# Short-term Climate Simulations of African Easterly Waves with a Global Mesoscale Model

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# Outline



*Dear Bo-Wen,*

*Thank you for your enlightening talk and the reprint. I think the higher dimensional Lorenz system is really interesting. It represent a conceptual breakthrough in our understanding of nonlinear systems. Carry on, have fun and let's keep in touch.*

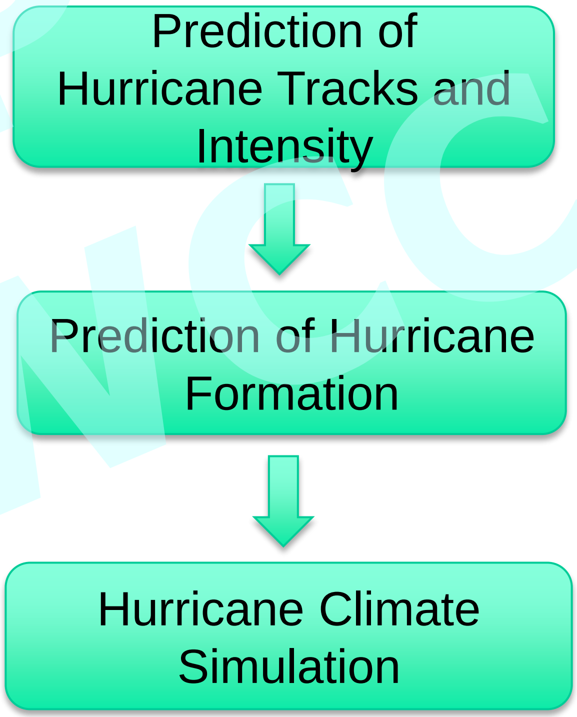
All the best,

# Major Scenarios in Decadal Survey Missions

Two of Major Scenarios in Decadal Survey missions are:

- **<u>Extreme Event Warnings</u>** (near-term goal): Discovering predictive relationships between meteorological and climatological events and less obvious precursor conditions from massive data sets

- **<u>Climate Prediction</u>** (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 <u>Advanced Data Processing</u> Group,
ESTO AIST PI Workshop Feb 8-11, 2010, Cocoa Beach, FL

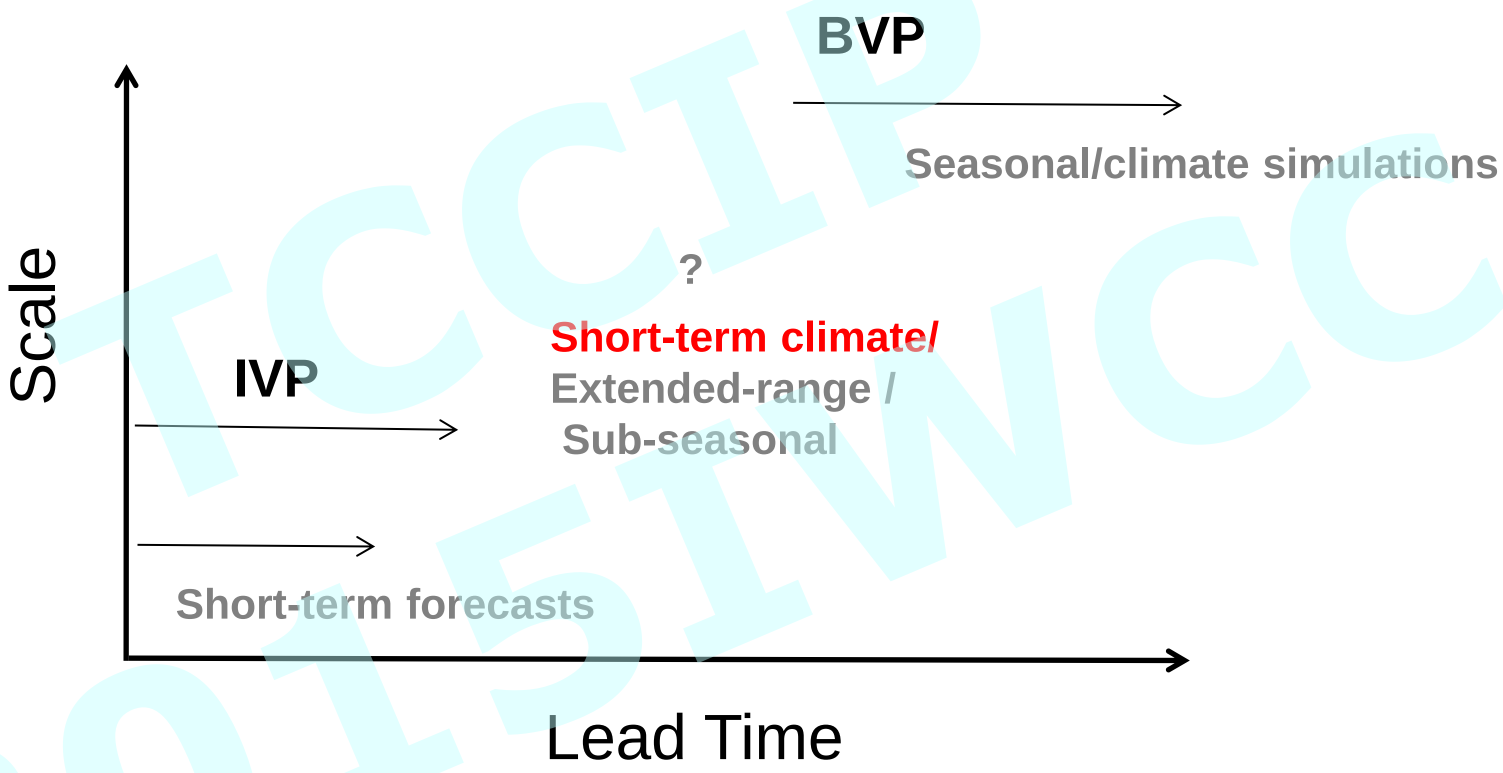
# Genesis: BVP or IVP?

IVP: initial value problem

BVP: boundary value problem

- Weather: IVP (small temporal/spatial scale evolution of solutions, “transient” solutions
- Climate: BVP (large-scale averaged states, equilibrium states)
- Genesis (of AEWs): BVP?
- Subsequent Evolution of AEWs: IVP? (“transient solutions”)

# Short-term Climate Simulations: IVP or BVP



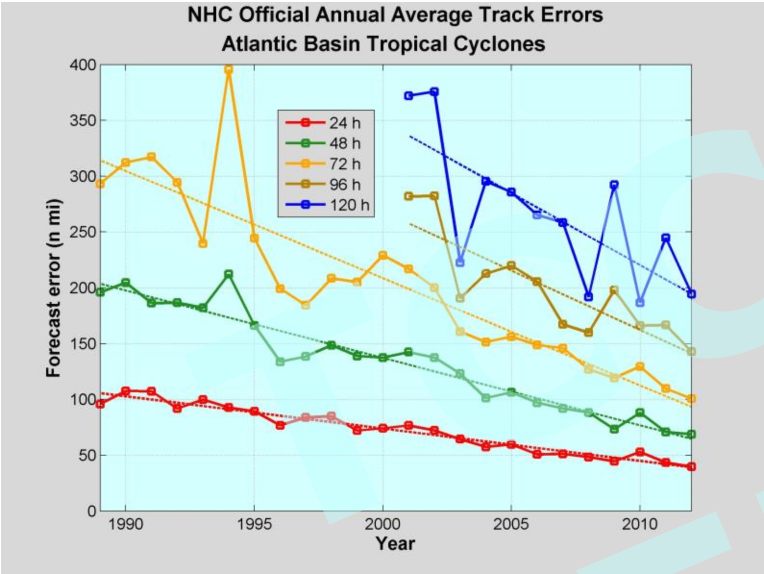



**IVP**: initial value problem

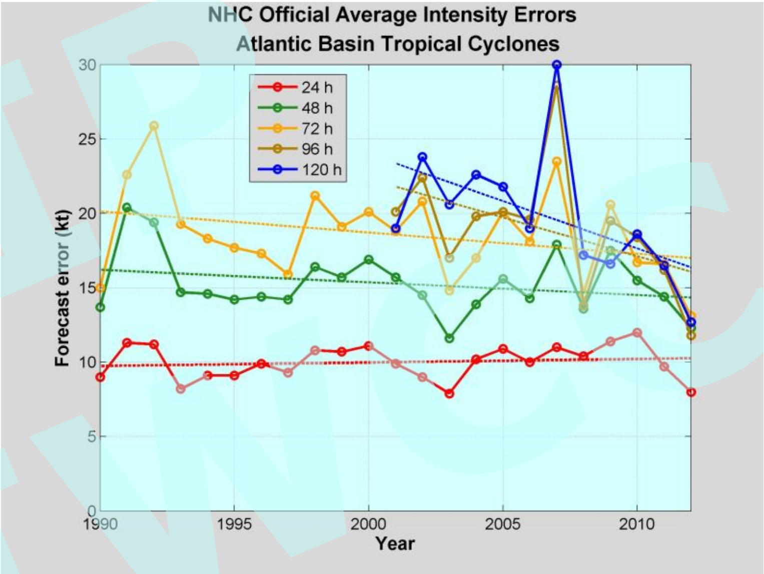
**BVP**: boundary value problem / forced problem

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

**Track Errors (1989-2012)**




**Intensity Errors (1990-2012)**



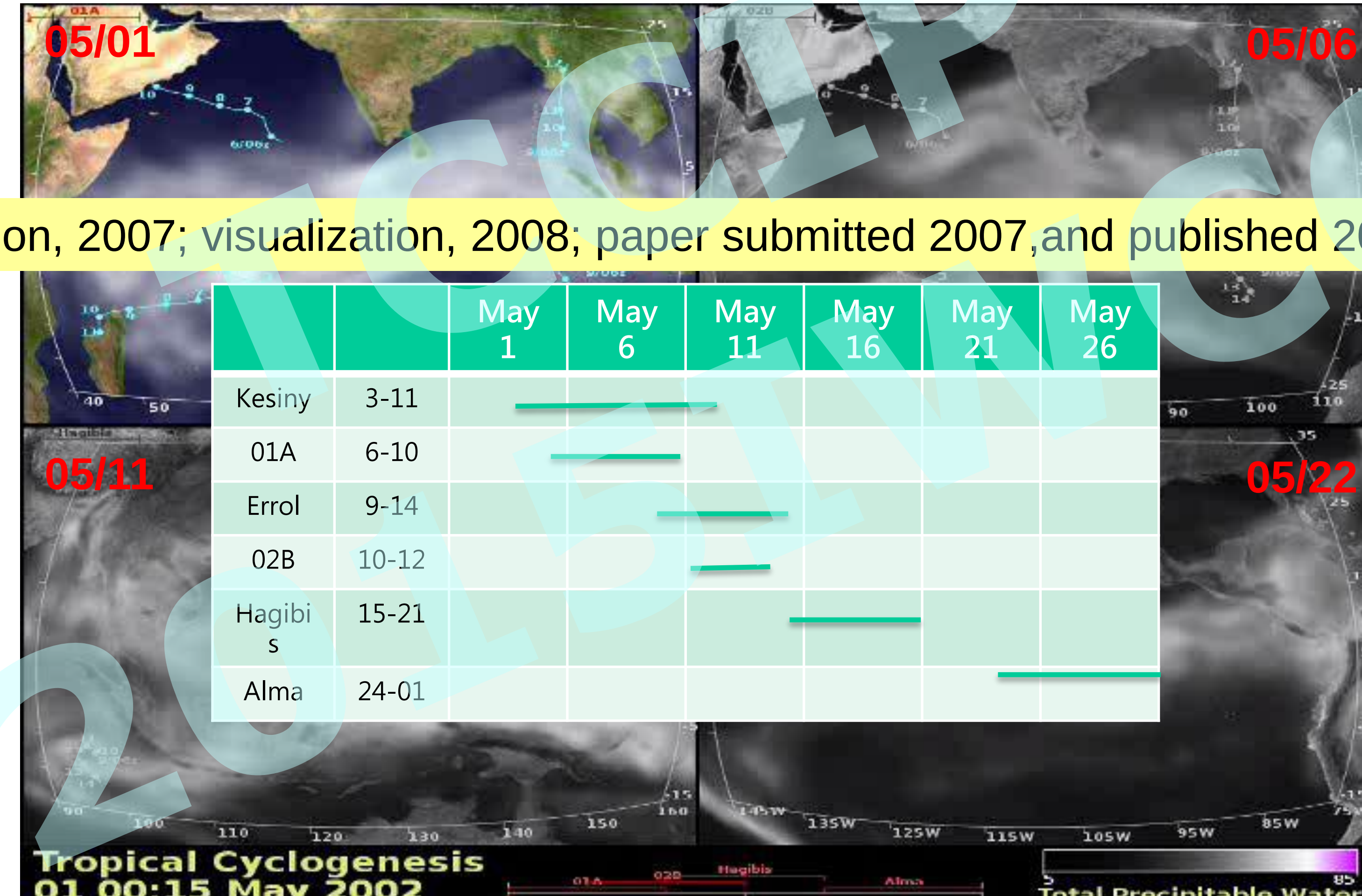

better

During the past twenty years, track forecasts have been steadily improving (left panel), but Intensity forecasts have lagged behind until recently (e.g., 2012) (right panel).

*``…the general problem of tropical cyclogenesis remains in large measure, one of the greatest mysteries of the tropical atmosphere."* – Kerry Emanuel of MIT, *The Divine Wind (2005).*

# Predicting Genesis of Six TCs in May 2002

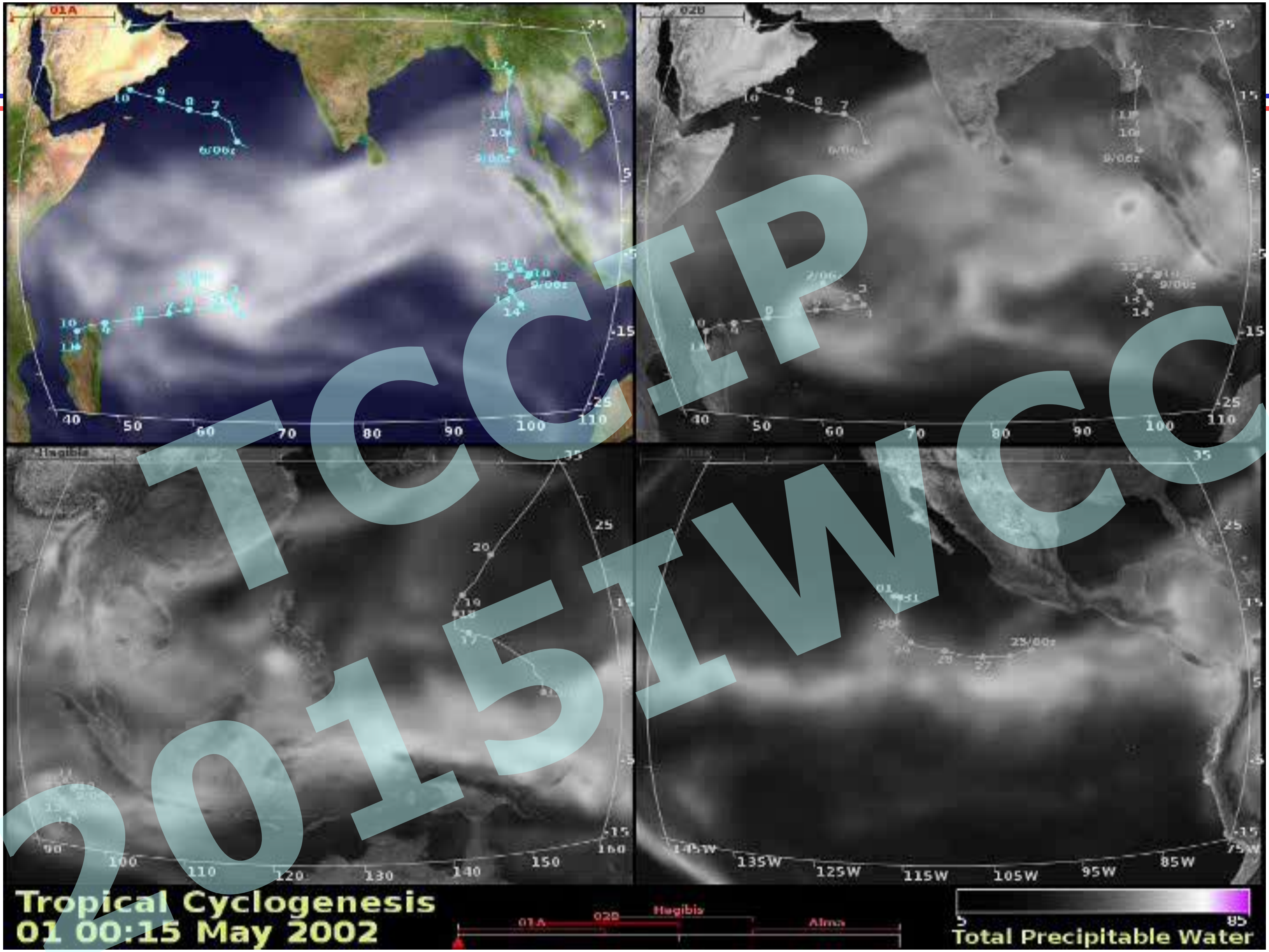
*``Although some aspects of the transformation of atmospheric disturbances into tropical cyclones are relatively well understood, the general problem of tropical cyclogenesis remains in large measure, one of the greatest mysteries of the tropical atmosphere.”* – Kerry Emanuel, *The Divine Wind (2005)*




simulation, 2007; visualization, 2008; paper submitted 2007,and published 2012, **28pp**

| | | May 1 | May 6 | May 11 | May 16 | May 21 | May 26 |
|---|---|---|---|---|---|---|---|
| Kesiny | 3-11 | | | | | | |
| 01A | 6-10 | | | | | | |
| Errol | 9-14 | | | | | | |
| 02B | 10-12 | | | | | | |
| Hagibis | 15-21 | | | | | | |
| Alma | 24-01 | | | | | | |

**Best tracks (observations) indicated by blue lines**


01A
02B
Tropical Cyclogenesis
01 00:15 May 2002
Hagibis
Alma
5
85
Total Precipitable Water

# Tropical Cyclone Formation and Tropical Waves

Remarkable simulations of TC formation and different tropical waves include:

- TC Nargis (2008) and an Equatorial Rossby (ER) Wave (Shen et al., 2010a)
- Hurricane Helene (2006) and an African Easterly Wave (AEW; Shen et al., 2010b)
- Twin TCs (2002) and a mixed Rossby Gravity (MRG) Wave (Shen et al., 2012)

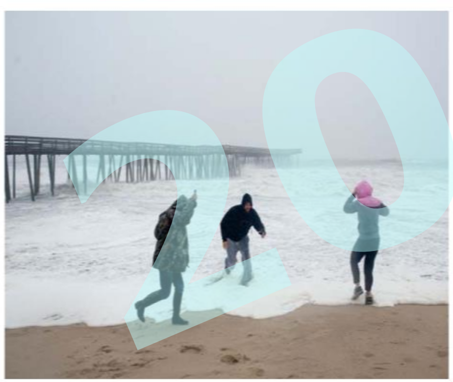
The Wall Street Journal
October 28, 2012

October 28, 2012, 8:17 PM ET

## Why America Has Fallen Behind the World in Storm Forecasting

Article | Comments (22)

COMMENTARY By KERRY EMANUEL



Reuters

AGU Geophysical Research Letter
September 19, 2013

**Genesis of Hurricane Sandy (2012) simulated with a global mesoscale model**

B.-W. Shen,[1,2] M. DeMaria,[3] J.-L. F. Li,[4] and S. Cheung[5]

Received 30 July 2013; revised 5 September 2013; accepted 6 September 2013; published 19 September 2013.

Article first published online: 19 SEP 2013 | DOI: 10.1002/grl.50934

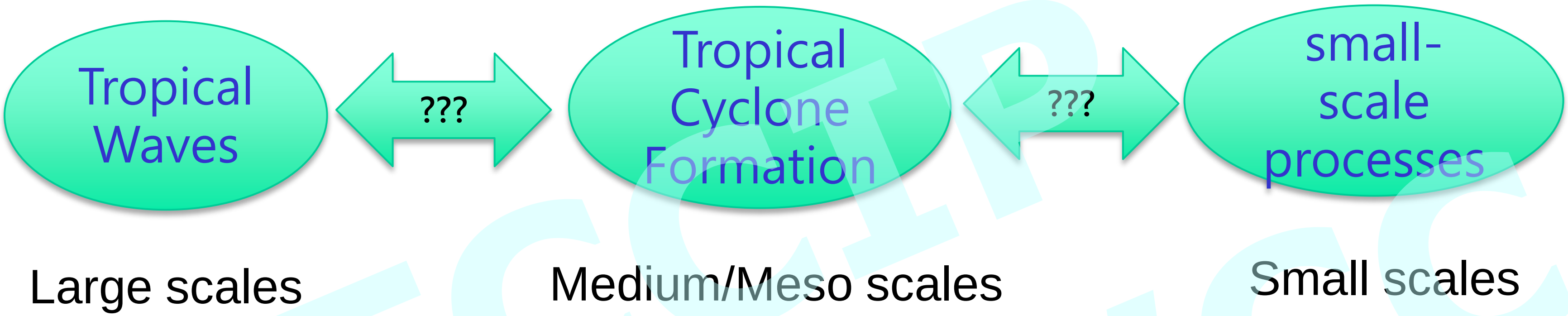
**Key Points**

- A GMM produced a remarkable 7-day track and intensity forecast of TC Sandy
- Sandy's genesis was realistically simulated with a lead time of up to six days
- The lead time is attributed to the improved simulations of multiscale systems

# Questions

- Why high-resolution GCMs have skills?
- Are the simulations of TC genesis consistent with Chaos theory?
- Is nonlinearity a source of chaos? (if so, is it good to increase a model's resolution?) (additional fixed points?)
- What are the controlling factors in the eastward or westward movement of Hurricane Sandy in the models?
- What are the characteristics of solutions near a saddle point? What are the controlling factors in the accuracy of solutions near the saddle point?
- Nonlinearity can lead to diverged trajectories at a finite time in a non-dissipative Loren model with r=0 or r≠0.

# Scientific Goals



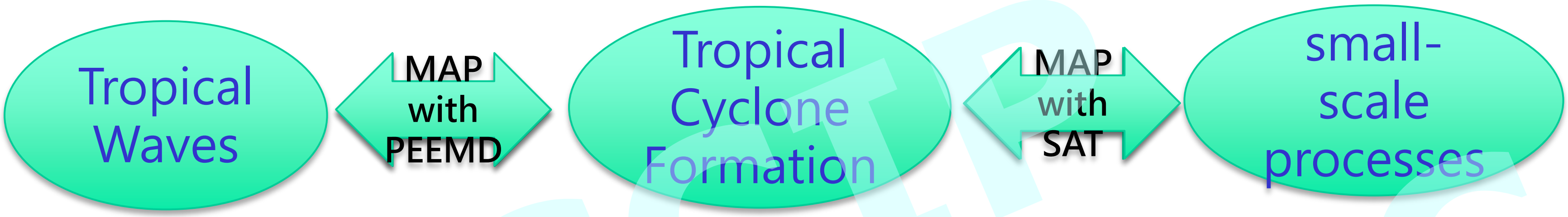

1. **to what extent can large-scale flows determine the timing and location of Tropical Cyclone (TC) genesis?**

   **(e.g., downscaling)**

2. **to what extent can resolved small-scale processes impact solutions' stability (or predictability)?**

   **(e.g., upscaling)**

# Scientific Goals




Large scales | Medium/Meso scales | Small scales

1. **to what extent can large-scale flows determine the timing and location of Tropical Cyclone (TC) genesis?**

   **(e.g., downscaling)**

2. **to what extent can resolved small-scale processes impact solutions' stability (or predictability)?**

   **(e.g., upscaling)**

MAP: Multiscale Analysis Package
PEEMD: Parallel Ensemble Empirical Mode Decomposition
SAT: Stability Analysis Tool

# Supercomputing, Visualization, and Modeling

# Early Efforts with Global Models
## (1999~2003)

- Lin, S.-J., S. Nebuda, **<u>B.-W. Shen</u>**, J.-D. Chern, W. Sawyer, and A. DaSilva, 2001: DAO's suggestions to the software design of CAM. (informal technical note). March 16, 2001. [CA
atmosphere model]

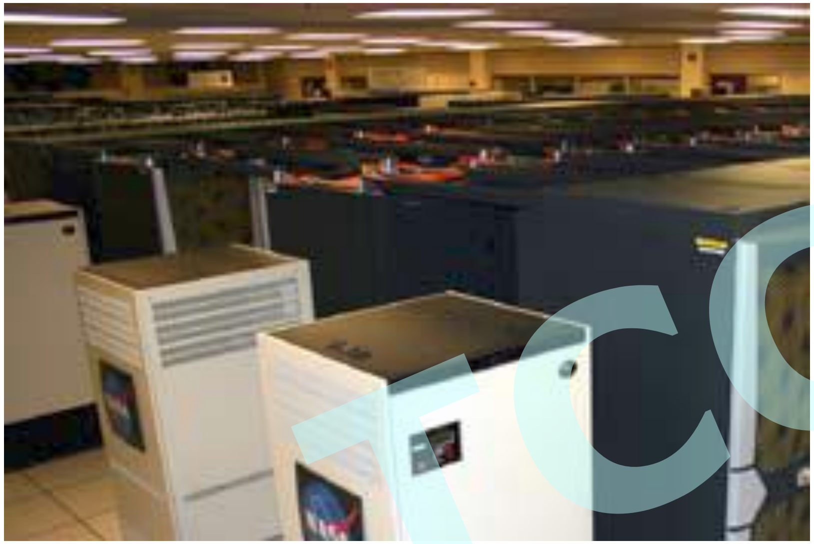
Climate model

- Chang, Y., S. D. Schubert, S.-J. Lin, S. Nebuda, **<u>B.-W. Shen</u>**, 2001: The climate of the FVCCM-3 Model. NASA/GSFC Technical Report Series on Global modeling and Data Assimilation, **vol 20**, p. 127.
- Radakovich, J. D., G. Wang, J.-D. Chern, M. G. Bosilovich, S.-J. Lin, S. Nebuda, and **<u>B.-W. Shen</u>**, 2003: Implementation of the NCAR Community Land Model (CLM) in the NASA/NCAR finite-volume Global Climate Model (fvGCM). 14th Symposium on Global Change and Climate Variations.
- Lin, S.-J., **<u>B.-W. Shen</u>**, W. P. Putman, J.-D. Chern, 2003: Application of the high-resolution finite-volume NASA/NCAR Climate Model for Medium-Range Weather Prediction E
- EUG Joint Assembly, Nice, France, 6 - 11 April 2003.

