

# Integration of the NASA CAMVis and Multiscale Analysis Package (CAMVis-MAP) for Tropical Cyclone Climate Study

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and  
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Mesoscale Atmospheric Processes Laboratory  
Greenbelt, MD, March 05, 2012

Multiscale Interactions of Tropical Cyclone Formation and Tropical Waves  
as Revealed by NASA Advanced Technologies



## Acknowledgements

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- NASA/GSFC: Wei-Kuo Tao (CO-PI for AIST08), William K. Lau, Jiundar Chern, Chung-Lin Shie, Kuo-Sen Kuo, Jenny Wu
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- NASA/JPL: Frank Li (CO-I), Peggy Li
- UCAR: Richard Anthes
- Navy Research Lab: Jin Yi
- NOAA/AOML: Robert Atlas
- NC A&T State U.: Yuh-Lang Lin
- NASA/ARC: Bron Nelson (CO-PI for AIST08) , Piyush Mehrotra (CO-I), Samson Chang (CO-PI for AIST11), Chris Henze, Bryan Green, David Ellsworth, Johnny Cheung, control-room
- Funding sources: NASA ESTO (Earth Science Technology Office) **AIST (Advanced Information System Technology) Program**; NASA Modeling, Analysis, and Prediction (MAP) Program; National Science Foundation (NSF) Science and Technology Center (STC)

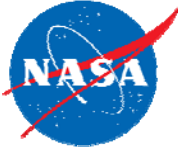
### **Project Title of AIST-08-0049 (PI: Shen)**

**C**oupling NASA **A**dvanced Multi-Scale **M**odeling and Concurrent **V**isualization Systems for Improving Predictions of Tropical High-Impact Weather (**CAMVis**), March 2009 – April 2012

### **Project Title of AIST-11-0012 (PI:Shen):**

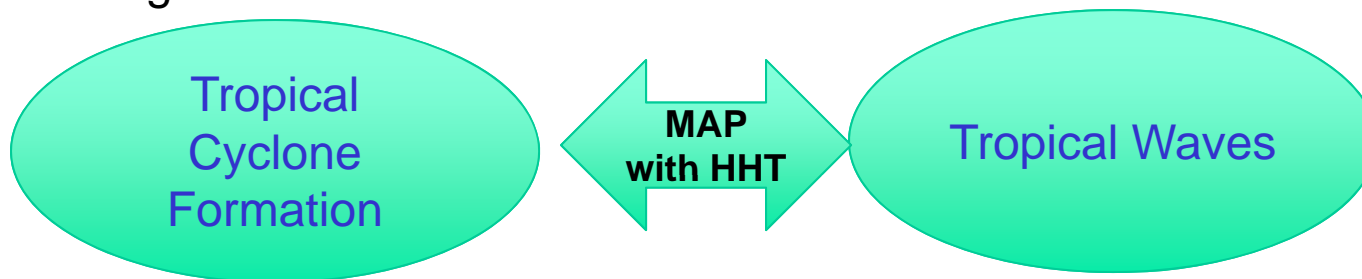
Integration of the NASA CAMVis and **M**ultiscale **A**nalysis **P**ackage (**CAMVis-MAP**) for Tropical Cyclone Climate Study, May 2012 – April 2015

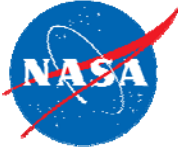




## Outline

- Introduction (Decadal survey missions; research interests)
- NASA Global Multiscale Modeling, Supercomputing Technology and Concurrent Visualization Systems
- Scientific Demos (status of AIST08 project)
  - 1: Formation of Tropical Cyclone Nargis (2008) associated with an Equatorial Rossby Wave
  - 2: Formation of Twin Tropical Cyclones (2002) associated with a mixed Rossby Gravity Wave
  - 3: Formation of Hurricane Halene (2006) associated with an African Easterly Wave
- Future Tasks (highlights of AIST11 project; MAP with HHT)
- Concluding Remarks





## Scenarios in Decadal Survey

- **Extreme Event Warnings** (near-term goal): Discovering predictive relationships between meteorological and oceanographic conditions and less obvious precursor conditions from marine observations and model interactions; modulations and feedbacks between long term scale and small/short-term scale flows

Prediction of Hurricane Tracks and Intensity



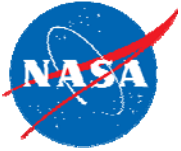
Prediction of Hurricane Formation



- **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 of satellite and complementary Earth Science data products to improve model predictions.

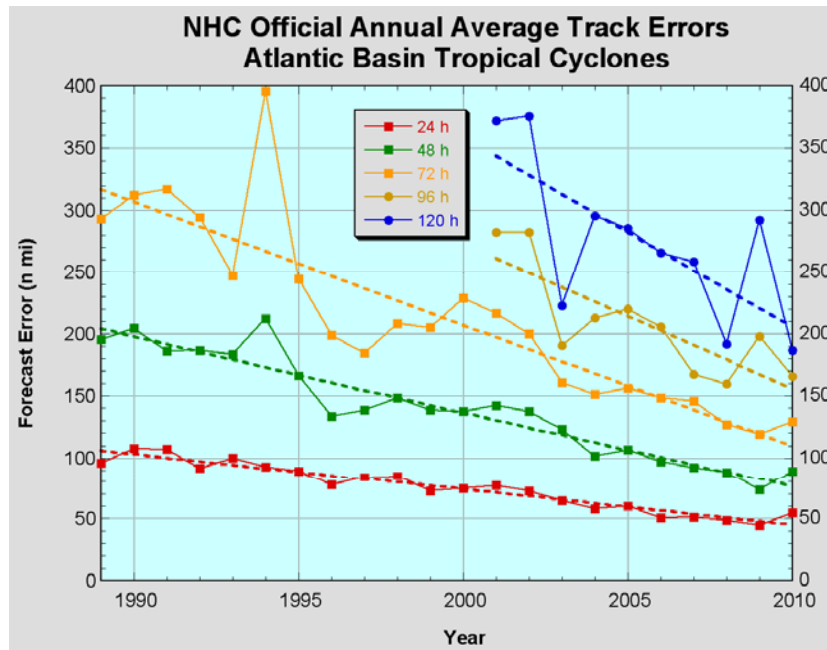
Hurricane Climate Simulation

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



## Progress of Hurricane Forecasts (by National Hurricane Center)

### Track Errors (1989-2010)



↓  
better

### Intensity Errors (1990-2010)

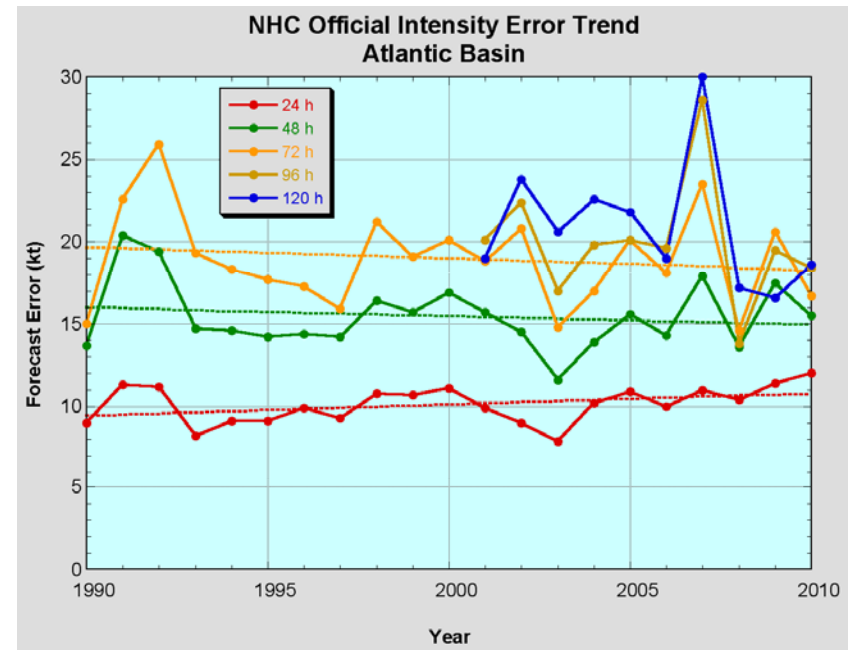


Figure: The progress of hurricane forecasts by National Hurricane Center. Horizontal axis indicates year, and vertical axis shows forecast errors. Lines with different color show different forecast intervals. During the past twenty years, track forecasts have been steadily improving (left panel), but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

