Cloud-system resolving simulations with the NASA Goddard Earth Observing System global atmospheric model (GEOS-5)

William M. Putman[1] and Max Suarez[1]

Received 9 June 2011; revised 20 July 2011; accepted 24 July 2011; published 26 August 2011.

[1] The NASA Global Modeling and Assimilation Office (GMAO) has developed a global non-hydrostatic cloud-system resolving capability within the NASA Goddard Earth Observing System global atmospheric model version 5 (GEOS-5). Using a non-hydrostatic finite-volume dynamical core coupled with advances in the moist physics and convective parameterization the model has been used to perform cloud-system resolving experiments at resolutions as fine as 3.5- to 14-km globally. An overview of preliminary results highlights the development of mid-latitude cyclones, the overall representation of global tropical convection, intense convective activity within the eye wall and outer rain bands of the 2009 Atlantic hurricane Bill validated by satellite observations, and the seasonal predictability of global tropical cyclone activity with realistic intensities. These preliminary results provide motivation for the use of GEOS-5 to simulate multi-scale convective systems within a global model at cloud resolving resolutions. **Citation:** Putman, W. M., and M. Suarez (2011), Cloud-system resolving simulations with the NASA Goddard Earth Observing System global atmospheric model (GEOS-5), *Geophys. Res. Lett.*, *38*, L16809, doi:10.1029/2011GL048438.

1. Introduction

[2] The development of global non-hydrostatic atmospheric general circulation models capable of cloud system resolving weather/climate prediction has progressed steadily with the accessibility of large supercomputing resources and the improved scalability of models. This has permitted experimentation at resolutions as fine as 3.5-km globally capable of resolving cloud clusters of deep convection in the tropics [*Satoh et al.*, 2008; *Tomita et al.*, 2005]. Building on the conclusions from the World Modeling Summit for Climate Prediction [*Shukla et al.*, 2009], experimentation with very high-resolution global climate modeling has gained enhanced priority. The U.S. National Science Foundation has recently dedicated an entire 18,048-core Cray XT-4 supercomputer, Athena, for a series of global climate and weather simulations at resolutions ranging from 28- to 7-km [*Dirmeyer et al.*, 2011; J. L. Kinter et al., Revolutionizing climate modeling - Project Athena: A multi-institutional, international collaboration, submitted to *Bulletin of the American Meteorological Society*, 2011].

[3] Here we present selected simulations from a non-hydrostatic version of NASA's GEOS-5 global atmospheric model as examples of what gains may be obtained in both numerical weather prediction (NWP) and climate simulation by investing in higher resolution global simulations. We have performed a series of 20-day NWP simulations at 3.5- to 28-km globally, as well as 7-month seasonal climate simulations at 14-km. We will examine the impact of improved resolution on mid-latitude cyclogenesis, tropical convection, tropical cyclone structure, and the seasonal tropical climate.

2. Model Setup

[4] A cubed-sphere version of the non-hydrostatic finite-volume dynamical core has been developed in collaboration with the Geophysical Fluid Dynamics Laboratory at NOAA. The cubed-sphere development [*Putman and Lin*, 2007, 2009] provides the required scalability, while the Lagrangian non-hydrostatic dynamics [*Lin*, 2004, also Vertically Lagrangian control-volume discretization of the compressible Euler equations, manuscript in preparation, 2011] permits the exploration of cloud permitting high-resolution simulations. The physics of GEOS-5 [*Rienecker et al.*, 2008] are unchanged aside from modification of the relaxed Arakawa-Schubert convective parameterization [*Moorthi and Suarez*, 1992] to a non-precipitating shallow convection scheme by use of a stochastic Tokioka constraint. This constraint selectively suppresses the convection scheme by placing a random lower limit on the plume entrainment at resolutions capable of dynamically resolving convection [*Tokioka et al.*, 1988]. The Tokioka modification favors shallower convection with more strongly entraining clouds. As the Tokioka constraint is increased, deep convection is suppressed, and the modification works as an inhibition function allowing the grid-scale condensation scheme to become more active [*Lee et al.*, 2008].

