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Hurricane forecasts with a global mesoscale-resolving model: Preliminary results with Hurricane Katrina (2005)

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[1] It is known that General Circulation Models (GCMs) have insufficient resolution to accurately simulate hurricane near-eye structure and intensity. The increasing capabilities of high-end computers have changed this. The mesoscale-resolving finite-volume GCM (fvGCM) has been experimentally deployed on the NASA Columbia supercomputer, and its performance is evaluated in this study by choosing hurricane Katrina as an example. In late August 2005, Katrina underwent two stages of rapid intensification, and became the sixth most intense hurricane in the Atlantic. Six 5-day simulations of Katrina at both 0.25° and 0.125° show comparable track forecasts but the 0.125° runs provide much better intensity forecasts, producing the center pressure with errors of only ±12 hPa. In the runs examined in this study, the 0.125° simulates better near-eye wind distributions and a more realistic average intensification rate. To contribute to the ongoing research on the effects of disabling convection parameterization (CP), we present promising results by comparing 0.125° runs with disabled CPs against runs with enabled CPs. **Citation:** Shen, B.-W., R. Atlas, O. Reale, S.-J. Lin, J.-D. Chern, J. Chang, C. Henze, and J.-L. Li (2006), Hurricane forecasts with a global mesoscale-resolving model: Preliminary results with Hurricane Katrina (2005), *Geophys. Res. Lett.*, *33*, L13813, doi:10.1029/2006GL026143.

1. Introduction

[2] Hurricane track forecasts have been steadily improved over past decades, but the progress on intensity forecasts has been very slow. The representation of hurricane internal dynamics is crucial to accurately predict intensity [*Marks and Shay*, 1998], and has been studied with mesoscale models (MMs) at resolutions of 1–10 km for years [e.g., *Wu et al.*, 2003]. However, GCMs' insufficient resolution undermines intensity prediction [e.g., *Henderson-Sellers*, 1998]. Although computing power in industry keeps increasing at a rate of doubling the processor speed every 18 months, the science community is still limited by computing power to deploy ultra-high resolution GCMs, with the exception of *Ohfuchi et al.* [2004] at the Japan Earth Simulator Center. After the NASA Columbia supercomputer came into operation at Ames Research Center in late 2004, its superior computing power provided unprecedented opportunities for extremely computationally demanding tasks, thus making a mesoscale-resolving finite-volume GCM (fvGCM) possible. *Atlas et al.* [2005] presented remarkable hurricane forecasts with the 0.25° fvGCM, which has been running experimentally in realtime since 2004. More recently, *Shen et al.* [2006] successfully obtained promising simulations of hurricane tracks and mesoscale vortices (e.g., the Catalina Eddy and Hawaiian wakes) with the 0.125° model, giving a grid spacing of 10km in the midlatitude.

[3] Other than the computational issue, the validity of physics parameterizations (PPs) poses another challenge of conducting ultra-high resolution simulations. Among PPs, convection parameterization (CP) is recognized as a crucial limiting factor affecting hurricane forecasts in both MMs and GCMs [e.g., *Elsberry et al.*, 1992]. In MMs, a resolution of 4km is necessary to resolve clouds explicitly, thereby removing the dependence of CPs. This implies that CPs might still be needed in the 0.125° fvGCM. However, as shown by *Rosenthal* [1978] that the release of latent heat caused by convection could be explicitly resolved in a hydrostatic hurricane model at a resolution of 10–20 km, we are inspired to examine the impact of disabling the CPs on hurricane forecasts with the fvGCM.

[4] In this study, we choose hurricane Katrina, which devastated New Orleans and the surrounding Gulf Coast region. Katrina first appeared at 2100 UTC 23 August, 2005, moved across south Florida as a Category 1 hurricane, intensified to Category 5 with a minimum sea level pressure (MSLP) of 902 hPa over the Gulf of Mexico, weakened to Category 3 at its second landfall near New Orleans at 1100 UTC 29, and then dissipated over land on August 30. It caused damages estimated as high as $200 billion, and raised a challenge for intensity predictions with GCMs. We use the fvGCM, either with or without CPs, to simulate Katrina's track and also its intensity and near-eye wind distributions. First, we will briefly describe our model and numerical approach, then discuss results and give concluding remarks.

