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

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CAMVis Overview

The CAMVis project has completed its first year. CAMVis seeks to improve high-impact tropical weather prediction by seamlessly integrating NASA technologies (e.g., multi-scale modeling, supercomputing and visualization) to create a real-time, high-resolution, weather prediction tool.

Objectives:

- Improve understanding of the roles of atmospheric moist thermodynamic processes and cloud-radiation-aerosol interactions with high resolution 3D visualizations
- Inter-compare satellite observations and model simulations at fine resolution, aimed at improving understanding of consistency of satellite-derived fields
- Improve real-time prediction of high-impact tropical weather (e.g., hurricanes) at different scales

Extending the lead time and reliability of hurricane forecasts is important for saving lives and mitigating economic damage.

High-Impact Tropical Weather: Hurricanes

Each year tropical cyclones (TCs) cause tremendous economic losses and many fatalities throughout the world. Examples include Hurricane Katrina (2005),and TC Nargis.

Hurricane Katrina (2005)

- Cat 5, 902 hPa, with two stages of rapid intensification
- The sixth-strongest Atlantic hurricane ever recorded.
- The third-strongest land-falling U.S. hurricane ever recorded.
- The costliest Atlantic hurricane in history. ($75 billion)

Severe Tropical Storm Nargis (2008)

- Deadliest named cyclone in the North Indian Ocean Basin
- Short lifecycle: 04/27-05/03, 2008; identified as TC01B at 04/27/12Z by the Joint Typhoon Warning Center (JTWC).
- Very intense, with a Minimum Sea Level Pressure of 962 hPa and peak winds of 135 mph (~Category 4)
- High Impact: damage ~ $10 billion; fatalities ~ 134,000
- Affected areas: Myanmar, Bangladesh, India, Sri Lanka

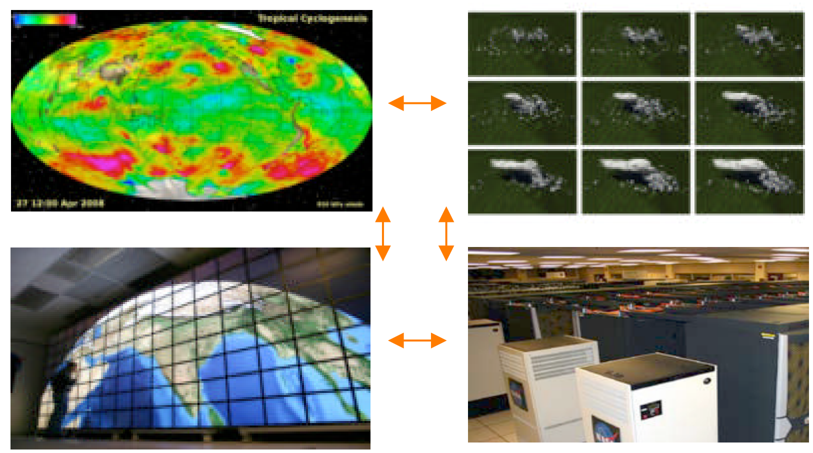
Predicting High Impact Tropical Weather

- It has been suggested that large-scale tropical weather systems may regulate the activities of tropical cyclones
  - Madden-Julian Oscillations (MJOs)
  - Monsoonal circulation
  - Tropical easterly waves
- Therefore, improving predictions of large-scale flows may be helpful in extending the lead-time of TC prediction
- Limited computing resources have made it difficult to accurately improve predictions with traditional global models
  - Insufficient grid spacing
  - Physics parameterizations (cumulus parameterization [CP] development has been very slow)

Approach

CAMVis integrates recent technologies to address high impact tropical weather prediction:

- NASA Supercomputers: Columbia and Pleiades
- Hyperwall-2 Visualization Cluster
- NASA Concurrent Visualization System
  - Couples NASA Supercomputers and hyperwall-2
  - Asynchronous processing/visualization of model output
- High-resolution (~10km) global model: fvGCM
- Multiscale Modeling Framework
  - Goddard Cumulus Ensemble (GCE) + fvGCM = fvMMF
  - Many CRMs (Cloud Resolving Models) embedded in GCM
  - Overcome “CP deadlock”



Major NASA Supercomputers

Columbia Supercomputer (ranked 2nd in the world in late 2004)

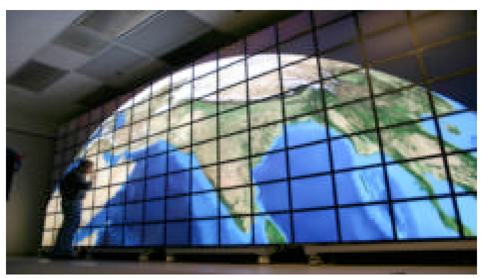
- **Based on SGI® NUMAflex™ architecture,** 20 SGI® Altix™ 3700 superclusters - each with 512 processors, global shared memory across 512 processors
- **10,240 Intel Itanium® 2 CPUs,** current processor speed is 1.5 gigahertz, current cache size is 6 megabytes
- **20 terabytes total memory,** 1 terabyte of memory per 512 processors

Pleiades Supercomputer (ranked 6th in 2010)

- **773 teraflops (LINPACK benchmark)**
- **144 Compute Cabinets** (64 nodes per cabinet; 9,216 nodes)
- **81,920 cores in total**
- **Xeon 5472 (Harpertown), Xeon 5570 (Nehalem), Xeon 5670 (Westmere)**
- **127 TB memory**
- **3.1 PB disk space**
- **Largest InfiniBand network: 9,216 nodes**
  - **Partial 11D hypercube**
  - **Direct visualization cluster connections**

Hyperwall-2

- Supercomputer-scale visualization system
  - 8x16 LCD tiled panel display
  - 245 million pixels
- 128 nodes
  - Dual-socket quad-core Opterons
  - 1024 cores, 128 GPUs
- InfiniBand (IB) interconnect
- IB to Pleiades
  - 2D torus topology
  - 32 links to Pleiades
  - 9x2 switches
  - High-bandwidth concurrent visualization



Concurrent Visualization: Why We Do It

- Large time-varying simulations generate more data than can be saved
  - Problem gets worse as processing power increases
  - Models increase spatial and temporal-resolution
- Saving data to mass storage consumes a significant portion of runtime
- Only a small fraction of timesteps are typically saved and important dynamics may be missed
- Our solution: Concurrent Visualization (CV)

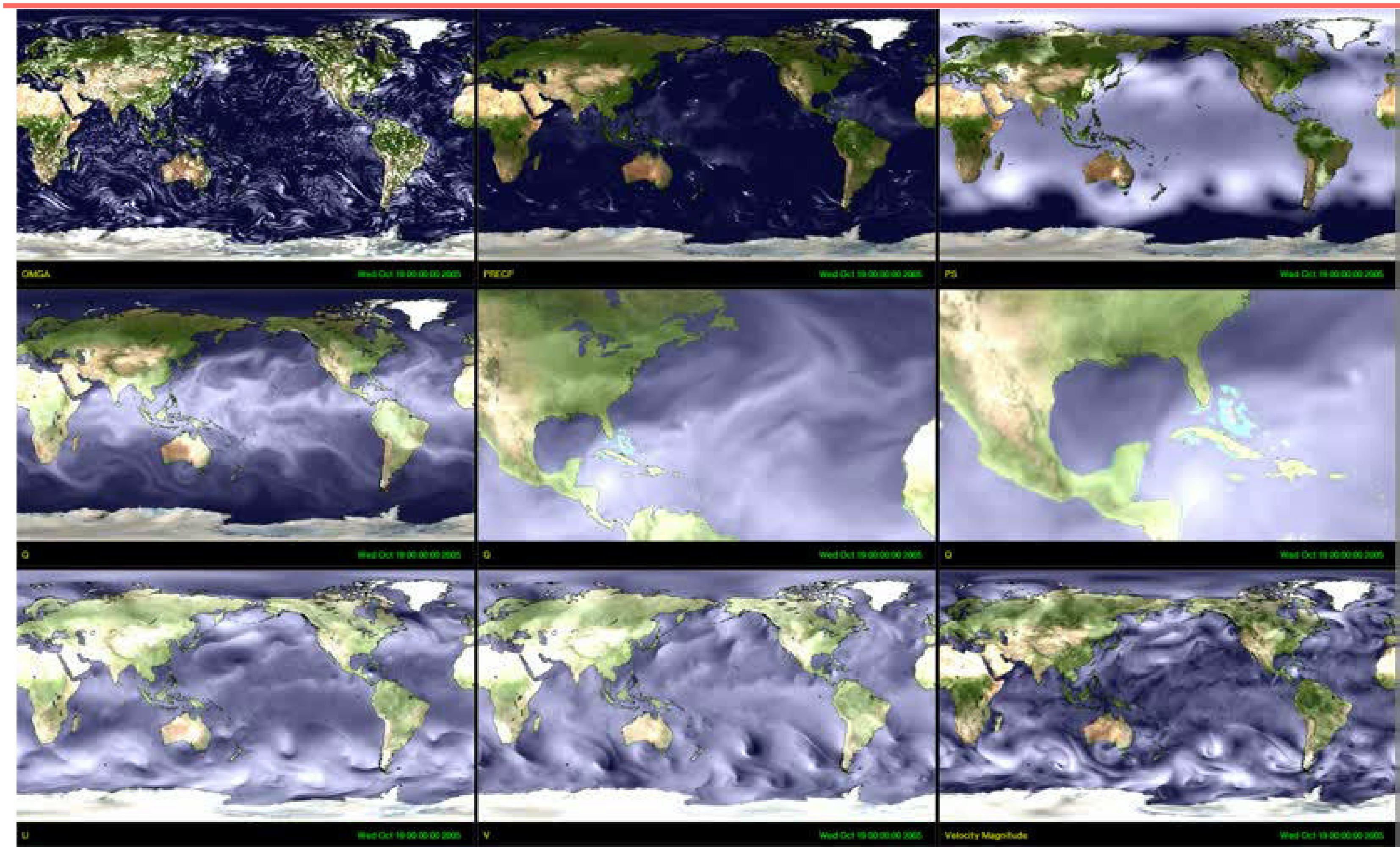
Concurrent Visualization: Approach

- Extract data directly from running simulation for asynchronous processing
  - Add instrumentation to the simulation code, usually quite minimal
- Simultaneously produce a series of visualizations
  - Many fields
  - Multiple views
- Generate and store images, movies, and “extracts”
- Send visualizations of current simulation state almost anywhere, including web
  - Images of current state kept up-to-date in web browser
  - Stream progressively growing movies to remote systems
- Hyperwall-2: parallel rendering, asynchronous I/O

Concurrent Visualization: Benefits

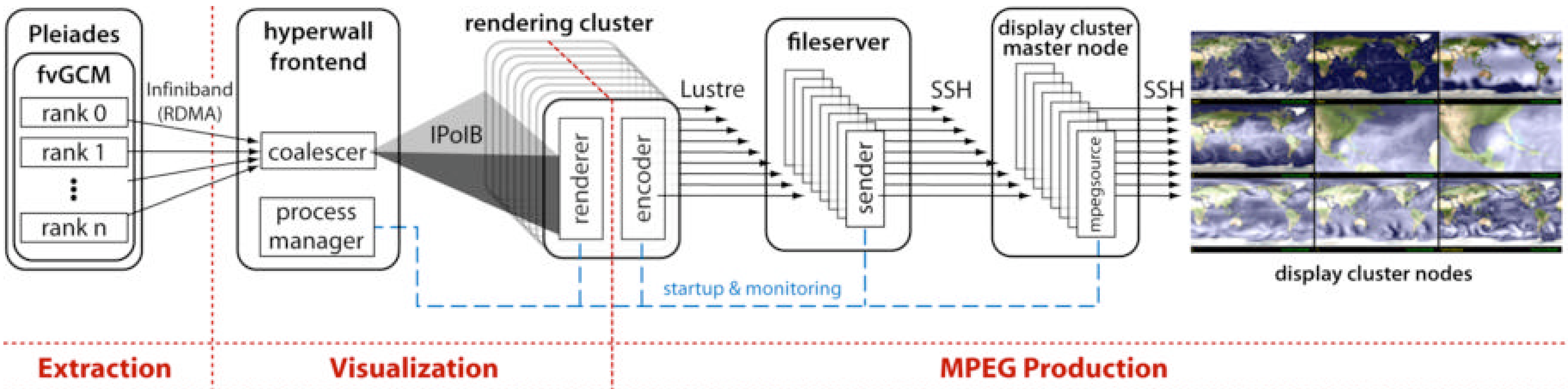
- Higher temporal resolution than post-processing
  - Avoids disk space and write speed limits
  - Output typically 10-1000x greater than standard I/O
- See current state of simulation as its running
  - Application monitoring or steering
  - Detect serious job failures that might otherwise cause waste of system resources
- Minimal impact to application
  - Data is offloaded to vis cluster for concurrent processing
- Reveals features not otherwise observable
  - Has consistently revealed previously unknown dynamics