[5] Retaining the RAS convection scheme with the Tokioka constraint sets GEOS-5 apart from the Nonhydrostatic ICosahedral Atmospheric Model (NICAM) model [*Satoh et al.*, 2008] work with an ultra-high resolution global model. NICAM has demonstrated the capability for ultra-high resolution global models to predict realistic lifecycles of tropical cyclones [*Fudeyasu et al.*, 2008, 2010a, 2010b] with explicit cloud microphysics and without subgrid scale convective parameterization. We will demonstrate this capability with GEOS-5 using a traditional moist physics package for atmospheric general circulation models (AGCMs) and including a convective parameterization that has been tuned to act primarily as a non-precipitating shallow convection scheme. This distinction is not trivial, it uniquely positions GEOS-5 to perform global experiments in the range of 1- to 14-km, a 'gray zone' in global modeling between the cloud-scale and the meso-beta scale where the need for some

[1]NASA Global Modeling and Assimilation Office, Goddard Space Flight Center, Greenbelt, Maryland, USA.

This paper is not subject to U.S. copyright.
Published in 2011 by the American Geophysical Union.

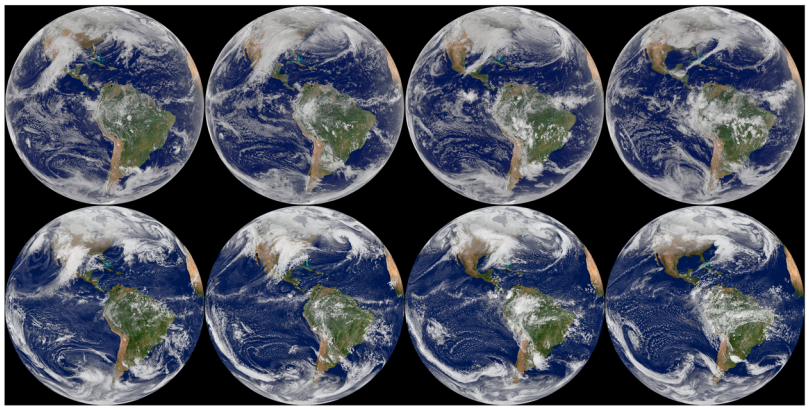

Figure 1. (top) Visible imagery from the GOES east satellite and (bottom) modeled clouds from GEOS-5 at 5-km globally seen daily (from left to right) at 17:45z 03–06 February 2010. Visible clouds from the model are displayed as a product of cloud fraction and optical thickness to emulate to GOES visible imagery.

form of sub-grid scale convective parameterization remains [*Weisman et al.*, 1997].

3. Experiments and Results

3.1. The 02-Feb-2010 to 22-Feb-2010 Weather Prediction

[6] A 20-day NWP experiment has been completed at 5-km global resolution. This experiment is initialized from a 50-km GEOS-5 analysis state on 02-Feb-2010 at 21z and covers the development and progression of three major winter storms that produced record snowfall in the Mid-Atlantic States on the 6th, 10th and 13th of February 2010. This also covers a very active South Pacific tropical cyclone period including category-4 tropical cyclone Oli, and twin-cyclones Pat and Rene (Movie S1 of the auxiliary material).[1]

[7] Full disk visible imagery from the GOES East satellite with cloud fields simulated by GEOS-5 at 5-km seen daily at 17:45z from 03-Feb-2010 through 06-Feb-2010 display the cyclogenesis of a major winter storm across the eastern United States (Figure 1). The strengthening of the southern stream of this storm by the anomalously warm El Nino waters of the eastern Pacific Ocean is clearly depicted in these cloud fields. The broken stratocumulus layer in the southeastern Pacific Ocean, deep convection over South America, and cumulus cloud streets forming behind the well-defined cold front stretching across the north Atlantic are also well represented within the model. This demonstrates the capability of GEOS-5 to represent these distinct features of cloud-resolving models using traditional physics packages for AGCMs adapted for use at these intermediate resolutions between the explicit cloud-scale (<1-km) and the meso-beta scale (>20-km). This is a critical capability that will allow GEOS-5 to be used to explore meso-scale cloud processes and their relation to the global circulation in this gray zone between the need for explicit cloud microphysics and full convective parameterization.

