Coupling NASA Advanced Multi-Scale Modeling and Concurrent Visualization Systems for Improving Predictions of Tropical High-Impact Weather (CAMVis)

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Abstract:

Among the scenarios in the Decadal Survey Missions (DSM) report (NRC, 2007), “Extreme Event Warning” is one of the top priority scenarios. It focuses on “discovering predictive relationships between meteorological and climatological events and less obvious precursor conditions from massive data sets.” To achieve this, our approach is to deploy the “Coupled Advanced Multi-Scale Modeling and Concurrent Visualization Systems (CAMVis)” by (1) integrating existing NASA technologies such as the NASA multi-scale modeling system, the Goddard Cumulus Ensemble model, the finite-volume General Circulation Model, and concurrent visualization systems; (2) improving the parallel scalability of the coupled multi-scale modeling system to take full advantage of the next-generation peta-scale supercomputers; (3) significantly streamlining data flow for fast processing and 3D visualizations; and (4) developing visualization modules for the fusion of NASA satellite data. In this paper, we will discuss the project progress and then discuss future tasks needed to support the DSM.

1. Introduction

To achieve the goal of “Extreme Event Warning”, we start with making an attempt of extending the lead time and reliability of hurricane forecasts (e.g., track and intensity), which is important for saving lives and mitigating economic damage. The urgent need for doing this is

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1 The National Research Council (NRC) 2007 Earth Science decadal survey, which was completed at the request of NASA and other government agencies, recommends that: “The U.S. government, working in concert with the private sector, academe, the public, and its international partners, should renew its investment in Earth-observing systems and restore its leadership in Earth science and applications.”

2 Examples include precipitation from the Tropical Rainfall Measuring Mission (TRMM) and surface winds from the Quick Scatterometer (QuikSCAT).
evidenced by extreme weather events such as Hurricane Katrina in 2005 (Shen et al., 2006) and Tropical Cyclone Nargis in 2008 (Shen et al., 2010), which caused tremendous damage and numerous fatalities. It has been suggested that large-scale tropical weather systems such as Madden-Julian Oscillations (MJOs, Madden and Julian, 1973), monsoonal circulations and tropical easterly waves may regulate tropical cyclone (TC) activity. To this end, improving the prediction of these large-scale flows might be helpful for extending the lead-time for TC prediction. However, due to limited computing resources, it has been a challenge to accurately improve these tropical weather systems with traditional global models. Two of the major limiting factors in these models are insufficient grid spacing and poor physics parameterizations (e.g., cumulus parameterizations, CP).

Thanks to recent advances in global weather/climate modeling and supercomputing, there is now a great potential to mitigate the aforementioned issues. In late 2004, NASA’s Columbia supercomputer started operation (Biswas et al., 2007), providing groundbreaking computing power for Earth modeling. Later, the NASA high-end concurrent visualization (CV) system version 1 (Ellsworth et al., 2006), in which model outputs are extracted for analysis while the simulation is still running, was developed as a powerful tool for efficiently processing and visualizing massive volumes of high spatial- and temporal-resolution model data. In late 2008, a new supercomputer, Pleiades, was installed at the NASA Ames Research Center (ARC), and provides 10 times Columbia’s computing power. Enabled by these advanced computational technologies, a high-resolution (~10km) global model (the finite-volume general circulation model, known as the fvGCM) was deployed and used to generate remarkable forecasts of intense hurricanes (Atlas et al., 2005; Shen et al., 2006, 2010). More importantly, in contrast to the first approach by deploying a high-resolution fvGCM, an innovative approach that applies a massive number of Goddard Cumulus Ensemble models (GCEs, Tao and Simpson, 1993) and the fvGCM has been proposed and used to overcome the CP deadlock in GCMs (e.g., Tao et al., 2008). This approach is called the multiscale modeling framework (MMF) or super-parameterization, wherein

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3 Depending on their location, TCs are referred to by other names, such as hurricanes (in the Atlantic region), typhoons (in the West Pacific region), tropical storms, cyclonic storms, and tropical depressions.
4 The “physics parameterizations” are designed to “improve” the model’s deficiency regard to unresolved physical processes due to the coarse resolution GCMs.
5 It has been shown that the development of CPs has been very slow, and their performance is a major limiting factor in weather/hurricane simulations.
A GCE is run (at a resolution of 4km, currently) in place of the CP in each of the fvGCM’s coarse grids (e.g., 250km or 100km). As a result, the MMF\(^6\) has the combined advantages of the global coverage of a GCM and the sophisticated microphysical processes of a GCE. Both the high-resolution fvGCM and MMF can be run without having to rely on CPs, and are used to examine the impact of grid-resolved convection and interaction with radiation on the simulation of the aforementioned large-scale tropical systems.

