Hurricane forecasting with the high-resolution NASA finite volume general circulation model

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[1] A high-resolution finite volume general circulation model (fvGCM), resulting from a development effort of more than ten years, is now being run operationally at the NASA Goddard Space Flight Center and Ames Research Center. The model is based on a finite volume dynamical core with terrain-following Lagrangian control volume discretization and performs efficiently on massive parallel architectures. The computational efficiency allows simulations at a resolution of a quarter of a degree, which is double the resolution currently adopted by most global models in operational weather centers. Such fine global resolution brings us closer to overcoming a fundamental barrier in global atmospheric modeling for both weather and climate, because tropical cyclones can be more realistically represented. In this work, preliminary results are shown. Fifteen simulations of four Atlantic tropical cyclones in 2002 and 2004, chosen because of varied difficulties presented to numerical weather forecasting, are performed. The fvGCM produces very good forecasts of these tropical systems, adequately resolving problems like erratic track, abrupt recurvature, intense extratropical transition, multiple landfall and reintensification, and interaction among vortices. **Citation:** Atlas, R., O. Reale, B.-W. Shen, S.-J. Lin, J.-D. Chern, W. Putman, T. Lee, K.-S. Yeh, M. Bosilovich, and J. Radakovich (2005), Hurricane forecasting with the high-resolution NASA finite volume general circulation model, *Geophys. Res. Lett.*, *32*, L03807, doi:10.1029/2004GL021513.

1. Introduction

[2] Numerical forecasting of tropical cyclones presents several difficulties for general circulation models (GCMs), the most important being the resolution. To increase the resolution of GCMs for operational use is not trivial, because it involves many aspects ranging from purely theoretical to computational. Since operational weather forecasts need to be released in real time, the resolution currently adopted by many operational centers around the world, of the order of 0.5°, represents a compromise between the contrasting needs of minimum possible computing resources and maximum possible resolution. However, tropical cyclones are not fully resolved by GCMs at such resolution and appear as broad and weak vortices with vertical structure resembling the observed only to a first approximation.

[3] In this article we show that some of these limitations are overcome with the new finite volume General Circulation Model (fvGCM) developed at the NASA Goddard Space Flight Center (GSFC), and currently being run at a resolution of quarter of a degree. This increase in resolution brings a fundamental improvement in the way in which hurricanes are being represented and predicted. We present the results of 15 fvGCM experiments in simulating four tropical systems: Gustav and Isidore (2002), and Bonnie and Charley (2004).

2. The Model

[4] The fvGCM is based on the finite volume dynamical core with terrain-following Lagrangian control volume discretization documented by *Lin* [2004]. The development of the finite volume dynamical core at NASA GSFC is the result of more than ten years of intense effort, in which the most fundamental steps are: 1) development of algorithms for transport processes of water vapor [*Lin et al.*, 1994]; 2) development of multidimensional "Flux-Form Semi-Lagrangian Transport" scheme (FFSL) [*Lin and Rood*, 1996]; 3) adaptation of the FFSL algorithm to the shallow water dynamical framework [*Lin and Rood*, 1997]; 4) development of a simple finite volume integration method for computing pressure gradient in general terrain-following coordinates [*Lin*, 1997].

[5] A crucial aspect of the fvGCM development is its high computational efficiency, possible thanks to a careful design aimed to optimize performance on a variety of computational platforms including distributed memory, shared memory and hybrid architectures. The high resolution fvGCM, developed as a part of the ALTIX project, is currently being run on one 512-CPU SGI-Altix system, which is one node of a supercomputer named Columbia, operational at the NASA Ames Research Center (ARC). The Altix nodes use Intel Itanium-II 1.5 GHz processors, and are running ProPack Linux operating systems. At a resolution of 0.25°, with 32 vertical levels, which is the one adopted for this work, it takes only about 3700 seconds to finish a 5-day forecast by using 240 CPUs. The global initial conditions (ICs) for the dynamic fields for all the 15 experiments are provided by the National Centers for

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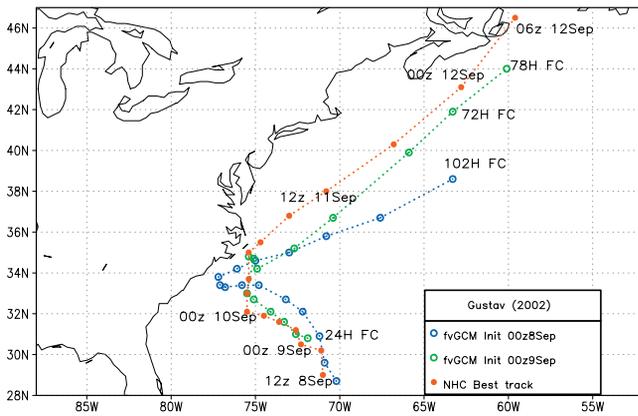
Figure 1. fvGCM simulations for Hurricane Gustav compared with the observed track by the National Hurricane Center (NHC). Each dot represents the center position at 6-hour time increments.