3.2. The 16-Aug-2009 to 21-Aug-2009 Weather Prediction

[8] 10-day NWP experiments at 3.5-, 7-, and 28-km initialized 16-Aug-2009 at 21z from a 50-km GEOS-5 analysis develop tropical storm Bill to a category 4 hurricane before weakening by the end of the 5-day forecast period (Movie S2 of the auxiliary material). OLR from the 3.5-km GEOS-5 forecast demonstrates improvement in the global clustering of multi-scale tropical convection over 28-km resolutions

[1]Auxiliary materials are available in the HTML. doi:10.1029/2011GL048438.

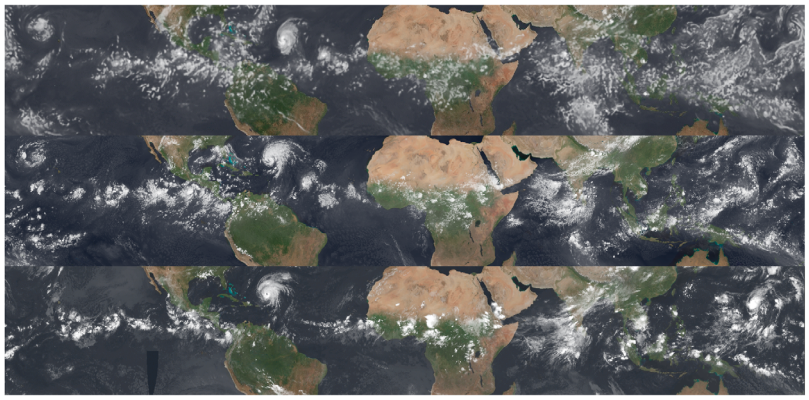

Figure 2. Globally merged Climate Prediction Center composite infrared brightness temperature data (bottom), OLR from GEOS-5 at (middle) 3.5-km and (top) 28-km as seen on 20-August-2009 at 18z, 69 hours into the 15-day forecasts with GEOS-5.