In section 2 of this article, we introduce the supercomputing, CV and global modeling technologies at NASA. We then discuss in section 3 how the CAMVis system built with these technologies can help provide insightful understanding of multiple physical processes and their multi-scale interactions with improved short-term (~5-10-day) forecasts of TCs and extended-range (30-day) simulations of large-scale MJOs. We conclude with a summary and discussion of future plans.

### 2. Supercomputing and Modeling Technology at NASA

#### 2.1 Supercomputers

![Image of NASA supercomputers](image)

*Figure 1: NASA supercomputers. Left panel: the Columbia supercomputer with (in late 2004) 20 SGI Altix superclusters with 10,240 Intel Itanium II CPUs and 20 TB total memory (e.g., Biswas et al., 2007). Right panel: the Pleiades supercomputer with 81,920 cores (with Xeon, Nehalem and Westmere processors) in total, 120+ TB memory, and 3,000+ TB disk space.*

\(^6\) The “current” MMF consists of a coarse-resolution (100-250km) fvGCM and thousands of copies of GCEs, and a new version of the MMF will include a high-resolution fvGCM.
In late 2004, the Columbia supercomputer (Biswas et al., 2007) came into operation at NASA ARC. It consists of twenty 512-CPU nodes, giving it 10,240 CPUs and 20 terabytes (TB) of memory (Figure 1). Columbia achieved a performance of 51.9 Tflop/s (trillion floating-point operations per second) with the LINPACK (Linear Algebra PACKage) benchmark. These large-scale computing capabilities enable complex problems to be resolved with large-scale modeling systems (e.g., Tao et al. 2008; Shen et al. 2006). In late 2008, the Pleiades supercomputer, an SGI Altix ICE system with a peak performance of 609 Tflop/s, was built as one of the most powerful general-purpose supercomputers. Recently, Pleiades has been upgraded to have 81,920 cores with a peak performance of 772.7 Tflops, 127 TB memory, and 3.1 Peta-byte disk space. This newly built system, which provides more than 10 times the computing power of Columbia, is expected to speed up scientific discovery at an unprecedented pace.

2.2 Concurrent Visualization System

It is well known that the substantial increase in data volume produced by high-resolution Earth modeling systems poses a great challenge to stage, handle, and manage these model outputs and compare them with satellite data. We believe that efficiently handling these massive datasets, from terabytes for short-term runs to petabytes for long-term runs, requires an innovative thought-process and approach. A technique that could achieve this goal, and has previously met with great success in visualizing high-volume data, is concurrent visualization (CV, Ellsworth et al., 2006; Green et al., 2010). In CV, a simulation code is instrumented such that its data can be extracted for analysis while the simulation is running without having to write the data to disk. By avoiding filesystem I/O and storage costs, CV has the benefit of providing much higher temporal resolution than is possible with traditional post-processing, enabling every timestep of a very high-resolution simulation to be captured for analysis. The other main benefit of CV is that it provides a view of a simulation in progress, which may be useful for application monitoring or steering. This can help detect serious job and avoid wasting system resources.
Figure 2: Top panel shows the new Concurrent Visualization (CV) System (Version 2). Rounded rectangles indicate systems, and rectangles indicate processes. The whole system (from left to right panels) consists of computing nodes ("Pleiades"), a middle-layer system ("coalescer"), and the hyperwall-2 128-node 8-core/node rendering cluster. These systems are used for data extraction, handling, and visualization and for MPEG image production and visualization display. Bottom panel displays the M-on-N configuration for parallel data communications between the M computing nodes and N visualization nodes in the CV (Green et al., 2010).
In 2005, CV technology was first developed and integrated into the high-resolution fvGCM on the original hyperwall system (49 screens). A 3x3-screen “mini-hyperwall” was used for looping the resulting movies. Recently, a new improved CV system (version 2) has been deployed (Figure 2, top panel), which consists of a front-end system for data extraction (“coalescer”), a middle-layer system for data handling and data rendering, and a back-end system for data display. “Extractions” include domain slices or subvolumes, cutting planes, isosurfaces, streamlines, and other feature-extraction products. The size of an extract can vary widely, depending on what features are captured, while the size of a movie is determined only by the image resolution and the compression level achieved during encoding. The great advantage of extracts is that they represent an intermediate data product, which can be loaded into a viewer at a later time for interactive analysis.

