize tropical cyclones with diabatic digital filtering. We have tested the results of the diabatic digital filtering initialization with the 2-hour cutoff period and obtained properly balanced initial conditions.

Diabatic digital filtering initialization can be conducted by two integration strategies (Fig. 2) to integrate the model backward and forward. The strategy-A integrates the model adiabatically backward for the half initialization period and then diabatically forward for the full initialization period, while the strategy-B integrates the model adiabatically backward for the full initialization period, filters the fields, and then integrates the model diabatically forward for the full initialization period. The strategy-B has better-balanced initial conditions in the forward diabatic integration, but it costs 1/3 more than the strategy-A. In the preliminary test with several real data cases, we find that the strategy-B doesn't improve the forecast much. We will conduct more tests to make the final choice.

To test and evaluate the diabatic digital filtering initialization, we use a case of very unbalanced analysis fields for tropical cyclone Katrina at 00 UTC 29 August 2005. The 3-km resolution analysis fields (Fig. 3) are from 3D-Var analysis using 13 synthetic wind observations. The unbalance is mainly due to poor first guesses, with a 60-km position error, and the 3D-Var corrects more wind than mass fields. As a result, the wind and mass centers are dislocated (Figs. 3a,b). The diabatic digital filtering initialization with a 2-hour

cutoff period gives much better balanced initial conditions with collocated wind and mass centers (Figs. 4a,b) and much smooth changes from initial conditions to 1-hour forecast (Figs. 4c,d). To better demonstrate the impact of diabatic digital filtering initialization on improving initial conditions, we have compared the initial time evolution of maximum wind speed and central sea-level pressure for 6-hour forecast without initialization, with adiabatic digital filtering initialization, and with diabatic digital filtering initialization (Fig. 5). It clearly shows that the diabatic digital filtering initialization remarkably improve the balance in the initial conditions.

(b) Task 2: *Develop a nudging method to ensure initialized solutions to be close to observed cyclone position and structure*

Since the diabatic digital filtering initialization involves with asymmetric time integration between backward and forward integration, the initialized fields may position tropical cyclones significantly away from the analyzed locations. However, as we have selected a more efficient window and demonstrated that -1 to $+1$ hour time integration is sufficient to filter out high frequency components, the “draft away” problem is not an issue anymore. In all experiments we have done so far, the initialized tropical cyclone locations are very close to their analyzed locations. The nudging turns out to be unnecessary at this time. We will revisit this work in the future if it becomes necessary.

(c) Task 3: *Test and evaluate different lateral boundary treatments for the backward and forward initialization integrations*

We have tested and evaluated different methods to handle lateral boundary conditions in backward and forward initialization time integration. For inner meshes, we find out that the standard time-dependent Davies type boundary condition treatment works very well. For outmost mesh, the time-dependent and fixed lateral boundary conditions give very similar results since the length of initialization integration needs only ± 1 hour. For simplicity in handling ground conditions, we decide to use fixed boundary conditions for outmost mesh in diabatic digital filtering initialization.