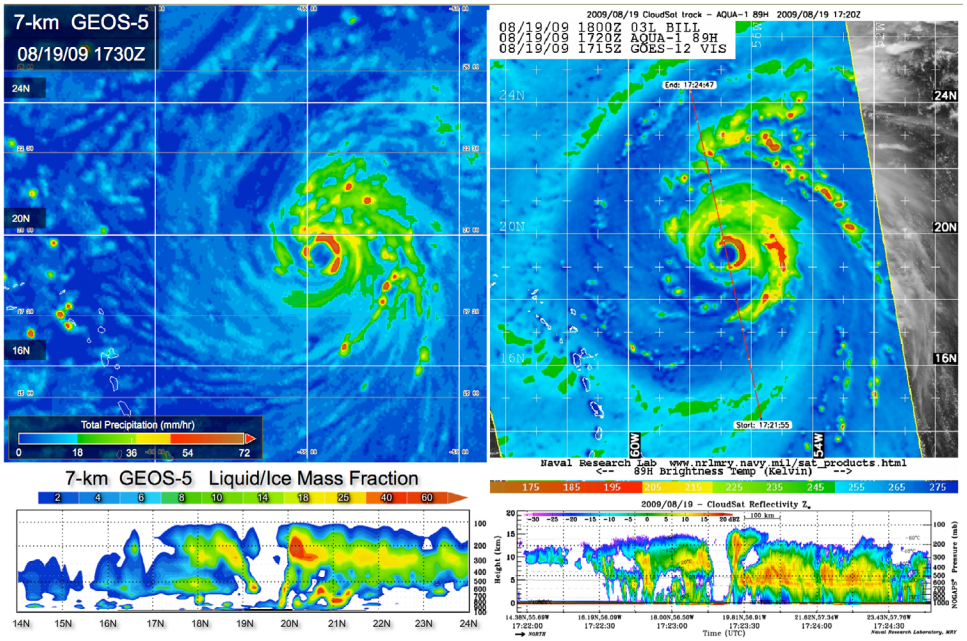

Figure 3. NASA's satellite CloudSat captured an eye overpass of category 4 Hurricane Bill on 19-August-2009 at 17:20z (bottom right), the 89 GHz AMSR-E instrument onboard the Aqua spacecraft (top right) reveals deep convection and low brightness temperatures (<−117 F) as shown by the bright red and deep brown colors (Image Credits: NASA/JPL/The Cooperative Institute for Research in the Atmosphere (CIRA), Colorado State University). Precipitation rates from GEOS-5 at 7-km (top left) mirror the horizontal structure of deep convection as observed by the AMSR-E instrument, while a vertical cross-section of liquid and ice fractions from GEOS-5 (bottom left) depicts the well defined eye-wall and deep thunderstorms in the surrounding convection.

(Figure 2). While a general representation of tropical convection is represented by the coarse resolution 28-km result, only with increased resolution is GEOS-5 able to capture the multi-scale convection in a way that reflects the observed atmosphere from composite infrared imagery. Specifically, while the large scale circulation of the Atlantic hurricane Bill is captured at 28-km, the 3.5-km simulation is able to simulate the individual convective cells that make up this circulation and form the surrounding rainbands of the hurricane. The clusters of multi-scale organized convection are even more prevalent throughout the inter-tropical convergence zones, the Indian monsoon region, and the Pacific warm pool; in these regions the impact of resolution is clearly evident as GEOS-5 at 3.5-km is able develop individual convective

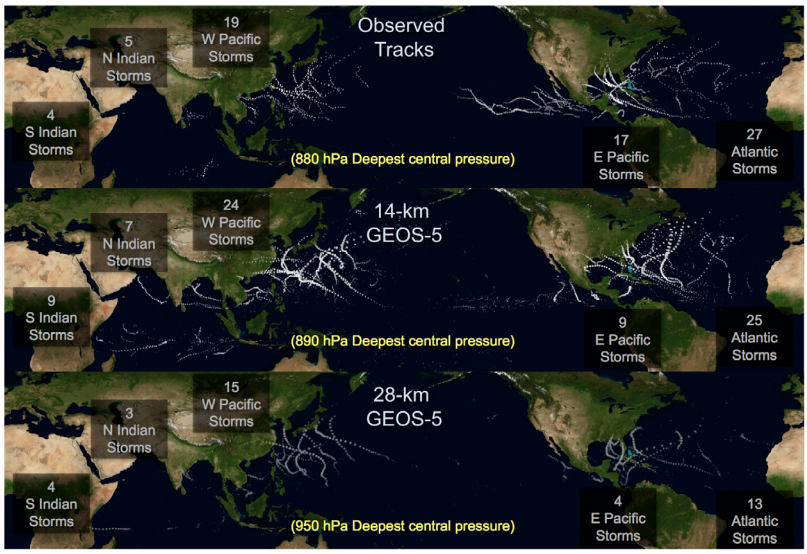

Figure 4. Global tropical cyclone tracks from May through December 2005 as (top) observed, and simulated in nature runs with GEOS-5 at (middle) 14-km and (bottom) 28-km. Counts of total tropical cyclones for each basin are presented along with the minimum value of observed/modeled sea level pressure over all storms.

cells that are organizing into large clusters similar to those found in observations.

[9] At resolutions of 10-km and finer the inner structure of hurricane Bill becomes increasingly realistic. Convective activity within the eye-wall and in the surrounding rain bands form with horizontal scales commensurate with AIRS satellite observations (Figure 3, top). The vertical distribution of liquid and ice fractions from GEOS-5 show a well-defined eye wall, with deep convection and ice cloud formation at the 200–300 hPa levels as observed by CloudSat reflectivity (Figure 3, bottom).

