Coupling Advanced Modeling and Visualization to Improve High-impact Tropical Weather Prediction

Dr. Bo-Wen Shen (PI)

ESSIC, University of Maryland, College Park
and
NASA Goddard Space Flight Center

AGU 2011 Fall Meeting
San Francisco, December 08, 2011

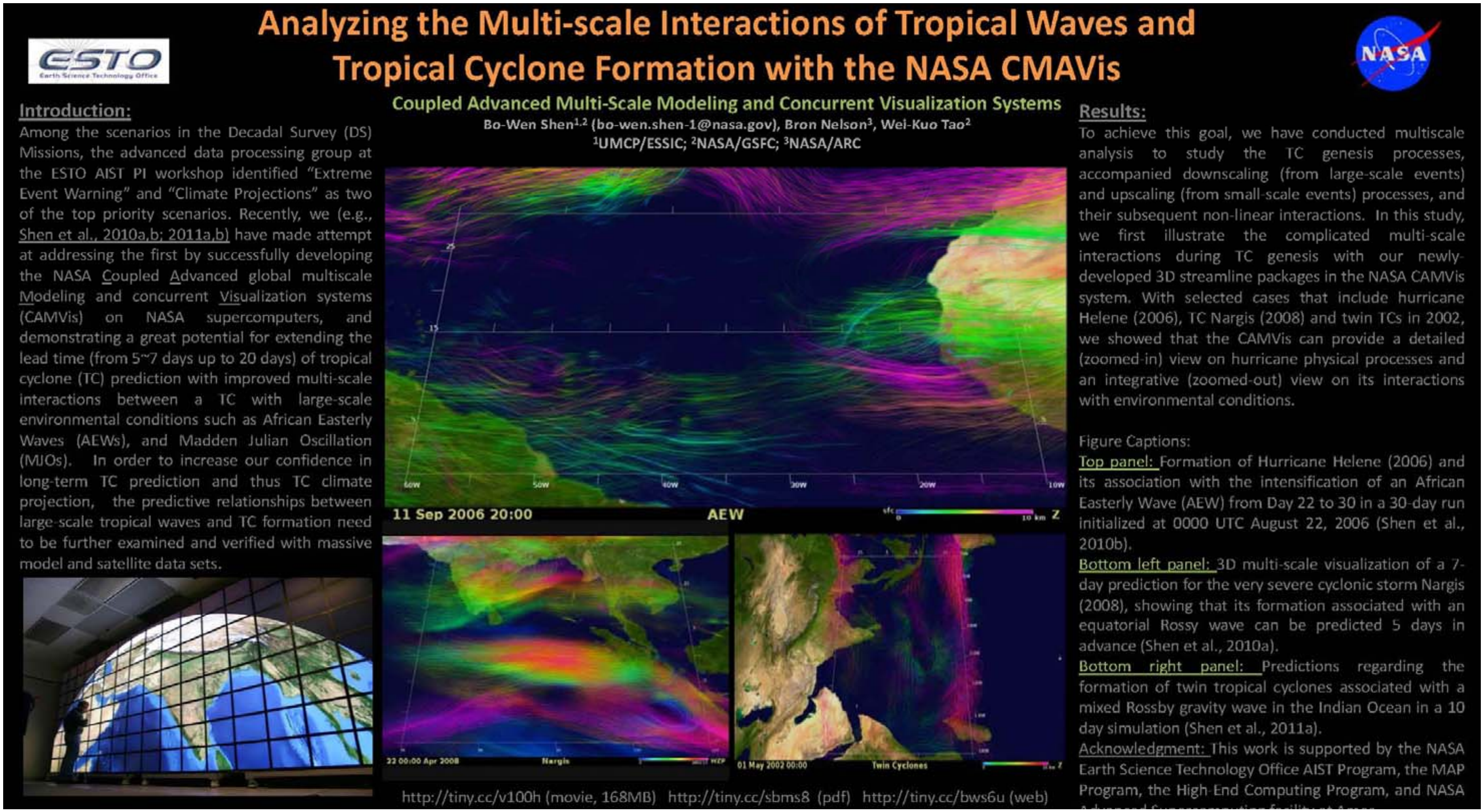
Project Title of AIST-08-0049:
Coupling NASA **A**dvanced Multi-Scale **M**odeling and Concurrent **Vis**ualization Systems for Improving Predictions of Tropical High-Impact Weather (**CAMVis**)

Acknowledgements

- NASA/GSFC: Wei-Kuo Tao (CO-PI), William K. Lau, Jiundar Chern, Christa Peters-Lidard, Oreste Reale, Kuo-Sen Kuo, Jenny Wu
- NASA/JPL: Frank Li (CO-I), Peggy Li (CO-I)
- UCAR: Richard Anthes
- Navy Research Lab: Jin Yi
- NOAA/AOML: Robert Atlas
- UMCP: Antonio Busalacchi (CO-I)
- NC A&T State U.: Yuh-Lang Lin
- NASA/ARC: Bron Nelson (CO-PI), Chris Henze (CO-I), Bryan Green (CO-I), Piyush Mehrotra (CO-I), David Ellsworth (CO-I), Henry Jin, Johnny Chang, Samson Cheung, C. Schulbach, R. Ciotti, C. Niggley, S. Chang, W. Thigpen, B. Hood A. Lazanoff, K. Freeman, J. Taft, control-room

- Funding sources: NASA ESTO (Earth Science Technology Office) AIST (Advanced Information System Technology) Program; NASA Modeling, Analysis, and Prediction (MAP) Program; NASA Energy and Water Cycle Study (NEWS) Program; National Science Foundation (NSF) Science and Technology Center (STC)

ePoster (IN43B-1446)
(Earth and Space Science Informatics)



http://tiny.cc/v100h (movie, 168MB) http://tiny.cc/sbms8 (pdf) http://tiny.cc/bws6u (web)

Outline

- Introduction
- NASA Global Multiscale Modeling, Supercomputing Technology
  and Concurrent Visualization Systems
- Scientific Demos:
  1: Formation of Tr… 98) associated with …
  2: Formation of … ssociated with …
  3: Formation of Hu… sociated with an Africa…
- Concluding Remarks

Tropical Cyclone (TC) Formation

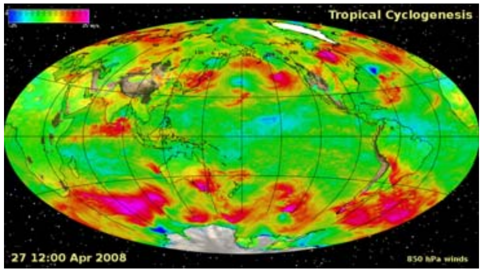
Tropical Waves

Objectives

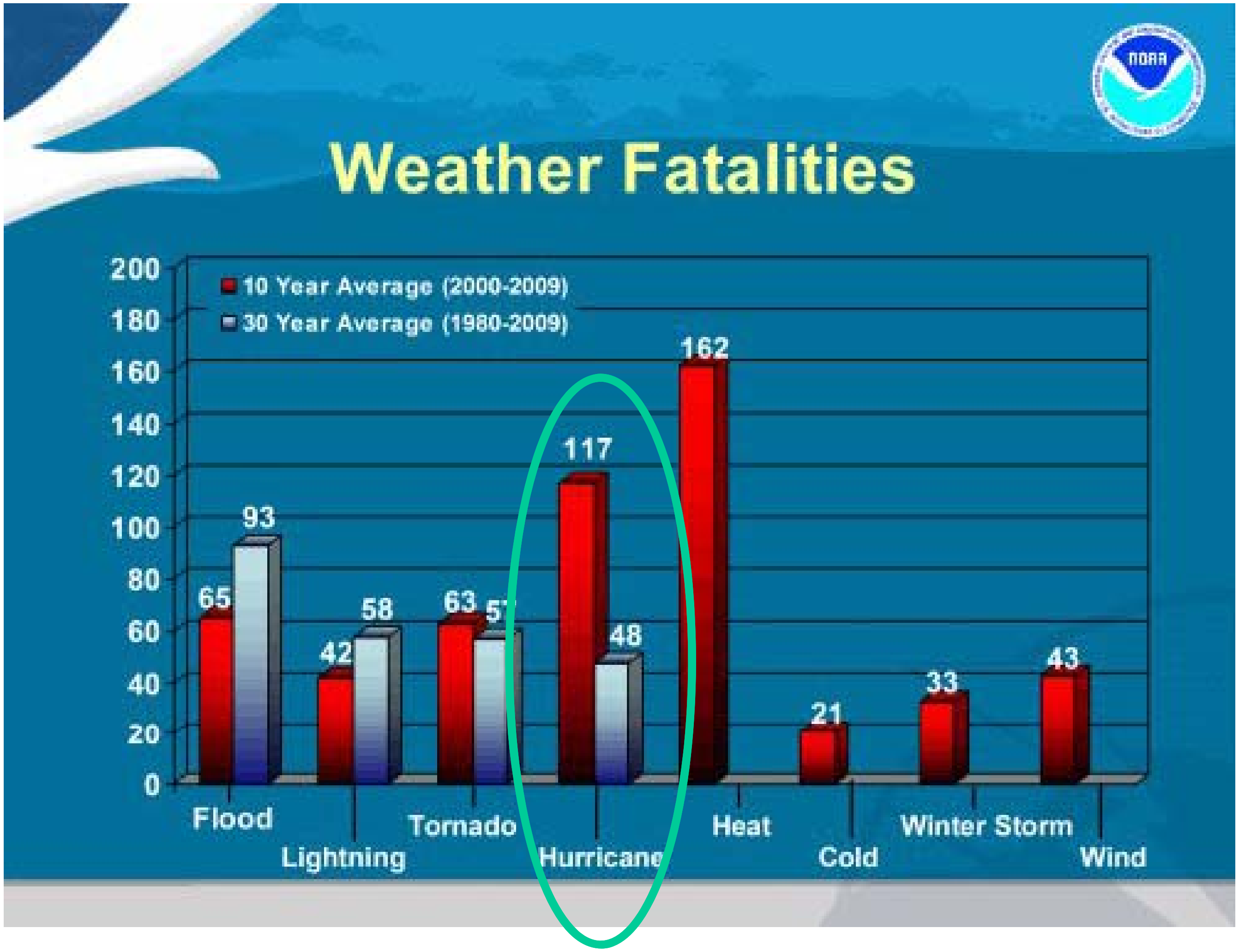
CAMVis weather prediction tool is being developed to achieve the following goals by seamlessly integrating NASA technologies (including advanced multiscale modeling visualizations and supercomputing):

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



The U.S. Natural Hazard Statistics



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

High-impact Tropical Weather: Hurricanes

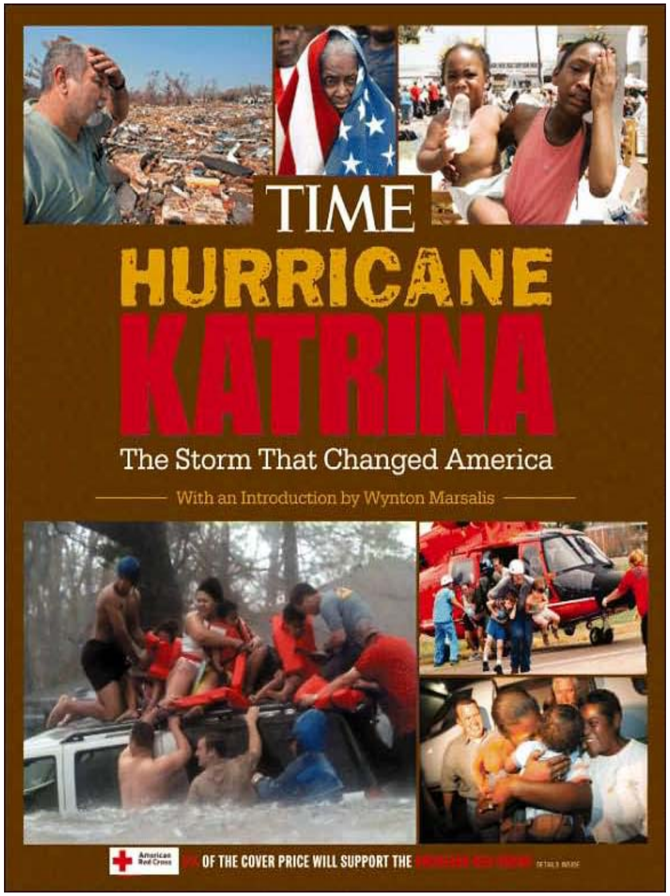
Each year tropical cyclones (TCs) cause tremendous economic losses and many fatalities throughout the world. Examples include Hurricane Katrina (2005), which is the costliest Atlantic hurricane in history, and TC Nargis, which is one of the 10 deadliest TCs of all time.