Weather model

- **Unix System and Network Programming:** Unix curses, device control (serial I/O), file system control, inter-process communication (pipes, semaphore, shared memory, TCP/IP sockets), process control, signal handling.
- **System Administration:** Unix/Linux/MS windows system installation.
- **Supercomputing (Parallel/Distributed/Cluster Computing):** MPI (Message Passing Interface), MPI-2 remote memory access, MLP (Multi-Level Parallelism), OpenMP, ESMF (Earth Science Modeling Framework), POSIX Threads, and JAVA Threads. Knowledge of Gird computing.
- **Software:** Fortran (F77/F90/F95), OOP (Object Oriented Programming), C/C++, JAVA, Basic, Pascal, UNIX Shells, UNIX m4 script, PERL, Python, PHP, HTML, XML, XHTML, CGI, AWK. CVS (Concurrent Version System), GNU Make, gdb, LaTex, MATLAB, VMWARE, Secure Shell, MS-Office, VIS5D, AVS, GrADS, NCAR Graphics, GEMPAK.
- **Numerical Models:** MM4, MM5, ARPS, WRF, NASA GEOS-4, GEOS-5 (beta), NCAR CAM, MMF

# NASA Supercomputing and Visualization Systems



Pleiades Supercomputer (as Nov. 2014)

- one of a few petascale supercomputers
- $R_{max}$ of 3,375 teraflops (LINPACK); $R_{peak}$ of 3,988 teraflops
- 160,768 cores in total; Intel Xeon processors, Nehalem, Westmere, Sandy Bridge, Ivy Bridge
- 532 TB memory
- 3.1 PB disk space
- Largest InfiniBand network.

- Large-scale visualization system
  - 8x16 LCD tiled panel display
  - 245 million pixels
- 128 nodes
  - 1024 cores, 128 GPUs
- InfiniBand (IB) interconnect to Pleiades
  - 2D torus topology
  - High-bandwidth

# The Global Mesoscale Model

1. Model Dynamics and Physics:

   - The finite-volume dynamical core (Lin 2004);
   - The NCAR physical parameterizations, and NCEP SAS as an alternative cumulus parameterization scheme
   - The NCAR land surface model (CLM2, Dai et al. 2003)

2. Computational design, scalability and performance (suitable for running on clusters or multi-core systems)

**<u>Shen,B.-W.</u>,** R. Atlas, O. Oreale, S.-J Lin, J.-D. Chern, J. Chang, C. Henze,and J.-L. Li, 2006b: Hurricane Forecasts with a Global Mesoscale-Resolving Model: Preliminary Results with Hurricane Katrina(2005). Geophys. Res. Lett., L13813, doi:10.1029/2006GL026143. (This has been selected as an AGU Journal Highlight, and has also been highlighted in *Science*, 25 August, 2006)

**<u>Shen,B.-W.</u>,** R. Atlas, J.-D. Chern, O. Reale, S.-J. Lin, T. Lee, and J.Change 2006a: The 0.125 degree Finite Volume General Mesoscale Circulation Model:Preliminary simulations of mesoscale vortices. Geophys. Res. Lett., 33, L05801, doi:10.1029/2005GL024594.

# Physics Parameterizations

- Moist physics:

  -Deep convections: Zhang and McFarlane (1995);

  Pan and Wu (1995, aka NCEP/SAS)

  -Shallow convection: Hack (1994)

  -large-scale condensation (Sundqvist 1988)

  -rain evaporation
- Boundary Layer

  - first order closure scheme

  - local and non-local transport (Holtslag and Boville 1992)
- Surface Exchange

  - Bryan et al. (1996)

Pan, H.-L., and W.-S. Wu, 1995: Implementing a mass flux convection parameterization package for the NMC medium-range forecast model. NMC office note, No. 409, 40pp. [Available from NCEP].

# Grid Cells vs. Grid Spacing

| Resolution | x | y | Grid cells | |
|---|---|---|---|---|
| 1° (~110km) | 288 | 181 | 52 K | |
| 0.5° (~55km) | 576 | 361 | 208 K | |
| 0.25° (~28km) | 1000 | 721 | 721 K | |
| 0.125° (~14km) | 2880 | 1441 | 4.15 M | |
| 0.08° (~9km) | 4500 | 2251 | 10.13 M | Y2005 |
| | | | | |
| MMF (2D CRM) | 144x64 | 90 | 829 K | Y2005~2006 |

The 1/12 degree model with 48 vertical levels has 480 M grid points.
In comparison, the hyperwall-2 is able to display 245 M pixels.

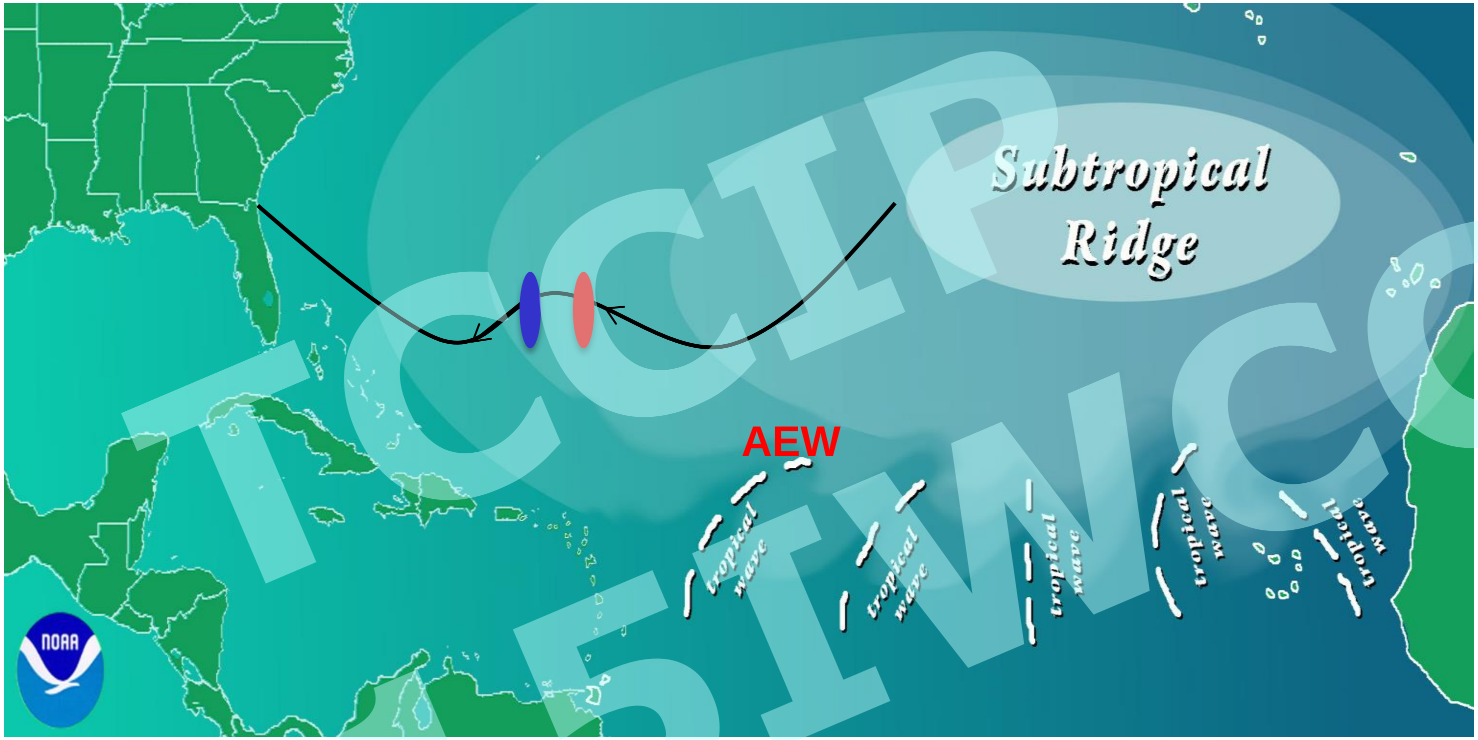
# Short-term Climate Simulations of AEWs and AEJ

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. (4 figures)

Shen, B.-W., W.-K. Tao, and M.-L. Wu, 2010b: Auxiliary Materials for Paper 2010GL044355. (8 figures)

Wu, Y.-L., B.-W. Shen, S. Cheung, J.-L. Li, Z. Liu, 2014: Resolving Multiscale Processes in Tropical Cyclogenesis Using Parallel EEMD. AGU Fall Meeting, San Francisco, CA. December 15-19, 2014. (a manuscript to be submitted in March, 2015)

# African Easterly Waves (AEWs)

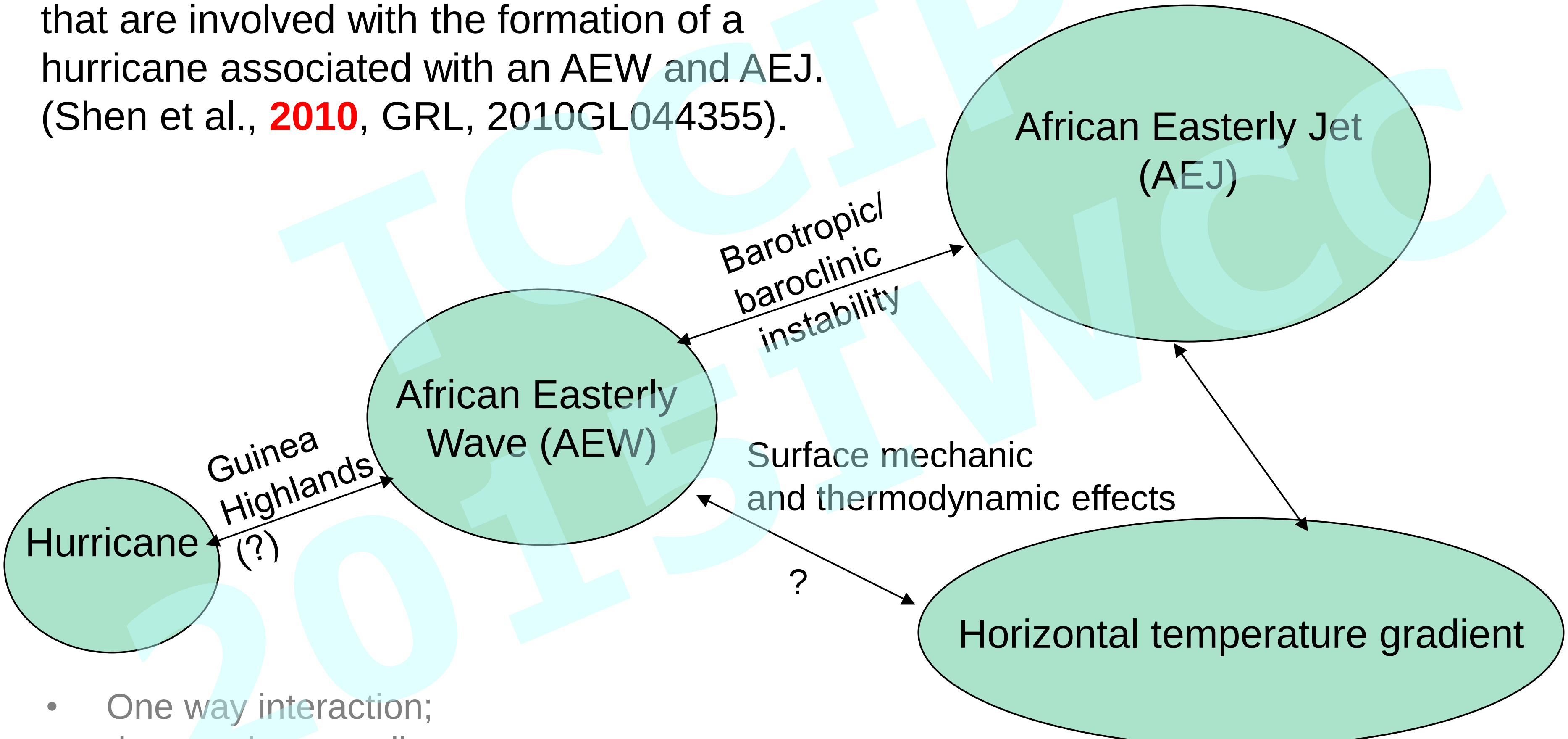



- During the summer time (from June to early October), African easterly waves (AEWs) appear as one of the dominant synoptic weather systems in **West Africa.**
- These waves are characterized by an average westward-propagating speed of 11.6 m/s, an average wavelength of 2200km, and a period of about 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*

# Multiscale Interaction during Hurricane Formation

Figure S1. A schematic diagram showing the multiple processes and multi-scale interactions that are involved with the formation of a hurricane associated with an AEW and AEJ. (Shen et al., **2010**, GRL, 2010GL044355).

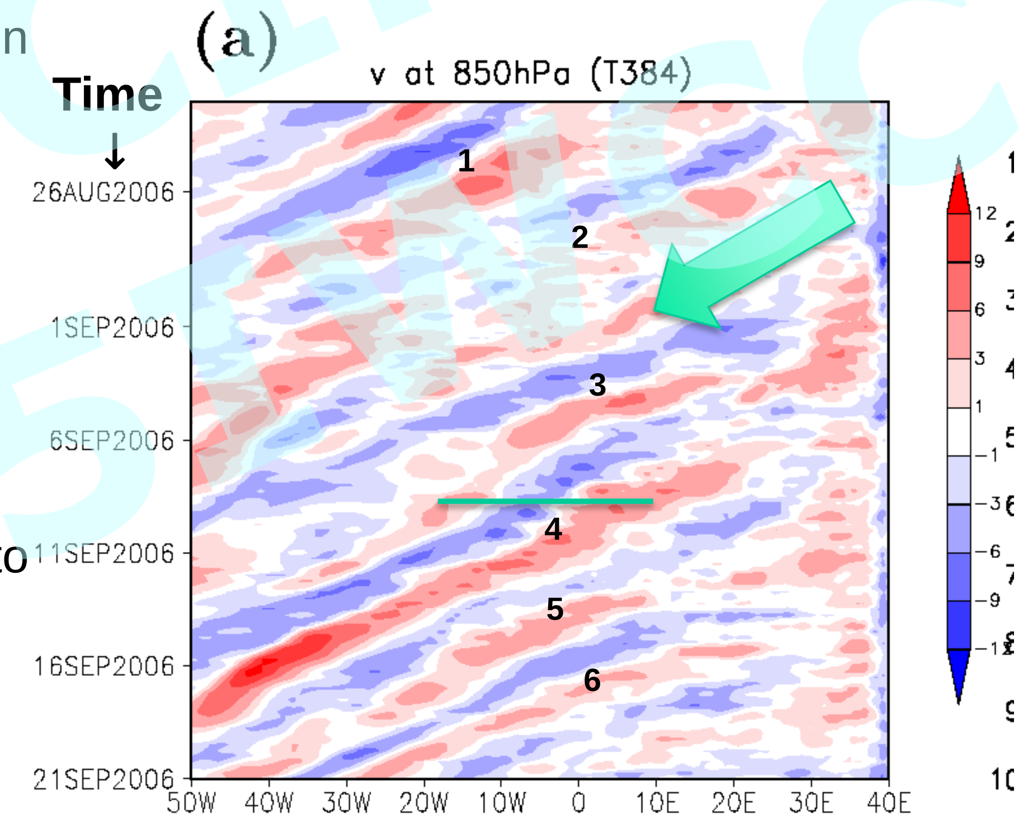



- One way interaction;
- downscale cascading;
- no or limited feedbacks from smaller-scale flows

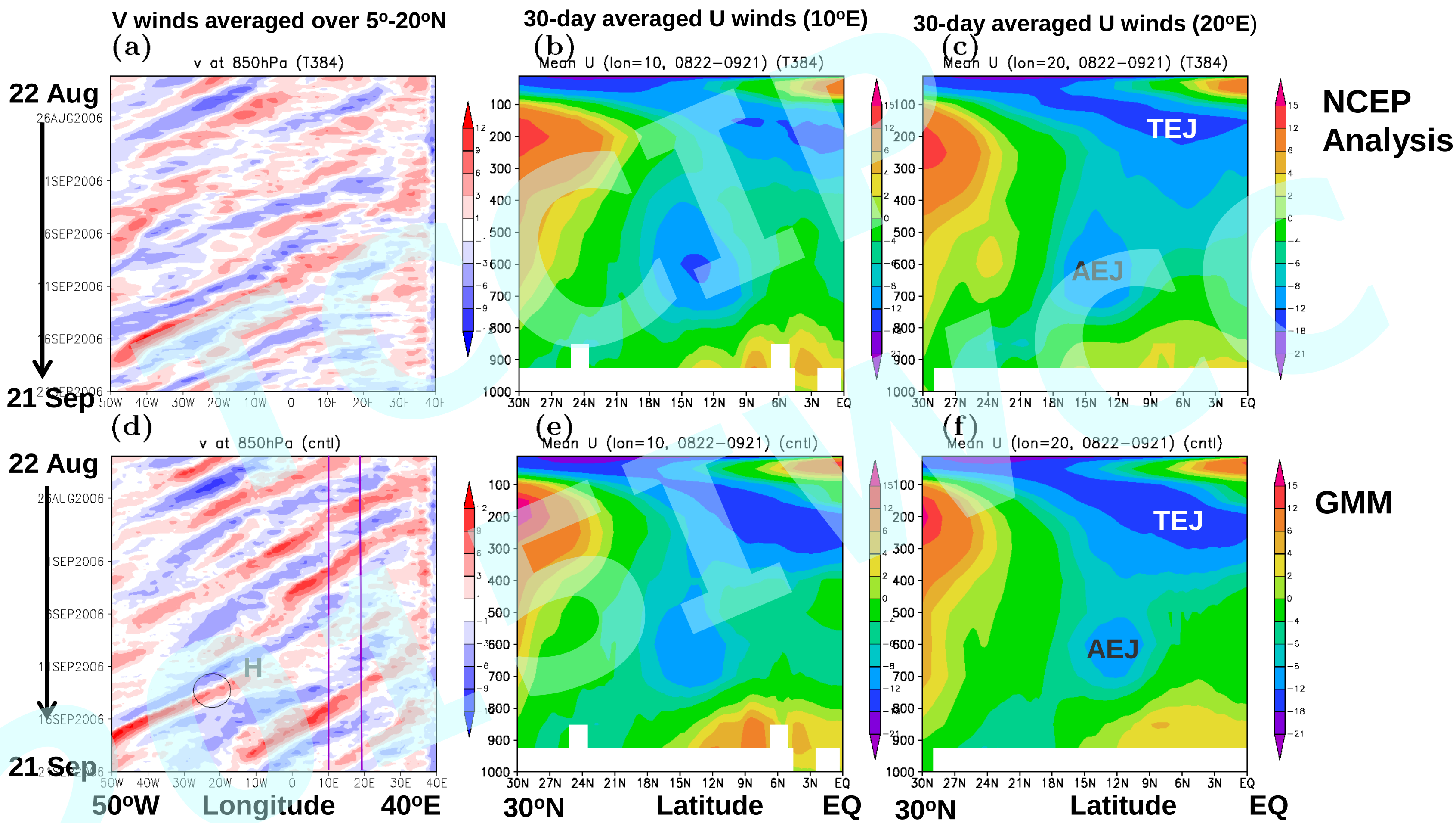
# AEWs in late August 2006

- The NASA African Monsoon Multidisciplinary Analyses (NAMMA) field campaign was launched in August 2006, providing a great opportunity to characterize the frequency of AEWs, their evolution over continental western Africa.

- During the 30-day observation period between late August and late September, there were six AEWs documented that appeared over Africa, propagated westward, and then passed by the Cape Verde Islands.
- In early September, an observed AEW developed into a Cape Verde storm--Hurricane Helene (Brown, 2006).