3.3. The 14-km "Nature Runs"

[10] Building on the improved representation of convection and tropical cyclone structure, GEOS-5 has been used to prepare "Nature Runs" (NRs) at 14-km globally. These AMIP-style NRs are free running simulations initialized from 50-km analyses and forced only by observed sea surface temperatures and climatological aerosol emissions. With increased resolution non-hydrostatic global models have demonstrated a capability of better representing the characteristics of tropical cyclones in a warming climate [*Yamada et al.*, 2010]. The NRs described here are intended to provide a valuable resource for performing observing system simulation experiments [*Atlas*, 1997; *Reale et al.*, 2007; *Zhang and Pu*, 2010] within the GEOS data assimilation system. For this purpose, GEOS-5 must be able to represent realistic tropical cyclone tracks and intensities, as well as their natural variability on seasonal time-scales.

[11] Global tropical cyclone activity is detected in GEOS-5 using a standard vortex tracking tool developed for atmospheric general circulation models [*Camargo and Zebiak*, 2002]. GEOS-5 demonstrates a capability to predict realistic occurrences of tropical cyclone activity in terms of frequency and track location in all basins (Figure 4). The

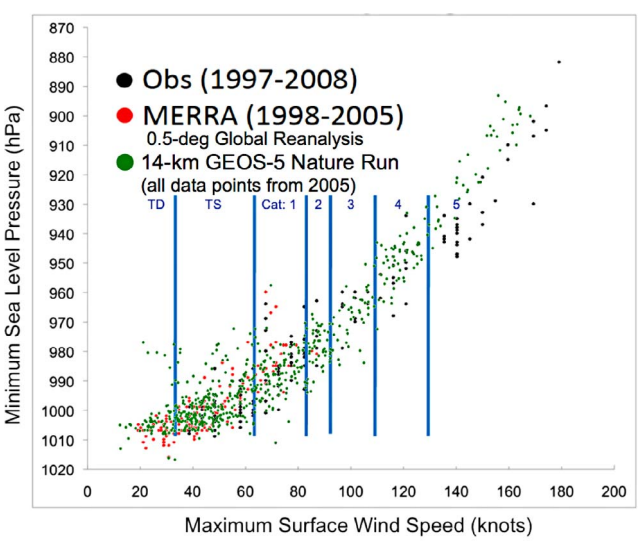

Figure 5. Minimum sea level pressure and maximum near surface winds as observed in all Atlantic tropical cyclones from 1997–2008 (black circles), for all Atlantic tropical cyclones from MERRA (a 50-km re-analysis using GEOS-5 from 1998–2005, red circles), and for all 3-hourly observed Atlantic tropical cyclones from a 14-km nature run with GEOS-5 (green circles).

Table 1. Categorization of Atlantic tropical cyclones for 2005 and 2006 from observations and a 14-km GEOS-5 Nature Run

	2005		2006	
	Obs	14-km GEOS-5	Obs	14-km GEOS-5
TS	12	10	5	4
Cat 1	7	7	3	3
Cat 2	1	1	0	2
Cat 3	2	3	2	0
Cat 4	1	2	0	2
Cat 5	4	2	0	0
TOTAL	27	25	10	11
MAJOR	7	7	2	2

2005 Atlantic basin activity reflects the unusually high number of storms for the period from May-Dec, as GEOS-5 simulates 25 storms compared with the 27 observed. The western Pacific and Indian Ocean basins are slightly overactive in the model, while the eastern Pacific is less active than observed.

[12] The distribution of minimum central pressure and maximum near surface wind speeds from GEOS-5 reflects a distribution similar to observations for all Atlantic storms from 1997 to 2008 (Figure 5). The deepest central pressure modeled by GEOS-5 was 890 hPa in an Atlantic hurricane, compared with 880 hPa in the observations, and the maximum winds modeled reach in excess of 160 knots. This marks a substantial improvement from the MERRA reanalysis performed with GEOS-5 at 50-km resolution, where the maximum intensity for Atlantic hurricanes reaches only category 2 strength.

