Joint Hurricane Testbed: Year-1 Annual Report

Dynamic Initialization to Improve Tropical Cyclone Intensity and Structure Forecasts

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April 2006

1. Introduction

The goal of this project is to develop and implement a dynamic initialization procedure to balance initial conditions for tropical cyclone forecasts by hurricane Weather Research Forecasting (HWRF) model and Coupled Ocean-Atmosphere Mesoscale Prediction System (COAMPS®[1]). In both models, the initial conditions for tropical cyclone forecasts are prepared by 3-dimension variational (3D-Var) analysis. The analyzed fields may be significantly unbalanced due to poor quality of background fields and inadequate balance conditions included in the 3D-Var. Figure 1 shows such an example from COAMPS 3D-Var analysis, in which the mass field center was dislocated from the wind circulation center. The obviously unbalanced initial conditions were results of bad background fields (a large cyclone position error) and unbalanced corrections made to the mass and wind fields by 3D-Var due to improper geostrophic coupling constraints. As a consequence, large oscillations occurred in the first 2 hours of the model forecast integration (Figs. 1b,d). Furthermore, diabatic forcing plays an important role in balancing tropical cyclone circulation and it is difficult to be included in the balance constraints of 3D-Var. Therefore, a proper diabatic initialization procedure is needed after the 3D-Var to remove the unbalanced part initial conditions for tropical cyclone forecasts. Since diabatic static initialization has convergence problems (Williamson and Temperton 1981, Rasch 1985), we have chosen a dynamic initialization procedure using diabatic digital filtering to balance initial conditions for improving tropical cyclone intensity and structure forecasts. In the first year, we develop the diabatic digital filtering initialization with COAMPS; and in the second year, we adapt the developed initialization procedure for HWRF.

2. Digital Filtering

A dynamic initialization procedure assumes all unbalanced components are in high frequency and they can be removed from the initial conditions by filtering out components with frequencies higher than a cutoff frequency. Digital filter is a very selective low-pass filter that can best achieve the filtering purpose of the dynamic initialization. In frequency domain, the digital filtering operates as

$$F_{out}(\varpi) = F_{in}(\varpi) * H(\varpi), \quad where\ H(\varpi) = \begin{cases} 1, & |\varpi| \le \varpi_c \\ 0, & |\varpi| > \varpi_c \end{cases} \qquad (1)$$

where ϖ_c is the cutoff frequency, and F_{in} and F_{out} is the frequency component before and after the filtering, respectively. In physical domain, after applying the convolution theory and a truncated inverse Fourier transform, the digital filtering works as

$$\tilde{f}_n = \sum_{k=-\infty}^{\infty} h_k f_{n-k} \approx \sum_{k=-N}^{N} h_k f_{n-k} \qquad (2)$$

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

where $\tilde{f}_n$ is the filtered field at time n, f_{n-k} is the original field at time (n-k), and $h_k = \frac{\sin(k\varpi_c \Delta t)}{k\pi}$ is the inverse Fourier transform of $H(\varpi)$ with Δt time step. Unfortunately, the Fourier transform of h_k converges very slowly and the response function of the filter shows large amplitude oscillations beyond the cutoff frequency (Fig. 2), known as Gibbs' phenomenon. The negative response function is especially troublesome. It not only allows a high frequency component leaking through the filtering process but also ends up with opposite amplitude. A well-known solution to this problem is to apply a window function w_k together with the filtering weight h_k to improve the convergence rate and reduce the negative ripples. With a window applied, the digital filtering now works as

$$\tilde{f}_n = \sum_{k=-N}^{N} h_k w_k f_{n-k} \qquad (3)$$

There are many window functions developed for different purposes of digital filtering. After an extensive survey, we have selected 5 windows for further evaluation. They are

Lanczos window: $w_n = \frac{\sin[n\pi/(N+1)]}{n\pi/(N+1)}, \qquad 0 < n < N$,

Hamming window: $w_n = 0.54 + 0.46\cos(\frac{2n\pi}{2N+1})$,

Riesz window: $w_n = 1 - (\frac{n}{N+1})^2$,

Kaiser window: $w_n = \frac{l_0\{\beta[1-(\frac{n}{N+1})^2]^{1/2}\}}{l_0(\beta)}, \quad l_0(x):$ Bessel function, and