CV Results: MAP05 Hurricane Tracking Output During Hurricane Wilma



- 48x higher temporal resolution animations showed new features
  - Pressure waves at startup
  - Identified cause of numerical instability

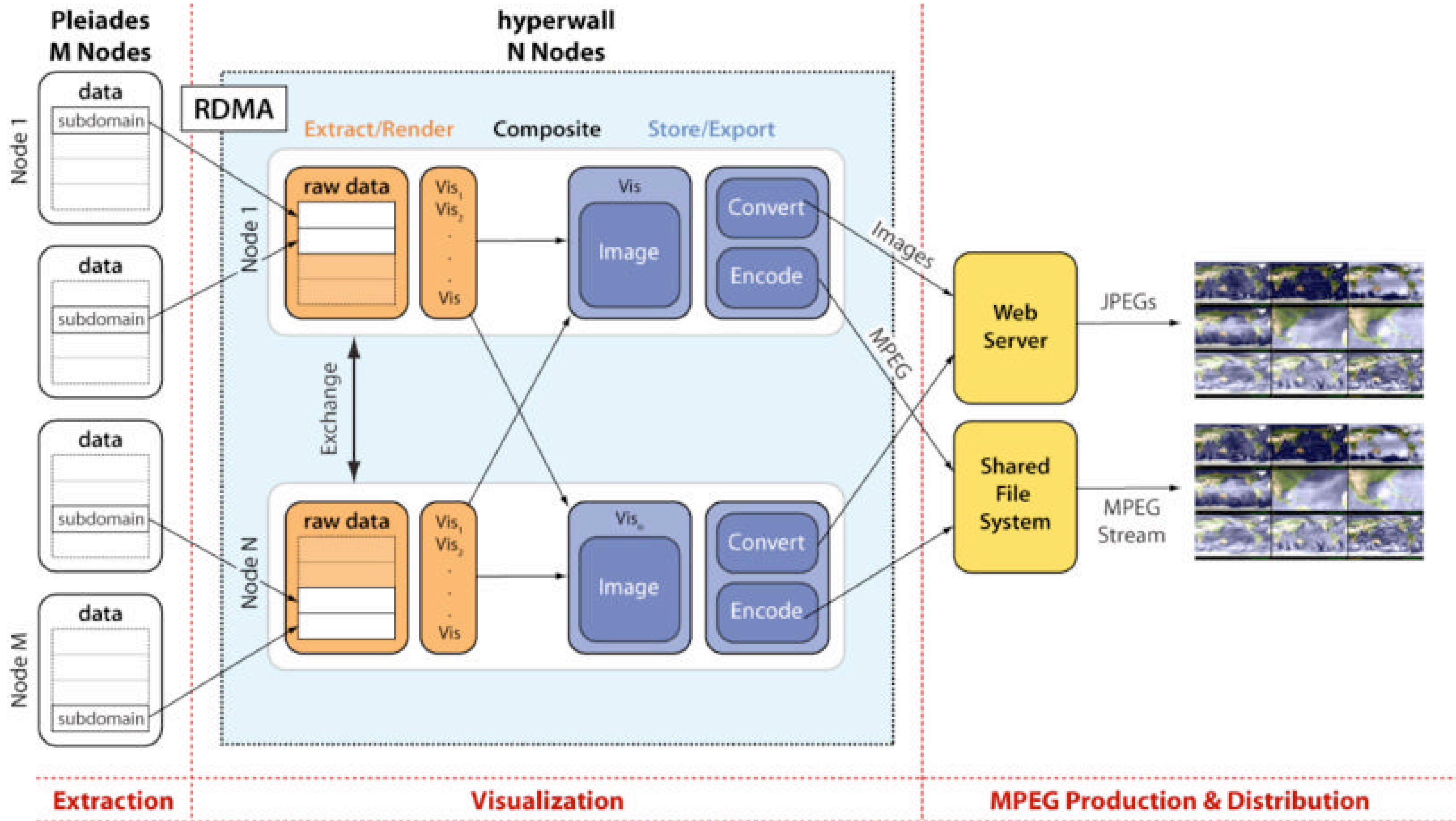
Concurrent Visualization System v2.0



- Originally developed for Columbia shared-memory system
- Modified for distributed-memory Pleiades supercomputer
- MPI processes transfer data (3D domain) via IB RDMA
- Domain recomposed ("coalesced") on frontend node
- Data is processed and broadcast to renderers
- Frontend node is the bottleneck

New Pleiades/hyperwall-2 IB fabric offers a better way

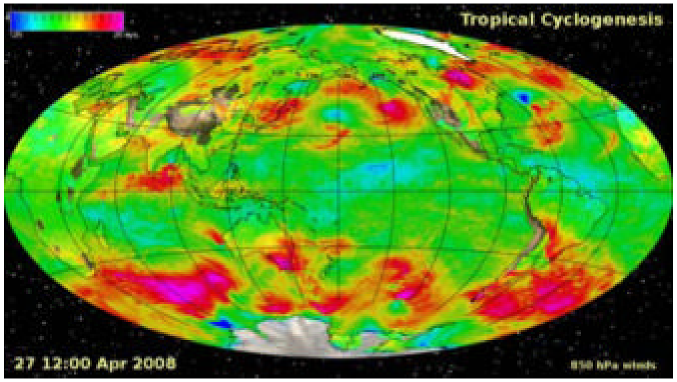
M-on-N Concurrent Visualization Model: Large-scale 3D Concurrent Visualization

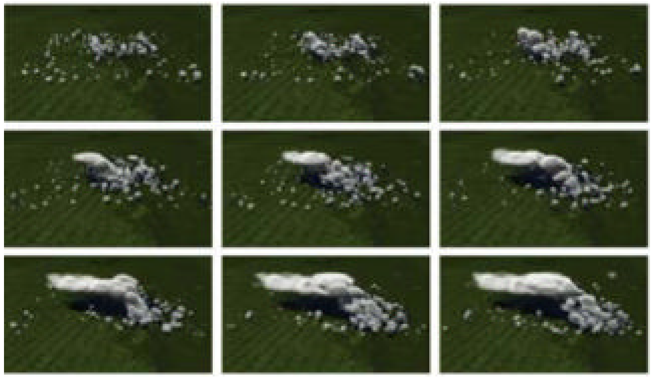


- M-on-N model takes advantage of new Pleiades-hyperwall-2 IB network topology
- Uses the simulation's parallel decomposition

Multi-Scale Modeling Framework (MMF)

- fvGCM + embedded Cloud Resolving Models (CRMs)
  - Global coverage + sophisticated microphysical processes
- Goddard Cumulus Ensemble (GCE) cloud model
- GCEs embedded at every gridpoint
  - Replaces Cumulus Parameterization (CP)
- Current configuration
  - 2 degree fvGCM
  - 13,104 2D GCEs, at 4km resolution currently
  - 3D GCEs are needed to improve simulations





fvMMF Simulations with 2D GCEs

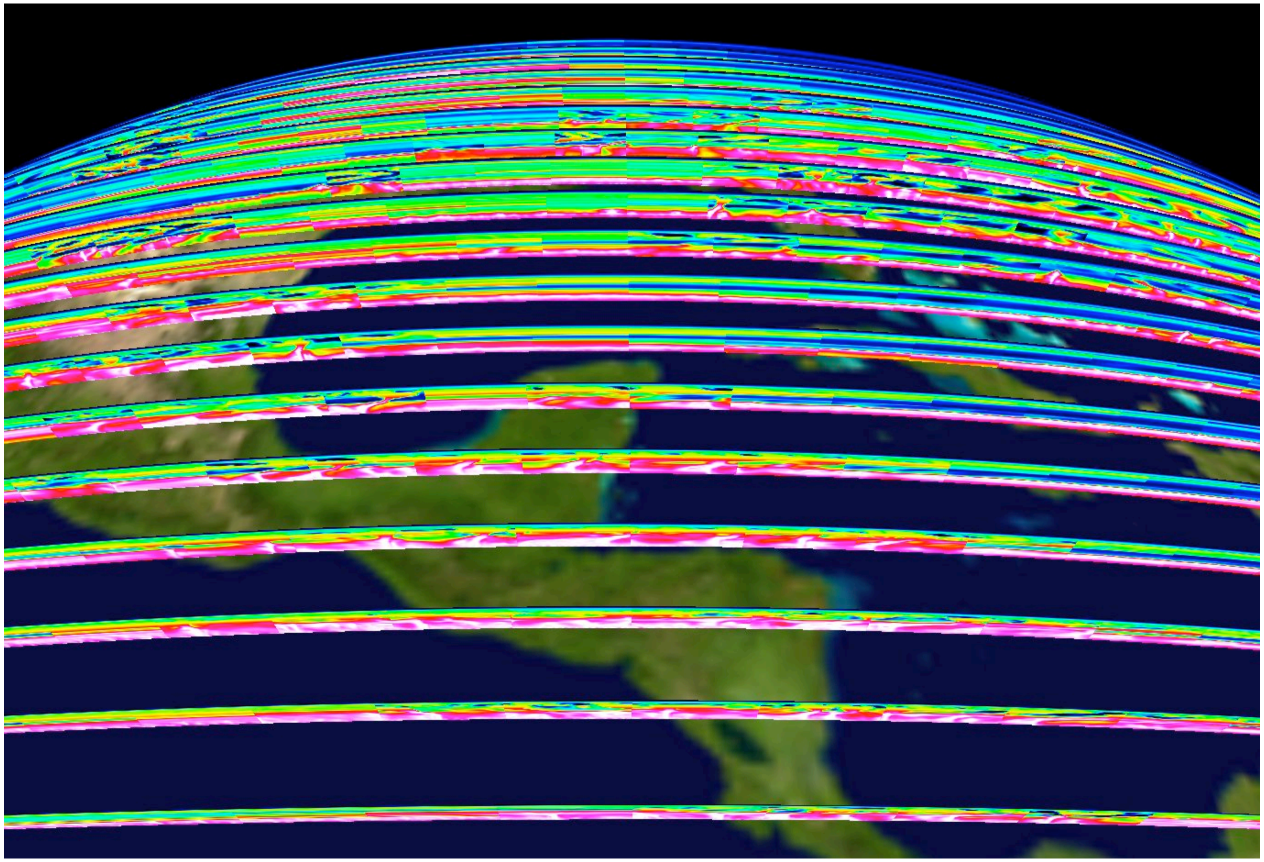
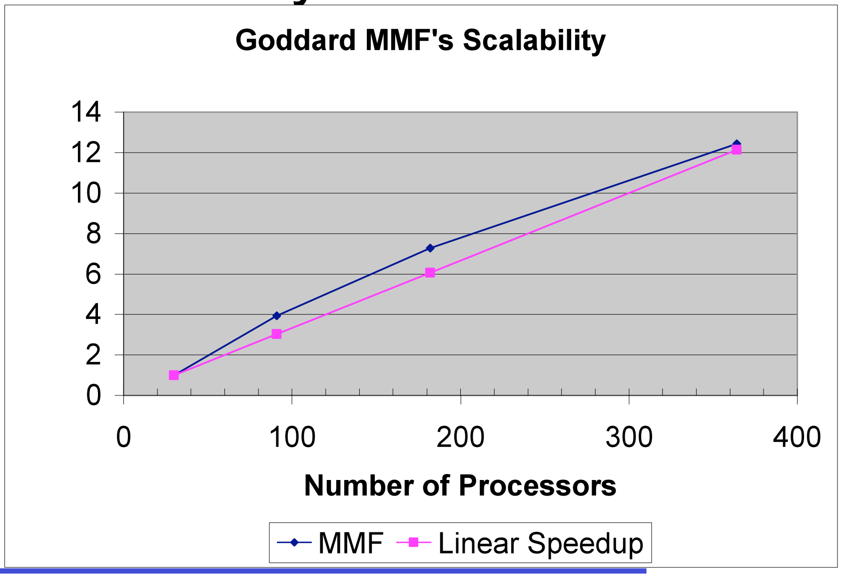


Figure: Visualization of fvMMF simulations for humidity with embedded 2D GCEs, showing 91 X-Z 2D slices along latitudes at an interval of 2°. This indicates the importance of implementing 3D GCEs to improve simulations. This version of fvMMF consists of the fvGCM and the prototype of the so-called mgGCE.