Hurricane Katrina (2005)

- Cat 5, 902 hPa, with two stages of rapid intensification
- The sixth-strongest Atlantic hurricane ever recorded.
- The third-strongest landfalling U.S. hurricane ever recorded.
- The costliest Atlantic hurricane in history! ($75 billion)
- http://en.wikipedia.org/wiki/Hurricane_Katrina

Severe Tropical Storm Nargis (2008)

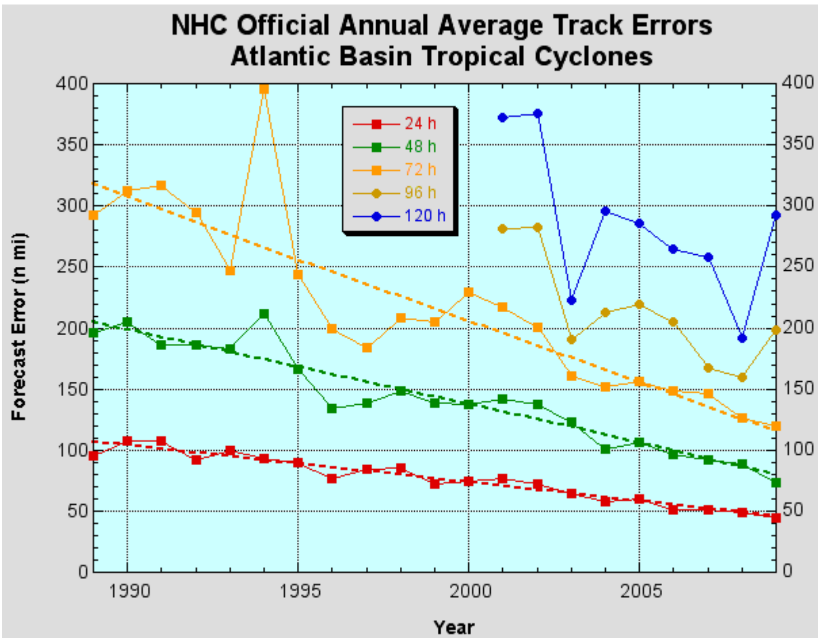
- Deadliest named cyclone in the North Indian Ocean Basin
- Short lifecycle: 04/27-05/03, 2008; identified as TC01B at 04/27/12Z by the Joint Typhoon Warning Center (JTWC).
- Very intense, with a Minimum Sea Level Pressure of 962 hPa and peak winds of 135 mph (~Category 4)
- High Impact: damage ~ $10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



Progress of Hurricane Forecasts
(by National Hurricane Center)

Track Errors (1989-2009)

better



Intensity Errors (1990-2009)

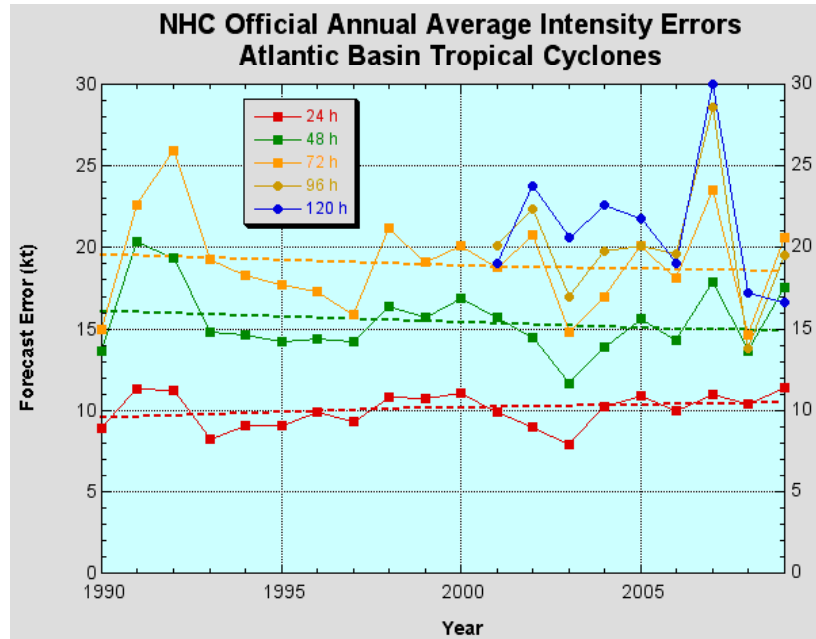
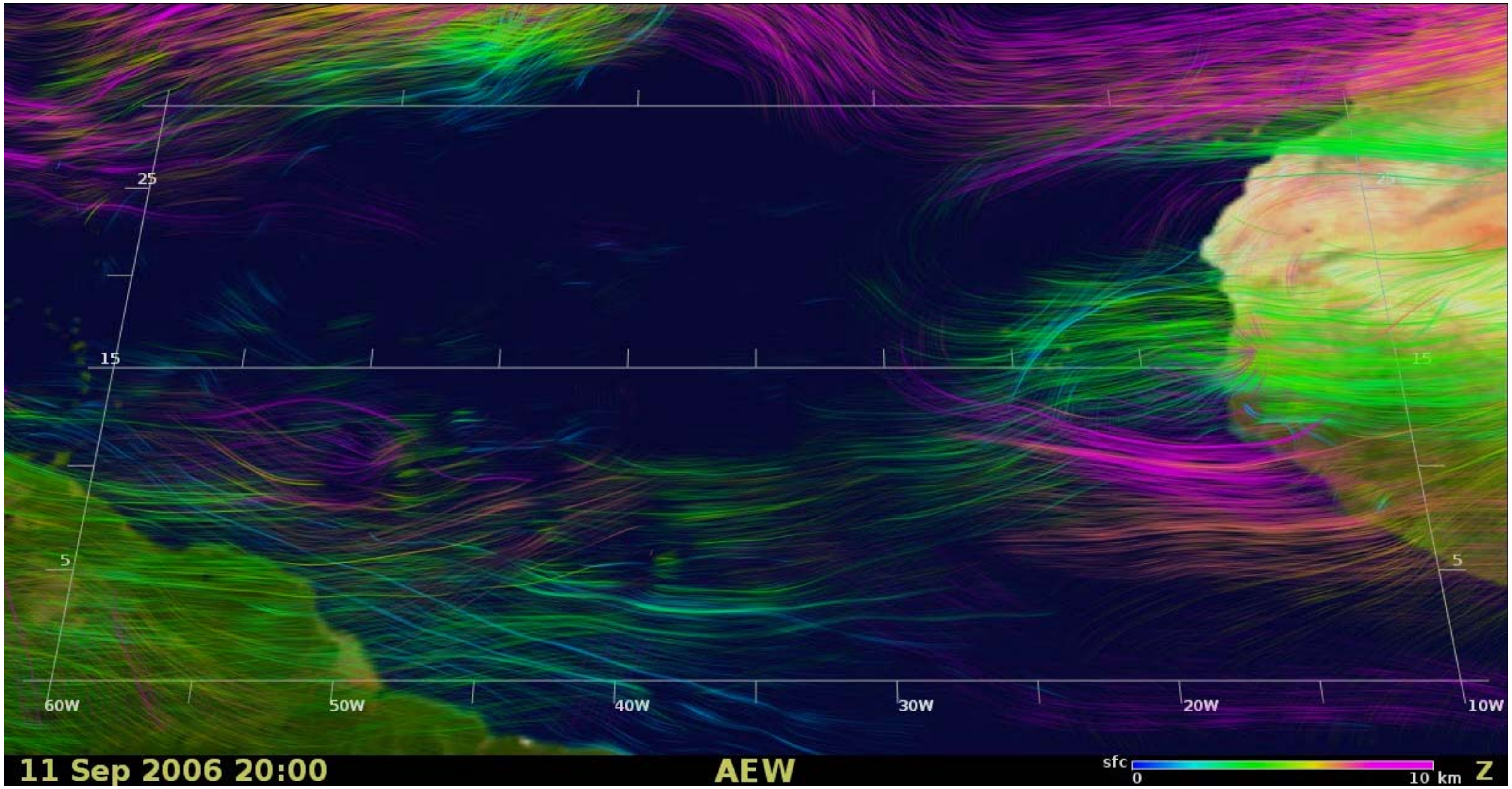


Figure: The progress of hurricane forecasts by National Hurricane Center. Horizontal axis indicates year, and vertical axis shows forecast errors. Lines with different color show different forecast intervals. *<u>During the past twenty years, track forecasts have been steadily improving (left panel),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

What Can We Expect in the next 10 years?

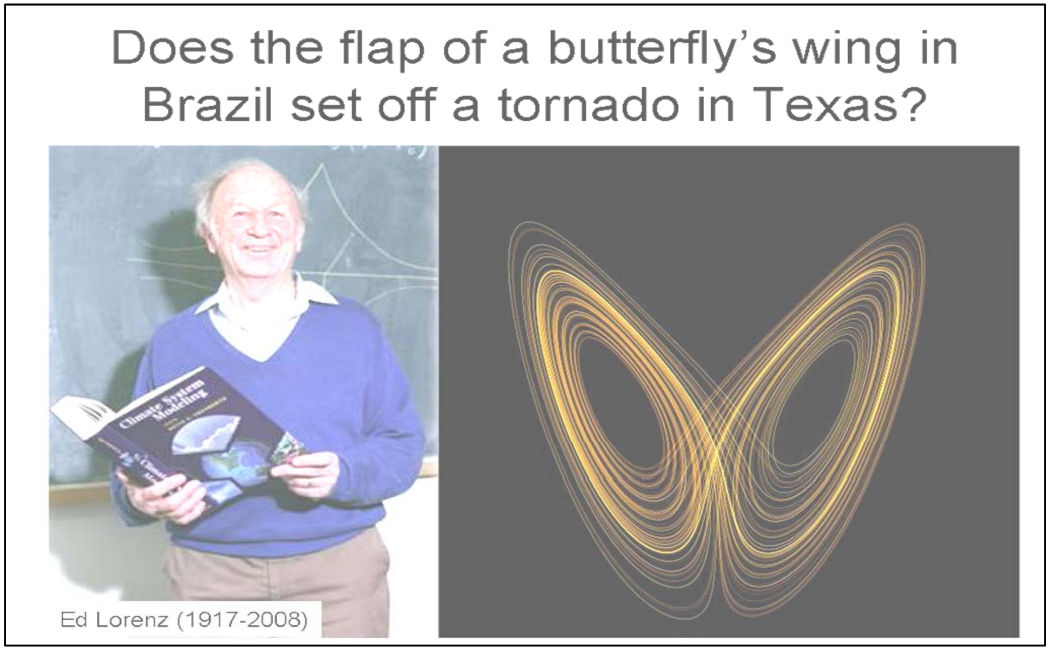
Formation of Hurricane Helene (2006)



- 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
- 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., L18803

Is the atmosphere more predictable than we assume?

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

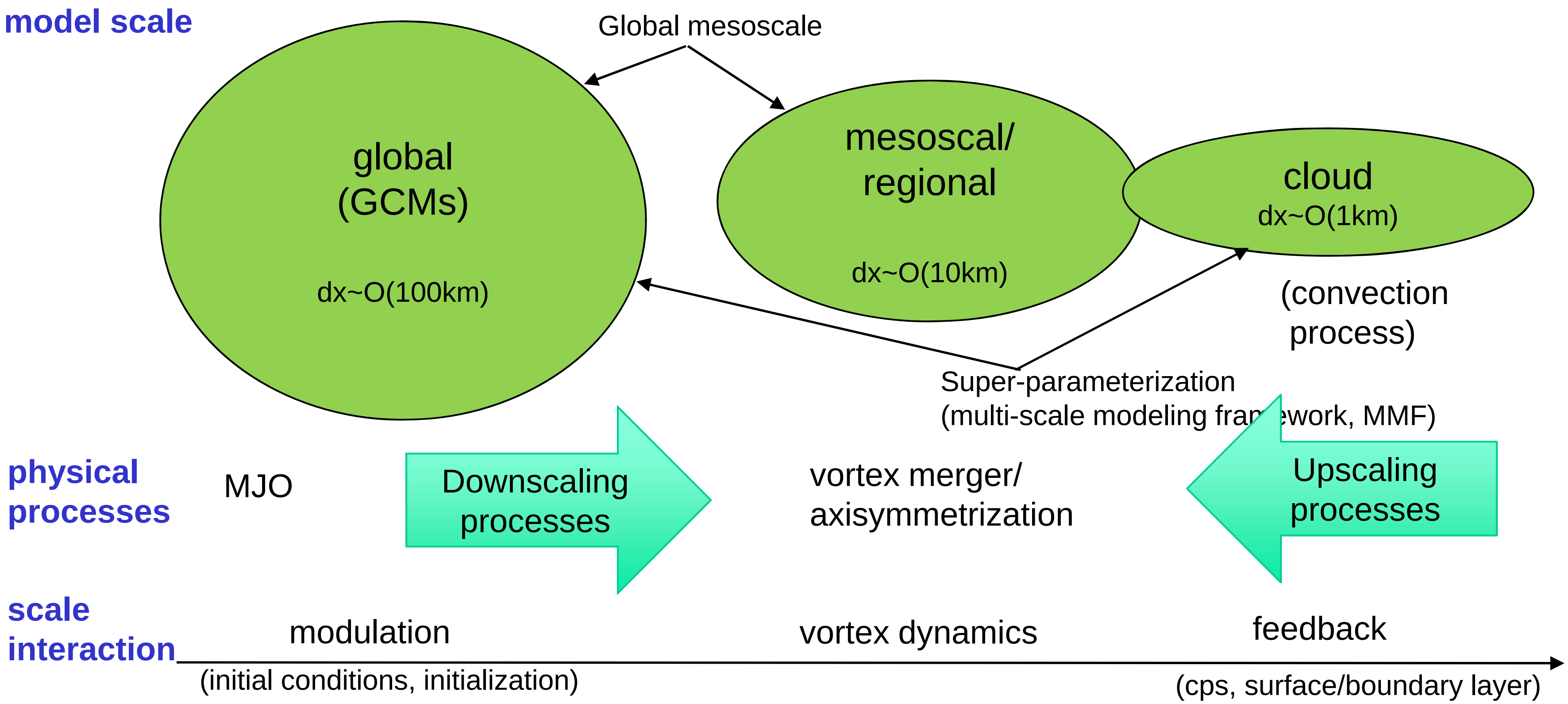


Courtesy of Anthes (2011) and Wikipdeia

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

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).