Dolph-Chebyshev: $w_n = \frac{1}{w_0(2N+1)}[1 + 2\gamma \sum_{m=1}^{N} T_{2N}(x_0 \cos\frac{\theta_m}{2})\cos m\theta_n]$,

where $x_0 = \cosh(\frac{1}{2N}\cosh^{-1}\gamma)$, $\theta_m = \frac{2\pi m}{(2N+1)}$, $\theta_n = \frac{2\pi n}{(2N+1)}$, *and* T_{2N} is Chebyshev polynomial

The former three are fixed windows and the latter two are adjustable windows with β and γ as the adjustable parameters. Kaiser window is designed to minimize the energy norm of the stop band and Dolph-Chebyshev window is designed to limit the maximum ripple size of the stop band. The consideration factors to choose a proper window are (1) complexity of the calculation, (2) width of the transition band, and (3) ripple size of the stop band. Since the weights of filter window are calculated only once in the digital filtering initialization procedure, the complexity of the window calculation is not an issue in this case. Since very high frequency components of the atmosphere circulation have very small magnitudes anyway, the very high frequency ripples of the stop band should have little impacts on the digital filtering initialization. Therefore, a desired filter window 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 adjustable parameters to give the maximum ripple size of the stop band no more than 1% of input signals. Among the 5 windows, Riesz window shows the smallest improvement in reducing the Gibbs' oscillations (Fig.3). It reduces the maximum ripple size of the stop band by roughly ½ only. The Hamming window has the smallest size of ripples in the stop band but with a significantly wider transition band than others. The rest of 3 windows have similar ripple sizes in the stop band while the Dolph-Chebyshev window provides the filter with the narrowest transition band. We therefore, choose the Dolph-Chebyshev window for the diabatic digital filtering initialization.

There are several ways to apply the digital filter for removing high frequency components from the initial conditions: adiabatic digital filtering, diabatic digital filtering method 1, and diabatic digital filtering method 2 (Fig. 4). The adiabatic digital filtering integrates the forecast model adiabatically backward for ½ cutoff period and then integrates from the original initial conditions adiabatically forward for another ½ cutoff period to obtain the necessary information of the forecast trajectory for the digital filtering. The diabatic digital filtering method 1 integrates the forecast model adiabatically backward for ½ cutoff period and then integrates diabatically forward for 1 cutoff period to get the trajectory information for the digital filtering. The diabatic digital filtering method 2 integrates the forecast model adiabatically backward for 1 cutoff period, apply digital filtering, and then integrates from the filtered results diabatically forward for 1 cutoff period. The method 2 applies the digital filtering twice and should be more selective in filtering out unbalanced high frequency components. However it costs ¼ more than the method 1 in the initialization integration. Because the adiabatic backward and diabatic forward integrations are not symmetric, the diabatic digital filtering initialization may end up with tropical cyclone locations different from their originally analyzed locations. If the difference is significant, the diabatic initialization procedure may degrade track forecast.

Besides selecting a window function and integration method, another important decision of the digital filtering is to choose the cutoff period. The cost of the dynamic initialization is directly influenced by the choice of the cutoff period since the length of initialization integration is totally determined by the cutoff period. Typically, the cutoff period for mesoscale model initialization is chosen to be 6 hours. It is the cutoff period we used in the past for COAMPS with Lanczos window. However, with Dolph-Chebyshev window, after many numerical experiments, we found that a 2-hour cutoff period is sufficient to filter out most of the unbalanced components in initial conditions for COAMPS tropical cyclone forecast. This finding is quite significant. The short cutoff period not only saves initialization cost but also minimizes the possible negative impact on track forecast caused by the asymmetric integrations. For example, the degradation in Isabel track forecast using 6h cutoff period with Lanczos window is now changed to the improvement in the track forecast using 2h cutoff period with Dolph-Chebyshev window (Fig. 5). The nudging consideration originally planned is not necessary any more with the 2h cutoff period. The +1h and –1h initialization integrations also make the treatments of lateral and ground boundary conditions in the initialization integrations less important, since those boundary conditions do not change much during the short 1h initialization integrations. We therefore, fix the lateral and ground boundary conditions in both adiabatic and diabatic initialization integrations.

