



Recent Development of the NASA CAMVis for Tropical Cyclone Studies

Bo-Wen Shen (PI)

ESSIC, University of Maryland, College Park

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Project Title of AIST-08-0049:

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





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1.1 FTEs for Project CAMVis



Outline

1. Introduction
2. NASA Supercomputing Technology
3. Technology Approach: Global Multiscale Modeling and Concurrent Visualization Systems
4. Scientific Demos: Predictions and Visualizations of Tropical Cyclone Formation and its Multiscale Interaction with Environmental Conditions
5. Conclusion and Future Tasks

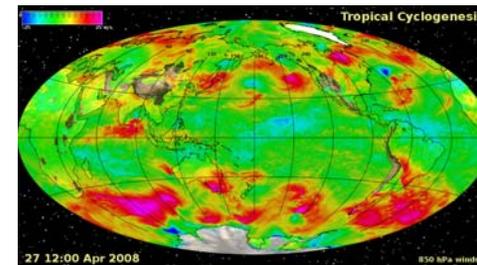


Objectives

CAMVis weather prediction tool is being developed to achieve the following goals by seamlessly integrating NASA technologies (including advanced multiscale modeling visualizations and supercomputing):

- to inter-compare satellite observations (e.g., TRMM precipitation and QuikSCAT winds) and model simulations at fine resolution, aimed at improving understanding of consistency of satellite-derived fields;
- to improve the insightful understanding of the roles of atmospheric moist thermodynamic processes and cloud-radiation-aerosol interactions with high temporal and spatial-resolution 3D visualizations;
- to improve real-time prediction of high-impact tropical weather at different scales.

Project CAMVis has the potential for supporting the following NRC Decadal Survey Earth Science missions: ACE, XOVWM, PATH, SMAP, 3D-Winds.





Highlights of Decadal Survey Missions (recommended by National Research Council)

- **Aerosol -Cloud-Ecosystems Mission (ACE, 2010-2013):** *to reduce uncertainty about climate forcing in aerosol-cloud interactions*
- **Extended Ocean Vector Winds Mission (XOVWM, 2013-2016):** *to further improve hurricane forecasts and warnings (suggested by previous studies with QuikSCAT winds)*
- **ICES at-II Mission (2010-2013):** *to address the contribution of changing terrestrial ice cover to global sea level; thus, to project the effects of sea-level change on growing populations and infrastructure along almost all coastal regions*
- **Precipitation and All-weather Temperature and Humidity (PATH) Mission (2016-2020):** *to provide early identification and reliable forecasting of the track and intensity of tropical cyclones with observations of three-dimensional atmospheric temperature and water vapor, as well as sea surface temperature and precipitation fields under all weather conditions*
- **Soil Moisture Active-Passive Mission (SMAP, 2010-2013):** *to improve flood forecasts and thus improve the capability to protect downstream resources through assimilation of satellite-derived soil moisture that is a key control on evaporation and transpiration at the land atmosphere boundary*
- **3D Tropospheric Winds from Space-based Lidar MISSION (3D-Winds, 2016-2020):** *to provide more accurate, more reliable, and longer-term weather forecasts, which are driven by fundamentally improved tropospheric wind observations from space.*

Project CAMVis information system has the potential for supporting the Decadal Survey Missions, as indicated with underlines. Examples are discussed with QuikSCAT winds and TRMM precipitations in the following.



Scenarios in Decadal Survey

- **Extreme Event Warnings** (near-term goal): Discovering predictive relationships between meteorological and climatological events and less obvious precursor conditions from massive data sets → multiscale interactions; modulations and feedbacks between large/long-term scale and small/short-term scale flows
- **Climate Prediction** (long-term goal): Robust estimates of primary climate forcings for improved climate forecasts, including local predictions of the effects of climate change. Data fusion will enhance exploitation of the complementary Earth Science data products to improve climate model predictions.

Courtesy of the Advanced Data Processing Group,
ESTO AIST PI Workshop Feb 8-11, 2010, Cocoa Beach, FL





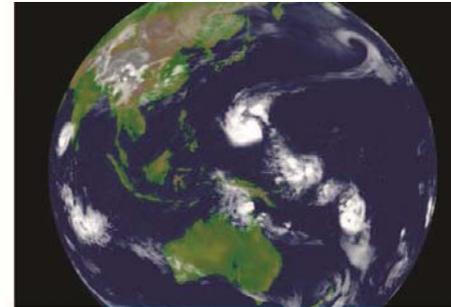
Expectations from the Earth Science Community: Challenges with high-resolution GCMs

- In August 2006, Bo-Wen Shen was featured in Science magazine for the 5-day predictions of Katrina with a high-resolution global model on the NASA Columbia supercomputer. Two other studies by Japanese were also featured in the article. In the last paragraph, the following question was raised: ***“Is new science being produced or just really cool pictures?”***
- In 2011, Richard Anthes of UCAR featured our hurricane simulations prominently in his talk and paper. Then, he raised a visioning question: ***“Beating predictability theory – long-range forecasts of severe weather by 2025?”***

Demons and Butterflies
 Beating predictability theory--long-range forecasts of severe weather by 2025?

Talk to be presented at Harry Otten Symposium on Past and Future of Meteorology Wageningen, Netherlands 13 May 2011

Science, August, 2006, p1040



METEOROLOGY

Sharpening Up Models for a Better View of the Atmosphere

The exponential rise of computing power and the 2002 arrival of the great Earth Simulator computer have driven atmospheric models to extremes

Machines simulating Earth's atmosphere are producing ever-more-detailed pictures of weather and climate, thanks to ever-increasing computer power. And that new detail is now beginning to let researchers shed some of the approximations and downright fabrications they once needed to get anything useful out of their models. The new view of the atmosphere "look[s] very, very different" from that of less detailed model simulations, says modeler Jerry D. Mahlihan of the National Center for Atmospheric Research in Boulder, Colorado. "It's a very important thing to do."

Supercomputers now run at once-undreamed-of speeds—many tens of teraflops (tens of trillions of floating-point operations per second). In weather forecasting models, part of this exponentially improving computing power has always gone into increasing model resolution. Modelers do that by moving the isolated points at which atmospheric properties are calculated—the model's grid points—closer together. It's like a pointillist painter going from big splotches of color to smaller and smaller dots that show greater and greater detail. Global weather forecasting models are down to grid-point spacing of a few tens of kilometers in the horizontal. Climate modelers, in contrast, have favored a spacing of about 200 kilometers, says modeler Kevin Hamilton of the University of Hawaii,

Manoa. That gave them simulations that bore some resemblance to real weather maps but that ran for not just a week but centuries. Then, in 2002, Japanese researchers turned on the 40-teraflops Earth Simulator. "The Japanese had two advantages," says Hamilton. "They were willing to invest an enormous amount of money, on the order of a billion [U.S.] dollars." And they had some very clever engineers figuring out how to build a unique, hybrid supercomputer that efficiently combines the conventional approach of simultaneously running large numbers of cheap processors with processors specially designed to accelerate atmospheric model calculations.

Spared by the Earth Simulator, climate and meteorology researchers in Japan and around the world are pushing the resolution of their global models to new extremes. In a *Geophysical Research Letters* paper published 14 July, modeler Bo-Wen Shen of NASA's Goddard Space Flight Center in Greenbelt, Maryland, and colleagues report how they simulated 5 days in the life of Hurricane Katrina on NASA's newer, 61-teraflops Columbia supercomputer at the Ames Research Center in Mountain View, California. Global models have generally failed to produce intense tropical storms, but when the resolution was dropped from 20 kilometers to 10 kilometers, the simulated Katrina intensified to about the

Sharper still, typhoon Suda (center) looks almost real in this 3.5-kilometer simulation.

same extremely low central pressure as the real Katrina. It had winds nearly as strong spiraling around a suitably compact eye.

Shen and his colleagues then turned off the model's convective parameterization, the part of the model that tells it how, where, and when buoyant air will rise in puffy clouds and thunderheads. Even without that guidance, the simulated storm bore the same strong resemblance to the real thing. Apparently, the higher-resolution model was producing realistic convection—which powers tropical cyclones—all by itself from the smaller details of hurricane workings, without being told what to do.

In another high-resolution tropical cyclone study, reported last April, modeler Kazuyoshi Oouchi of the Earth Simulator Center in Yokohama, Japan, and colleagues simulated 10 years of global tropical cyclone activity both under present conditions and under warmer, greenhouse conditions. On the Earth Simulator, they ran a 20-kilometer-resolution model. Under present conditions, the model produced a reasonable rendition of the number, strength, and geographic distribution of storms. Under greenhouse warmth, the number of tropical cyclones around the world actually decreased 30%, but the number of more intense storms increased substantially. That supports upward trends in storm intensity recently reported from analyses of observations (*Science*, 5 May, p. 676).

Global simulations have driven resolution to even smaller scales. Modeler Hiroaki Muram and colleagues at the Frontier Research Center for Global Change in Yokohama, Japan, have been running a model called NICAM—Nonhydrostatic Icosahedral Atmosphere Model—on the Earth Simulator at resolutions of 7 and 3.5 kilometers. That is nearly fine enough to resolve individual clouds. When run without convective parameterization, the 7-kilometer-resolution version of NICAM showed signs of being less sensitive than a lower-resolution model to rising greenhouse gases.

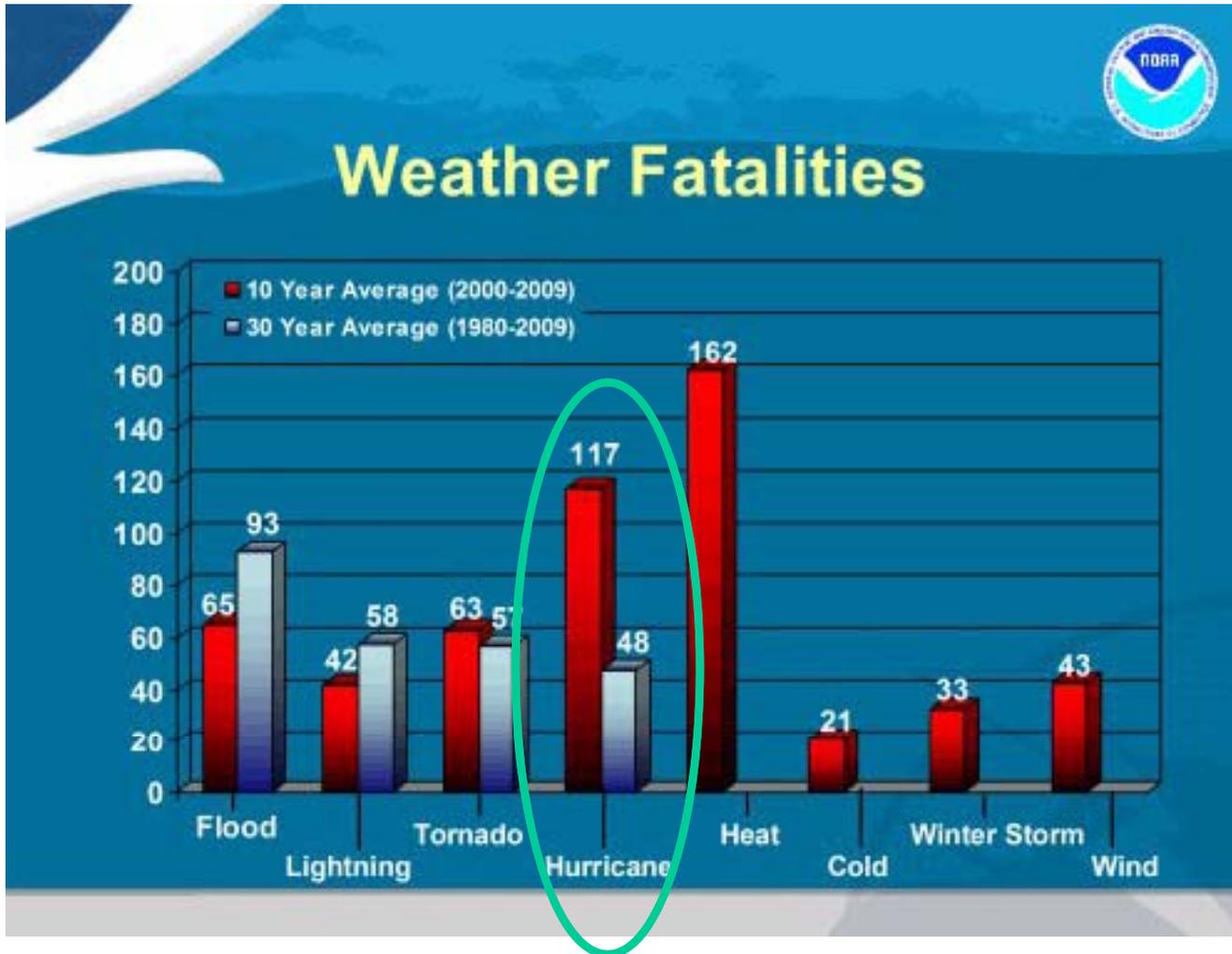
The new high-resolution work is producing intriguing hypotheses, says Mahlihan. But he and others still have reservations. "Is new science being produced or just really cool pictures?" he asks. With some exciting resources growing exponentially and stalling not, he says, computer power might overwhelm the available brainpower. All the more reason to remember that a model—no matter how super—is only a model.

—RICHARD A. KERR





The U.S. Natural Hazard Statistics



<http://www.weather.gov/os/hazstats.shtml>





Scientific Goals

Accurate predictions of tropical cyclone(TC) activity at a large lead time can save lives and reduce economic costs.

To improve our understanding of mesoscale predictability for tropical cyclones (TCs) with the aim of extending the lead time of TC prediction and studying TC climate, experiments in recent papers (Shen et al., 2010a,b,c; 2011) were performed to address the following questions:

- to what extent can large-scale flows determine the timing and location of TC genesis; Predictive relationship; zoomed-out view
- if and how realistically can a high-resolution global model depict those processes. Process studies; zoomed-in view

The CAMVis is developed to show:

(1) downscaling (zoomed-in) processes ----- **reductionism**

(2) scale interaction (zoomed-out) processes ----- **Integrative view/thinking**

with (1) simulated structures of TCs, and (2) nonlinear multiscale interaction of TCs with environmental flows such as tropical easterly waves.



NASA Supercomputing and Visualization Systems



Pleiades Supercomputer (ranked 3rd in late 2008; 6th in June, 2010; 11th in late 2010; 7th in June, 2011)

- R_{\max} of 1,088 teraflops (LINPACK); R_{peak} of 1,315 teraflops
- 111,104 cores in total; Xeon 5472 (Harpertown), Xeon 5570 (Nehalem), Xeon 5670 (Westmere)
- 185 TB memory
- 3.1 PB disk space
- Largest InfiniBand network: 11,648 nodes; Partial 11D hypercube; Direct visualization cluster connections

- 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 to Pleiades
 - 2D torus topology, 32 links to Pleiades
 - 9x2 switches
 - High-bandwidth concurrent visualization





The First Numerical Weather Prediction on ENIAC

- Von Neumann recognized weather forecasting, a problem of both great practical significance and intrinsic scientific interest, as an ideal problem for an automatic computer.
- The invention of the first electronic general-purpose computer **ENIAC** (Electronic Numerical Integrator And Computer) in mid-1940s enabled Charney, Fjortoft, and von Neumann fulfill the dream of Richardson's (1922) on numerical weather prediction (NWP). Four 24-hour forecasts were made, and each 24 hour integration took about 24 hours of computation.

Reference:

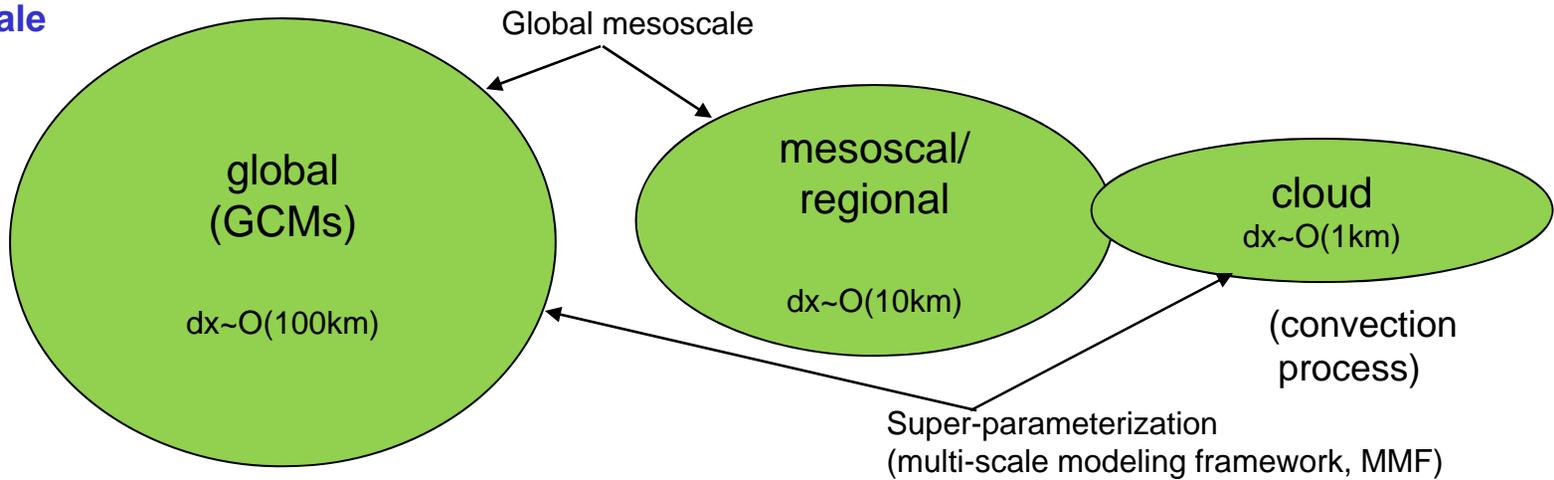
- Charney, J. G., R. Fjortoft, and J. von Neumann, 1950: Numerical Integration of the Barotropic Vorticity Equation. *Tellus*, 2, 237-254.
- *“Even though the advancement of NWP also depends heavily on the arrival of the modern observing system and the complexities of the lately numerical models, the subsequent improvements of NWP have been paced primarily by advances in computer technology.”* by F. G. Shuman, *Weather and Forecasting*, 4, 286-296, 1989.
- In 1994, the NOAA/NCEP was running its GCM at one degree resolution on its C90 supercomputer which has 16 CPUs with a peak performance of 15.3 GFlops. In contrast, three CPUs on Altix (at a speed of 1.5 GHz) could provide a comparable aggregate performance of 18 GFlops, and therefore one 512-CPU Altix node provide computational power 170 times larger than C90.



Multiscale Modeling Approach

To improve the prediction of TC's formation, movement and intensification, we need to improve the model to accurately simulate interactions across a wide range of scales, from the large-scale environment (deterministic), to mesoscale flows, down to convective-scale motions (stochastic).

model scale



physical processes

MJO

Tropical Easterly Waves

vortex merger/ axisymmetrization

CISK/WISHE

scale interaction

modulation

vortex dynamics

feedback

(initial conditions, initialization)

(cps, surface/boundary layer)

CISK: conditional instability of second kind; **CPs:** cumulus parameterizations; **MMF:** multiscale modeling framework;

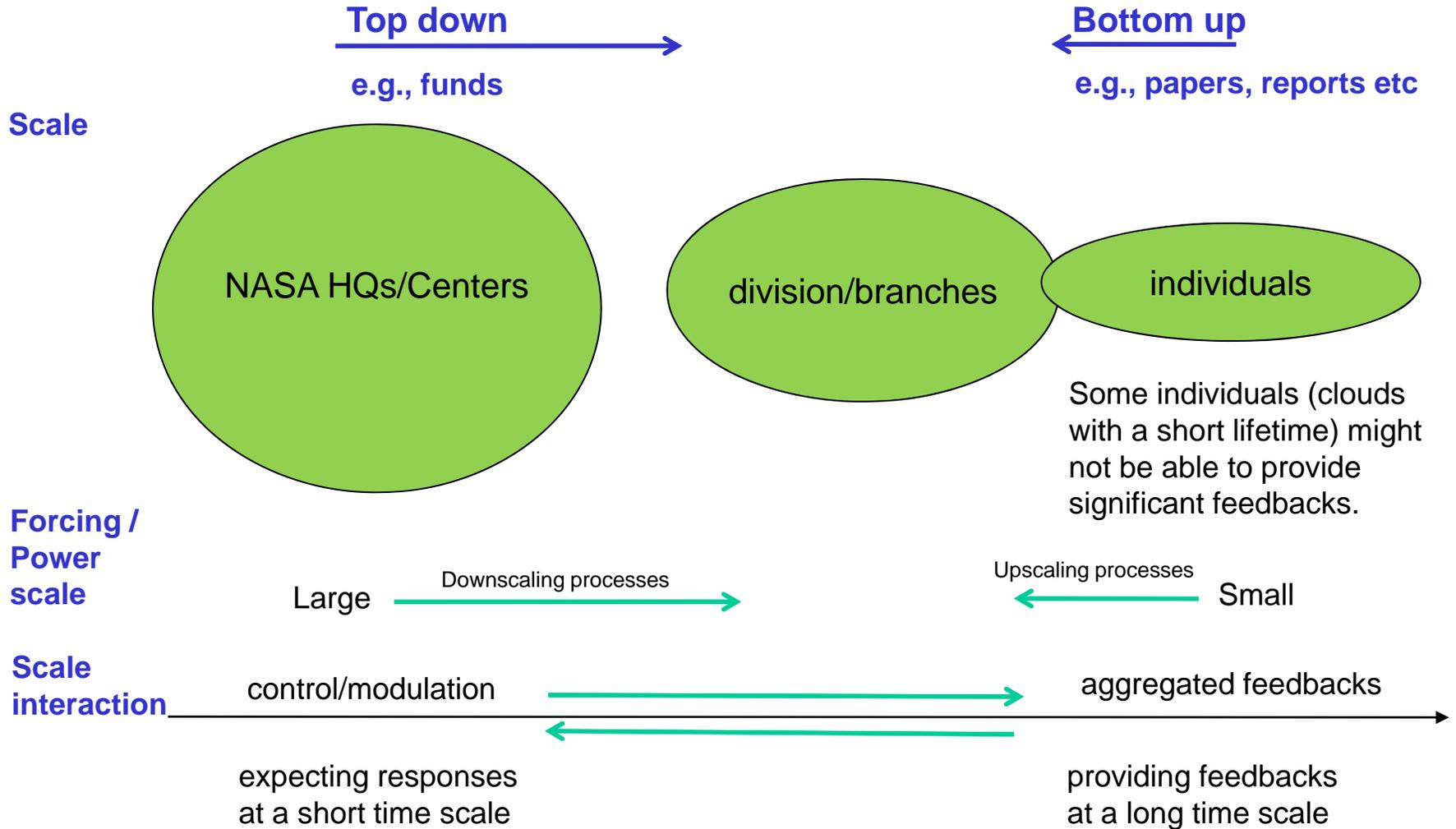
MJO: Madden-Julian Oscillation; **TC:** Tropical Cyclone; **WISHE:** Wind induced surface heat exchange;





Similarity

Is an individual (a cloud) the source of predictability?