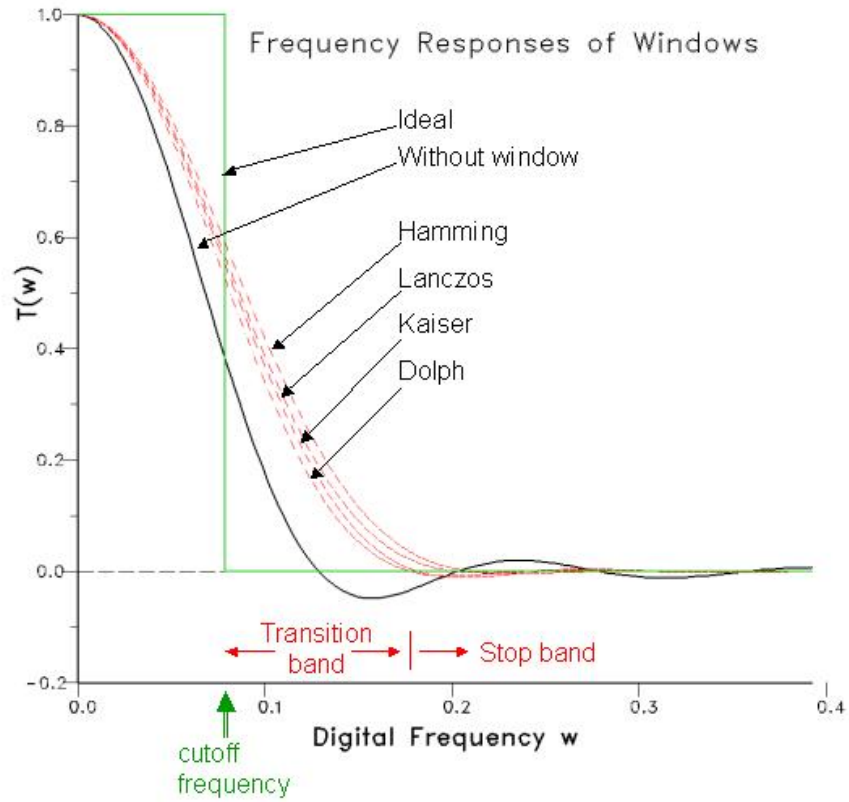


Fig. 1. Frequency responses of low-pass digital filters with 4 different windows (red dashed) and without windows (black solid), comparing with the ideal filter (green).

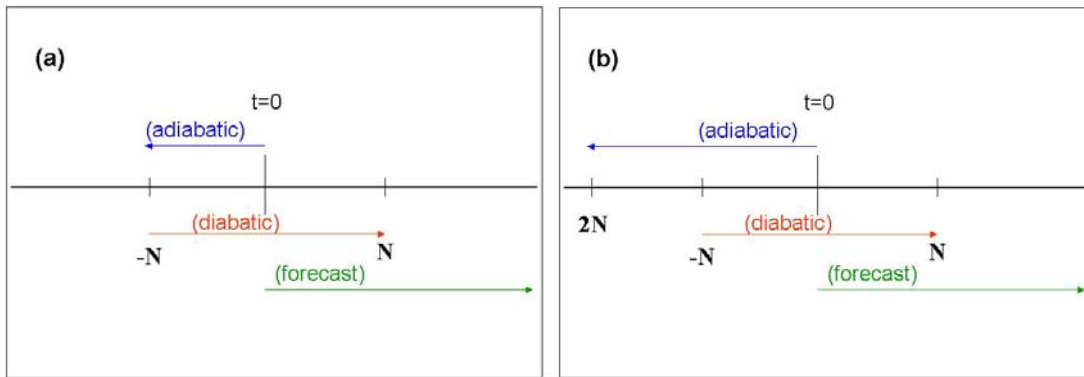


Fig. 2. Schematic diagrams of (a) strategy-A, and (b) strategy-B time integration for diabatic digital filtering initialization.

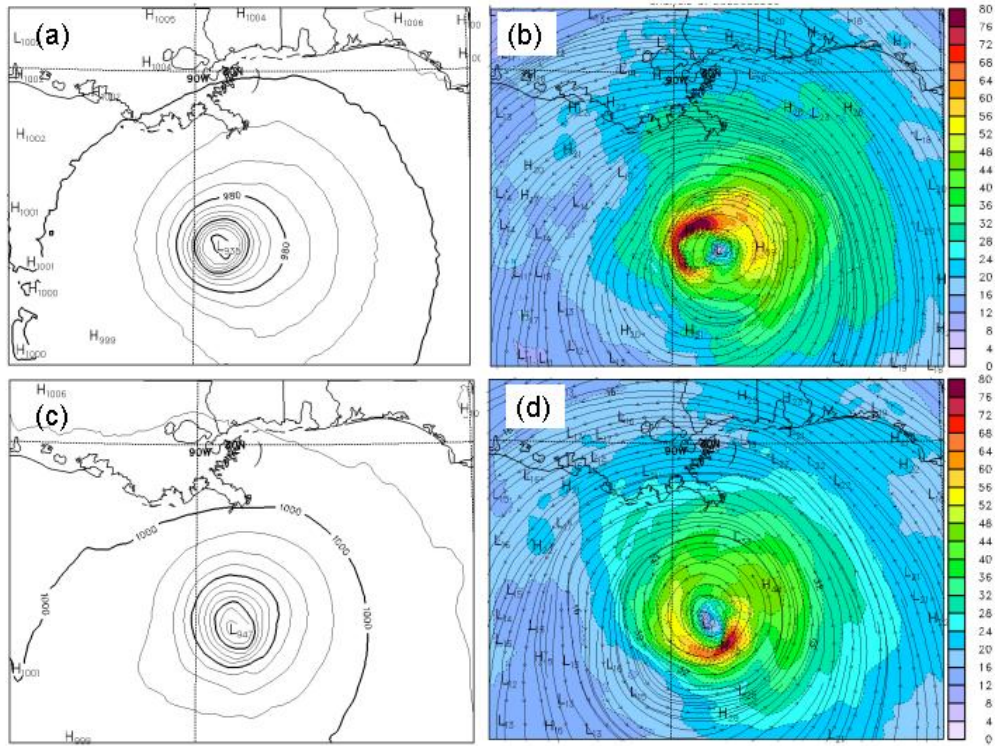


Fig 3. Initial conditions of (a) sea-level pressure and (b) 850 mb wind, and 1-hour forecast of (c) sea-level pressure and (d) 850 mb wind for Katrina forecast without initialization.