3. Test Results

We have completed the code development for digital filtering with Dolph-Chebyshev window and modified COAMPS time integration loops to accommodate for the three integration methods of the digital filtering initialization. We have tested the initialization procedure with different model resolutions for 14 tropical cyclone cases. The results are very promising in all cases. Figure 6 shows the sea level pressure and 850-mb wind of the same case in Fig.1, but after the digital filtering initialization. The large initial oscillations are effectively removed by the diabatic digital filtering with both methods, while the adiabatic digital filtering only marginally reduces the initial oscillations (Figs. 6b,d). The result demonstrates the necessity of including diabatic forcing in getting balanced initial conditions for tropical cyclone forecast. In this example, even though 3D-Var analyzes a relatively strong tropical cyclone circulation, the large part of the analyzed near core circulation is unbalanced according to COAMPS forecast model physics. The diabatic digital filtering removes the unbalanced part and ends up with a better balanced but weaker tropical cyclone circulation (see Figs. 1a,c and Figs. 6a,c). This also demonstrates the importance of a skillful forecast model even in obtaining initial conditions for tropical cyclone forecast. The small difference between the diabatic methods 1 and 2 in this case and others (not shown) suggest that the extra filtering in the method 2 makes no significant impacts on the initialization result. The diabatic method 1 is therefore, our choice of the digital filtering initialization. Figure 7 shows the results of diabatic method 1 for two of other cases we have tested. The diabatic digital filtering with Dolph-Chebyshev window and 2h cutoff period effectively removes most of unbalanced components in the initial conditions of these two cases as well.

We have evaluated the impacts of the dynamic digital filtering initialization on COAMPS track and intensity forecasts. In all 14 tested cases, the track forecasts were slightly influenced by the diabatic digital filtering initialization, especially in the first 24 hours. A larger impact was found in the intensity forecast. The averaged forecast errors of the 14 cases show 7 to 12 nautical miles improvement in the track forecast after 36 hours and 2 to 3 m/s intensity forecast improvement in the later period, although the large degradation of 6 m/s is found in the initial time (Fig. 8). The large degradation of COAMPS intensity forecast in the initial period mainly reflects the underprediction bias of the COAMPS forecast model in tropical cyclone intensity forecast. The intensity forecast improvement in the later forecast period certainly suggests that the diabatic digital filtering initialization would have a larger positive impact in the intensity forecast if the forecast model physics allowed a stronger circulation after the diabatic initialization. The impacts of the dynamic digital filtering initialization on HWRF track and intensity forecasts may be different from those for COAMPS since HWRF uses a different data assimilation method and may have a different bias in the intensity forecast. More tests are conducing for COAMPS forecasts to get statistically significant impact scores on COAMPS track and intensity forecasts by the dynamic digital filtering initialization.

4. Tasks and Budget for Year 2

The development of dynamic initialization with diabatic digital filtering has been progressed very well in the first year. The finding of the short 2h cutoff period with the efficient Dolph-Chebyshev window makes the diabatic digital filtering a more attractive solution for tropical cyclone initialization. In the next year, we will perform the following two tasks to complete the project.

Task 4: Port the dynamic initialization using the diabatic digital filtering method to HWRF

As we are satisfied with the performance of the dynamic initialization developed with COAMPS at NRL, we will port the dynamic initialization procedure to HWRF. We will collaborate with the HWRF development team to implement the code in the HWRF. We will modify the diabatic digital filtering code to fit the HWRF model infrastructure and environments, and add the initialization integration loops to HWRF time integration routines. Frequent interactions with the HWRF development team will be done through emails and phone calls.

Task 5: Test, evaluate, and implement the dynamic initialization to COAMPS and HWRF

Once the dynamic initialization procedure using the diabatic digital filtering is successfully implemented in the HWRF, we will first conduct forecast experiments similar to those we have done with COAMPS to confirm the initialization procedure has been properly installed. We will then conduct extensive forecast experiments to evaluate and adjust the diabatic digital filtering initialization procedure for both COAMPS and HWRF to achieve the goal of improving tropical cyclone structure and intensity forecasts.