As of June 2008, NASA’s 128-screen hyperwall-2, capable of rendering one-quarter-billion pixel graphics, was built at NASA ARC as one of the world's highest resolution scientific visualization and data exploration systems. Compared to the original 49 screens and 100BASE-T interconnect, the hyperwall-2 has 128 screens with modern graphics cards, an InfiniBand interconnect, and is fully integrated into the NASA supercomputing environment. The hyperwall-2’s 1,024-CPU cores and 475 terabytes of fast disk provide an excellent environment for parallel feature extraction and extract storage. In addition, hyperwall-2’s high-speed interconnect makes fully 3D concurrent visualization possible.

To efficiently exchange data between the computing and visualization nodes, we have implemented the M-on-N configuration for the CV pipeline, as shown in Figure 2 (bottom panel). The M-on-N configuration allows different domain decomposition within computing and visualization nodes. After decomposition, each portion of the entire domain within a computing (visualization) node is referred as to a sub-domain (sub-region). The boxes on the left represent the multiple (M) MPI processes of a fvGCM job with each one responsible for simulation within a sub-domain. At startup, each MPI process in the fvGCM job creates a connection with the Infiniband RDMA (remote data memory access) protocol to one of the N MPI processes spawned from the hyperwall job, using an M-on-N mapping where M>=N. At the end of each timestep, the raw output on each computing node is transferred directly via its RDMA connection to its corresponding peer process on the specific hyperwall node. The hyperwall job then performs
feature extraction and "sort-last" rendering\textsuperscript{7} in parallel wherein each of its child MPI processes renders an image from its own data, then these “individual” images from all of the child MPI processes are sorted and composited into a complete image in a PPM format, which can be passed to an encoder for movie generation. Finally, a series of these complete images are converted to JPEG, which can be easily delivered to a web server for display.

In order to maximize the results from a single simulation run, multiple products are usually generated, representing various fields and regions of interest, numerous feature-extraction and visualization techniques. As part of the CV pipeline, the resulting animations are streamed, as they are being generated, to the remote displays at the facilities of the principal scientists. When time-stamped outputs arrive from the computing nodes, each visualization node sequentially computed all of the requested visualizations, producing one image per visualization request. The node which assembles the final composite image is assigned in a round-robin fashion, so that the encoders are spread out across the cluster.

Depending on the visualization produced, additional data exchange may occur within the hyperwall (visualization) nodes. Visualizations such as scalar volume rendering, cutting planes, and iso-surfaces are easily implemented within the "sort-last" renderer, with only ghost-cell\textsuperscript{8} exchange needed for the sub-domain boundaries. However, for performing vector visualization techniques within the subregions, which may cover several sub-domains on different nodes, it may be convenient to fully reconstruct a subregion of interest on each of the visualization nodes.

\subsection*{2.3 Multiscale Modeling System}

The first version of the multi-scale modeling system with unified physics (Tao et al., 2008) has been successfully developed at NASA Goddard Space Flight Center (GSFC) and deployed on the Columbia supercomputer. It has since been ported and tested on the Pleiades supercomputer. As shown in Figure 3, the system consists of the finite-volume GCM (fvGCM; Lin 2004; Atlas et

\textsuperscript{7} Sort-last rendering is a type of parallel rendering where each processor has a subset of the overall scene geometry, and uses that subset to produce an image with both color and depth information. These images are then combined by using the depth information to select, for each pixel, the color that came from the geometric object closest to the viewer.