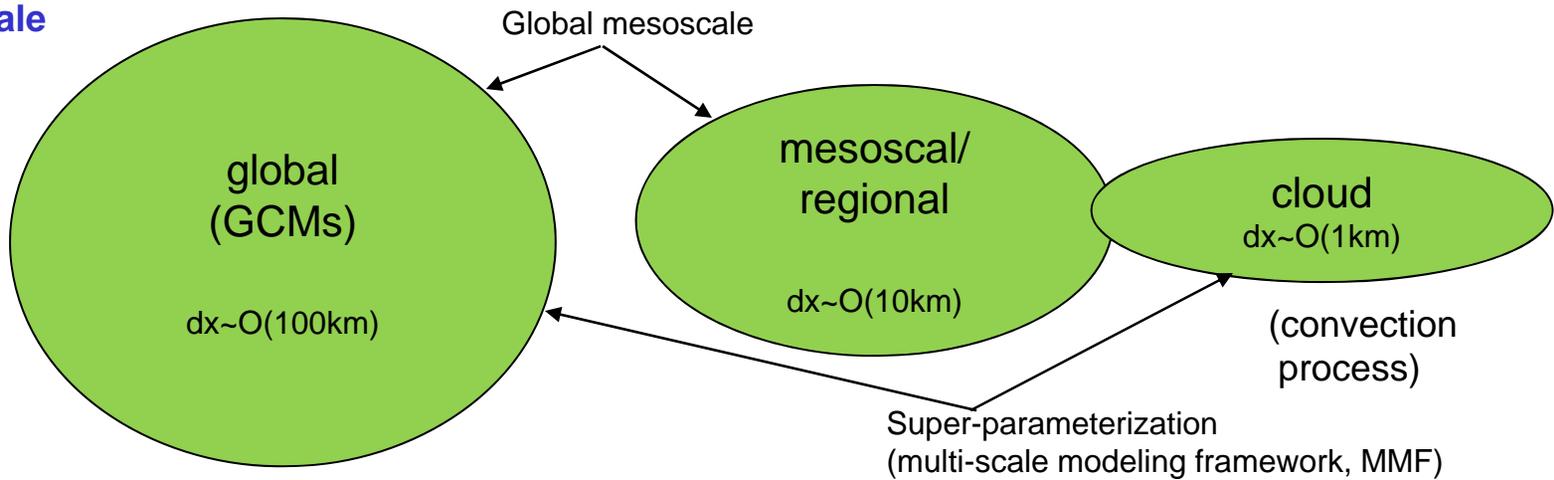




Multiscale Modeling Approach

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scale interaction

modulation (initial conditions, initialization)	vortex dynamics	feedback (cps, surface/boundary layer)
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Challenges

- Satellite Data Challenges:

- o) Massive data storage
- o) Display/visualizations (~TB)

The cloud parameterization problem is ``deadlocked'' in the sense that our rate of progress is unacceptably slow during the past 40 years (Randall et al.,2003)

- Modeling Challenges:

- o) Explicit representation of (the effects of) convective-scale motions
- o) Verification of model simulations at high spatial and temporal resolutions
- o) Understanding and representation of multiscale interactions

- Computational Challenges:

- o) Real-time requirements with supercomputing
- o) Efficient data I/O (at runtime) and data access (via massive storage systems)
- o) Parallel computing and parallel I/O with new processors (e.g., *multi-cores*)
- o) Processing and visualizations of massive data volumes with large-scale multiple-panel display system

Satellite, Numerical Models, and Supercomputing Technology





Concurrent Visualization: Why and How?

1. Large time-varying simulations generate more data than can be saved
 - Problem gets worse as processing power increases
 - Models increase spatial and temporal-resolution
2. Saving data to mass storage consumes a significant portion of runtime
3. Only a small fraction of timesteps are typically saved and important dynamics may be missed

process huge data efficiently

1. Extract data directly from running simulation for asynchronous processing
 - Add instrumentation to the simulation code, usually quite minimal
2. Simultaneously produce a series of visualizations
 - Many fields; • Multiple views
3. Generate and store images, movies, and “extracts”
4. 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
5. Use hyperwall-2 for parallel rendering and asynchronous I/O

generate visualizations while model is still running





Concurrent Visualization: Benefits

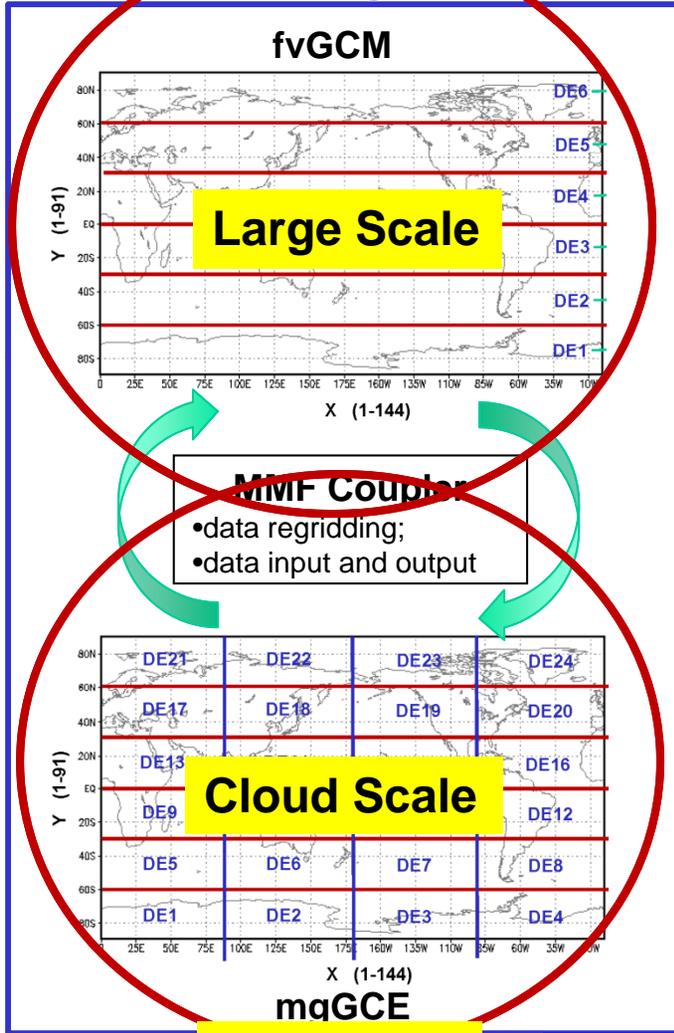
- Higher temporal resolution than post-processing
 - Avoids disk space and write speed limits
 - Output typically 10-1000x greater than standard I/O
- See current state of simulation as its running
 - Application monitoring or steering
 - Detect serious job failures that might otherwise cause waste of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



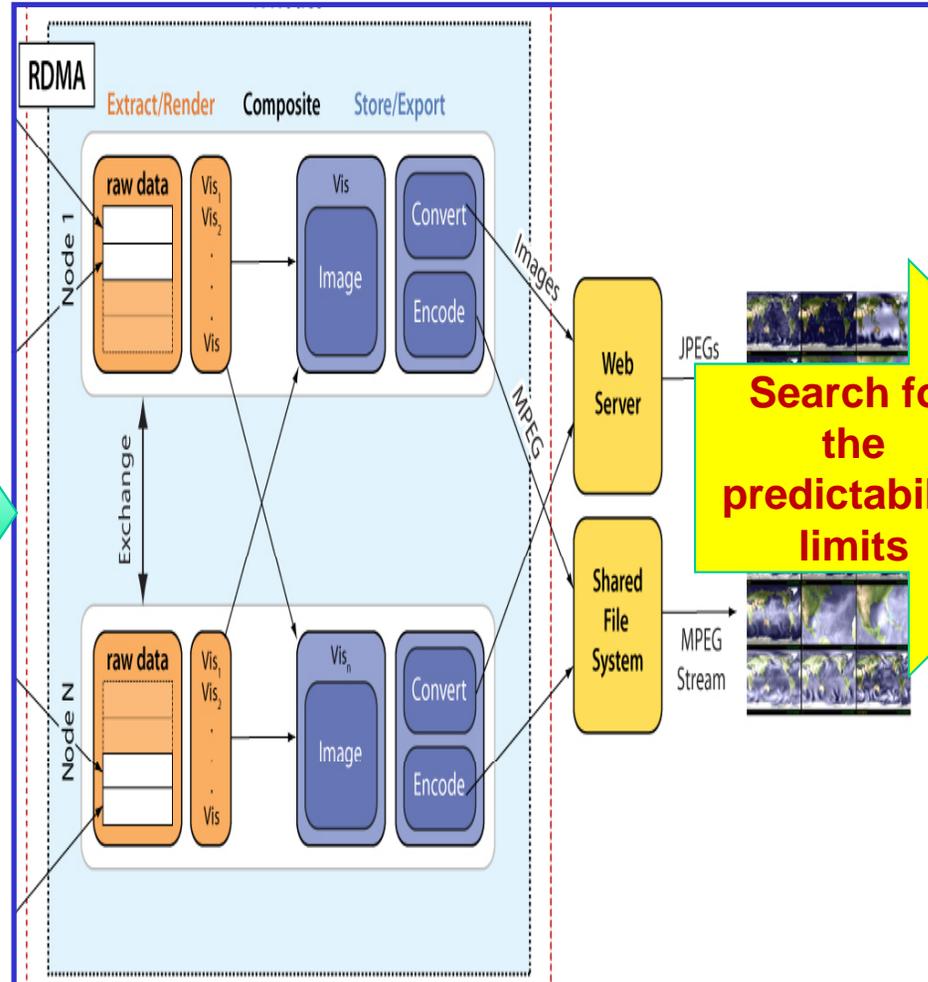
Architecture of the CAMVis v1.0

(the **C**oupled **A**dvanced **M**ultiscale modeling and concurrent **V**isualization systems)

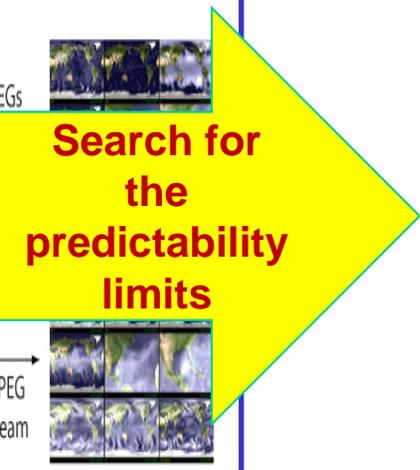
Multi-scale Modeling with "M" nodes



Current Visualization with "N" nodes



Real-time Display



Simulation

Parallel Transfer

Visualization

comparison with satellite

Discovery

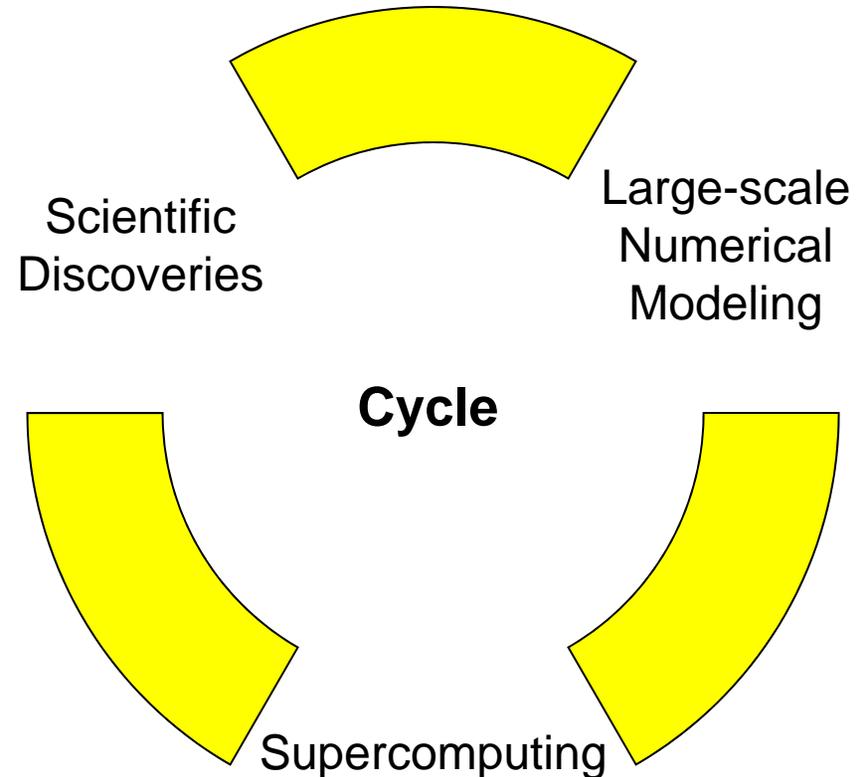




A Science-Driven Approach

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



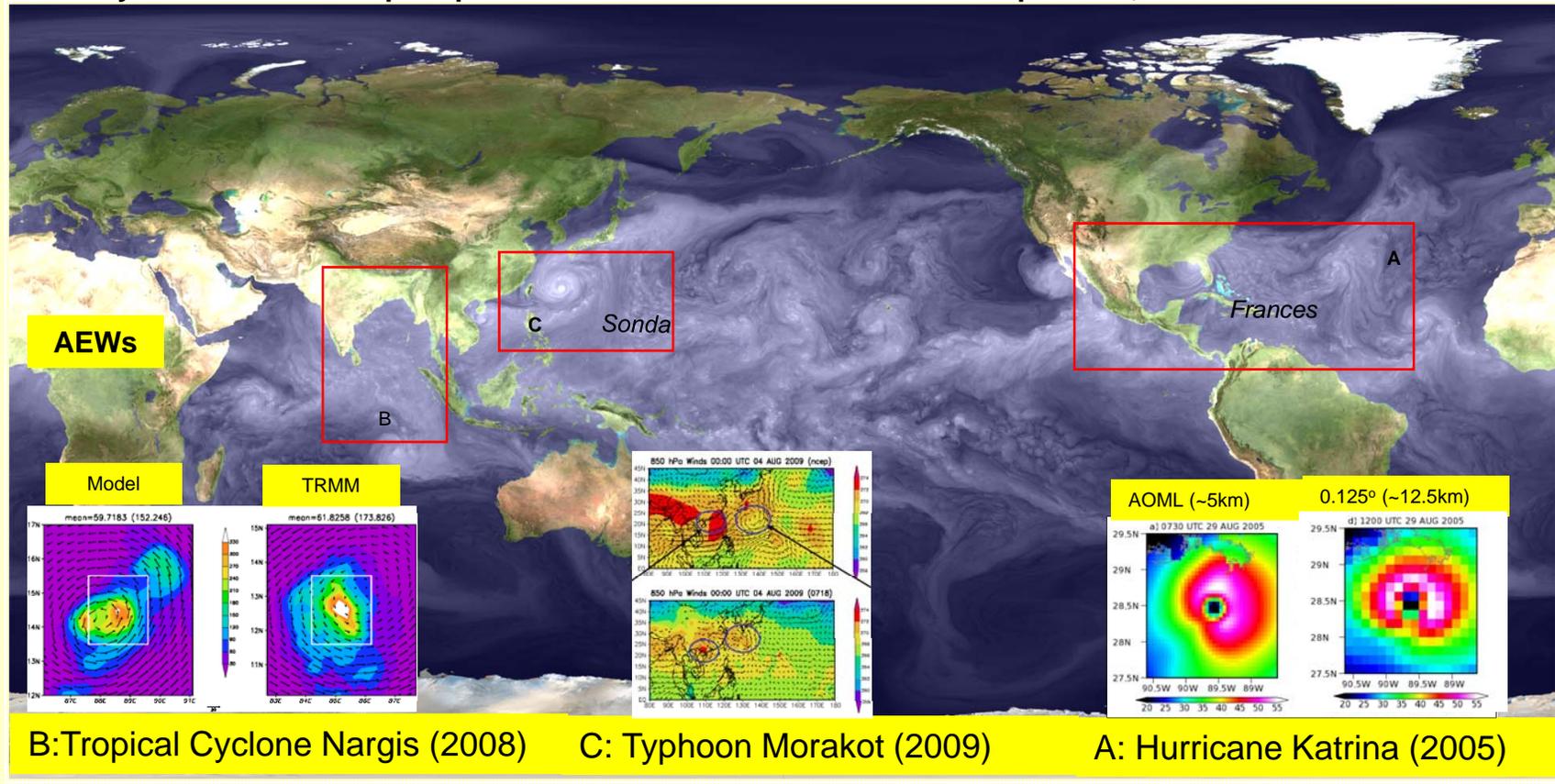
Upscaling to a Mission-Driven Approach





Predicting High-impact Tropical Cyclones with the NASA CAMVis

5-day forecasts of total precipitable water initialized at 0000 UTC 1 September, 2004 with the 1/12° fvGCM



B: Tropical Cyclone Nargis (2008)

- Cat 4, MSLP of 962 hPa
- Deadliest named cyclone in the North Indian Ocean Basin
- damage ~ \$10 billion; fatalities ~ 134,000

C: Typhoon Morakot (2009)

- Cat 2, MSLP of 954 hPa
- Record-breaking rainfall of **2327mm** (accumulated)
- damage ~ \$6.2 billion; fatalities ~ 789

A: Hurricane Katrina (2005)

- Cat 5, MSLP of 902 hPa
- The sixth-strongest Atlantic hurricane ever recorded.
- The third-strongest landfalling U.S. hurricane ever recorded.
- The costliest Atlantic hurricane in history! (\$75 billion)

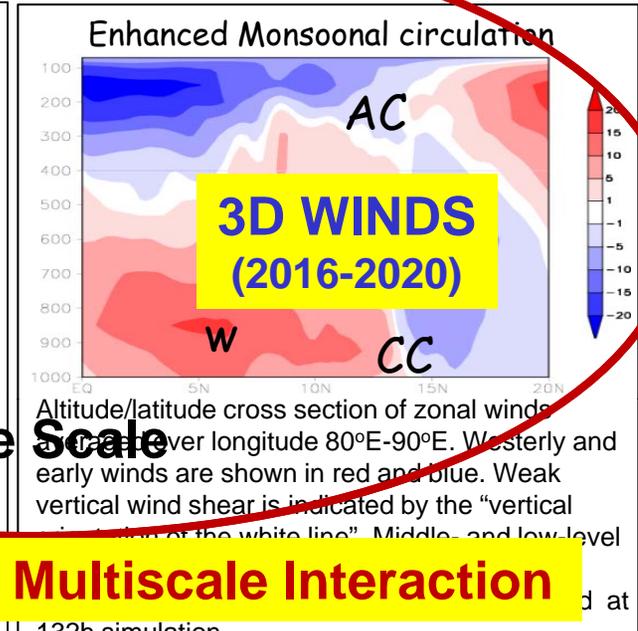
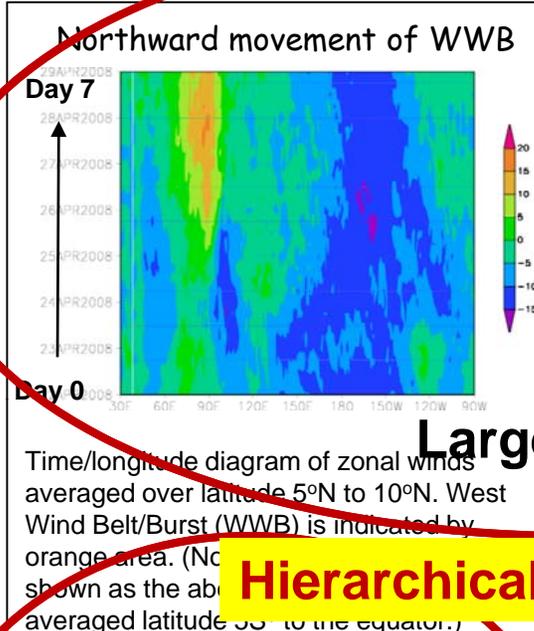
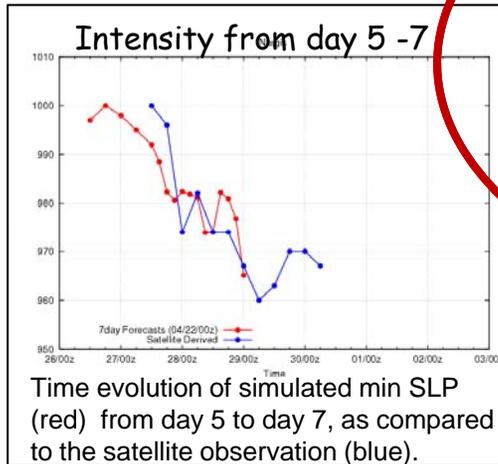