These tasks will be performed mainly at Monterey using NRL and NCEP computers. A method of accessing to NCEP computer systems will be established to run and test the diabatic digital initialization for HWRF in the NCEP computer environment. Two trips to EMC are planned to discuss issues and interact with the project point of contact at EMC.

YEAR 2 BUDGET – UNCHANGED FROM ORIGINAL PROPOSAL

Year 2:

Salary and Fringe:	$ 58,800
Overhead:	$ 32,500
Travel:	$ 3,700
Total:	$ 95,000

The salary, fringe, and overhead charges indicated in the project budget are sufficient to cover 44% of the NRL civilian employee for one year. The budgeted travel includes attending the Interdepartmental Hurricane Conference and two visits to the NCEP.

5. Reference

Rasch, P. J., 1985: Developments in normal model initialization. Part 1: A simple interpretation for normal model initialization. Mon. Wea. Rev., **113**, 1746-1752.

Williamson, D. L., and C. Temperton, 1981: Normal mode initialization for a multi-level gridpoint model. Part 2: Nonlinear aspects. Mon. Wea. Rev., **109**, 744-757.

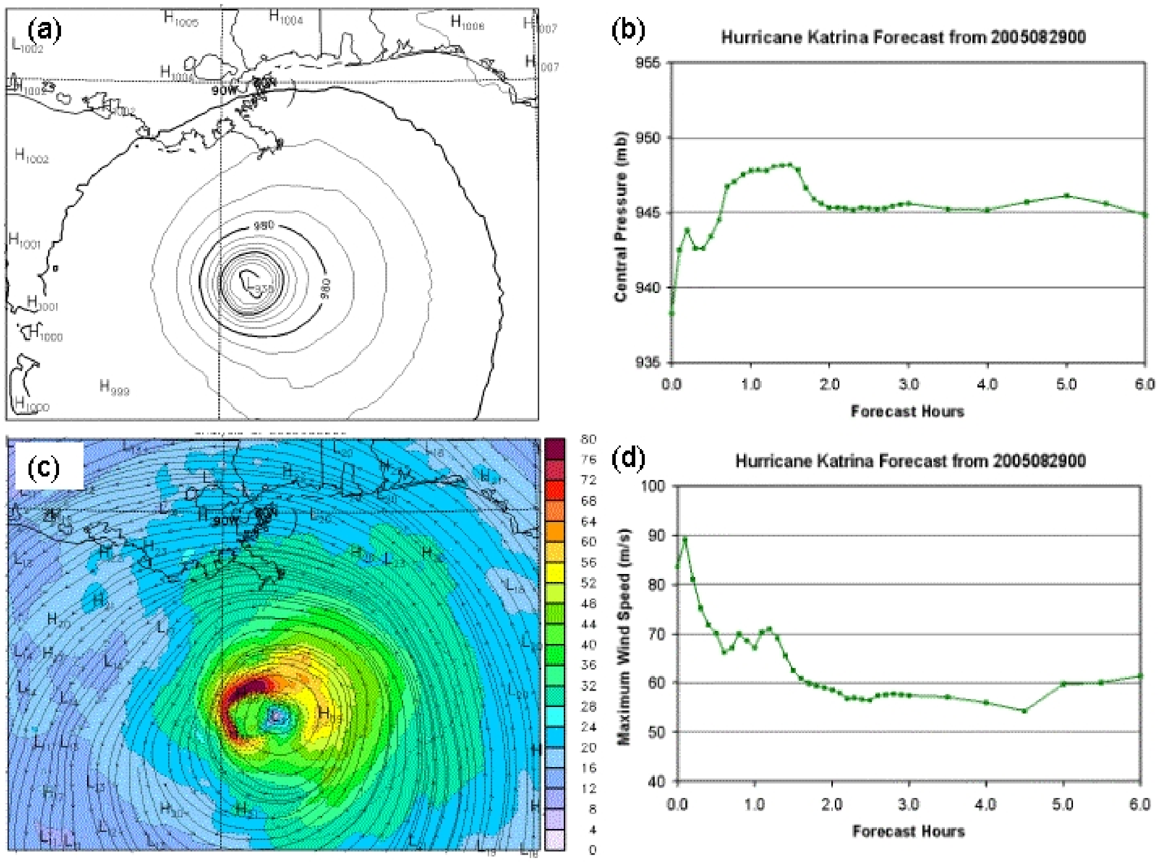

Fig 1. An example of very unbalanced initial conditions from 3-km resolution 3D-Var analysis: (a) sea-level pressure in mb, (b) cyclone central pressure in the first 6h forecast, (c) 850-mb wind in m/s, and (d) maximum wind in the first 6h forecast.

