The 0.125 degree finite-volume general circulation model on the NASA Columbia supercomputer: Preliminary simulations of mesoscale vortices

B.-W. Shen,[1,2] R. Atlas,[3] J.-D. Chern,[1,4] O. Reale,[1,4] S.-J. Lin,[5] T. Lee,[6] and J. Chang[7,8]

Received 14 September 2005; revised 29 December 2005; accepted 23 January 2006; published 2 March 2006.

[1] The NASA Columbia supercomputer was ranked second on the TOP500 List in November, 2004. Such a quantum jump in computing power provides unprecedented opportunities to conduct ultra-high resolution simulations with the finite-volume General Circulation Model (fvGCM). During 2004, the model was run in realtime experimentally at 0.25 degree resolution producing remarkable hurricane forecasts (Atlas et al., 2005). In 2005, the horizontal resolution was further doubled, which makes the fvGCM comparable to the first mesoscale resolving General Circulation Model at the Earth Simulator Center (Ohfuchi et al., 2004). Nine 5-day 0.125 degree simulations of three hurricanes in 2004 are presented first for model validation. Then it is shown how the model can simulate the formation of the Catalina eddies and Hawaiian lee vortices, which are generated by the interaction of the synoptic-scale flow with surface forcing, and have never been reproduced in a GCM before. **Citation:** Shen, B.-W., R. Atlas, J.-D. Chern, O. Reale, S.-J. Lin, T. Lee, and J. Chang (2006), The 0.125 degree finite-volume general circulation model on the NASA Columbia supercomputer: Preliminary simulations of mesoscale vortices, *Geophys. Res. Lett.*, *33*, L05801, doi:10.1029/2005GL024594.

1. Introduction

[2] Atmospheric modeling activities have been conventionally divided into three major categories based on scale separations, inclusive of synoptic-scale, meso-scale, and micro-scale modeling. General Circulation Models (GCMs) at about 35–50 km resolution have been running at major operational centers for synoptic-scale weather prediction, while mesoscale models (MMs) have been developed at higher resolutions to resolve small scale weather events in limited areas. GCMs and MMs offer both advantages and disadvantages. Among major sources of weather forecasting errors are insufficient resolution to resolve fine-scale structure in GCMs, and inaccurate information imposed at lateral boundaries in MMs.

[3] With computing power rapidly increasing at a rate approximately following Moore's law (doubling the speed every 18 months), some of the limitations could be overcome by either increasing GCMs' resolutions or extending the domain of MMs to the entire globe. After the Earth Simulator came into operation in early 2002, the first mesoscale resolving GCM at about 10 km resolution has been successfully developed by *Ohfuchi et al.* [2004]. In spite of the potential limits of the hydrostatic assumption and physics parameterizations, which were designed and tuned for coarser resolutions, they have successfully simulated realistic mesoscale weather events and multi-scale interactions in a global environment. However, no direct comparisons with observations had been attempted.

[4] The performance of the fvGCM in weather and hurricane predictions with resolutions from 1°, 0.5° to 0.25° have been discussed by *Lin et al.* [2004] and *Atlas et al.* [2005]. The 0.25° fvGCM was one of the first very high resolution GCMs running experimentally on twice-daily basis, and provided very good landfall and track predictions of the major hurricanes in 2004. Encouraged by the above successes, we have doubled the resolution to 0.125° to further investigate the impact of increasing resolution on weather and hurricane prediction.

[5] In this article, we compare numerical results with observations which include the Best Tracks (BTs) from the National Hurricane Center (NHC) and the Global Forecast System (GFS) T254 analysis data from the National Centers for Environmental Prediction (NCEP). We will briefly introduce the fvGCM and the Columbia Supercomputer, and then discuss the numerical results of the track predictions of hurricanes, the Catalina Eddy, and Hawaiian wakes.