\textsuperscript{8} In the parallel computing world, ghost-cells are the points outside the boundary of the target domain but are needed for computing (e.g., rendering).
al., 2005; Shen et al., 2006) at a coarser (100-250 km) resolution and thousands of copies of a cloud model (i.e., GCE, Tao and Simpson, 1993) at a 4km or finer resolution. With the current model configurations, 13,104 GCEs are run concurrently to explicitly simulate cloud processes in the global environment, providing cloud feedbacks to the atmospheric state in the fvGCM. The high-resolution fvGCM was first deployed on the Columbia supercomputer (and later on Pleiades), producing remarkable forecasts of intense hurricanes in 2004 and 2005 (Shen et al., 2006; 2010). Both the MMF and high-resolution fvGCM, which can be run with no dependence on CPs, are powerful tools for examining and understanding the impacts of grid-resolved convections.

![Image](image1.png)

**Figure 3:** The NASA global multiscale modeling system, consisting of the global model (fvGCM) and thousands of copies of cloud models (e.g., GCE). Left panel: visualization of a 5-day low-level wind simulation with the global model during the Nargis period (see details in Figure 5). Right panel: 3D visualization of cloud water and ice are depicted in white with 9 cloud models in a 6° × 7.5° area, giving 13,104 cloud models in the global environment.

### 2.3.1 Computational enhancement:

At runtime, 95% or more of the total wall-time for running the MMF is spent on the multiple copies of the GCEs. Thus, wall-time could be significantly reduced by efficiently distributing the large number of GCEs over a massive number of processors on a supercomputer. However, the original implementation, in which each of the 13,104 GCEs is embedded on a grid point in the fvGCM, has very limited parallel scalability with a total number of CPUs up to 30. To overcome this difficulty, a different strategic approach is proposed to couple the fvGCM and GCEs as discussed below. From a computational perspective, the concept of “embedded GCEs” should be
completely forgotten, as it restricts the view on the data parallelism of the fvGCM. Instead, the 13,104 GCEs should be viewed as a *meta global GCE* (mgGCE) in a *meta gridpoint system*. With this concept in mind, each of the two distinct parts (or “components”; the fvGCM and mgGCE) in the MMF could have its own scaling properties. Since most of wall-time in MMF runs is spent on the GCEs, a scalable mgGCE could substantially reduce the wall-time. In addition, it becomes feasible to implement an MPMD (multiple programs multiple data) parallelism for the MMF with the mgGCE and the fvGCM. Currently, the coarse-resolution fvGCM is running with 1D domain decomposition because it costs a small percentage of the wall time in MMF runs. The technical approaches for this implementation with 2D domain decomposition in the mgGCE are briefly summarized as follows: (1) a master process allocates a shared memory arena for data redistribution between the fvGCM and mgGCE by calling the Unix `mmap` function; (2) the master process spawns multiple (parent) processes with a 1D domain decomposition in the y direction by a series of Unix `fork` system calls; (3) each of these parent processes then forks several child processes with another 1D domain decomposition along the x direction in the mgGCE; (4) data gathering in the fvGCM (mgGCE) is done along the y direction (along the x direction and then the y direction); (5) synchronization is implemented with the atomic `__sync_add_and_fetch` function call on the Columbia supercomputer. While steps (1), (2), and (5) were previously used in MLP (multiple level parallelism), this methodology is now extended to the multi-component system (namely, the fvGCM and mgGCE; see Shen et al., 2009 for details). Very promising scalability up to 364 CPUs has been achieved with preliminary benchmarks that show a speedup of (3.93, 7.28, and 12.43) by increasing the number of CPUs from 30 to (91, 182, and 364) CPUs, respectively, (Shen et al., 2009). This encouraging speedup is achieved largely because the current mgGCE where each GCE running with periodic lateral boundary conditions has no ghost cells among different GCEs. This new MMF (with a scalable mgGCE) and CV is being integrated on the Pleiades and hyperwall-2 and is called the CAMVis. Further enhancement (e.g., scalability and functionality) is also being conducted.

**3. Scientific Applications:**

In the following sections, visualizations from the CAMVis system with improved convective/cloud processes are discussed to illustrate (1) improved short-term (~5-7 days)
predictions for the formation of twin TCs associated with a large-scale MJO; (2) insightful visualizations of multiple processes and their scale interactions that lead to the formation of TC Nargis (2008); (3) improved extended-range (~30 days) simulations of a large-scale MJO; and (4) inter-comparisons between model simulations and satellite measurements at comparable resolutions.