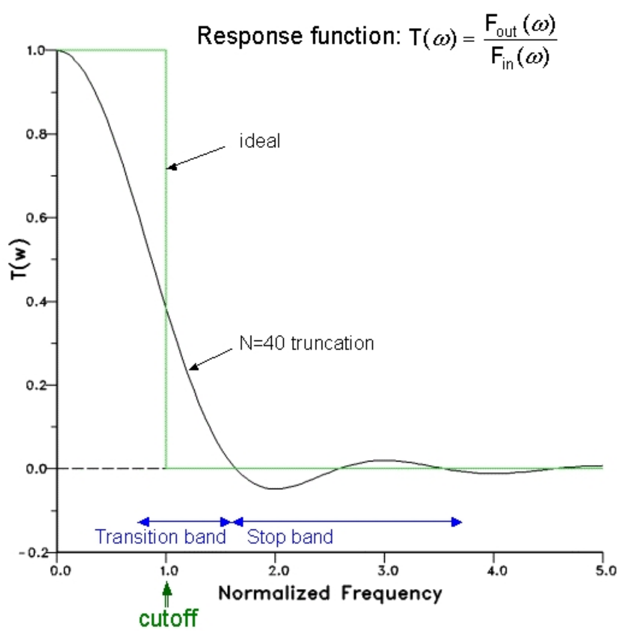

Fig 2. Response function of a digital filter with N=40 truncation and no windows.

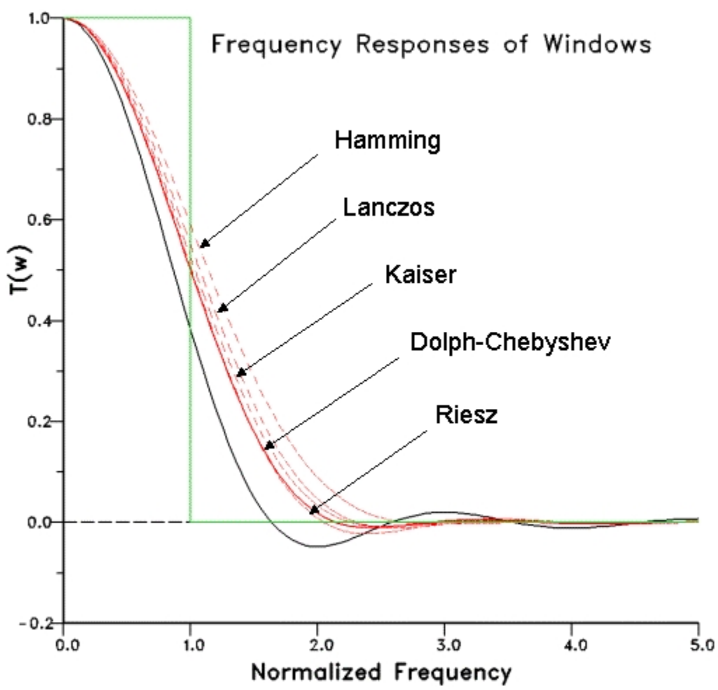

Fig 3. Same as Fig.2, except with 5 different windows.