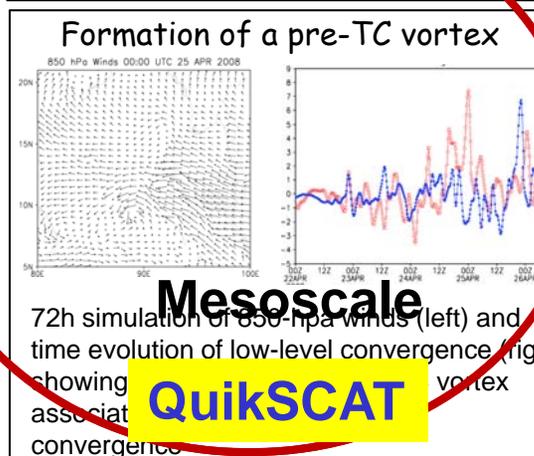
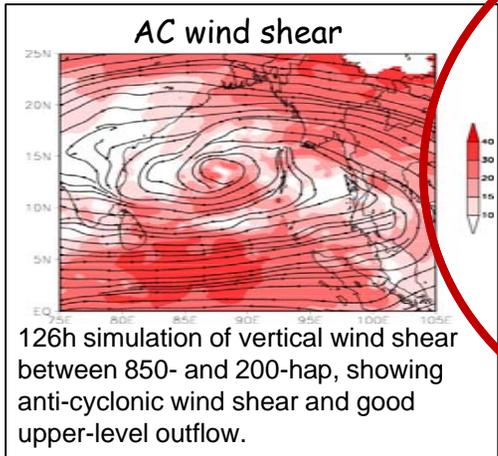
Hierarchical Multiscale interactions of Nargis (2008)

which devastated Burma in May 2008, causing tremendous damage (~\$10 billion) and numerous fatalities (~150,000 deaths),

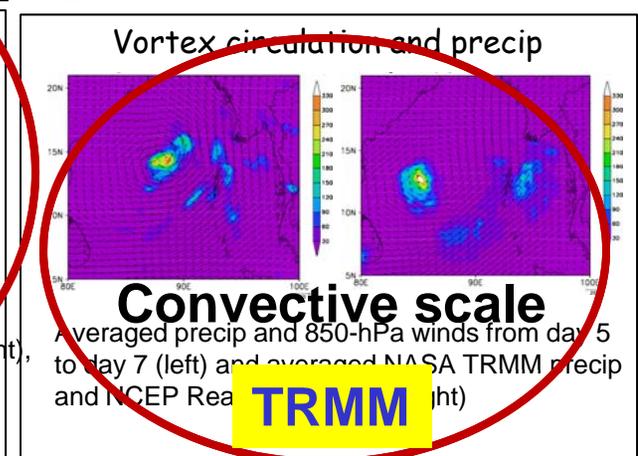
7-day global multiscale simulations suggest the following favorite factors for the formation and initial intensification of tropical cyclone Nargis:



Hierarchical Multiscale Interaction



Mesoscale
QuikSCAT

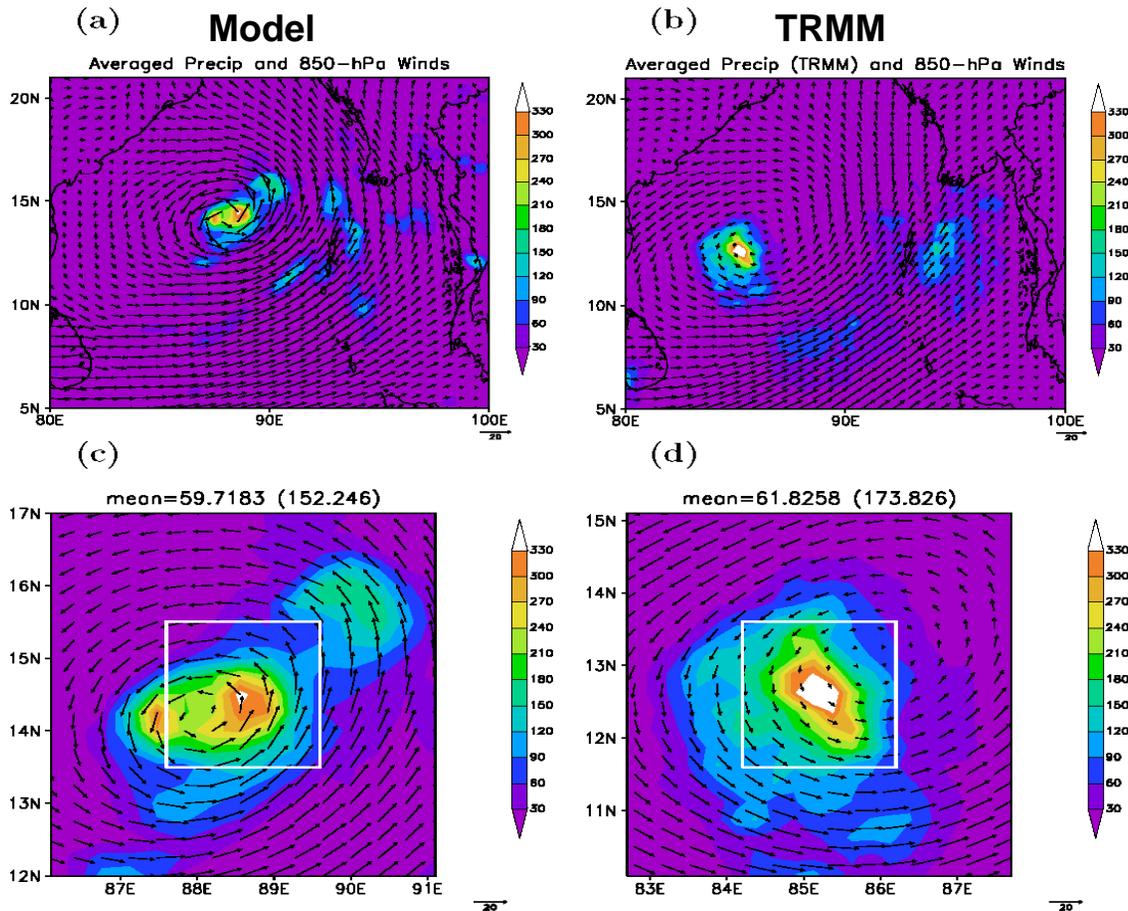


Convective scale
TRMM





Averaged precipitation and wind vectors for Nargis



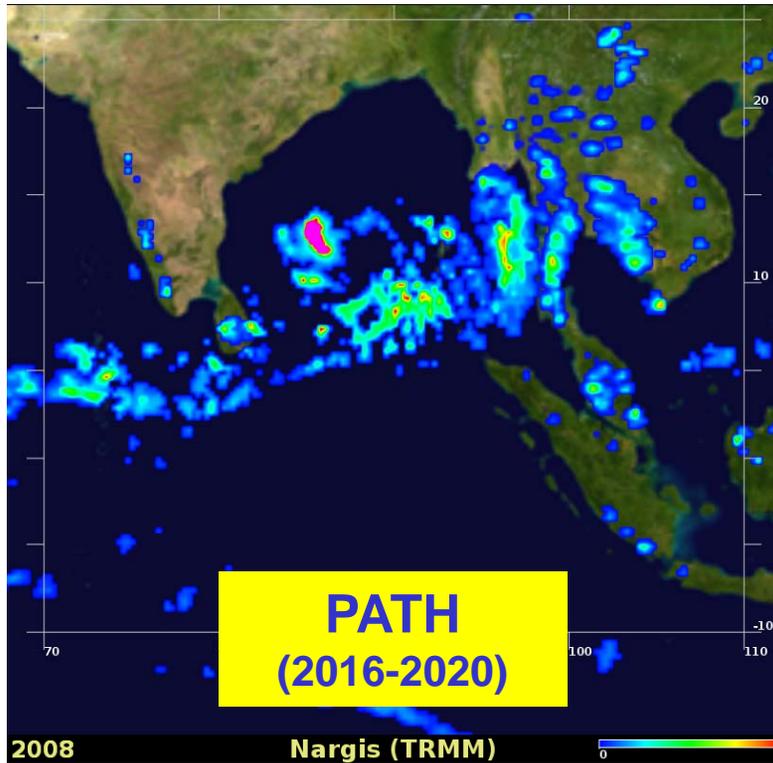
The domain-averaged precipitation in the 5° (2°) box is 59.7 (152.2) mm/day for the model and 61.8 (173.8) mm/day for TRMM. **This indicates an underestimate of 3.4% (12.4%) in the 5° (2°) average precipitation** by the model with a larger discrepancy for 2° average precipitation. This indicates the difficulty in automatically selecting a sample domain size, because an accurate assessment of the simulated precipitation associated with the vortex, including its location and scale, is important for quantitative comparison.

Averaged precipitation and wind vectors. (a) The 2-day average precipitation (shaded) and 850-hPa winds (vectors) from 0000 UTC April 27 (day 5) to 29 (day 7) and (b) NASA TRMM precipitation and NCEP analysis winds. (c, d) The same fields as Figures 10a and 10b, respectively, in a 5° box, centered at the maximum of precipitation near the vortex center.

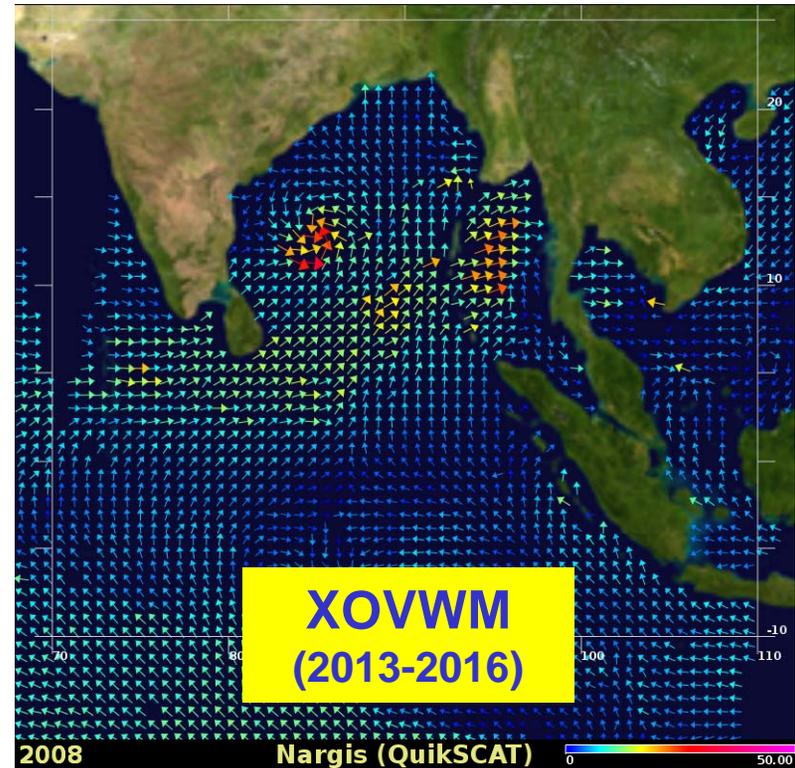


“Fusion” of TRMM and QuikSCAT Data into CAMVis

1500 UTC April 27 2008



1200 UTC April 28 2008



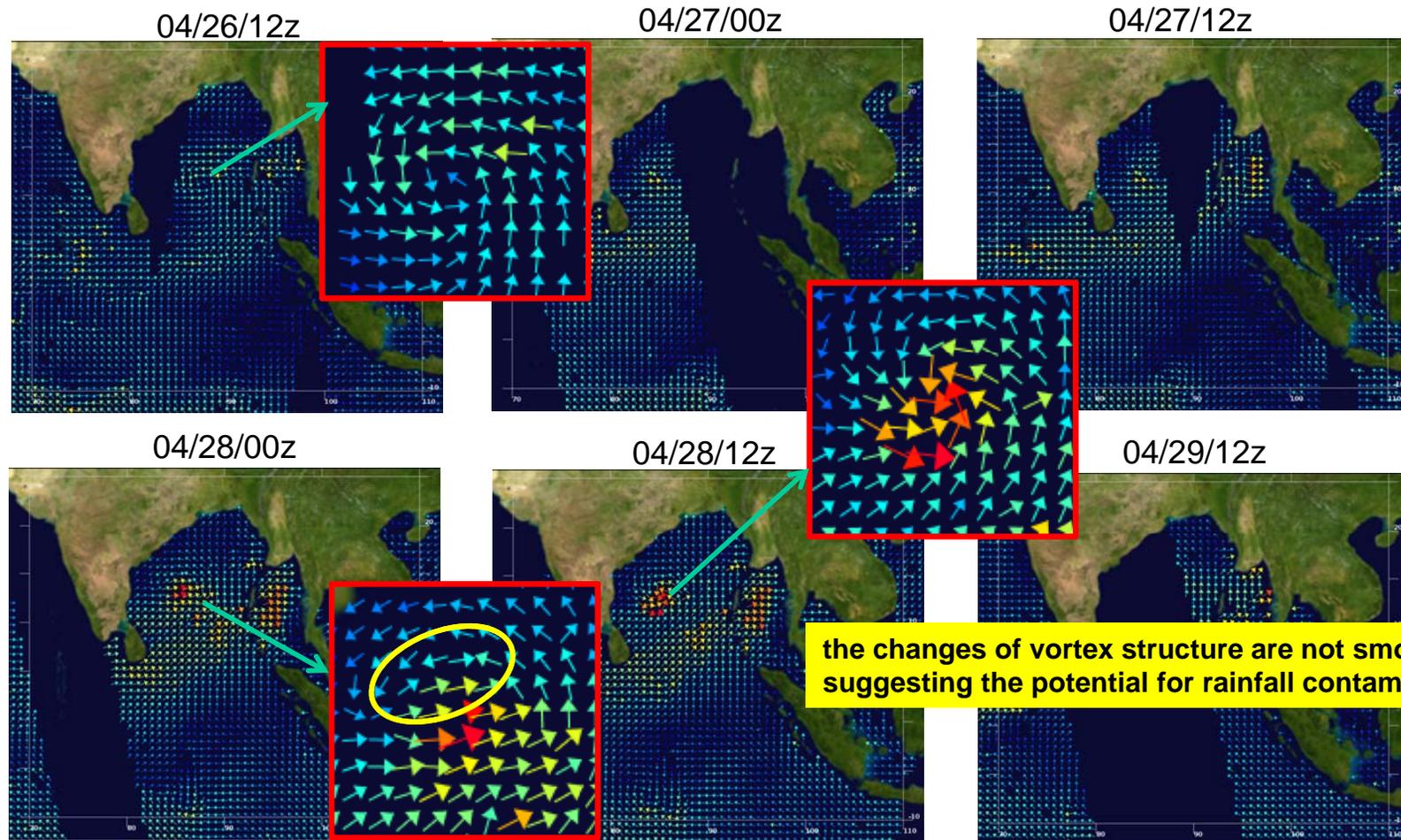
Initial implementation of a visualization module into the CAMVis information system, including data convert and vector plotter for TRMM satellite-derived precipitation (left panel) and QuikSCAT winds (right panel), respectively. These figures show the TC Nargis (2008).

Shen, B.-W., W.-K. Tao, and B. Green, 2010c: Coupling NASA Advanced Multi-Scale Modeling and Concurrent Visualization Systems for Improving Predictions of Tropical High-Impact Weather (CAMVis). Computing in Science and Engineering, 23 Nov. 2010. IEEE computer Society Digital Library. IEEE Computer Society, <http://doi.ieeecomputersociety.org/10.1109/MCSE.2010.141> (impact factor 0.973)





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.





Nargis (2008) and an Equatorial Rossby Wave

Very severe cyclonic storm Nargis devastated Burma (Myanmar) in May 2008, caused tremendous damage (~\$10 billion) and numerous fatalities (~130,000 deaths), and became one of the 10 deadliest tropical cyclones (TCs) of all time. To increase the warning time in order to save lives and reduce economic damage, it is important to extend the lead time in the prediction of TCs like Nargis. Seven-day high-resolution global simulations with real data show that the initial formation and intensity variations of TC Nargis can be realistically predicted up to 5 days in advance (bottom). Preliminary analysis (slide 7) suggests that improved representations of the following environmental conditions and their hierarchical multiscale interactions were the key to achieving this lead time: (1) a westerly wind burst and equatorial trough, (2) an enhanced monsoon circulation with a zero wind shear line, (3) good upper-level outflow with anti-cyclonic wind shear between 200 and 850 hPa, and (4) low-level moisture convergence.

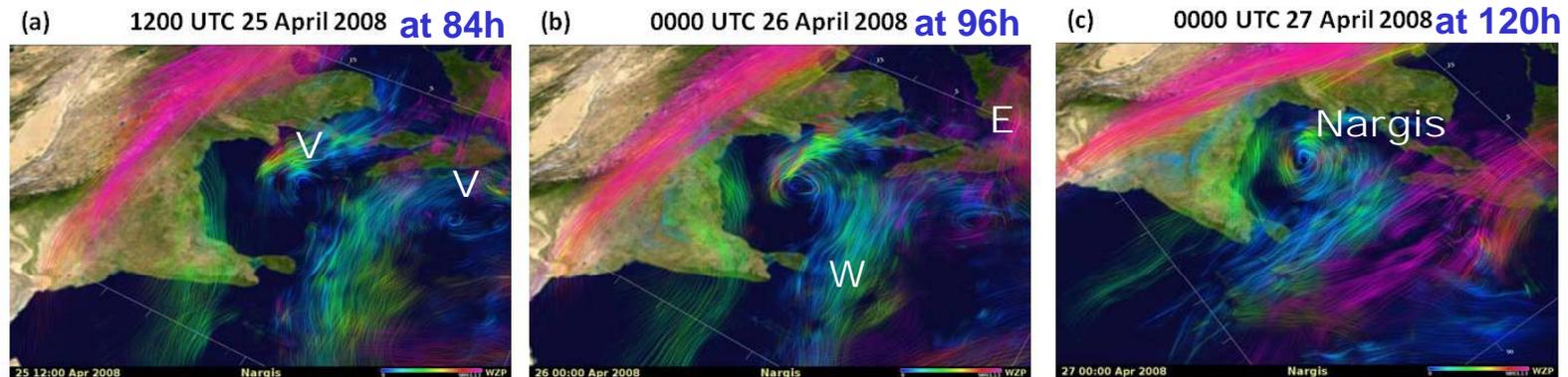


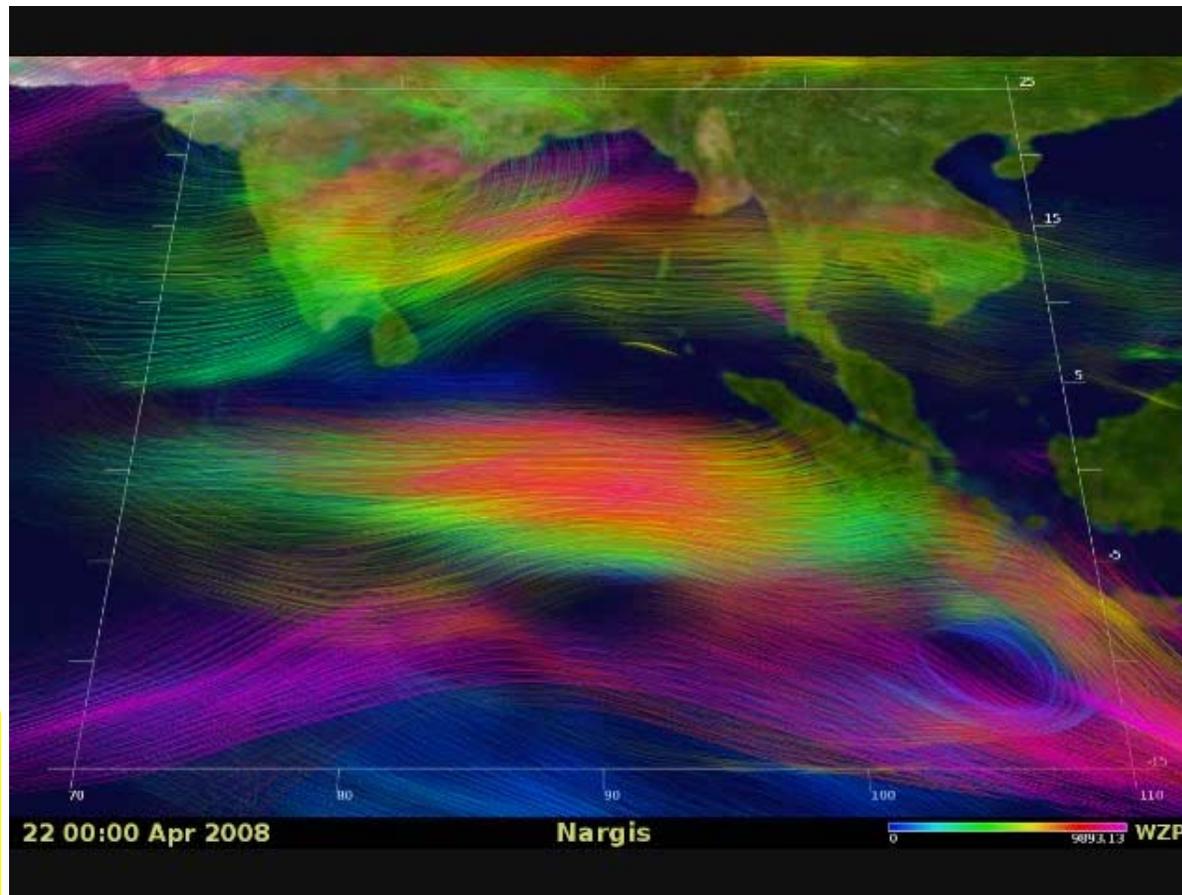
Figure: Realistic 7-day simulations of the formation and initial intensification of TC Nargis (2008) initialized at 0000 UTC April 22, 2008, showing streamlines at different levels. Low-level winds are in blue and upper-level winds in red: (a) formation of a pair of low-level mesoscale vortices (labeled in 'V') at 84h simulation, which are associated with an equatorial Rossby wave; (b) intensification of the northern vortex (to the left); (c) formation of TC Nargis associated with the enhancement of the northern vortex. 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).