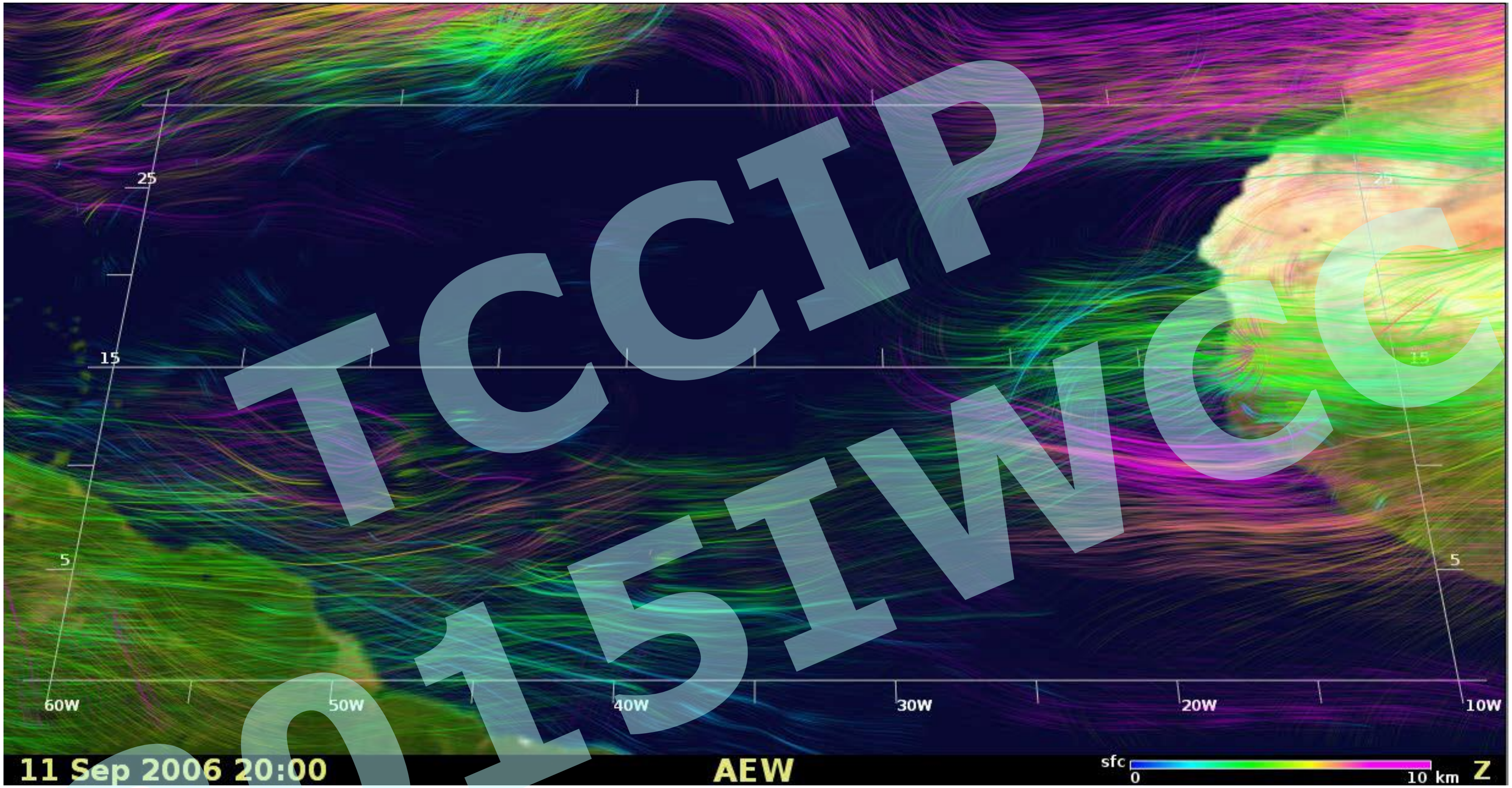


# Five AEWs in 30-day Simulations



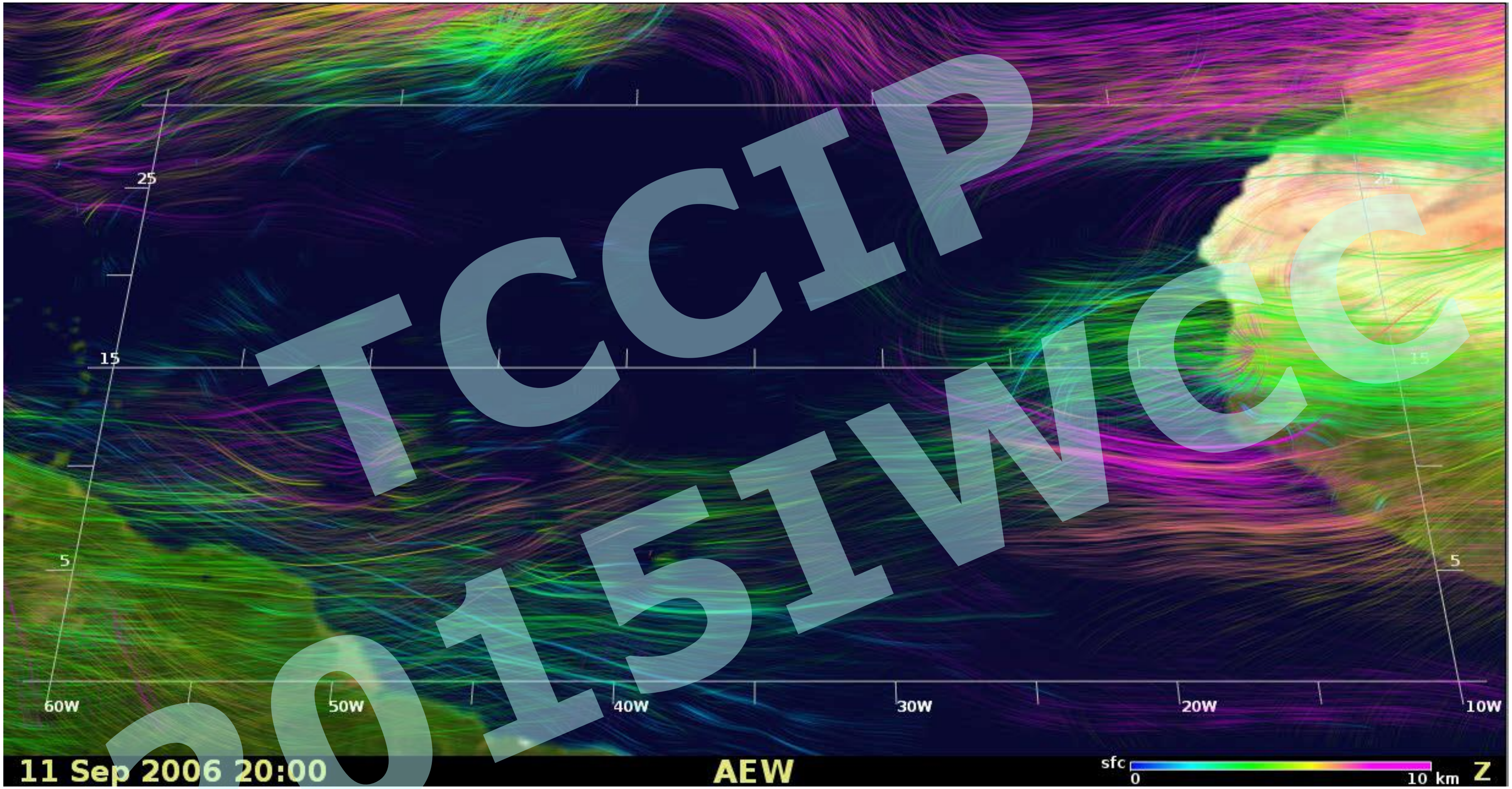

(init at 00zz Aug 22, 2006)

# Formation of Hurricane Helene (2006)



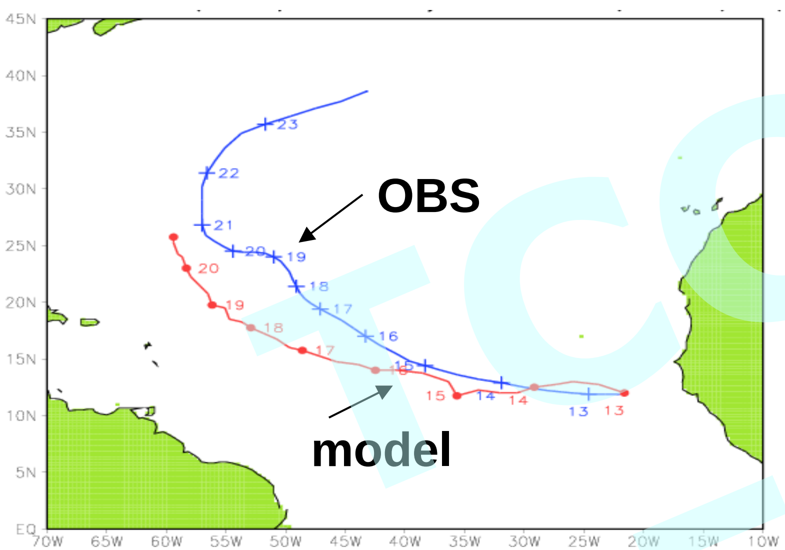



- Simulations from Day 20 to Day 30 in a run initialized at 00Z Aug 22, 2006. http://goo.gl/arWSZ
- Upper-level winds in red; middle-level winds in green; low-level winds in blue
- Low-level CC (cyclonic circulation); Upper-level AC (anticyclonic circulation)
- Shen, B.-W. W.-K. Tao and M.-L. Wu, 2010b: African Easterly Waves in 30-day High-resolution Global Simulations: A Case Study during the 2006 NAMMA Period. *GRL.*, L18803

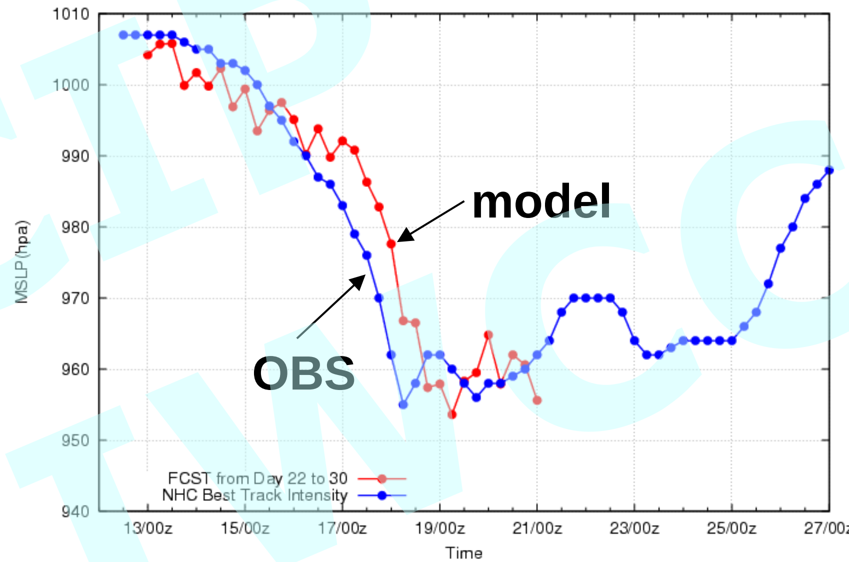

25
15
5
60W
50W
40W
30W
20W
10W
11 Sep 2006 20:00
AEW
sfc
0
10 km
Z

# Simulations of Helene between Day 22-30

## Track Forecast




## Intensity Forecast

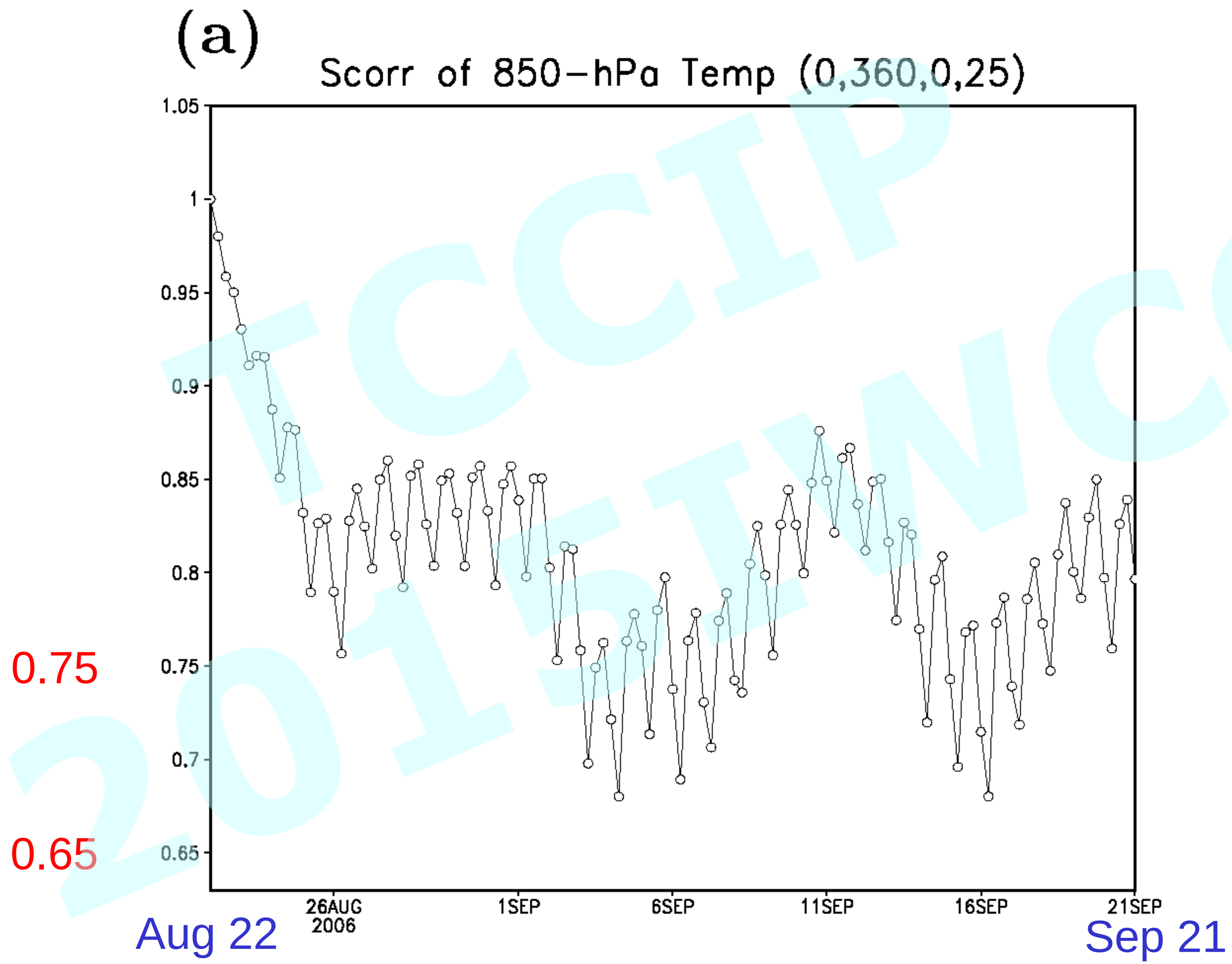



**to what extent can large-scale flows (e.g., an AEW) determine the movement and intensification of Hurricane Helene?**

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.

(Helene: 12-24 September, 2006)

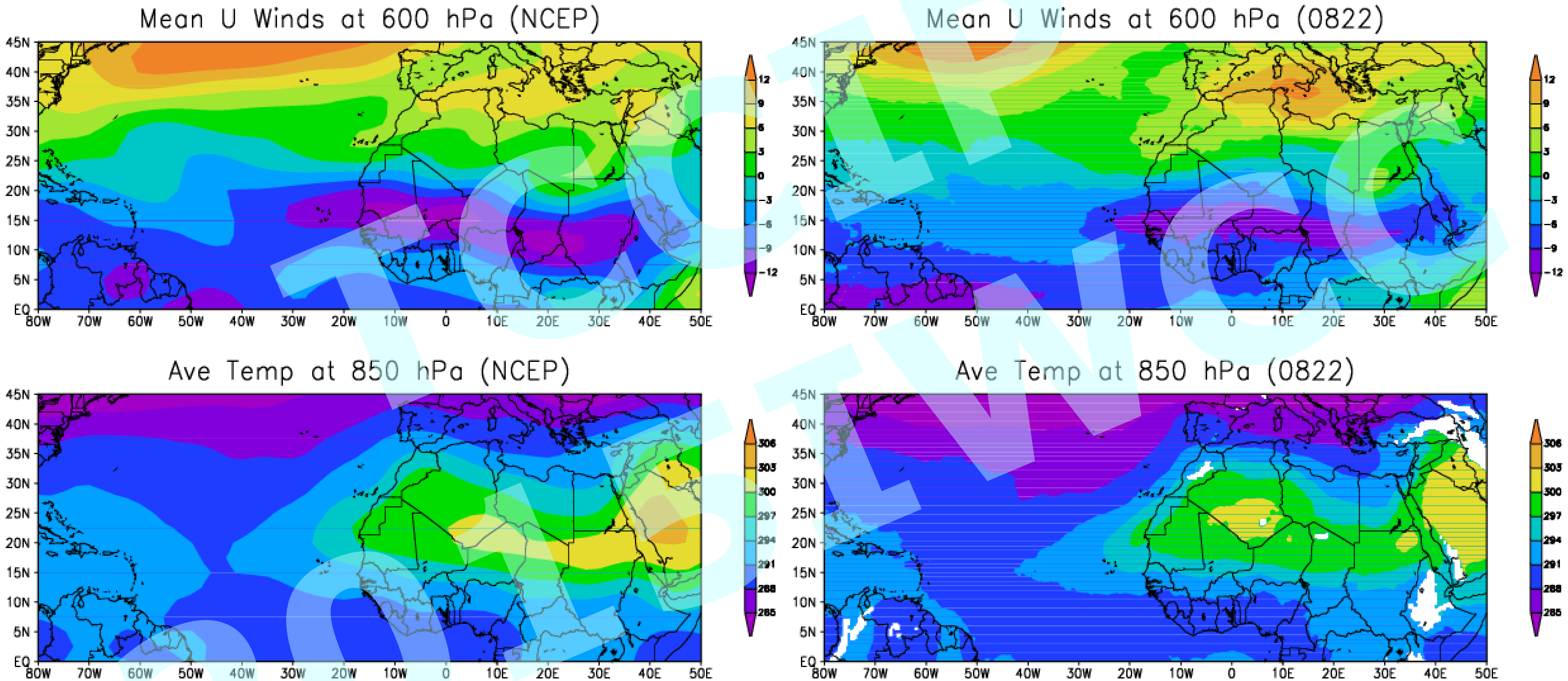
# Correlation Coefficients in a 30 Days Run



# 30-day Averaged U Winds and Temp

NCEP Reanalysis

Model Simulations




(init at 00zz Aug 22, 2006)

$$\frac{\partial U_g}{\partial z} = \frac{-R}{fH}\frac{\partial T}{\partial y}$$

# Sensitivity Experiments

| Case id | Dynamic IC | Clm and Physics IC | SST | Guinea Highlands | Remarks |
|---|---|---|---|---|---|
| cntl | 08/22 | 08/22 | weekly | | |
| A | 08/23 | 08/23 | weekly | | |
| B | 08/24 | 08/24 | weekly | | Impact of initial "perturbations" |
| C | 08/25 | 08/25 | weekly | | |
| D | 08/22 | Climate clm | weekly | | |
| E | 08/22 | 06/22 | weekly | | Impact of initial land surface conditions |
| F | 08/22 | 08/22 | climate | | **Impact of SSTs** |
| G | 04/22 | 08/22 | weekly | | Changed date to be 08/22/2006 |
| H | 06/22 | 08/22 | weekly | **Impact of "physics"** | Changed date to be 08/22/2006 |
| I | 08/22 | 08/22 | weekly | A factor of 0.6 in heights | **Impact of terrains** |

# Sensitivity Experiments

- Sensitivity to initial perturbations (e.g., AEJ)

Case D

- Sensitivity to initial land surface conditions ➔ e.g., dissipation of an initial AEJ
  → impact of soil moisture

- Sensitivity to surface sea temperatures (SSTs) → oceanic feedbacks on AEW simulations; impact on large-scale flows in the upstream, subsequent atmosphere-land interactions, initiation of multiple AEWs, intensification of the 4th AEW and formation of the model 'Helene'

Case G

- Sensitivity to physics (with realistic land surface conditions) ➔ e.g., initial development of an AEJ

- Impact of a reduced mountain height on the simulations of upstream flows

Examining other factors (forcing) that control the evolution of the AEJ, AEW and thus hurricane formation!

# Sensitivities to Initial Conditions

# Empirical Mode Decomposition (EMD)

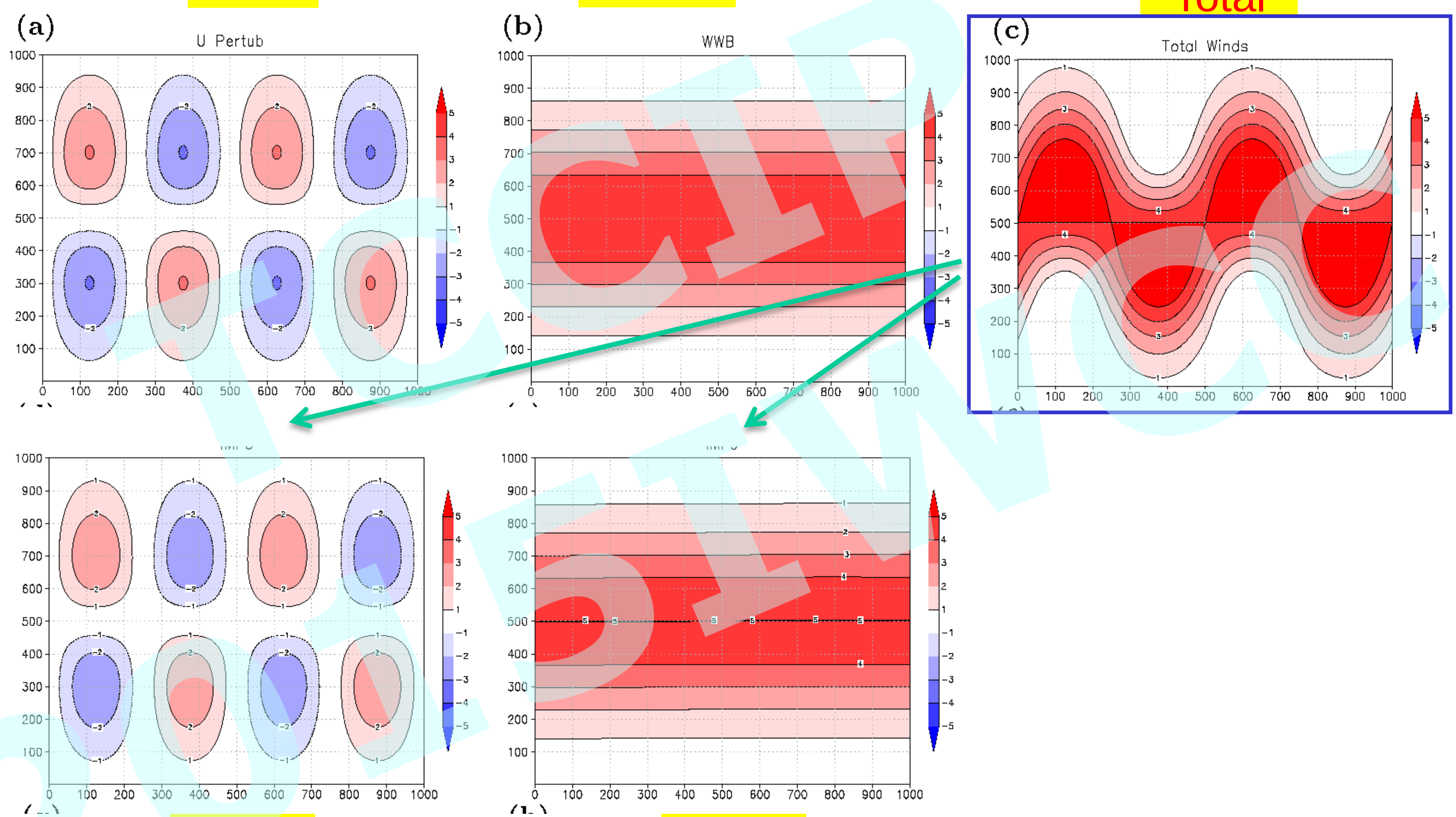
1. **to what extent can large-scale flows determine the timing and location of Tropical Cyclone (TC) genesis?**

   **(e.g., downscaling)**

1. HHT (Hilbert Huang Transform, Huang et al., 1998) consists of Empirical mode decomposition (EMD) and Hilbert Transform.
2. The data-driven EMD method is Complete, Orthogonal, Local, and Adaptive (COLA), which is ideal for the local and nonlinear analysis.
3. EMD generates a set of intrinsic mode functions (IMFs), each of which has features with comparable scales (Wu and Huang 2009, and references therein).
4. EMD performs like a filter bank (e.g., a dyadic filter); the unique feature suggests a potential for hierarchical multiscale analysis.

# Decompositions of an MRG wave with the PEEMD

Analytical Solutions




IMFs

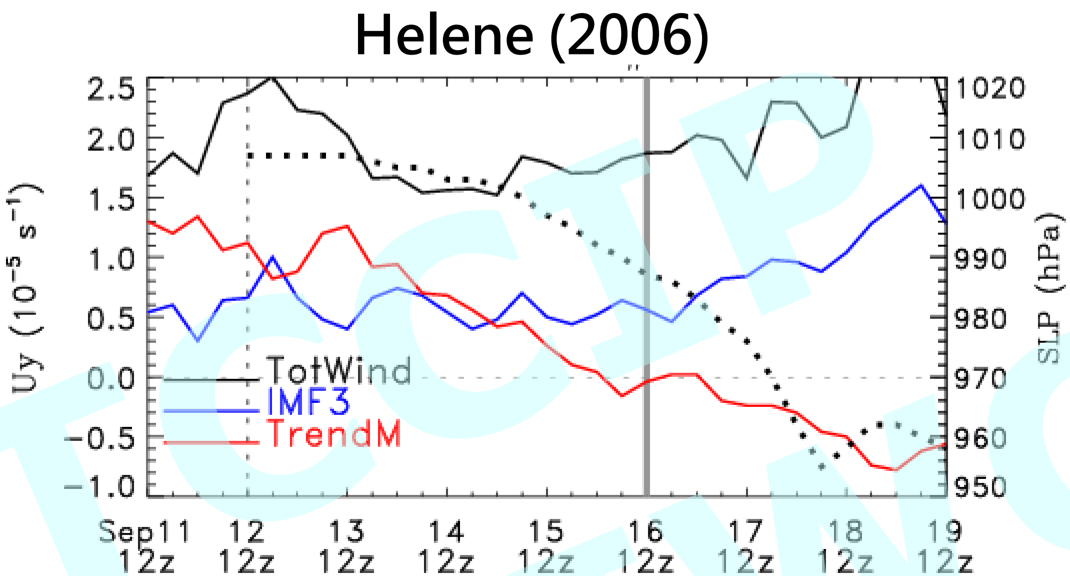
IMF6

(an oscillatory mode)

IMF9

(a trend mode)

# Multiscale Processes in TC Genesis and Intensification




Shear and sea level pressure (black dotted line) variation along storm track. Vertical thin dotted and coarse solid grey lines indicates TD and Hurricane classification points, respectively. Plotted shear for IMF3 and Trend mode has been multiplied by 2.

Dwindling of the trend mode shear and its departure from the total wind tendency during storm intensification seem to suggest that the downscaling transfer of Trend mode shear to the short wave mode (IMF3) in the process.

18 out of 41 cases show such behavior.

# AEWs and Tropical Cyclogenesis during 2004-2013

| Year | No. of hurricanes | No. of TDs/TSs | No. of AEWs |
|---|---|---|---|
| 2004 | 4(4) | 6(8) | 28 |
| 2005 | 0(1) | 3(6) | 28 |
| 2006 | 1(1) | 3(4) | 26 |
| 2007 | 2(5) | 4(5) | 28 |
| 2008 | 2(1) | 3(4) | 28 |
| 2009 | 1(2) | 4(5) | 30 |
| 2010 | 4(4) | 6(7) | 26 |
| 2011 | 1(1) | 4(5) | 27 |
| 2012 | 0(0) | 5(7) | 27 |
| 2013 | 1(1) | 3(4) | 24 |
| total | 15(18) | 41(55) | 271 |

The number of hurricanes and Tropical Depressions/Tropical Storms (TDs/TSs) from NHC best tracks dataset, and AEWs, July through September, 2004-2013. On average, roughly 1 in 7 (41/271=6.6) AEWs developed into tropical cyclones, consistent with previous study. The numbers in parentheses include storms not of AEW origin.