[13] Table 1 categorizes all storms for the Atlantic basin from our 2005 and 2006 Nature Runs. The inter-seasonal variability in the Atlantic basin is simulated well by GEOS-5 showing both a decrease in the number of storms from 2005 to 2006 as well as a decrease in the intensities as no category 5 storms were simulated or observed and the number of major storms (category 3 and higher) decreased to only 2.

4. Summary

[14] The limit of global hydrostatic models has been reached with resolutions of 10- to 20-km. Results from a global non-hydrostatic version of GEOS-5 demonstrate the potential for improved representation of global tropical convection and tropical cyclones below 14-km using traditional AGCM physics packages adapted for these intermediate resolutions between the explicit cloud-scale and the meso-beta scale. The capability of GEOS-5 to represent the genesis stages of tropical cyclones and the internal structure of their mature stages provides a valuable tool for studying the inter-seasonal variability of tropical cyclone activity in terms of both frequency and intensity within a high-resolution global climate model. We plan to extend the lengths of simulations at 7- to 3.5-km to evaluate seasonal climate predictability at these resolutions and evaluate a two-moment cloud microphysics scheme [*Morrison and Gettelman*, 2008; *Barahona and Nenes*, 2008] that we expect will improve the representation of cloud properties at resolutions of 5-km and finer. Follow-on experiments with GEOS-5 will explore the general variability of global tropical convection in more detail, in particular the size and distribution of multi-scale convective clusters, and in-depth analysis of the role of convective

parameterization versus the large-scale physics, and the representation of the Madden-Julian Oscillation.

[15] **Acknowledgment.** The Editor thanks two anonymous reviewers for their assistance in evaluating this paper.

References

Atlas, R. (1997), Atmospheric observations and experiments to assess their usefulness in data assimilation, *J. Meteorol. Soc. Jpn.*, *75*(1B), 111–130.

Barahona, D., and A. Nenes (2008), Parameterization of cirrus cloud formation in large-scale models: Homogeneous nucleation, *J. Geophys. Res.*, *113*, D11211, doi:10.1029/2007JD009355.

Camargo, S. J., and S. E. Zebiak (2002), Improving the detection and tracking of tropical cyclones in atmospheric general circulation models, *Weather Forecast.*, *17*, 1152–1162, doi:10.1175/1520-0434(2002)017<1152:ITDATO>2.0.CO;2.

Dirmeyer, P. A., et al. (2011), Simulating the hydrologic diurnal cycle in global climate models: Resolution versus parameterization, *Clim. Dyn.*, doi:10.1007/s00382-011-1127-9, in press.

Fudeyasu, H., Y. Wang, M. Satoh, T. Nasuno, H. Miura, and W. Yanase (2008), Global cloud-system-resolving model NICAM successfully simulated the lifecycles of two real tropical cyclones, *Geophys. Res. Lett.*, *35*, L22808, doi:10.1029/2008GL036003.

Fudeyasu, H., Y. Wang, M. Satoh, T. Nasuno, H. Miura, W. Yanase (2010a), Multiscale interactions in the lifecycle of a tropical cyclone simulated in a global cloud-system-resolving model: Part I: Large-scale and storm-scale evolutions, *Mon. Weather Rev.*, *138*, 4285–4304, doi:10.1175/2010MWR3474.1.

Fudeyasu, H., Y. Wang, M. Satoh, T. Nasuno, H. Miura, W. Yanase (2010b), Multiscale interactions in the lifecycle of a tropical cyclone simulated in a global cloud-system-resolving model: Part II: System-scale and mesoscale processes, *Mon. Weather Rev.*, *138*, 4305–4327, doi:10.1175/2010MWR3475.1.

Lee, M.-I., M. J. Suarez, I.-S. Kang, I. M. Held, and D. Kim (2008), A moist benchmark calculations for the atmospheric general circulation models, *J. Clim.*, *21*, 4934–4954, doi:10.1175/2008JCLI1891.1.

Lin, S.-J. (2004), A 'vertically Lagrangian' finite-volume dynamical core for global models, *Mon. Weather Rev.*, *132*, 2293–2307, doi:10.1175/1520-0493(2004)132<2293:AVLFDC>2.0.CO;2.