2. The Supercomputer and the Model

[6] The Columbia Supercomputer, operating at the NASA Ames Research Center (ARC), consists of twenty 512-cpu nodes, which give 10,240 cpus, 20 Tera-Byte (TB) memory, and a theoretical peak performance of 60 TFLOPs (trillion floating-points operations per second). As of November 8, 2004, Columbia achieved a performance of 51.9 TFLOPs on the LINPACK (Linear Algebra Package) benchmark, and was ranked second on the TOP500 list. The cc-NUMA (cache-coherent Non-Uniform Memory Access) architecture within one node supports up to 1 TB shared memory. Nodes are connected via a high-speed InfiniBand interconnect, and each node can be running independently. These unique features enable us to increase model resolu-

[1]Laboratory for Atmospheres, NASA Goddard Space Flight Center, Greenbelt, Maryland, USA.
[2]Science Application International Corporation, Beltsville, Maryland, USA.
[3]NOAA Atlantic Oceanographic and Meteorological Laboratory, Miami, Florida, USA.
[4]Goddard Earth Sciences and Technology Center, University of Maryland, Baltimore County, Baltimore, Maryland, USA.
[5]NOAA Geophysical Fluid Dynamics Laboratory, Princeton, New Jersey, USA.
[6]NASA Headquarters, Washington, DC, USA.
[7]NASA Ames Research Center, Moffett Field, California, USA.
[8]Computer Sciences Corporation, Moffett Field, California, USA.

0094-8276/06/2005GL024594$05.00

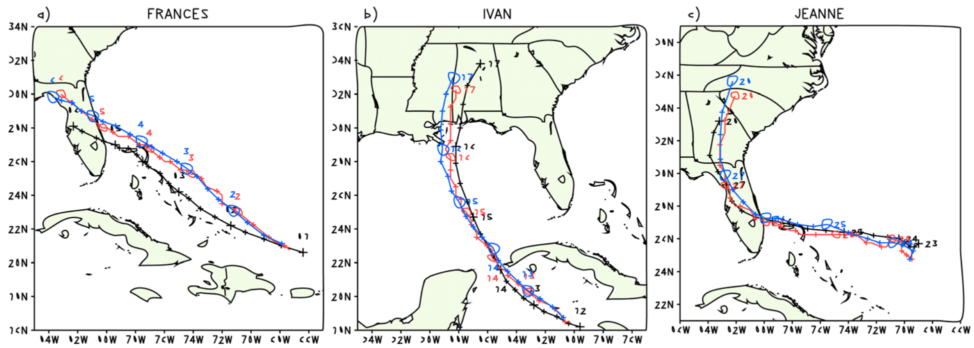

Figure 1. NASA high resolution five-day track predictions of hurricanes (a) Frances initialized at 0000 UTC 1 September, (b) Ivan initialized at 0000 UTC 12 September, and (c) Jeanne initialized at 0000 UTC 23 September, 2004. The blue (red) lines represent the tracks from 0.125 (0.25) degree simulations, while the black lines represent the best track from the National Hurricane Center. Each dot represents the center position at 6-hour time increments.

tions to explicitly resolve mesoscale circulations rarely simulated before in GCMs.

[7] The term "fvGCM" has been historically used to refer to the model which has been developed over 10 years at the NASA Goddard Space Flight Center and previously referred to as the NASA fvGCM. The model includes the finite-volume dynamic core [*Lin et al.*, 2004; *Lin*, 2004], NCAR CCM3 physics, and the NCAR Community Land Model (CLM), and is still the only global operational weather forecast model with finite-volume dynamics. It was originally designed for climate studies at a coarser resolution of about $2 \times 2.5^\circ$, and its resolution was increased to 1° in 2000, 0.5° in 2002, 0.25° in 2004, and 0.125° in 2005. All simulations presented in this article were performed with 32 stretched vertical levels, while some simulations with 64 levels were also performed to confirm our conclusions. The dynamic time step in all simulations is 15 seconds.