Wide year-to-year variation of storm (TD/TS and hurricane) numbers in the selected region. Near invariant for the number of AEWs annually, except for a quieter 2013.

# Scientific Goals

**2. to what extent can resolved small-scale processes impact solutions' stability (or predictability)?**

**(e.g., upscaling)**

- Increase or decrease complexities of the Lorenz model (3DLM) by deriving high-order Lorenz models (5DLM and 6DLM) or non-dissipative Lorenz model (NLM)
- Apply the SAT to examine the stability of the above modified Lorenz models with the aim of understanding the impact of increased degree of nonlinearity, dissipation or heating terms on solutions' stability (Understanding the role of nonlinearity in chaotic responses)
- Investigate the possibility of applying the SAT (e.g., the calculations of eLE) to determining the predictability of global models

# Lorenz Models

D, H, and N refer to as the dissipative terms, the heating term, and nonlinear terms associated with the primary modes (low wavenumber modes), respectively. $D_s$, $H_s$, and $N_s$ refer to as the dissipative terms, the heating term, and nonlinear terms associated with the secondary modes (high wavenumber modes), respectively. NLM refers to the non-dissipative Lorenz mode.

| | D | H | N | $D_s$ | $H_s$ | $N_s$ | Critical points for (X,Y) | $r_c$ | Remarks |
|---|---|---|---|---|---|---|---|---|---|
| Linearzied 3DLM | V | V | | | | | | "1" | Unstable as r>1 |
| 3DLM | V | V | V | | | | $X_c = Y_c = \pm\sqrt{b(r-1)}$ | 24.74 | |
| 3D-NLM | | V | V | | | | $(X_c, Y_c) = (\pm\sqrt{2\sigma r}, 0)$ | | conservative |
| 5DLM | V | V | V | V | | V | $X_c = Y_c \sim \pm\sqrt{2b(r-1)}$ | 42.9 | $X_c = Y_c = \pm\sqrt{b(Z_c + 2Z_{1c})}$ |
| 6DLM | V | V | V | V | V | V | | 41.1 | |


**Shen, B.-W., 2014a:** Nonlinear Feedback in a Five-dimensional Lorenz Model. *J. of Atmos. Sci.* **71**, 1701–1723. doi: http://dx.doi.org/10.1175/JAS-D-13-0223.1

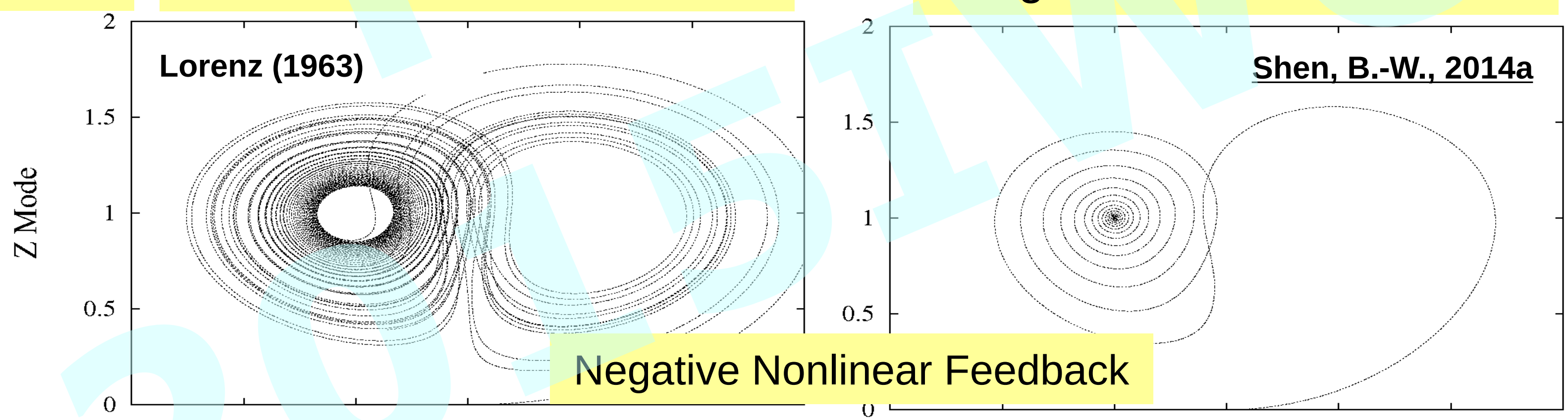
**Shen, B.-W., 2014b:** On the Nonlinear Feedback Loop and Energy Cycle of the Non-dissipative Lorenz Model. *Nonlin. Processes Geophys. Discuss.*, 1, 519-541, 2014. www.nonlin-processes-geophys-discuss.net/1/519/2014/

**Shen, B.-W., 2014c:** Nonlinear Feedback in a Six-dimensional Lorenz Model. Impact of an Additional Heating Term. (to be submitted to JAS)

# Are the simulations of TC genesis consistent with Chaos theory?

- The butterfly effect of first kind: _*sensitive dependence on initial conditions*_.
- The butterfly effect of second kind: _*a metaphor (or symbol ) for indicating that small perturbations can alter large-scale structure*_.
- Lorenz's studies suggested finite predictability and nonlinearity as the source of chaos.
- Increased degree of nonlinearity (e.g., multiscale interactions) can stabilize solutions and thus improve simulations (Shen et al., 2014a,b).

r=25 | Lorenz Model | High-order Lorenz Model




The studies by Lorenz (1963, 1972) laid the foundation for chaos theory, which was viewed as the third scientific revolution of the 20th century after relativity and quantum mechanics (e.g. Gleick, 1987; Anthes 2011).

# A Brief Summary of High-resolution Lorenz Models

1. The 3DLM contains nonlinearity, heating, and dissipative terms.

(by introducing some of above terms, additional modes can change the stability of existing critical points and/or introduce additional critical points)

2. Two simplified 3DLMs include (i) nonlinearity only or (ii) nonlinearity and a heating term (appearance of a saddle points). → sources of chaos;
3. The 5DLM has increased degree of nonlinearity (with additive dissipative terms). → negative nonlinear feedback → improved stability;
4. The 3DLMP with a parameterized dissipative term produces solution's stability comparable to that in 5DLM (a comparable equilibrium state) but different time evolution of solutions (a different transient solution); coarse resolution runs may produce a comparable climate (but different weather).
5. The 6DLM introduces an additional heating term, →(slightly) positive nonlinear feedback; excessive precipitation in high resolution runs may indicate appearance of chaotic responses → additional "smoothing terms" may be added to stabilize solutions by some modelers.

Additional modes in the 5DLM do not introduce additional critical points; a comparison of the 6DLM with the 5DLM does not suggest significant changes in the characteristics of critical points. Shen (2014a, b, c).

# Calling Sequences: Rearrangements

However, any conditionally convergent series can be rearranged to give a different sum. To illustrate this fact let's consider the alternating harmonic series

**6** $$1 - \frac{1}{2} + \frac{1}{3} - \frac{1}{4} + \frac{1}{5} - \frac{1}{6} + \frac{1}{7} - \frac{1}{8} + \cdots = \ln 2$$

(See Exercise 36 in Section 11.5.) If we multiply this series by $\frac{1}{2}$, we get

$$\frac{1}{2} - \frac{1}{4} + \frac{1}{6} - \frac{1}{8} + \cdots = \frac{1}{2}\ln 2$$

Inserting zeros between the terms of this series, we have

**7** $$0 + \frac{1}{2} + 0 - \frac{1}{4} + 0 + \frac{1}{6} + 0 - \frac{1}{8} + \cdots = \frac{1}{2}\ln 2$$

Now we add the series in Equations 6 and 7 using Theorem 11.2.8:

**8** $$1 + \frac{1}{3} - \frac{1}{2} + \frac{1}{5} + \frac{1}{7} - \frac{1}{4} + \cdots = \frac{3}{2}\ln 2$$

Notice that the series in 8 contains the same terms as in 6, but rearranged so that one negative term occurs after each pair of positive terms. The sums of these series, however, are different. In fact, Riemann proved that

> if $\Sigma\, a_n$ is a conditionally convergent series and $r$ is any real number whatsoever, then there is a rearrangement of $\Sigma\, a_n$ that has a sum equal to $r$.

A proof of this fact is outlined in Exercise 44.

Diurnal Oscillation

# Coupling: Training and Stabilizer Wheels

+ diagnostic equation

In the (regional) models, the interaction is one way.

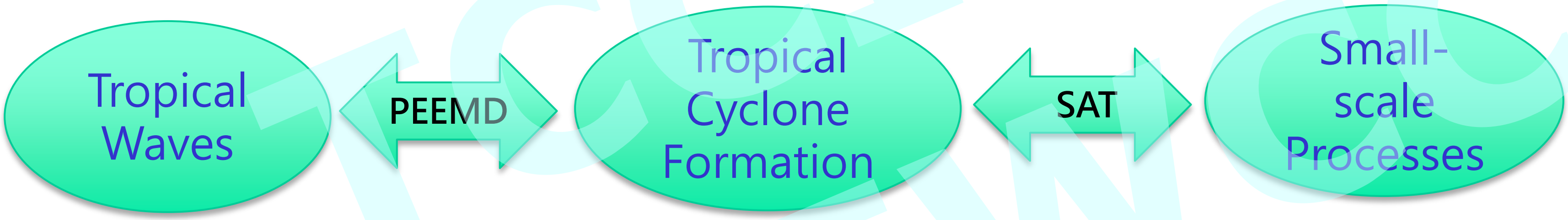
- Heavy Duty BMX Training Wheels for 20-Inch BMX Wheel Bicycles, boys or girls frame
- Heavy-Duty Steel Tubing to Support over 200lbs! Do not settle for unsafe universal axle mounted training wheels

# Coupling: Training Wheel and Bicycle Trailer

Its own memory?

# Summary

- The statistical characteristics of multiple (6) AEWs (including initiation and propagation) are realistically simulated in short-term climate (30 days) simulations. Remarkable simulations of a mean African Easterly Jet (AEJ) are also obtained.
- 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 4$^{th}$ AEW is realistically simulated.




1. **to what extent can large-scale flows determine the timing and location of TC genesis? (downscaling)**
2. **to what extent can resolved small-scale processes impact solutions stability (or predictability)? (upscaling)**

- With the PEEMD, we showed the the impact of downscaling processes associated with the trend mode (e.g., basic state) on the intensification of the oscillatory modes (e.g., AEW and hurricane Helene).
- By deriving high-order Lorenz models and simplifying the original Lorenz model, we discussed the role of increased degree of nonlinearity and the source of chaos.

# 5DLM (Shen, 2014, JAS)

**Top 10**
**Most Read JAS Articles**

(previous 12 months)

A Study of Aerosol Impacts on Clouds and Precipitation Development in a Large Winter Cyclone - Thompson & Eidhammer

Atmospheric Predictability: Why Butterflies Are Not of Practical Importance - Durran and Gingrich

A Unified Convection Scheme (UNICON). Part I: Formulation - Park

How Does the Quasi-Biennial Oscillation Affect the Stratospheric Polar Vortex? - Watson & Gray

Representing Equilibrium and Nonequilibrium Convection in Large-Scale Models - Bechtold et al.

Three-Dimensional Structure and Evolution of the MJO and Its Relation to the Mean Flow - Adams & Wallace

The Formation of Wider and Deeper Clouds as a Result of Cold-Pool Dynamics - Schlemmer & Hohenegger

Nonlinear Feedback in a Five-Dimensional Lorenz Model - Shen

A Unified Convection Scheme (UNICON). Part II: Simulation - Park

The Influence of Environmental Low-Level Shear and Cold Pools on Tornadogenesis: Insights from Idealized Simulations - Markowski & Richardson

## Nonlinear Feedback in a Five-Dimensional Lorenz Model

**Bo-Wen Shen**

*Earth System Science Interdisciplinary Center, University of Maryland, College Park, College Park, and NASA Goddard Space Flight Center, Greenbelt, Maryland*

### Abstract

In this study, based on the number of modes, the original three-dimensional Lorenz model (3DLM) is generalized with two additional modes [five-dimensional Lorenz model (5DLM)] to examine their role in the predictability of the numerical solutions and to understand the underlying processes that increase the solution stability. As a result of the simplicity of the 5DLM with respect to existing generalized Lorenz models (LMs), the author is able to obtain the analytical solutions of its critical points and identify the role of the major nonlinear term in the solution's stability, which have previously not been documented in the literature. The nonlinear Jacobian terms of the governing equations are analyzed to highlight the importance of selecting new modes for extending the nonlinear feedback loop of the 3DLM and thus effectively increasing the degree of nonlinearity (i.e., the nonlinear mode–mode interactions) in the 5DLM. It is then shown that numerical solutions in the 5DLM require a larger normalized Rayleigh number $r$ for the onset of chaos and are more predictable than those in the 3DLM when $r$ is between 25 and 40 and the Prandtl number $\sigma$ is 10. The improved predictability is attributable to the negative nonlinear feedback enabled by the new modes. The role of the (negative) nonlinear feedback is further verified using a revised 3DLM with a parameterized nonlinear eddy dissipative term. The finding of the increased stability in the 5DLM and revised 3DLM with respect to the 3DLM is confirmed with the linear stability analysis and the analysis of the Lyapunov exponents using different values of $r$ and $\sigma$. To further understand the impact of an additional heating term, results from the 5DLM and a higher-dimensional LM [e.g., the six-dimensional LM (6DLM)] are analyzed and compared.

Keywords: Nonlinear dynamics, Differential equations, Lyapunov vectors, Numerical analysis/modeling, Climate prediction, Numerical weather prediction/forecasting

Received: July 22, 2013; Final Form: December 3, 2013

# Inspirational Comments

## Some earlier work on mesoscale predictability

Rick Anthes [anthes@ucar.edu]

**Sent:** Sunday, February 20, 2011 11:06 AM

**To:** Shen, Bo-Wen (GSFC-612.0)[UNIV OF MARYLAND COLLEGE PARK]

Hi Bowen,

I have gone through some of your presentations and note with special interest your comments on scale interactions and predictability of tropical cyclones. I did some work closely related to this in the 1980s, and hypothesized that some mesoscale systems of importance were predictable far in advance if the proper large-scale conditions were known. I put these papers in a folder on my webshare at www.fin.ucar.edu/antheswebshare/ and a summary of them is attached. You might find some of these ideas from 25 years ago interesting. I think your recent work is confirming my hypotheses and thoughts, and I am glad to see this! 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!

Rick

--

Dr.Richard A. Anthes

# Backup Slides

# Summary

1. We first discuss the model's performance and the enabling roles of supercomputing technology with the simulations and visualizations of three convective systems, two of which turn into a twin TC. Sensitivities of simulations to model configurations are also examined.
2. The statistical characteristics of multiple AEWs (including initiation and propagation) are realistically simulated in short-term climate simulations. Remarkable simulations of a mean African Easterly Jet (AEJ) are also obtained.
3. 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).
4. 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 $4^{th}$ AEW is realistically simulated.
5. In the experiment with climate SSTs, differences appear in the $5^{th}$ and $6^{th}$ AEWs, implying that the effects of using climatological SSTs on the simulation of AEW initiation begin to occur after 15-20 days of integration.
6. The reduced height of Guinea highlands causes significant differences in the simulations of AEWs since Day 15. For example, the initiation of the $4^{th}$, $5^{th}$ and $6^{th}$ AEWs are influenced by this change, and the downstream development of AEWs (e.g., the $2^{nd}$ and $4^{th}$ AEWs) becomes weaker.

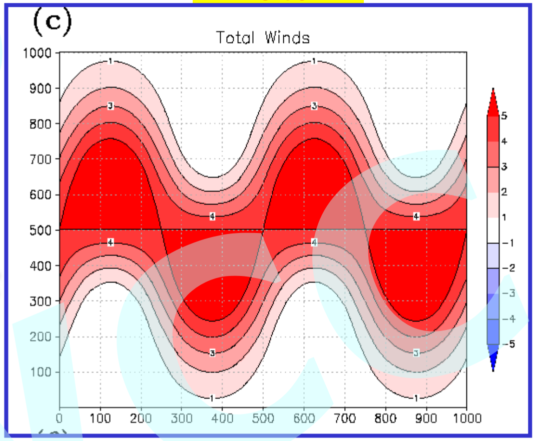
# Decompositions of an MRG wave with the PEEMD

Analytical Solutions

U'

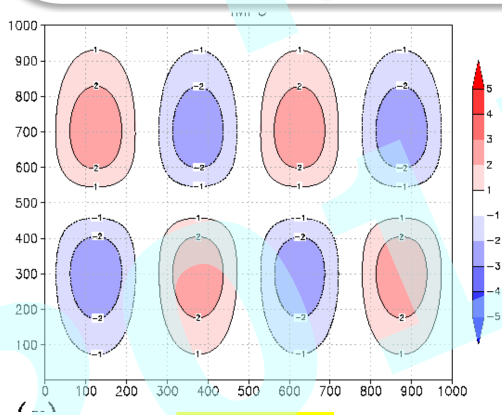
WWB

Total



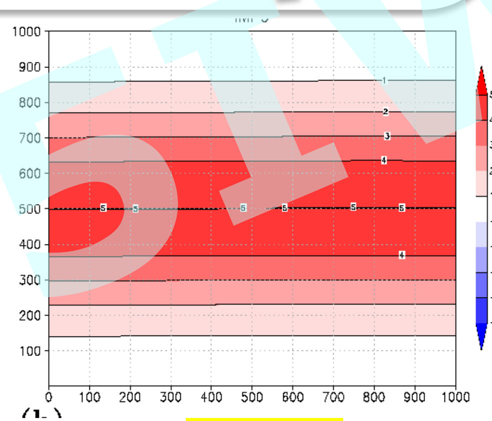

EEMD

IMFs



IMF6

(an oscillatory mode)



IMF9

(a trend mode)

# Conditional Convergence

Given any series $\Sigma\, a_n$, we define a series $\Sigma\, a_n^+$ whose terms are all the positive terms of $\Sigma\, a_n$ and a series $\Sigma\, a_n^-$ whose terms are all the negative terms of $\Sigma\, a_n$. To be specific, we let

$$a_n^+ = \frac{a_n + |a_n|}{2} \qquad\qquad a_n^- = \frac{a_n - |a_n|}{2}$$

Notice that if $a_n > 0$, then $a_n^+ = a_n$ and $a_n^- = 0$, whereas if $a_n < 0$, then $a_n^- = a_n$ and $a_n^+ = 0$.

(a) If $\Sigma\, a_n$ is absolutely convergent, show that both of the series $\Sigma\, a_n^+$ and $\Sigma\, a_n^-$ are convergent.

(b) If $\Sigma\, a_n$ is conditionally convergent, show that both of the series $\Sigma\, a_n^+$ and $\Sigma\, a_n^-$ are divergent.

# NCAR CAM 5.0

Consider the general prediction equation for a generic variable $\psi$,

$$\frac{\partial \psi}{\partial t} = D(\psi) + P(\psi) \ , \tag{2.1}$$

where $\psi$ denotes a prognostic variable such as temperature or horizontal wind component. The dynamical core component is denoted $D$ and the physical parameterization suite $P$.

dynamical processes, resolved

physical processes, unresolved

The total parameterization package in CAM 5.0 consists of a sequence of components, indicated by

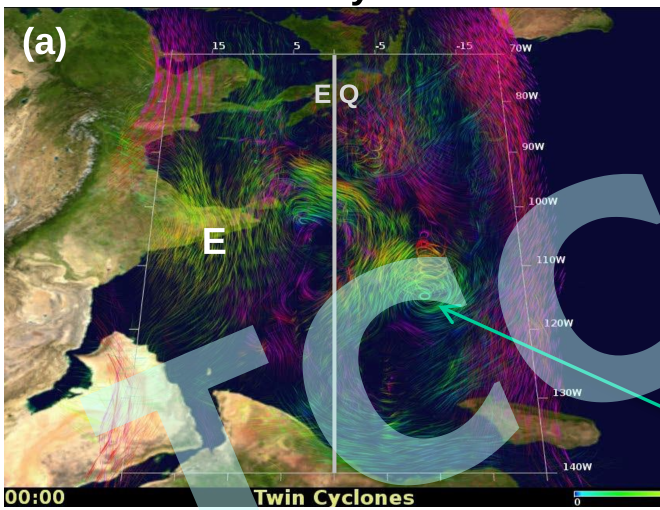
$$P = \{M, R, S, T\} \ , \tag{2.9}$$

where $M$ denotes (Moist) precipitation processes, $R$ denotes clouds and Radiation, $S$ denotes the Surface model, and $T$ denotes Turbulent mixing. Each of these in turn is subdivided into various components: $M$ includes an optional dry adiabatic adjustment (normally applied only in the stratosphere), moist penetrative convection, shallow convection, and large-scale stable condensation; $R$ first calculates the cloud parameterization followed by the radiation parameterization; $S$ provides the surface fluxes obtained from land, ocean and sea ice models, or calculates them based on specified surface conditions such as sea surface temperatures and sea ice distribution. These surface fluxes provide lower flux boundary conditions for the turbulent mixing $T$ which is comprised of the planetary boundary layer parameterization, vertical diffusion, and gravity wave drag.

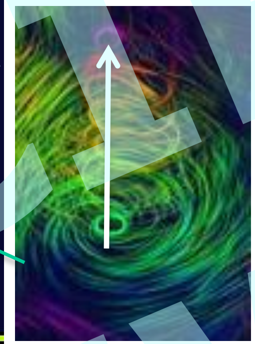
No direct interactions among different parameterizations!