2. Model and Numerical Experiments

[5] The fvGCM has three major components: 1)finite-volume dynamics, 2)NCAR CCM3 physics, and 3)NCAR

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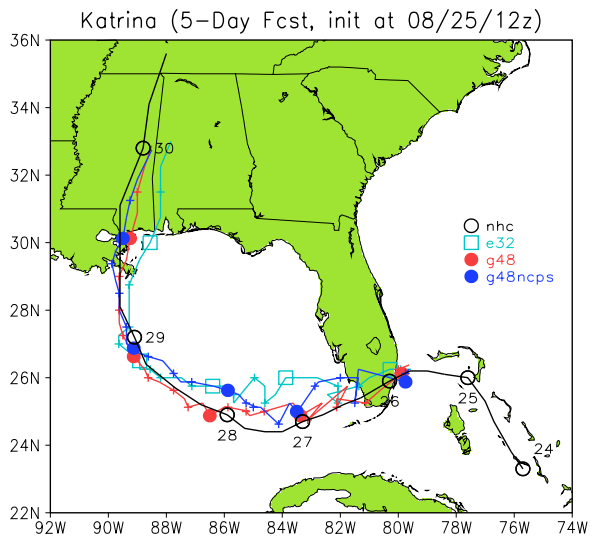

Figure 1. Five-day track predictions of hurricane Katrina initialized at 1200 UTC 25 August, 2005. The light blue, red, and blue lines represent the tracks from 0.25°, 0.125° simulations and 0.125° simulation with no cps. Each dot represents the center position at 3-hour time increments. The black line represents the advisory track with a 6-hour time increment from the National Hurricane Center.

Community Land model [e.g., *Lin and Rood*, 1997; *Lin*, 2004]. In the model, *Zhang and McFarlane* [1995] and *Hack* [1994] schemes are used for deep convection and shallow-and-midlevel convection respectively. With these CPs disabled, latent heat release is from grid-scale condensation processes. Dynamic initial conditions (ICs) and sea surface temperature (SST) are obtained from the GFS T384 analysis data and 1° optimum interpolation SST of National Centers for Environmental Prediction. No vortex initialization (e.g., bogusing) scheme is applied on the ICs.

[6] In this work, six 5-day simulations of Katrina initialized from 1200 UTC 25 to 0000 UTC 28 AUG at the 0.125° resolution with 48 stretched vertical layers are conducted and compared to the realtime 0.25° results. We will mainly discuss the forecasts initialized at 1200 UTC 25 AUG, because Katrina experienced two stages of rapid intensification (RI) during the 5-day period. Here, the RI as defined by *Kaplan and DeMaria* [2003] requires a maximum surface wind (MSW) speed increase of 55.4 km/r/day. For convenience, g48 (e32) will be referred to as the 0.125° (0.25°) run at the aforementioned time, and g48-ncps as the 0.125° run without CPs. The rest of the Katrina's forecasts and other test runs are documented in Figures S1–S5 of the auxiliary material[1] to confirm our conclusions.

3. Numerical Results

3.1. Model Tests

[7] The performance of the 0.125° fvGCM on hurricane track forecasts was first illustrated in nine 5-day simulations of hurricanes Frances, Ivan, and Jeanne in 2004 [*Shen et al.*, 2006]. Additional fourteen 5-day forecasts of hurricane Emily at 0000 and 1200 UTC from 11 to 17 July, 2005 are presented in Figure S1 to validate the approach of disabling CPs. A systematic evaluation for major hurricanes in 2004 and 2005, requiring tremendous time and computing resources, is currently being conducted. In contrast to the 0.25° realtime forecasts which have a persistent bias toward the right-hand side of the best track in the first seven runs, the 0.125° track forecasts without CPs have a smaller bias (Figure S1). By performing simulations of Katrina with enabled or disabled CPs, we will further discuss the intensity forecast and the near-eye wind distributions, which are for the first time tentatively simulated with a GCM. The model is run without any specific tuning.

3.2. Track and Intensity Predictions of Katrina

[8] Katrina's track and intensity evolution from NHC advisories are shown in Figures 1 and 2, and the phases of its intensity evolution (see also Table S1 in the auxiliary material) can be summarized as: (1) slow weakening and intensification; (2) the first RI from 26/15Z to 27/09Z with an averaged intensification rate (AIR) of 77.3 km/h/day; (3) intensity maintenance; (4) the second RI from 28/03Z to 28/21Z with an AIR of 112 km/h/day; (5) weakening and landfalling.