<http://www.nhc.noaa.gov/verification/verify5.shtml>

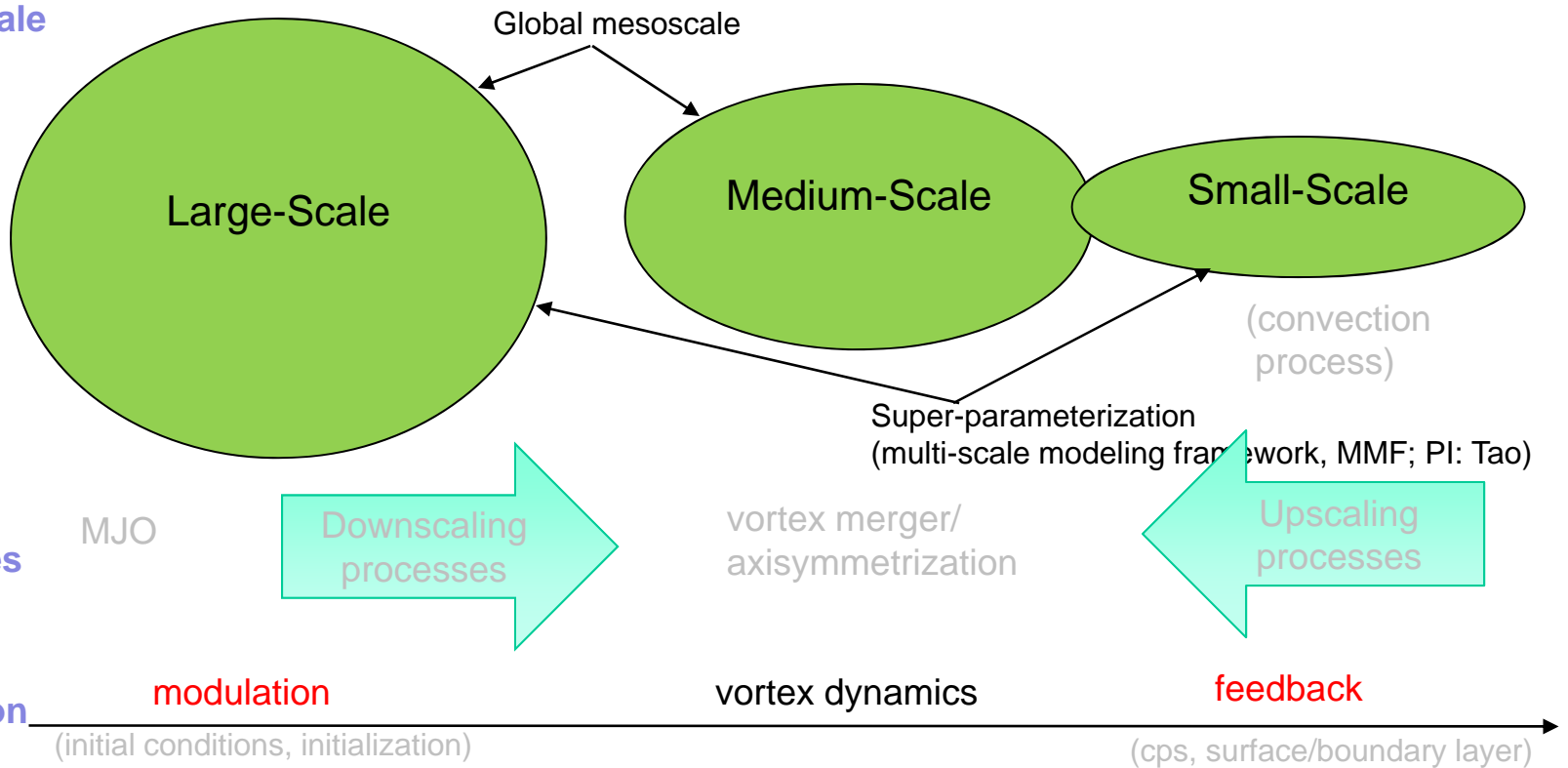




# Multiscale Modeling Approach

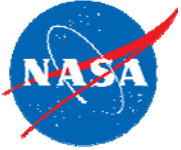
To improve the prediction of TC's formation, movement and intensification, we need to improve the model to accurately simulate interactions across a wide range of scales, from the large-scale environment (deterministic), to mesoscale flows, down to convective-scale motions (stochastic).

model scale



**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;



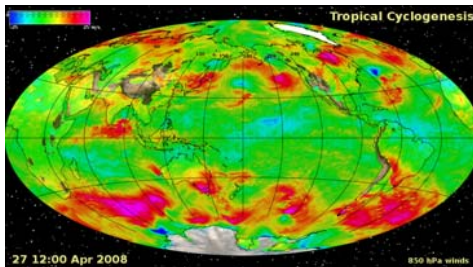


## Objectives (AIST08 Project)

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

1. 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;
2. 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;
3. 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.



9km in the Tropics; 6.5 in mid-latitudes

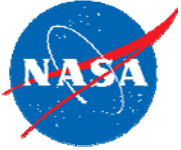


128-panel hyperwall with 128 nodes



$R_{\max}$  of 1,088 teraflops with 111,104 cores





## Concurrent Visualization: Why and How?

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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

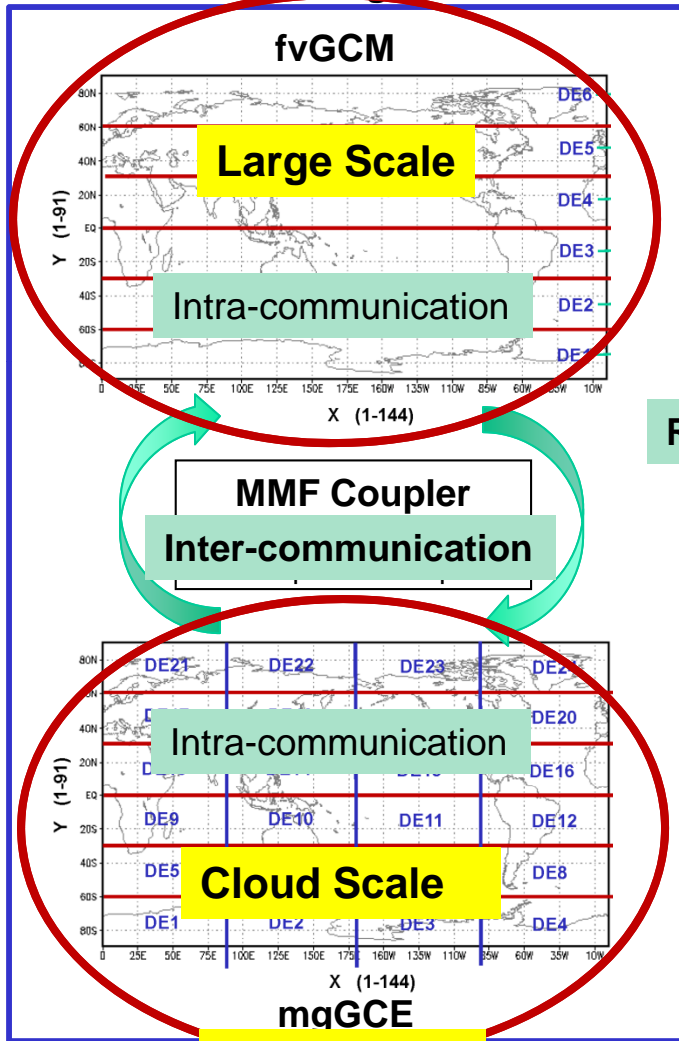




# Architecture of the CAMVis v1.0

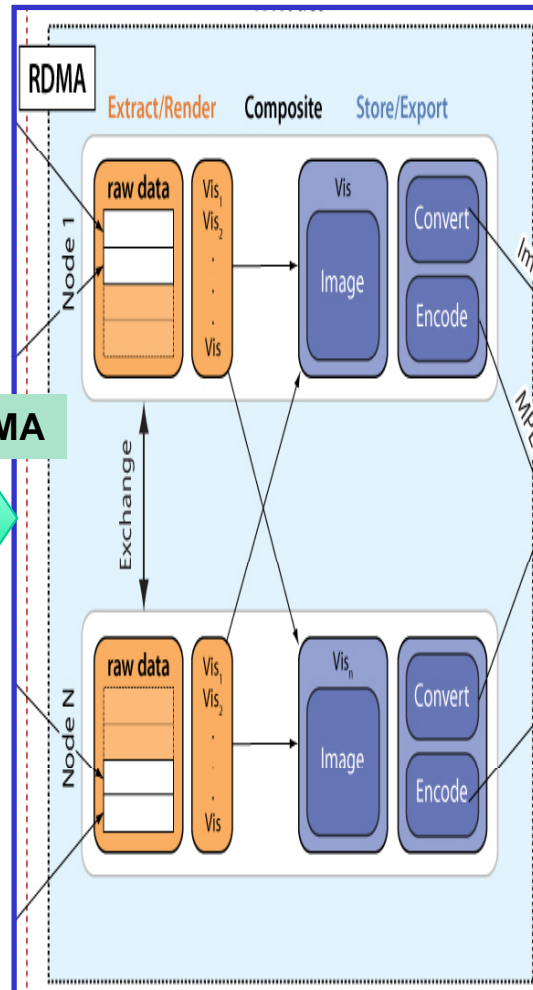
(the **C**oupled **A**dvanced **M**ultiscale modeling and concurrent **V**isualization systems; Shen et al. 2011)