# Visualizations of Twin TCs in May 2002
## (vortex phasing; init at 00Z May 1)

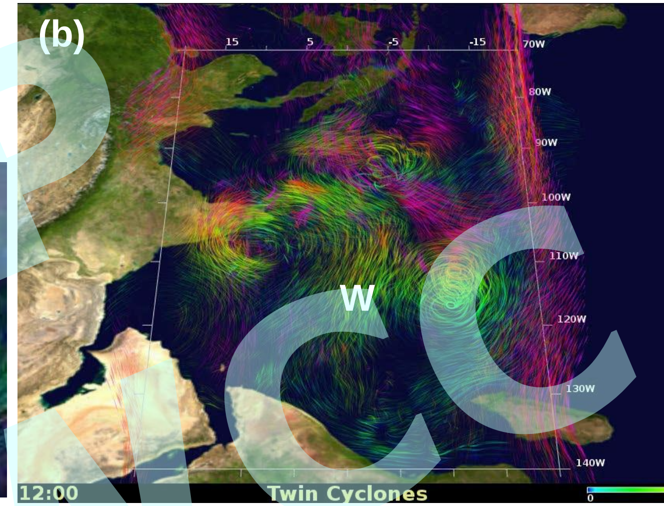

00Z 03 May 2002




Kesiny



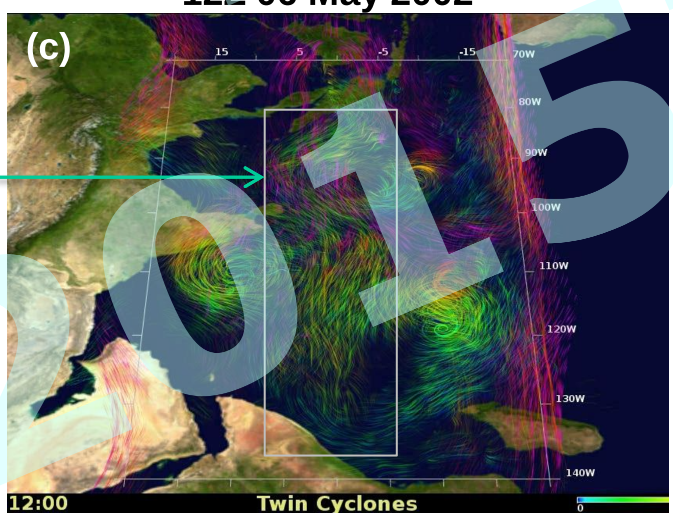
12Z 05 May 2002




Moving poleward, contracting in scale, and intensifying

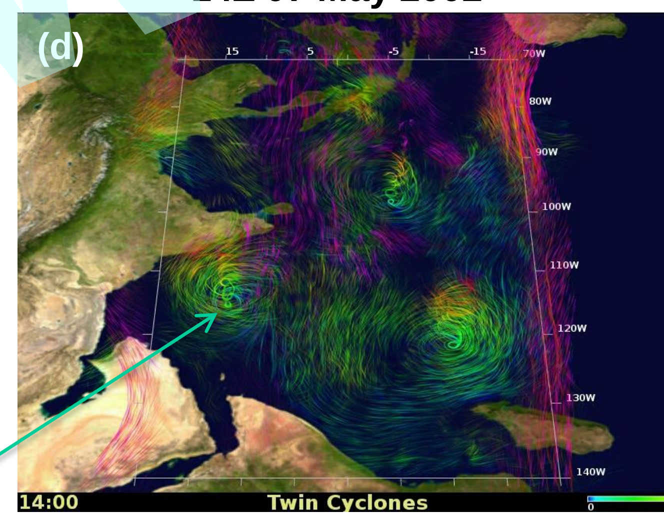
persistent vs. impulsive forcing

12Z 06 May 2002



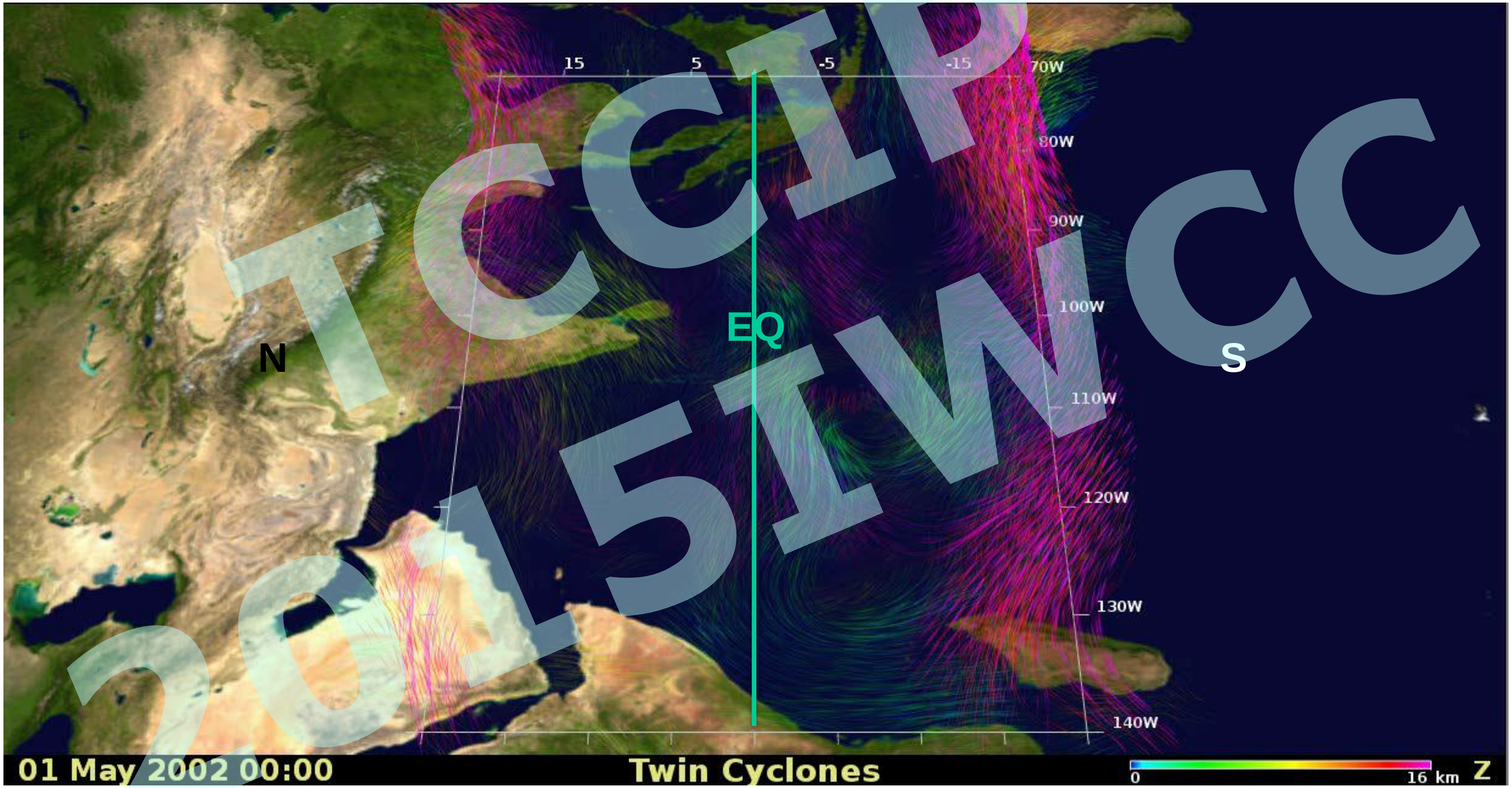

TC01A

14Z 07 May 2002



# Evolution of Twin TCs and the MRG Wave

The successive formation of multiple TCs may be associated with the appearance of a mixed Rossby gravity (MRG) wave. http://goo.gl/qXH2p

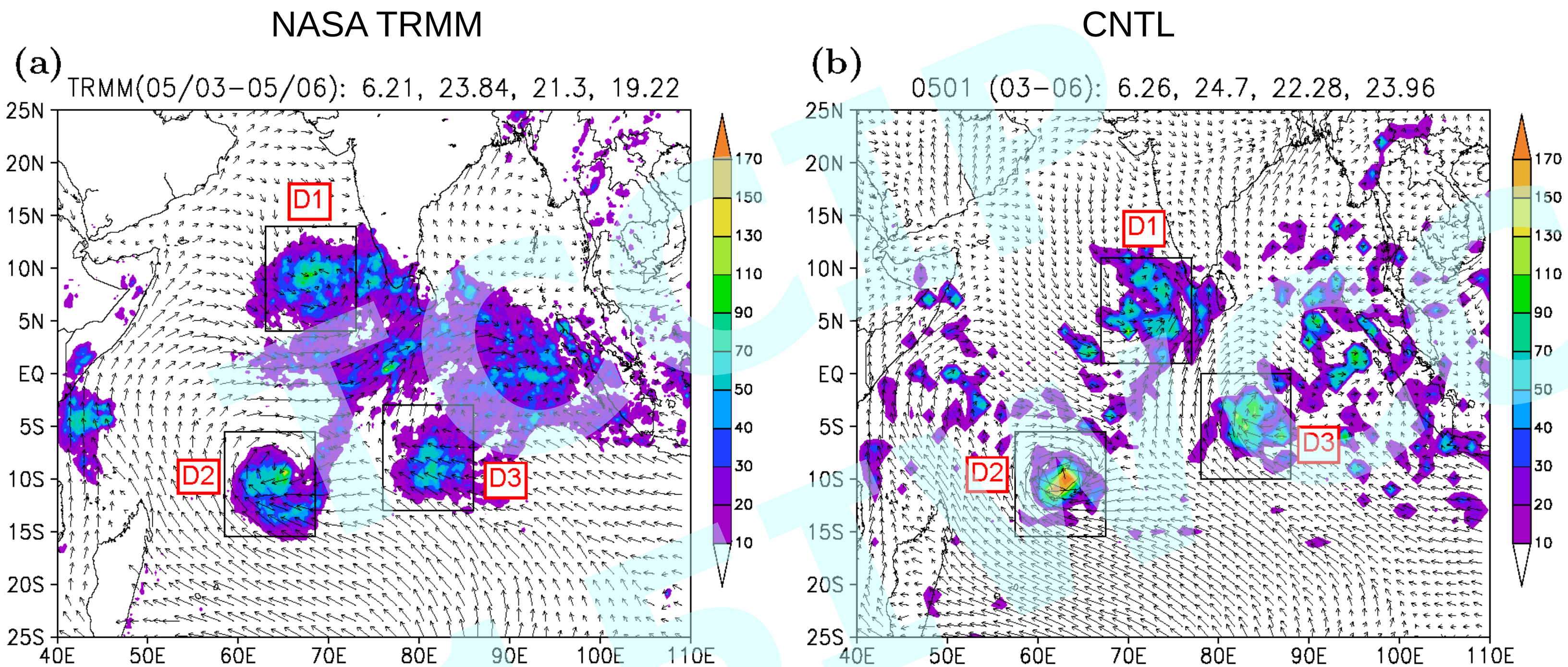





- **Shen, Bo-Wen,** Bron Nelson, W.-K. Tao, and Y.-L. Lin, **2013a:** Advanced Visualizations of Scale Interactions of Tropical Cyclone Formation and Tropical Waves. Computing in Science and Engineering, vol. 15, no. 2, pp. 47-59, March-April 2013, doi:10.1109/MCSE.2012.64

# Precipitations of the Three Convective Systems

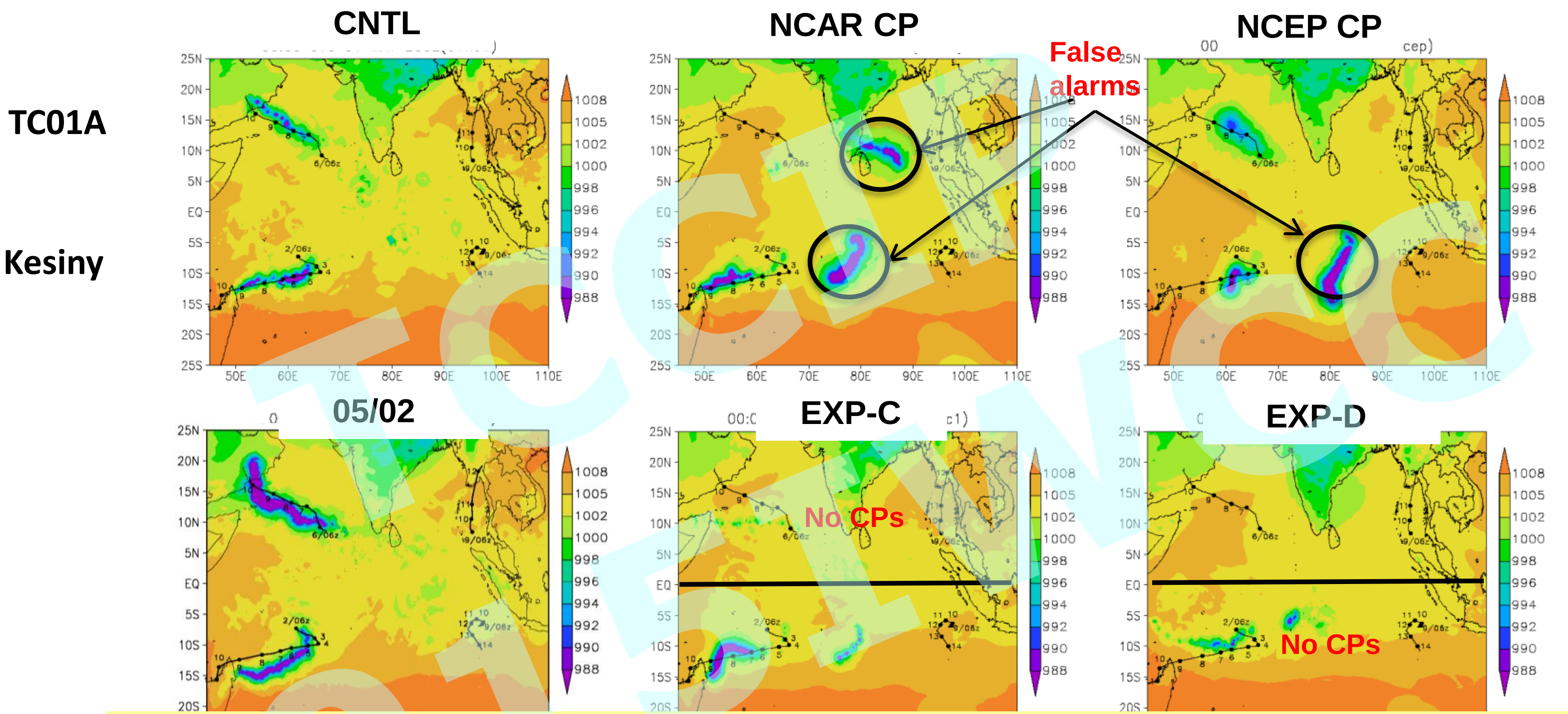
## Moistening




Precipitation (mm/day) averaged over 000 UTC May 03-06, 2002 from (a) NASA TRMM, (b) the control run which is initialized at 0000 UTC May 1, 2002. Relative errors ($E_i$) are 0.81, 2.35, 4.6, 24.67 for the large domain, sub-domains 1, 2, 3 (D1, D2, D3), respectively. Each of the sub-domains contains a 10ºx10º box.

$\mathbf{E_i} = (P_i - P_{TRMM})/P_{TRMM}$, where $\mathbf{P_i}$ (mm/d) indicates the domain average precipitation, and $P_{TRMM}$ is the corresponding domain average precipitation from TRMM.

# Sensitivity Experiments

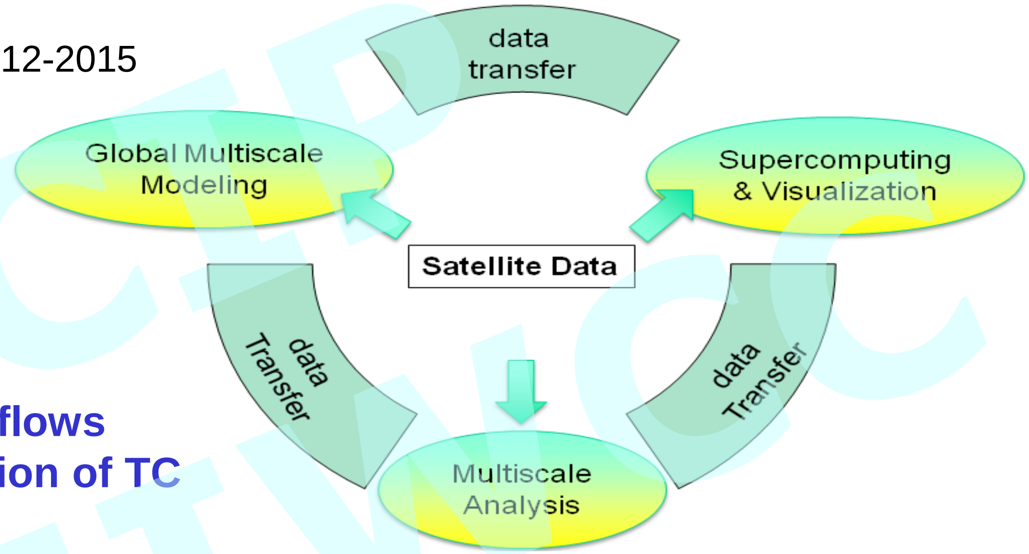



- The performance of a specific CP may be case dependent, (dependence of “large-scale conditions”?)
- The regional improvement (or change) in the moist processes with a different CP may not be sufficient for improving the formation of a specific TC.
- A specific CP may also affect the simulation of environmental conditions (such as the mixed Rossby gravity wave) and thus TC formation

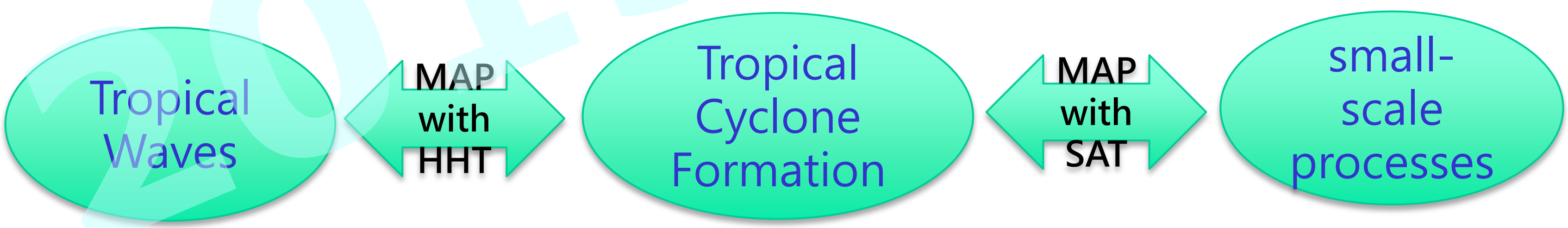
# Future Tasks

Current Project NASA AIST CAMVis: 2012-2015

MAP: Multiscale Analysis Package
HHT: Hilbert Huang Transform
SAT: Stability Analysis Tool




- **to what extent can large-scale flows determine the timing and location of TC genesis? MAP/HHT**
- **to what extent can resolved small-scale processes impact solutions stability (or predictability)? MAP/SAT**



# EMD as Bank Filters

EMD performs like filter banks (e.g., a dyadic filter) and generates IMFs each of which has features with comparable scales (Wu and Huang 2004), which indicates its potential for hierarchical multiscale analysis.

The right figure displays the first 9 IMFs for the Gaussian White Noises with $2^{20}$ (1 million) points, showing the characteristics of the bank filters (i.e., a dyadic filter). Here, f and T represent frequency and period, respectively. $\omega = 1/T$

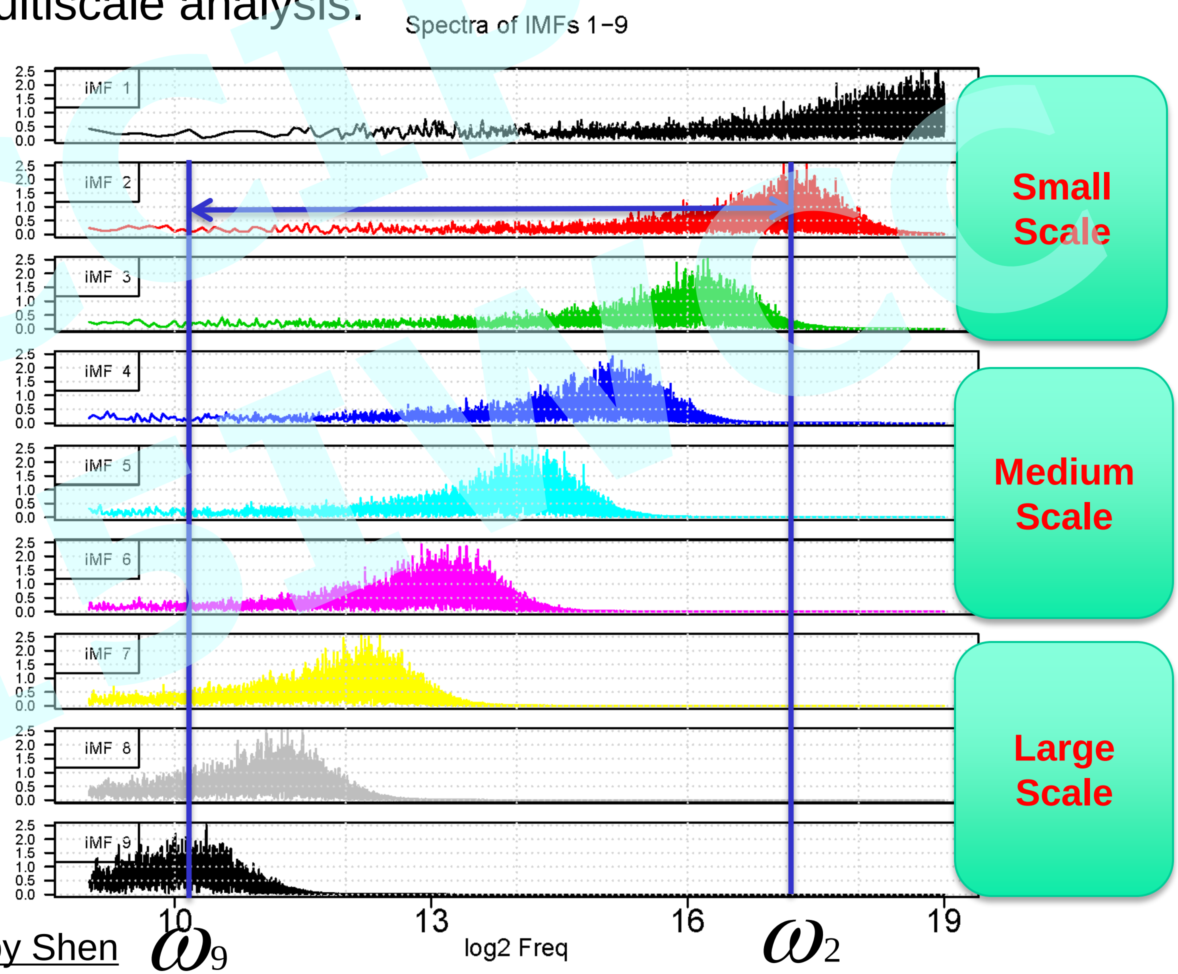
$$\log_2(\omega) = -\log_2(T)$$

$$\log_2(\omega_2) - \log_2(\omega_9) = 7$$

$$\log_2(T_{n+1}) - \log_2(T_n) = 1$$

$$T_{n+1}/T_n = 2$$

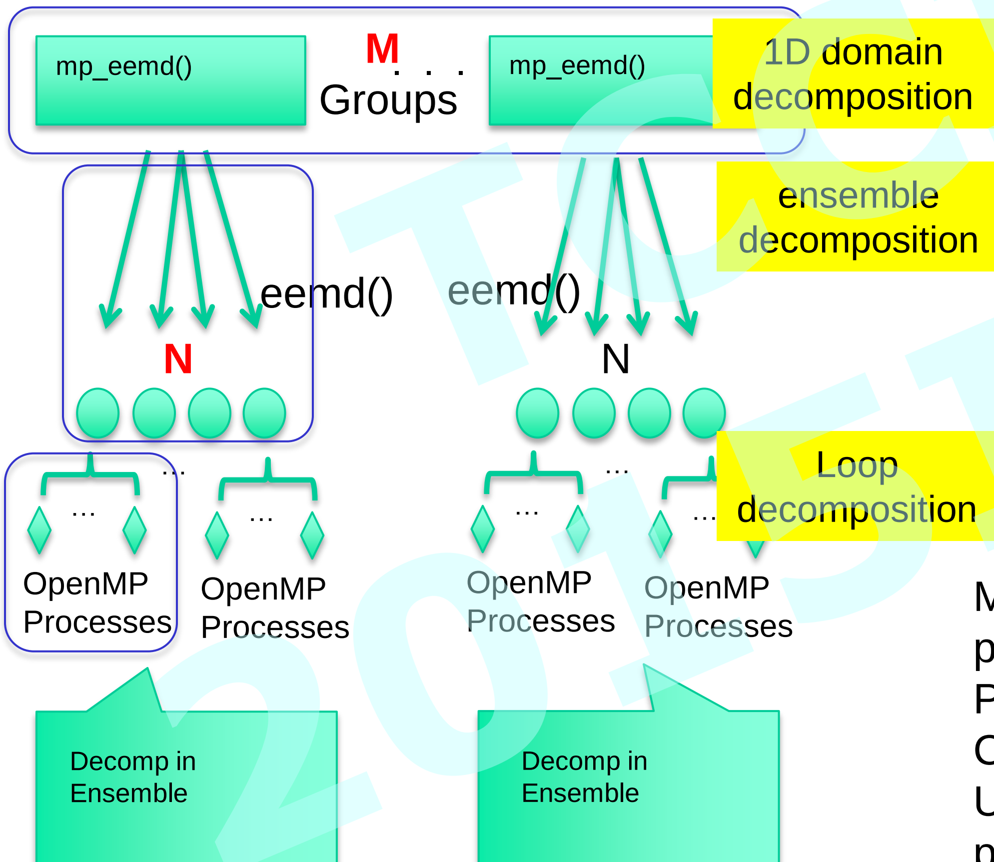
Doubling of the mean period




Reproduced with a different presentation by Shen

# II: Three Level Parallelism:

The 3-Level parallelism is achieved with the fine-grain OpenMP inside all the N members in each M process.