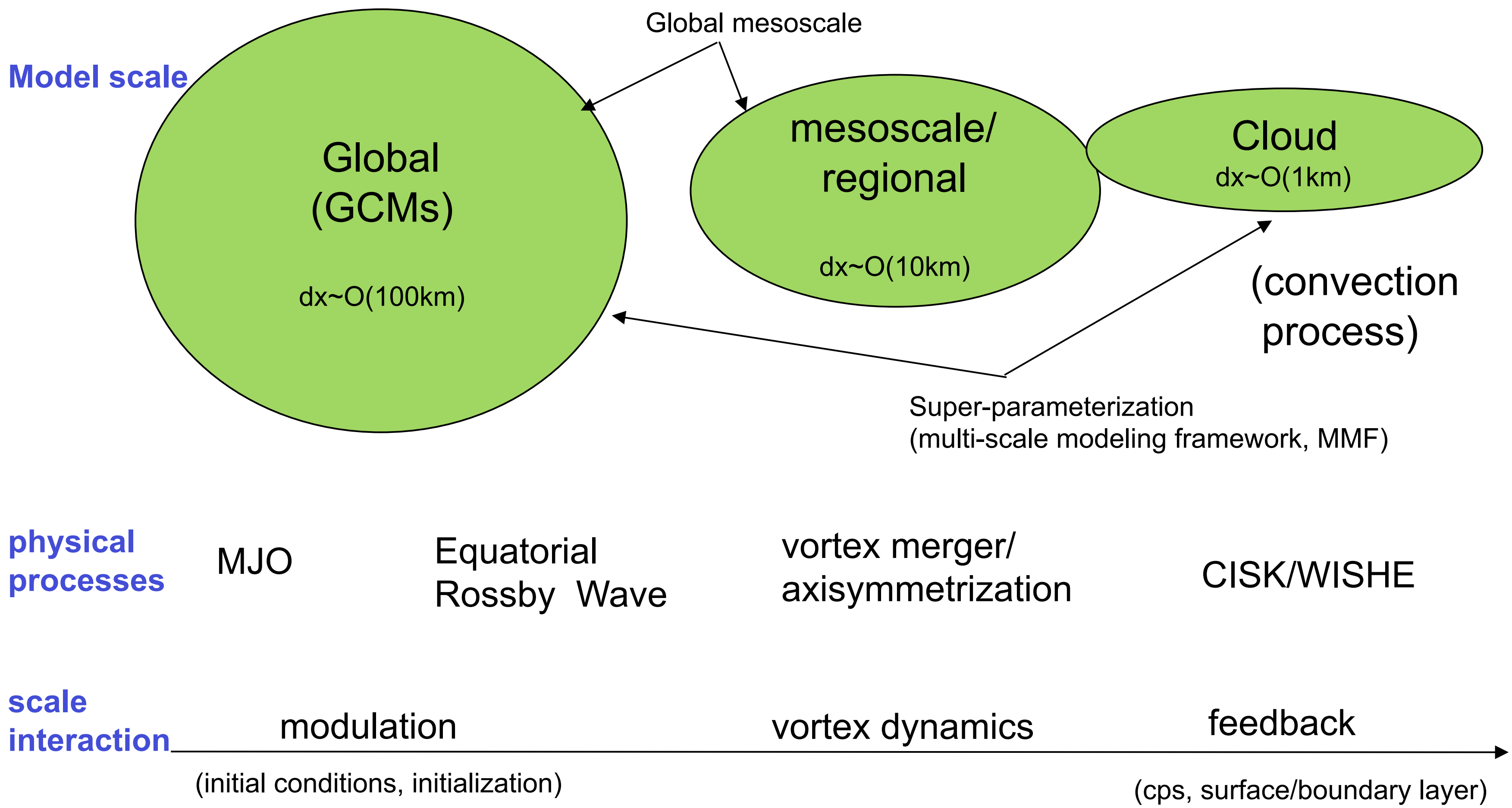
MMF Computational Enhancement: mgGCE

- GCEs used 95% of MMF execution time
  - Scalability was limited to 30 CPUs
- New approach: meta global GCE (mgGCE)
  - Meta gridpoint system, instead of embedded GCEs
  - FvGCM and GCE components are distinct
    - Each have their own scaling properties
- A scalable mgGCE could substantially reduce wall-time

Figure: Scalability of the Goddard MMF with a proof-of-concept parallel implementation. This figure shows that a linear speedup is obtained as the number of CPUs increases from 30 to 364. The original MMF could use only 30 CPUs production runs (see also Shen et al., 2009c).



Multiscale Interactions of TC Formation

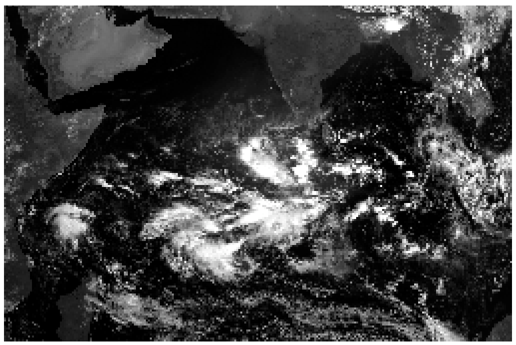


CISK: conditional instability of second kind; **CPs:** cumulus parameterizations; **MMF:** multiscale modeling framework; **MJO:** Madden-Julian Oscillation; **TC:** Tropical Cyclone; **WISHE:** Wind induced surface heat exchange;

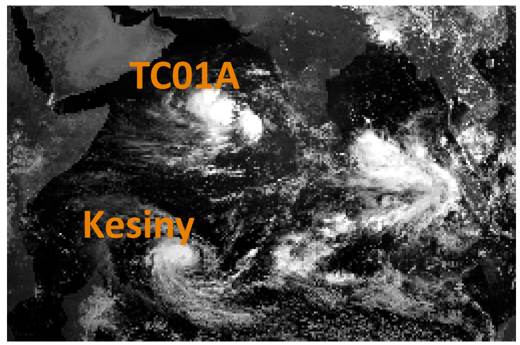
Simulation and Visualization of Twin Tropical Cyclones

Previous studies suggest that twin tropical cyclones (TCs), symmetric with respect to the equator, may occur associated with a large-scale Madden-Julian Oscillation (MJO). Here, it is shown that high-resolution simulations of twin TCs associated with the MJO in 2002 are in good agreement with the satellite observations.

0630 UTC 1 May 2002



0000 UTC 6 May 2002



0000 UTC 9 May 2002

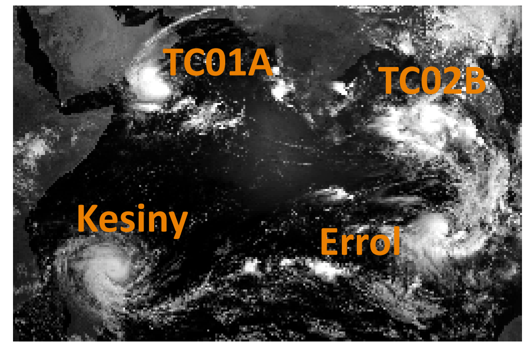
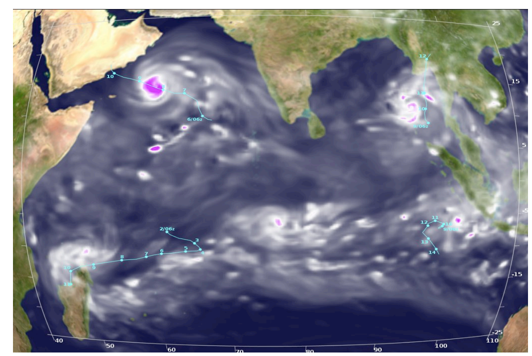
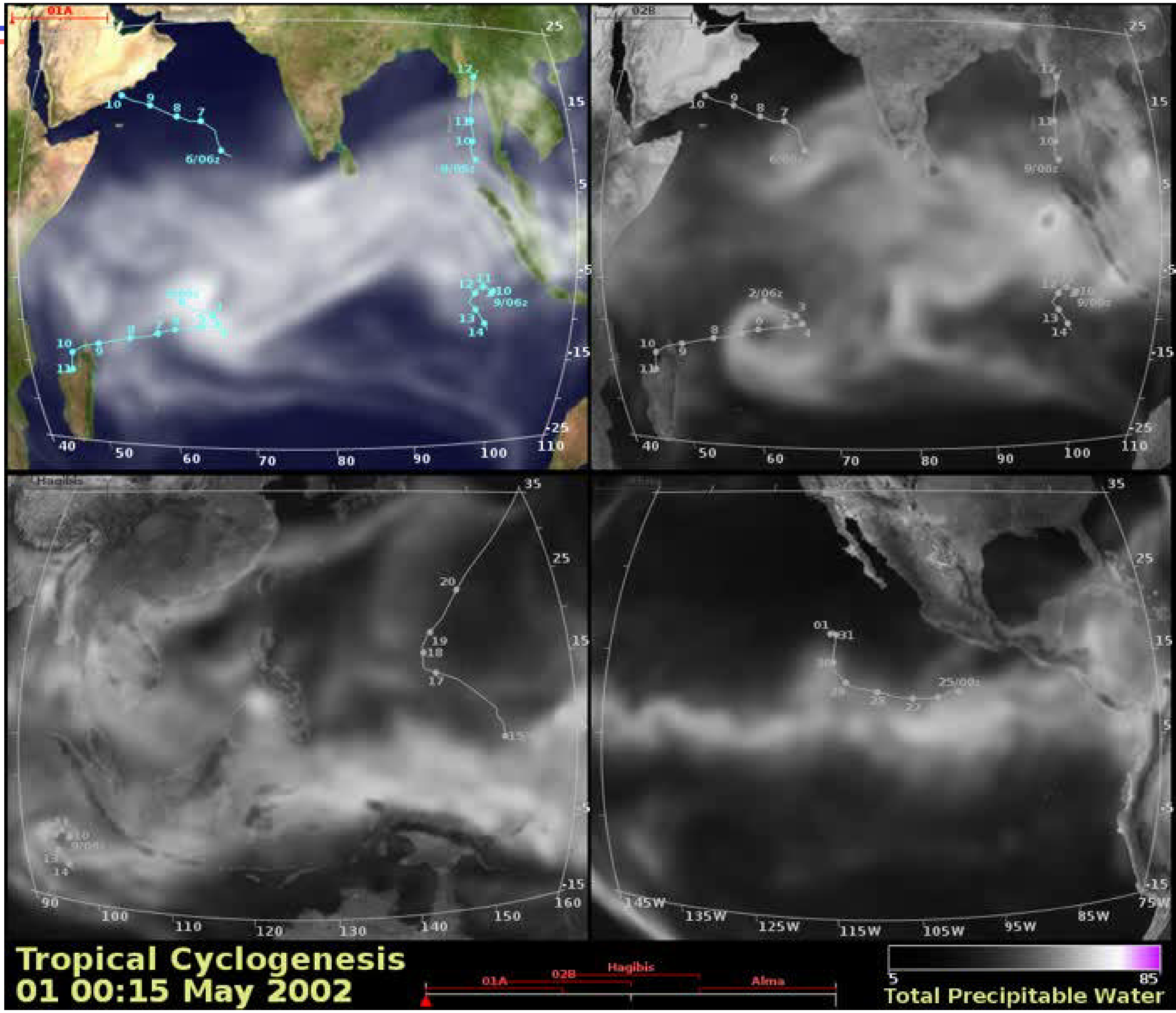


*Figure : Predictions regarding the formation of twin tropical cyclones in the Indian Ocean: (a) MJO-organized convection over the Indian Ocean at 0630 UTC 1 May 2002. When the MJO moved eastward, two pairs of twin TCs appeared sequentially on 6 May (b) and 9 May (c), including TC 01A, Kesiny, TC 02B and Errol. Two TCs (01A and 02B) with anti-clockwise circulation appeared in the Northern Hemisphere, while two TCs (Kesiny and Errol) with clockwise circulation in the Southern Hemisphere; (d) Four-day forecasts of total precipitable water, showing realistic simulations of TC's formation and movement (see **Shen et al.**, 2010 for details).*



Shen, B.-W., W.-K. Tao, R. Atlas, Y.-L. Lin, C.-D. Peters-Lidard, J.-D. Chern, K.-S. Kuo, 2009: Forecasting Tropical Cyclogenesis with a Global Mesoscale Model: Preliminary Results for Twin Tropical Cyclones in May 2002. (to be submitted)

Twin Tropical Cyclones



3D Visualization of Multiscale Processes Associated With the Formation of Nargis (2008)

The 3D visualization is to illustrate (1) the formation of a pair of low-level vortices; (2) the transformation of the northern vortex into the TC Nargis; (3) the suppression of the southern vortex.