## Multi-scale Modeling with "M" nodes



**Simulation**

## Current Visualization with "N" nodes

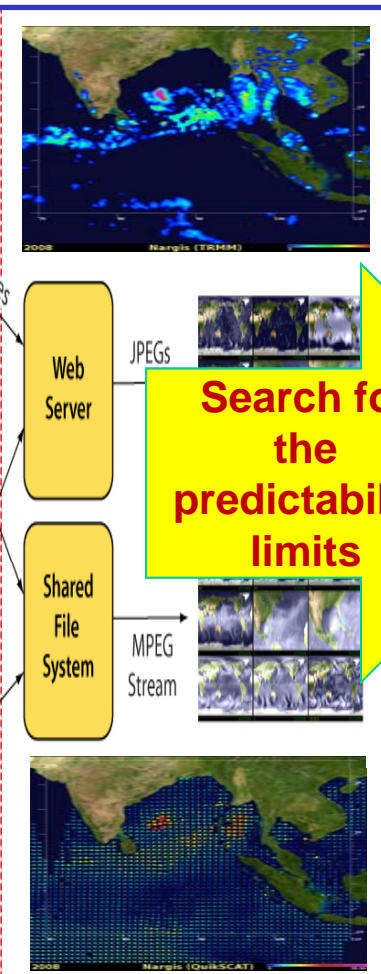


**Parallel Transfer**

**Visualization**

**comparison with satellite**

## Real-time Display



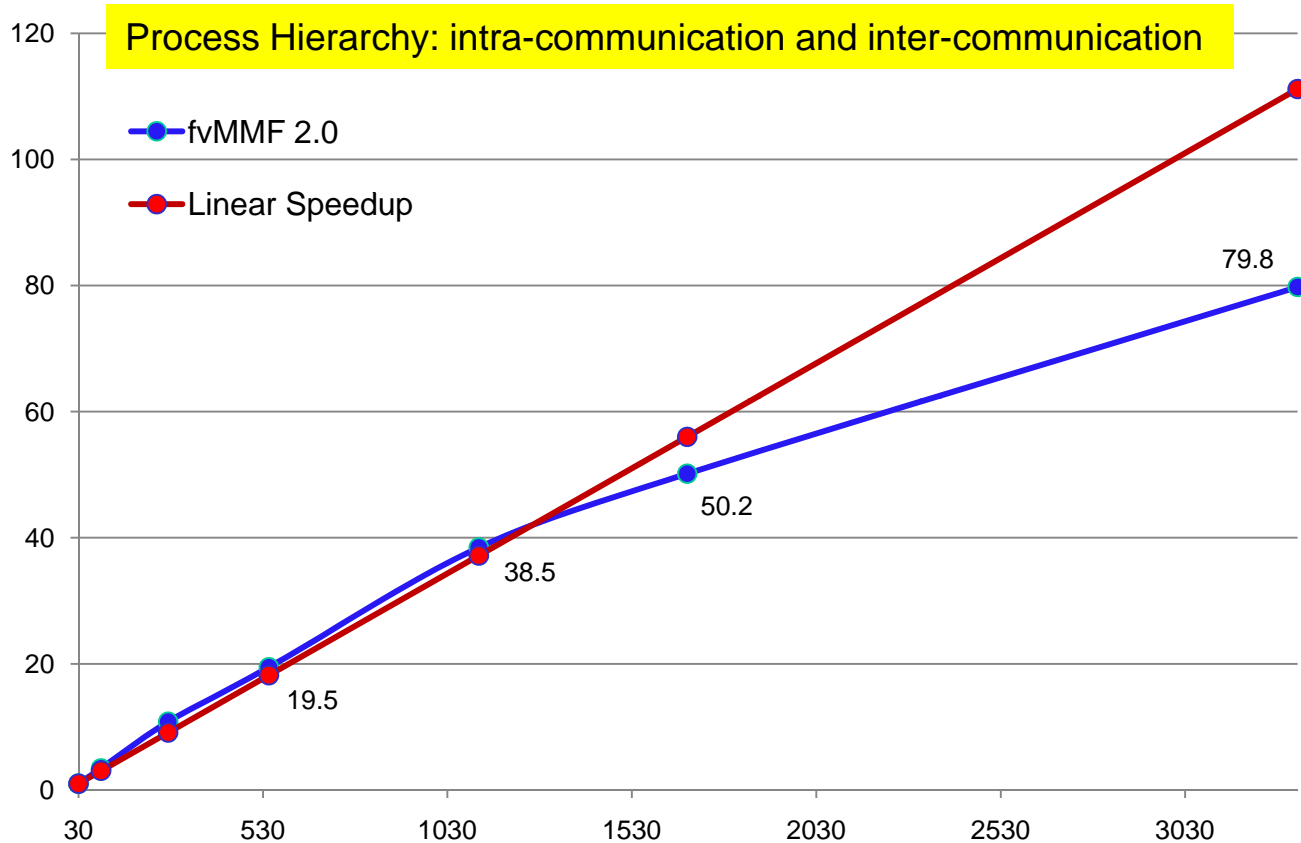
**Search for the predictability limits**

**Discovery**





## Performance of fvMMF 2.0 on Pleiades



Implementation led and completed by Bron Nelson (CO-PI)

fvMMF consists of one fvGCM and 13,104 copies of GCE.

Currently, fvGCM is running at a 2.5 degree resolution, and GCEs are at a 4km resolution.

The benchmark is based on 5-day runs with standard modeling configurations for climate simulations.

Compared to another version?

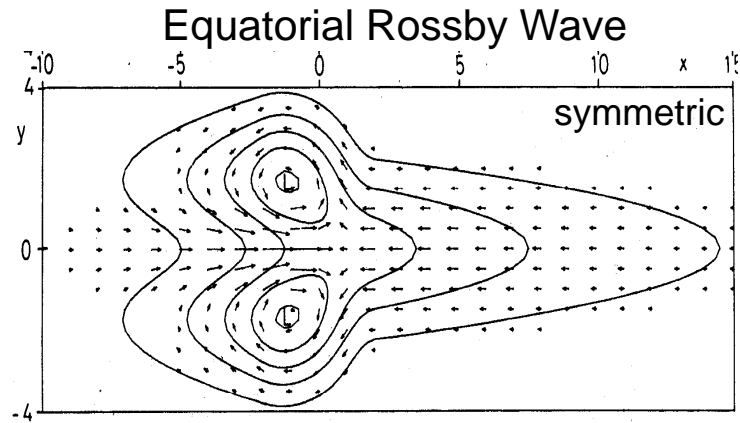
### Major Features:

1. Scalable, two-level parallelism on Pleiades (distributed memory) supercomputer;
2. A speedup of 79.8 by increasing the number of cores from 30 to 3335, which allows to finish a 30-day run within 41 minutes;
3. Bit-by-bit results with different CPU configurations;
4. Enabling high-resolutions and higher-dimensions for Goddard Cumulus Ensemble (GCE) model



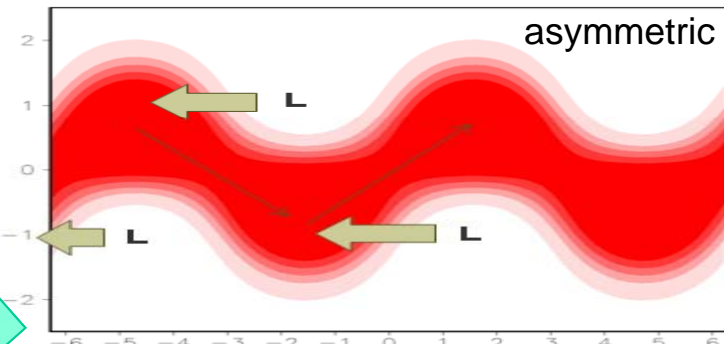


# Tropical Waves and TC Formation



An equatorial Rossby wave, appearing in Indian Ocean, is **symmetric** with respect to the equator.

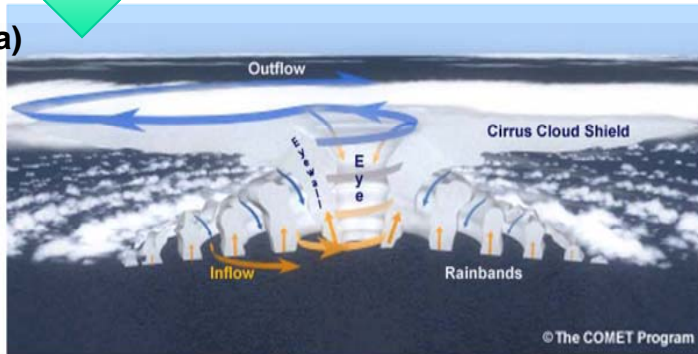
## Mixed Rossby Gravity (MRG) Wave



MRG waves, **asymmetric** with respect to the equator, occasionally appear in Indian Ocean or West Pacific

TC Nargis  
(Shen et al., 2010a)

## Hurricane's Structure



Twin TC  
(Shen et al., 2012a)

## African easterly waves (AEWs)



Helene  
(Shen et al., 2010b)

Featured in the article by Dr. Rick Anthes of UCAR entitled:  
"Turning the tables on chaos: Is the atmosphere more predictable than we assume?" UCAR Magazine, spring/summer 2011.

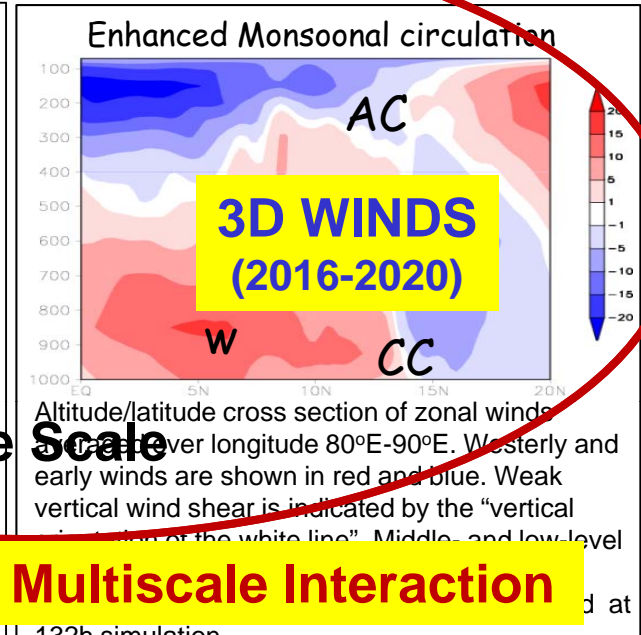
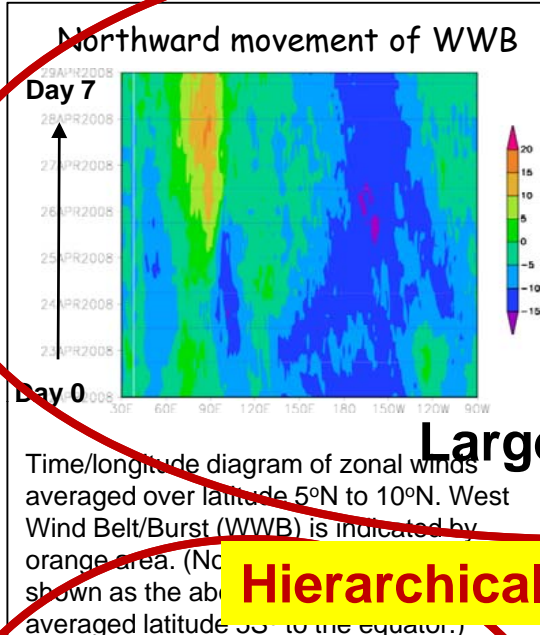
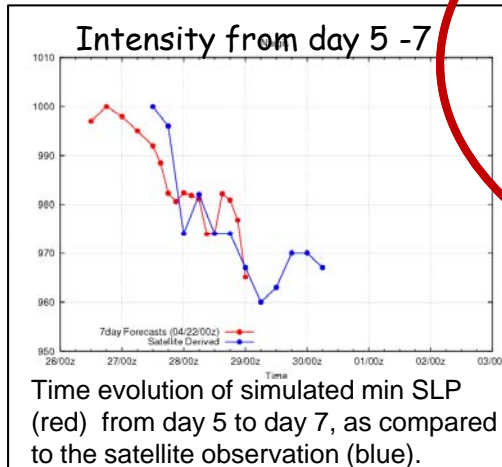