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;

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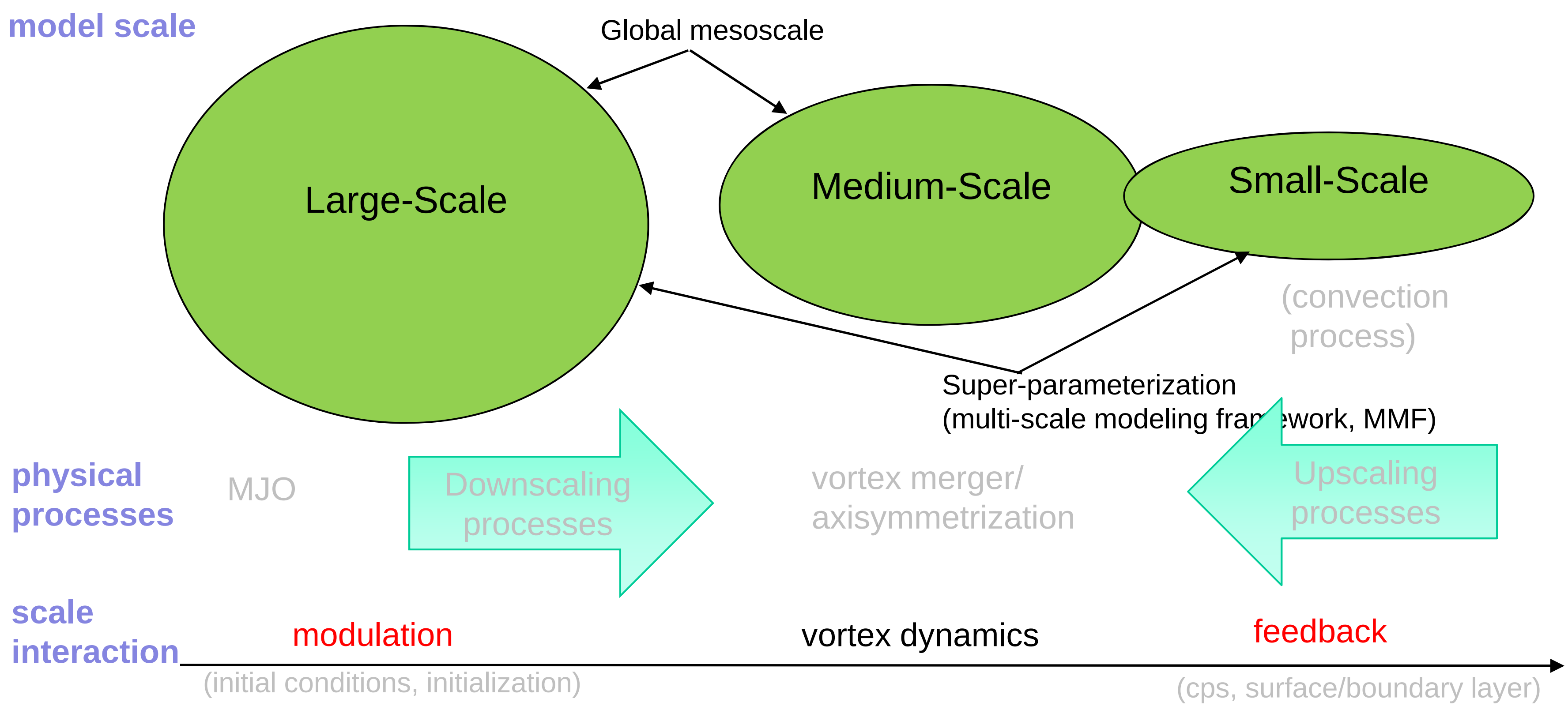

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NASA Supercomputing and Visualization Systems

Pleiades Supercomputer (ranked 3rd in late 2008; 7th in November, 2011)

- one of a few petascale supercomputers
- 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)
- 281 TB memory
- 3.1 PB disk space
- Largest InfiniBand network:

- 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

Challenges

- Satellite Data Challenges:
  - o) Massive data storage
  - o) Display/visualizations (~TB)
- Modeling Challenges:

  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)

  - 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

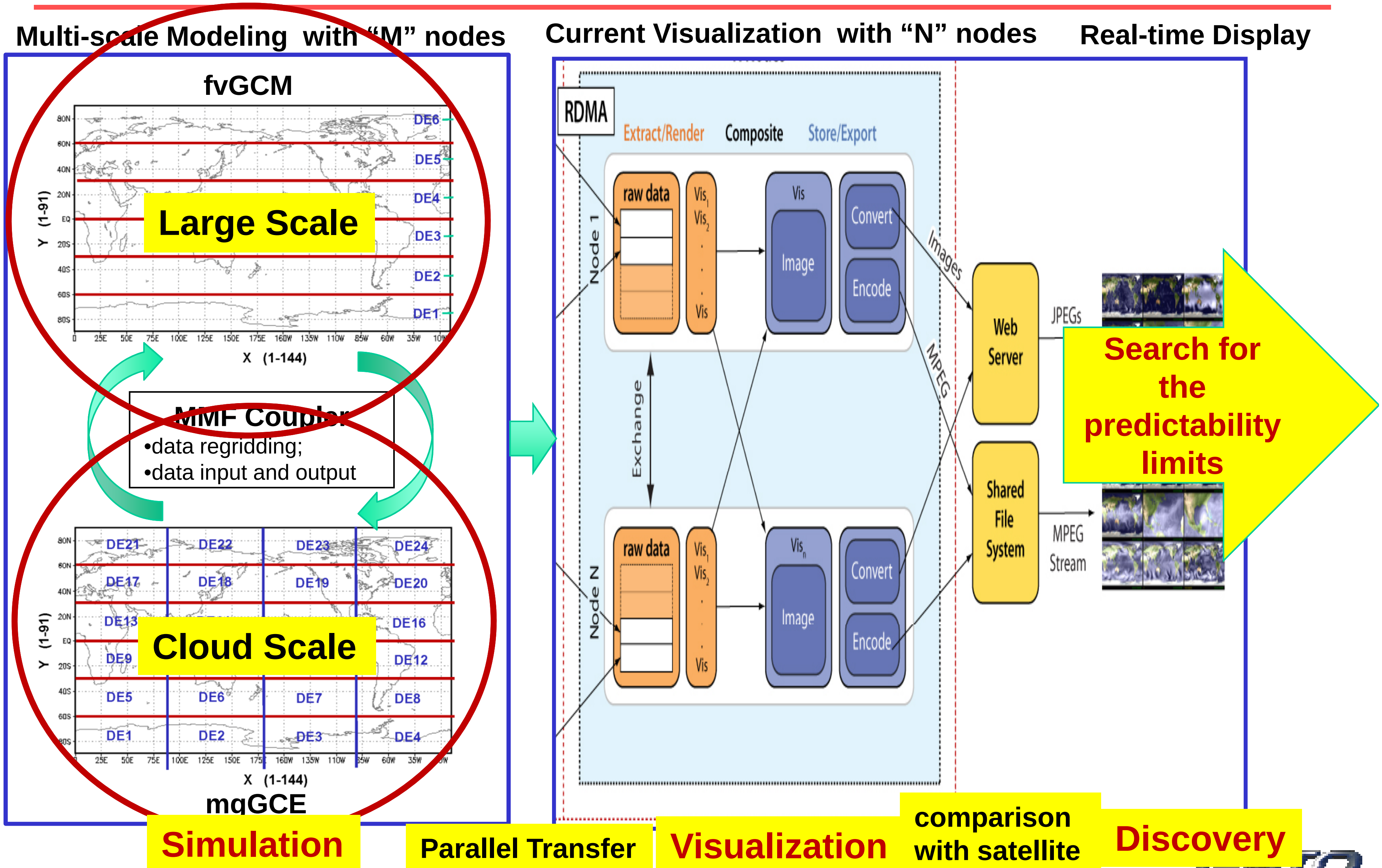
process huge data efficiently

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

Architecture of the CAMVis v1.0

(the Coupled Advanced Multiscale modeling and concurrent Visualization systems)



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
- Minimal impact to application (e.g., performance)
  - Data are offloaded to vis cluster for concurrent processing
- See current state of simulation as its running
  - Application monitoring or steering
  - Detect serious job failures that might otherwise cause waste of system resources
- Reveals features not otherwise observable
  - Has consistently revealed previously unknown dynamics

Scientific Demos

A series of papers (Shen et al., 2010a,b; Shen et al., 2011a,b) 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

1. Very severe cyclonic storm Nargis (2008) and its association with an Equatorial Rossby wave (Shen et al., 2010a,2011a)
2. Twin tr... 2002 and their ... mixed ... wave (Shen et ...
3. Hurrica... its association w... Easterly wave (AEW) (Shen et al., 2010b);
4. Typhoon Morakot (2009) and monsoon circulations (Shen et al., 2011d)

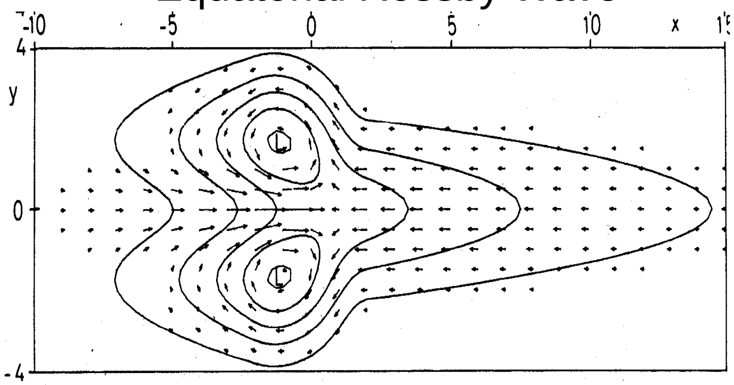
Tropical Cyclone (TC) Formation

Tropical Waves

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.

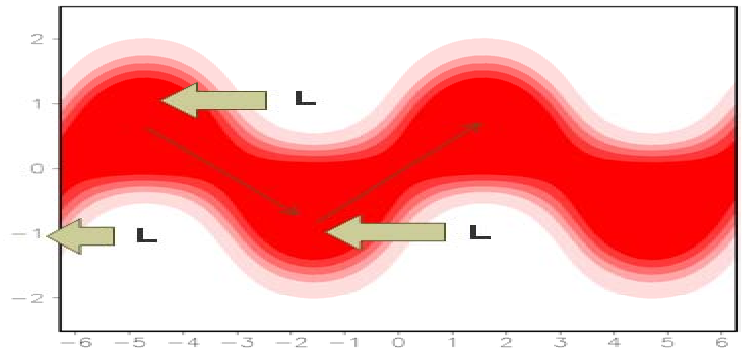
Tropical Waves and TC Formation

Equatorial Rossby Wave



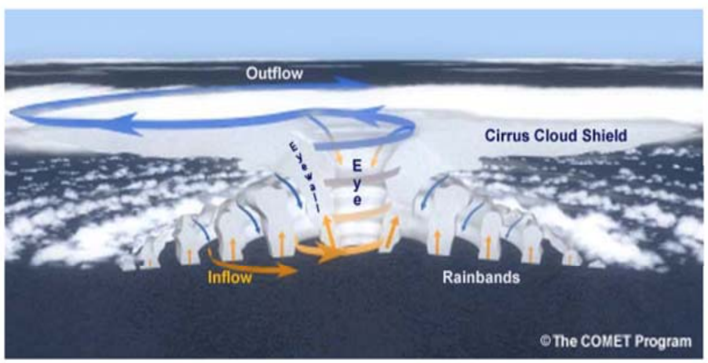
An equatorial Rossby wave, appearing in Indian Ocean, is **symmetric** with respect to to the equator.