7-day Forecast of Genesis of Cyclone Nargis (2008) 00 UTC 22 Apr-00UTC 29 Apr

An Integrative view with advanced global modeling, supercomputing, and visualization technologies

- Upper-level winds in red
- Low-level winds in blue



fusion of satellite data;
the search for
predictive index

Bo-Wen Shen et al., JGR, 115, D14102, doi:10.1029/2009JD013140, 2010

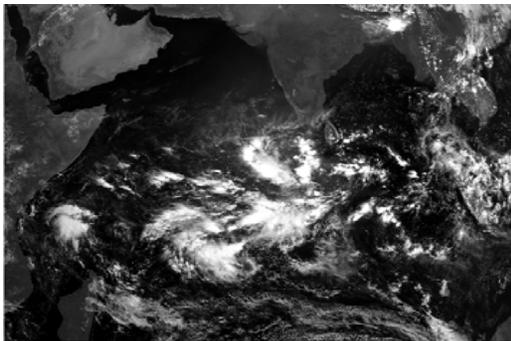




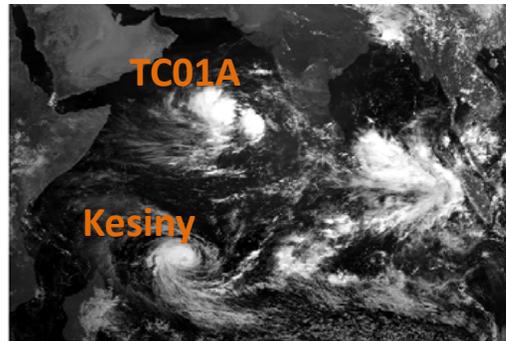
Twin Tropical Cyclones and an MJO in May 2002

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. Multiscale Interactions between a mixed Rossby gravity wave and the twin TC are shown in slide 9.

0630 UTC 1 May 2002



0000 UTC 6 May 2002



0000 UTC 9 May 2002

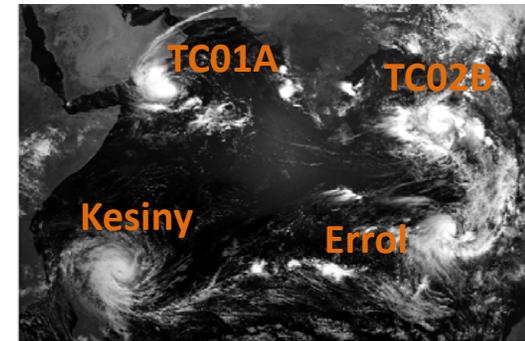


Figure: Predictions regarding the formation of twin tropical cyclones in the Indian Ocean: (a) MJO-organized convection over the Indian Ocean at 0630 UTC 1 May 2002. When the MJO moved eastward, two pairs of twin TCs appeared sequentially on 6 May (b) and 9 May (c), including TC 01A, Kesiny, TC 02B and Errol. Two TCs (01A and 02B) with anti-clockwise circulation appeared in the Northern Hemisphere, while the other 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., 2010c and 2011 for details).



Shen, B.-W., W.-K. Tao, et al. 2011: Forecasting Tropical Cyclogenesis with a Global Mesoscale Model: Preliminary Results for Twin Tropical Cyclones in May 2002. (to be submitted)



Brief Summary

Scenarios	Current Progress and Challenges	CAMVis Current Capabilities (as of February, 2011)
Real-time global multiscale modeling of hurricane or tropical cyclones (TCs)	limited scalability and significant I/O overheads	a revised parallelism for improving scalability (up to 364 CPUs with a speedup of 12 as compared to an earlier version); implementation of concurrent visualization to significantly reduce I/O overheads and thus enable high temporal-resolution (~7-15 minutes) global simulations
TC track forecast	steadily improving with a lead time of up to 96 hours during the past 20 years; as of 2008 and 2009, the 120h track errors of about 200 and 290 knots (~370 and 537 km) in Atlantic basin, respectively; still very challenging in other basins	remarkable 5-day forecasts of intense hurricanes in 2004 and 2005. e.g., a 5-day Katrina track error of 320 km with timing and location errors of 6h and 30km at landfall, respectively; a 7-day track error of 250km for the Nargis; thirteen 5-day forecasts of Hurricane Ivan (2004), giving an average error of about 280km at 120h predictions.
TC intensity forecast	progress being slow during the past twenty years, mainly because of the nature of multiscale interactions in TC dynamics	realistic 5-day intensity forecasts in limited number of cases (e.g., Ivan, 2004; six Katrina forecasts of the center pressure with errors of only ± 12 hPa
TC formation forecast	experimental with a lead time of 48 hours at some operational centers (no official forecasts for the location and subsequent path)	realistic formation forecasts for twin TC (2002) 3~5 days in advance; for Nargis (2008) 5 days in advance; for hurricane Helene (2006) 22 days in advance
AEW forecast	"experimental" at some sites	realistic predictions of formation for multiple AEWs in two 30-day runs in 2004 and 2006, respectively



Why Predictable?

Anthes, R., 2011: "Turning the Tables on Chaos: Is the atmosphere more predictable than we assume?"

Anthes (2011, UCAR Magazine) discussed **predictability**, the foundation of predictions, as follows:

- Gottfried Leibniz (1646-1716), Pierre-Simon Laplace (1749-1827) and others: the future is predictable -- **deterministic predictability**
- Lorenz (1917-2008): perfect deterministic forecasts of weather were impossible --- "**chaos theory**", which is one of the three great scientific revolutions of the 20th century.
- In the early 1960s, J. Charney, C. Leith, Y. Mintz, and J. Smagorinsky suggested that the limit to useful deterministic predictions of large scale (synoptic) atmospheric motion was about two weeks. --- **practical predictability**
- Conducting simulations with his high-resolution regional model in 1980s, Anthes hypothesized that mesoscale features might be predictable one to three days in advance if synoptic-scale features could be accurately modeled. --- **mesoscale predictability**
- He illustrated recent amazing mesoscale predictions:
 1. Morris Weisman et al. (2011) describe a successful forecast of a mesoscale vortex with a derecho, a **extended mesoscale predictability**
 2. Shen et al. (2010a) reported a successful 7-day prediction of TC Nargis formation in the Indian Ocean;
 3. Shen et al. (2011) reported a successful 10-day prediction of twin TC formation and movement in the Indian Ocean;
 4. Shen et al. (2010b) reported a successful 4-week prediction for the initiation of multiple AEWs and formation of Hurricane Helene in the Atlantic.



An African wave forming to the lee of the Ethiopian Highlands might well portend a hurricane threatening the Texas coast two weeks later—butterflies or no butterflies



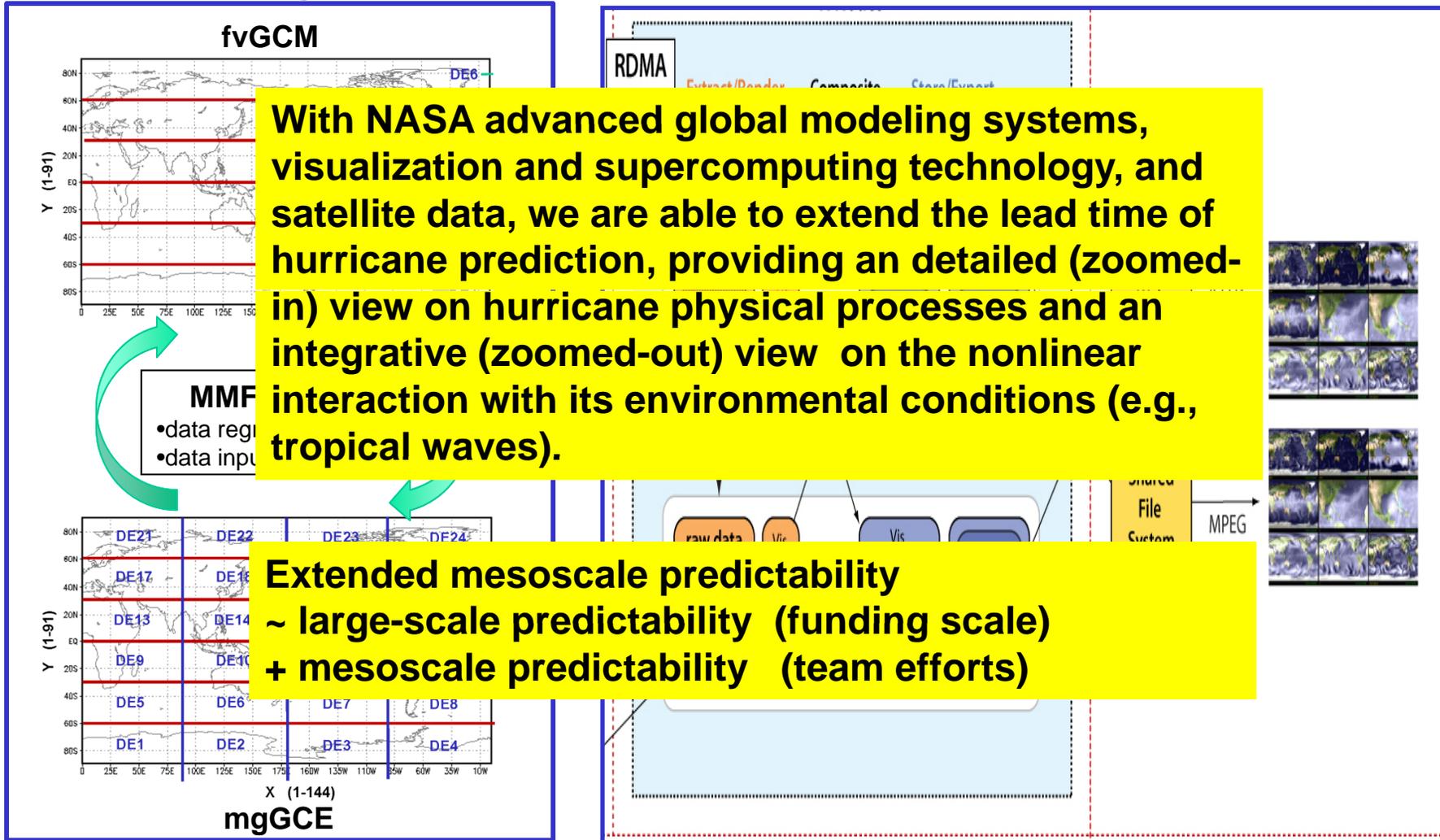


Concluding Remarks

Multi-scale Modeling with "M" nodes

Current Visualization with "N" nodes

Real-time Display



Simulation

Extraction

Visualization

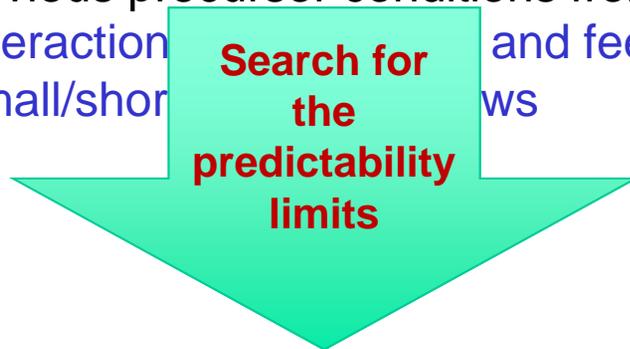
MPEG generation





Scenarios in Decadal Survey

- **Extreme Event Warnings** (near-term goal): Discovering predictive relationships between meteorological and climatological events and less obvious precursor conditions from massive data sets → multiscale interaction and feedbacks between large/long-term scale and small/short-term scale

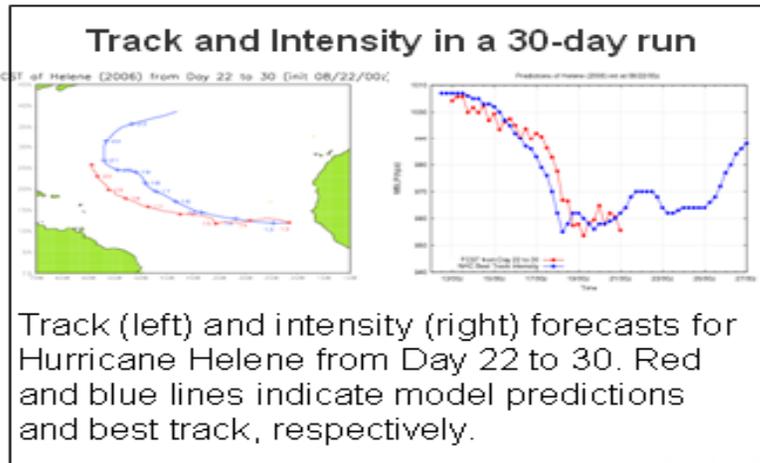


- **Climate Prediction** (long-term goal): Robust estimates of primary climate forcings for improved climate forecasts, including local predictions of the effects of climate change. Data fusion will enhance exploitation of the complementary Earth Science data products to improve climate model predictions.

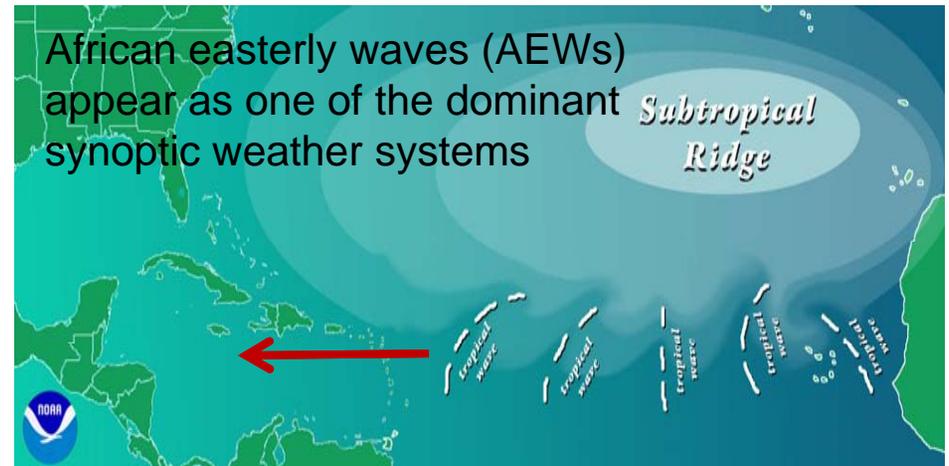
We are building a very complicated information system (with 1.1 FTEs) for a simple view on physical processes and a profound answer to the the fundamental but challenging predictability problem.



Search for the Limits of Mesoscale Predictability: Discovering the Predictive Relationship during the Nonlinear Multiscale Interactions with HHT



Shen et al, 2010, *Geophys. Res. Lett.*, L18803.



Contributed by Chris Landsea, <http://www.aoml.noaa.gov/hrd/tcfaq/A4.html>

To extend the lead time of formation prediction for this type of hurricane, it is important to predict the **nonlinear** interactions of a **non-stationary** AEW with its environments. We propose to (1) simulate these multiscale interactions and (2) visualize the complicated physical processes with the CAMVis, and then to (3) extend the HHT from 1D to 2D and apply it to develop an index to quantitatively examine the predictive relationship between AEW's activities and TC formation and understand the role of soil moistures on these simulations.

Proposal in Preparation: Impacts of soil moistures, SMAP, 2010-2013

Improving Tropical Cyclone Predictions using the Hilbert-Huang Transform (HHT) Algorithm and Global Modeling Systems: the search of predictability limits





Conclusion: mesoscale predictability

To extend the lead time of TC prediction, we investigate the multiscale interactions of tropical waves and TC formation, including: (a) very severe cyclonic storm Nargis (2008) and its association with an Equatorial Rossby wave; (b) twin TCs in May 2002 and their association with a mixed Rossby gravity wave; and (c) Hurricane Helene (2006) and its association with an AEW. It is found that TC formation can be realistically with a lead time of 5 days and 3~5 days in cases (a) and (b), respectively. Of interest is the potential to extend the lead time for predicting the formation of Helene (e.g., a lead time of up to 22 days) as the 4th AEW is re

Extended mesoscale predictability

~ large-scale predictability (funding scale)

+ mesoscale predictability (team efforts)

Nearly 25 years ago, Dr. Anthes developed a global mesoscale model, and he has worked with a

- *the development of mesoscale weather systems may be classified as occurring through one or both of two mechanisms: (i) forcing on the mesoscale from inhomogeneities at the earth's surface and (ii) internal modifications of large-scale flow patterns that lead to smaller-scale circulations.*

He then made the following hypotheses on the mesoscale predictability:

- *an accurate specification of large-scale thermodynamic and momentum fields, together with realistic physical forcing at the surface, adequate representation of diabatic effects in the free atmosphere, and the appropriate resolution, may be sufficient to predict the evolution of some mesoscale systems for hours or even a few days in advance of their development; and*
- *when there are no strong mesoscale circulations present initially, it may be unnecessary to observe and analyze mesoscale detail for the model's initial conditions.*

Our case studies enabled by the global mesoscale model and supercomputing technology seem to support the above hypotheses by Dr. Anthes. However, much work is still required to assure the model's consistent performance. In addition, as the mesoscale predictability (of TCs) is dependent of the representation of the large-scale flows, we will examine the extended-range (~15-30 days) simulations of large-scale flows such as AEWs and MJOs (e.g., slide 11) in order to extend the lead time of TC predictions.





Highlights of Research Papers

A series of papers (Shen et al., 2010a,b,c; Shen et al., 2011a,b) which have been published or are being prepared show that the lead time of TC formation prediction can be extended by improving the simulation of large-scale tropical waves and their multiscale interactions using the NASA high-resolution global modeling and supercomputing technologies. Examples include

- [Twin tropical cyclones in May 2002 and their association with a mixed Rossby gravity wave](#) (Shen et al., 2011a)
- [Very severe cyclonic storm Nargis \(2008\) and its association with an Equatorial Rossby wave](#) (Shen et al., 2010a,c);
- [Hurricane Helene \(2006\) and its association with an African Easterly wave](#) (Shen et al., 2010b);
- [Typhoon Morakot \(2009\) and monsoon circulations](#) (Shen et al., 2011b)

To verify model's performance, NASA observations from field campaign (such as NAMMA) and satellites at comparable resolutions (e.g., QuikSCAT and TRMM) are used for inter-comparisons (Shen et al., 2010a,b,c,d).



Acknowledgements:

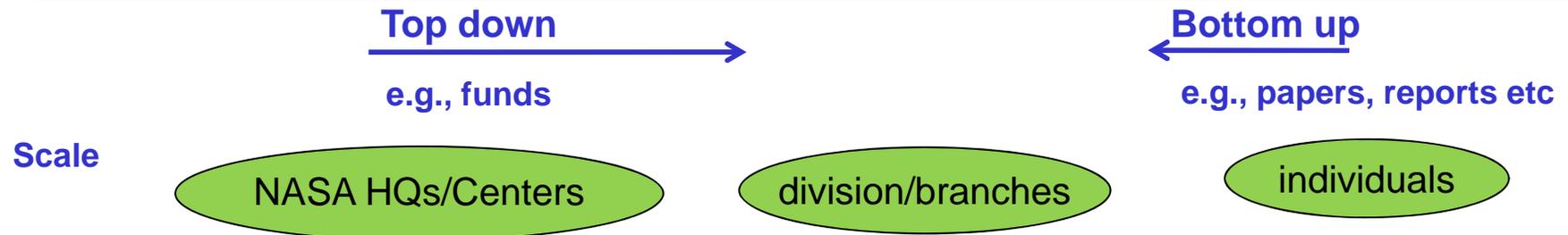
We are grateful for the following organizations for supporting this study: NASA ESTO; AIST Program; MAP Program; NEWS, NSF STC, the NASA HEC Program and NAS.