[9] In this study, the term "intensity evolution" will refer mainly to the temporal variation of MSLPs, while changes in MSW are documented to check whether the model storms experience RIs. As shown in Figure 1 and Figure S2, all of six track forecasts at 0.25° and 0.125° are comparable, and four of them are remarkably good. The displacement errors

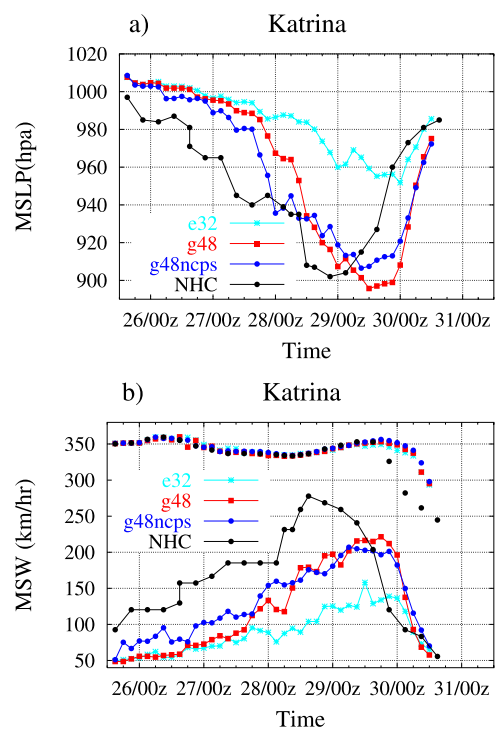

Figure 2. Intensity evolution of hurricane Katrina. (a) Minimum sea level Pressures and (b) maximum 10m surface winds (MSW) with solid lines and maximum potential intensity (MPI) with points along the corresponding tracks. Each dot represents the intensity at 3-hour time increments.

[1]Auxiliary material is available at ftp://ftp.agu.org/apend/gl/2006gl026143.

(DEs) at 24, 48, 72, 96, 120 hours are 19, 182, 60, 225, 289 km for e32, and 24, 93, 9.7, 169, 306 km for g48, respectively. While e32 DE is larger at an earlier time (e.g., 48 h), g48 DEs are within 100 km up to 72 h. Larger errors at 96 h and 120 h for both runs are due to slower simulated speeds, resulting in a timing error at landfall of about 8 h. DEs at landfall for the e32 and g48 are of 50 km and 14 km, respectively. It should be noted that the complex coastal topography near New Orleans is not fully resolved by the model, making the above comparisons problematic.

[10] The corresponding intensity forecasts are shown in Figure 2 and Figure S3. The timing of the maximum intensity for g48 (e32) is off about 15 h (27 h), because of lower predicted speed. The 0.25° runs predict values of MSLPs higher than observations (OBS) with errors of 20–45 hPa, but the 0.125° MSLP forecasts are much closer to OBS with errors of ±12 hPa. With the timing lag considered, intensity errors from 0.125° simulations are smaller before landfall, but larger after landfall. The latter simply indicates that a weaker model-predicted storm with a timing lag could have smaller intensity errors when the real storm is weakening. The intensity evolution for g48 can be identified as three major stages: (1) initial slow intensification, (2) RI from 27/15Z to 29/12Z with an AIR of 66 km/h/day, and (3) weakening during landfalling. In contrast to OBS, both e32 and g48 have only one stage of deepening. The former has a larger timing delay, while the latter has a longer intensification period. Notice that the run initialized at 0000 UTC 26 AUG has a larger DE at landfall but provides better intensity evolution because its landfall timing is better (Figures S2–S3). The predicted lowest MSLP from each of 0.125° forecasts is very encouraging, but the model AIR over the whole period before weakening is relatively larger, due to the fact that the initial vortex in each run is at least 10 hPa weaker than the observed one.

[11] SST is one of the major factors affecting hurricane intensity, though it is not a good intensity predictor. As suggested by the maximum potential intensity (MPI) theory of *Emanuel* [1988], SST, relative humidity (RH), and the outflow temperature of the tropical cyclone (TC) could provide an upper bound on the TC's intensity. By further simplifying the MPI theory, *DeMaria and Kaplan* [1994] obtained an empirical function defined as: $MPI = A + B \exp[C(SST - SST_0)]$, where $A = 34.2$ m/s, $B = 55.8$ m/s, $C = 0.1813°C^{-1}$, and $SST_0 = 30°C$. Substituting the SST along a track into the above equation produces the variations of MPI. In Figure 2b, the MPIs associated with different tracks provide thermodynamic upper bounds to check the model's maximum intensity, and also indicate the spatial changes of weighted SST along the tracks. The highest MPI along the Advisory Track is about 353 km/h, of which Katrina, with the MSW of 280 km/h, reaches about 80%. Historically, only 16% of Atlantic TCs during 1962–1992 reached this percentage [*DeMaria and Kaplan*, 1994]. In addition, all of the predicted maximum intensities are still about or below 80% of the MPIs, demonstrating model realistic performance. Before landfall, model storms with slower predicted speeds stay longer over warm ocean, indicated by large MPIs, so they intensify further.