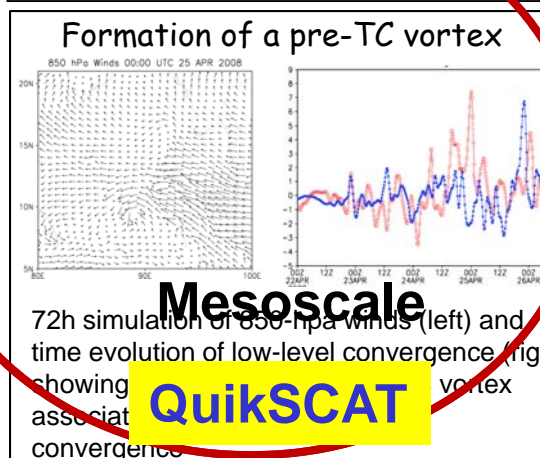
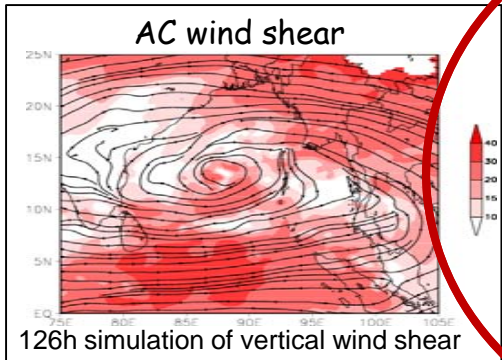
# Hierarchical Multiscale interactions of Nargis (2008)

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

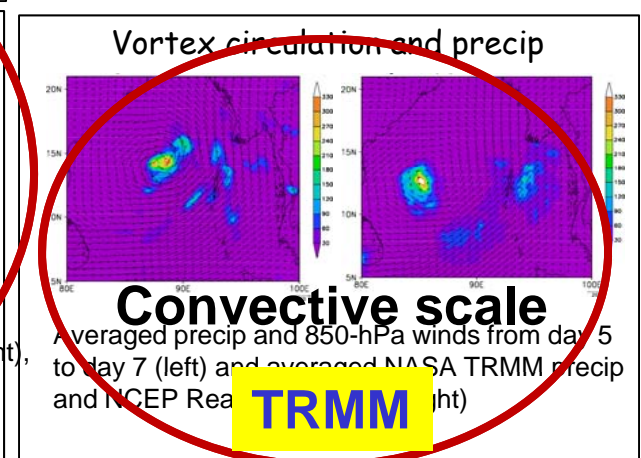
7-day global multiscale simulations suggest the following favorite factors for the formation and initial intensification of tropical cyclone Nargis:



**Hierarchical Multiscale Interaction**



**Mesoscale**  
**QuikSCAT**



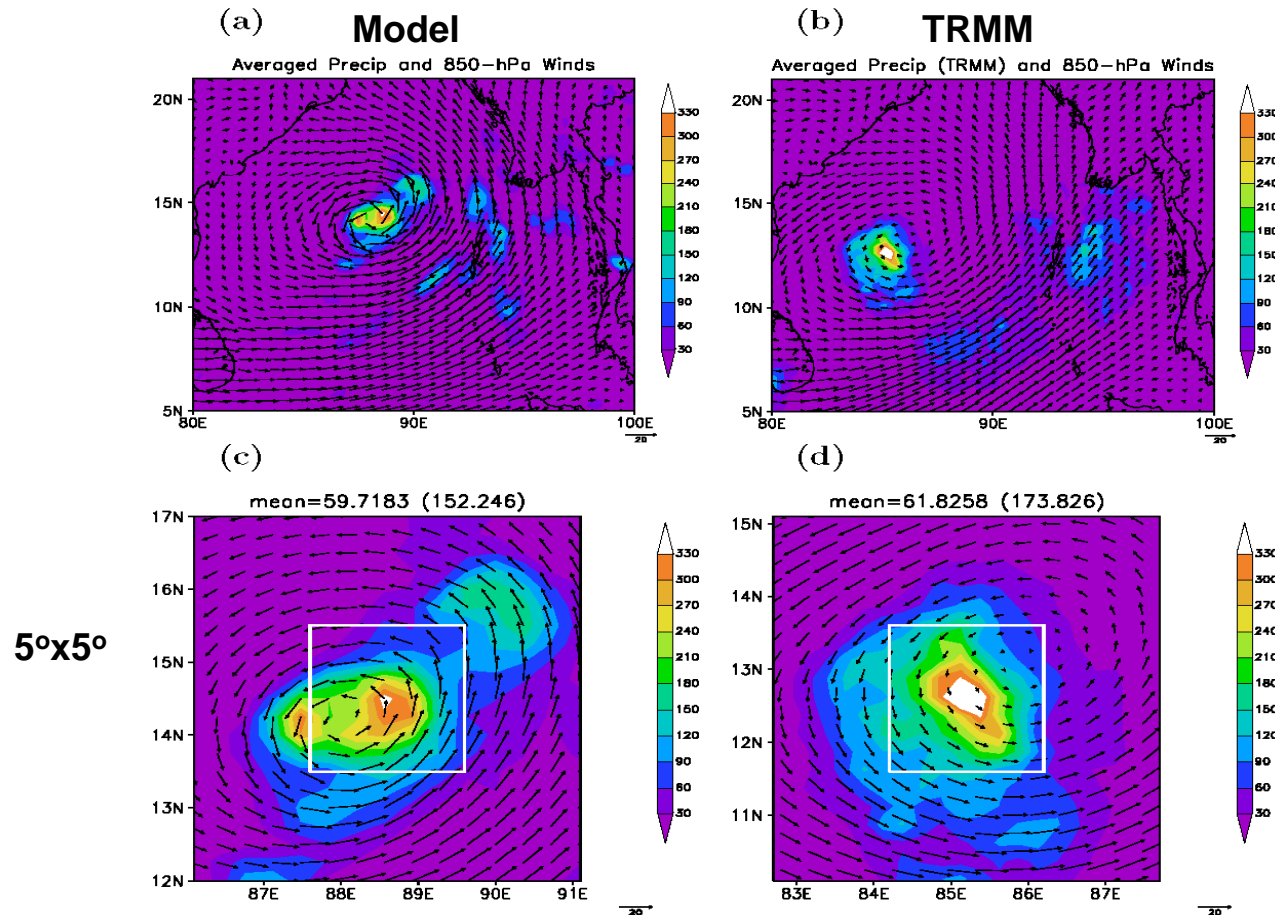
**Convective scale**  
**TRMM**

Why there is an assumption of a pre-existing disturbance in hurricane theories (such as CISK and WISHE)? → toy top spinning mechanism





# Averaged Precipitation and Wind Vectors for Nargis



The domain-averaged precipitation in the  $5^\circ$  ( $2^\circ$ ) 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  $5^\circ$  ( $2^\circ$ ) average precipitation** by the model with a larger discrepancy for  $2^\circ$  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  $5^\circ$  box, centered at the maximum of precipitation near the vortex center.