Mixed Rossby Gravity (MRG) Wave



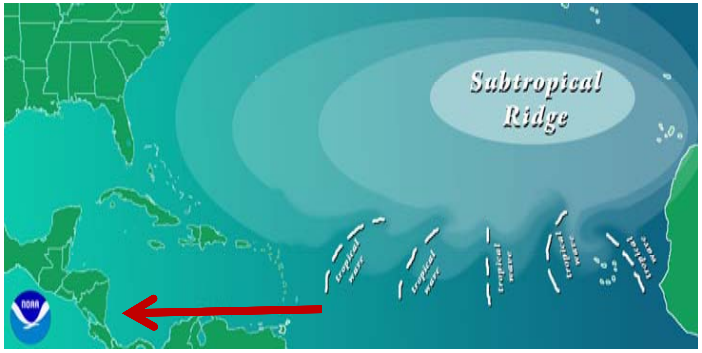
MRG waves, **asymmetric** with respect to to the equator, occasionally appear in Indian Ocean or West Pacific

Hurricane's (TC's) Structure



1.Eyewall: dense thunderstorms surrounding its eye
2.Low-level Inflow: counter clockwise circulation
3.Upper-level Outflow: clockwise circulation
4.Elevated warm-core: warmer temperature at its center

African easterly waves (AEWs)



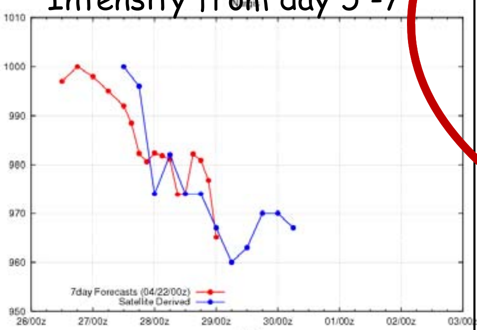
AEWs appear as one of the dominant synoptic weather systems. Nearly 85% of intense hurricanes have their origins as AEWs (e.g., Landsea, 1993).

Hierarchical Multiscale interactions of Nargis (2008)

which devastated Burma in May 2008, causing tremendous damage (~$10 billion) and numerous fatalities (~130,000 deaths),

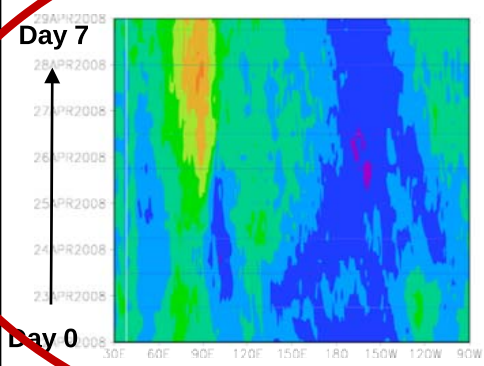
7-day global multiscale simulations suggest the following favorite factors for the formation and initial intensification of tropical cyclone Nargis:

Intensity from day 5 -7



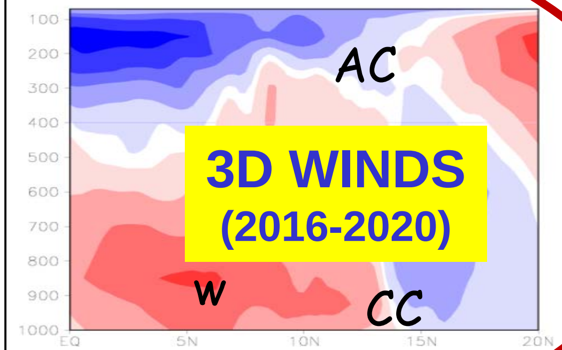
Time evolution of simulated min SLP (red) from day 5 to day 7, as compared to the satellite observation (blue).

Northward movement of WWB



Time/longitude diagram of zonal winds averaged over latitude 5ºN to 10ºN. West Wind Belt/Burst (WWB) is indicated by orange area. (No... shown as the ab... averaged latitude 5S to the equator.)

Enhanced Monsoonal circulation



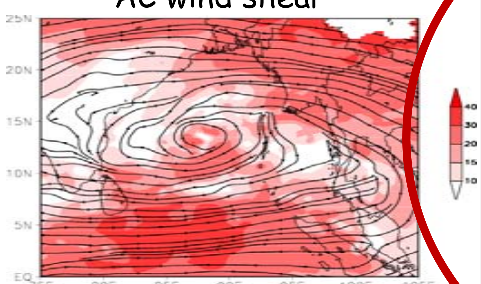
Altitude/latitude cross section of zonal winds averaged over longitude 80ºE-90ºE. Westerly and early winds are shown in red and blue. Weak vertical wind shear is indicated by the "vertical orientation of the white line". Middle- and low-level ... d at 132h simulation.

3D WINDS (2016-2020)

Large Scale

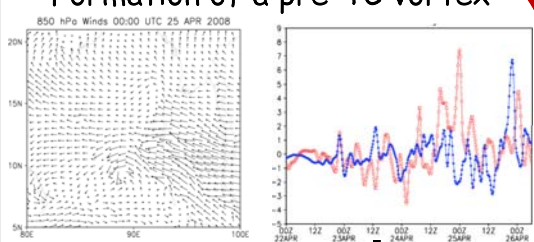
Hierarchical Multiscale Interaction

AC wind shear



126h simulation of vertical wind shear between 850- and 200-hap, showing anti-cyclonic wind shear and good upper-level outflow.

Formation of a pre-TC vortex

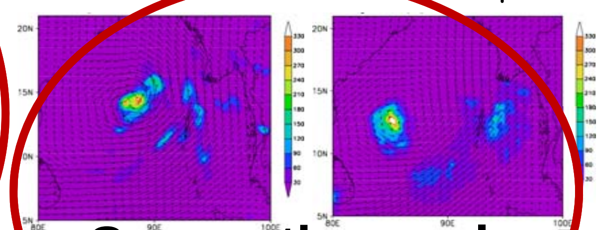


72h simulation of 850-hpa winds (left) and time evolution of low-level convergence (right), showing ... vortex associat... convergence

Mesoscale

QuikSCAT

Vortex circulation and precip



Averaged precip and 850-hPa winds from day 5 to day 7 (left) and averaged NASA TRMM precip and NCEP Rea... (right)

Convective scale

TRMM

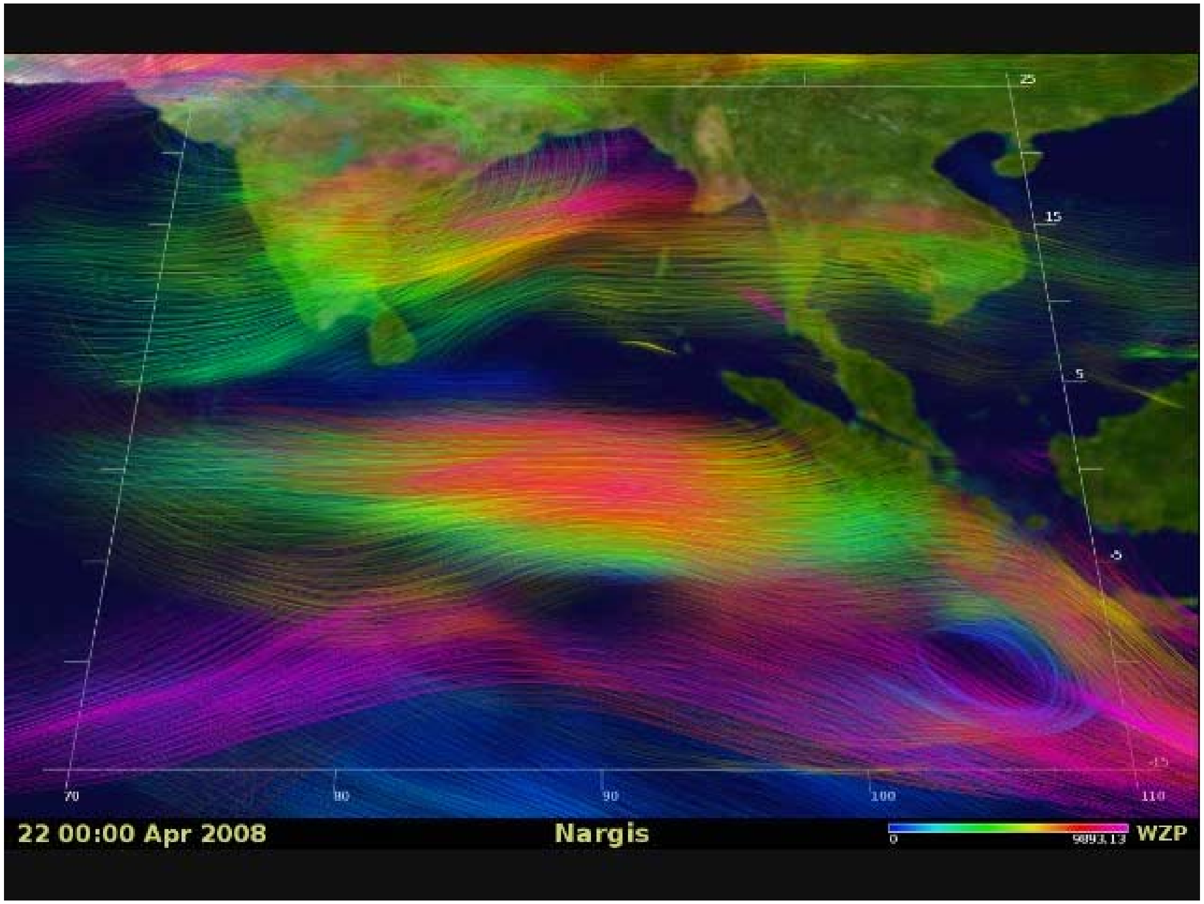
7-day Forecast of Genesis of Cyclone Nargis (2008)

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



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

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.

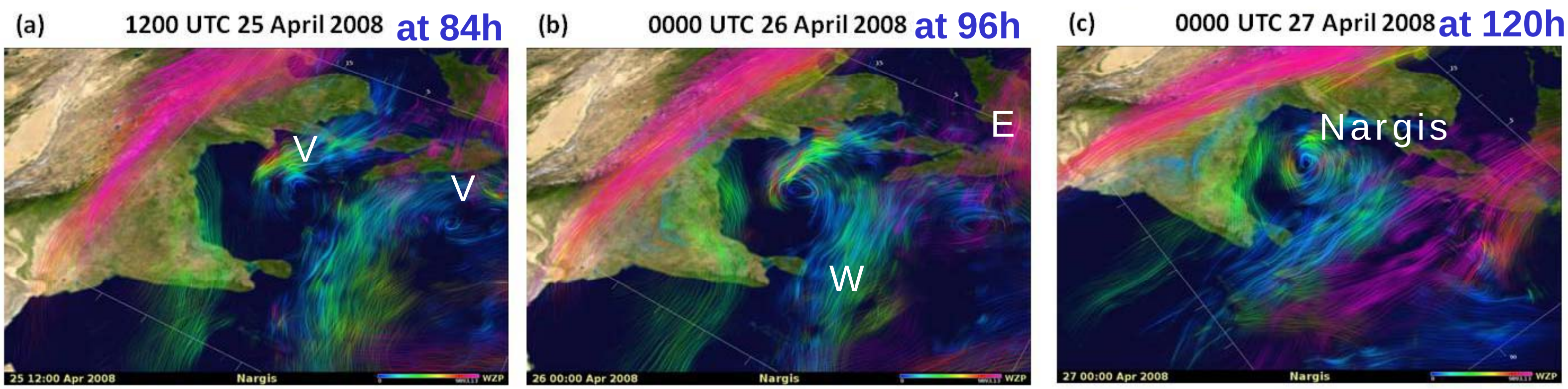
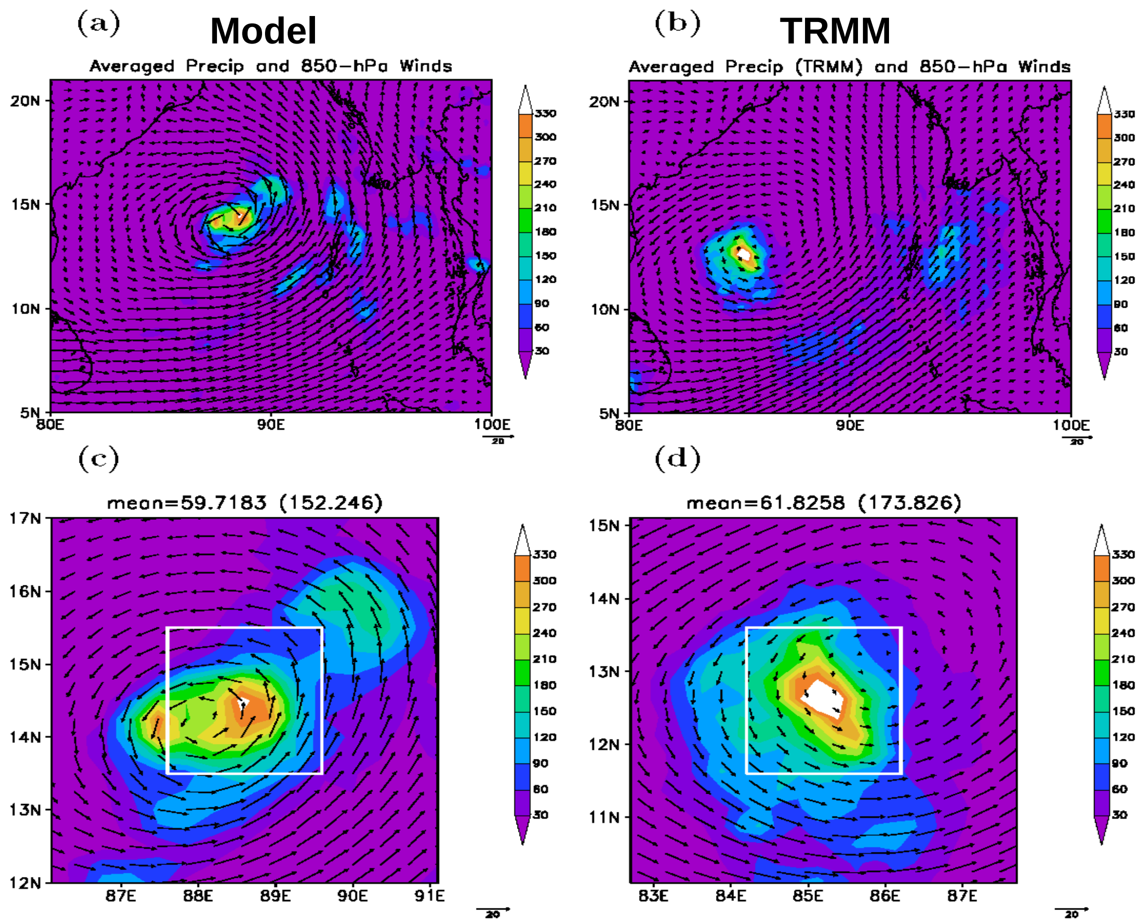


Figure: Realistic 7-day simulations of the formation and initial intensification of TC Nargis (2008) initialized at 0000 UTC April 22, 2008, showing streamlines at different levels. Low-level winds are in blue and upper-level winds in red: (a) formation of a pair of low-level mesoscale vortices (labeled 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).