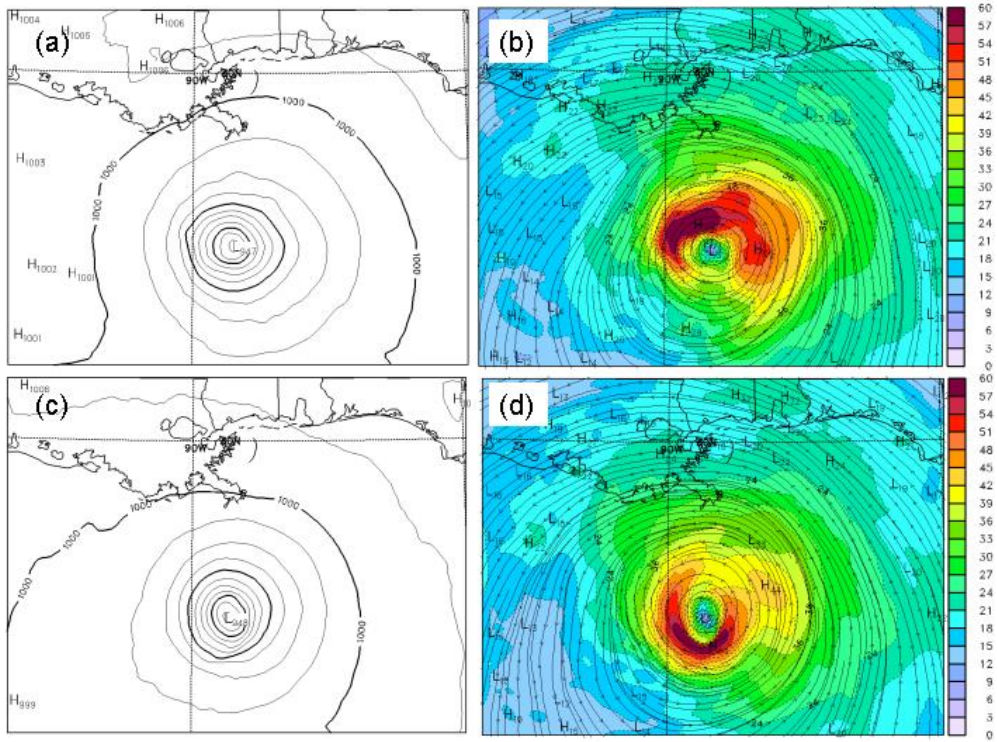


Fig 4. Same as in Fig. 3, except with diabatic digital filtering initialization.

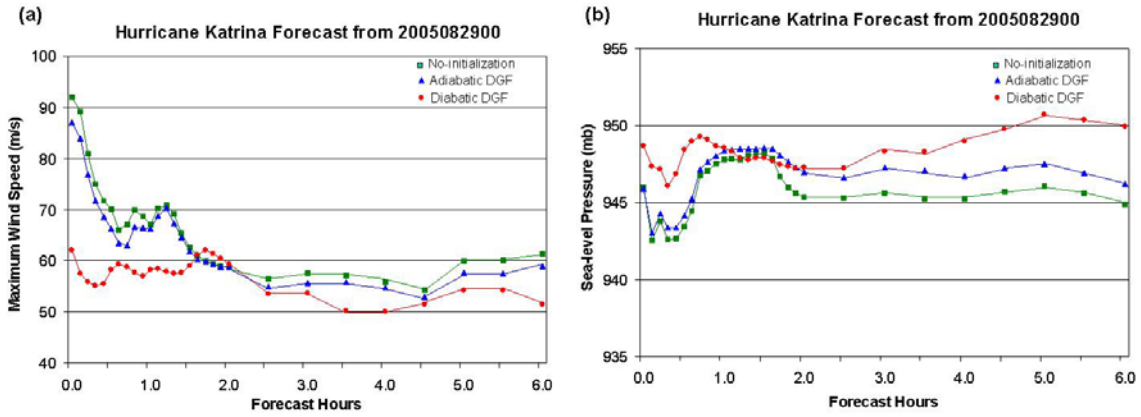


Fig 5. Six-hour hurricane Katrina forecast of (a) maximum wind and (b) central sea-level pressure by COAMPS with diabatic digital filtering initialization (red circles), adiabatic digital filtering initialization (blue triangles), and without initialization (green boxes). The values are plotted in every 6 and 30 minutes before and after 2-hour forecast, respectively.