[12] It has been suggested that warm SST anomalies are an important factor contributing to more intense hurricanes in 2005 [e.g., *Virmani and Weisberg*, 2006], and to Katrina's intensification (e.g., M. Kafatos et al., Anomalous gulf heating and Hurricane Katrina's rapid intensification, 2005, available at http://arxiv.org/ftp/physics/papers/0509/0509177.pdf). However, to examine the effects of SST variations on intensity evolution would require a fully coupled atmosphere-ocean model and is beyond the goal of this paper.

3.3. Simulations Without CPs

[13] The internal structure of the hurricane has convective-scale variations. The g48-ncps, giving a comparable track to g48, is performed to show the effects of disabling CPs on intensity variations. It has DEs of 89.5, 90, 47.5, 111, 320 km at 24, 48, 72, 96, 120 hours, and timing and location errors of 6h and 30km at landfall, respectively. The five stages are: (1) slow intensification, (2)the first RI from 27/15Z to 28/00Z with an AIR of 106.7 km/h/day, (3) slow variation, (4) the second RI from 28/21Z to 29/09Z with an AIR of 69.4 km/h/day, and (5) weakening. The model storm in g48-ncps with the lowest MSLP of 906.5 hPa is weaker than in the g48 case, does not over-deepen, and its intensity is closer to the observed 902 hPa. In contrast, *Bender and Ginis* [2000] simulated stronger hurricanes without CP than with CP. In spite of g48 and g48-ncps experiments having different convection processes, the predicted tracks are comparable, suggesting that the impact of SST on intensity variation is also comparable, as indicated by the corresponding MPI variations in Figure 2b. Therefore, these runs provide a very unique testbed to understand not only the role of large-scale forcing in determining convection, but also the role of parameterized convection on intensity evolution.

[14] Figure 3 compares the model 10m winds near the hurricane center in a 2° × 2° box with the AOML high-resolution (0.0542°) analysis data. The counterpart of Figure 3 with no interpolation is presented in Figure S4 for direct comparison. Since near-eye wind distribution depends on surface roughness, model times are chosen so that the predicted centers are close to the AOML data just before landfall. While the e32 (Figure 3b) gives a larger radius of maximum wind (RMW) because of insufficient resolution, the 0.125° runs (Figures 3c and 3d) predict the RMW and wind speeds in better agreement with the AOML winds (Figure 3a), despite small spatial and temporal differences. This suggests that the 0.125° run with a finer grid spacing can simulate better the near-eye wind distributions and produce more realistic intensity. Moreover, g48-ncps simulates wind magnitudes and storm "asymmetry" better than g48, and gives more realistic spiral bands (Figure S5), as compared to the satellite image available from http://rsd.gsfc.nasa.gov/goes/pub/goes/050829.katrina.jpg. Convections at some spots might be too intense and will be analyzed in detail.

4. Concluding Remarks

[15] In this work, we present preliminary simulations of hurricane Katrina's intensity and near-eye wind distributions obtained with the mesoscale-resolving fvGCM on the NASA Columbia supercomputer. Without degrading the track prediction skill with respect to the 0.25° simulations,