3.1 Simulations of Twin Tropical Cyclone Formation associated with an MJO

Figure 4: Predictions regarding the formation of twin tropical cyclones in the Indian Ocean: (a) MJO-organized convection over the Indian Ocean at 0630 UTC 1 May 2002. When the MJO moved eastward, two pairs of twin TCs appeared sequentially on 6 May (b) and 9 May (c), including TC 01A, Kesiny, TC 02B and Errol. Two TCs (01A and 02B) with counter-clockwise circulations appeared in the Northern Hemisphere, while two TCs (Kesiny and Errol) with clockwise circulations appeared in the Southern Hemisphere; (d) Four-day forecast of total
precipitable water, showing realistic simulations of TC formation and movement (a journal article is in preparation)

It has been documented that the nearly simultaneous formation of two TCs straddling the equator at low latitudes occasionally may occur in the Indian Ocean and West Pacific Ocean. These TCs are called “twins” as they are nearly symmetric with respect to the equator. Previous studies showed that this twin TC activity can be modulated by the large-scale MJO. For example, in early May 2002, large-scale organized convection associated with an MJO event was observed in the Indian Ocean (Figure 4a). While the MJO was continuously progressing eastward, two pairs of twin TCs (Figures 4b-4c) appeared. To capture the genesis, a 10-day forecast was initialized at 0000 UTC 6 May, as shown in Figure 4d. The genesis and movement of three of these TCs (02B, 01A and Kesiny) were simulated realistically; however, for the southern entity of the second pair of twin TCs (Errol), only less-organized convection was simulated.

3.2: 3D visualization of TC Nargis (2008)

Very severe cyclonic storm Nargis (2008) is the deadliest named TC in the North Indian Ocean Basin, causing over 133,000 fatalities and $10 billion in damage. An increased lead time in the prediction of TC Nargis would have increased the warning time and may therefore have saved lives and reduced economic damage. Global high-resolution simulations using real data (Shen et al., 2010) showed that the initial formation and intensity variations of TC Nargis could be realistically predicted with position errors of 200km at a lead time of up to five days. Experiments also suggested that the accurate representation of environmental flows such as a westerly wind burst associated with an MJO is important for predicting the formation of this kind of TC. To provide a simplified view of these multiple processes, 3D visualizations could prove very powerful, as discussed below.

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9 Shen, B.-W., W.-K. Tao, et al., 2010: Application of a Global Mesoscale Model for Predicting the Formation of Twin Tropical Cyclones associated with a Madden-Julian Oscillation, (to be submitted). In this article, the simulated tracks and precipitations in 10-day runs are verified against observations.
Figure 5: Realistic 7-day simulations of the formation and initial intensification of TC Nargis (2008) initialized at 0000 UTC 22 April 2008, showing streamlines at different levels. Low-level winds are in blue and upper-level winds in red. (a) Formation of a pair of low-level vortices (labeled ‘V’) at 84h simulation. (b) Intensification of the northern vortex (on the left) (c); Formation of TC Nargis associated with the enhancement of the northern vortex; (d) Intensification of TC Nargis associated with upper-level outflow and moist processes, indicated by the enhanced upper-level outflow circulation. Approaching upper-level easterly winds (labeled ‘E’) increase the vertical wind shear, suppressing the enhancement of the southern vortex (on the right).

In contrast to the twin TC case, simulating and understanding processes for developing TC Nargis and the non-developing vortex (the counterpart to Nargis in the Southern Hemisphere) are equally important. A set of 3D, high-temporal-resolution animations with CAMvis was produced for the above illustration. Snapshots of streamline visualization at different vertical levels are shown in Figure 5. Low-level winds are shown in blue, and upper-level winds in red. In Figure 5a, ending at 1200 UTC 25 April 2002, a pair of low-level vortices (labeled ‘V’) appeared in...
the Northern and Southern Hemispheres, showing the potential for the formation of a pair of twin TCs. As time progressed, the (low-level) westerly wind belt/burst (labeled ‘W’) moved northward, enhancing the horizontal wind shear and therefore intensifying the northern vortex into TC Nargis (Figure 5b-c). With other favorable conditions, including good upper-level outflow, TC Nargis continued to intensify (Figure 5d). In contrast, at 0000 UTC April 26 (Figure 5b), upper-level easterly winds (labeled ‘E’), which moved over top of the southern vortex, increased the vertical wind shear and therefore suppressed the enhancement of the southern vortex (Figure 5b). Other unfavorable factors (such as the proximity to the Equator) also contributed to the lack of TC formation in the Southern Hemisphere during this period.