Averaged precipitation and wind vectors for Nargis

5^ox5^o



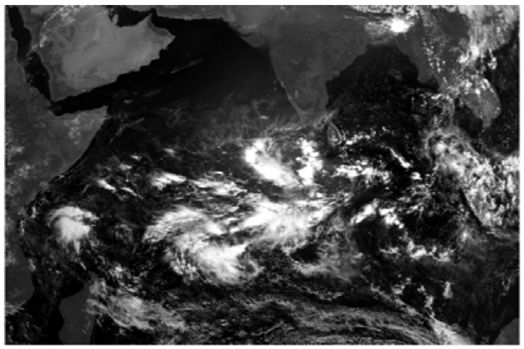
The domain-averaged precipitation in the 5^o (2^o) box is 59.7 (152.2) mm/day for the model and 61.8 (173.8) mm/day for TRMM. **This indicates an underestimate of 3.4% (12.4%) in the 5^o (2^o) average precipitation** by the model with a larger discrepancy for 2^o average precipitation. This indicates 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^o box, centered at the maximum of precipitation near the vortex center.

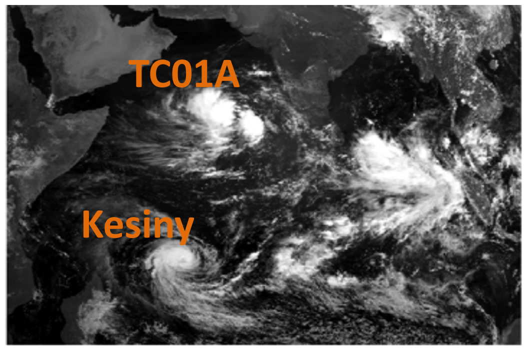
Twin TCs and a MRG wave in May 2002

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 9.

0630 UTC 1 May 2002



0000 UTC 6 May 2002



0000 UTC 9 May 2002

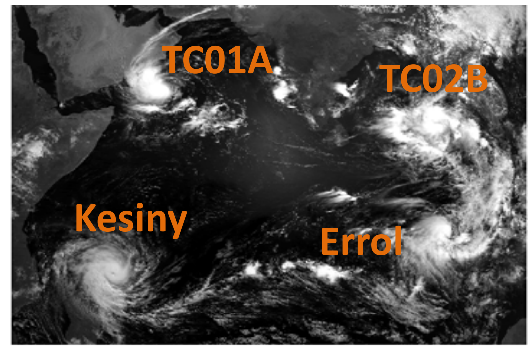
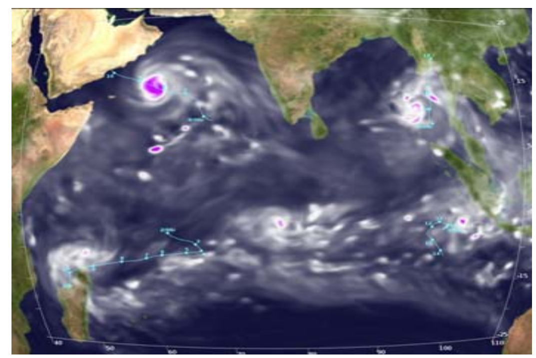
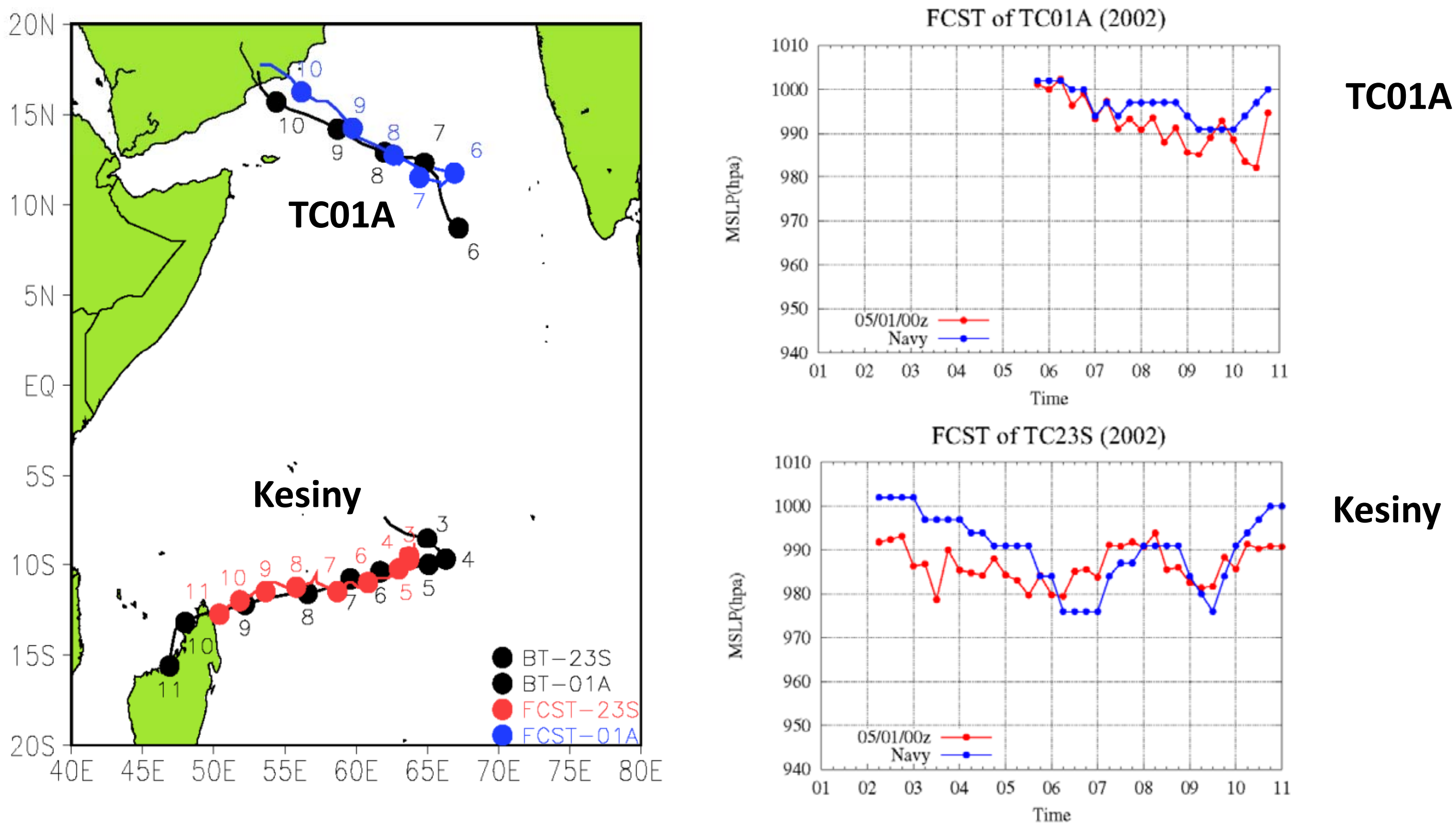


Figure: Predictions regarding the formation of twin tropical cyclones in the Indian Ocean: (a) MJO-organized convection over the Indian Ocean at 0630 UTC 1 May 2002. When the MJO moved eastward, two pairs of twin TCs appeared sequentially on 6 May (b) and 9 May (c), including TC 01A, Kesiny, TC 02B and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



Shen, B.-W., et al. 2011b: Genesis of Twin Tropical Cyclones Revealed by a Global Mesoscale Model: the Role of Mixed Rossby Gravity Wave (to be submitted)

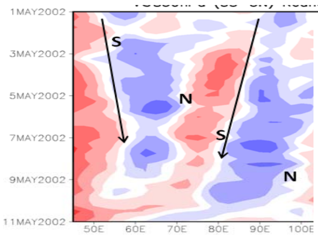
Track and Intensity Forecasts for a twin TC

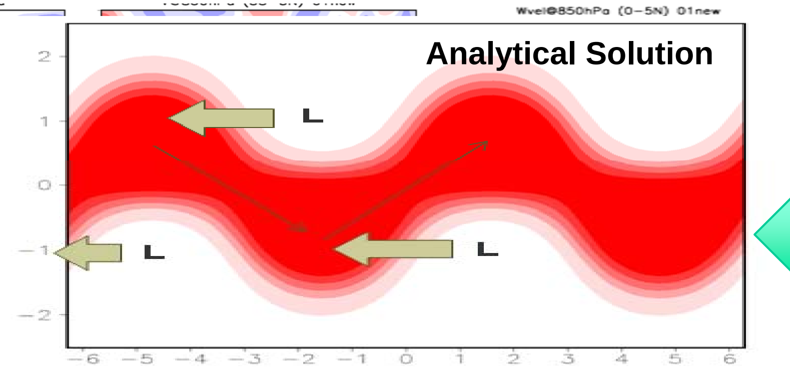


Track (a) and Intensity (MSLP) simulations of TCs 01A (b) and 23S (c) from the 10-day control run initialized at 0000 UTC 1 May 2002. The first record for TC 23S and 01A was issued at 0600 UTC 3May and1800UTC 5 May, respectively.

Interactions of Twin TCs and MRG wave

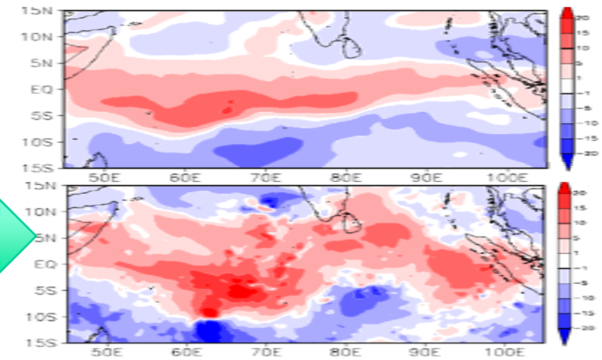
Wavelength reduction of mixed Rossby gravity (MRG) wave





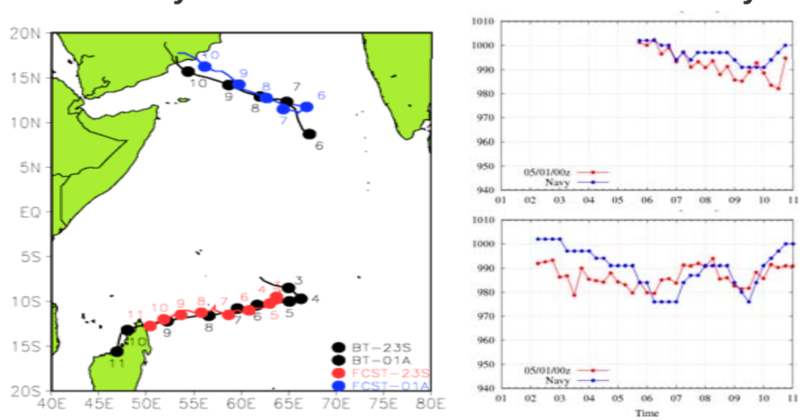
Time/longitude diagra
10-day control run ini
winds are indicated ir
the sloping northerly t
about the equator are likely associated with an MRG wave.(c) Time/longitude diagram of 850mb vertical velocity (shaded) and meridian winds (contour).

MRG Wave Development



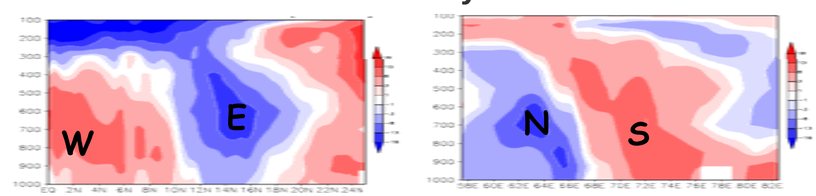
Simulations of 850-hPa zonal winds at the initial time and the integration of 96 hours.