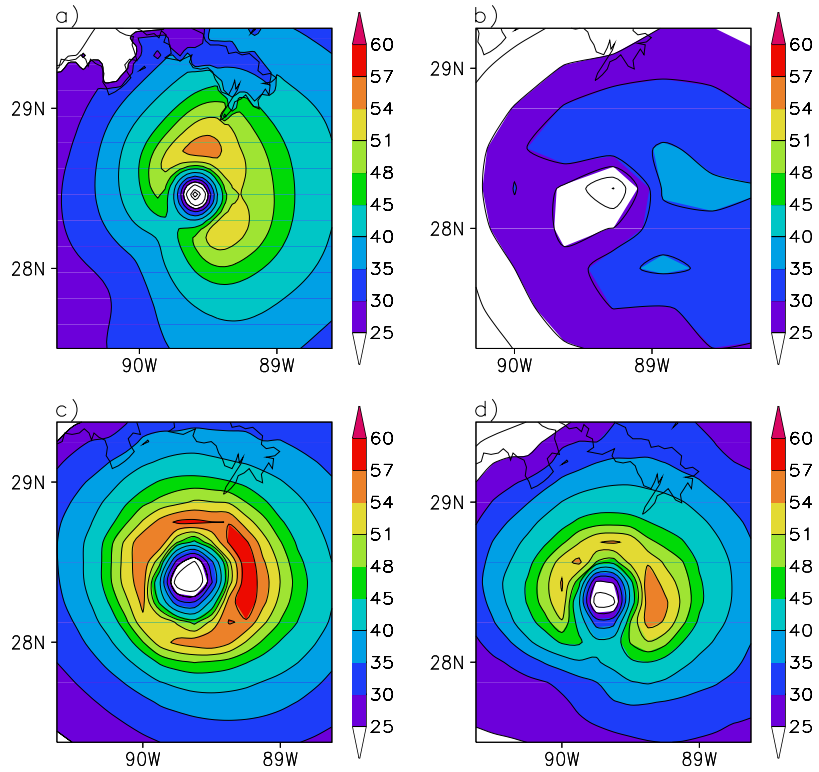

Figure 3. Comparison of wind distribution near the hurricane eye in a 2 × 2 degree box among (a) AOML high-resolution (0.0542°) surface wind analysis data at 0730 UTC AUG 29, (b) the 0.25° 10m winds at 99h simulations ending 1500 UTC 29, (c) the 0.125° 10m winds at 99h simulations ending 1500 UTC 29, and (d) the 0.125° 10m winds without convection parameterization at 96h simulations ending 1200 UTC 29.

the 0.125° produce improvements on intensity forecast with errors in center pressure of only ±12 hPa. Despite the fact that prediction of the near-eye surface wind distribution, which highly depends on static stability and surface roughness, is challenging with GCMs, the 0.125° model simulates the speed and radius of maximum surface wind in good agreement with the AOML high-resolution wind analysis, thus improving the representation of Katrina's near-eye structure with respect to the 0.25° model. Furthermore, we present the first 5-day global ultra-high resolution simulation with the convection parameterization (CP) disabled, showing better intensity prediction and near-eye winds than the control run.

[16] Both 0.25° and 0.125° forecasts show timing lags in track and intensity and could not accurately capture the two stages of rapid intensification. In spite of these limitations, which might be due to the lack of the vortex initialization and other components discussed below, our 0.125° results are still encouraging, being comparable to the forecasts by the mesoscale Weather Research and Forecasting (WRF) model at a similar resolution of 12km (e.g., http://www.mmm.ucar.edu/prod/rt/wrf/hur12/200508XX00/hur_track.png, here XX is from 25 to 29). Relatively larger intensification rates are observed in the 0.125° runs. Possible reasons for the over-intensification are 1) uncertainties of CPs, 2) lack of feedback from sea surface temperature (SST) changes associated with air-sea interaction and also longer time for model storms over ocean, and 3) lack of non-hydrostatic effects. Although the run without CP gives a more realistic intensification rate, the impacts of disabling CP need to be evaluated further, and are currently being studied for major hurricanes in 2004 and 2005. Fixed SST in time could generate a stronger hurricane, since the cooling effect on SST due to air-sea interaction is not taken into account [e.g., *Bao et al.*, 2000]. Our experiments suggest that hydrostatic assumption at a resolution of 0.125° may still hold some validity. However, we are also aware that high-resolution simulations without non-hydrostatic effects could produce stronger storms, as shown by Nolan et al. (Simulations of Hurricane Isabel (2003) in the WRF, GFDL, and ZETAC models, 2004, available from author at dnolan@rsmas.miami.edu).

[17] While the mesoscale-resolving model provides a research tool to investigate some interesting topics both in science and computation, to address all of the aforementioned issues, we need to develop a global non-hydrostatic cloud- and eddy-resolving Earth modeling system, as described by *Lin et al.* [2004], and to couple it with an advanced data assimilation system, inclusive of a vortex relocator. With the coupled system, we expect to improve simulations of detailed hurricane dynamics and thereby improve intensity forecasts.

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