3.3 MJO Simulations with the MMF

In the previous subsection, we have shown the TC formation associated with an MJOs. Here, we discuss the model’s performance regarding the simulation of an MJO. It is known that the accurate prediction of tropical activity at sub-seasonal scales (~30 days) is crucial for extending numerical weather prediction beyond two weeks, and accurate forecasting of an MJO is among the challenges. With a 45- to 60-day time scale, eastward-propagating MJOs, which are typically characterized by deep convection originating over the Indian Ocean, have one of the most prominent large-scale features of the tropical general circulation. The MMF provides an innovative approach to investigate the multiple processes and multi-scale interactions which are important for improving MJO simulations. Figure 6 shows the 30-day simulation of an MJO event initialized at 0000 UTC December 13 2006, illustrating that the life cycle of the MJO is successfully captured and therefore that the model has the potential for examining the impact of an MJO on climate simulations.
Figure 6: A 30-day simulation of an MJO initialized at 0000 UTC December 13, 2006, as shown by the 200-hpa velocity potential. This simulation captures several major features usually associated with an MJO: (1) initiation of large-scale organized convection in the Indian Ocean in panel (b), (2) intensification in panel (c), (3) slow propagation (prior to reaching the Maritime continent) in panels (c-d), (4) followed by fast propagation in panels (d-e), and (5) weakening in panel (f). However, this simulated MJO also produces stronger vertical motion than observations.

3.4: Inter-comparisons between model simulations and satellite measurements

As precipitation is a good indicator for energy source of an intensifying TC and low-level wind speeds for the measurement of TC intensity, data fusion of NASA TRMM precipitation and QuikSCAT winds into the CAMVis system becomes valuable for inter-comparisons of high-resolution model simulations with satellite measurements. Recently, we have developed data conversion and visualization modules for this purpose. Figures 7a and 7b show TRMM precipitation and QuikSCAT winds during the lifetime of TC Nargis (2008), respectively.
Figure 7: Initial implementation of a visualization module into the CAMVis information system, including data converter and vector plotter for TRMM satellite-derived precipitation (left panel) and QuikSCAT winds (right panel), respectively.

With the new capability for data fusion, QuikSCAT winds for Nargis (2008) are inter-compared with high-resolution model simulations with the aim of assessing the data consistent accuracy in the representation of mesoscale vortex circulation and thus improving formation prediction. The assurance of data continuity (or consistency) is important for accurately tracing a TC’s movement or identifying its formation. From the zoomed-in panels of Figure 8, it is clearly shown that the changes of vortex structure are not smooth (e.g., the less realistic vortex in Figure 8d), suggesting the potential for rainfall contamination in the derived wind distributions. This might impact the detection of the formation of a TC.
Figure 8: Vector visualizations of NASA QuikSCAT winds during the initial formation and intensification of Nargis (2008) from 1200 UTC April 26, 2009 at a time interval of 12 hours. Zoomed-in windows are used to track the evolution of the mesoscale vortex with a closed circulation at 04/26/12z, 04/28/00z and 04/28/12z, respectively.

4. Concluding Remarks:

To support NASA missions and reduce the time to scientific discovery, we propose to seamlessly integrate the NASA advanced modeling and supercomputing technologies. Our plan is to improve the CAMVis system’s performance by taking full advantage of Pleiades’ computing power, and to improve the simulations of cloud processes with 3D GCEs and to implement and test more sophisticated cloud schemes. The coupled system will be improved to address the interactions of clouds, radiation, and aerosols, in order to advance our understanding of the detailed 3D structure of these fields and to investigate their impact on tropical weather prediction by inter-comparing these high-resolution simulations with NASA high-resolution satellite observations. These satellites include current missions such as TRMM and QuikSCAT as well as future missions such as Global Precipitation Measurement and Aerosol-Cloud Ecosystems, and 3D-Winds missions described in the NRC Decadal Survey (2007). This paper summarizes the
project progresses on the development and deployment of CAMVis and its application to improving simulations of high-impact tropical weather systems including mesoscale tropical cyclones and large-scale Madden-Julian Oscillations (MJOs).