This visualization is produced by the NASA CAMVis information system with the following configurations:

- Model: NASA fvGCM;
- Model spatial resolution: 1/4 degree;
- time step: 900 seconds in physics,
  45 seconds in dynamics;
- # of horizontal grid points: 1000x721;
- simulation length: 7 days;
- I/O: every physics time step;
- file size: 716 GB with 61 vertical levels
- wall-time: 2 hours with 240 CPUs

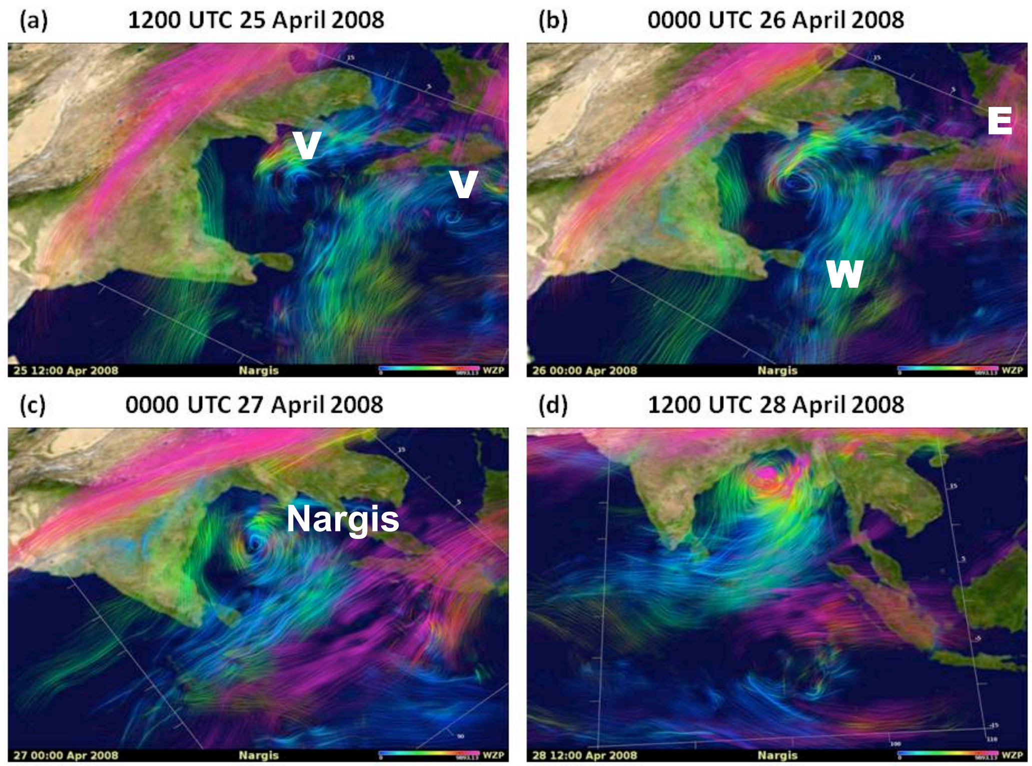
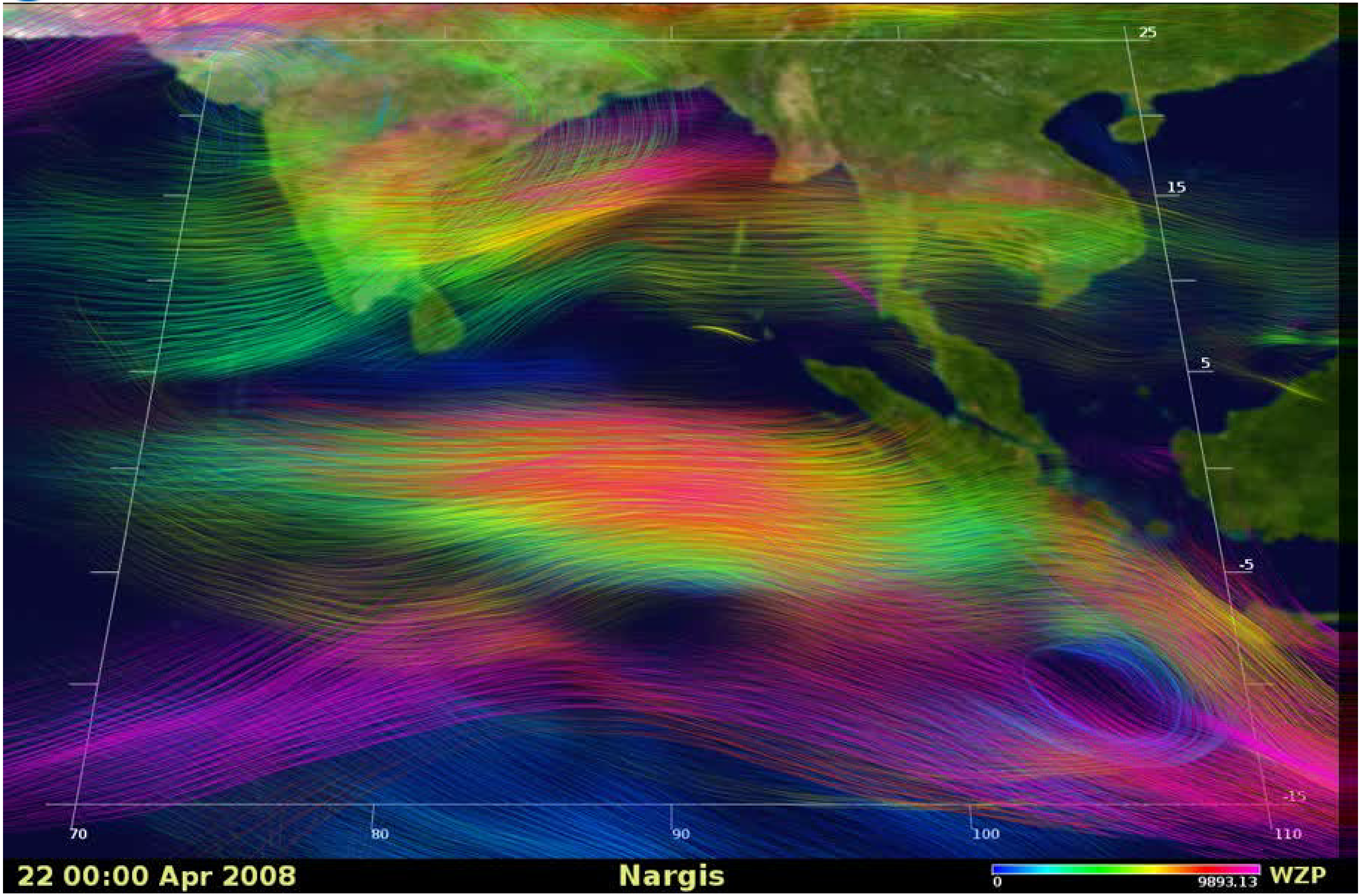


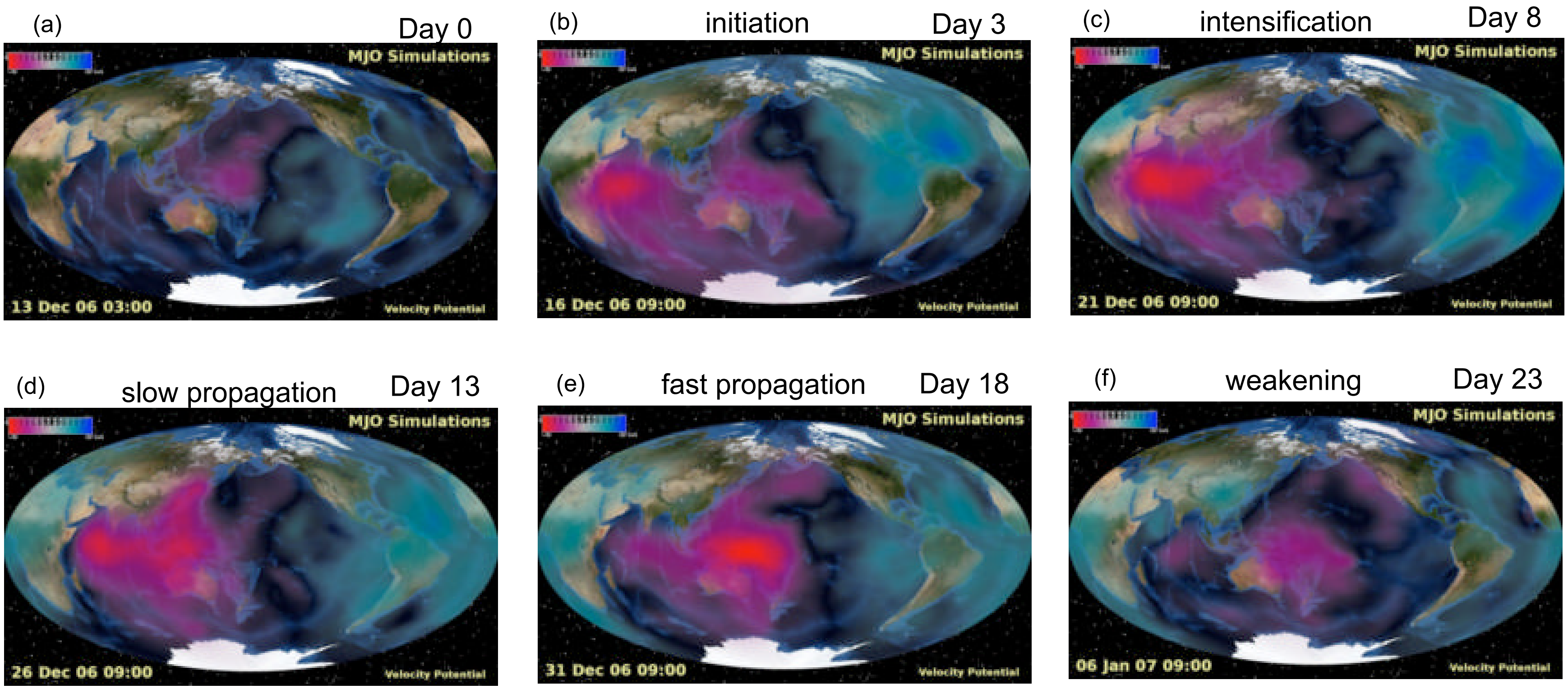
Figure : Realistic 7-day simulations of the formation and initial intensification of TC Nargis (2008) initialized at 0000 UTC April 22, 2008, showing streamlines at different levels. Low-level winds are in blue and upper-level winds in red: (a) formation of a pair of low-level mesoscale vortices (labeled in 'V') at 84h simulation. (b) intensification of the northern vortex (to 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 easterly upper-level winds (labeled in 'E') increase the vertical wind shear, suppressing the enhancement of the southern vortex (to the right) in panel (b).

Cyclone Nargis



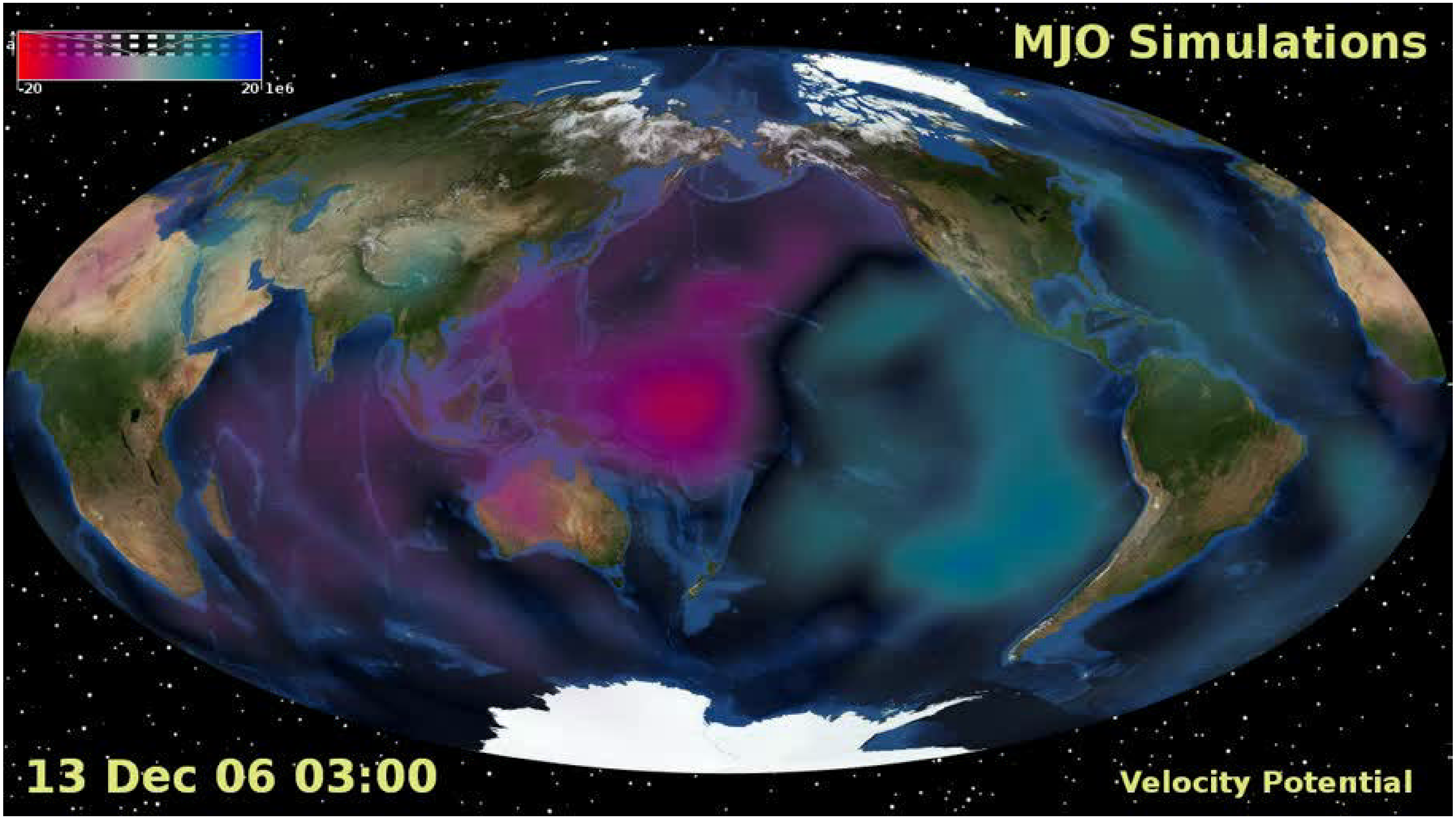
30-day Simulations of an MJO in Dec 2006

One of the challenges in predicting an MJO is to simulating its life cycle, including initiation/ formation, intensification, propagation, and weakening. This figure shows the life cycle of the MJO in December, 2006 is realistically simulated in a 30-day run with the model.