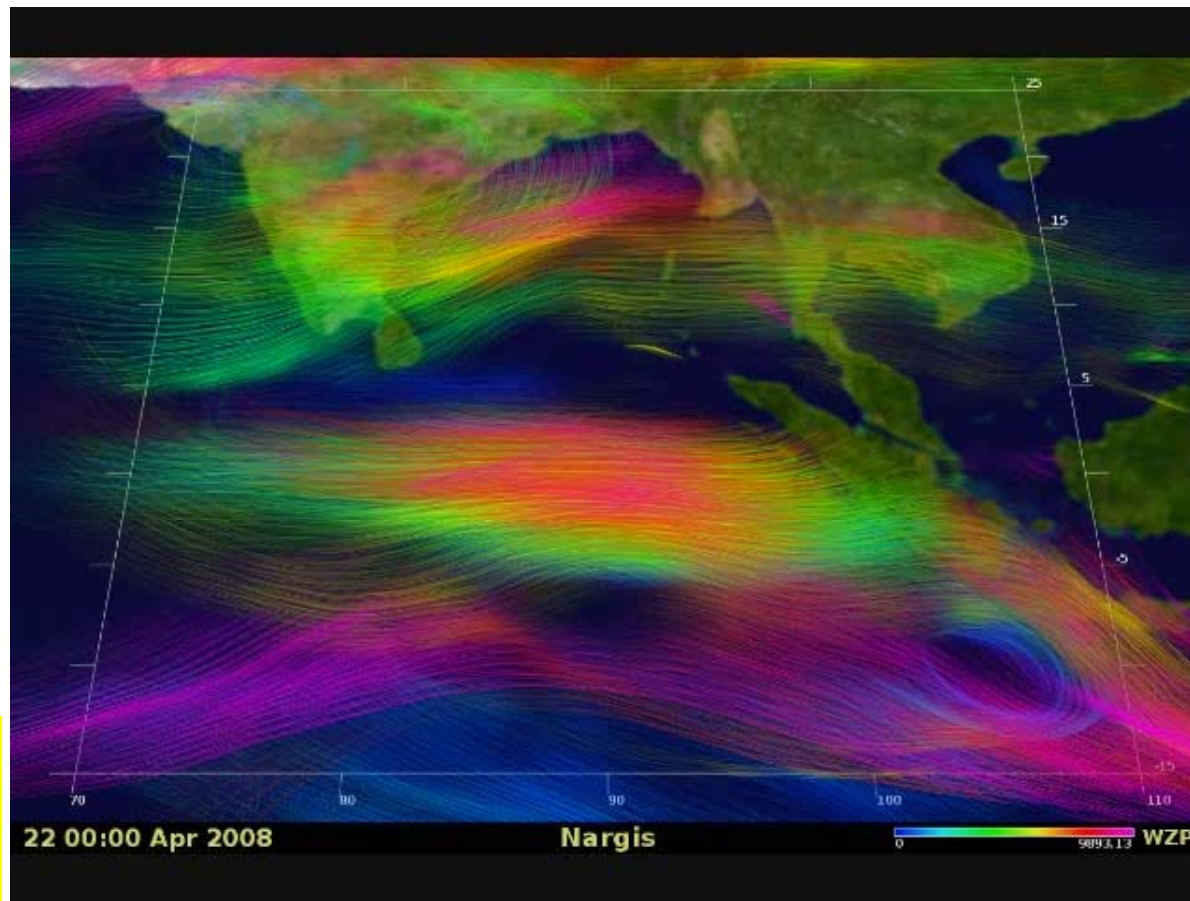




## 7-day Forecast of Genesis of Cyclone Nargis (2008) 00 UTC 22 Apr-00UTC 29 Apr

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

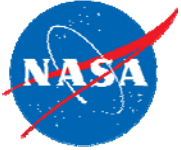
- Upper-level winds in red
- Middle-level winds in green
- Low-level winds in blue



fusion of satellite data;  
the search for  
predictive index

Shen, B.-W., W.-K. Tao, W. K. Lau, R. Atlas, 2010a, JGR, **115**, D14102, doi:10.1029/2009JD013140.

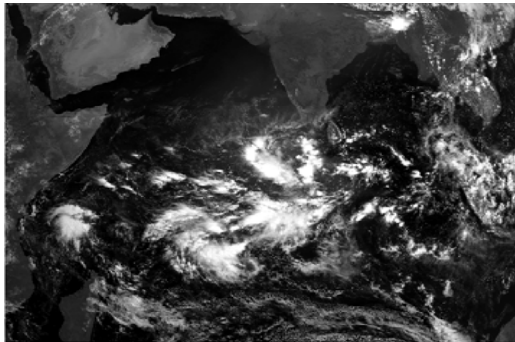




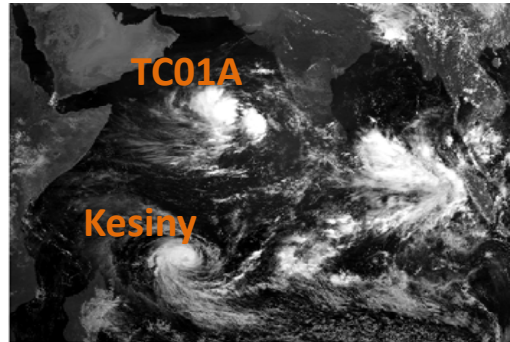
## Twin TCs and a MRG wave in May 2002

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 28.

0630 UTC 1 May 2002



0000 UTC 6 May 2002



0000 UTC 9 May 2002

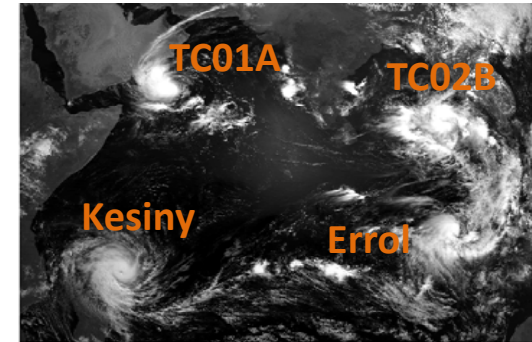
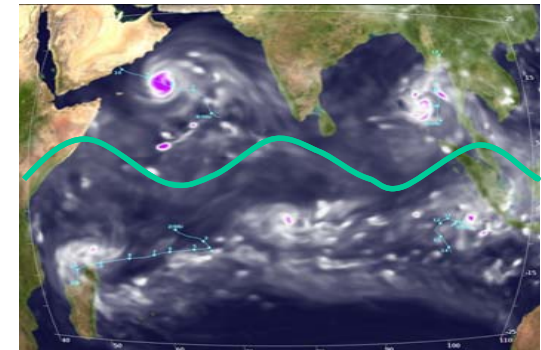


Figure: Predictions regarding the formation of twin tropical cyclones in the Indian Ocean: (a) MJO-organized convection over the Indian Ocean at 0630 UTC 1 May 2002. When the MJO moved eastward, two pairs of twin TCs appeared sequentially on 6 May (b) and 9 May (c), including TC 01A, Kesiny, TC 02B and 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., 2011 and 2012a for details).



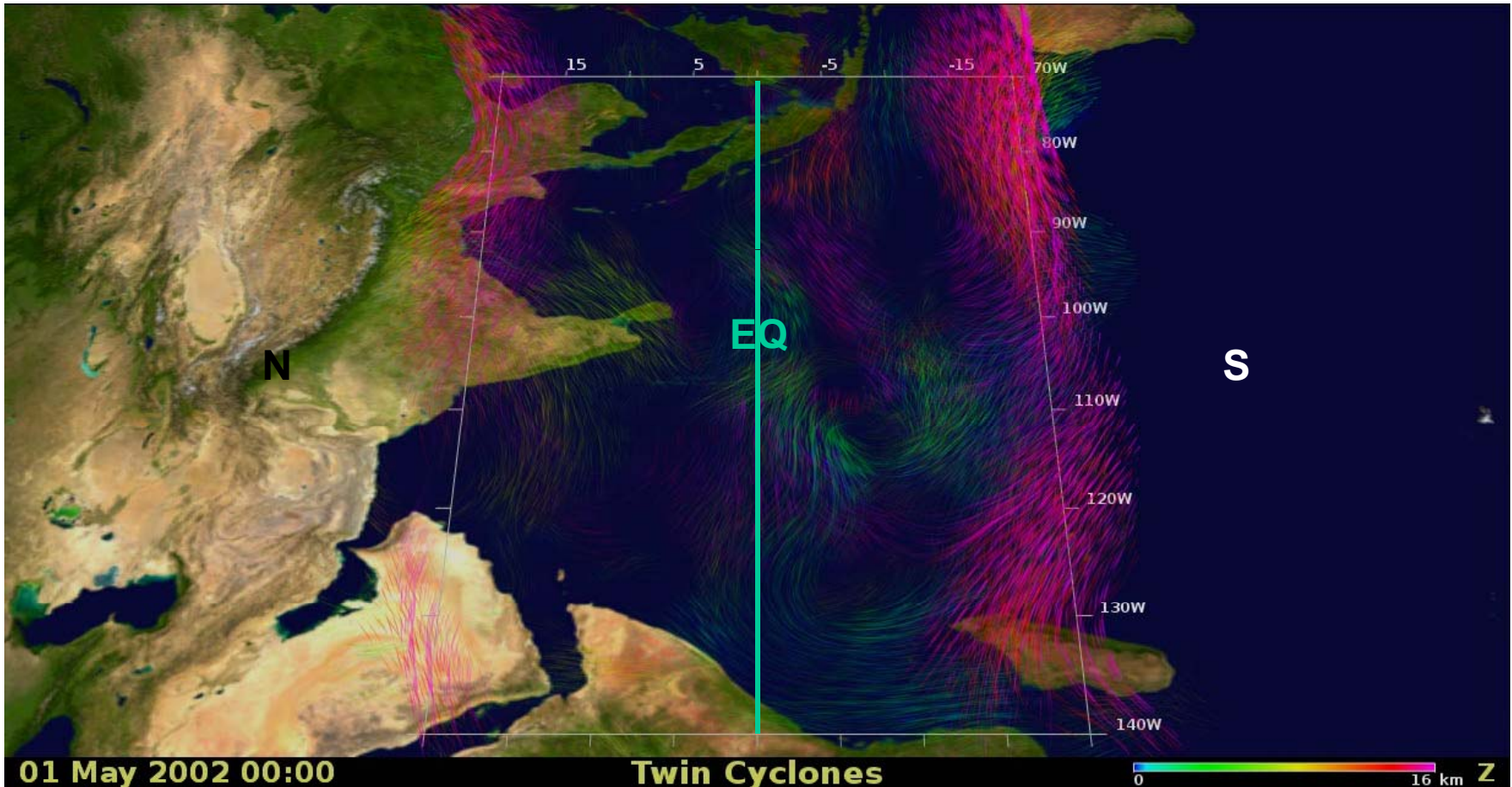
**Shen, B.-W., W.-K. Tao, and Y.-L. Lin, 2012a: Genesis of Twin Tropical Cyclones Revealed by a Global Mesoscale Model: the Role of Mixed Rossby Gravity Wave (submitted to AGU-JGR in Jan. 2012)**





## Evolution of Twin TCs and the MRG Wave

The successive formation of multiple TCs may indicate the appearance of a mixed Rossby gravity (MRG) wave.