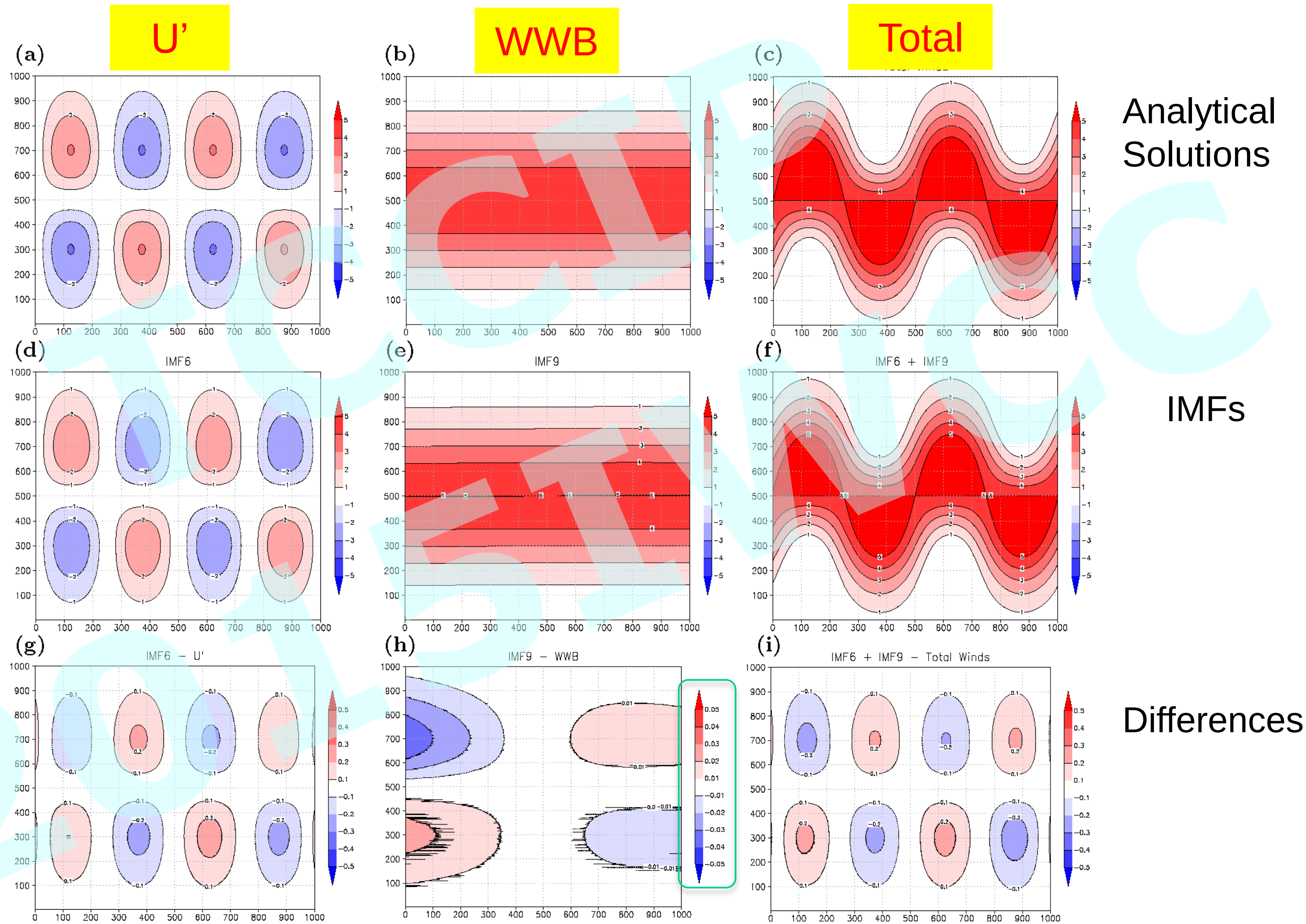



## Speedup

| M | N | OMP1 | OMP2 | OMP4 |
|---|---|---|---|---|
| 2 | 1 | 1.99 | 3.66 | 6.28 |
| 2 | 2 | 3.79 | 6.33 | 10.92 |
| 4 | 2 | 7.46 | 12.52 | 21.57 |
| 4 | 4 | 13.72 | 21.65 | 33.99 |
| 25 | 4 | 80.40 | 127.79 | 200.50 |
| 100 | 4 | 286.35 | 459.04 | 721.30 |
| 100 | 16 | 449.16 | 100 nodes | |

Multiple runs for the MRG case with 1001x1001 points and en=1000 were performed on Pleiades. Sandy processors were used; each CPU has 8 cores, and each node has 16 cores. Using 100 nodes, the MPI-OMP hybrid parallelism produces the best performance.

# Decompositions of MRG wave with the PEEMD




September 2013

# Summary

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# Future Tasks

Current Project NASA AIST CAMVis: 2012-2015

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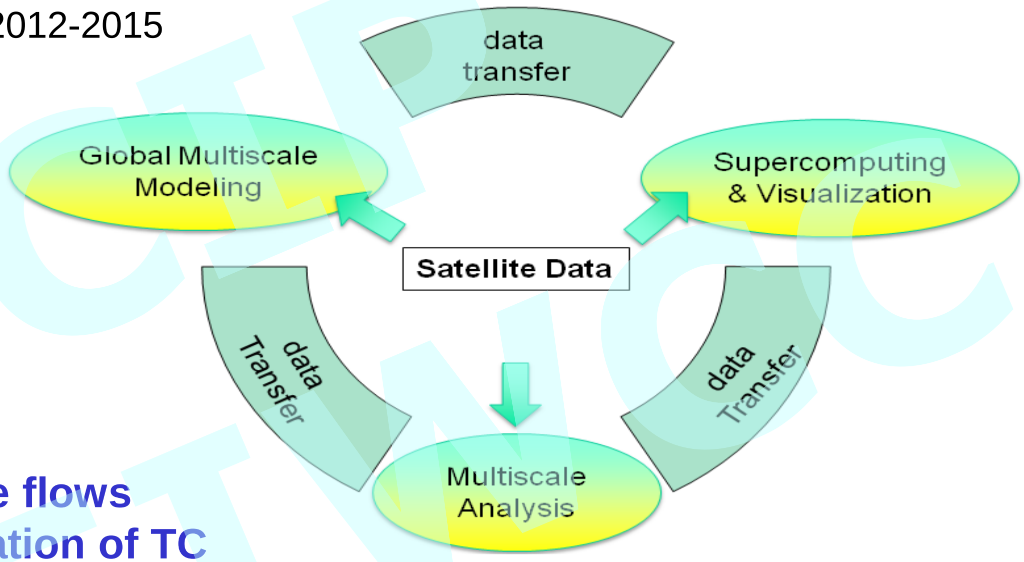
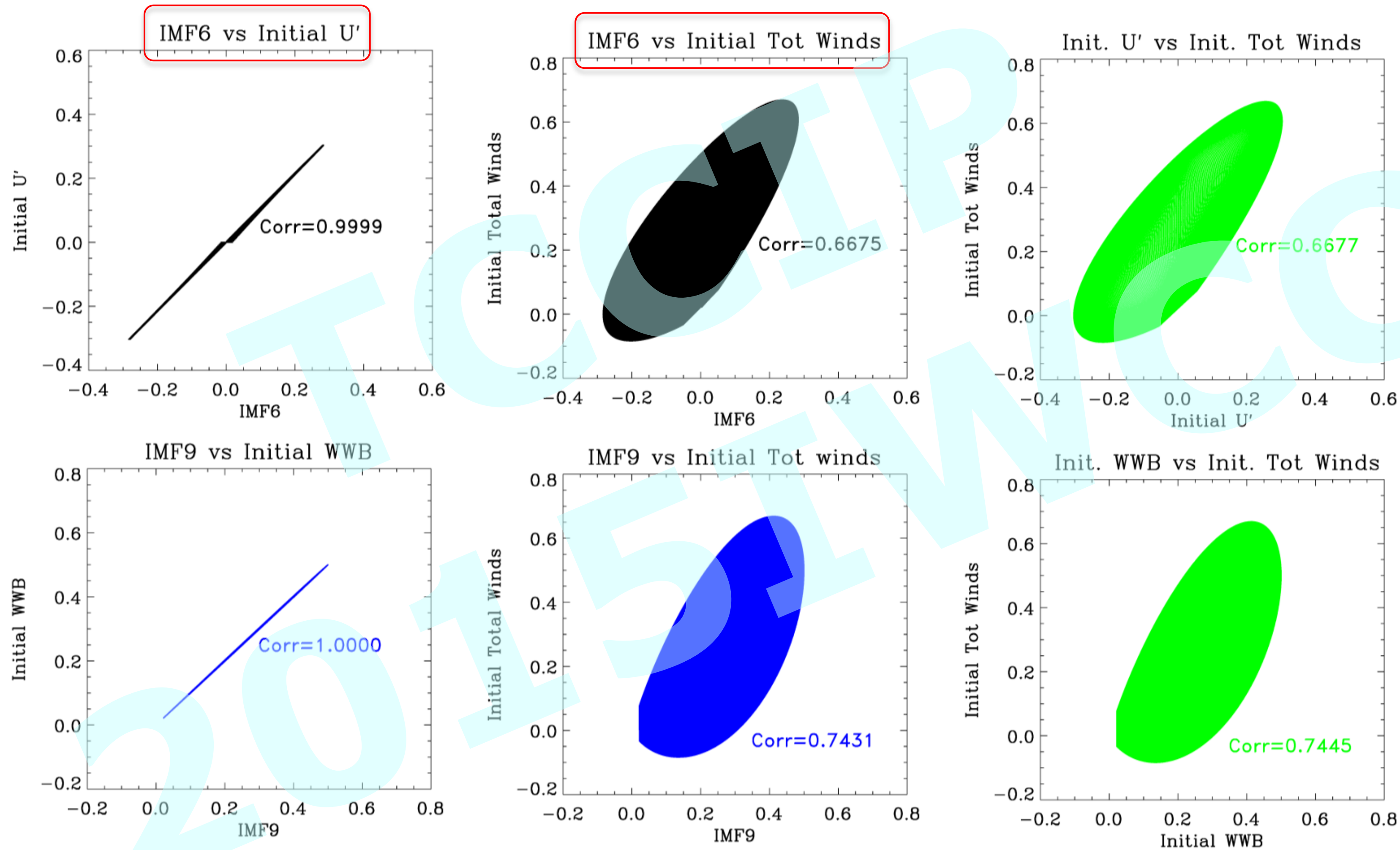



- **to what extent can large-scale flows determine the timing and location of TC genesis? MAP/HHT**
- **to what extent can resolved small-scale processes impact solutions stability (or predictability)? MAP/SAT**

Questions or Comments? bwshen@gmail.com or bo-wen.shen-1@nasa.gov

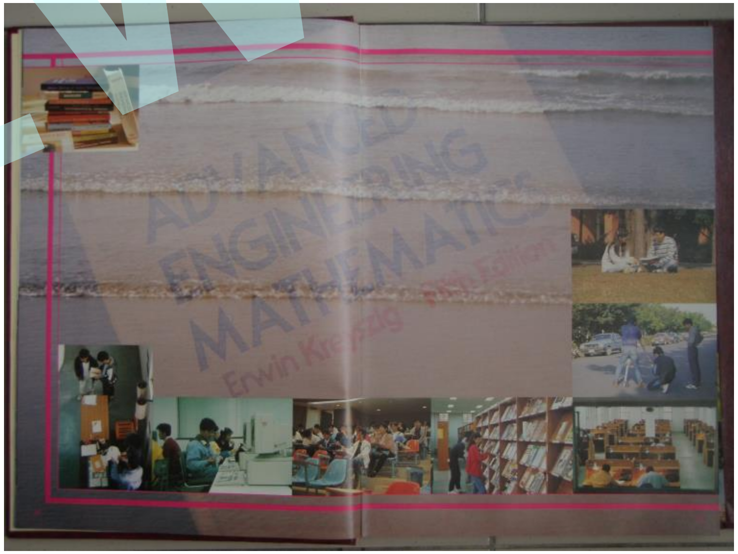
# Correlation and Scatter Plots



| | Linear 3DLM | 3D-NLM | 3DLM | 5DLM | 6DLM | |
|---|---|---|---|---|---|---|
| Linear 3DLM | NA | | unstable | | | |
| 3D-NLM | | NA | | | | |
| 3DLM | | restoring forcing | NA | | | |
| 5DLM | | | NNF | NA | | |
| 6DLM | | | | Heating | NA | |
| | | | | | | |

# 疾風知馬力
# Hurricane tests the power of technology

- 疾風知勁草，板蕩識忠臣
  Strong winds test the strength of grass;
- 路遙知馬力，日久見人心
  Distance tests a horse's stamina;
- 疾風知馬力
  Hurricane tests the power of technology



# Backup Slides

# Persistent vs. Impulsive Forcing in Toy Top Spinning

Formation (initial spinning)

Intensification with energy supply

persistent forcing

Impulsive forcing

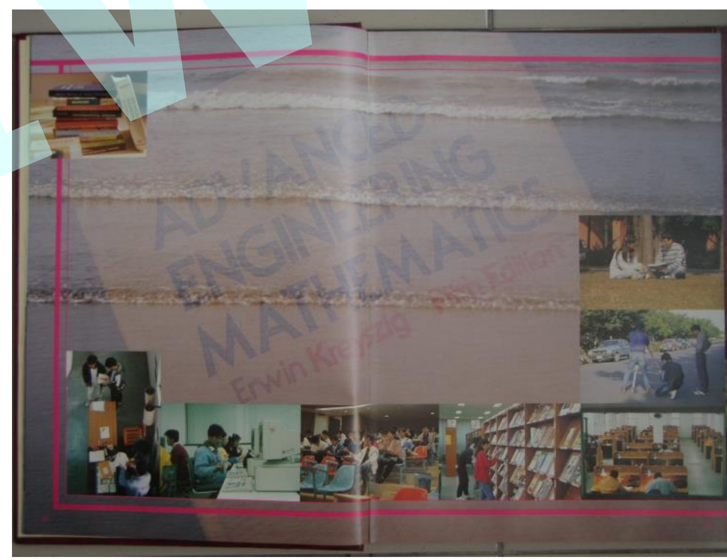
Nearly 85% of intense hurricanes have their origins as AEWs (Landsea, 1993).

Large-scale Forcing

Small-scale Forcing

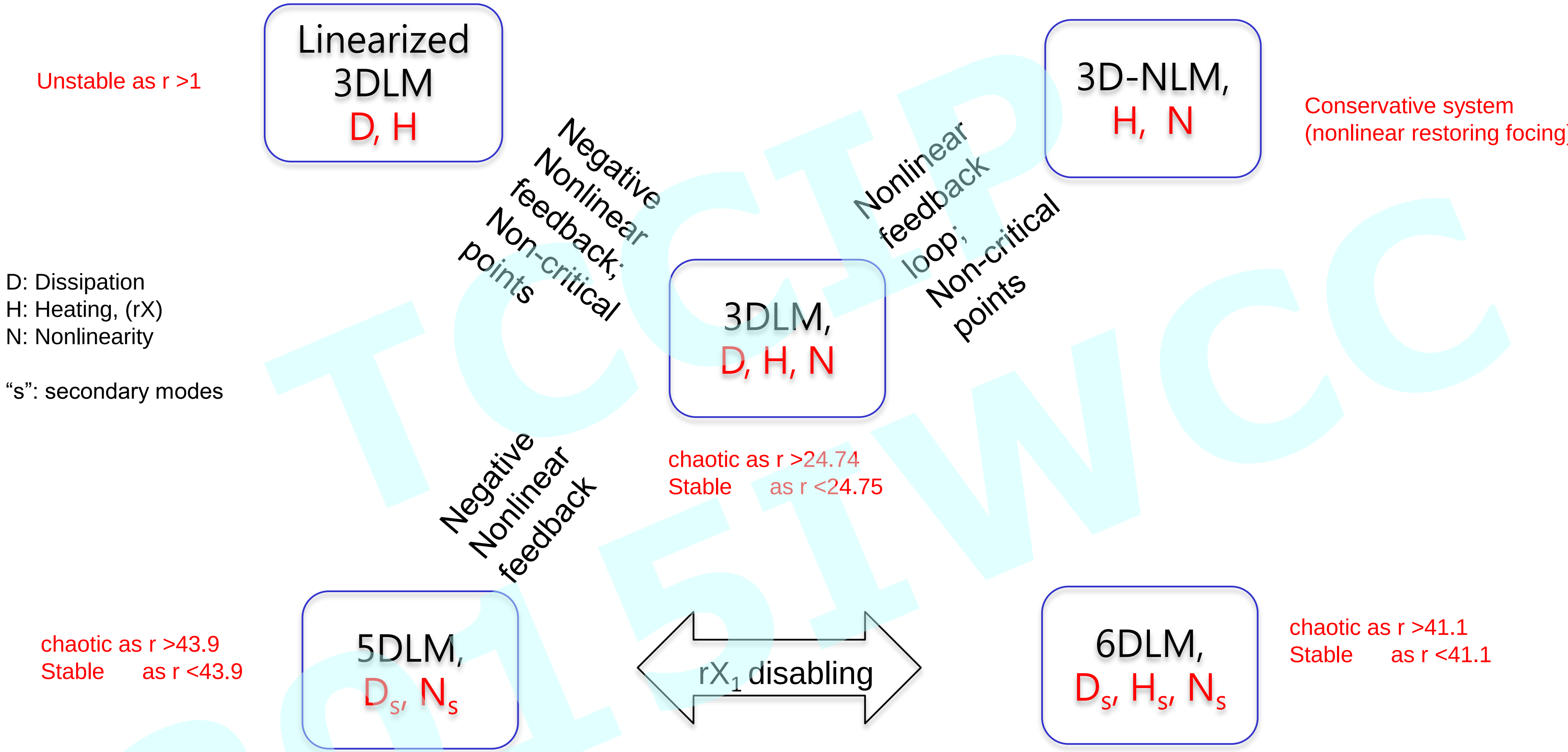
# 疾風知馬力
# Hurricane tests the power of technology

- **疾風知勁草，板蕩識忠臣**
  Strong winds test the strength of grass;
- **路遙知馬力，日久見人心**
  Distance tests a horse's stamina;
- **疾風知馬力**
  Hurricane tests the power of technology



- 十年磨一劍

# Competing Impacts in Lorenz Models





**Shen, B.-W., 2014a:** Nonlinear Feedback in a Five-dimensional Lorenz Model. *J. of Atmos. Sci.* in press.

**Shen, B.-W., 2014b:** On the Nonlinear Feedback Loop and Energy Cycle of the Non-dissipative Lorenz Model. (submitted to NPGD)

**Shen, B.-W., 2014c:** Nonlinear Feedback in a Six-dimensional Lorenz Model. Impact of an Additional Heating Term. (submitted to JAS)

# Lorenz Models

D, H, and N refer to as the dissipative terms, the heating term, and nonlinear terms associated with the primary modes (low wavenumber modes), respectively. $D_s$, $H_s$, and $N_s$ refer to as the dissipative terms, the heating term, and nonlinear terms associated with the secondary modes (high wavenumber modes), respectively. NLM refers to the non-dissipative Lorenz mode.

| | D | H | N | $D_s$ | $H_s$ | $N_s$ | Critical points for (X,Y) | $r_c$ | remarks |
|---|---|---|---|---|---|---|---|---|---|
| Linearzied 3DLM | V | V | | | | | | "1" | Unstable as r>1 |
| 3DLM | V | V | V | | | | $X_c = Y_c = \pm\sqrt{b(r-1)}$ | 24.74 | |
| 3D-NLM | | V | V | | | | $(X_c, Y_c) = (\pm\sqrt{2\sigma r}, 0)$ | | conservative |
| 5DLM | V | V | V | V | | V | $X_c = Y_c \sim \pm\sqrt{2b(r-1)}$ | 42.9 | $X_c = Y_c = \pm\sqrt{b(Z_c + 2Z_{1c})}$ |
| 6DLM | V | V | V | V | V | V | | 41.1 | |
| | | | | | | | | | |


**Shen, B.-W., 2014a:** Nonlinear Feedback in a Five-dimensional Lorenz Model. *J. of Atmos. Sci.* in press.

**Shen, B.-W., 2014b:** On the Nonlinear Feedback Loop and Energy Cycle of the Non-dissipative Lorenz Model. (submitted to NPGD)

**Shen, B.-W., 2014c:** Nonlinear Feedback in a Six-dimensional Lorenz Model. Impact of an Additional Heating Term. (submitted to JAS)

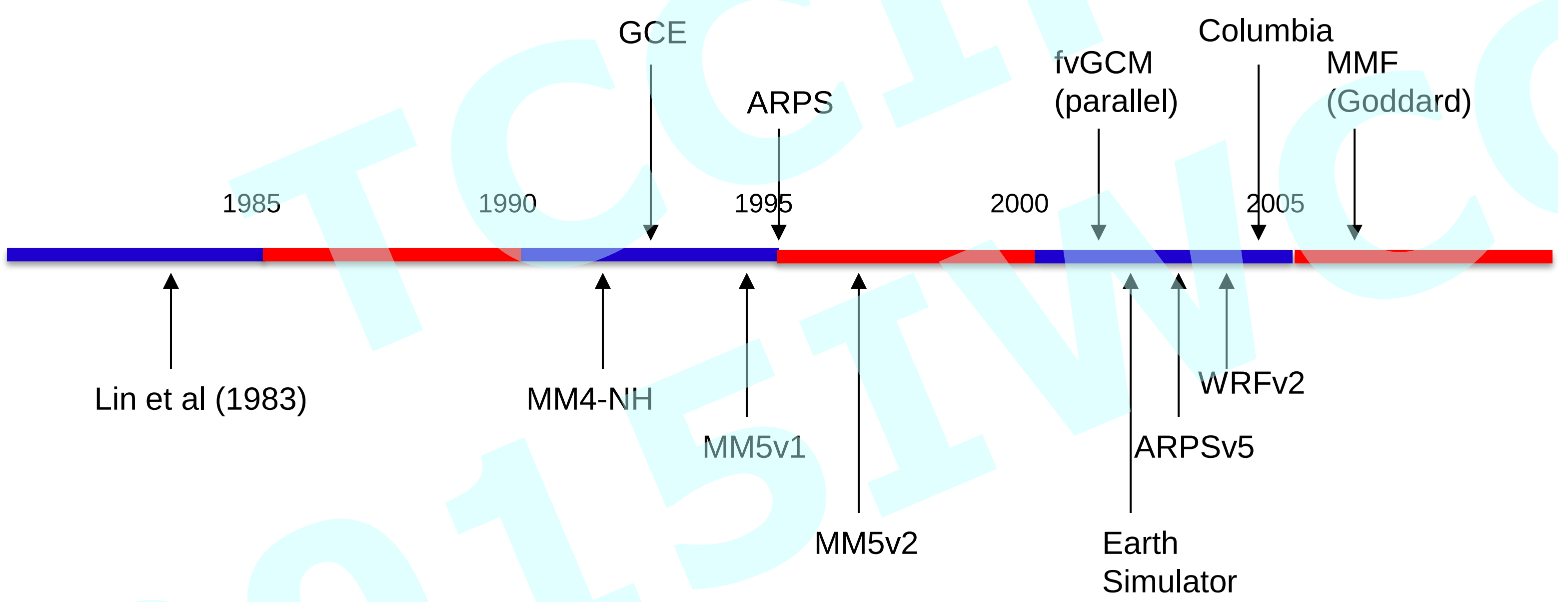
# Linear Theory of a 3D flow over an isolated mountain at a wide range of scales

| scale 水平尺度 | | 0.1km | 0.7km | 7km | 10km | 25km | 50km | 70km | 100km | 143km | 700km |
|---|---|---|---|---|---|---|---|---|---|---|---|
| buoyancy 浮力 | ← 可以忽略 | | → 開始重要 | hydrostatic → 靜力平衡 | | | | | | | |
| Coriolis 科氏力 | ← 可以忽略 | | | | | | | → NG 開始重要 | | | QG → 準地轉平衡 |
| 垂直方向的運動型態 | ← 幾乎全部爲侷陷模 | | → 傳播模比重較大 | → ← 幾乎全部爲傳播模 | | | | → 侷陷模比重較大 | | | → 幾乎全部爲侷陷模 |
| $u'\&v'$ | 偶 流 | 近似偶流 | | 源 流 | 詳細說明請見第五章 | | | | | | 渦漩流 |
| $p'$(地面) | H-L-H | → 山後$H$漸減弱 | | H-L | | H-L-H → $H$漸加強 $L$漸減弱 | | H-H-H | H-H | | -H- |
| $p'$(高層) | -L- | | H-L-H | H-L | | H-L-H | | H-H-H | | H-H | -H- |
| $\xi$(地面) | | | | | | P-N → $P, N$均漸減弱且範圍縮小 | | N-P | | N-P-N | -N- |
| $\xi$(高層) | | | | | | P-N-P | | N-P | N-P-N | N-P-N-P | -N- |

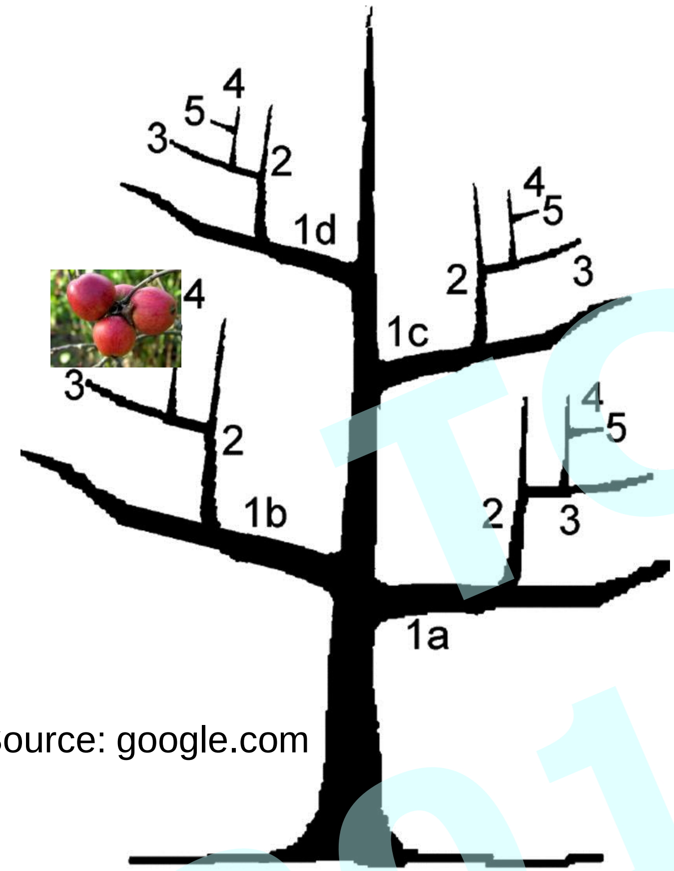
Resolved scale: 10km, 4dx=10km, dx=2.5km.