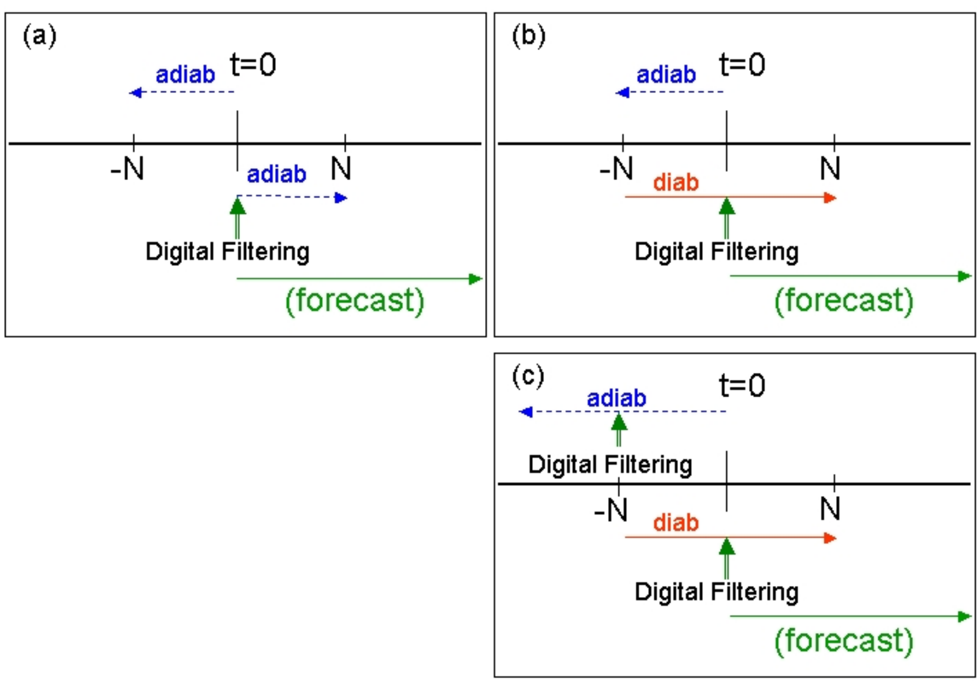

Fig 4. Three Initialization integration methods for digital filtering: (a) adiabatic, (b) diabatic method 1, and (3) diabatic method 2.

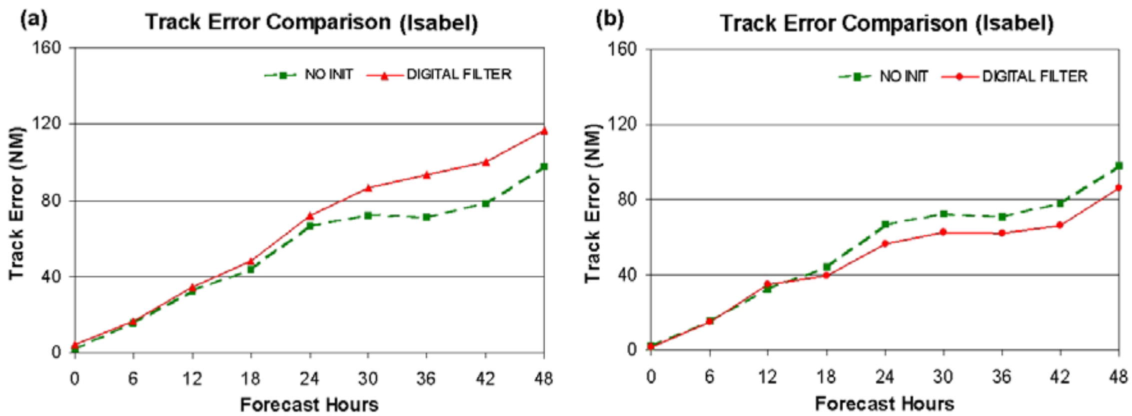

Fig. 5. Track forecast comparison with (red) and without (green) diabatic digital filtering using (a) 6h cutoff period with Lanczos window, and (b) 2h cutoff period with Dolph-Chebyshev window.