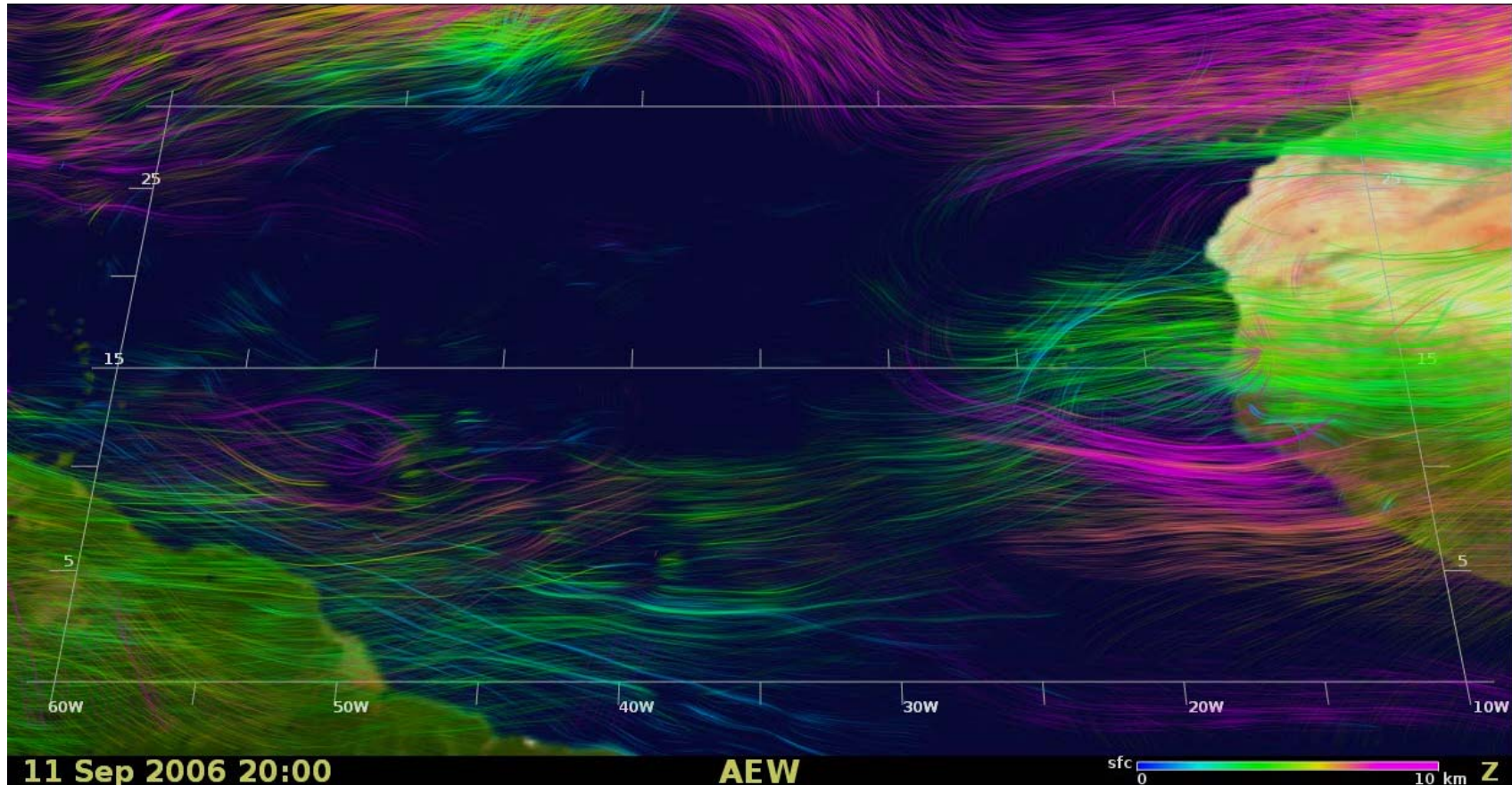


Shen et al., 2012a,2012c (submitted to AGU-JRL and IEEE CiSE in January, 2012)





## Formation of Hurricane Helene (2006)



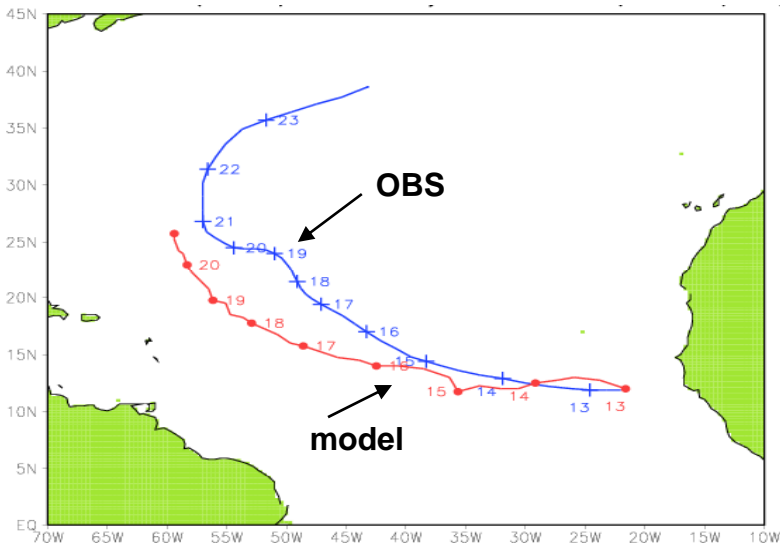
- Simulations from Day 20 to Day 30 in a 30-day run initialized at 0000 UTC Aug 22, 2006.
- **Upper-level winds in red; middle-level winds in green; low-level winds in blue**
- Low-level CC (cyclonic circulation); Upper-level AC (anticyclonic circulation)
- Shen, B.-W. W.-K. Tao and M.-L. Wu, 2010b: African Easterly Waves in 30-day High-resolution Global Simulations: A Case Study during the 2006 NAMMA Period. *GRL.*, L18803