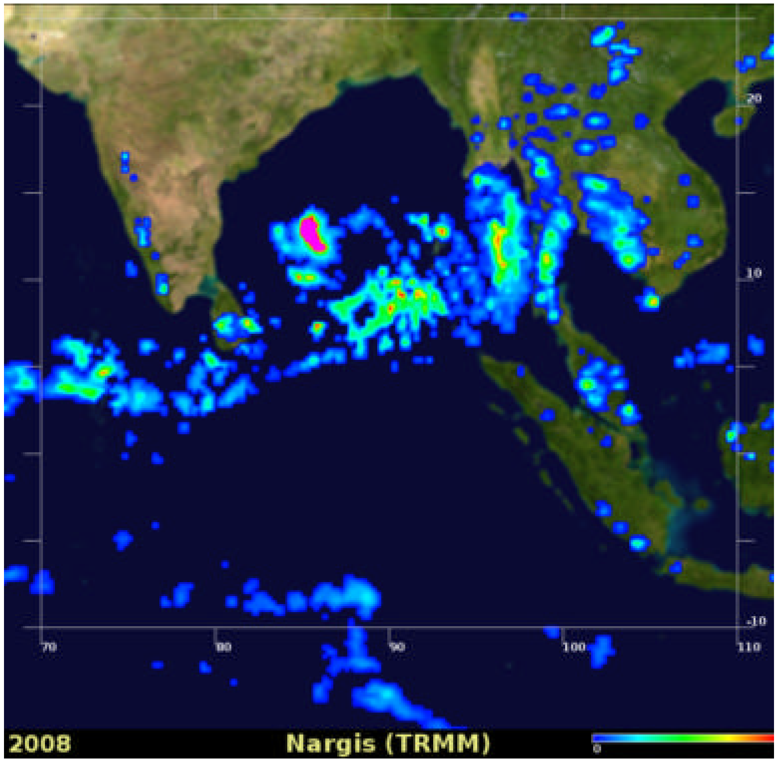
A 30-day simulation of an MJO initialized at 0000 UTC December 13, 2006, as shown in 200 hpa velocity potential. This MMF simulation captures several major features usually associated with an MJO: (1) initiation of large-scale organized convection in the Indian Ocean in panel (b), (2) intensification as shown in panel (c), (3) slow propagation (prior to reaching the Maritime continent), (4) followed by fast propagation, and (5) weakening. However, this simulated MJO also produces stronger vertical motion than does the NCEP/GSF reanalysis.

30-day simulations of an MJO in Dec 2006

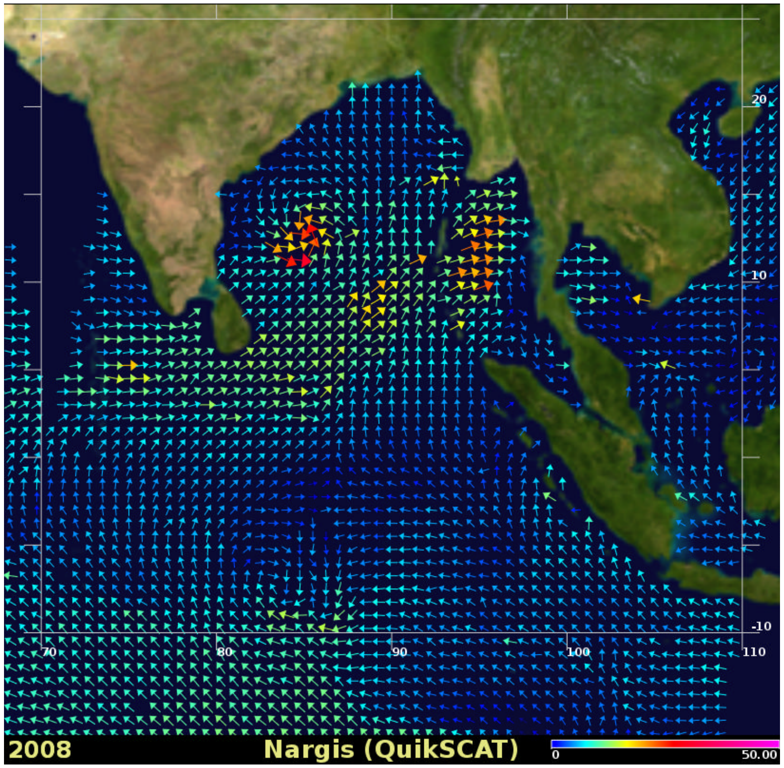


Inter-Comparisons Between Simulations and Satellite Measurements

1500 UTC April 27 2008



1200 UTC April 28 2008



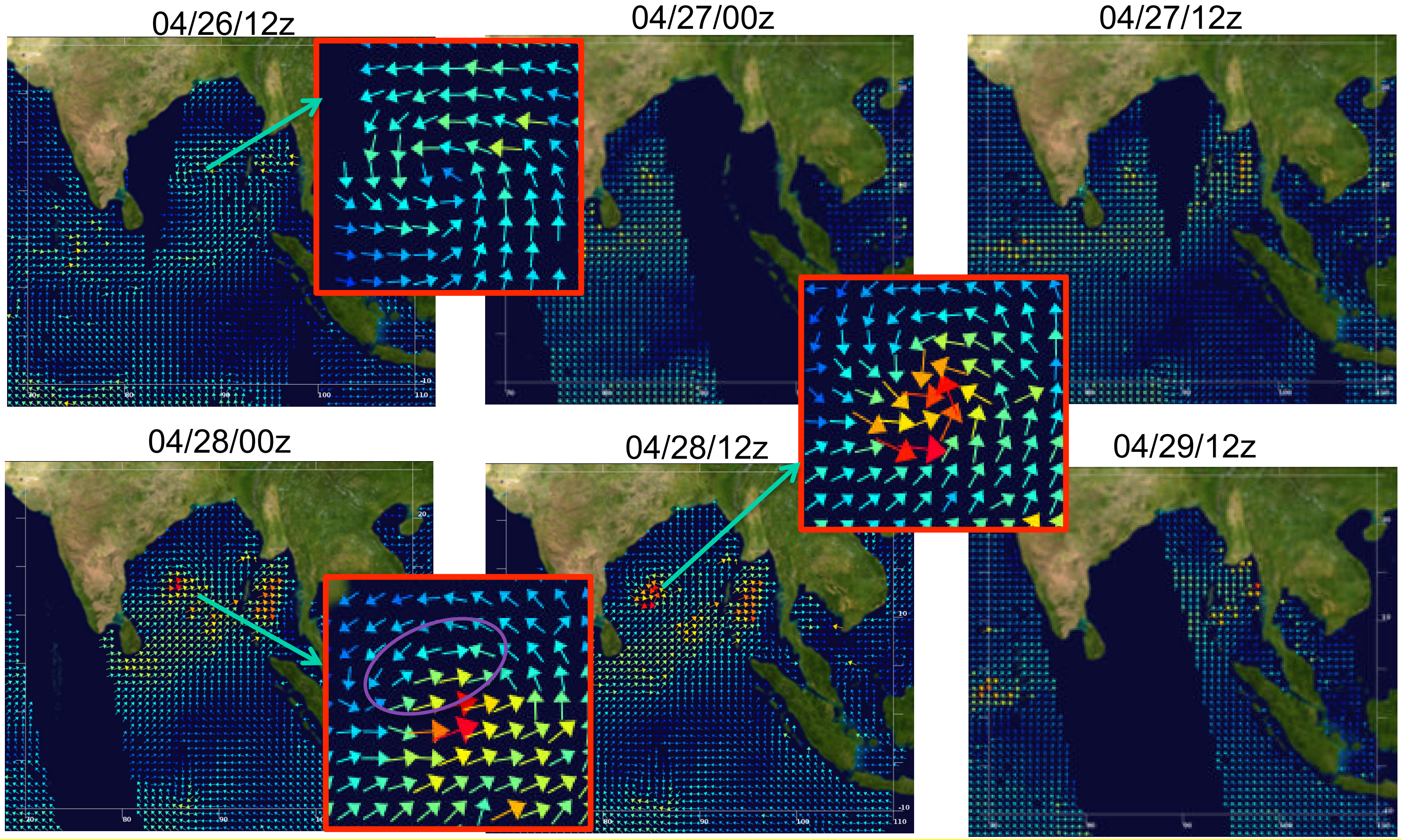
Initial implementation of a visualization module into the CAMVis information system, including data convert and vector plotter for TRMM satellite-derived precipitation (left panel) and QuikSCAT winds (right panel), respectively. These figures show the TC Nargis (2008).

Conclusion

- Integrate NASA advanced modeling and supercomputing technologies to improve prediction of high impact tropical weather
- TC dynamics involve multiple processes and multi-scale interactions
- Newly deployed modeling systems are able to address this problem and are showing encouraging results.
- The coupled concurrent visualization system can help process massive output from multi-scale models efficiently, with high temporal resolution
  - Provides real-time visualization and monitoring of models
  - Developing advanced visualizations within the M-on-N model

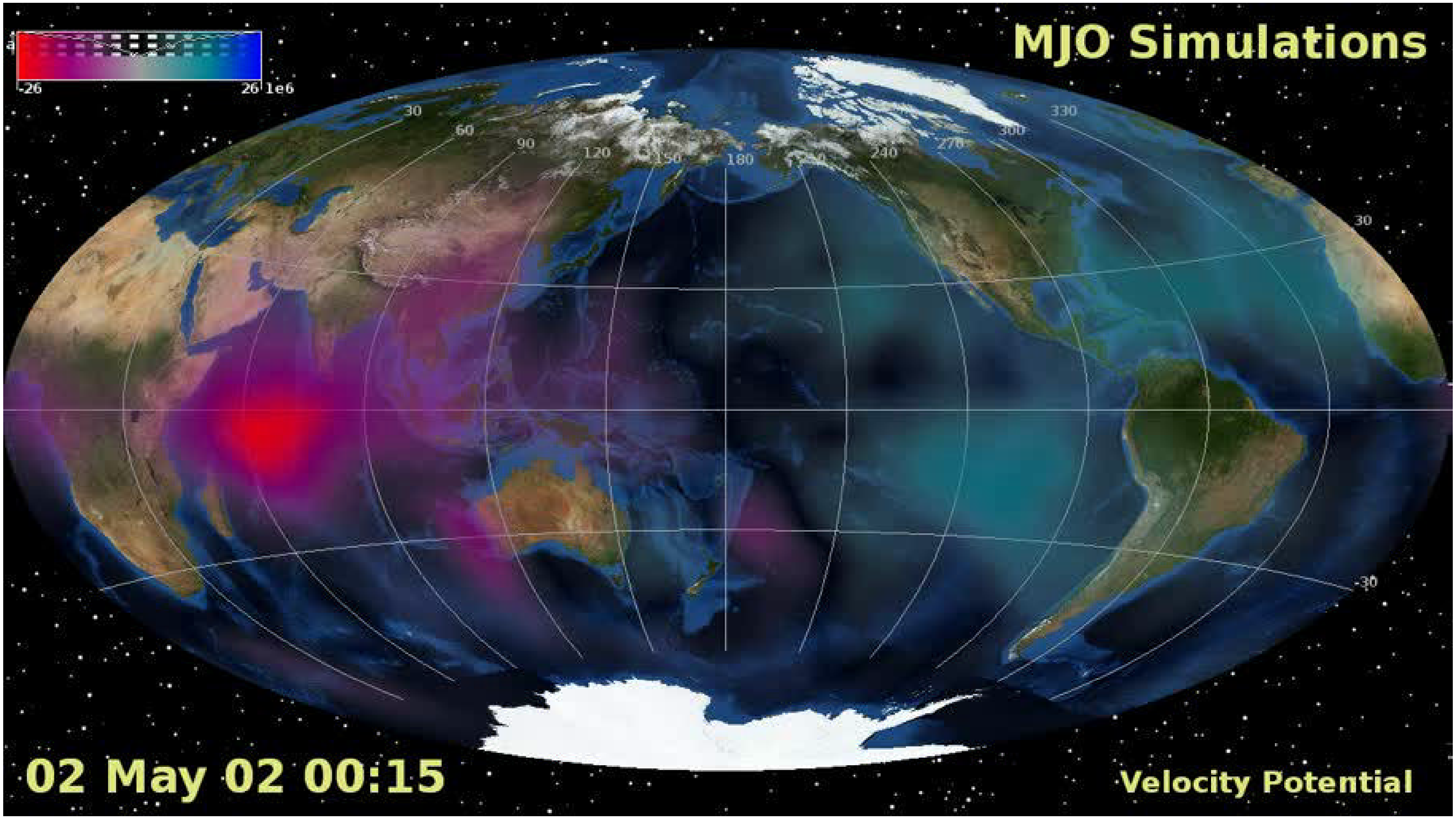
Backup Slides

QuikSCAT Winds for Nargis (2008)