10-day Fcst of Twin TCs' Track and Intensity



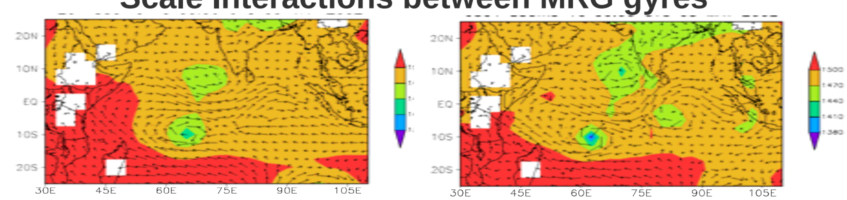
Track (a) and Intensity simulations of TCs 01A (b) and 23S (c) from the 10-day run initialized at 00Z 1 May 2002, as compared to the observations. The first record for TC 23S (01A) was issued at 06Z 3May (18Z 5 May).

Evolution of Low-level Cyclonic Circulation



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

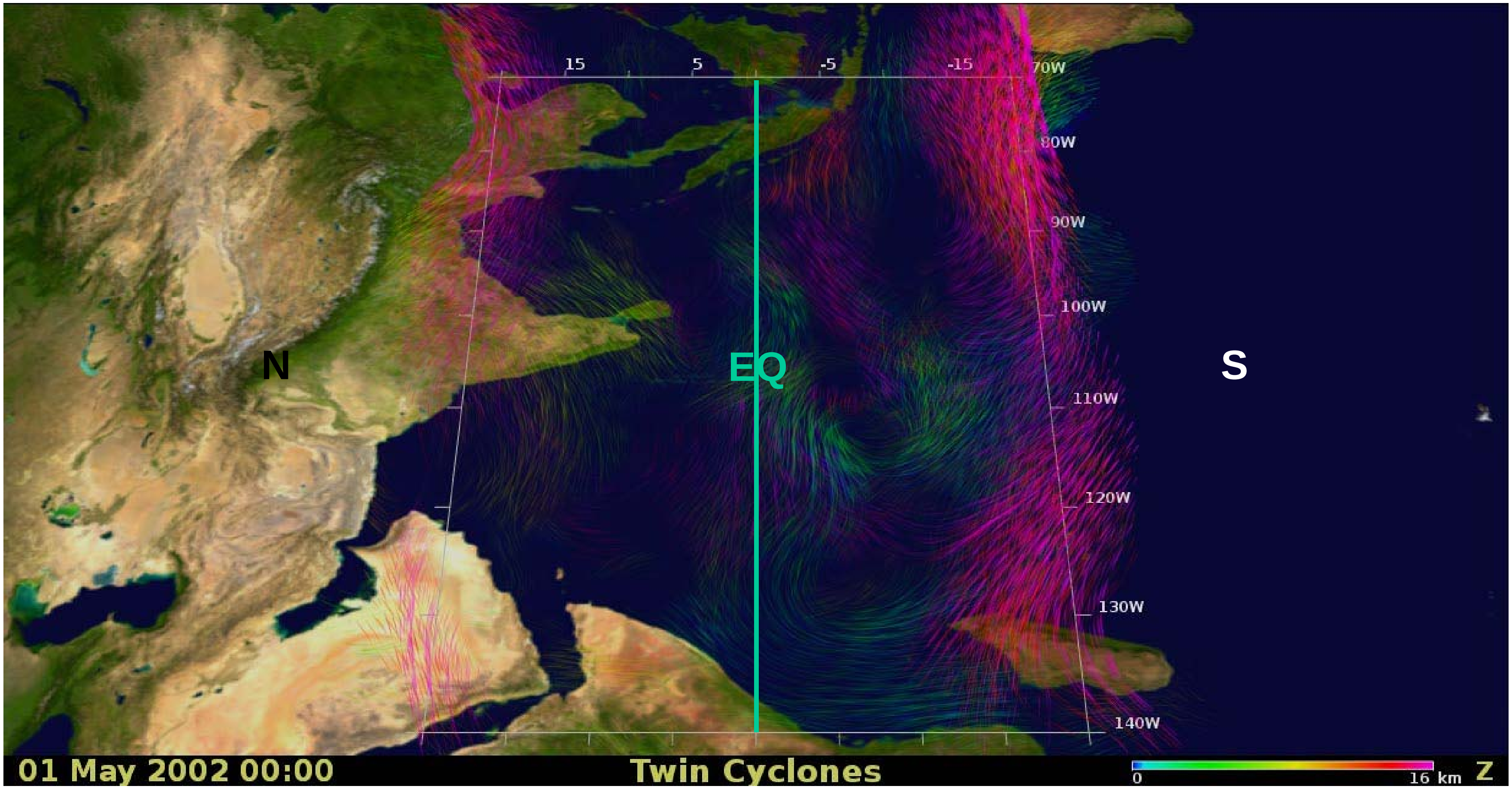
Scale Interactions between MRG gyres



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

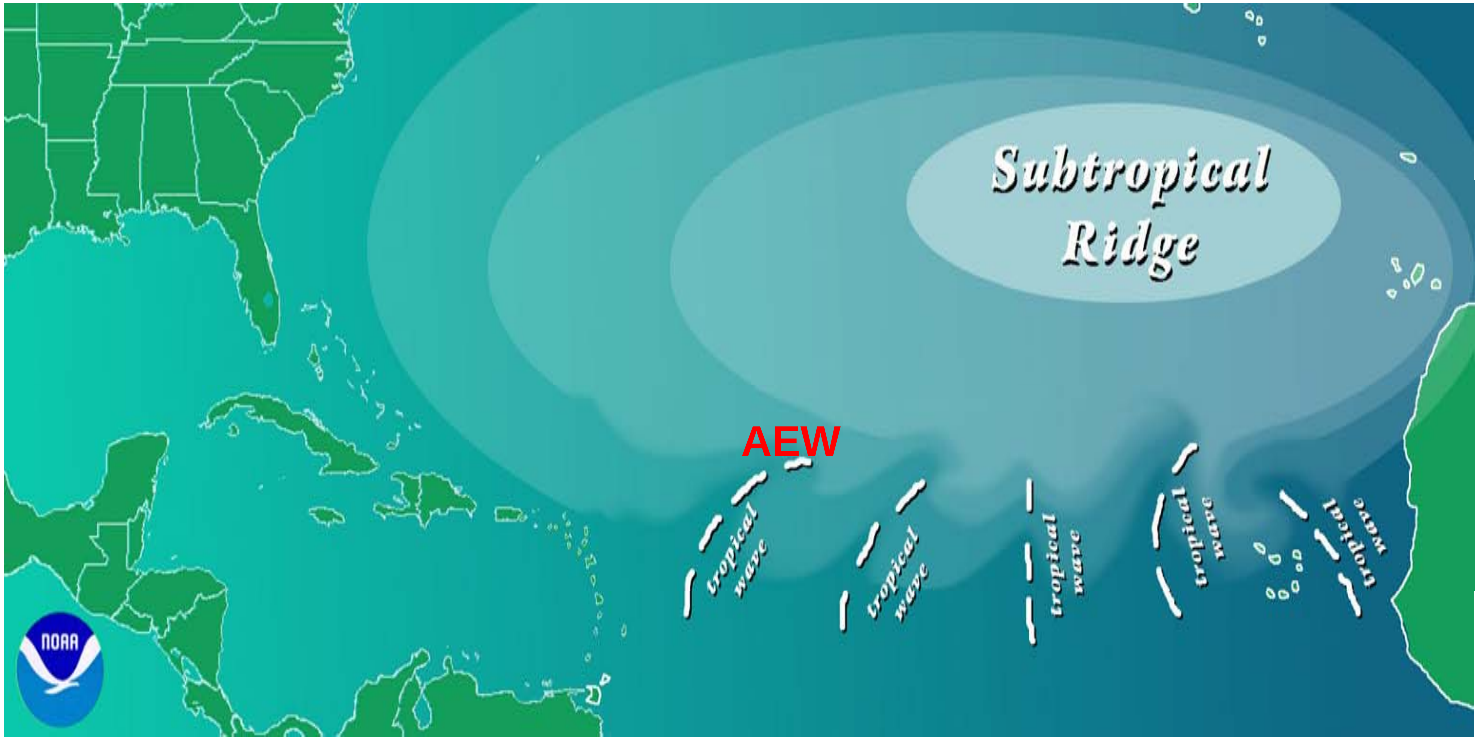
ESTO

Evolution of Twin TCs and the MRG Wave



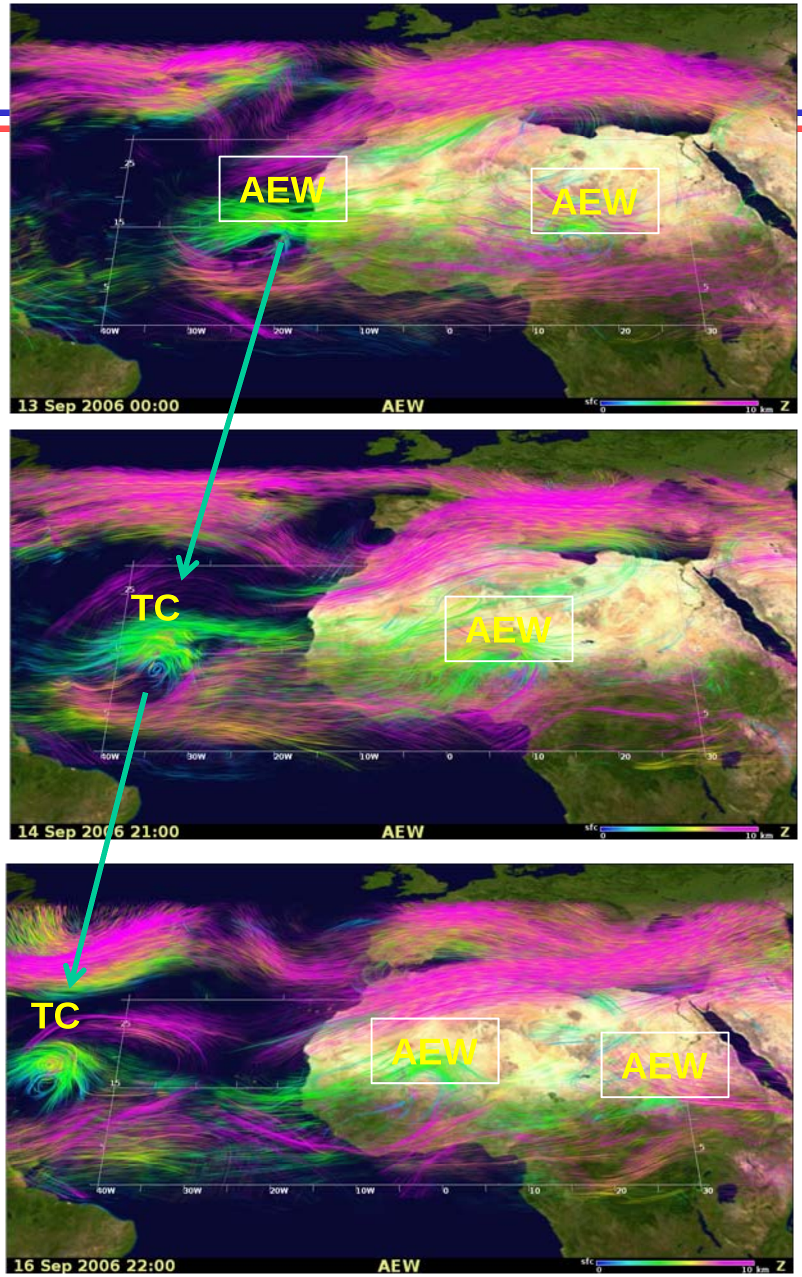
The successive formation of multiple TCs may indicate the appearance of a mixed Rossby gravity (MRG) wave.

African Easterly Waves (AEWs)



- During the summer time (from June to early October), African easterly waves (AEWs) appear as one of the dominant synoptic weather systems in West Africa.
- These waves are characterized by an average westward-propagating speed of 11.6 m/s, an average wavelength of 2200km, and a period of about 2 to 5 days.
- Nearly 85% of intense hurricanes have their origins as AEWs [e.g., Landsea, 1993].