Shen, B.- W., 1992: The Linear Solution of a Three-Dimensional Flow over an Isolated Mountain, Master Thesis, National Central University, Taiwan, (in Chinese) p. 85

# A Personal Note on the History of Numerical Modeling



# An Analogy: Stability of a Tree




Source: google.com

Hierarchy

Am J Bot. 2006 Oct;93(10):1522-30. doi: 10.3732/ajb.93.10.1522.

**Mechanical stability of trees under dynamic loads.**

James KR, Haritos N, Ades PK.

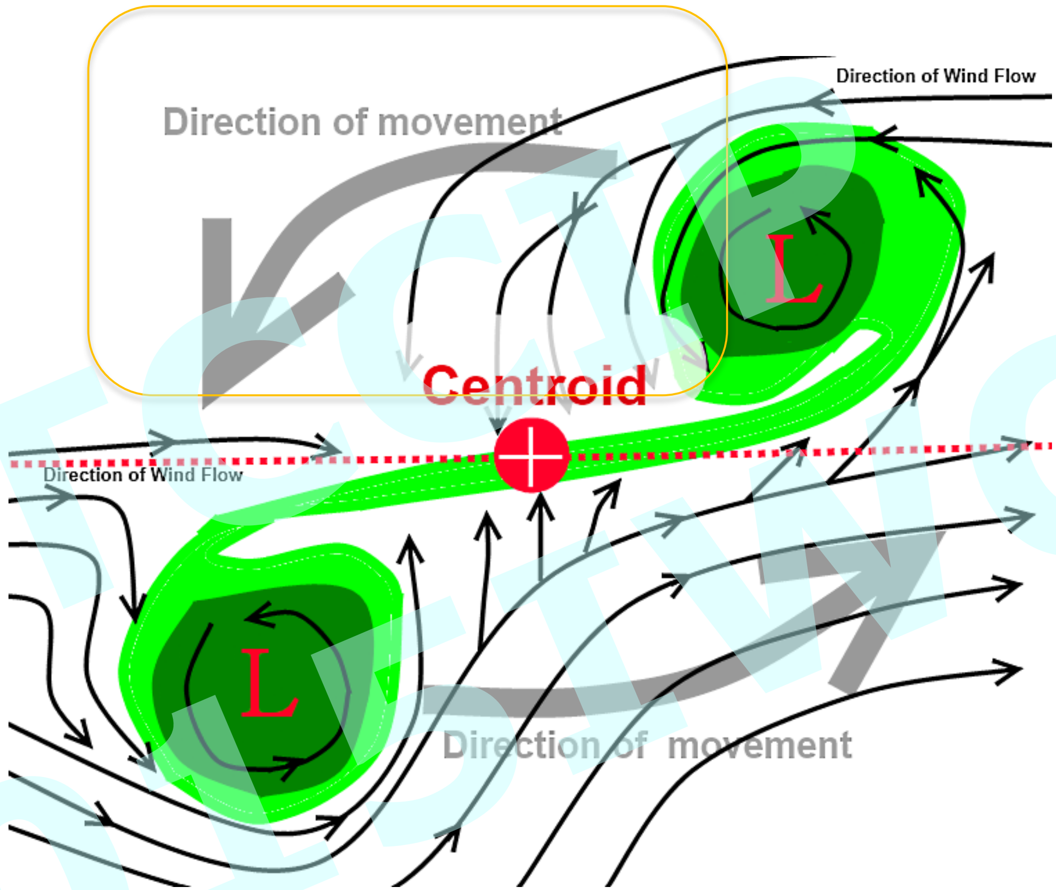
School of Resource Management, Faculty of Land and Food Resources, University of Melbourne, Melbourne, Australia, 3001;

**Abstract**

Tree stability in windstorms and tree failure are important issues in urban areas where there can be risks of damage to people and property and in forests where wind damage causes economic loss. Current methods of managing trees, including pruning and assessment of mechanical strength, are mainly based on visual assessment or the experience of people such as trained arborists. Only limited data are available to assess tree strength and stability in winds, and most recent methods have used a static approach to estimate loads. Recent research on the measurement of dynamic wind loads and the effect on tree stability is giving a better understanding of how different trees cope with winds. Dynamic loads have been measured on trees with different canopy shapes and branch structures including a palm (Washingtonia robusta), a slender Italian cypress (Cupressus sempervirens) and trees with many branches and broad canopies including hoop pine (Araucaria cunninghamii) and two species of eucalypt (Eucalyptus grandis, E. teretecornus). Results indicate that sway is not a harmonic, but is very complex due to the dynamic interaction of branches. A new dynamic model of a tree is described, incorporating the dynamic structural properties of the trunk and branches. The branch mass contributes a dynamic damping, termed mass damping, which acts to reduce dangerous harmonic sway motion of the trunk and so minimizes loads and increases the mechanical stability of the tree. The results from 12 months of monitoring sway motion and wind loading forces are presented and discussed.

The branch mass contributes a dynamic damping, which acts to reduce dangerous harmonic sway motion of the trunk and so minimizes loads and increases the mechanical stability of the tree.

# Fujiwhara Effect (binary interaction)



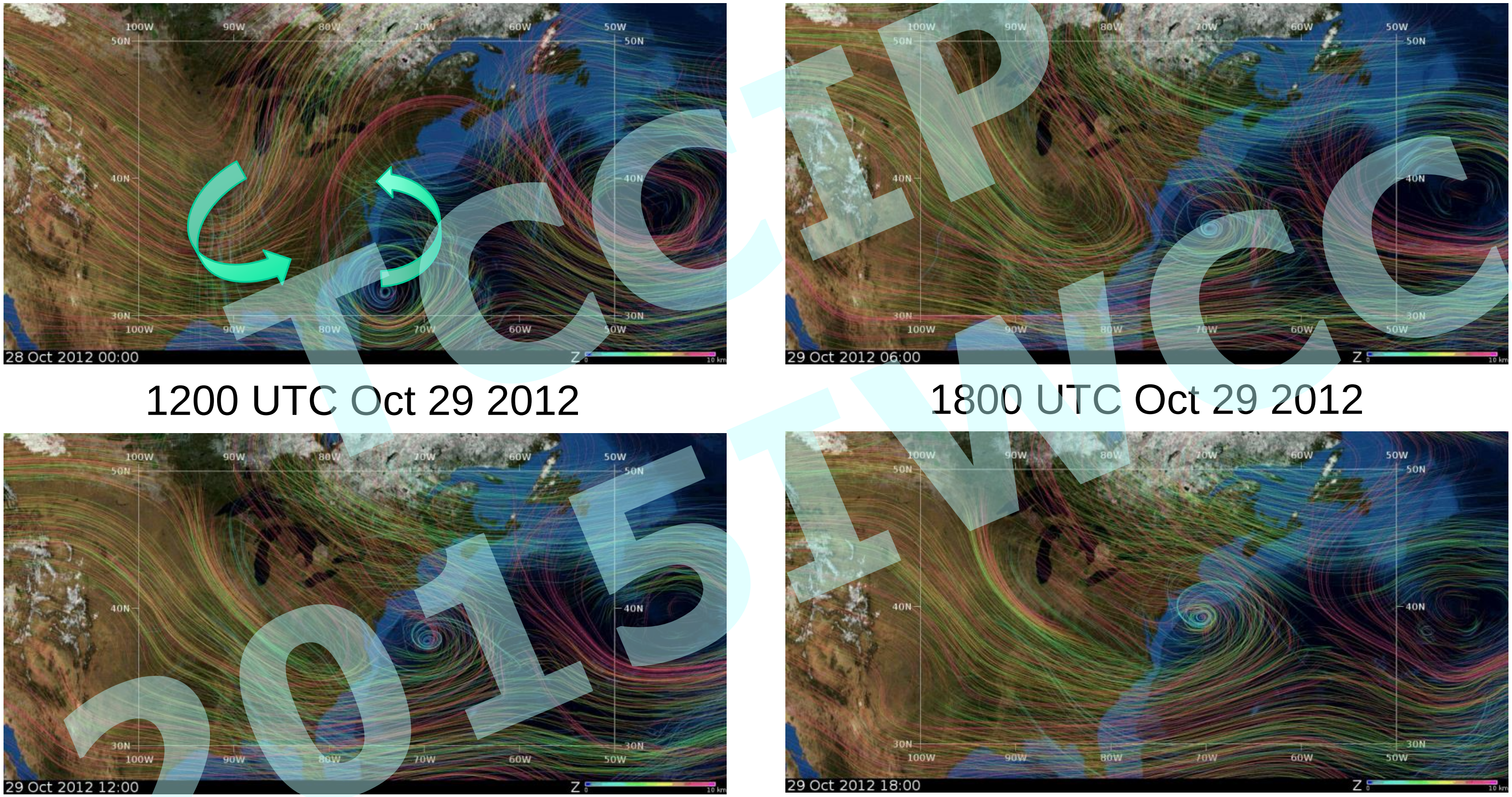

The National Weather Service defines the Fujiwhara Effect as *the tendency of two nearby tropical cyclones to rotate cyclonically about each other*.

The **Fujiwhara effect**, named after Sakuhei Fujiwhara, is sometimes referred to as **Fujiwara interaction** or **binary interaction**.

# Visualization of Vortex Interaction

0000 UTC Oct 28 2012 | 0600 UTC Oct 29 2012

1200 UTC Oct 29 2012 | 1800 UTC Oct 29 2012




Collaboration with Dr. David Ellsworth of NASA/ARC/NAS

# Marsupial Paradigm
## (Dunkerton, Montgomery and Wang, ACP, 2009)

- A recent trend to understand the tropical cyclogenesis processes is to examine the role of the Rossby critical layer (CL) associated with a tropical easterly wave.
- Though CL dynamics have been studied with idealized models extensively, it is still challenging to examine its role in weather prediction models.
- Among the challenges are determining the propagation (or phase) speed of the "wave" and increasing grid spacing to resolve the CL accurately.
- In addition to the "classical" CL, different types of CLs may exist, including inertia CLs associated with the inclusion of the Coriolis force, and a Rossby CL in a QG system (e.g., **Shen and Lin, 1999; Shen, 1998**).
- Depending on the relative importance of environmental factors such as static stability, vertical wind shear and the Coriolis force, a CL may absorb, reflect or over-reflect the energy of approaching disturbances.
- Thus, the efficiency of energy absorption/reflection by the resolved CL in numerical models needs to be examined carefully to understand its impact on hurricane formation.


Shen, B.- W., and Y.-L. Lin, 1999: Effects of Critical Levels on Two-Dimensional Backsheared Flow over an Isolated Mountain Ridge on an f-plane. ***J. of Atmos. Sci.,*** 56, 3286-3302.

Shen, B.-W., 1998: Inertia Critical Layers and Their Impacts on Nongeostrophic Baroclinic Instability. **Ph.D. Dissertation.** North Carolina State Univ., p. 255.

# Notes on Scale Transition

- During the processes of TC intensification, (local) Rossby radius of deformation is reduced, energy trapping associated heating is more efficient, (namely less energy carried outward by propagating gravity waves via the geostrophic/gradient-wind adjustment)
- “scale separation” is reduced as the inertial instability increases -> individual clouds become more and more under the control of the balanced dynamics
- Molinari and Dedek (1992, p 329): *Ooyaman noted that it was this characteristic that allowed the success of CP in numerical simulation of mature hurricanes*
- $L_R = NL/(vor+f)^{1/2}(2V/R+f)^{1/2}$; *N Brunt-Vaisala Freq,*

# Comparisons

- Role by the large scale flows: providing a protective environment, (→ no explicit downscaling transfer)
- "neutral Rossby-type modes" (→ no instability associated with the large-scale wave mode)
- Pouch's size does not change with time, suggesting that large-scale flows cannot change the size of pouch

# Questions

- What are the major dynamics for the "easterly wave CL" that are related to the formation (or appearance) of a pouch?
- how the critical latitude, which can "absorb" wave energy, may help develop a pouch that provides a protective environment for a mesoscale vortex to grow.
- The (original) conceptual model of the marsupial paradigm is based on the existence of a CL. However, the original figure (Figure 1 of DMW09) indeed describes a barotropic Rossby wave critical latitude that appears as a singular point in a quasi-geostrophic potential vorticity equation (Andrews et al., 1987, p 253-257).
- The fundamental dynamics of the CL (Bretherton, 1966), defined by the AMS glossary, are as follows: *as waves approach this level from above or below, the vertical component of group velocity approaches zero, causing elimination of the wave as its energy is absorbed and transferred to the mean wind.*

# Questions

- What are the controlling factors that determine the longitudinal and latitudinal scales of the pouch?
- Based on stability analysis on the "environmental flows," the (longitudinal) wavelength of the dominant wave mode may be determined by the eigen-mode with the largest growth rate, which depends on the magnitude of wind shear.
- Therefore, for the Sandy case, a specific question to be addressed is: how does the complicated shear make the scale selection of the Kelvin cat's eye flow?
- And what's the relevance of the scale selection to the (longitudinal and latitudinal) scales of the pouch?
- Specifically, it is important to check whether a saddle point exists between the westerly winds and easterly winds (which are associated with the Caribbean Gyre and easterly wave, respectively), and how it helps determine the Kevin cat's eye flow and the pouch.

# Published Articles since 2010

**Journal Articles:**

1. **<u>Shen, B.-W., </u> 2013d:** Nonlinear Feedback in a Five-dimensional Lorenz Model. *J. of Atmos. Sci.* in press.
2. **<u>Shen, B.-W.,</u>** M. DeMaria, **J.-L. F. Li and S. Cheung, <u>2013c:</u>** Genesis of Hurricane Sandy (2012) simulated with a global mesoscale model, *Geophys. Res. Lett., 40,* 4944–4950, *doi:*10.1002/grl.50934.
3. ... Tropical
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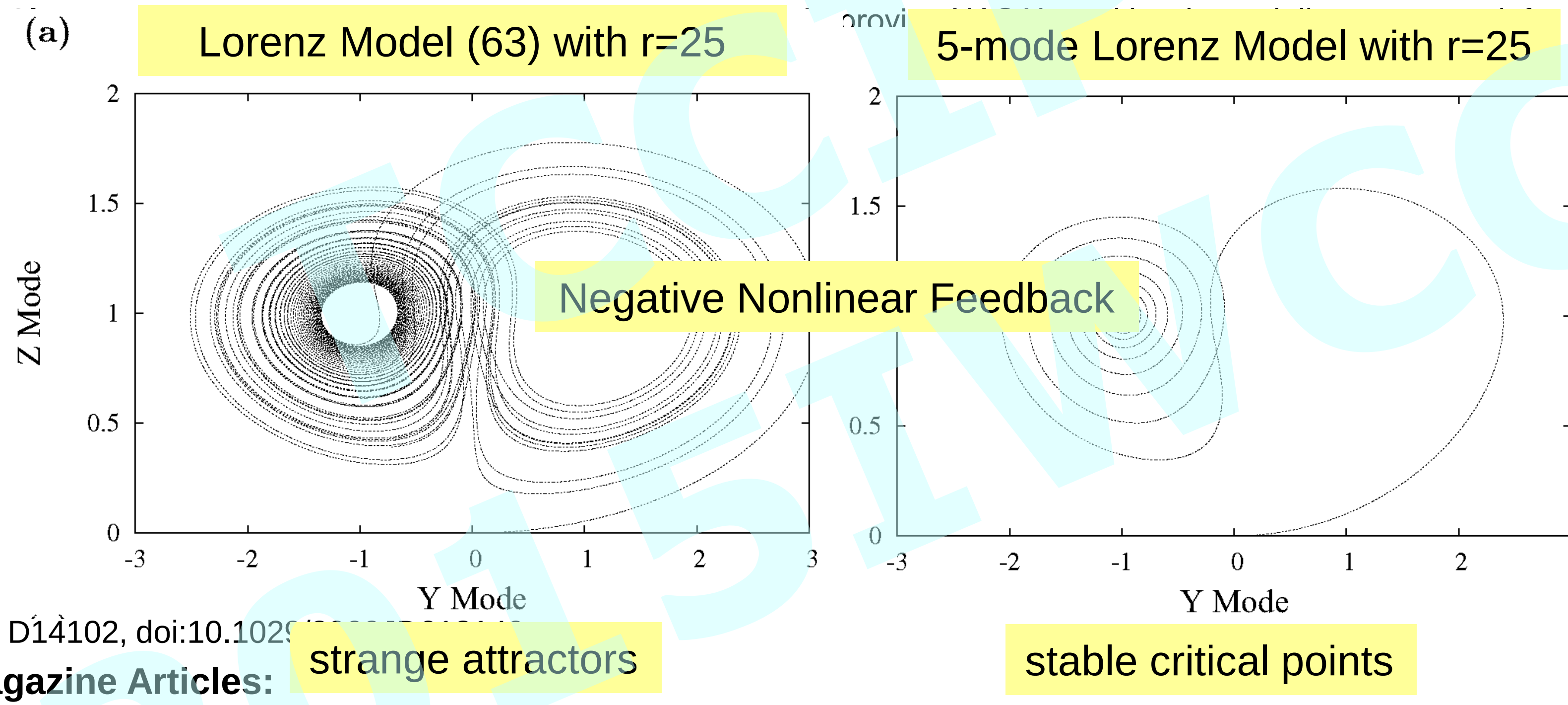
8. ... odel: ... 5, D14102, doi:10.1029...

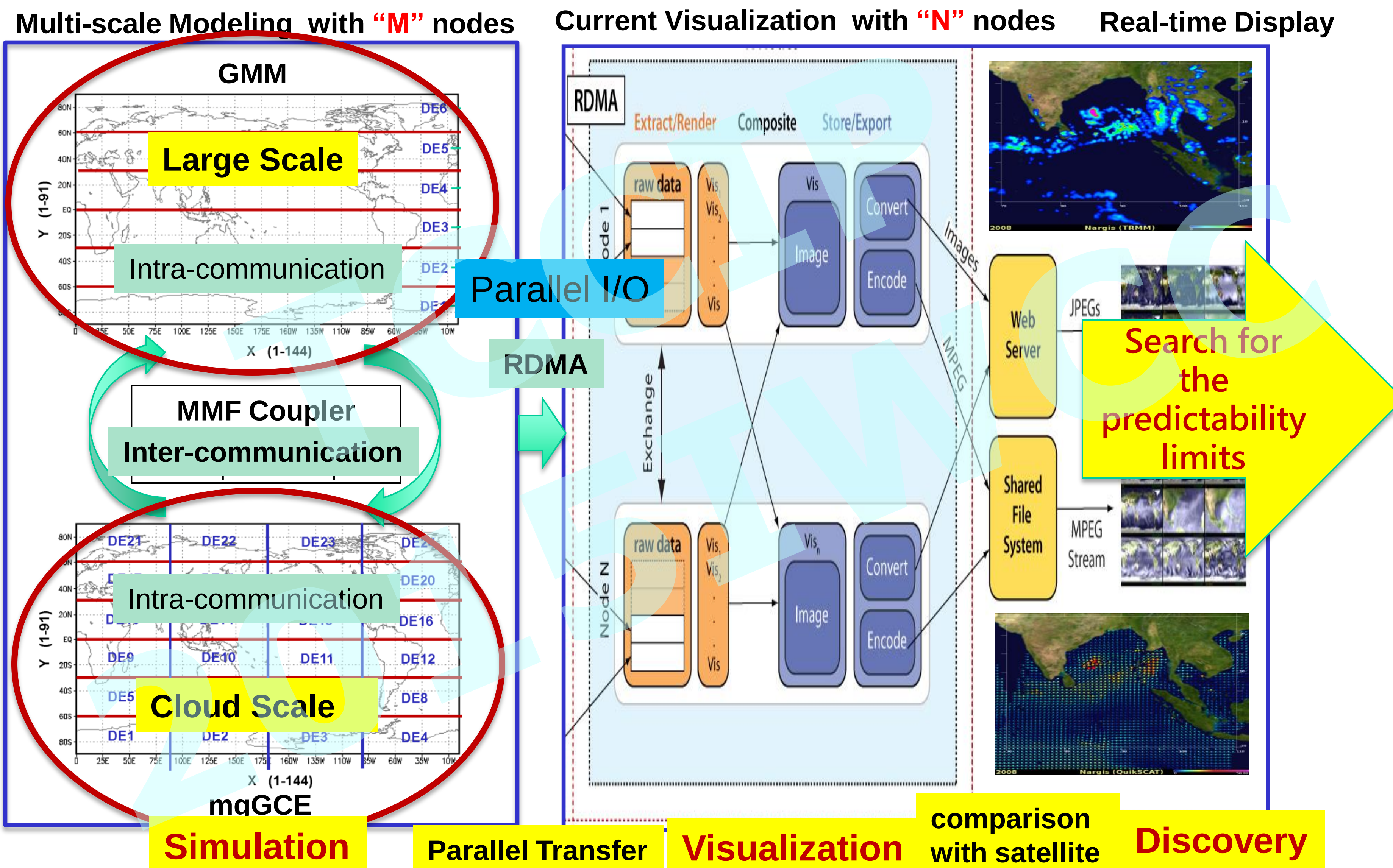



**Magazine Articles:**

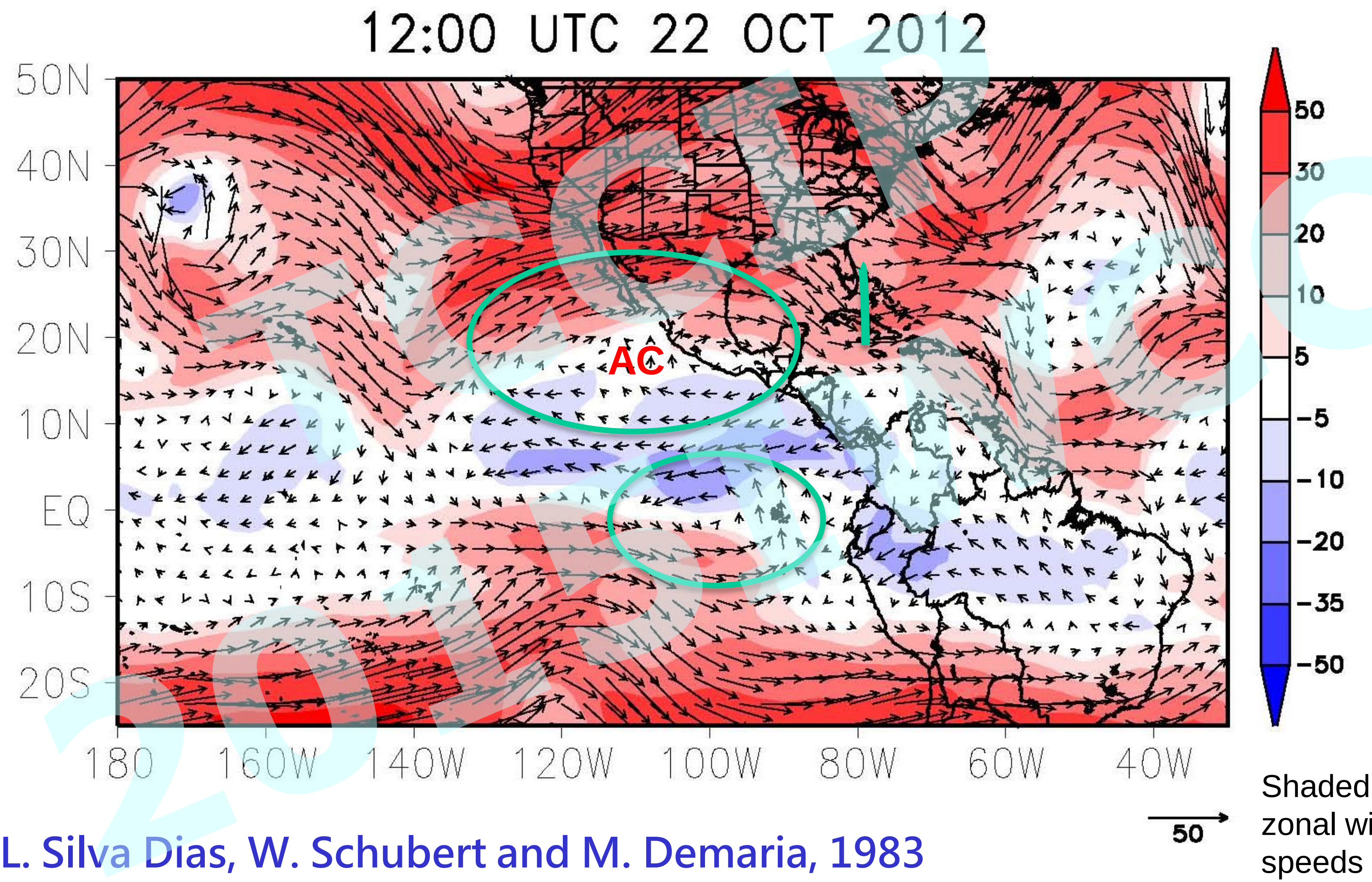
- **<u>Shen, B.-W., S. Cheung, J.-L. F. Li, and Y.-L. Wu, 2013e:</u>** Analyzing Tropical Waves using the Parallel Ensemble Empirical Model Decomposition (PEEMD) Method: Preliminary Results with Hurricane Sandy (2012), NASA ESTO Showcase . IEEE Earthzine. posted December 2, 2013.
- **<u>Shen, B.-W., 2013f:</u>** Simulations and Visualizations of Hurricane Sandy (2012) as Revealed by the NASA CAMVis. NASA ESTO Showcase. IEEE Earthzine. posted December 2, 2013.