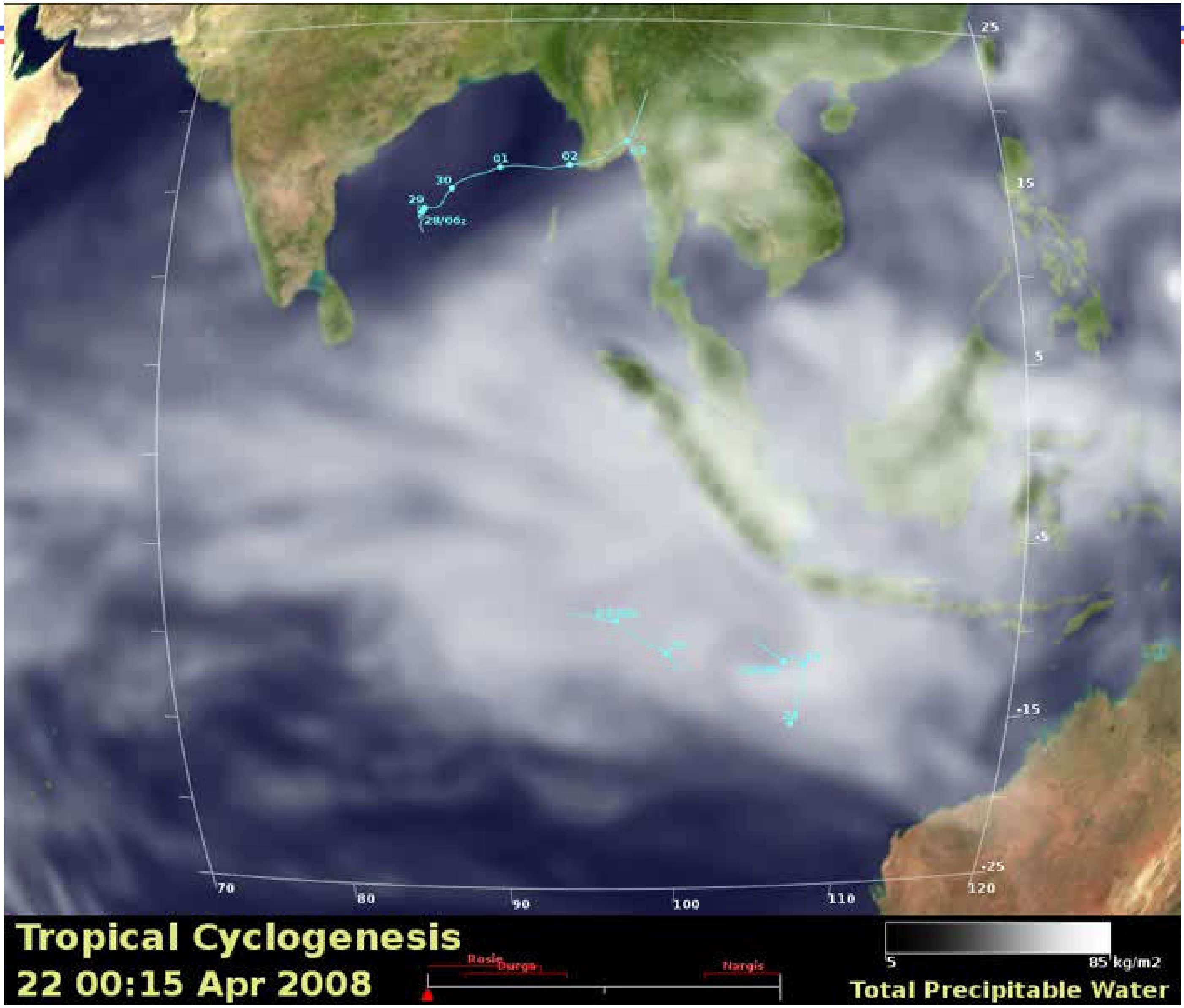


Data continuity (or consistency) is important for tracing a TC movement or identifying its formation. This above figure with QuikSCAT winds for Nargis (2008) is inter-compared with high-resolution model simulations, aimed at understanding the data consistent accuracy in the representation of mesoscale vortex circulation and thus improving formation prediction.

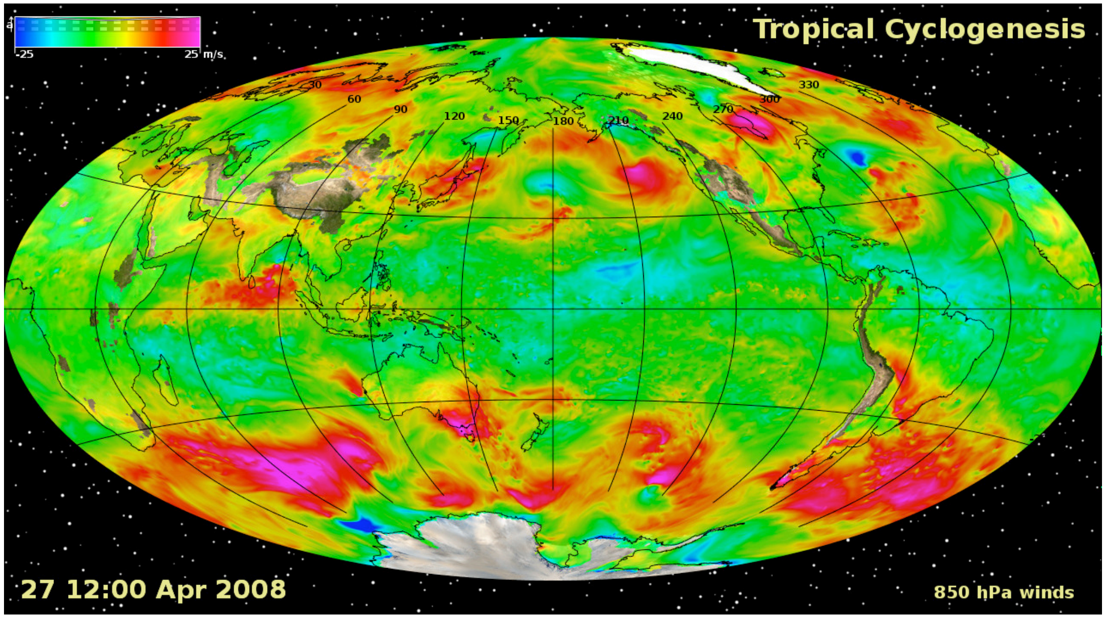
15-day simulation of an MJO in 2002



Cyclone Nargis



Global Multiscale Modeling System



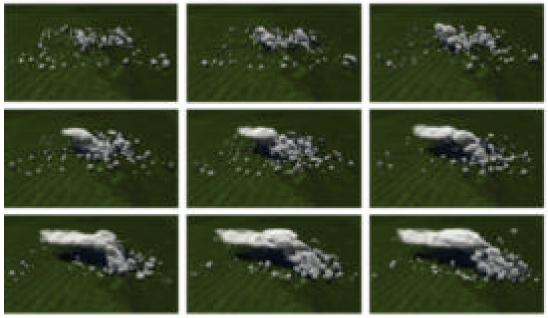


Figure : The NASA global multiscale modeling system (Tao et. al., 2009), consisting of the global model (fvGCM) and thousands of copies of cloud models (GCE). Left panel: visualization of a 5-day low-level wind simulation with the fvGCM, showing the formation of severe tropical storm Nargis (2008) in the Indian Ocean. Right panel: 3D visualization of cloud processes with 9 copies of GCE in a 6°x7.5° area, giving 13,104 cloud models in the global environment.

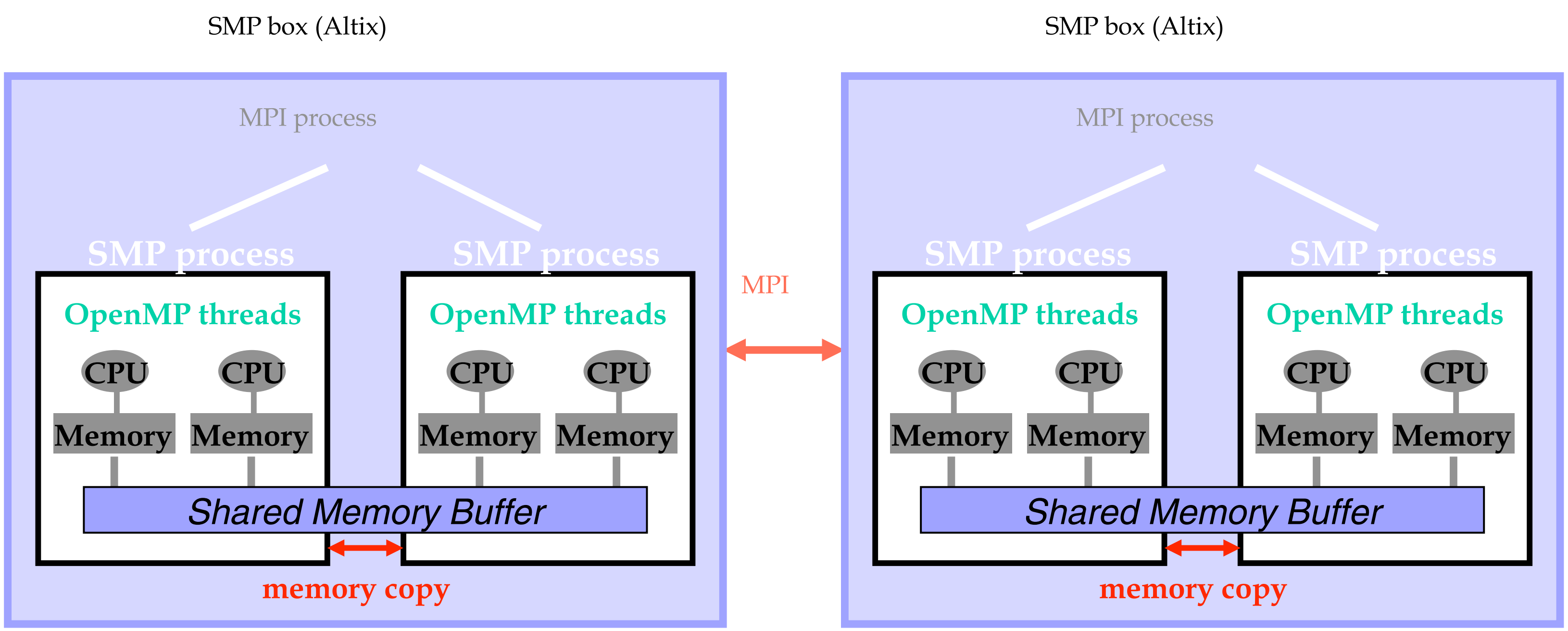
Shen, B.-W., W.-K. Tao, J.-D. Chern, and R. Atlas, 2009: Scalability Improvements in the NASA Goddard Multiscale Multicomponent Modeling Framework for Tropical Cyclone Climate Studies. International Conference for High-Performance Computing in ASIA-Pacific Region 2009. Proceedings, p249-256. Kaohsiung, Taiwan, March 2-5, 2009.