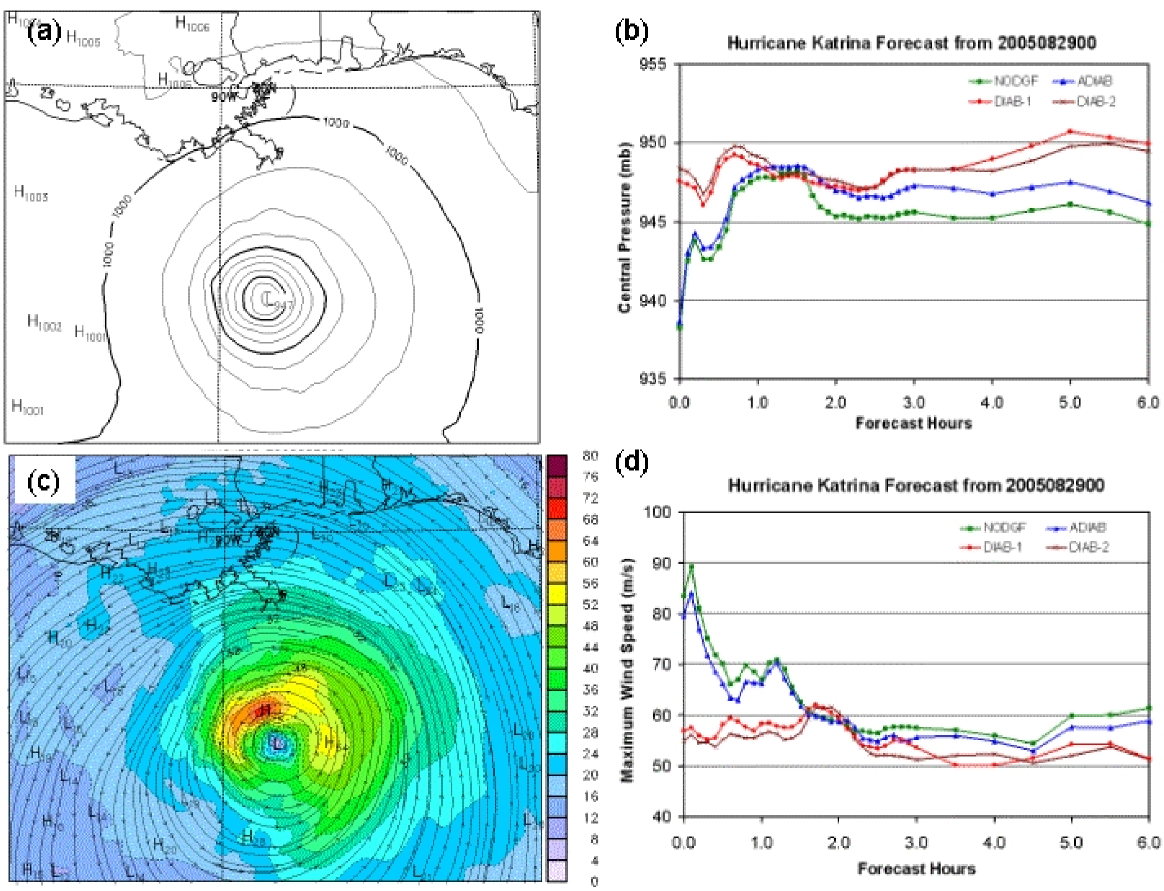

Fig 6. Same as Fig.1; except after digital filtering initialization (a), (c) by diabatic method 1; and (b), (d) by adiabatic (blue), diabatic method 1 (red) and diabatic method 2 (purple).