Previously, each of the individual components of the CAMVis system has been successfully developed and tested on the Columbia supercomputer by the authors (e.g., Shen et al. 2006 for the high-resolution fvGCM; Tao et al. 2008 for the GCE and MMF version 1; Ellsworth and Green et al. 2006 for CV version 1). Currently, the deployment of the new version of the individual components (e.g., Shen et al. 2009 for performance-enhanced MMF; Green et al. 2010 for CV version 2) and the initial CAMVis system on the new NASA supercomputer Pleiades have been completed. As the multiple-scale modeling system can simulate weather and climate at high spatial and temporal resolution, coupling these modeling and concurrent visualization systems can help process massive volumes of output efficiently and provide insightful understanding of the complicated physical processes. The CV system is equipped with the 128-screen hyperwall-2 and is connected via high-speed InfiniBand to the Pleiades supercomputer. The CV system has the following primary benefits: first, it enables one to monitor system runtime status and thereby detect serious failures that could waste system resources; second, it enables the use of much higher temporal resolution as I/O and storage space requirements are largely obviated; and third, it can help visualize complicated physical processes with 3D visualizations.

For scientific applications with the CAMVis system, we first illustrate the association of twin TC formation with the passage of a large-scale MJO, which has been used to help improve our understanding of their relationship (e.g., their multi-scale interactions). Detailed model analyses are being documented in a separate study. The second example is the visualization of severe cyclonic storm Nargis (2008), which devastated Burma (Myanmar) in May 2008 and caused massive damages and numerous fatalities. As it has been shown by Shen et al. (2010) that improved representations of multi-scale interactions are the key to extending the lead time of predicting Nargis, CAMvis was indeed used to generate quick 3D visualizations for capturing some of critical processes before detailed analyses were conducted. In addition, we demonstrate that with an extended-range (30-day) simulation, the modeling system is capable of simulating the life cycle of the MJO event in 2006, aimed at extending the lead time of short-term TC prediction. The improved simulation of the MJO could potentially improve long-term (climate) simulations.
of tropical cyclones. An example of inter-comparing high-resolution model simulations with satellite measurements is also shown to assure the detection of TC formation.

We will continue to improve the accuracy and computational performance of the CAMVis. While the high-resolution fvGCM can generate 5-day forecasts in real time\textsuperscript{10}, our short-term goal is to scale the CAMvis (e.g., MMF and mgGCE as well) up to several (~2000-3000) thousands of CPUs to finish 5-day real-time forecasts. A long-term goal is to take full advantage of Pleiades to scale the model (e.g., up to 13,104 or higher cores) and thus to improve long-term climate simulations. Our vision is that the ultimate CAMVis system will enable researchers, policy and decision makers, and educators to monitor (zoom in/out) global model simulations at a wide range of spatial and temporal resolutions in real time.

Acknowledgement:

We would like to thank four reviewers, the associate Editor and the Editor for their valuable suggestions, which have substantially improved the manuscript. We are grateful for the following organizations for their support: the NASA Earth Science Technology Office, the Advanced Information Systems Technology Program, the NSF Science and Technology Center, the NASA Modeling, Analysis Prediction Program, the Energy and Water Cycle Study, the NASA High-End Computing Program, and the NASA Advanced Supercomputing facility at ARC, and the NASA Center for Computational Science at GSFC. We would like to thank Mr. Steve Lang for proofreading this manuscript.

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\textsuperscript{10} For weather application studies, the real time requires the simulation to be done within one walltime hour. Thus, to make a real-time prediction, the number of required CPUs is dependent on model’s resolution, I/O time interval, etc. For example, it takes about 35 (75) minutes to finish 5- (30-)day 0.25 degree forecasts with 240 (720) cores on Pleiades.