Selected References:

- Anthes, R., 2009: A Note on “*Summary of Predictability Papers*”.
- Shen, B.-W., W.-K. Tao, W. K. Lau, R. Atlas, 2010a: Predicting Tropical Cyclogenesis with a Global Mesoscale Model: Hierarchical Multiscale Interactions During the Formation of Tropical Cyclone Nargis (2008) . J. Geophys. Res., 115, D14102, doi:10.1029/2009JD013140.
- Shen, B.-W., W.-K. Tao, and M.-L. C. Wu, 2010b: African Easterly Waves in 30-day High-resolution Global Simulations: A Case Study during the 2006 NAMMA Period. Geophys. Res. Lett., L18803, doi:10.1029/2010GL044355.
- Shen, B.-W., W.-K. Tao, and B. Green, 2010c: Coupling NASA Advanced Multi-Scale Modeling and Concurrent Visualization Systems for Improving Predictions of Tropical High-Impact Weather (CAMVis). Computing in Science and Engineering, 23 Nov. 2010. IEEE computer Society Digital Library. IEEE Computer Society.
- Shen, B.-W., W.-K. Tao et al., 2010d: Genesis of Twin Tropical Cyclones Revealed by a Global Mesoscale Model: the Role of Mixed Rossby Gravity Wave (to be submitted)
- Tao, W.-K., J. Chern, et al, 2009: Multi-scale modeling system: Development, applications and critical issues, *Bull. Amer. Meteor. Soc.*



Potential Impacts on Modeling and DAS from Project CAMVis



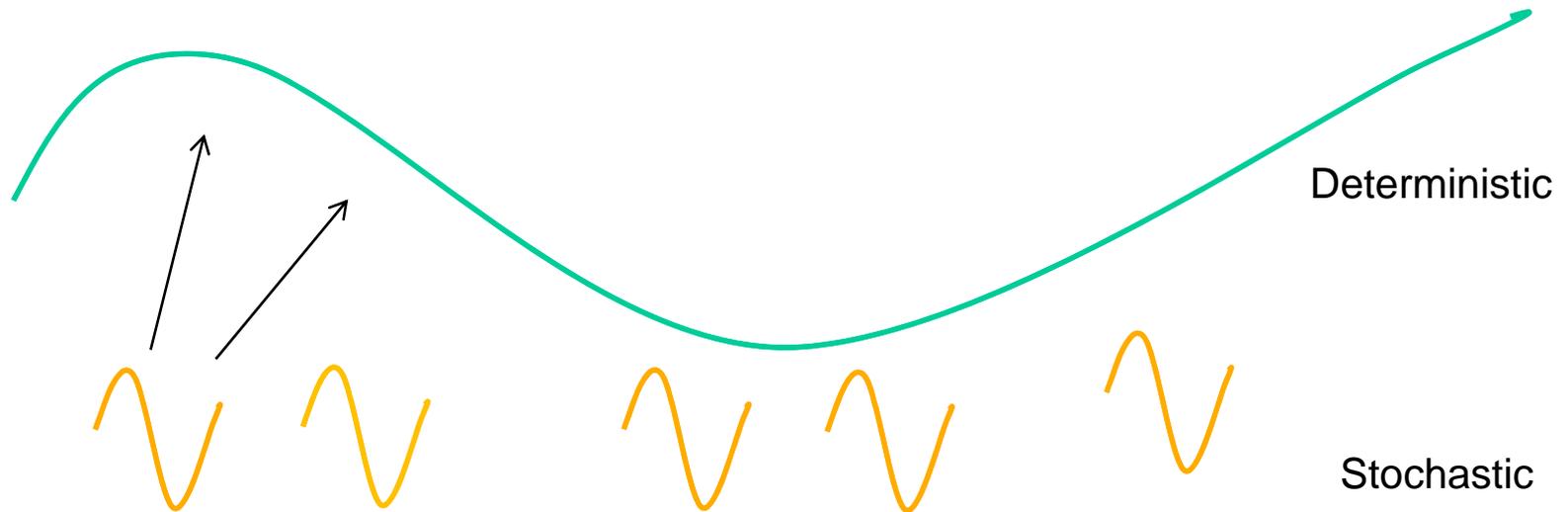
- 1) *Predictability at a smaller scale may depend on that at a larger-scale. Namely, when there are no strong mesoscale circulations present initially, it may be unnecessary to observe and analyze mesoscale detail for the model's initial conditions.*
- 2) *Predictability at a smaller scale is usually shorter. Namely, its initial errors will grow faster, thus contaminating the entire simulations. It is important to understand and simulate the modulation of smaller-scale flows by the larger-scale flows, thus limiting or constraining the growth of the errors associated with smaller-scale flows.*
- 3) *High-resolution dynamical processes might provide constraints on the error growth at smaller-scales, via non-linear interaction processes which generate much smaller-scale dissipated turbulence.*
- 4) *However, column-based physics parameterizations (PPs) might create unexpected (unintuitive) problems. These PPs are applied at each of grid points and thus loosely/indirectly inter-connected via dynamical processes. Thus, as a solution is increasing, # of grid points is increasing and the “freedoms “ associated with PPs increase rapidly. → it requires additional treatments.*
- 5) *In addition, most of PPs are asymptotic, but not analytic, suggesting that solutions do not converge with an increasing resolution. Most of them were tested with imposed large-scale conditions, namely with only one-way interaction. Thus, their performance in a two-way interaction environment requires more studies. Some of them (e.g., cloud processes related) were tested with an boundary value problem approach but not rigorously tested with an initial value problem approach (inclusive of a life cycle) . Thus, their performance on the simulation of non-stationary (moving) systems at a different stage of a life cycle and/or at different time scales is less known.*



-
- Q1: how to manage the increasing number of copies of PPs efficiently and their aggregated feedbacks to the (meso-scale) weather events globally;
 - Similarly, how to manage the increasing number of individuals (downscaling) and assure the aggregated feedbacks of individuals to the goals of divisions, center and/or HQs (upscaling).



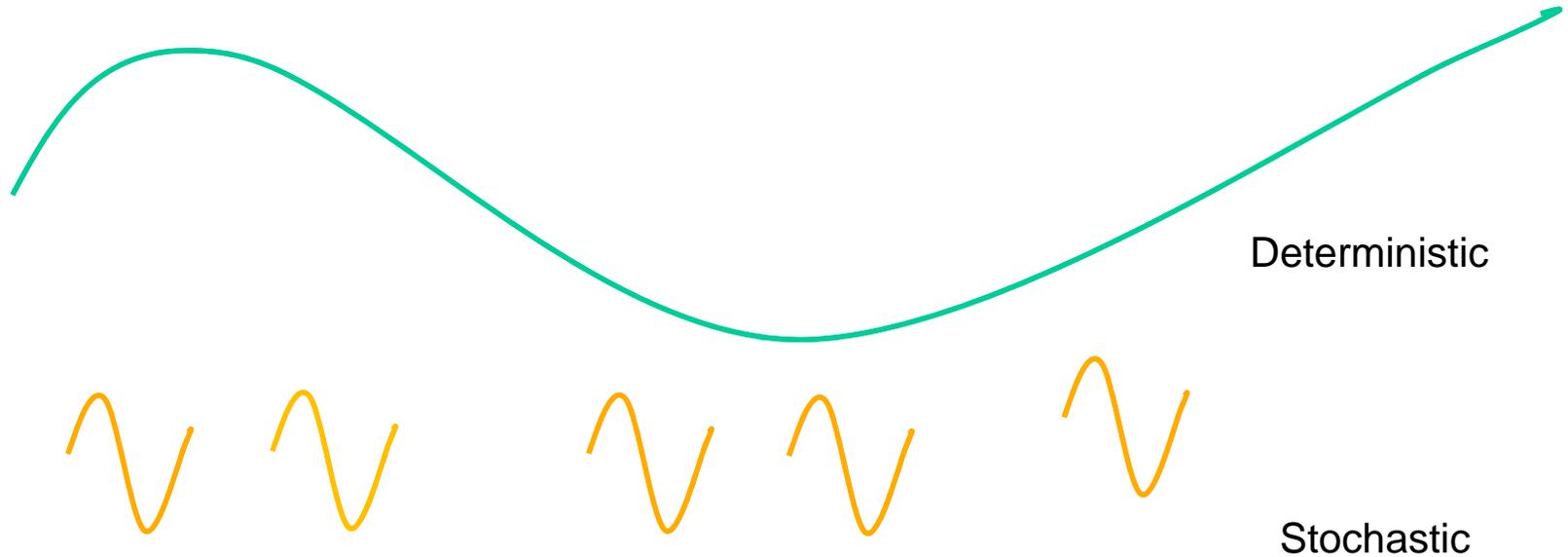
Scale Interactions



1. Is the initiation of small-scale weather system an IVP?
2. Is the initiation of any consecutive small-scale system an IVP? Does the initiation of the new system depend on the previous small-scale system or the large-scale (environmental) system?
3. If depending on the large-scale system, to what extent the previous small-scale system could impact/change the large-scale system? Phases (timing) and magnitudes (intensity). → what's impact scale in timing and spacing (on 2nd, 3rd, 4th small-scale system?) (similarly, does the resolved small-scale systems in the lcs have impact on the evolution of subsequent small-scale systems?)
4. From a modeling perspective, spin-up run time and initialization time are equally important.



Scale Interactions



Lifetime of a small-scale weather system (SWS): initiation, intensification, decaying etc.
Q: what's the feedback over a lifecycle? How about aggregate feedbacks over multiple lifecycles

- If a SWS is stochastic: is initiation or/both evolution stochastic? Is its feedback stochastic? What happens if its feedback weaker than other forcing?
- Timing of initiation depends on (i) physical processes and (ii) model spin-up run processes
- GCM vs. mg-GCE (3D, IVP?) \leftrightarrow AGCM vs. OGCM ("strong" 2D surface condition, BVP?)



Research Highlights (2010)

1. **CMPS Research Discovery Award:** University of Maryland at College Park, April 2010, cited as one of four “Research Breakthroughs” by University of Maryland, College Park.
2. **Results from Shen et al. (2010a, JGR) featured in NASA News** entitled “*Supercomputer Reproduces a Cyclone’s Birth, May Boost Forecasting*” which is derived the study by Shen, Tao, Lau and Atlas 2010 (JGR). This story reported the advance in supercomputing and high-resolution global modeling at NASA. **Follow-up stories appeared in MSNBC, PhysOrg.com, National Geographic--Indonesia, ScienceDaily, EurekAlert, Yahoo News, TechNews Daily, Scientific Computing, HPCwire, Asian News International etc.** It was also translated in Chinese by Science and Technology Division, Taipei Economic and Cultural Representative Office in the United States (駐美國台北經濟文化代表處科技組).
3. **Research results featured prominently by Dr. Richard Anthes (president of UCAR)** in the article entitled: “Turning the Tables on Chaos: is the atmosphere more predictable than we assume?”



Backup Slides



Richardson's Dream on Weather Prediction

- V. Bjerknes in 1904 pointed out that forecasting is fundamentally an initial-value problem with basic system of equations.
- In his book in 1922, Richardson described the numerical procedures of how to integrate governing equations and the parallel paradigm of how to distribute tasks and performing subtasks in parallel.
- The conceptual parallelism described provides so many similarities to the current parallelisms adapted by most of numerical models. The only difference between his “forecast factory” and modern supercomputers is the PEs itself, and his PEs are indeed the human.

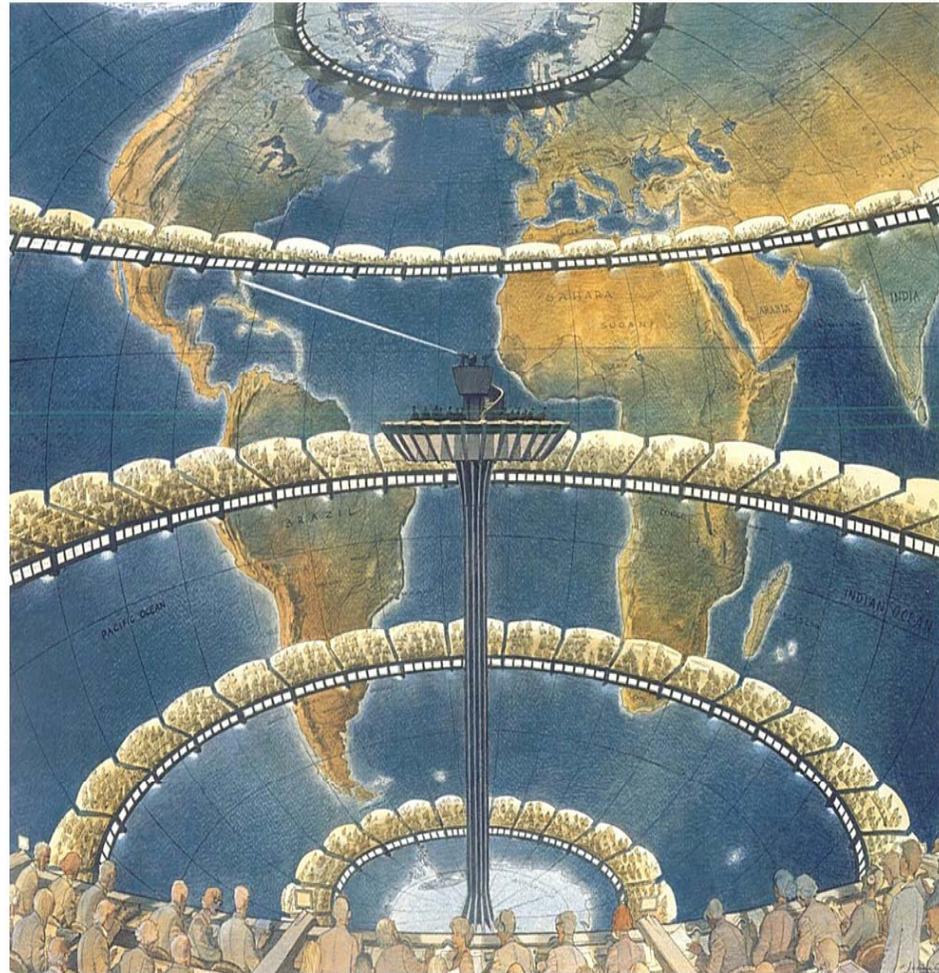
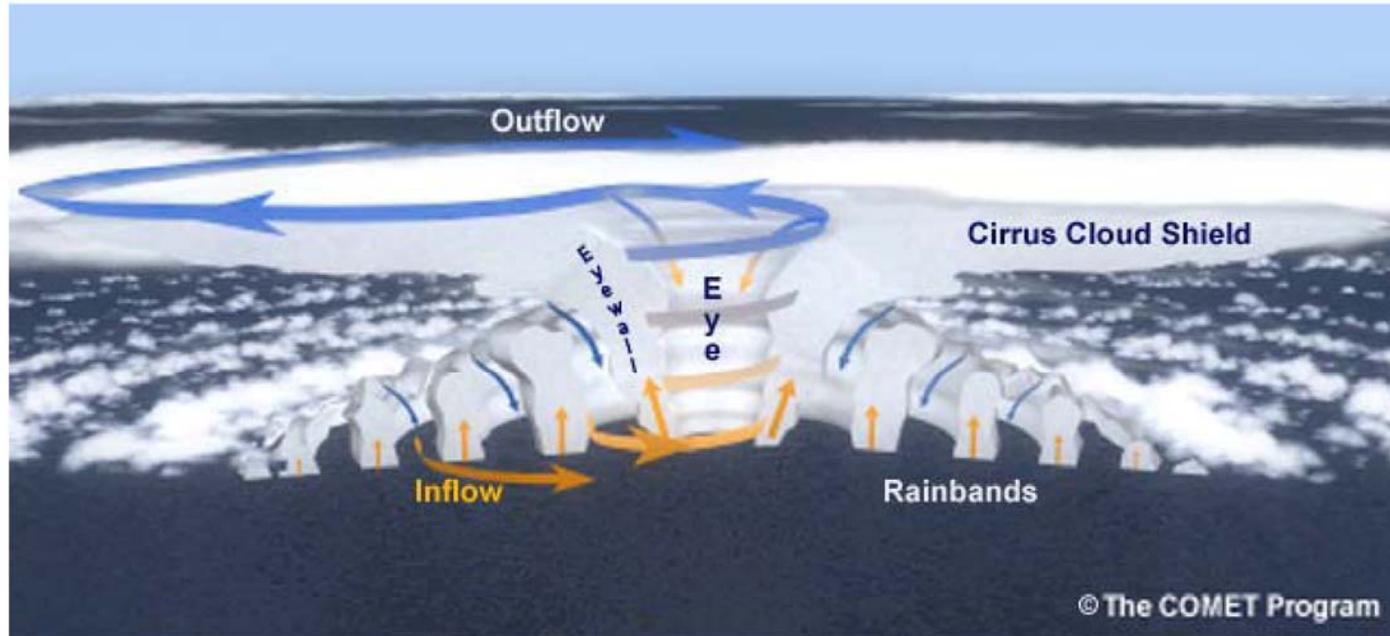


Fig. 5. An artist's impression of Richardson's Forecast Factory (© François Schuiten).

Richardson, L. F., 1922: *Weather Prediction by Numerical Process*. Cambridge Univ. Press, 236pp.



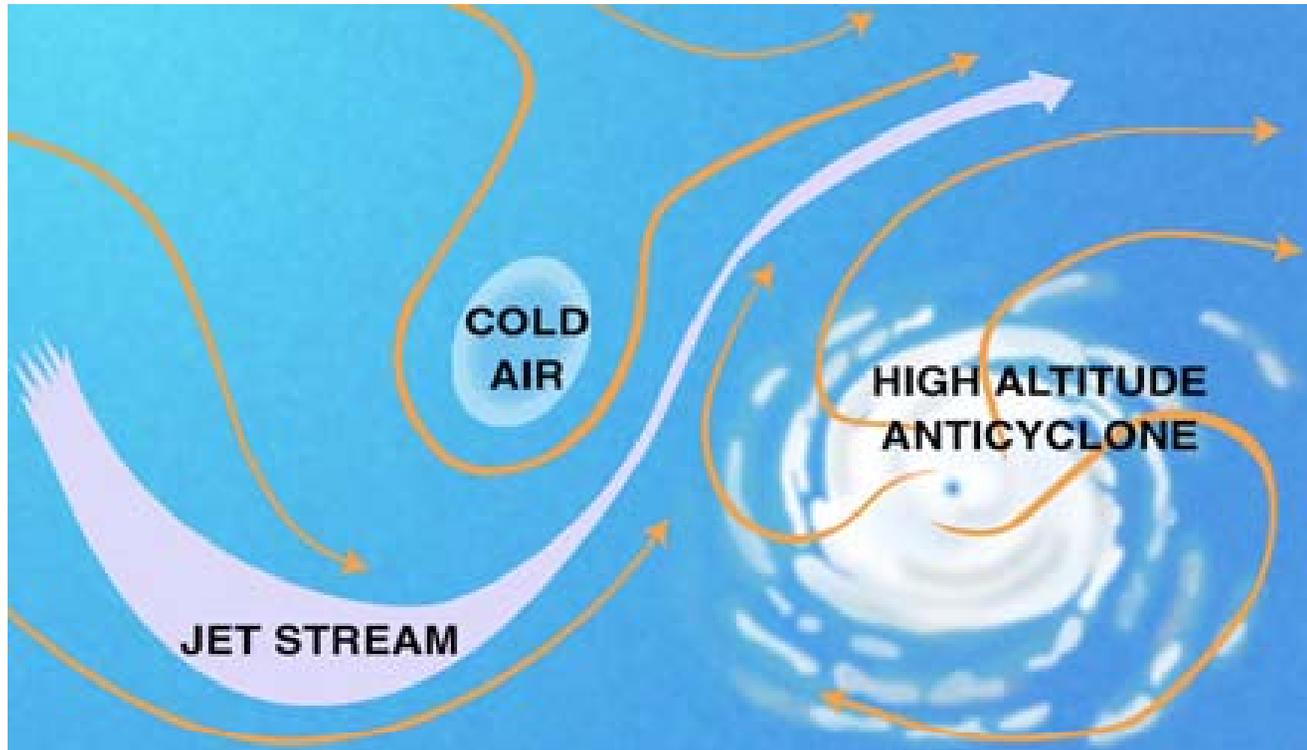
Hurricane ABC



1. **Eye:** A region in the center of a hurricane (tropical storm) where the winds are light and skies are clear to partly cloudy.
2. **Eyewall:** A wall of dense thunderstorms that surrounds the eye of a hurricane.
3. **Low-level Inflow:** counter clockwise circulation
4. **Upper-level Outflow:** clockwise circulation
5. **Elevated warm-core:** At a given level in the atmosphere, the cyclone's temperature is warmer at its center than at its periphery