Moorthi, S., and M. J. Suarez (1992), Relaxed Arakawa-Schubert. A parameterization of moist convection for general-circulation models, *Mon. Weather Rev.*, *120*, 978–1002, doi:10.1175/1520-0493(1992)120<0978:RASAPO>2.0.CO;2.

Morrison, H., and A. Gettelman (2008), A new two-moment bulk stratiform cloud microphysics scheme in the Community Atmospheric Model (CAM3). Part I: Description and numerical tests, *J. Clim.*, *21*, 3642–3659, doi:10.1175/2008JCLI2105.1.

Putman, W., and S. Lin (2007), Finite-volume transport on various cubed-sphere grids, *J. Comput. Phys.*, *227*(1), 55–78, doi:10.1016/j.jcp.2007.07.022.

Putman, W., and S. Lin (2009), A finite-volume dynamical core on the cubed-sphere grid, in *Numerical Modeling of Space Plasma Flows: ASTRONUM-2008*, *Astron. Soc. Pac. Conf. Ser.*, vol. 406, pp. 268–276, Astron. Soc. of the Pac., San Francisco, Calif.

Reale, O., J. Terry, M. Masutani, E. Andersson, L. P. Riishojgaard, and J. C. Jusem (2007), Preliminary evaluation of the European Centre for Medium-Range Weather Forecasts (ECMWF) nature run over the tropical Atlantic and African monsoon region, *Geophys. Res. Lett.*, *34*, L22810, doi:10.1029/2007GL031640.

Rienecker, M. M., et al. (2008), The GEOS-5 data assimilation system - Documentation of versions 5.0.1, 5.1.0, and 5.2.0, *NASA Tech. Memo.*, *2008–104606*.

Satoh, M., T. Matsuno, H. Tomita, H. Miura, T. Nasuno, and S. Iga (2008), Nonhydrostatic Icosahedral Atmospheric Model (NICAM) for global cloud resolving simulations, *J. Comput. Phys.*, *227*, 3486–3514, doi:10.1016/j.jcp.2007.02.006.

Shukla, J., R. Hagedorn, B. Hoskins, J. Kinter, J. Marotzke, M. Miller, T. N. Palmer, and J. Slingo (2009), Revolution in climate prediction is both necessary and possible: A declaration at the World Modelling Summit for Climate Prediction, *Bull. Am. Meteorol. Soc.*, *90*, 175–178, doi:10.1175/2008BAMS2759.1.

Tokioka, T., K. Yamazaki, A. Kitoh, and T. Ose (1988), The equatorial 30–60 day oscillation and the Arakawa-Schubert penetrative cumulus parameterization, *J. Meteorol. Soc. Jpn.*, *66*, 883–901.

Tomita, H., H. Miura, S. Iga, T. Nasuno, and M. Satoh (2005), A global cloud-resolving simulation: Preliminary results from an aqua planet experiment, *Geophys. Res. Lett.*, *32*, L08805, doi:10.1029/2005GL022459.

Weisman, M. L., W. C. Skamarock, and J. B. Klemp (1997), The resolution dependence of explicitly modeled convective systems, *Mon. Weather Rev.*, *125*, 527–548, doi:10.1175/1520-0493(1997)125<0527:TRDOEM>2.0.CO;2.

Yamada, Y., K. Oouchi, M. Satoh, H. Tomita, and W. Yanase (2010), Projection of changes in tropical cyclone activity and cloud height due to greenhouse warming: Global cloud-system-resolving approach, *Geophys. Res. Lett.*, *37*, L07709, doi:10.1029/2010GL042518.

Zhang, L., and Z. Pu (2010), An Observing System Simulation Experiment (OSSE) to assess the impact of Doppler wind lidar (DWL) measurements on the numerical simulation of a tropical cyclone, *Adv. Meteorol.*, *2010*, 743863, doi:10.1155/2010/743863.

W. M. Putman and M. Suarez, NASA Global Modeling and Assimilation Office, Goddard Space Flight Center, Code 610.1, Greenbelt, MD 20771, USA. (William.M.Putman@nasa.gov)