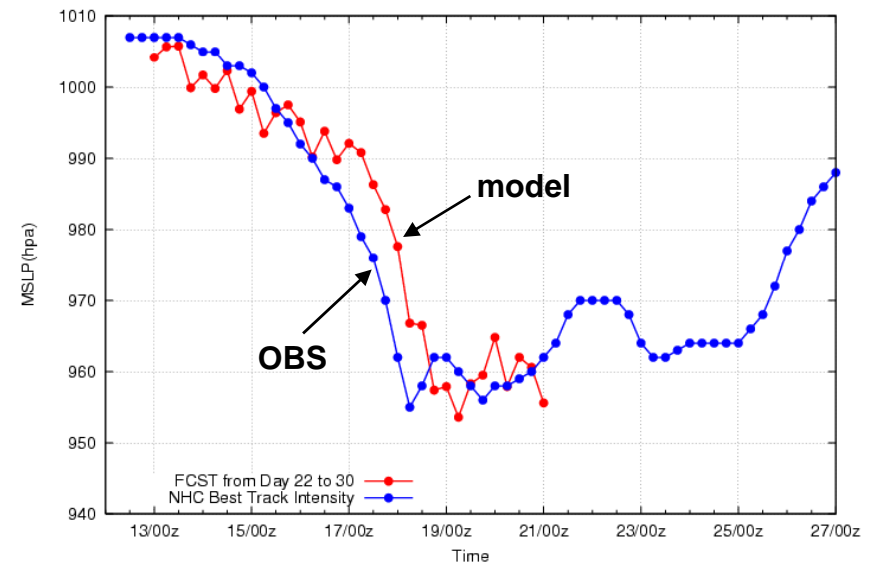


## Simulations of Helene (2006) between Day 22-30 (Helene: 12-24 September, 2006)

### Track Forecast



### Intensity Forecast



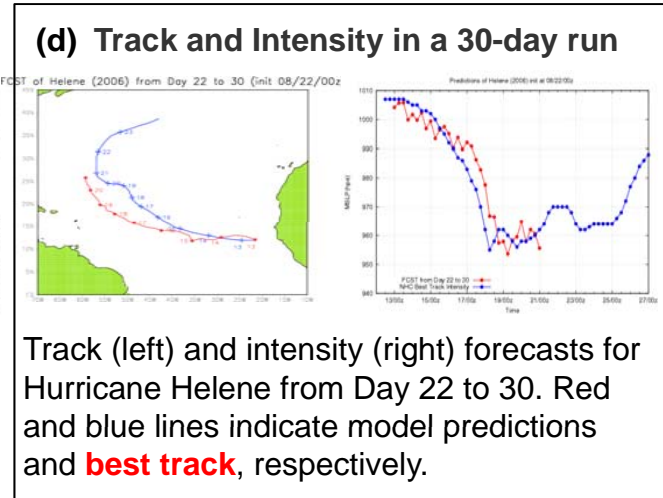
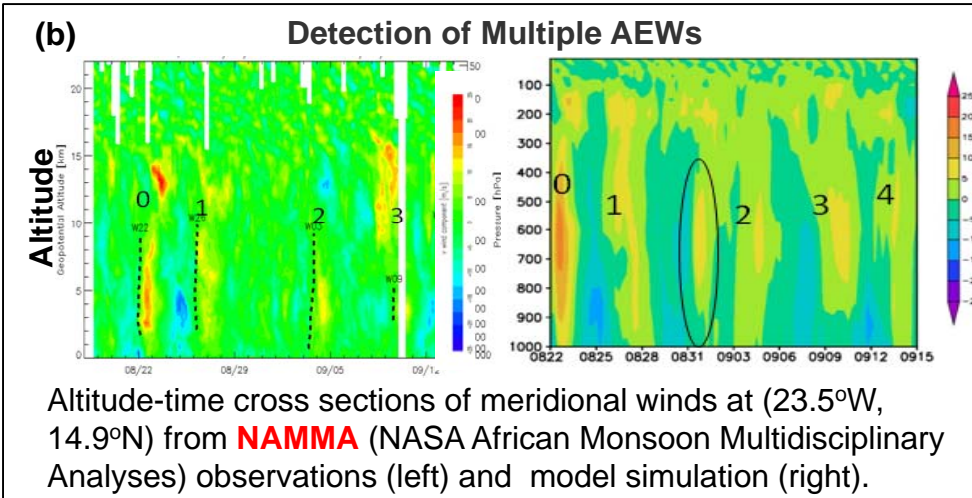
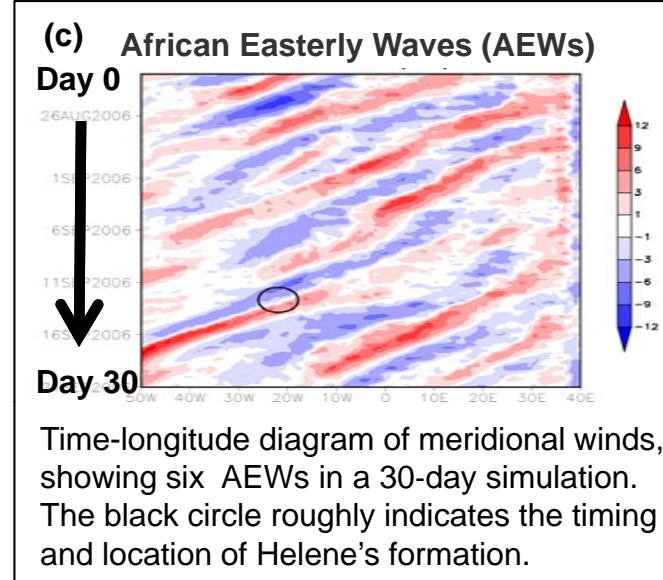
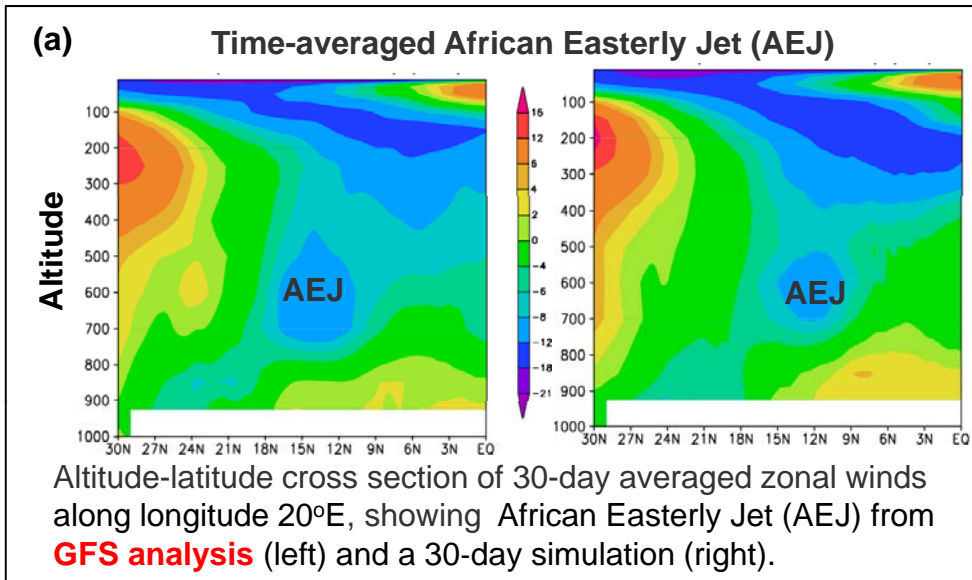
Future work:

to study multiscale interactions among TEJ, AEJ, AEWs, hurricanes and surface mechanic and thermodynamic processes

Shen, B.-W., W.-K. Tao, and M.-L. Wu, 2010b: African Easterly Waves and African Easterly Jet in 30-day High-resolution Global Simulations. A Case Study during the 2006 NAMMA period. Geophys. Res. Lett., L18803, doi:10.1029/2010GL044355.

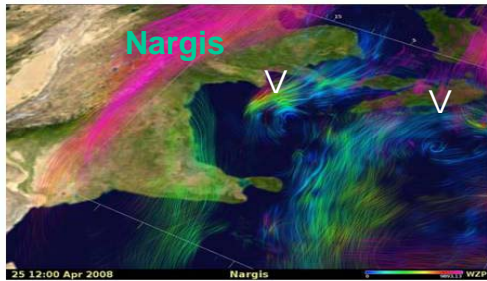


# Multiscale Interactions of AEJ, AEWs, Hurricane and Surface Processes in a 30-day run

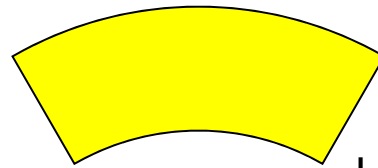




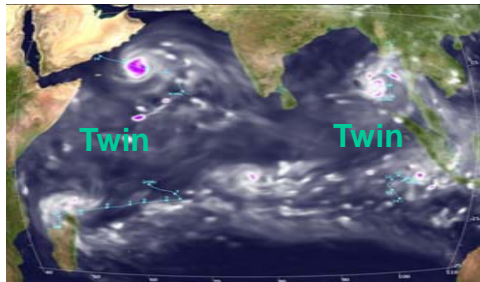
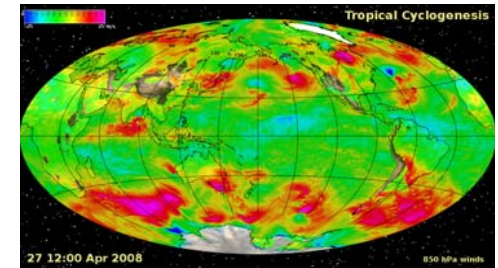
# A Summary of the AIST08 CAMVis Project



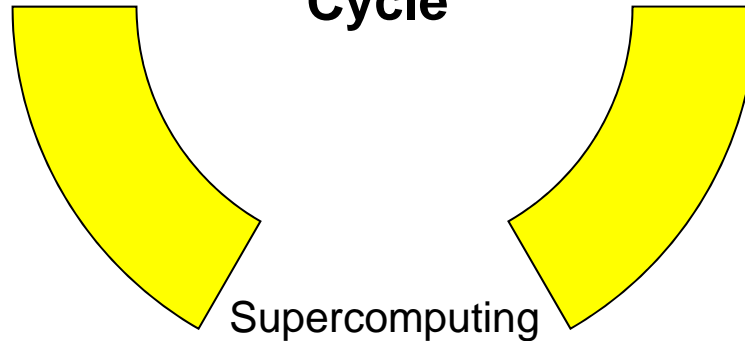
Scientific Discoveries



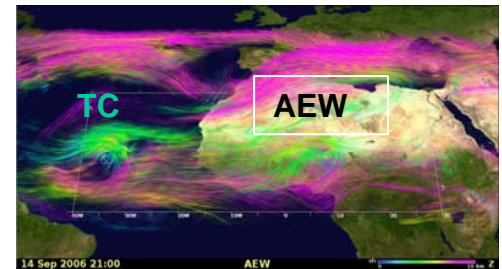
Large-scale Numerical Modeling



Cycle



Supercomputing



The CAMVis is developed to illustrate:

- downscaling (zoomed-in) processes --- **reductionism**
- scale interaction (zoomed-out) processes --- **Integrative view/thinking**





## Is the atmosphere more predictable than we assume?

- Why does the high-resolution global model have skills?
- Is the above AEW simulation (in-)consistent with Chaos theory?



Courtesy of Anthes (2011) and Wikipdeia

- The butterfly effect of first kind: it means the sensitive dependence on initial conditions.
- The butterfly effect of second kind: it becomes a symbol that small perturbations can alter large-scale structure.



# An Analogy to Toy Top Spinning

Formation (initial spinning)

persistent forcing



~80 kg  
(176 lbs)

Intensification with energy supply

Impulsive forcing



Nearly 85% of intense hurricanes have their origins as AEWs.





# Is There a Butterfly Effect?

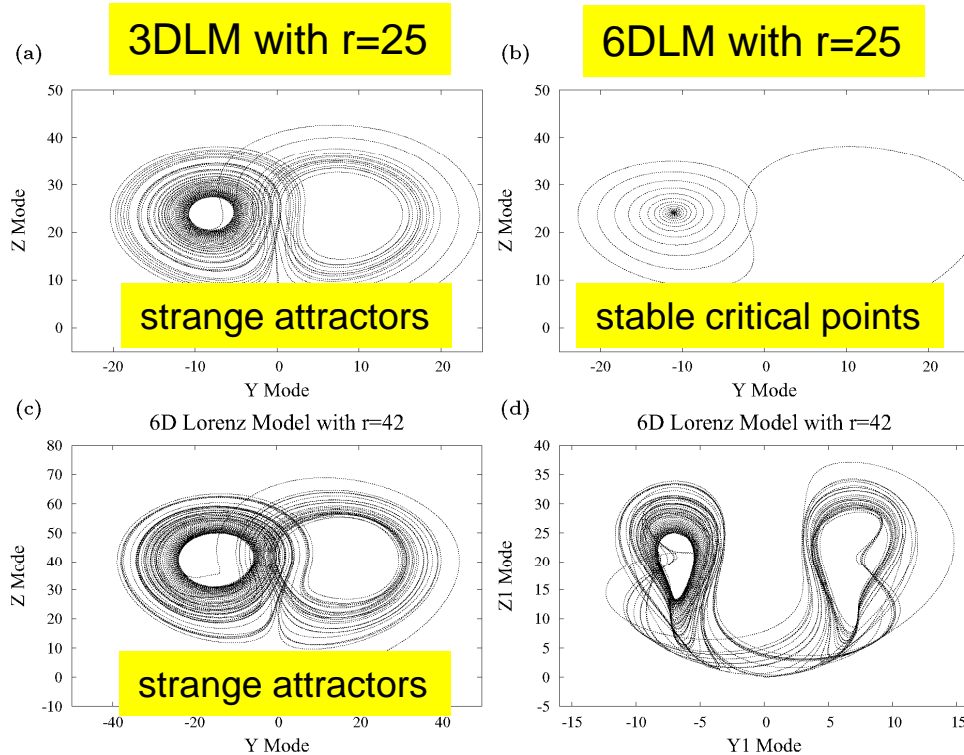


Figure 1: Phase space plots in the 3D (a) and 6D (b-d) Lorenz models. (a) A  $(Y, Z)$  plot with  $r=25$ . the so-called Lorenz strange attractors. (b) A  $(Y, Z)$  plot with  $r=25$ . (c) A  $(Y, Z)$  plot with  $r=42$  with attractors. (d) A  $(Y_1, Z_1)$  plot with  $r=42$ .