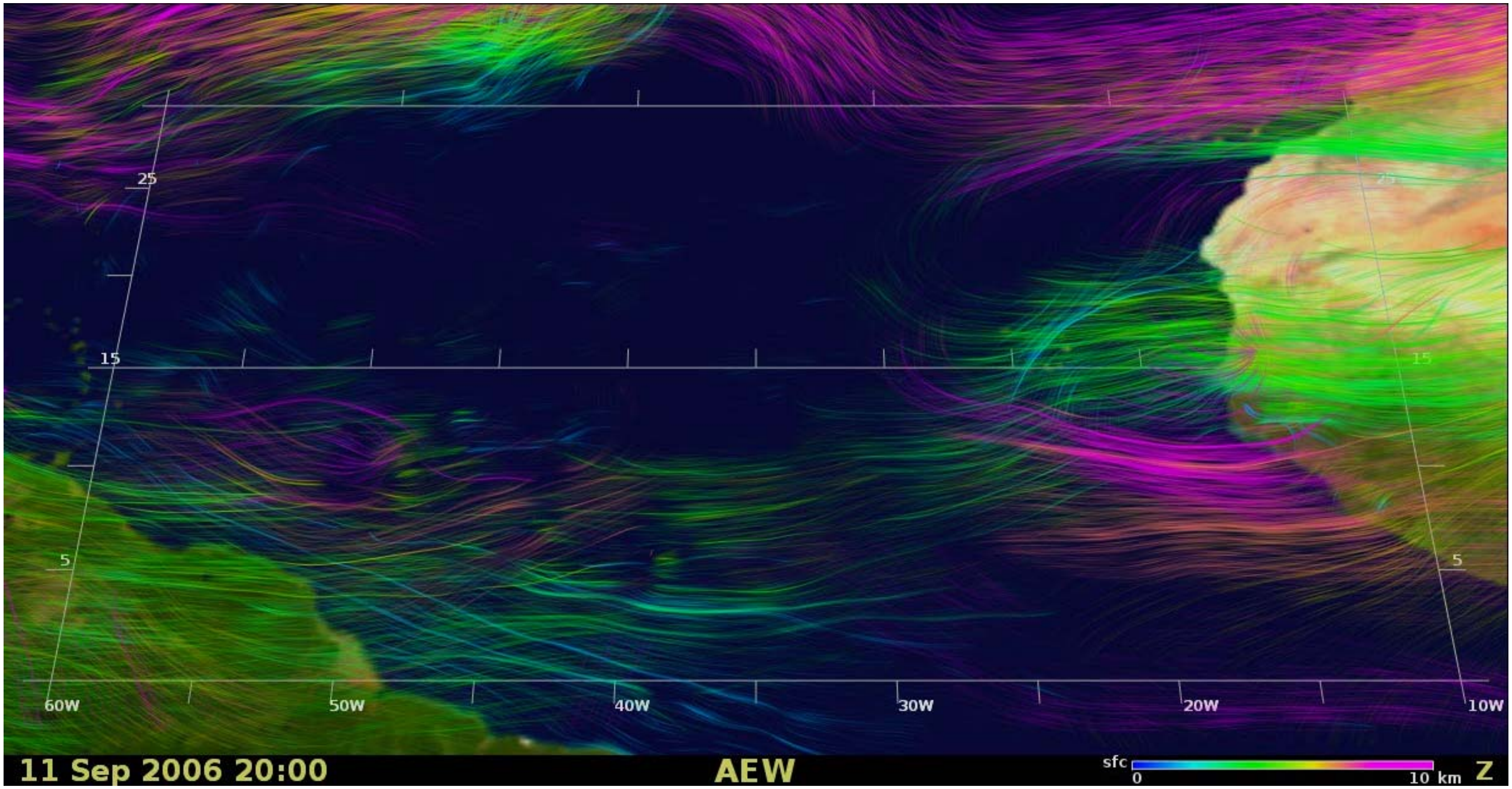
Contributed by Chris Landsea, http://www.aoml.noaa.gov/hrd/tcfaq/A4.html



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

Figure 7: *Formation of Hurricane Helene (2006) and its association with the intensification of an African Easterly Wave (AEW) in a 30-day run initialized at 0000 UTC August 22, 2006. Upper-level winds are in pink, middle-level winds in green and low-level winds in blue. (a) Initial formation of Helene as the AEW moves into the ocean, validated at 0000 UTC Sep. 13 (day 22); (b) initial intensification associated with intensified low-level inflow with counter clockwise circulation, validated at 2100 UTC Sep. 14; (c) further intensification with an enhanced outflow with clockwise circulation (indicated in pink), validated at 2200 UTC Sep. 16. An animation can be found: http://tiny.cc/j9ul9*

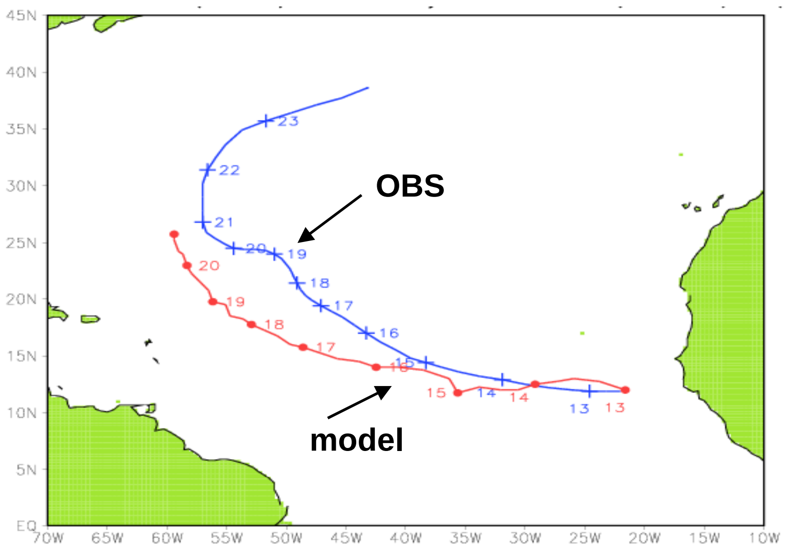
Formation of Hurricane Helene (2006)



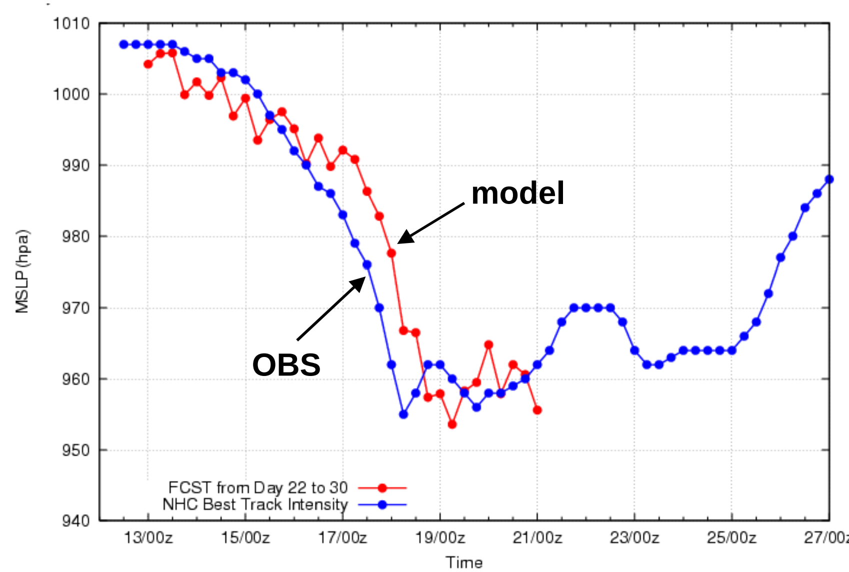
- Simulations from Day 20 to Day 30 in a 30-day run initialized at 0000 UTC Aug 22, 2006.
- Upper-level winds in red; middle-level winds in green; low-level winds in blue
- Low-level CC (cyclonic circulation); Upper-level AC (anticyclonic circulation)
- Shen, B.-W. W.-K. Tao and M.-L. Wu, 2010b: African 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

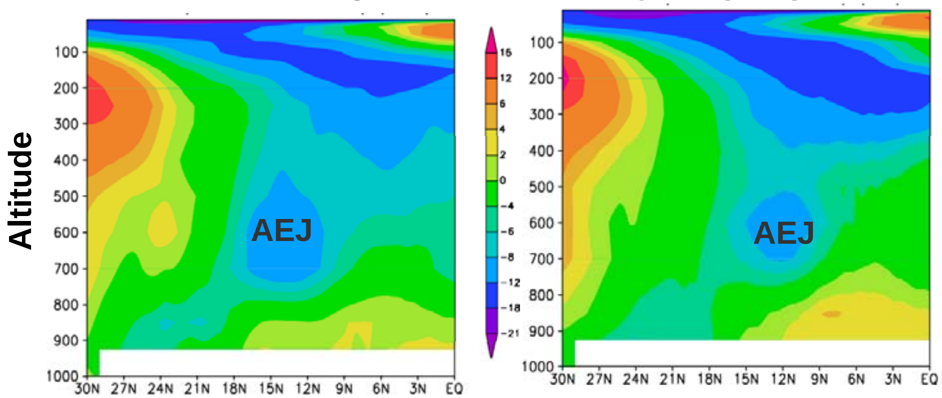


Future work:
to study multiscale interactions among TEJ, AEJ, AEWs, hurricanes and surface mechanic and thermodynamic processes

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.

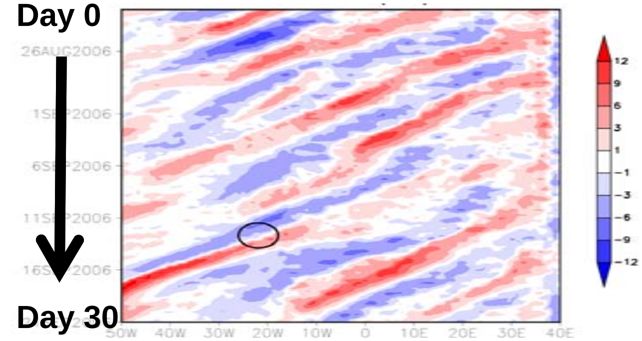
Multiscale Interactions of AEJ, AEWs, Hurricane and Surface Processes in a 30-day run

(a) Time-averaged African Easterly Jet (AEJ)



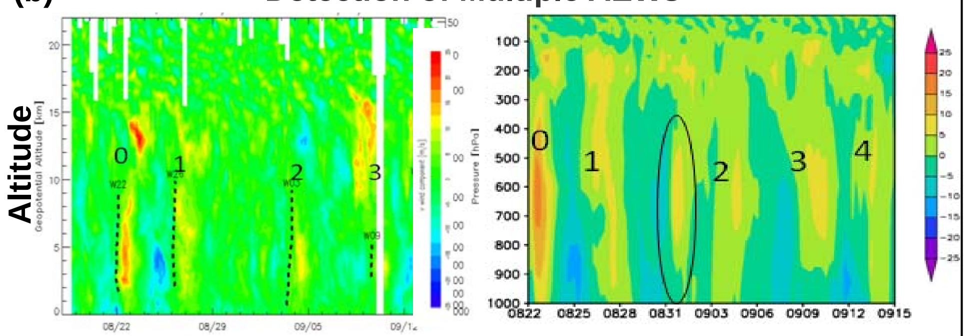
Altitude-latitude cross section of 30-day averaged zonal winds along longitude 20°E, showing African Easterly Jet (AEJ) from GFS analysis (left) and a 30-day simulation (right).

(c) African Easterly Waves (AEWs)



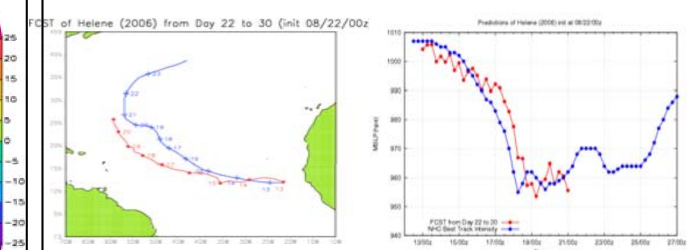
Time-longitude diagram of meridional winds, showing six AEWs in a 30-day simulation. The black circle roughly indicates the timing and location of Helene's formation.

(b) Detection of Multiple AEWs



Altitude-time cross sections of meridional winds at (23.5°W, 14.9°N) from NAMMA (NASA African Monsoon Multidisciplinary Analyses) observations (left) and model simulation (right).

(d) Track and Intensity in a 30-day run



Track (left) and intensity (right) forecasts for Hurricane Helene from Day 22 to 30. Red and blue lines indicate model predictions and best track, respectively.

Is There a Butterfly Effect?