[8] Dynamic initial conditions and sea surface temperature (SST) were obtained from the NCEP GFS T254 analysis data and 1° optimum interpolation (OI) SST. Both data sets are interpolated to the model's resolution. Two-year spin-up runs for land model were performed at the 0.25° resolution for operational use in 2004. The 0.125° runs are produced from a cold-start initialized at 0000 UTC 01 September 2004.

3. The Numerical Results

3.1. Model Validation on Track Predictions

[9] During 2004, real-time twice-daily 0.25° simulations, running experimentally on the Columbia supercomputer, provided accurate track predictions of the hurricanes Frances, Ivan, and Jeanne. The remarkable results on the days 1–3, 11–13 and 22–24 September, which include exceptionally good tracks for Ivan and Jeanne, are documented here as control runs. We then verify the corresponding 0.125° track predictions against the aforementioned 0.25° forecasts to assure the model's performance, inclusive of convection parameterization (CP). Such validation becomes very important for an ultra-high resolution model, since the behavior of errors associated with parameterized physical processes and interpolated SST at different resolutions is not known.

[10] Figure 1 compares the official BTs with model forecasts, one for each of the above hurricanes. For hurricane Frances (Figure 1a), the 0.25° run initialized at 0000 UTC 01 September has displacement errors (DEs) within 150 km up to 96h simulations, and DE at landfall of about 100 km. Most forecasts for Ivan were affected by a persistent bias toward the east of the BT. Interestingly, the forecast initialized at 0000 UTC 12 September predicted an extremely good track with DEs of less than 100 km up to 96 hours, and a DE at landfall within 50 km (Figure 1b). On Jeanne, earlier track predictions by many GCMs, including the fvGCM, could not capture the complicated loop to the east of FL, and had a northward or westward bias relatively to the BT. The fvGCM had a small DE of 100 km up to 96 hours from the run initialized at 0000 UTC 23 September (Figure 1c). Jeanne finally made landfall in FL, almost at the same location as hurricane Frances, and its DE at landfall is within only one grid point.

[11] The corresponding 0.125° simulations provided comparable tracks with slightly faster propagation speeds. Quantitative evaluations shown in Table 1, with DEs in km, reveal that the 0.125° and 0.25° forecasts compare well. In a few cases, especially in the early phase of the forecast, faster propagation speeds lead to larger errors. However, the 0.125° track prediction initialized at 0000 UTC 11 September for Ivan is better than the 0.25° forecast after 24 hours of integrations. These results demonstrate the first successful ultra-high resolution track predictions of real hurricanes with a GCM, and suggest that the passage from the well-tested 0.25° to the 0.125° resolution maintains a comparable quality in track predictions. The early study by *Ohfuchi et al.* [2004] with the first mesoscale resolving GCM showed realistic typhoon predictions, but had no comparisons with observations. In addition to the need of a high-resolution model, accurate hurricane predictions also require better initialization in the magnitude and structure of the initial vortex, high-resolution SST, SST changes associated with air-sea interaction, better-tuned CP schemes or more adequate CP schemes from MMs, etc. These topics, challenging to both mesoscale and global modelers, will be addressed in subsequent papers. In this study, however, the most important results from the 0.125 simulations are well-resolved mesoscale features such as the Catalina Eddy

Table 1. Summary of Results[a]

Init Time	0.25° DE	0.125° DE
	Frances	
00z01Sep	102,144,95,141,227	104,166,140,250,243
00z02Sep	90,114,174,246,306	90,141,203,222,222
00z03Sep	87,85,111,190,417	57,90,129,147,303
	Ivan	
00z11Sep	120,246,443,614,767	98,237,406,600,680
00z12Sep	91,94,59,80,234	108,152,144,92,195
00z13Sep	75,85,210,428,871	80,115,200,412,743
	Jeanne	
00z22Sep	130,198,59,180,256	112,110,87,240,257
00z23Sep	52,60,53,11,201	45,130,50,64,283
00z24Sep	53,68,130,238,343	49,66,137,158,354

[a]Init Time, initialization time; DE, displacement error (in km) at 24, 48, 72, 96 and 120 hours for 0.25° and 0.125° runs.

and the Hawaiian wakes, which will be discussed in the next sections.