Environmental Predictions (NCEP). These are interpolated horizontally and vertically [*Lin*, 2004] but no additional data assimilation or bogusing of any kind is performed.

3. The Experiments

3.1. Hurricanes Gustav and Isidore (2002)

[6] Gustav was a category 2 hurricane, that started as a subtropical depression at 1200 UTC 8 September [*Pasch et al.*, 2004]. The system moved erratically west-northwestward on 9 September and slowly strengthened. It then underwent a rapid tropical development becoming a tropical storm at 1200 UTC 10 September. Gustav skirted the North Carolina coast at about 2100 UTC, affecting it within the radius of maximum wind, and then abruptly recurved northeastward (J. Beven, Tropical cyclone report: Hurricane Gustav, 2002, http://www.nhc.noaa.gov/2002gustav.shtml). Although its intensity is not remarkable, it is worth noting that the system, after its sharp recurvature, underwent an intense extratropical transition (ET) becoming a strong baroclinic system (center pressure at about 970 hPa) by 0000 UTC 13 September.

[7] In Figure 1 the official observed National Hurricane Center (NHC) 'best track' (BT) of Gustav is displayed, together with the fvGCM forecast initialized at 0000 UTC 8 and 9 September. In the first simulation, Gustav is not yet present in the ICs. In spite of this severe limitation, the fvGCM develops a tropical cyclone-like vortex which approaches the North Carolina coastal line but then recurves to the ocean, as in the observations. The 48 and 72 hour forecasts are very good: the displacement error (of about 150–200 km) is small, considering the complex track. The subsequent run, initialized at 0000 UTC 9 September, is characterized by an even smaller error, due to a better defined vortex in the ICs. The simulation also represents very well the acceleration associated with the ET. Track errors of storms undergoing ETs are generally much larger [e.g., *Jones et al.*, 2003]. The fvGCM represents well also the storm's intensity at two different stages, both important phases of Gustav's lifecycle: the proximity to North Carolina around the recurving time and the completion of its ET. In Figures 2a and 2b, the sea level pressure (slp) is shown, relative to the initialization of the two runs, at 0000 UTC

8 and 9 September. In the central panels two forecasts issued from both initial conditions are shown. Figure 2c shows the 72-hour forecast for 0000 UTC 11 September (initialized at 0000 8 September). The model produces a small-scale low with about 999 hPa of center pressure, very accurately placed, as confirmed by Figure 2e (corresponding NCEP analyses for the same time). Figure 2d shows the 84-hour forecast for 1200 UTC 12 September, initialized at 0000 UTC 9 September, and in Figure 2f the corresponding NCEP validating analyses are plotted. The fvGCM, starting from the weak vortex in Figure 2b, produces a remarkable ET and generates a baroclinic low very close to New Foundland, in agreement with observations.