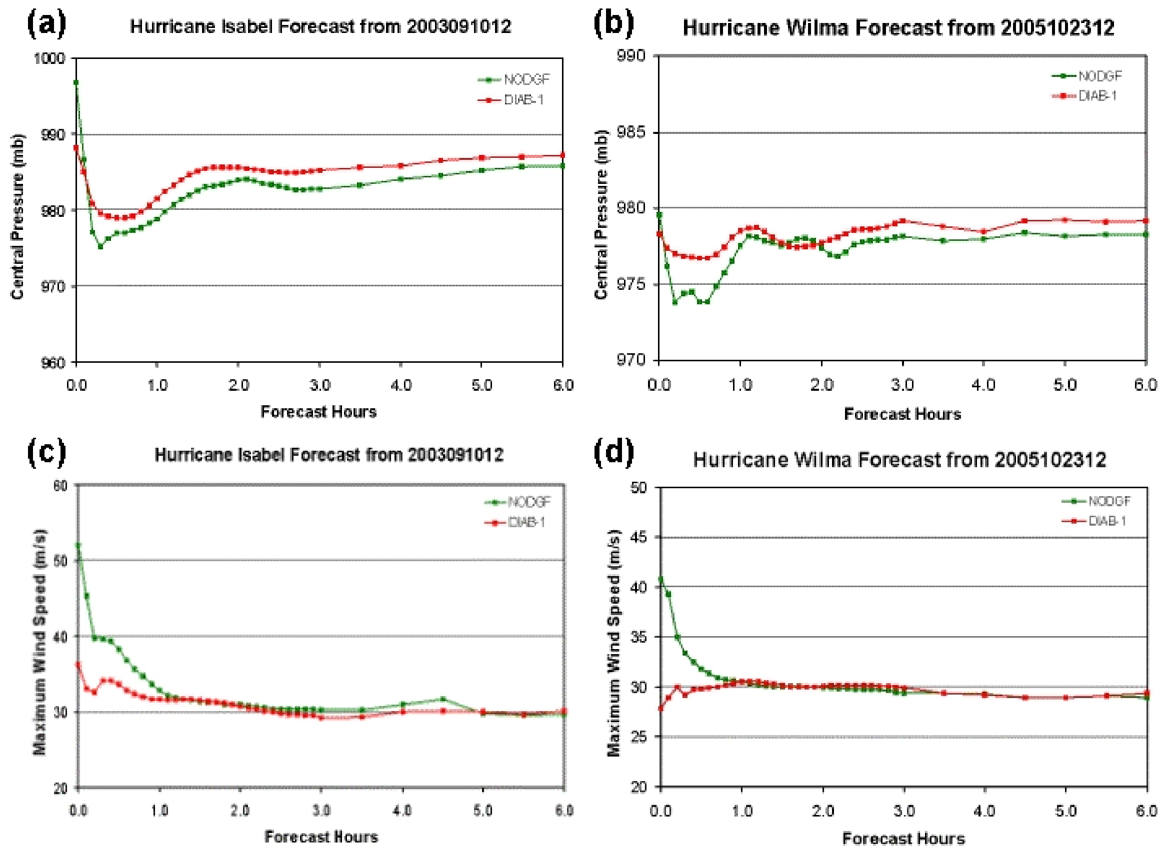

Fig 7. First 6h forecast of (a), (b) central pressure and (c), (d) maximum wind before (green) and after (red) diabatic method 1 filtering for tropical cyclones Isabel and Wilma.

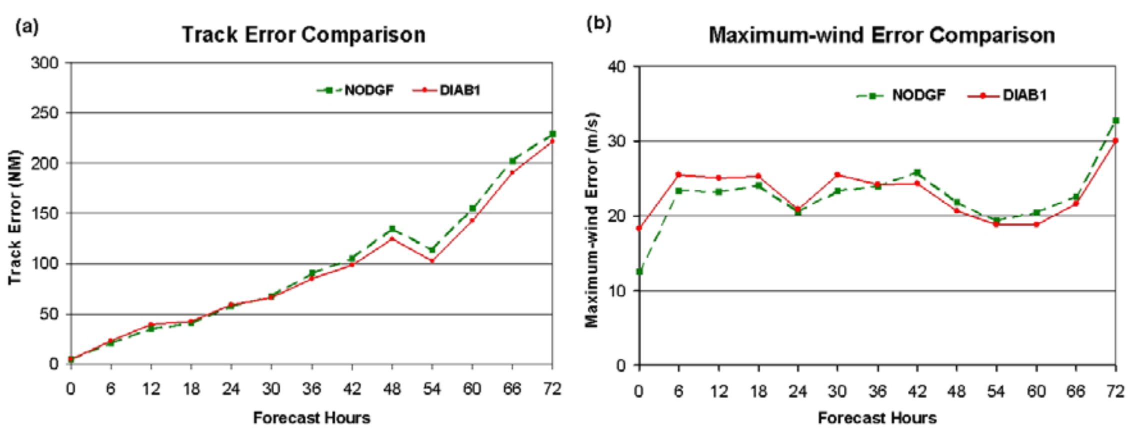

Fig. 8. Comparison of 14 cases averaged (a) track (nm) and (b) intensity (m/s) forecast errors with (red) and without (green) diabatic digital filtering initialization.