Hurricane ABC



Upper-level
flow with
clockwise
circulation

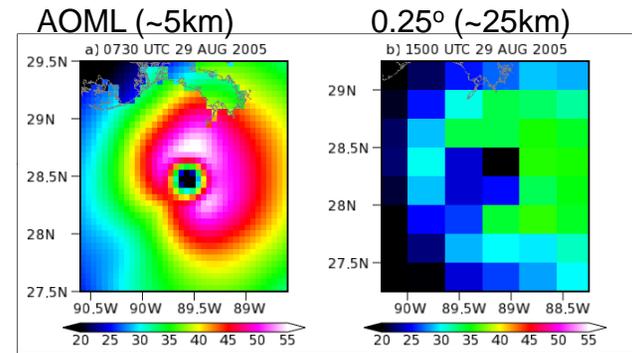
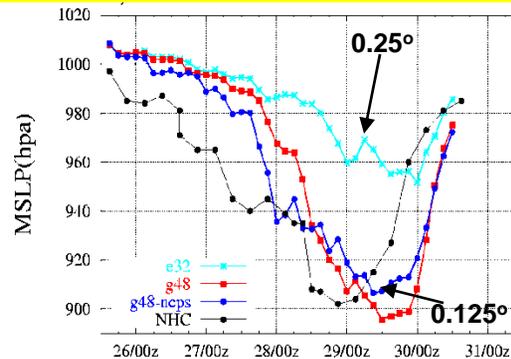
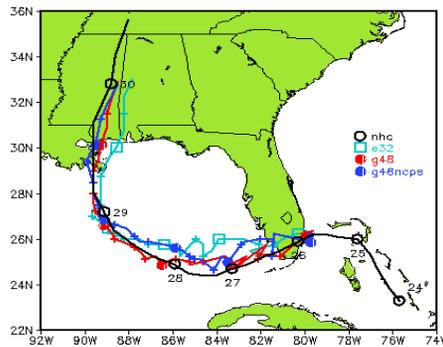
Upper level features that intensify the circulation inside a hurricane



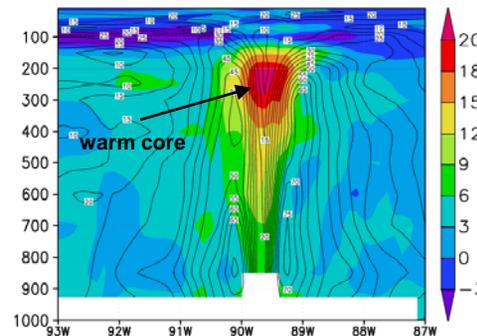
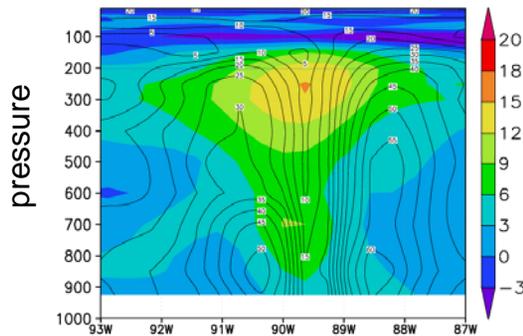
Forecasts of Katrina's Track, Intensity, Structures

Shen et al., 2006b, Geophys. Res. Lett., L13813:

- selected as Journal Highlight by American Geophysical Union
- featured in *Science* magazine (August, 2006)
- featured in the 2006 Annual report of SAIC (Science Application International Corp.)

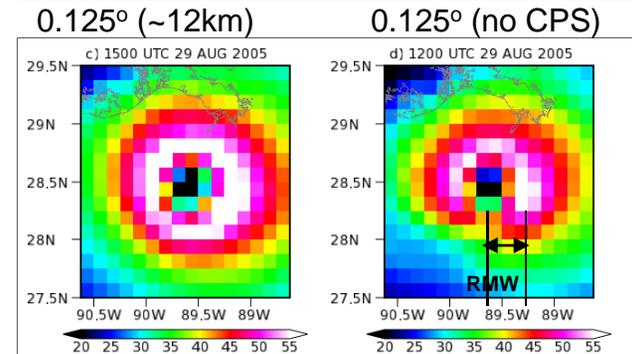


Landfall errors: e32 (1/4°): 50km, g48(1/8°): 14km, g48ncps (1/8° w/o CPS): 30km



GFS Analysis (~35km) valid at 08/29/12z

96 h Simulations with no CPS



Near-eye Wind Distributions in a 2°x2° box from 96h simulations, validated at 08/29/12z.

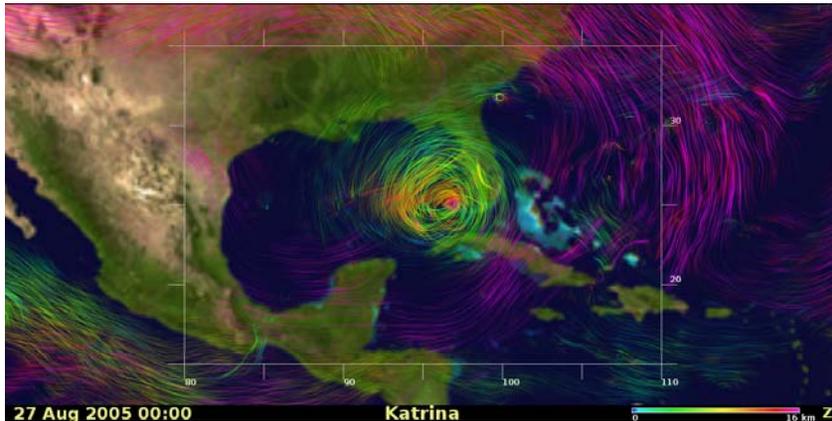
High-resolution runs simulate realistic intensity, radius of max wind (RMW) and warm core.



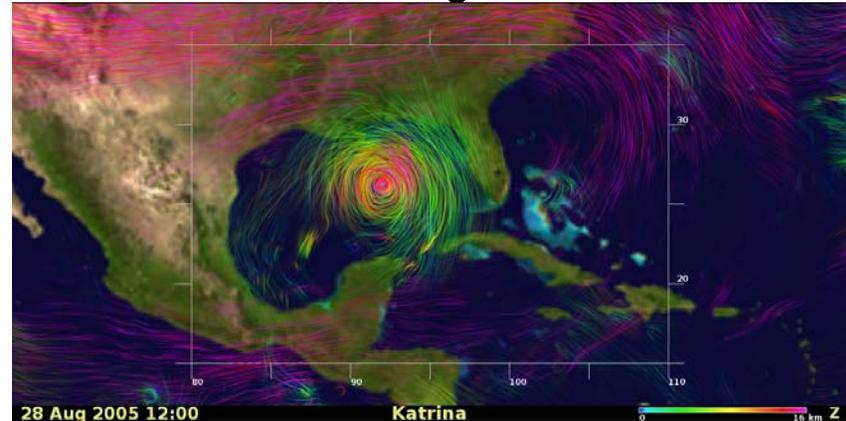


Visualization of Scale Interaction for Katrina

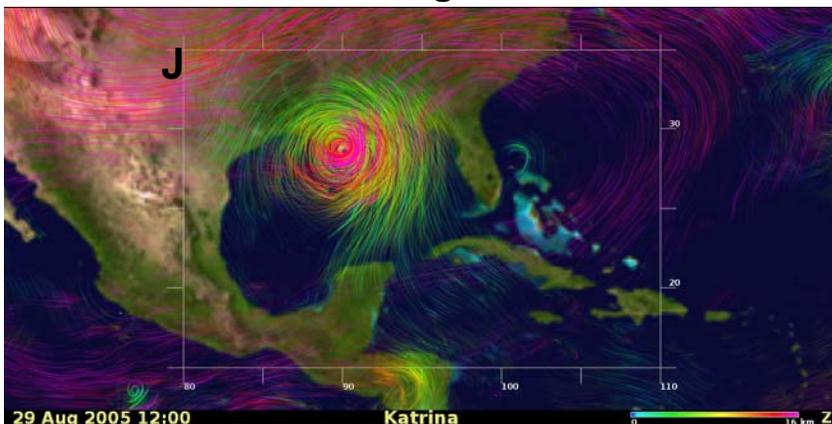
00Z 27 Aug 2005



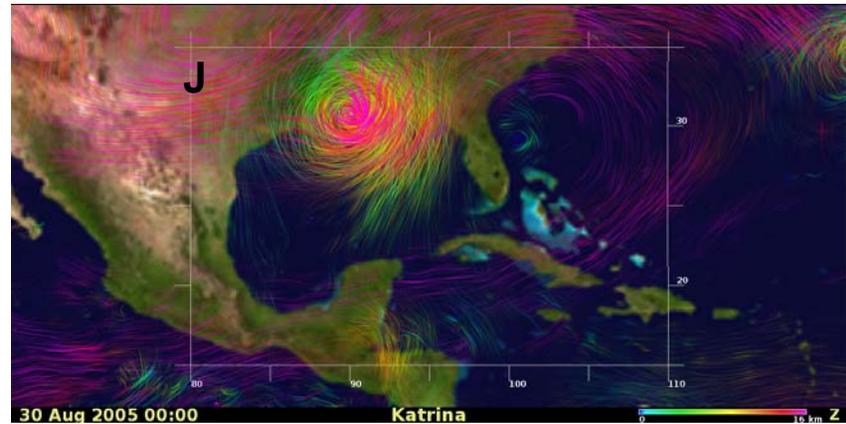
12Z 28 Aug 2005



12Z 29 Aug 2005



00Z 30 Aug 2005

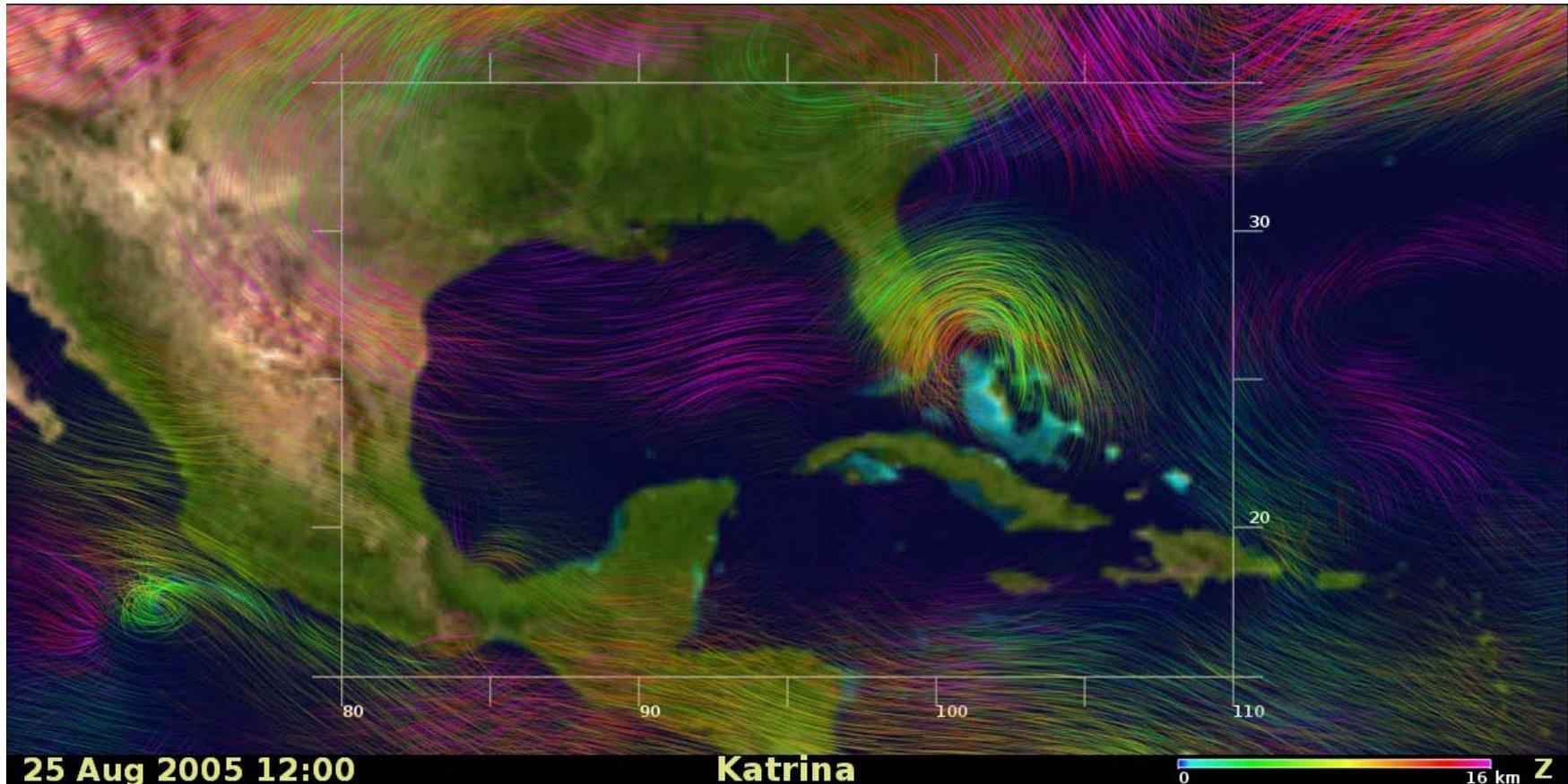


Katrina's intensification is indicated by the intensifying upper-level outflow in red (b). High-resolution animation shows that the intensification is associated with the Interaction of the Katrina's outflow and an approaching upper-level jet stream (c, d).





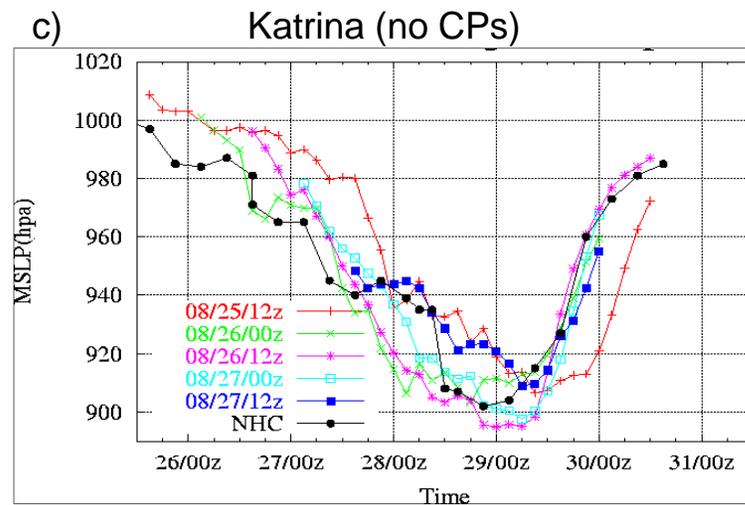
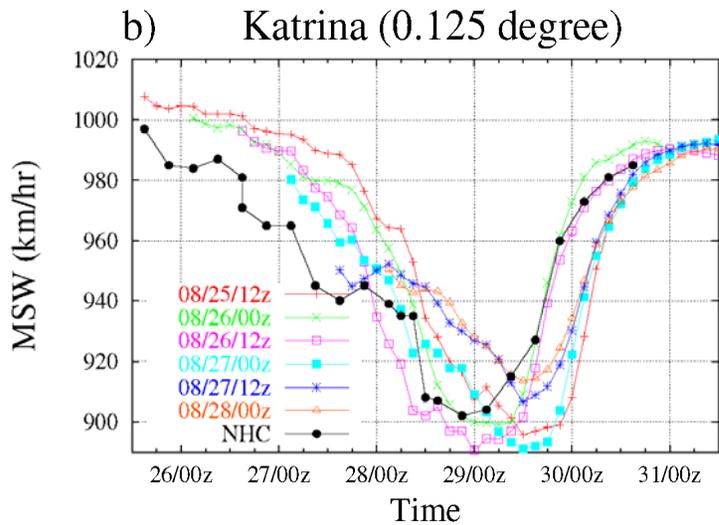
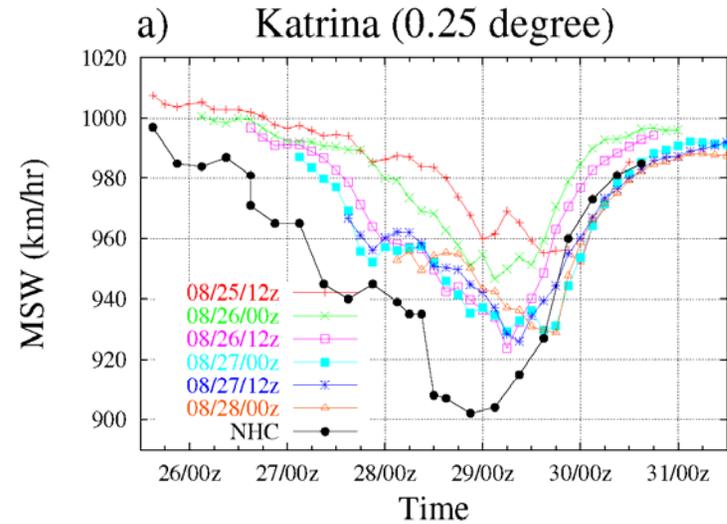
Visualization of Scale Interaction for Katrina



High-resolution animation shows that the intensification is associated with the Interaction of the Katrina's outflow and an approaching upper-level jet stream.



Forecasts of Katrina's Intensity

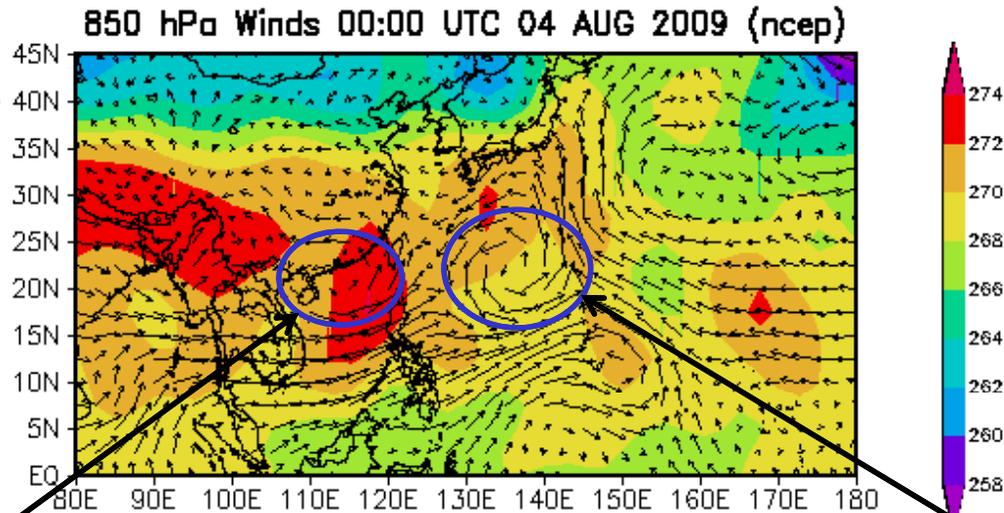




Predicting the Formation of Typhoon Morakot (2009): three extended-range (14~17) forecasts

850-hpa winds (vectors)
and 500-hpa
temperatures (shaded)

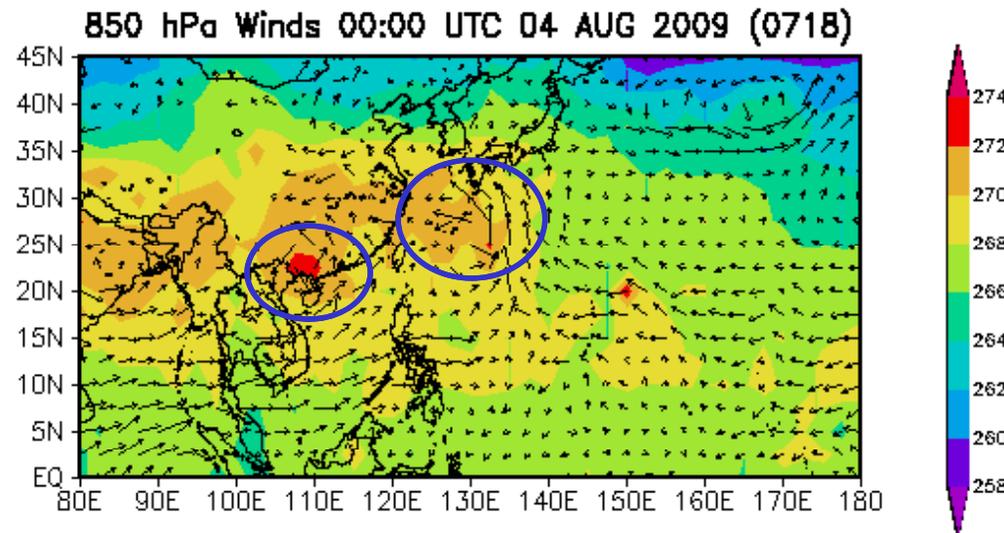
**NCEP Ana
validated at 00Z Aug 4**



Goni

Morakot

**Day 17
from a run initialized
at 00Z July 18**



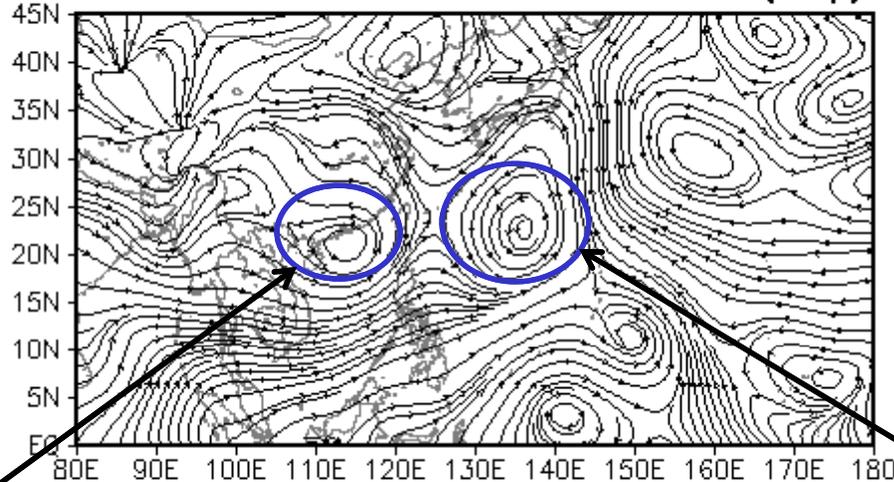


Predicting the Formation of Typhoon Morakot (2009): three extended-range (14~17) forecasts