3.2. The Catalina Eddy

[12] During late spring through early fall, a mesoscale cyclonic circulation is often observed near Catalina Island in the bight of Southern California where synoptic-scale northwesterly flow interacts with coastal terrains. This remarkable feature with a spatial and temporal scale of about 100–200 km and from few hours to several days is called the Catalina Eddy.

[13] Its prominent formative mechanism is lee troughing, which states that interaction between a synoptic-scale upper-level trough with coastal orography leads to the formation of a surface low. The consequent southerly wind generated by the alongshore pressure gradient combines with the ambient predominant northerly wind to form low-level cyclonic vorticity [*Mass and Albright*, 1989].

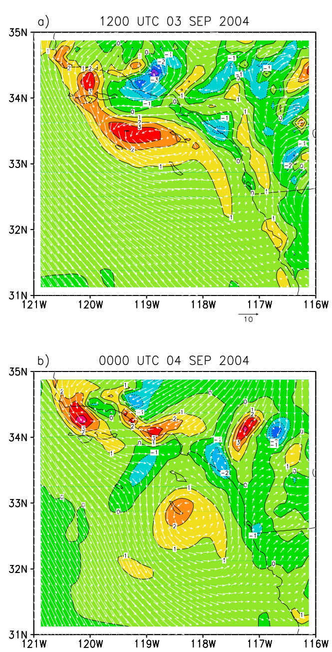

Figure 2. Simulations of the Catalina Eddy initialized at 0000 UTC 1 September 2004. (a) 60 h simulation and (b) 72 h simulation. The contour interval is 10^{-4} s^{-1}.

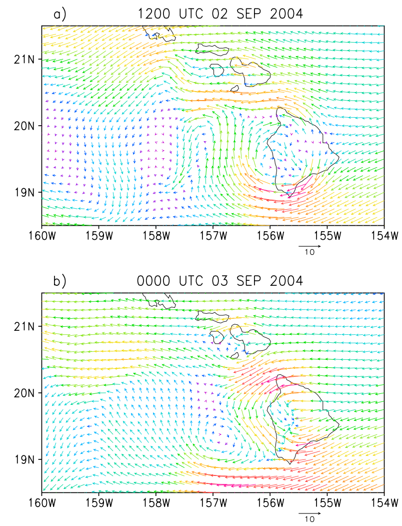

Figure 3. Simulations of the Hawaiian Vortices initialized at 0000 UTC 1 September 2004. (a) 36 h simulation and (b) 48 h simulation.

Therefore, to predict the Catalina Eddy accurately, a numerical model is required to not only simulate the time evolution of the synoptic-scale trough but also to resolve the mesoscale feature of the eddy [*Davis et al.*, 2000]. With a coarse-resolution GCM, forecasters could only infer the occurrence of the Catalina eddy by predicting either the passage of the upper-level trough or the existence of the alongshore pressure gradient. Although modern MMs theoretically have sufficient resolution to resolve the eddy, it has been recently shown that even an operational MM could not always accurately predict the formation and evolution of the eddy [*Hu and Liu*, 2002].

[14] Analyzing the model outputs from the runs discussed in Section 3.1, it has been observed that a weak Catalina eddy was first simulated along with the occurrence of a 500 hPa trough at 54h integrations from the run initialized at 0000 UTC 01 September. Figure 2 shows the simulated 10 m above-surface winds and vorticities (shaded) at 60- and 72- hour forecasts, respectively. A clear vortex associated with positive vorticities occurs near the Channel Islands (Figure 2a), propagates downstream (Figure 2b), and finally dissipates (not shown). By comparison, in the new NCEP/GFS T384 (35 km) analysis data, the location of the eddy could be inferred from the vorticity fields (not shown). However, a closed circulation appeared discontinuously in time, at 1200 UTC 3 and 0600 UTC 4 September.