Courtesy of Anthes (2011) and Wikipedia

1. Originally, the butterfly effect means the sensitive dependence on initial conditions.
2. It is inferred to become a symbol that small perturbations can alter large-scale structure.

Enhanced nonlinear interactions with additional modes can improve solution stability. (while some of smaller scale processes may provide important feedback, the other may have insignificant impact, indicating the asymmetric features of hierarchical scale interaction.)

**Shen, B.-W., 2012b:** Negative Feedback in a Generalized Lorenz Model (submitted to AGU-JGR in Jan., 2012)





## The Need of Multiscale Analysis Package (MAP)

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An even more challenging task of building statistics on the predictive relationships between TC activity and large-scale environmental conditions -and thus provide robust TC climate projections -- is still needed.

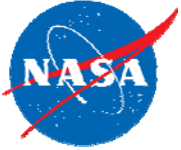
We need to quantitatively identify (i) the control and feedback processes between multi-scale weather events, which involve nonlinear multiscale interactions and (ii) the critical dynamical processes, which lead to TC formation and intensification but may appear only on a short time period or over a limited local area.

Therefore, it is crucial to conduct data exploiting activities with efficient multiscale analysis that can address

1. the **non-linearity** and **non-stationarity** in climate processes,
2. the spatial and **temporal locality** for regional/mesoscale weather events,
3. and less-known predictive relationships behind the massive volume of high-resolution satellite and model data.

→ Multi-dimensional space-wavenumber or time-frequency maps

The MAP will be developed under the support of AIST11 project (PI: Shen)



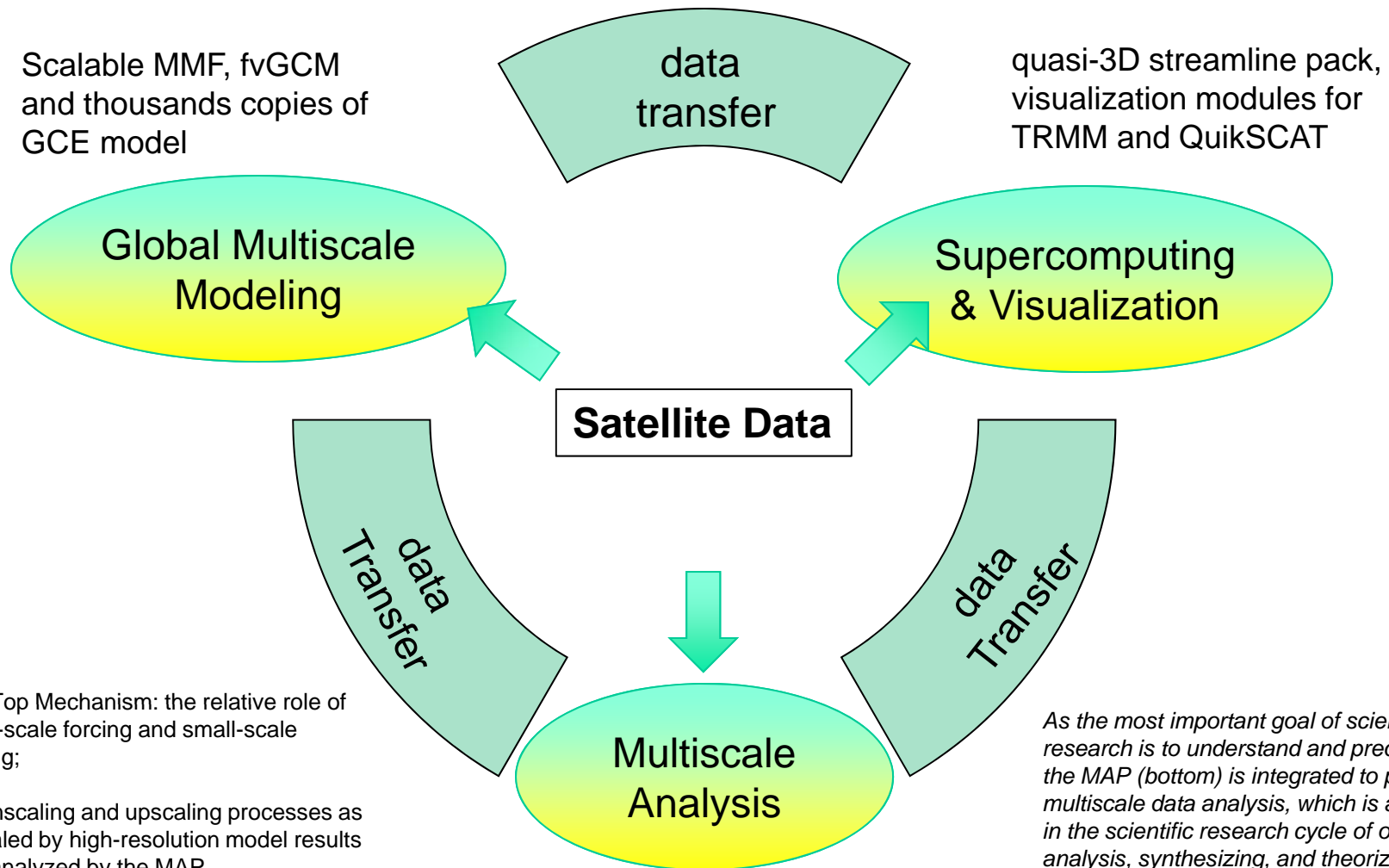
## Comparison among Hilbert Huang Transform (HHT), Fourier, and Wavelet Analysis

	Fourier	Wavelet	Hilbert ( <b>HHT</b> )
Basis	a priori	a priori	a posteriori adaptive
Frequency	convolution over global domain, uncertainty	convolution over global domain, uncertainty	differentiation over local domain, certainty
Presentation	Energy in frequency space	Energy in time-frequency space	Energy in time-frequency space
<b>Nonlinearity</b>	no	no	yes
<b>Nonstationarity</b>	no	yes	yes
Feature extraction	No	discrete: no, continuous: yes	yes
Theoretical base	complete mathematical theory	complete mathematical theory	empirical

Instantaneous frequencies as functions of time, which sharply identify imbedded structures



# Architecture of the CAMVis-MAP (Scalable Multiscale Analysis Package)

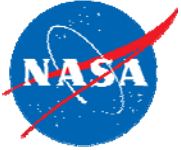


- Toy Top Mechanism: the relative role of large-scale forcing and small-scale forcing;
- Downscaling and upscaling processes as revealed by high-resolution model results and analyzed by the MAP
- The role of nonlinear effects in the generalized Lorenz model and high-resolution simulations

Scalable framework for global EMD, ensemble EMD and , multi-dimensional ensemble EMD

*As the most important goal of scientific research is to understand and predict nature, the MAP (bottom) is integrated to perform multiscale data analysis, which is a critical link in the scientific research cycle of observation, analysis, synthesizing, and theorizing. To speed up the time to solution, the MAP will be implemented with three-level parallelism on NASA supercomputers.*





## Selected Publications

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### Published:

- **Shen, B.-W.**, W.-K. Tao, and B. Green, **2011**: Coupling Advanced Modeling and Visualization to Improve High-Impact Tropical Weather Prediction (CAMVis), IEEE Computing in Science and Engineering (CiSE), vol. 13, no. 5, pp. 56-67, Sep./Oct. 2011, doi:10.1109/MCSE.2010.141. <http://sites.google.com/site/bowenshen159/cv/docs/Shen-et-al-2011-CiSE.pdf>
- **Shen, B.-W.**, W.-K. Tao, and M.-L. Wu, **2010b**: African Easterly Waves in 30-day High resolution Global Simulations: A Case Study during the 2006 NAMMA Period. Geophys. Res. Lett., 37, L18803, doi:10.1029/2010GL044355. <http://sites.google.com/site/bowenshen159/cv/docs/2010GL044355.pdf>
- **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. [http://sites.google.com/site/bowenshen159/cv/docs/Shen\\_2009JD013140.pdf](http://sites.google.com/site/bowenshen159/cv/docs/Shen_2009JD013140.pdf)
- Green, B., C. Henze, **B.-W. Shen**, 2010: Development of a scalable concurrent visualization approach for high temporal- and spatial-resolution models. Eos Trans. AGU, 91(26), West. Pac. Geophys. Meet. Suppl., Abstract A23B-142. AGU 2010 Western Pacific Geophysics Meeting, Taipei, Taiwan, June 22-25, 2010.

### Submitted:

- **Shen, Bo-Wen, 2012c**: Nonlinear Feedback in a Generalized Lorenz Model. (submitted to AGU JGR) <https://sites.google.com/site/bowenshen159/cv/docs/Shen-2012-GRL-draft.pdf>
- **Shen, Bo-Wen, B. Nelson, W.-K. Tao, and Y.-L. Lin, 2012b**: Advanced Visualizations of Scale Interactions of Tropical Cyclone Formation and Tropical Waves. (submitted to IEEE Computing in Science and Engineering) [http://sites.google.com/site/bowenshen159/cv/docs/Shen\\_2011-CiSE-draft.pdf](http://sites.google.com/site/bowenshen159/cv/docs/Shen_2011-CiSE-draft.pdf)
- **Shen, Bo-Wen, W.-K. Tao, and Y.-L. Lin, 2012a**: Genesis of Twin Tropical Cyclones as Revealed by a Global Mesoscale Model: The Role of Mixed Rossby Gravity Waves. (submitted to AGU JGR) <http://sites.google.com/site/bowenshen159/cv/docs/Shen-et-al-2012-JGR-draft.pdf>