[8] Isidore was a slow moving and relatively long-lived tropical cyclone with a fairly complex track. After two days of erratic behavior, it became Tropical Storm Isidore at 0600 UTC 18 September, hurricane at 1800 UTC 19 September, hit northwestern Cuba on the 21st, then recurved southward making a second landfall on the 23rd over the Yucatan peninsula as a category 3 hurricane (L. Avila, Tropical cyclone report: Hurricane Isidore, 2002, http://www.nhc.noaa.gov/2002isidore.shtml, hereinafter referred to as Avila, 2002). After landfall, the system became stationary, lingering for more than 24 hours over northern Yucatan. It then returned abruptly over water tracking northward and eventually making a third landfall over Louisiana at 0600 UTC 26 September, as a strong tropical storm [*Pasch et al.*, 2004]. In Figure 3 the NHC observed BT and the tracks obtained from 7 simulations of Hurricane Isidore are shown. The first two runs, initialized
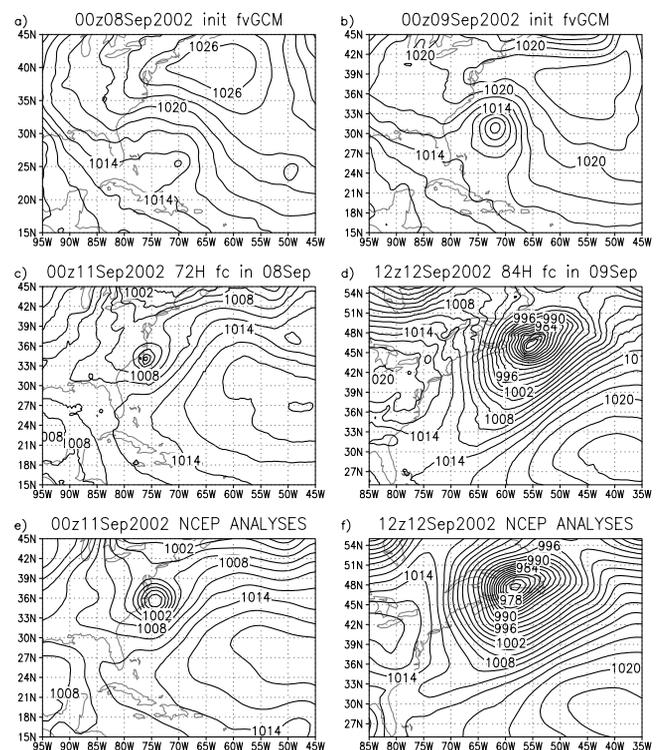

Figure 2. Slp (hPa). fvGCM ICs for 0000 UTC 8 and 9 September (a, b). 72 and 84 hour forecast initialized from 0000 UTC 8 and 9 September respectively (c, d). Corresponding NCEP validating analyses (e, f).
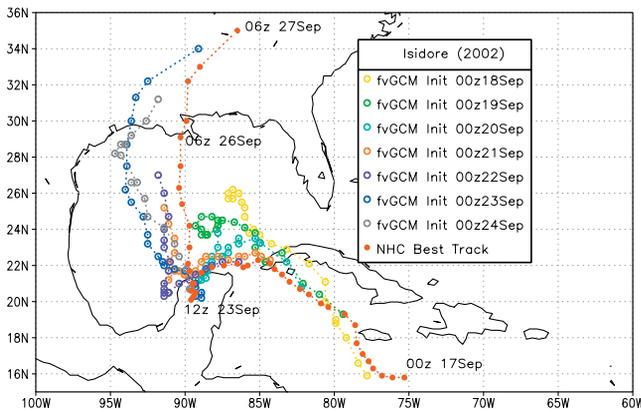
Figure 3. Same as Figure 1, but for Hurricane Isidore.

on 18 and 19 September, capture the landfall over Cuba in their 48- and 72-hour forecast very well. Eventually, the fvGCM attempts to force the cyclone recurving southward in the 4−5 day forecast but is penalized in these two firsts simulations by a very poor definition of Isidore in the ICs. The subsequent simulations have better defined signatures of the vortex in the ICs (although still far from optimal). In particular, the simulation initialized at 0000 UTC 20 September produces a very good track, encompassing in the

120-hour integration period the most relevant events of Isidore's lifecycle: landfall over western Cuba, southward recurvature and second landfall over the Yucatan.