Two-level parallelism

•MPI coarse grain across “nodes” (or “SMP boxes “, e.g. Columbia nodes)

•SMP (MLP) coarse grain within a node.

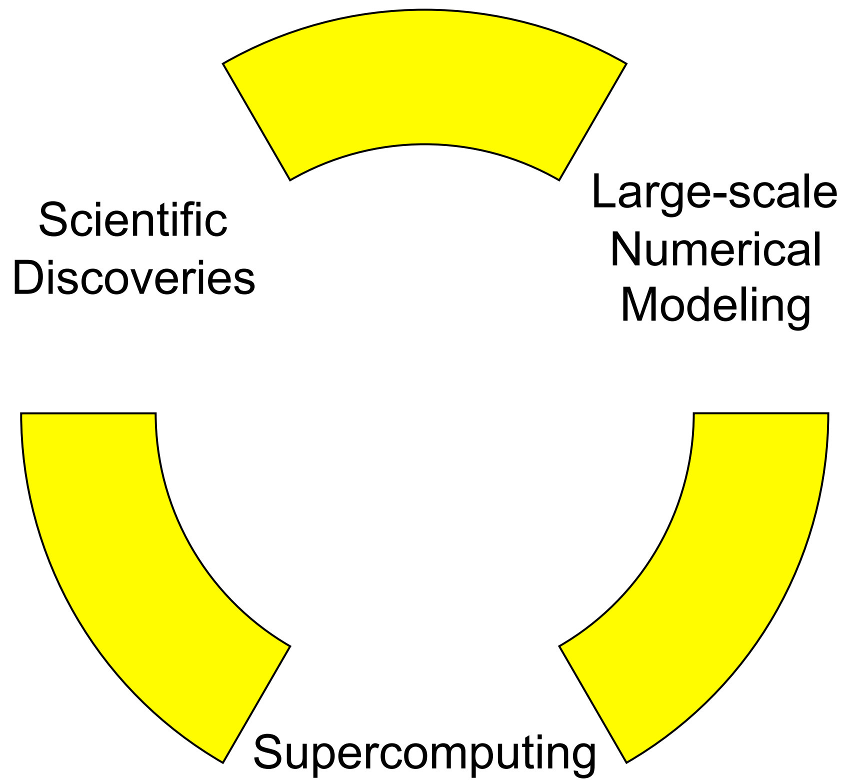
•OpenMP fine grain within a node.



A Science-Driven Approach

Goals:

- **to explore** the power of supercomputing technology (e.g., supercomputers and visualization systems) on the advancement of global weather and hurricane modeling;
- **to discover** how hurricanes form, intensify, and move with advanced numerical models;
- **to understand** the underlining mechanisms (how realistic the model depiction of TC dynamics)
- **to extend** the lead-time of hurricane predictions (and high-impact tropical weather predictions): from short-term (~5days) to extended-range (15~30 days) forecasts



Progress of Hurricane Forecasts
(by National Hurricane Center)

Track Errors | **Intensity Errors**

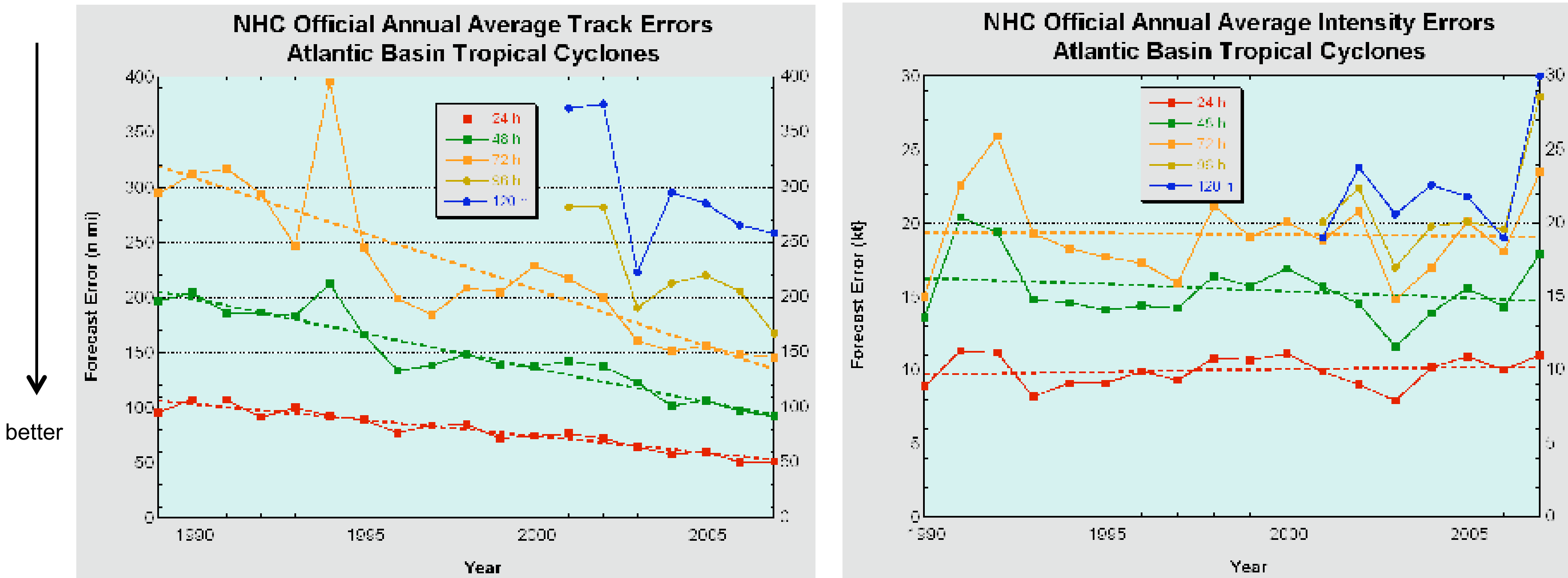


Figure: The progress of hurricane forecasts by National Hurricane Center. Horizontal axis indicates year, and vertical axis shows forecast errors. Lines with different color show different forecast intervals. *<u>During the past twenty years, track forecasts have been steadily improving (left panel), but Intensity forecasts have lagged behind (right panel).</u>*

Project Results

- Model computational performance on Columbia and Pleiades Supercomputers

- Concurrent (real-time) visualization system version 2.0

- 3D visualizations of tropical cyclone formation, aimed at understanding multiple processes and multiscale interactions that lead to TC formation

- Comparisons of model simulations with satellite-derived fields such as QuikSCAT winds and TRMM precipitation, aimed at increasing our confidences in model predictions and the consistency of satellite data

Columbia vs. Pleiades

	cpu	Cores per processor	Cores per node	Clock speed	Memory per core	cache
Columbia	Itanium-2	1*	4 (512)	1.5 GHz	2GB	6MB
Pleiades	Xeon (Harpertown)	4	8	3.0 GHz	1GB	6MB per pair of cores; no L3 cache
Pleiades	Nehalem	4	8	2.93 GHz	3GB	8MB L3 cache shared by the four cores in one processor

Nehalem:

- has no Front Side Bus, but uses QPI (QuickPath Interconnect with a bandwidth of 25.6 GB/s)
- uses SSE4.2 technology, instead of SSE4.1 used in Harpertown,
- has a Turbo boot mode,
- has memory of 24 GB/node, with respect to 8GB/node with Harpertown.

With a 32x8 (MPIxOMP) cpu configuration, running fvGCM with Nehalem is 40% faster than with Harpertown. With a 64x4 cpu configuration, it is 38% faster.

fvGCM benchmarks

RUN	Nodes (cores)	MPI procs	OMP threads	Total cores (used)	Throughputs (Days/24h)	Days/24h Per node
A	32(256)	32	4	128	213.8	6.68
B	32(256)	32	8	256	241.4	7.54
C	32(256)	64	4	256	281.5	8.80
D	16(128)	32	4	128	136.6	8.54
E	16(128)	16	8	128	108.7	6.79

Given N nodes (8*N cores), (2N MPI procs, 4 OMP threads) gives the best throughputs.

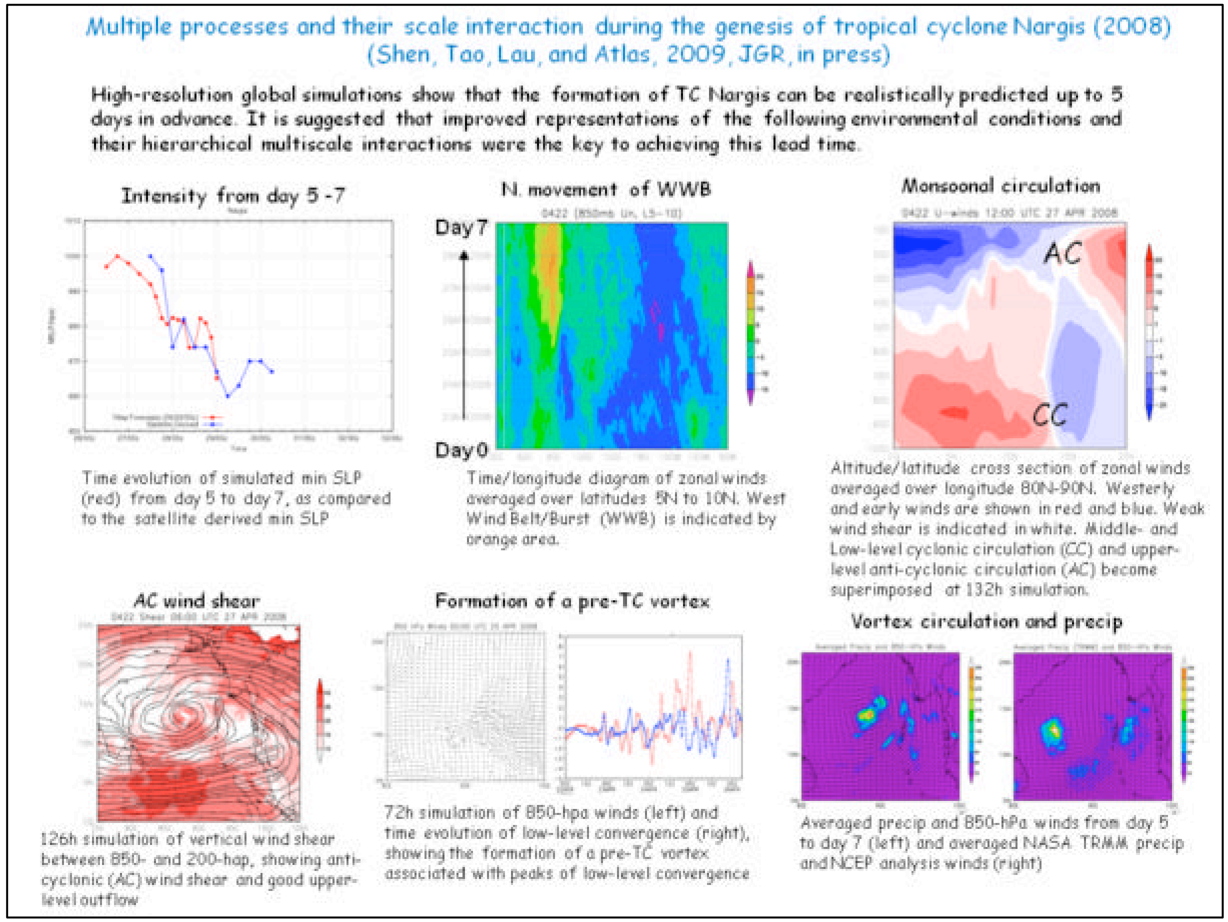
B1	32(256)	32	8	256	251.1	7.85
C1	32(256)	64	4	256	277.8	8.68
Bnh	32(256)	32	8	256	418.2	13.07
Cnh	32(256)	64	4	256	445.6	13.93

Cases A-E with 5-day simulations were conducted in September, 2009; Case B1, C1, Bns, and Cnh were conducted in January, 2010.
Harpertown CPUs are used in all cases except for Bnh and Cnh with Nehalem CPUs used

The need of 3D Visualizations for the representation of multiscale interactions

High-resolution simulations with this model show that the formation of TC Nargis can be realistically predicted up to 5 days in advance. It is suggested the improved representation of the environmental conditions (listed in the figure) and their hierarchical multiscale interactions were the key to achieving

Though these multiple processes and their scale interactions can be realistically simulated with the advanced global mesoscale model, presentation of these processes in a simple form for education and outreach purposes becomes very challenging. To achieve this goal, 3D visualizations will be illustrated in the next slide.



<u>Shen, B.-W., W.-K. Tao</u>, W. K. Lau, R. Atlas, 2009: Improving Tropical Cyclogenesis Prediction with a Global Mesoscale Model: Hierarchical Multiscale Interactions During the Formation of Tropical Cyclone Nargis (2008). (submitted to JGR, in press).