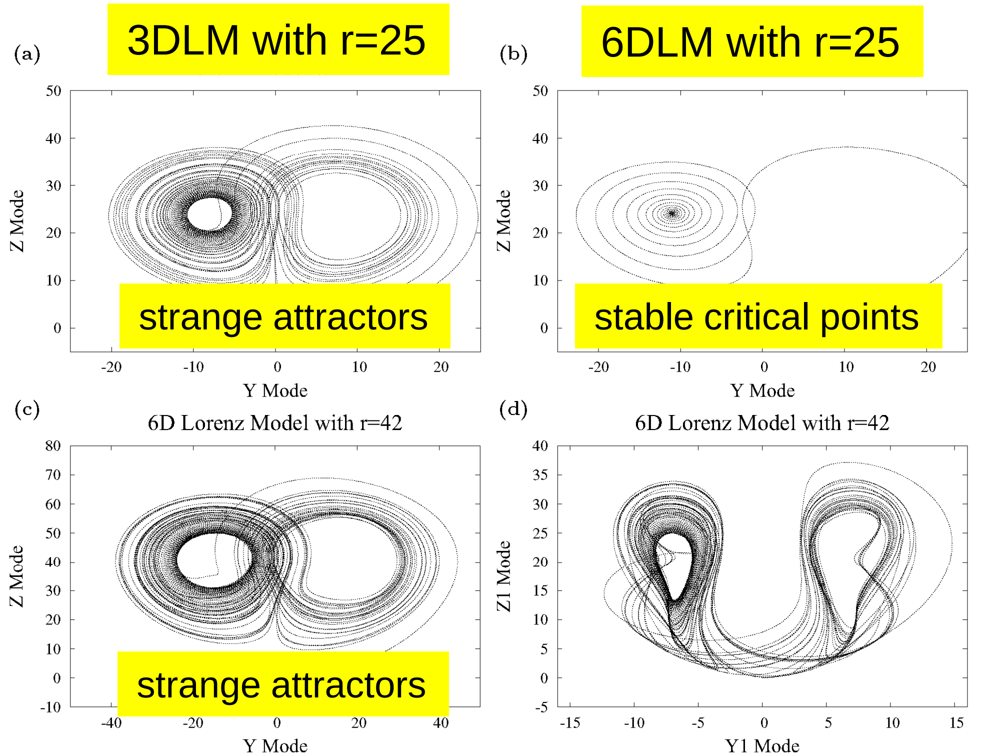
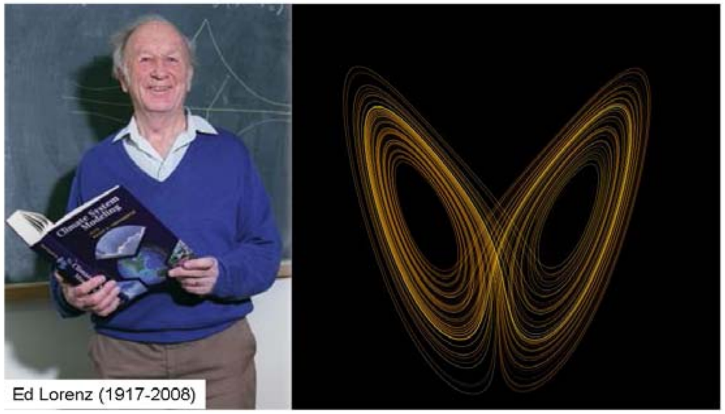


Figure 1: Phase space plots in the 3D (a) and 6D (b-d) Lorenz models. (a) A (Y, Z) plot with r=25. the so-called Lorenz strange attractors. (b) A (Y, Z) plot with r=25. (c) A (Y, Z) plot with r=42 witl attractors. (d) A (Y_1, Z_1) plot with r=42.

Does the flap of a butterfly's wing in Brazil set off a tornado in Texas?



Courtesy of Anthes (2011) and Wikipdeia

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.

Shen, B.-W., 2011c: Negative Feedback in a Generalized Lorenz Model (to be submitted in December, 2011)

An Analogy to Toy Top Spinning

Formation (initial spinning)

persistent forcing

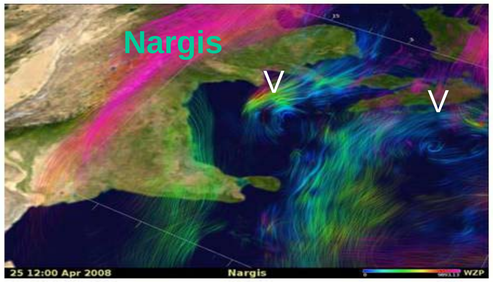
Intensification with energy supply

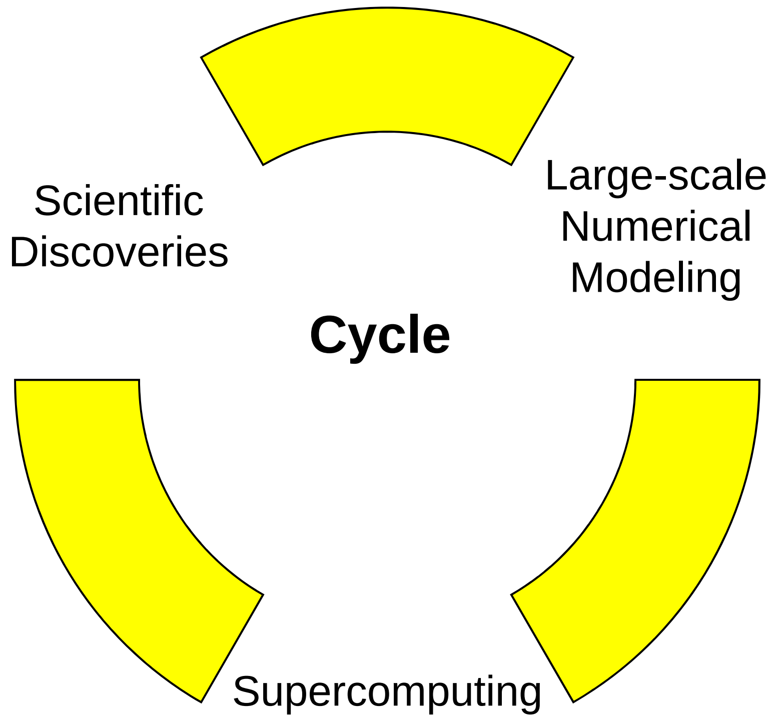
Impulsive forcing

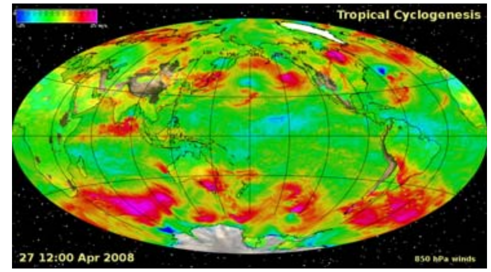
Large-scale Forcing

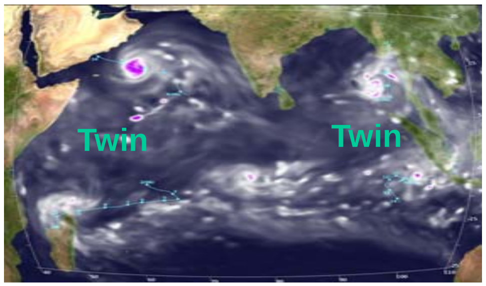
Small-scale Forcing

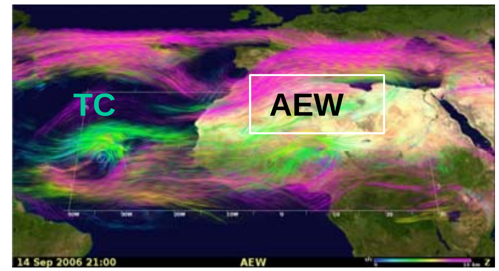
Concluding Remarks

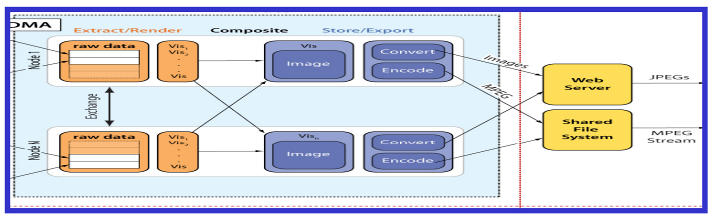






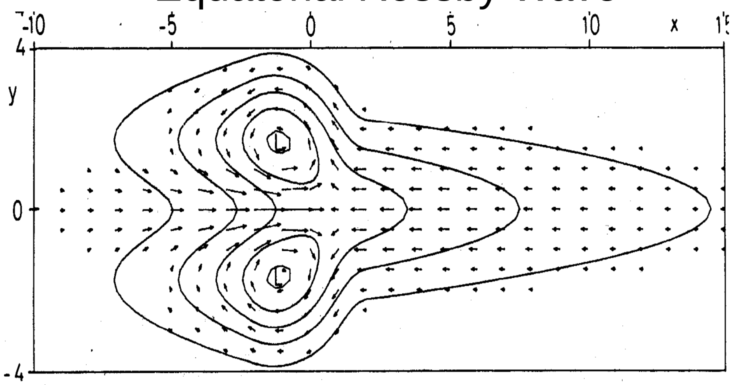






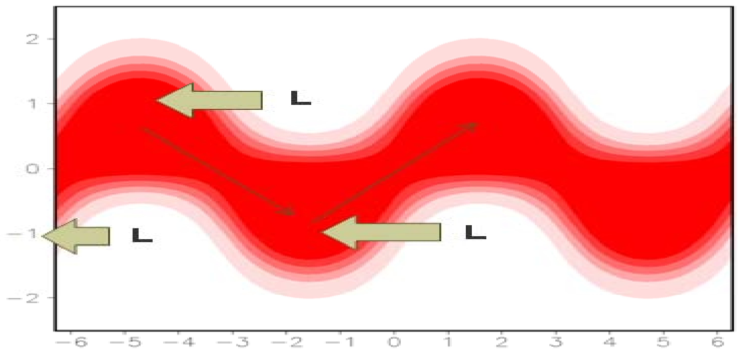
Tropical Waves and TC Formation

Equatorial Rossby Wave



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

Mixed Rossby Gravity (MRG) Wave

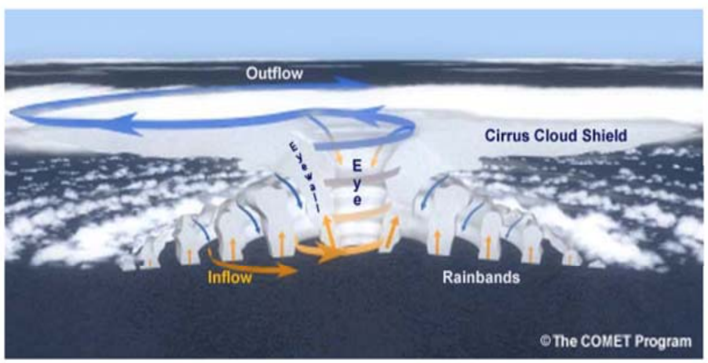


MRG waves, **asymmetric** with respect to to the equator, occasionally appear in Indian Ocean or West Pacific

Shen et al. (2010a)

Shen et al. (2011a)

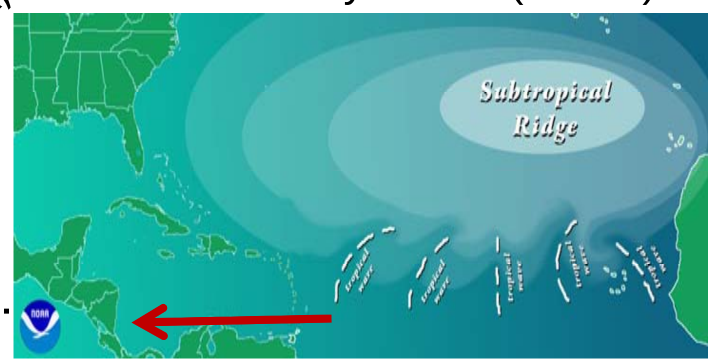
Hurricane's (TC's) Structure



1. **Eyewall:** dense thunderstorms surrounding its eye
2. **Low-level Inflow:** counter clockwise circulation
3. **Upper-level Outflow:** clockwise circulation
4. **Elevated warm-core:** warmer temperature at its center

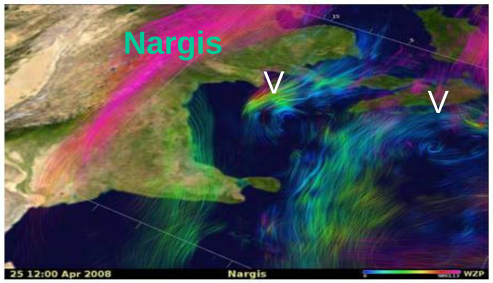
Shen et al. (2010b)

African easterly waves (AEWs)

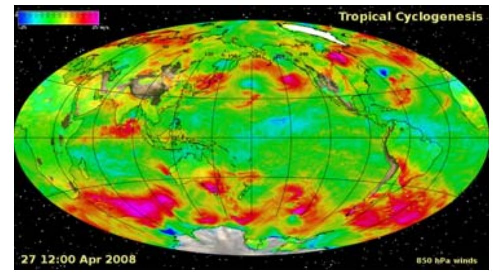


AEWs appear as one of the dominant synoptic weather systems. Nearly 85% of intense hurricanes have their origins as AEWs (e.g., Landsea, 1993).

Concluding Remarks

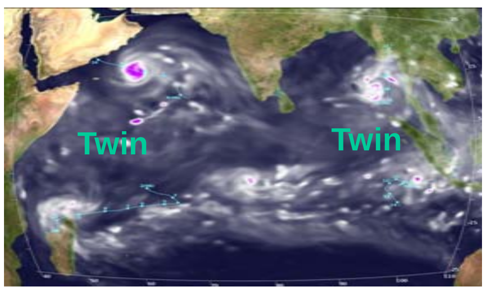


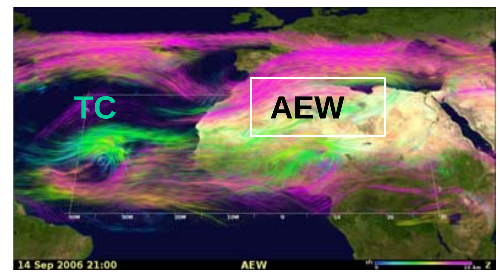
Scientific Discoveries



Large-scale Numerical Modeling

Cycle





Supercomputing