[9] The intensification in the fvGCM is also remarkable. The fvGCM initialized on September 20th, starts from a broad vortex, as defined in the global ICs, of 999 hPa (not shown). The actual observed value for that time is 979 hPa (Avila, 2002). However, in spite of this limitation, the dynamical core of the fvGCM can produce a minimum of approximately 960 hPa in the 60-hour forecast for 1200 UTC 22 September. The observed minimum center pressure is of 934 hPa and occurs at the same time (Avila, 2002). The observed and simulated change in intensity between 0000 UTC 20 September and 1200 UTC 22 September are both of the order of 40 hPa. In Figures 4a and 4b the slp pressure at this time is shown, together with the 1° NCEP analyses. The analyses are not able to represent the true intensity but provide an indication of Isidore's position. In Figures 4c and 4d, the zonal and meridional vertical cross sections of wind speed, relative vorticity and temperature, are shown, relative to the 60-hour forecast for the same time (1200 UTC 22 September). All the prominent features of observed hurricanes can be seen: a vertical column of low speed, a prominent warm core, an intense gradient of cyclonic vorticity away from the eye, wind and cyclonic vorticity maxima in the lower levels, and a hint of anticy-
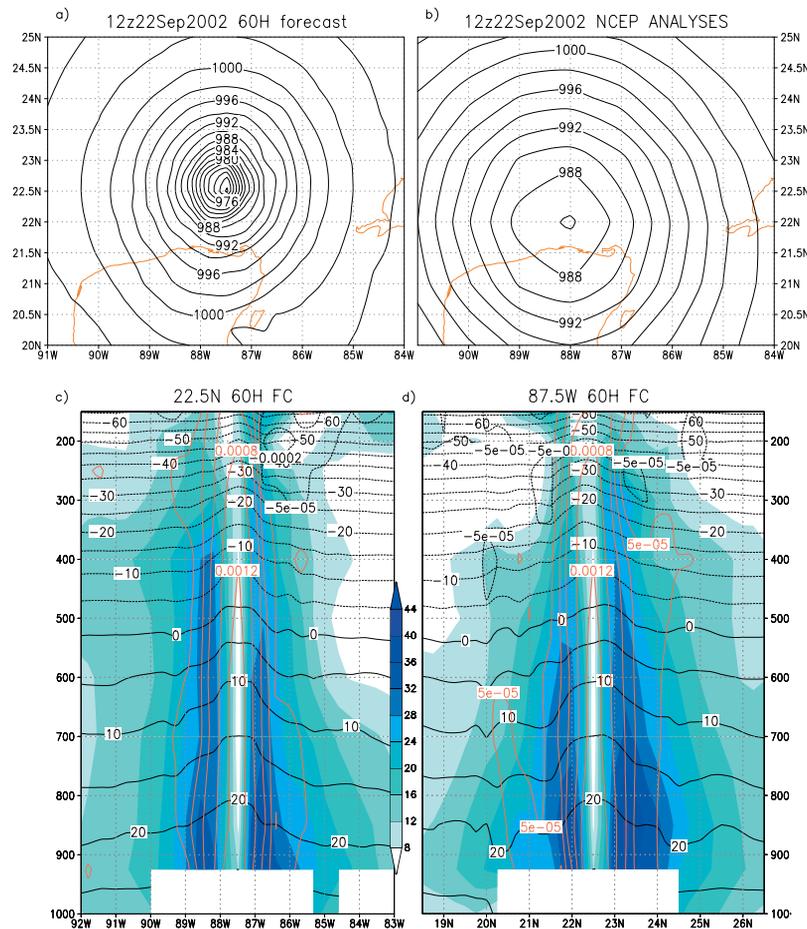

Figure 4. Slp (hPa) relative to 1200 UTC 22 September 2002: 60-hour forecast (a), NCEP validating analyses (b). Vertical cross sections relative to the 60-hour fvGCM forecast (c,d). Plotted are wind speed (ms^{-1}, shaded), relative vorticity (s^{-1} thick red/blue line), temperature (°C, solid black line).

clonic vorticity in the higher levels. Lower resolution GCMs may produce some of these features, but the radius of maximum wind is of the order of 2–300 km (whereas in our case it is of less than 100 km) and vorticity maxima are weaker and located at excessive altitude.

3.2. TS Bonnie and Hurricane Charley (2004)

[10] Bonnie was first spotted as a tropical depression on 3 August 2004. After a slow and discontinuous development it regained organization and was named as a tropical storm on 10 August, making landfall on the Florida panhandle on August 12th. Charley was a category 3 hurricane that was first seen as a tropical depression on 9 August, and went through a rapid development becoming a tropical storm on the 10th and a hurricane on the 11th. It eventually made landfall over southwestern Florida. In Figure 5, the NHC observed tracks from advisories are compared with our simulations. In the earliest simulation (initialized at 0000 UTC 11 August) the fvGCM is penalized by the complete absence of any vortex in correspondence to Charley. The later runs have a better initialization, but the discrepancy between the vortex as defined in the ICs and its actual intensity is still large. Because of this systematic problem, the fvGCM needs some spin-up time to actually build the hurricane vortex. Moreover, Bonnie's development seems to be affected by the presence of a well-defined vortex for Charley in our model. The better defined and deeper Charley appears to be in our integrations, the more to the east (and to observations) goes Bonnie's track. This suggests that Charley induces an eastward component of motion in Bonnie. However, in spite of the limitations derived from inadequate ICs, the tracks for Charley show a small dispersion, which indicates a substantial stability in the model's performance and its potential.