[15] The subsequent 0.125° forecasts initialized at 0000 UTC 02 and 03 September also provided consistent predictions of this eddy event, whereas simulations at coarser resolutions (0.25° and 0.5°) failed to produce it (not shown).

3.3. The Hawaiian Wakes

[16] In the lee sides of Hawaiian islands, mesoscale vortices and wakes of weak winds are often observed when east-northeasterly trade winds interact with the high mountains. Recently, positive/negative vorticities have been observed in NASA QuikSCAT seawinds data downstream of each of the four major Hawaiian islands [*Xie et al.*, 2001]. Numerical simulations of mesoscale vortices for a nonlinear

flow over an isolated mountain have been conducted to study the formation mechanism since late 1980 [e.g., *Smolarkiewicz and Rotunno*, 1989; *Smith*, 1989]. These lee vortices, which share many similarities with Von Karman vortices, were found to have a fundamentally different formation mechanism, and brought challenging tasks to mesoscale modelers.

[17] Idealized simulations identified the Froude number, which reflects the ratio of the kinetic energy to the potential energy, as a control parameter to understand wake dynamics. However, it has been found that other factors such as changes in upstream wind, boundary layer frictions, complexity of terrains, Coriolis force, and diurnal heating could also change the final appearance of the vortices/wakes [e.g., *Reisner and Smolarkiewicz*, 1994]. Due to the limited computing resources, the above effects were studied separately with limited domain sizes and short integration periods (12–24 hours) [e.g., *Ueyoshi and Han*, 1991].

[18] With the superior performance of the fvGCM and Columbia, the above difficulties can be overcome. Figure 3a shows the 10 m above-surface wind vectors at 36h simulations from the run initialized at 0000 UTC 1 September. Due to the collective effects of mountain blocking and nocturnal cooling, westerly winds are induced on the windward side, and a stagnation point occurs. The prevailing easterly flow are diverted around the high mountain of the Big Island. Near the lee side of the island, a vortex with anti-cyclonic (AC) vorticity is found. Further downstream, a lee trough with cyclonic vorticity indicates vortex shedding. A strong easterly gap flow could be identified between the Big and Maui islands. The AC vortex and the lee trough propagate further downstream at 48h forecast (Figure 3b). Due to the diurnal heating, the sea breeze enhanced the easterly flow on the windward side, and the windward stagnation point disappears. The gap flow becomes north-easterly. A pair of cyclonic and anti-cyclonic vorticities also appears in the lee side of the Maui Island. By comparison, 0.25° results showed the tendency of "vorticity shedding," but without well-defined closed circulations. NCEP/GFS analysis data also showed results similar to the 0.25° forecast. Possible wake interactions behind the Big and Maui Islands were also simulated, and will be discussed in a separate paper.

4. Conclusion

[19] Traditionally, GCMs and MMs have been developed by different research groups with different goals. Because of a breakthrough in computing power provided by the Columbia supercomputer, the 0.125° fvGCM becomes one of a few mesoscale resolving GCMs, and has a resolution comparable to the first mesoscale GCM at the Earth Simulator Center, and to the finest resolution of the NASA QuikSCAT 12.5 km seawinds data. Numerical simulations of mesoscale vortices, which include three major hurricanes, the Catalina Eddy and Hawaiian vortices in 2004, have been discussed to demonstrate the model's capability of simulating scale interactions between convection and large-scale flow, between coastal surface forcing and synoptic-scale flow, and between high mountains and nonlinear flow. To our knowledge, the fvGCM is the first to simulate the formation of these mesoscale vortices in a global environment. It is our belief that the model with accurate representation of mesoscale flows near surface inhomogeneities could provide 1) useful information near the areas (e.g., the coast) where the QuikSCAT seawinds might have larger errors, and 2) a framework for more accurate assimilation of QuikSCAT data.