# Architecture of the CAMVis v1.0

(the Coupled Advanced Multiscale modeling and concurrent Visualization systems; Shen e al. 2011)



# An AC and Trough at 200 mb
# (Sandy first appeared on Oct 22)



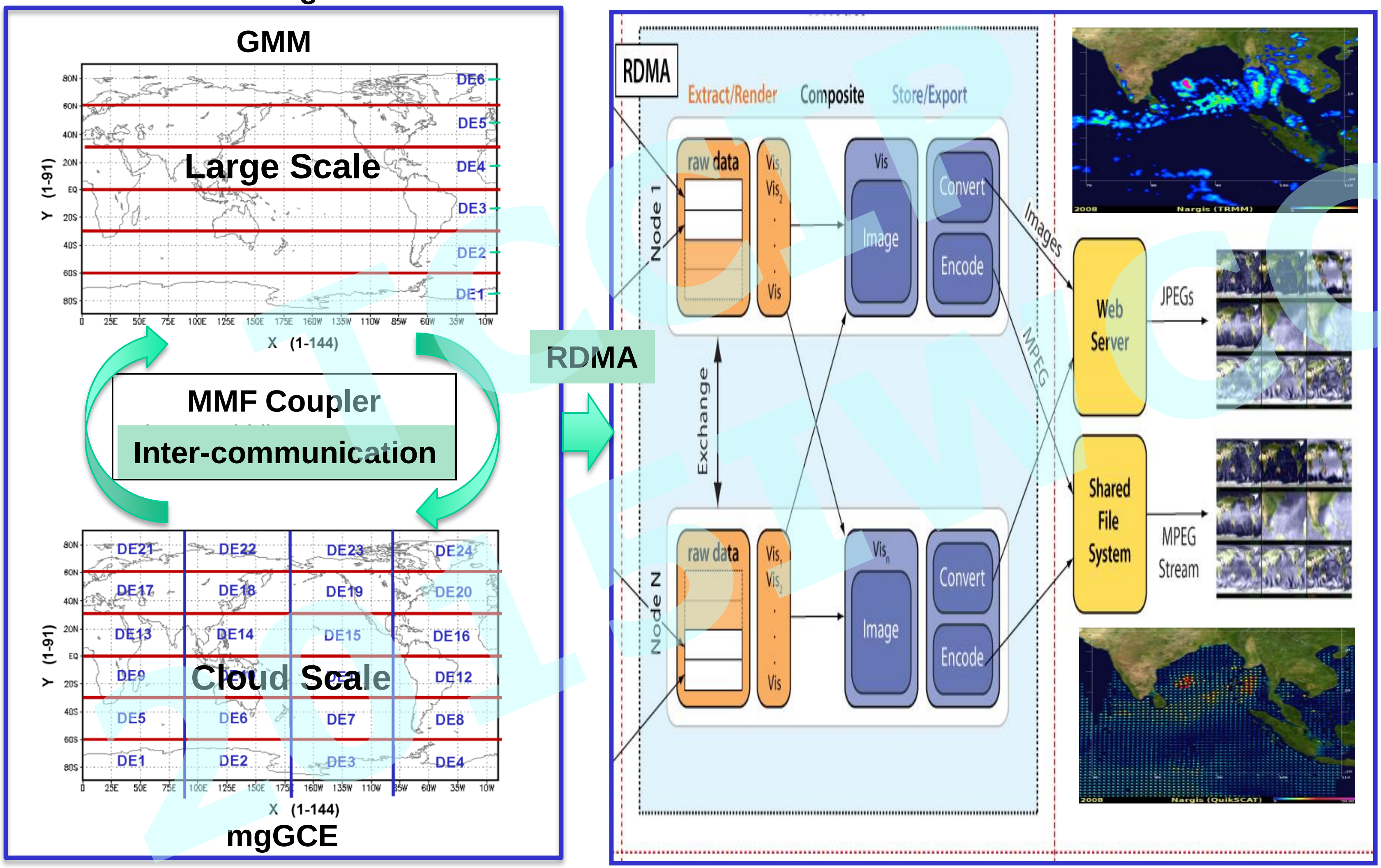

Shaded: zonal wind speeds

P. L. Silva Dias, W. Schubert and M. Demaria, 1983

# Architecture of the CAMVis v1.0

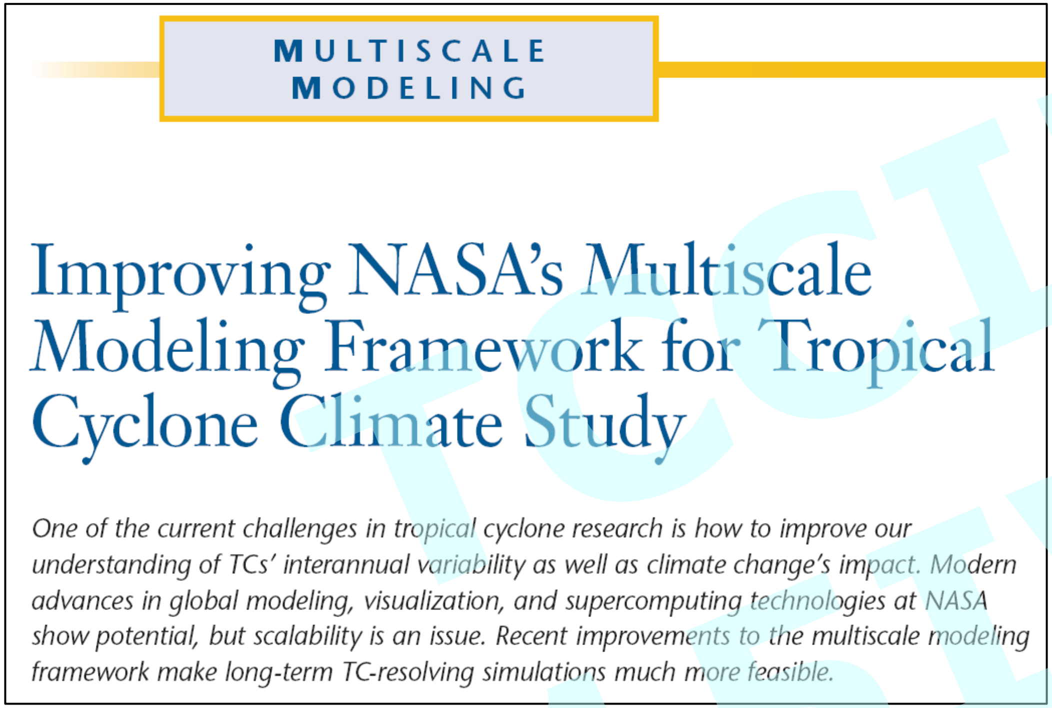
(the Coupled Advanced Multiscale modeling and concurrent Visualization systems; Shen e al. 2011)

**Multi-scale Modeling with "M" nodes** **Current Visualization with "N" nodes** **Real-time Display**




**Simulation** **Extraction** **Visualization** **MPEG generation**

# Shen, Nelson, Cheung and Tao (2013b) (IEEE CiSE, Sep/Oct, 2013)


MULTISCALE MODELING

Improving NASA's Multiscale Modeling Framework for Tropical Cyclone Climate Study

*One of the current challenges in tropical cyclone research is how to improve our understanding of TCs' interannual variability as well as climate change's impact. Modern advances in global modeling, visualization, and supercomputing technologies at NASA show potential, but scalability is an issue. Recent improvements to the multiscale modeling framework make long-term TC-resolving simulations much more feasible.*

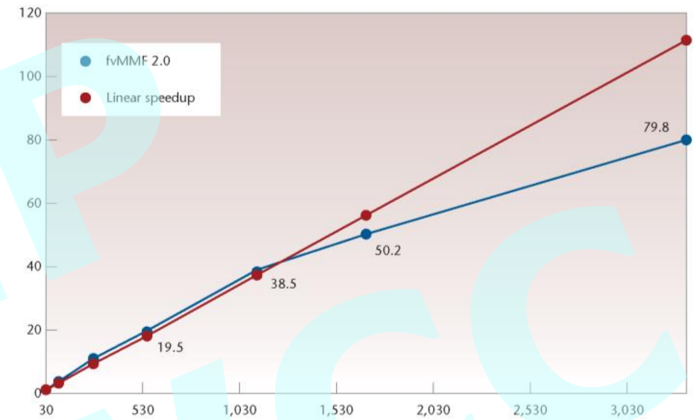



Figure 9. Parallel scalability of the MMF version 2.0 with a revised parallel implementation on the NASA Pleiades supercomputer. This figure shows that a speedup of nearly 80× is obtained as the number of cores increases from 30 to 3,335. Note that the original MMF could use only 30 cores.

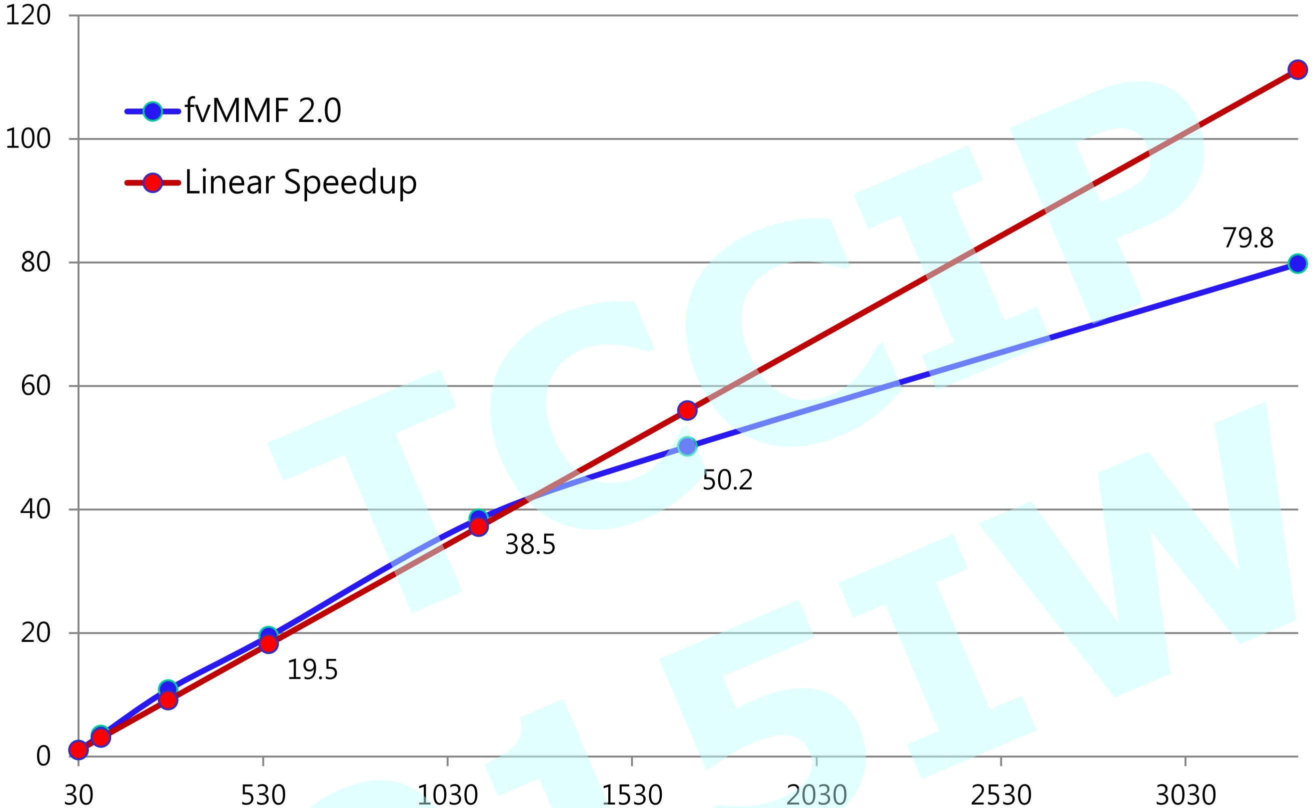
Key Points:

1. MPI inter-communicators are used for data exchange between two groups of processes that are running the two components, fvGCM and meta-global GCE (mg-GCE).
2. A two-level parallelism with load balancing is implemented into the coupled multiscale modeling framework.

   ➔ Parallelism for the PEEMD
3. The improved MMF achieves a speedup of nearly 80 as the number of cores increases from 30 to 3,335 on the Pleiades supercomputer, making it more feasible to perform climate simulations and increase model's resolutions.

# Performance of fvMMF 2.0 on Pleiades

## (the first climate model implemented with MPI inter- and intra- communications)




**Process Hierarchy: intra- and inter-communication**

MMF consists of one fvGCM and 13,104 (91x144) 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.

Major Features:

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

Shen, B.-W., B. Nelson, S. Cheung, W.-K. Tao, 2013b: Scalability Improvement of the NASA Multiscale Modeling Framework for Tropical Cyclone Climate Study. IEEE CiSE. no. 5, pp. 56-67, Sep./Oct. 2013

# Research News and Highlights (transfer between the KE and PE)

- 2004, ARC news story: Initial Columbia Results Promising
- 2005, AGU Highlight, (Atlas et al. 2005)
- 2006, AGU highlight, featured in ``Science'' (Shen et al., 2006a,b), cited as a global/mesoscale breakthrough
- 2007, Genesis simulations of six TCs in May 2002


- 2010, NASA News story (Shen et al., 2010a). Follow-up stories appeared in MSNBC, PhysOrg.com, National Geographic--Indonesia, ScienceDaily, EurekAlert, Yahoo News, TechNews Daily, Scientific Computing, HPCwire.
- 2011, featured in the magazine article entitled `` *Turning the Tables on Chaos: Is the atmosphere more predictable than we assume? '' (Anthes, 2011)*

# Genesis of Twin Tropical Cyclones

Shen, B.-W., W.-K. Tao, and Y.-L. Lin, and A. Laing, 2012: Genesis of Twin Tropical Cyclones as Revealed by a Global Mesoscale Model: The Role of Mixed Rossby Gravity Waves. *J. Geophys. Res.* 117, D13114, doi:10.1029/2012JD017450. 28pp.

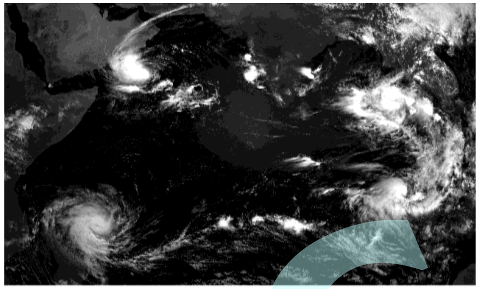
# Objective

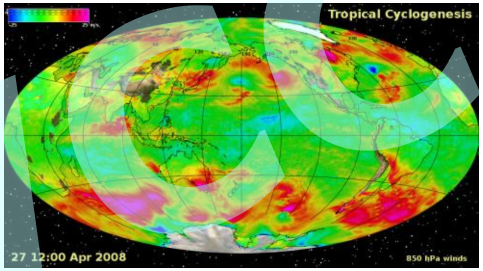
Develop a scalable, multiscale analysis tool, based on the Coupled Advanced multiscale Modeling and Visualization system (CAMVis), to improve extended-range tropical cyclone (TC) prediction and consequently TC climate projection by enabling:

- Understanding of the TC genesis processes, accompanying multiscale processes (both downscaling by large-scale events and upscaling by small-scale events), and their subsequent non-linear interactions

- Discovery of hidden predictive relationships between meteorological and climatological events.

This project targets the ACE, PATH, SMAP, Next-generation scatterometer, and 3D-Winds missions.






The scientific research cycle consists of Modeling, Observation, Analysis, Synthesizing, Theorizing (MOAST).

- **Climate**

  Climate in a narrow sense is usually defined as the "average weather," or more rigorously, as the statistical description in terms of the mean and variability of relevant quantities over a period of time ranging from months to thousands of years. The classical period is 3 decades, as defined by the World Meteorological Organization (WMO). These quantities are most often surface variables such as temperature, precipitation, and wind. Climate in a wider sense is the state, including a statistical description, of the climate system.

http://www.epa.gov/climatechange/glossary.html#C

# Grid Cells vs. Grid Spacing

| Resolution | x | y | Grid cells | |
|---|---|---|---|---|
| 1° (~110km) | 288 | 181 | 52 K | |
| 0.5° (~55km) | 576 | 361 | 208 K | |
| 0.25° (~28km) | 1000 | 721 | 721 K | |
| 0.125° (~14km) | 2880 | 1441 | 4.15 M | |
| 0.08° (~9km) | 4500 | 2251 | 10.13 M | Y2005 |
| | | | | |
| MMF (2D CRM) | 144x64 | 90 | 829 K | Y2005~2006 |

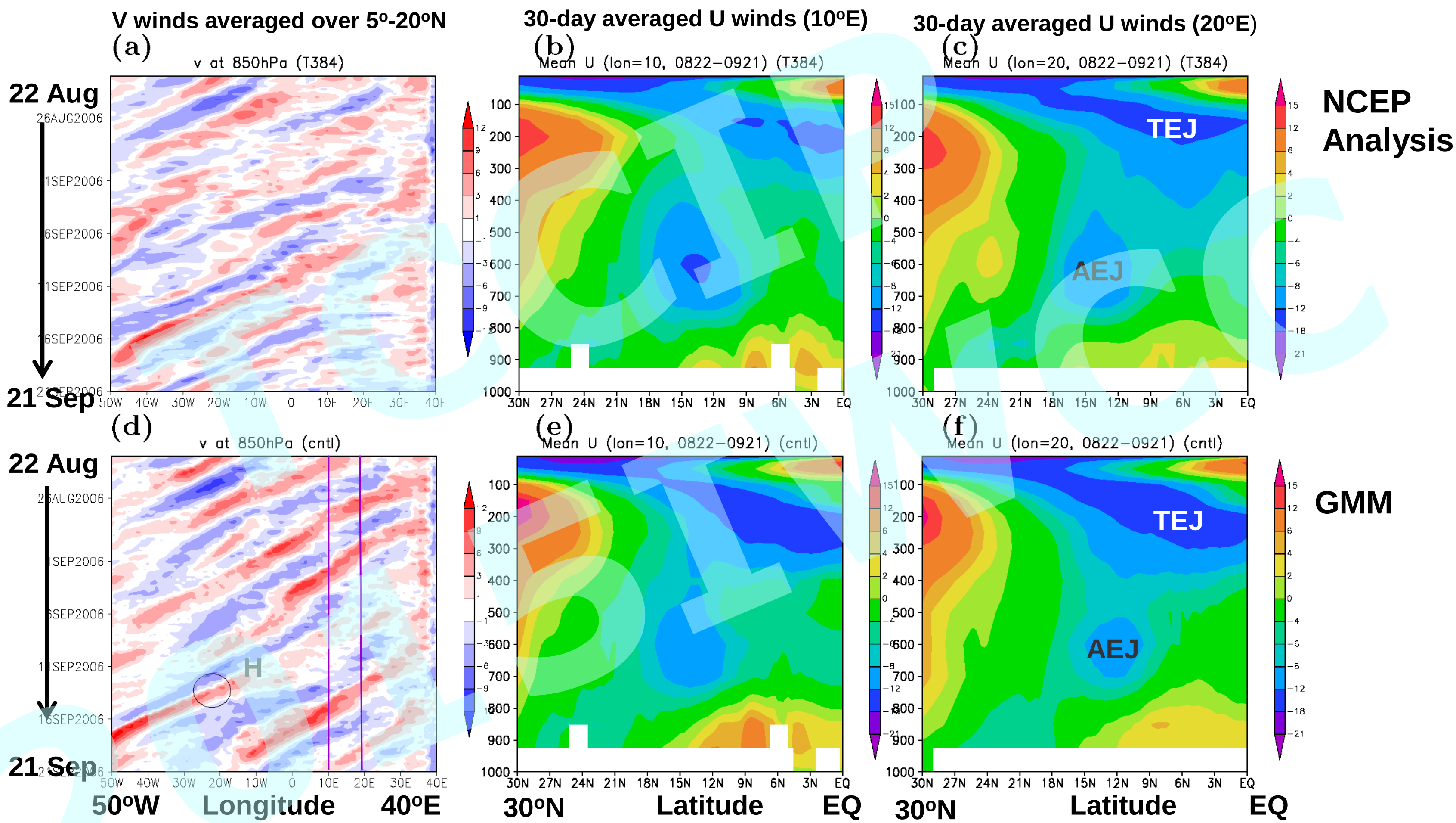
The 1/12 degree model with 48 vertical levels has 480 M grid points.
In comparison, the hyperwall-2 is able to display 245 M pixels.

# African Easterly Waves (AEWs)


- <u>During the summer time</u> (from June to early October), African easterly waves (AEWs) appear as one of the dominant synoptic weather systems in **<u>West Africa.</u>**
- These waves are characterized by an average westward-propagating speed of <u>11.6 m/s</u>, an average wavelength of <u>2200km</u>, and a period of about <u>2 to 5 days</u>.
- 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*

# Five AEWs in 30-day Simulations
## (init at 00zz Aug 22, 2006)



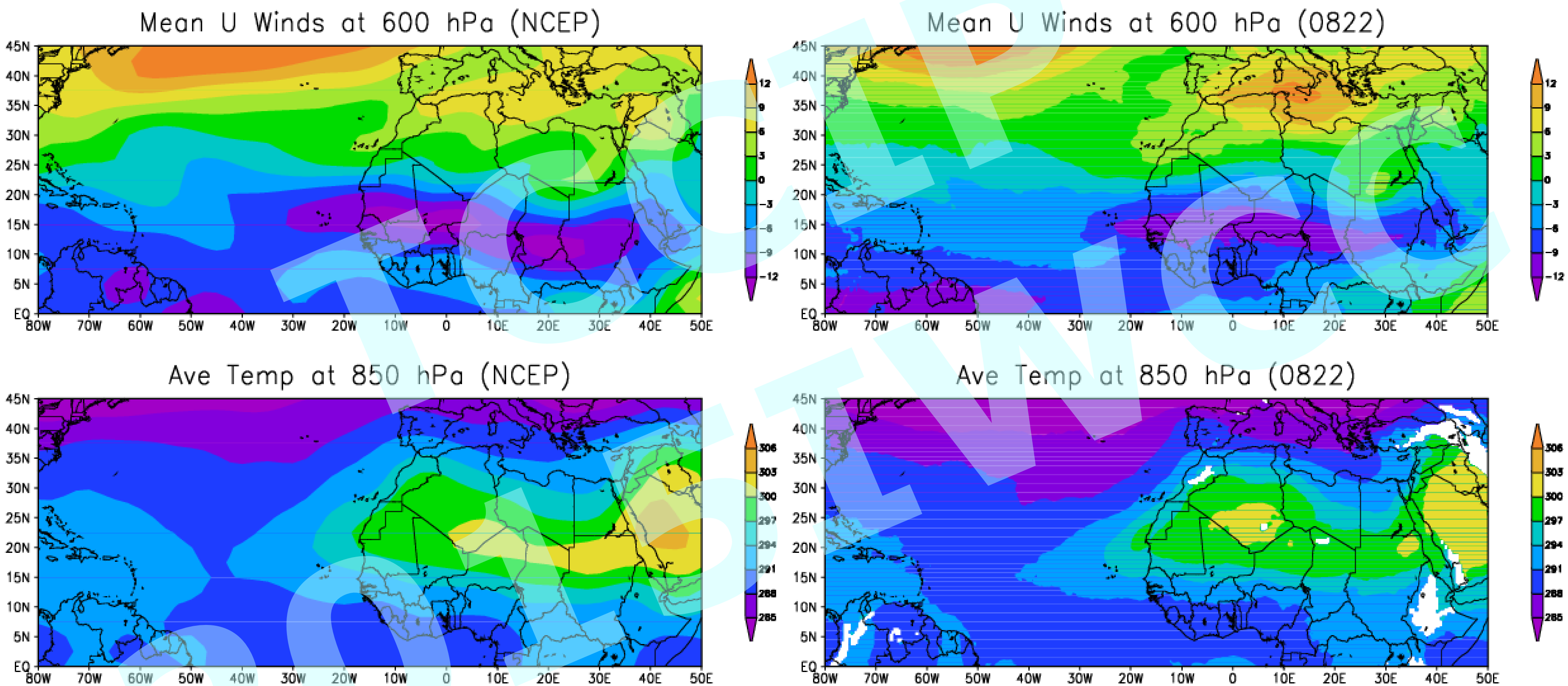


Shen, B.-W., W.-K. Tao, M.-L. Wu, 2010b: African Easterly Waves and African Easterly Jet in 30-day High-resolution Global Simulations. A Case Study during the 2006 NAMMA period. Geophys. Res. Lett., L18803, doi:10.1029/2010GL044355.

# 30-day Averaged U Winds and Temp

(init at 08/22/00z)

NCEP Reanalysis | Model Simulations




Shen, B.-W. et al., 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.