[11] Table 1 summarizes all the experiments and confirms that the best forecasts, in terms of track and intensity, are obtained when a well-defined vortex is present in the ICs, and/or when the model has sufficient spin-up time to build up a vortex before landfall. In fact, the simulations of Isidore initialized at 0000 UTC 20 and 21 September 2002 have a vortex in the ICs which is deeper than 1000 hPa, and in the simulation of Gustav initialized at
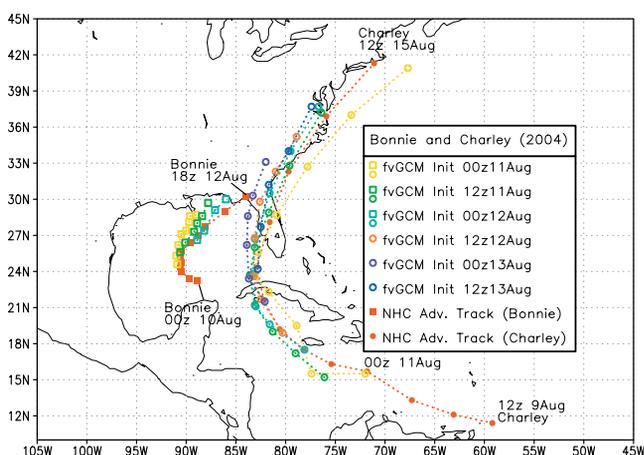
Table 1. Summary of Results[a]

IT	Ob/An	MSC	DE 48,72,96,120	DEL
2002: Gustav (Min obs slp 960 hPa at 06z 12Sep)				
00z8Sep	nontropical	980	150,190,820,–	–
00z9Sep	1004/1007	977	140,140,–,–	–
2002: Isidore (Min obs slp 934 hPa at 12z 22Sep)				
00z18Sep	1006/1007	968	260,240,430,630	240,–,–
00z19Sep	998/1005	962	280,300,340,410	100,–,–
00z20Sep	979/999	958	90,120,110,210	70,20,–
00z21Sep	964/991	948	140,130,170,280	–,50,–
00z22Sep	947/984	963	190,280,470,–	–,50,–
00z23Sep	950/982	974	200,400,–,–	–,–,330
00z24Sep	980/989	986	340,–,–,–	–,–,260
2004: Bonnie (Min obs slp 1000 hPa at 15z 11Aug)				
00z11Aug	1004/1011	1000	–,–,–,–	530
12z11Aug	1000/1010	1003	–,–,–,–	270
00z12Aug	1000/1010	1002	–,–,–,–	160
2004: Charley (Min obs slp 941 hPa 21z 13Aug)				
00z11Aug	999/NC	1008	240,100,220,–	30
12z11Aug	997/1011	1006	110,420,–,–	70
00z12Aug	993/1009	999	210,–,–,–	140
12z12Aug	984/1009	995	390,–,–,–	270
00z13Aug	975/1002	987	–,–,–,–	300
12z13Aug	967/998	993	–,–,–,–	30

[a]First column: initialization time (IT). Second: center slp (hPA) at IT: observed vs. analyzed (Ob/An). NC = no closed circulation. Third: minimum simulated center slp (MSC, hPa). Fourth: Displacement error (DE, km) at 48, 72, 96 and 120 hours (not computed after ET). Fifth: DE (km) at landfall (triple for Isidore).

0000 UTC 9 September 2002 the model has sufficient spin-up time to develop a deep cyclone. Conversely, the less satisfactory experiments are associated with Charley: in the first simulation there is no vortex in the ICs, in the subsequent three experiments the IC vortex center pressure is of about 1010 hPa, about 25 hPa less deep than observed. The runs initialized on 13 August have a deeper vortex, but still the slp difference between analyzed and observed vortex is large, and landfall occurs too soon for the dynamical core to deepen the system sufficiently.

4. Conclusions

[12] In this work, preliminary results obtained with the high resolution finite volume General Circulation Model developed at the NASA Goddard Space Flight Center are presented. Fifteen 5-day simulations involving four Atlantic tropical systems, chosen for their complex tracks, their dynamical differences, and their radically different life-cycles, are shown. The model, being run at the resolution of a quarter of a degree, has demonstrated the ability of capturing the development of all these very different systems, facing problems ranging from abrupt recurvature, intense extratropical transitions, multiple landfall with reintensification and interaction among vortices.

[13] An important problem faced is represented by the initialization. Although a global set of initial conditions at a resolution of a quarter of a degree is very ambitious and perhaps will not be attainable in the near future, an optimal use of satellite data, with selected data assimilation to improve the definition of the vortex at the initial stages, can compensate for the initialization deficiencies and bring further improvements to the performance of the fvGCM.

Figure 5. Same as Figure 1, but for Bonnie and Charley (2004). For clarity, positions are plotted at 6-hour and 12-hour time increments for Bonnie and Charley respectively.

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