15-day Simulations of an MJO in May 2002

Accurate prediction of tropical activity at sub-seasonal scales is crucial for extending numerical weather prediction beyond 2 weeks. Among the challenges of this goal is accurate forecasting of a Madden-Julian Oscillation (MJO). This figure is to show that both the fvGCM and fvMMF can realistically simulate the MJO up to 15 days.

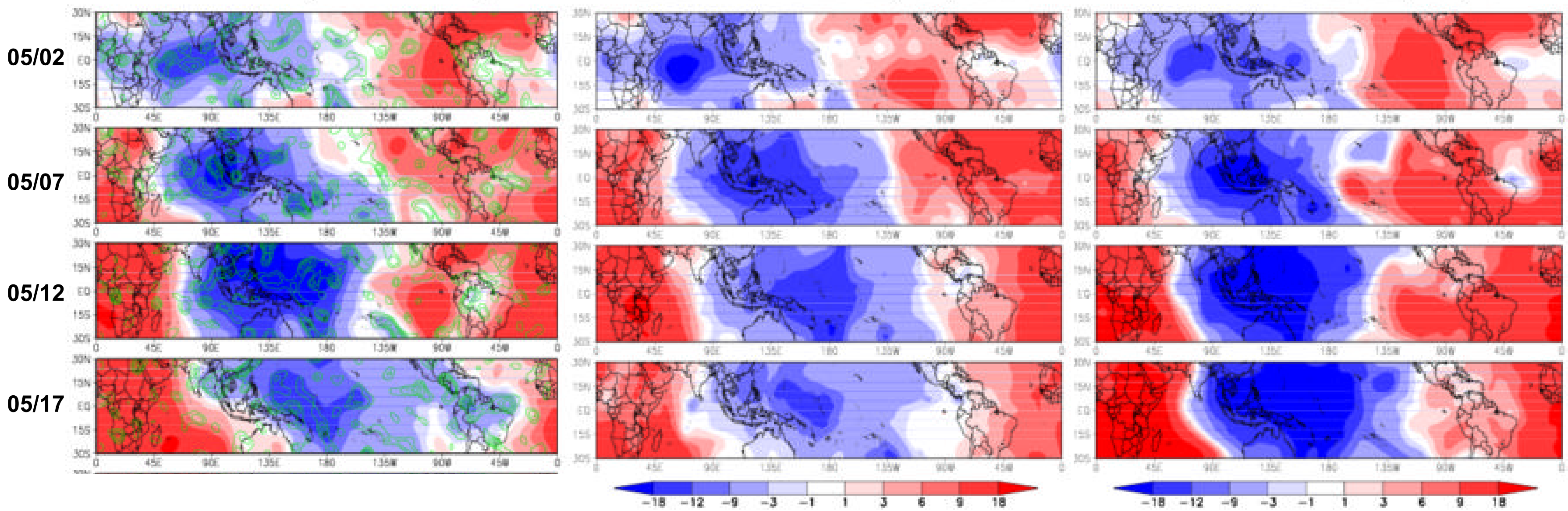


Figure. Velocity potential at 200 hPa every 5 days in May 2002 from NCEP analysis (left panels), 15-day fvGCM model predictions at 1/8 degree resolution (middle panels), and 15-day fvMMF model predictions (right panel). The velocity potential plots showed the observed and predicted patterns and propagations of Madden-Julian Oscillation (MJO). The high-resolution fvGCM is able to reproduce realistically the observed patters and intensity as NCEP analysis. The fvMMF even with coarse-resolution (2x 2.5 degree) is also able to predict the large-scale MJO event, except its intensity is somewhat overestimated .

Primary findings (computational part)

- Pleiades is faster than Columbia, apparently due to clock speed rather than memory.
- Intel compiler v11 does not perform better than v10.
- Aligning the variable does not give performance boost.
- If compile physdrv.F with aggressive optimization flag (-O3), the code can now be compiled with v11. A 8% improvement: 675.8984
- This benchmark shows that the optimal scalability is with 4 OMP threads.
- The degraded 8 OMP is due to ifort KMP and the long-complained front-end bus size. [~17% (6.89%) of the time is spent on __kmp_wait_sleep (__kmp_x86_pause). That is why the OMP performance (“scalability”) is not very good.]
- Computing nodes with Nehalem CPUs are available for production runs and will be used to support YOTC project. Nehalem CPU allows two settings, namely, Turbo-Boost and Hyperthread. From our simple experiments, we see that there is no effect on performance with Hyperthread on or off, but there is about 10% gain with Turbo-Boost on.
- With a 32x8 (MPIxOMP) cpu configuration, running fvGCM with Nehalem is 40% faster than with Harpertown. With a 64x4 cpu configuration, it is 38% faster.

Achievements (March 2009 - March 2010)

- Helped examine the feedbacks of resolved heating on the simulations of hurricane Katrina (2005), aimed at improving model's performance
- Helped visualize scale interactions of hurricane Ivan (2004), aimed at improving the understanding of the Ivan's intensification prior to its landfall
- Visualized the modulation by the large-scale flows (MJOs), and aggregate effects of small-scale convective events during the formation of two pairs of twin tropical cyclones in May 2002 in four 10-days simulations, showing triple-scale interactions
- Illustrated multiple processes and multi-scale interactions during the formation of TC Nargis (2008) with 3D visualizations
- Inter-compared model simulations and satellite-derived fields (e.g., QuikSCAT) to increase confidence level in model's simulations and data quality

WRF Concurrent Visualization: Typhoon Morakot

- HECC Visualization staff completed a simulation of 2009 Typhoon Morakot for the 96 hours around its passing over Taiwan, where the rainfall exceeded 2 meters. It was done for user Wei-Kuo Tao, NASA Goddard, as part of their research to improve the accuracy of weather simulation
- The highly detailed simulation took ~6.5 days using 224 CPUs, and used the Weather Research and Forecasting (WRF) Model 3.1 software
- Concurrent visualizations were generated using the hyperwall-2 system
- Simulation states were saved every 36 seconds—much more frequently than could be efficiently saved using standard netCDF I/O
- The simulation used 27 fields, 37 visualization configurations (one top-down for 2D fields, a vertical sum and vertical slice for 3D fields); showed 2 views per configuration for a total of 74 sets of frames—710,474 frames total; extracted 21 TB of field data; created 222 animations (three animation speeds for each of the 74 frame sets)

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Mission Impact: The visualization output gave researchers many detailed views to carefully study simulation performance for an important weather event—generating the same visualizations using traditional post-processing methods would have extended the simulation run so much that it would not be practical to get the same level of detail.

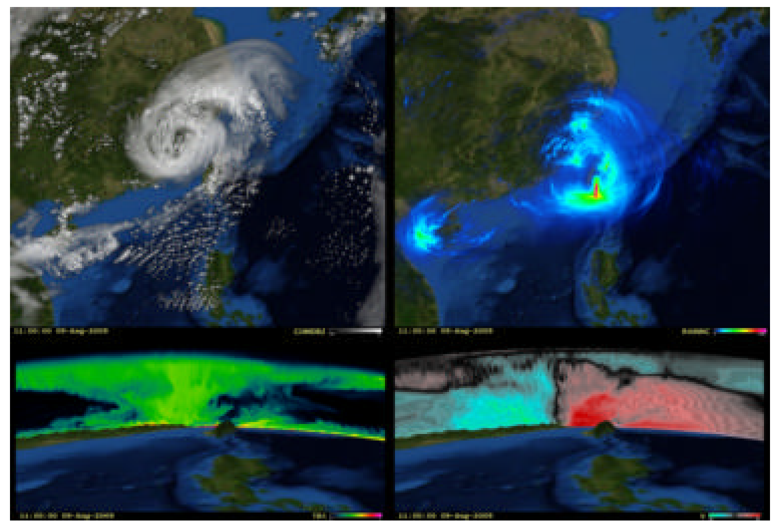
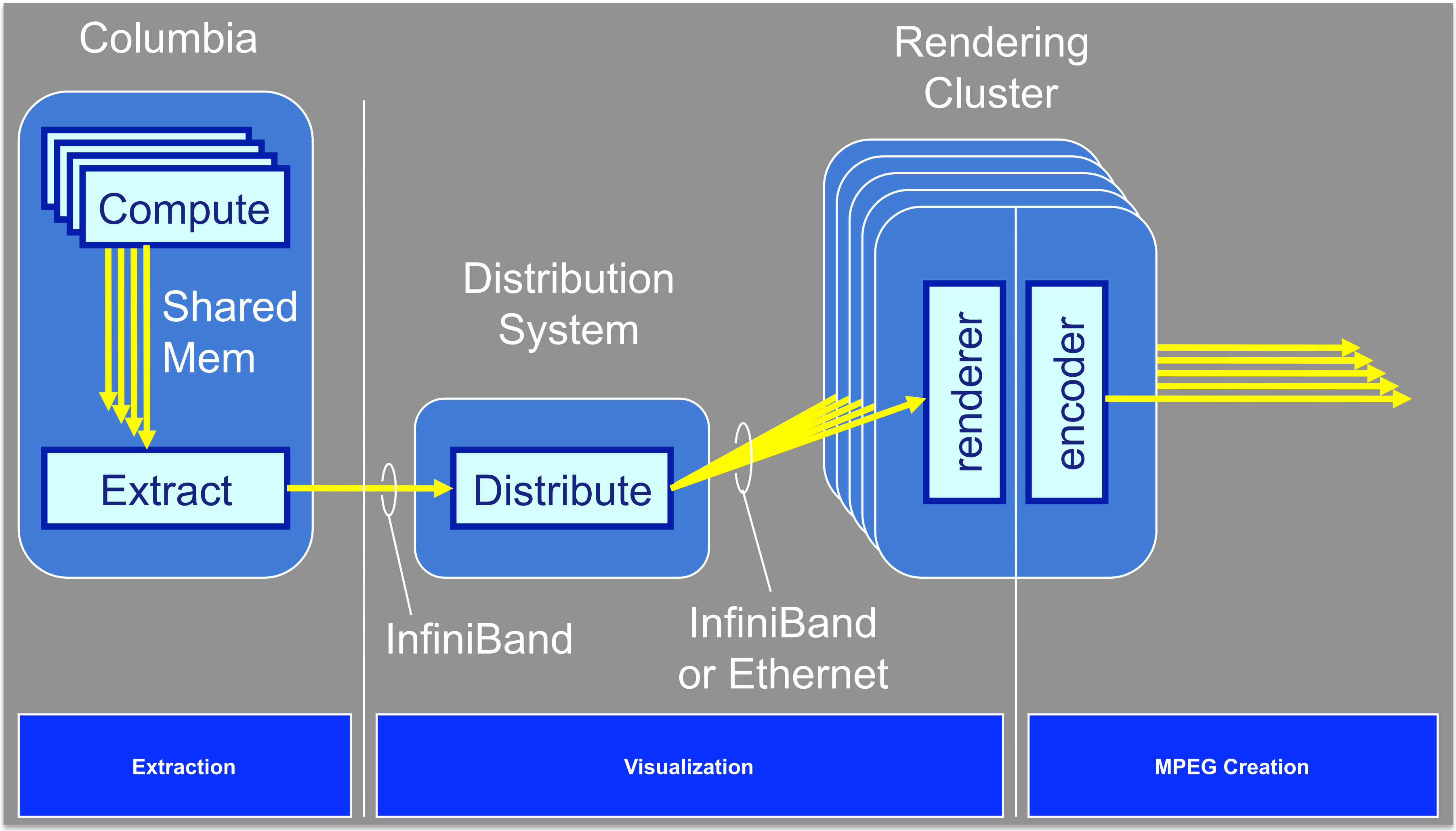


***Figure*:** Four of 74 visualizations produced during the HECC concurrent visualization run. Top left: simulated radar reflectivity; Top right: cumulative rainfall (magenta = 2 meters of rain); Bottom left: tracer field with a marker near the surface; Bottom right: north-south velocity (red indicates wind to the north, light blue/green shows wind to the south).

Columbia-CV System Architecture



fvGCM Instrumentation for CV

supporting NUMA, RDMA, M-on-N

call tap_register_fields()

Read configuration file "vis.rc"

NUMA: read requested-fields from file.

RDMA/M-on-N: determine hyperwall coalescer host, connect to receiver and send metadata via rdma_cm "connect" and IB Send verb.

call tap_mapit()

NUMA: map shared memory segment created by coalescer process.

RDMA/M-on-N: receive settings and requested-fields from coalescer via completion of IB Recv verb.

Do 9999 i=1, imax

call tap_dumpit()

9999 continue

NUMA: field data copied to shared memory; semaphore posted to notify coalescer.

RDMA/M-on-N: data written directly to buffer in coalescer process via IB RDMA Write verb.