850-hpa winds (vectors)
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temperatures (shaded)

**NCEP Ana
validated at 00Z Aug 4**

850 hPa Winds 00:00 UTC 04 AUG 2009 (ncep)

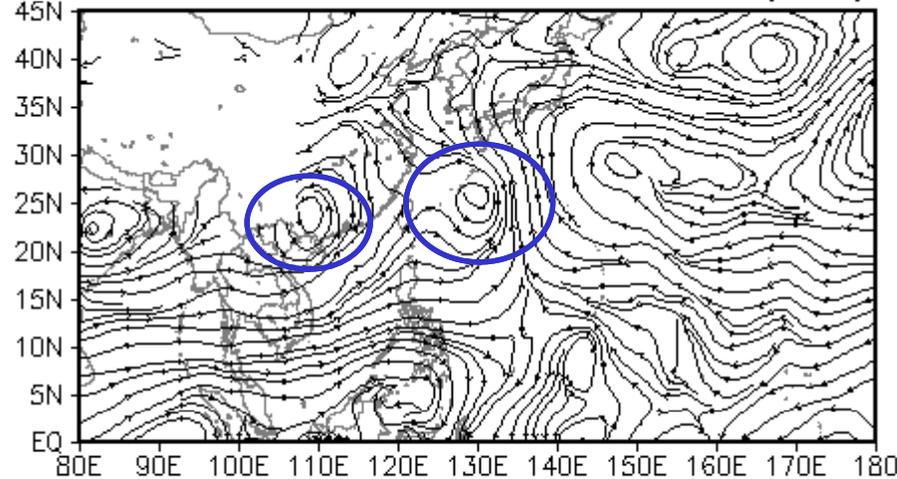


Goni

Morakot

**Day 17
from a run initialized
at 00Z July 18**

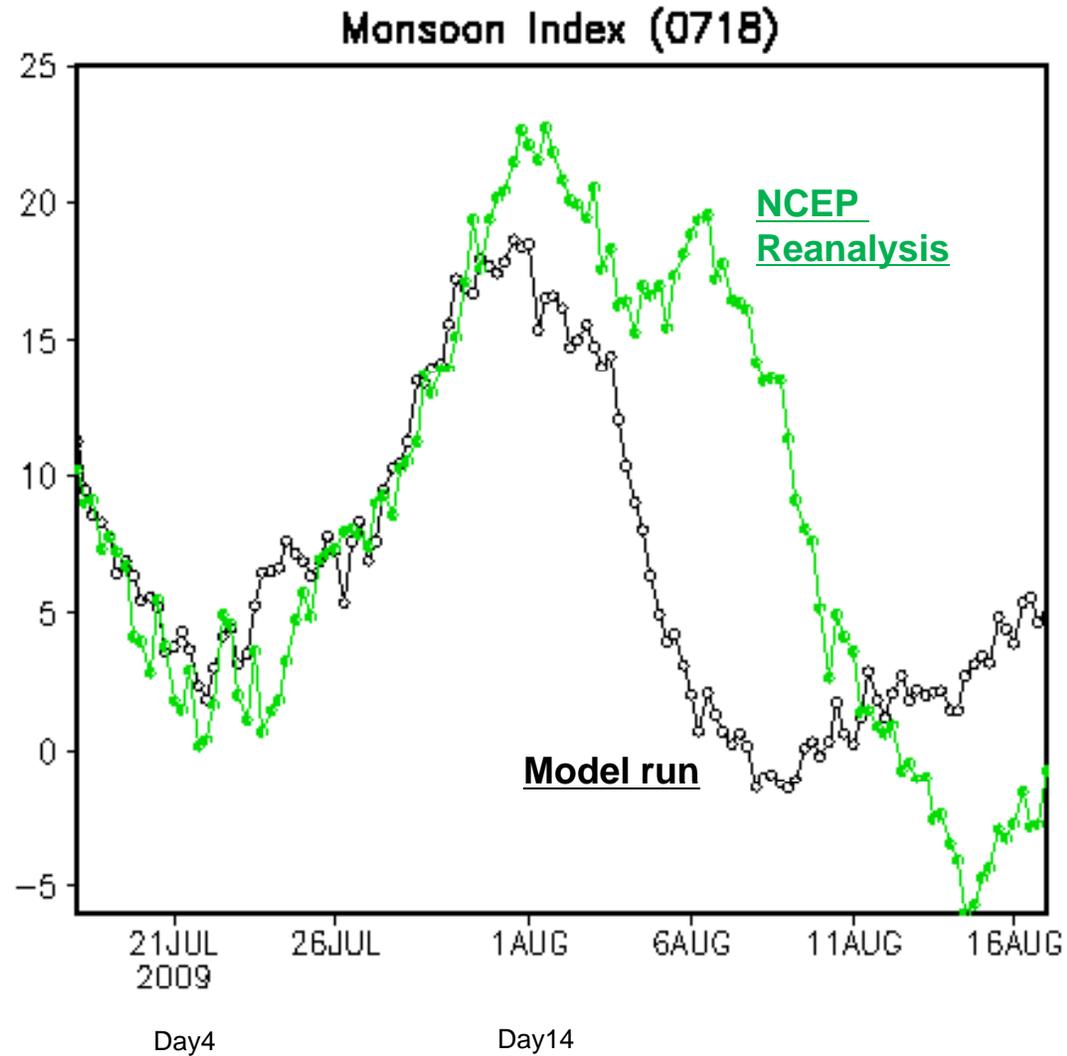
850 hPa Winds 00:00 UTC 04 AUG 2009 (0718)





Simulated Monsoon Index in a 30-day Run

$$U_{850}(5-15^{\circ}\text{N}, 100-130^{\circ}\text{E}) - U_{850}(20-30^{\circ}\text{N}, 110-140^{\circ}\text{E})$$

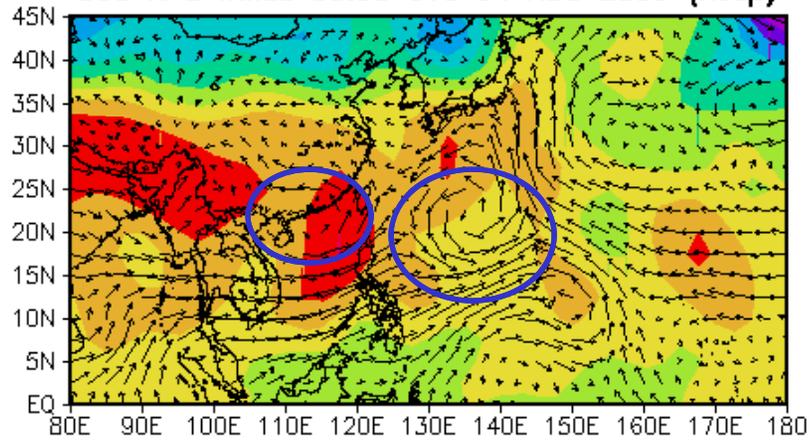




Predicting the Formation of Typhoon Morakot (2009): three extended-range (14~17) forecasts

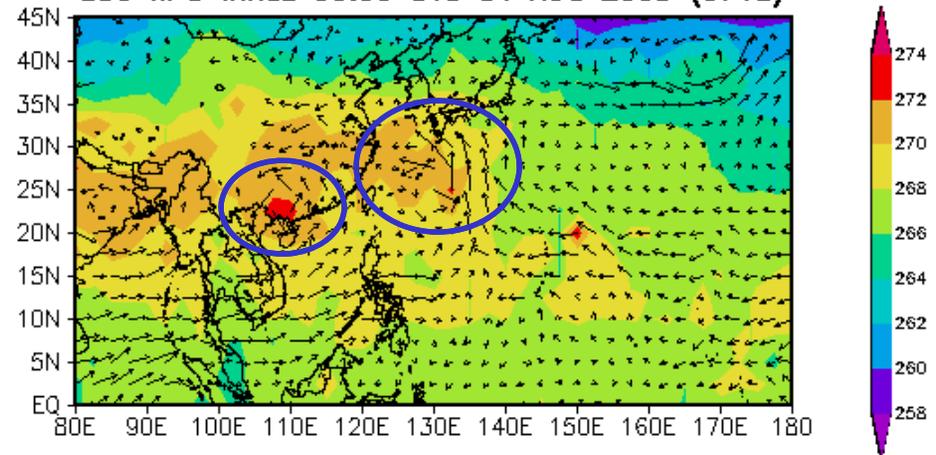
NCEP Ana validated at 00Z Aug 4

850 hPa Winds 00:00 UTC 04 AUG 2009 (ncep)



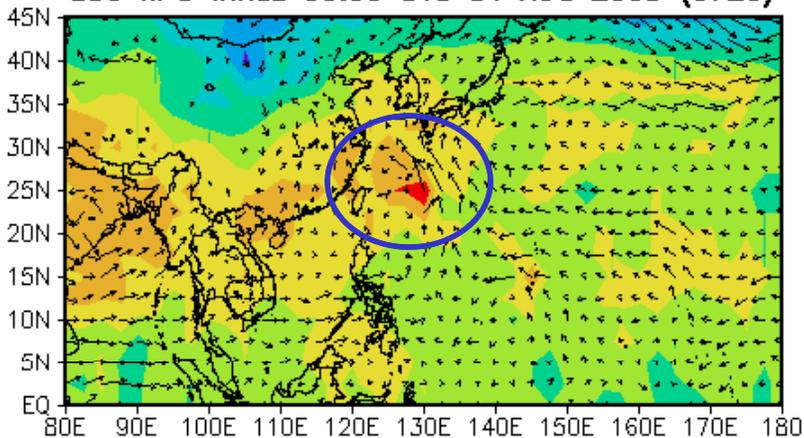
Day 17 (init at 00Z July 18)

850 hPa Winds 00:00 UTC 04 AUG 2009 (0718)



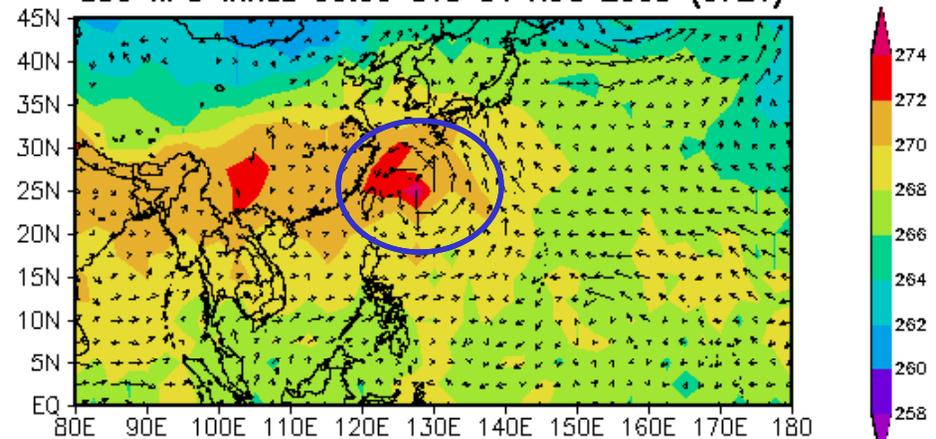
Day 15 (init at 00Z July 20)

850 hPa Winds 00:00 UTC 04 AUG 2009 (0720)



Day 14 (init at 00Z July 21)

850 hPa Winds 00:00 UTC 04 AUG 2009 (0721)

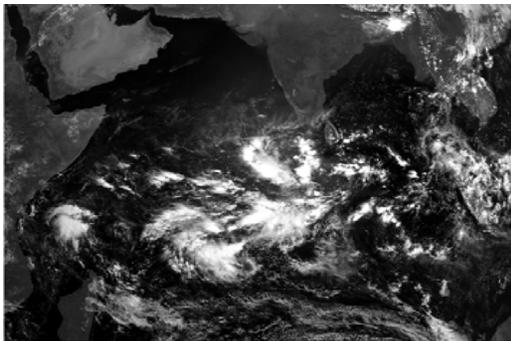




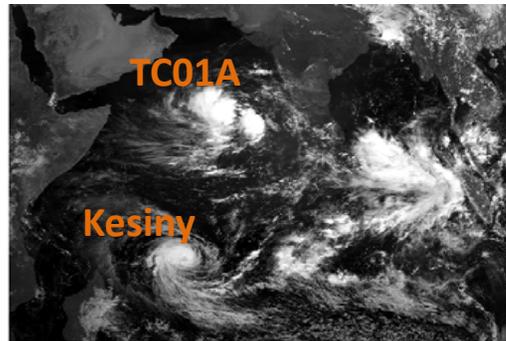
Twin Tropical Cyclones and an MJO in May 2002

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. Multiscale Interactions between a mixed Rossby gravity wave and the twin TC are shown in slide 9.

0630 UTC 1 May 2002



0000 UTC 6 May 2002



0000 UTC 9 May 2002

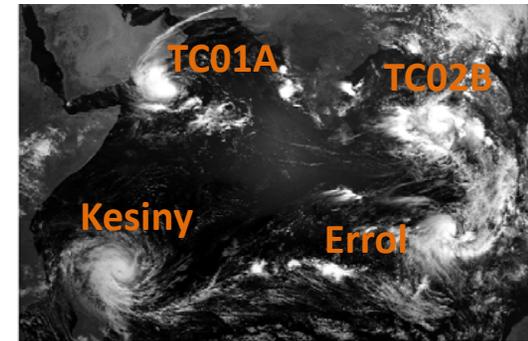


Figure: Predictions regarding the formation of twin tropical cyclones in the Indian Ocean: (a) MJO-organized convection over the Indian Ocean at 0630 UTC 1 May 2002. When the MJO moved eastward, two pairs of twin TCs appeared sequentially on 6 May (b) and 9 May (c), including TC 01A, Kesiny, TC 02B and Errol. Two TCs (01A and 02B) with anti-clockwise circulation appeared in the Northern Hemisphere, while the other 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., 2010c and 2011 for details).



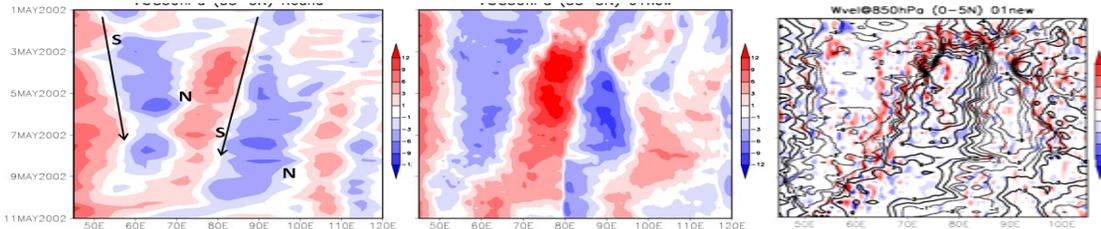
Shen, B.-W., W.-K. Tao, et al. 2011: Forecasting Tropical Cyclogenesis with a Global Mesoscale Model: Preliminary Results for Twin Tropical Cyclones in May 2002. (to be submitted)





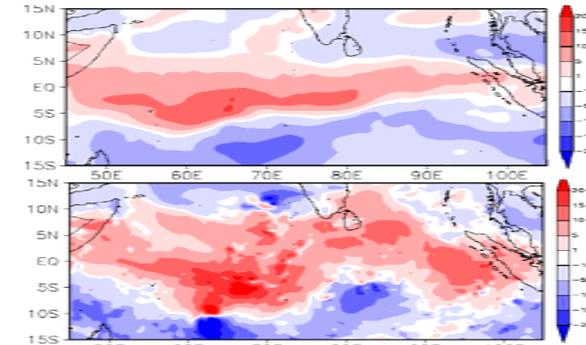
Interactions of Twin TCs and MRG wave

Wavelength reduction of mixed Rossby gravity (MRG) wave



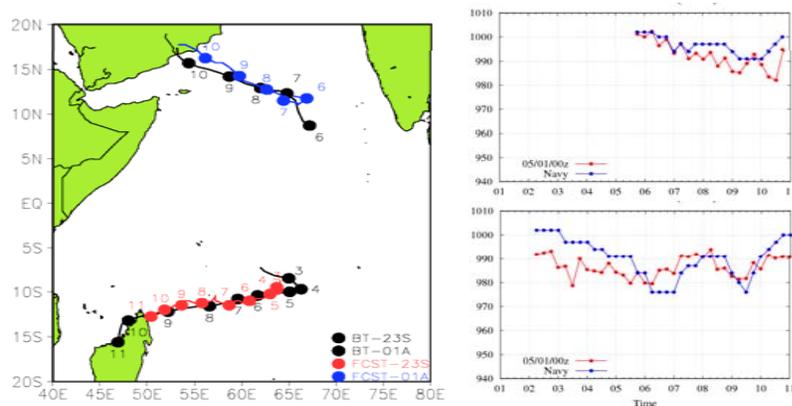
Time/longitude diagram of meridion winds from NCEP analyses (a) and the 10-day control run initialized at 00Z 1 May 2002 (b). Northerly (southerly) winds are indicated in red (blue). The westward-propagating disturbances with the sloping northerly to southerly flow couplets that are nearly asymmetric about the equator are likely associated with an MRG wave. (c) Time/longitude diagram of 850mb vertical velocity (shaded) and meridion winds (contour).

MRG Wave Development



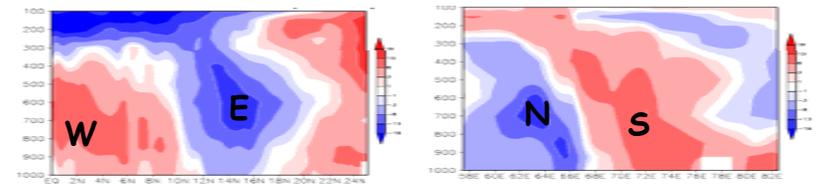
Simulations of 850-hPa zonal winds at the initial time and the integration of 96 hours.

10-day Fcst of Twin TCs' Track and Intensity



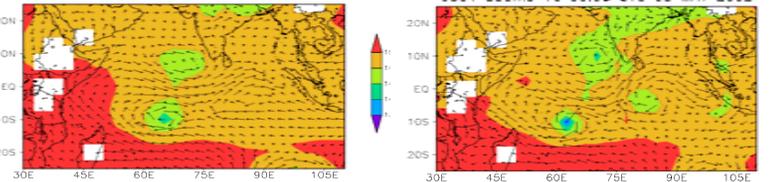
Track (a) and Intensity simulations of TCs 01A (b) and 23S (c) from the 10-day run initialized at 00Z 1 May 2002, as compared to the observations. The first record for TC 23S (01A) was issued at 06Z 3May (18Z 5 May).

Evolution of Low-level Cyclonic Circulation



120h simulations of zonal (left) and meridion winds (right)

Scale Interactions between MRG gyres



850-hPa winds (vectors) and geopotential heights (shaded) at 00Z 5 May 2002 from NCEP analyses (left) and the control run (right).