[20] Though physics parameterization schemes are designed and tuned for simulations at coarser resolutions, the 0.125° hurricane simulations still provide very encouraging results. However, comparable track predictions between 0.25° and 0.125° runs indicate that significant improvement of hurricane predictions will require better understanding of the role of physics parameterizations. Numerical experiments with the relaxation of deep and/or shallow convections have been conducted and will be the subject of a subsequent paper. Finally, non-hydrostatic extension to the finite-volume model is being developed and its significance at 0.125° resolution can be best evaluated against the hydrostatic results presented here.

[21] **Acknowledgments.** We would like to thank the reviewers for their valuable suggestions, which have substantially improved the manuscript, and thank the NASA Advanced Supercomputing (NAS) and NASA Center for Computational Sciences (NCCS) Divisions for strong support and use of computing and storage resources. Finally, we thank Dr. C. E. Henze for artistic visualizations, which are available at http://people.nas.nasa.gov/~chenze/GRL-200509/.

References

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.

Davis, C., S. Low-Man, and C. Mass (2000), Dynamics of a Catalina eddy revealed by numerical simulation, *Mon. Weather Rev.*, *128*, 2885–2904.

Hu, H., and W. T. Liu (2002), QuikSCAT reveals the surface circulation of the Catalina eddy, *Geophys. Res. Lett.*, *29*(17), 1821, doi:10.1029/2001GL014203.

Lin, S.-J. (2004), A vertically Lagrangian finite-volume dynamical core for global models, *Mon. Weather Rev.*, *132*, 2293–2307.

Lin, S.-J., R. Atlas, and K.-S. Yeh (2004), Global weather prediction and high-end computing at NASA, *Comput. Sci. Eng.*, *6*(1), 29–35.

Mass, C. F., and M. D. Albright (1989), Origin of the Catalina eddy, *Mon. Weather Rev.*, *17*, 2406–2436.

Ohfuchi, W., et al. (2004), 10-km mesh Mesoscale resolving simulations of the general atmosphere and ocean on the Earth Simulator, *J. Earth Simulator*, *1*, 8–34.

Reisner, J. M., and P. K. Smolarkiewicz (1994), Thermally forced low Froude number flow past three-dimensional obstacles, *J. Atmos. Sci.*, *51*, 117–133.

Smith, R. B. (1989), Comment on low Froude number flow past three dimensional obstacles. Part I: Baroclinically generated lee vortices, *J. Atmos. Sci.*, *46*, 3611–3613.

Smolarkiewicz, P. K., and R. Rotunno (1989), Low Froude number flow past three dimensional obstacles. Part I: Baroclinically generated lee vortices, *J. Atmos. Sci.*, *46*, 1154–1164.

Ueyoshi, K., and Y.-J. Han (1991), A three-dimensional simulation of airflow and orographic rain over the island of Hawaii, *J. Meteorol. Soc. Jpn.*, *69*, 127–152.

Xie, S.-P., W. T. Liu, Q. Liu, and M. Nonaka (2001), Far-reaching effects of the Hawaiian islands on the Pacific ocean-atmosphere system, *Science*, *292*, 2057–2060.

J.-D. Chern, O. Reale, and B.-W. Shen, Laboratory for Atmospheres, NASA Goddard Space Flight Center, Code 613, Greenbelt, MD 20771, USA. (bo-wen.shen.1@gsfc.nasa.gov)

R. Atlas, NOAA Atlantic Oceanographic and Meteorological Laboratory, 4301 Rickenbacker Causeway, Miami, FL 33149, USA.

S.-J. Lin, NOAA Geophysical Fluid Dynamics Laboratory, Princeton, NJ 08542, USA.

T. Lee, NASA Headquarters, Washington, DC 20546, USA.

J. Chang, NASA Ames Research Center, M/S 258-6, Moffett Field, CA 94035, USA.