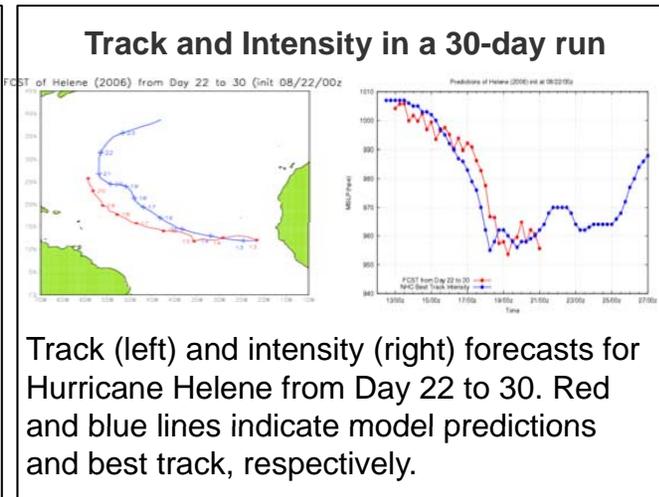
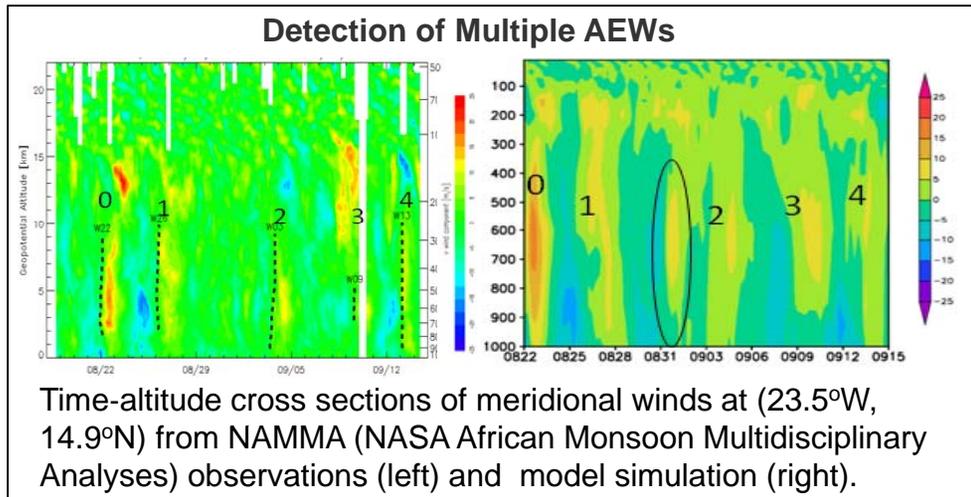
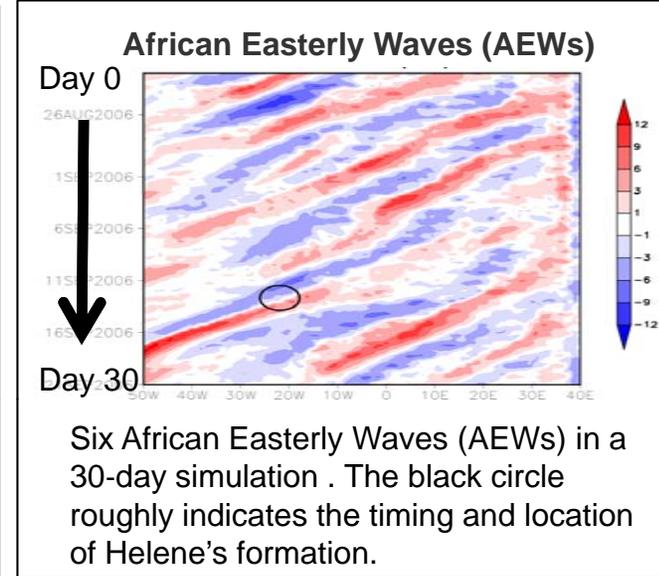
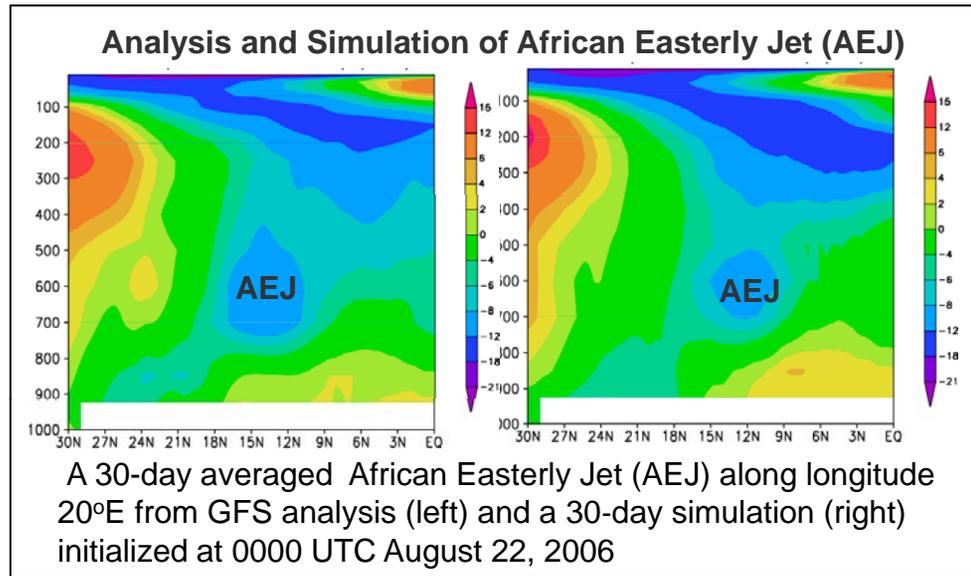


Multiscale Interactions (in the Twin TC case)

1. 10-day experiments initialized at 00Z 1 May 2002 suggest that a mixed Rossby gravity (MRG) wave with baroclinicity appeared initially as the integral of three gyres (S_1 , N_1 and S_2 in slide 9), all moving westward;
2. The MRG wave intensified in association with its wavelength reduction which is clearly shown by the faster westward phase speed in gyre S_2 than S_1 ;
3. As time progresses, low- and middle-level cyclonic circulation (CC) continued to develop and became “coherent” vertically, providing a favorable condition for TC genesis with zero vertical wind shear line centered at the CC;
4. The 1/4 wavelength phase lag between the meridian winds and the vertical velocity appears at the middle levels (e.g., 500 hpa) but is distorted at the low-level levels (e.g., 850 hpa), which is consistent with the conclusion of Holton (1975) that in-phase of geopotential height and the boundary friction induced convergence might contribute to the cut-off of the gyre (e.g., gyre N_1) from the equator;
5. After TC Kensiny and 01A formed on May 3 and May 6 respectively, these two TCs moved at different speeds and gradually appeared as a twin TC, indicating the transition of a MRG wave into an equatorial Rossby wave.



Multiscale Interactions of AEJ, AEWs, Hurricane and Surface Processes in a 30-day run





Multiscale Interactions (in the AEW case)

1. 30-day experiments initialized 00Z 22 August 2006 show that the statistical characteristics of multiple AEWs (including initiation and propagation) are realistically simulated with larger errors in the 5th and 6th AEWs. Remarkable simulations of a mean African Easterly Jet (AEJ) are also obtained.
2. While land surface processes may contribute to the predictability of the AEJ and AEWs (as a boundary value problem), the initiation and detailed evolution of AEWs still depend on the accurate representation of dynamic and land surface initial conditions and their time-varying nonlinear interactions (as an initial value problem).
3. Of interest is the potential to extend the lead time for predicting hurricane formation (e.g., a lead time of up to 22 days) as the 4th AEW is realistically simulated.
4. In the experiment with climate SSTs, differences appear in the 5th and 6th AEWs, implying that the effects of using climatological SSTs on the simulation of AEW initiation begin to occur after 15-20 days of integration.
5. The reduced height of Guinea highlands causes significant differences in the simulations of AEWs since Day 15. For example, the initiation of the 4th, 5th and 6th AEWs are influenced by this change, and the downstream development of AEWs (e.g., the 2nd and 4th AEWs) becomes weaker.



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.

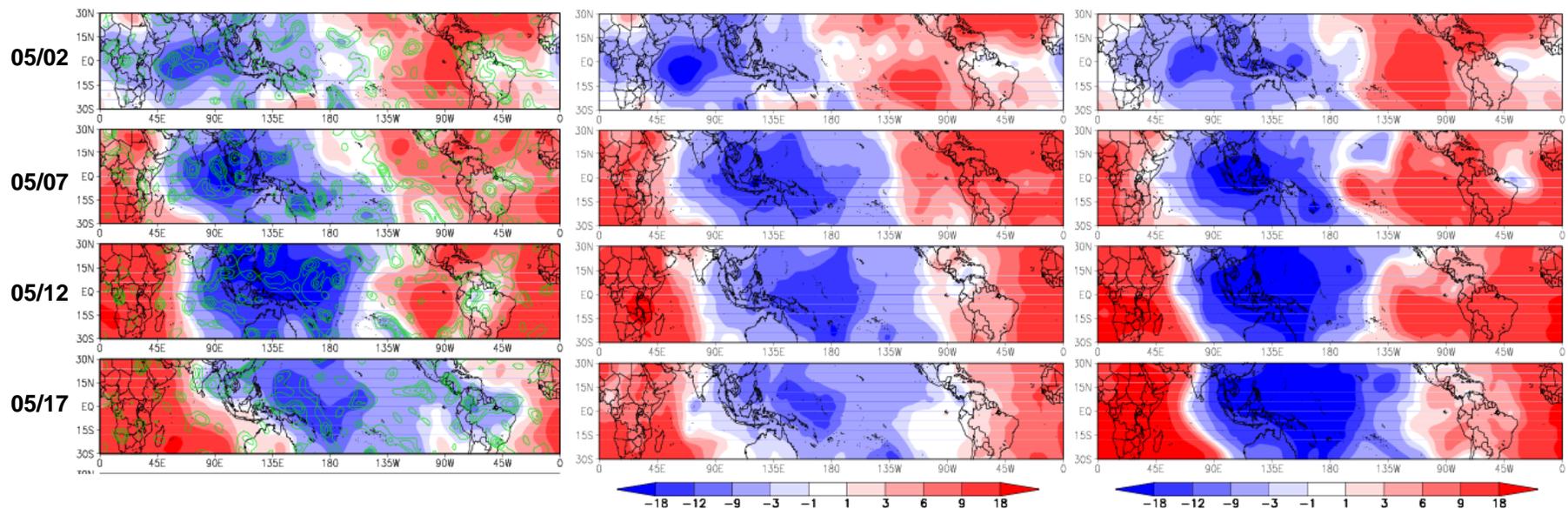


Figure: Velocity potential at 200 hPa every 5 days in May 2002 from NCEP analysis (left panels), 15-day fvGCM model predictions at 1/8 degree resolution (middle panels), and 15-day fvMMF model predictions (right panel). The velocity potential plots show the observed and predicted patterns and propagations of Madden-Julian Oscillation (MJO). The high-resolution fvGCM is able to reproduce realistically the observed patterns 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 .



30-day Simulations of an MJO in Dec 2006

One of the most challenges in predicting an MJO is to simulating its life cycle, including initiation or 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.

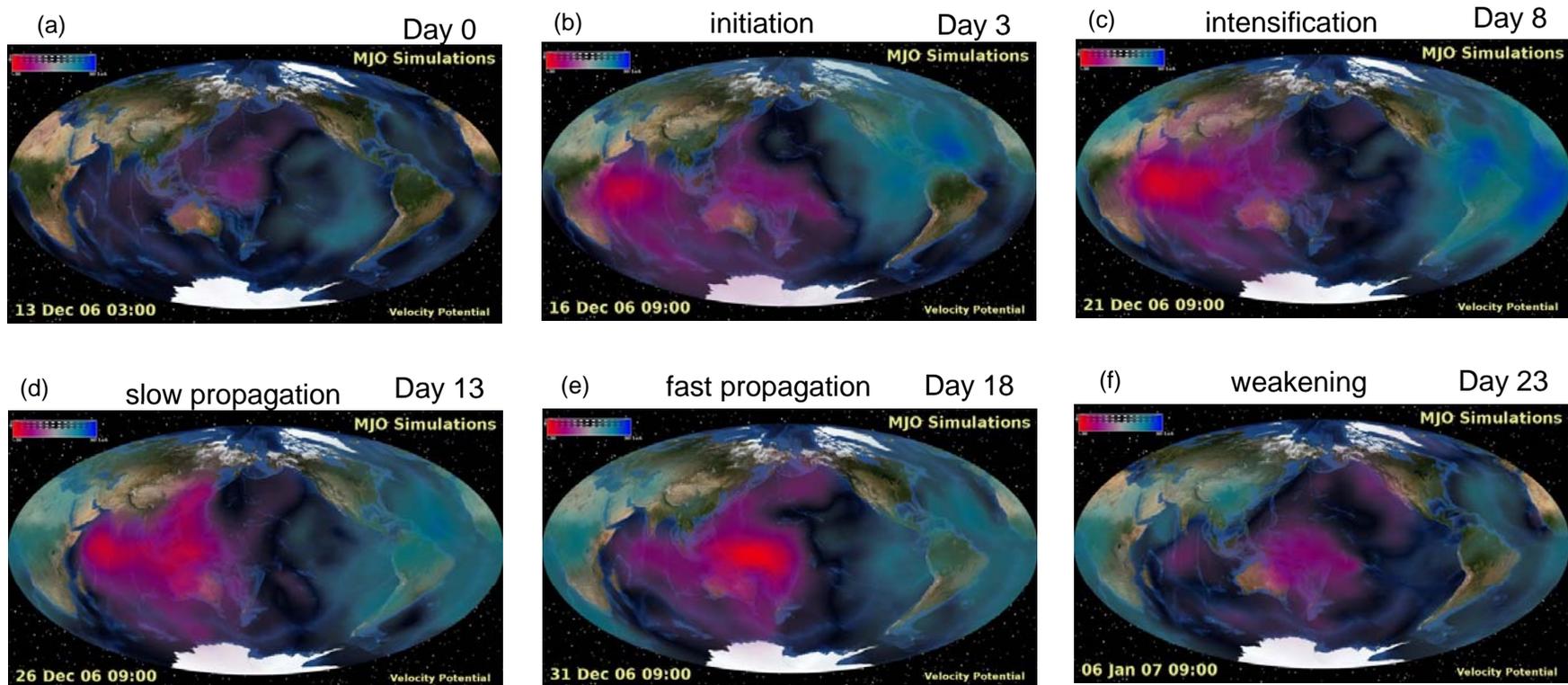


Figure: A 30-day simulation of an MJO initialized at 0000 UTC December 13, 2006, as shown in 200 hpa velocity potential. This simulation with the Goddard MMF (Tao et al., 2009) captures several major features usually associated with an MJO: (1) initiation of large-scale organized convection in the Indian 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.



Anthes' Hypotheses on Mesoscale Predictability in 1980s

- *An easier problem, from the observational point of view, is the simulation of mesoscale phenomena which develop within large-scale, routinely observed circulations. The development of mesoscale weather systems may be classified as occurring through one or both of two mechanisms: (1) forcing on the mesoscale from inhomogeneities at the earth's surface and (2) internal modifications of large-scale flow patterns that lead to smaller-scale circulations.*
- *When there are no strong mesoscale circulations present initially, it may be unnecessary to observe and analyze mesoscale detail for the model's initial conditions.*
- *An accurate specification of large-scale thermodynamic and momentum fields, together with realistic physical forcing at the surface, adequate representation of diabatic effects in the free atmosphere, and the appropriate resolution, may be sufficient to predict the evolution of some mesoscale systems for hours or even a few days in advance of their development.*
- *In short, the key to accurate prediction of tropical cyclogenesis is the get the right large-scale fields, have sufficient resolution for TC spinup, and appropriate physics!*

References:

- *A note on "Summary of Predictability Papers", by Dr. R. A. Anthes in July, 2009*
- *An email with the subject of "Some Earlier Work on Mesoscale Predictability" by Dr. R. A. Anthes in February, 2011*

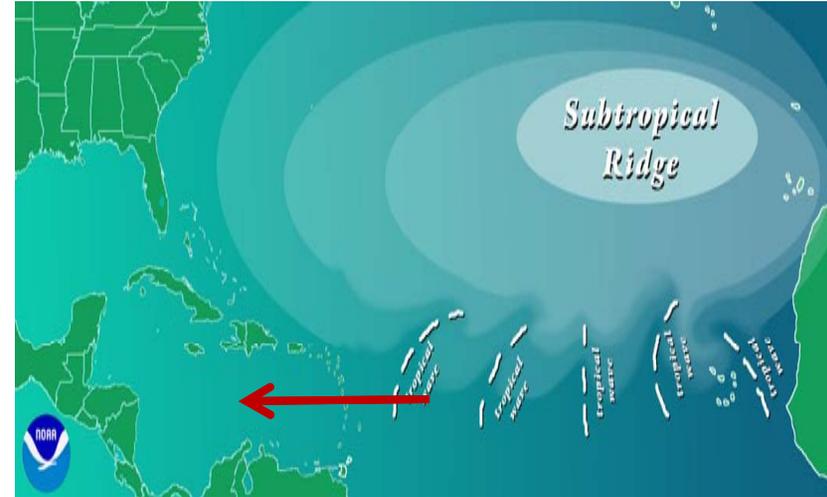


A mixed IVP-BVP Problem



BEIJING (AP) - The U.S. has failed to advance out of the first round of both the men's and women's 400-meter relays at the Olympics, dropping the baton in each race.

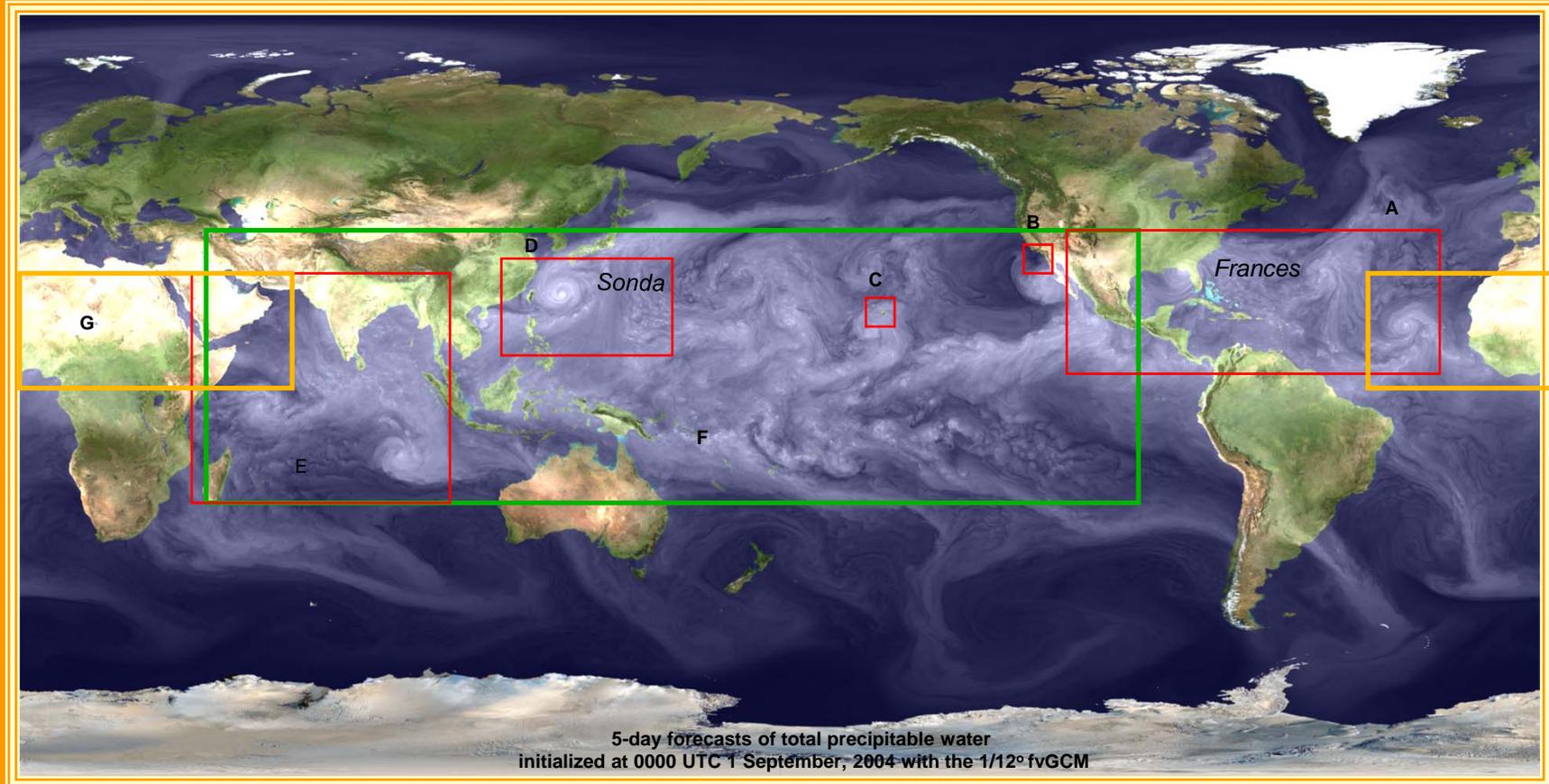
- Each runner represents an initial value problem with fresh imposed energy.
- System performance depends on the aggregated performance from all of the runners each of whom receives initial “system” momentum and relays this momentum further with his own energy.



Contributed by Chris Landsea,
<http://www.aoml.noaa.gov/hrd/tcfaq/A4.html>

- Each AEW represents an initial value problem with its energy from another source (e.g., surface process).
- System performance depends on the aggregated performance from all of the AEWs.

Predicting High-impact Tropical Weather with the NASA CAMVis



F: Madden-Julian Oscillation (MJO)

D: Typhoon
Asian Mei-Yu Front

A: Atlantic Hurricanes

G: African Easterly Wave (AEW)

E: Twin Tropical Cyclones

B: Catalina Eddy

C: Hawaiian Lee Wakes