Analyzing Tropical Waves Using the Parallel Ensemble Empirical Model Decomposition Method: Preliminary Results from Hurricane Sandy

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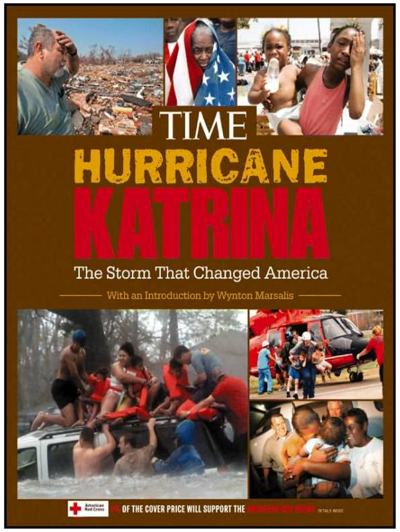
Outline

1. Introduction
2. Hurricane Simulations with the NASA CAMVis
3. The Parallel Ensemble Empirical Mode Decomposition (PEEMD)
4. Multiscale Analysis with the PEEMD
    - Idealized cases with tropical waves
    - Real-world cases (Hurricane Sandy and Helene)
5. Summary and Future Tasks

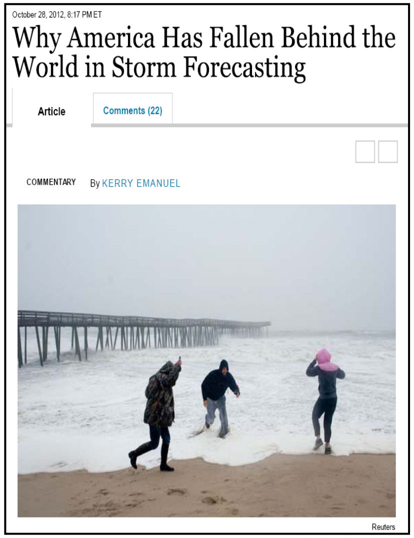
High-impact Tropical Weather: Hurricanes

Each year tropical cyclones (TCs) cause tremendous economic losses and many fatalities throughout the world. Examples include Hurricanes Katrina (2005) and Sandy (2012).



Hurricane Katrina (2005) (<u>Shen et al., 2006b; 2013a</u>)

- 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! ($100+ billion)


October 28, 2012, 8:17 PM ET

Why America Has Fallen Behind the World in Storm Forecasting

COMMENTARY By KERRY EMANUEL

Reuters

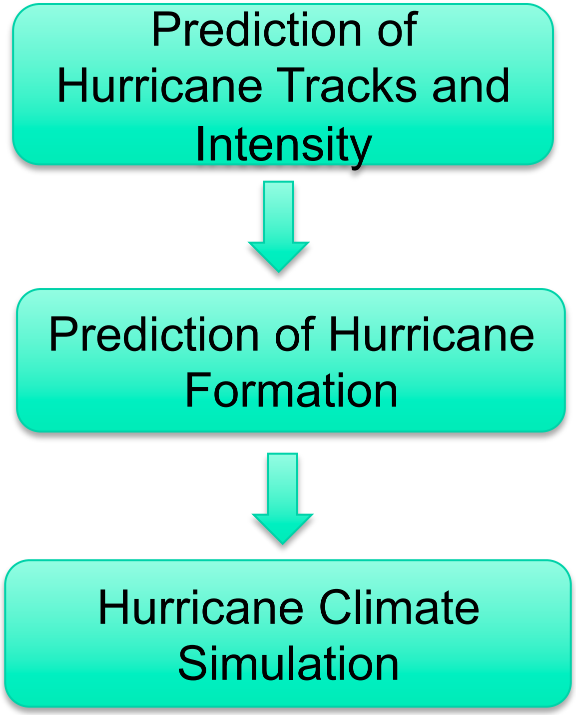
Hurricane Sandy (2012) (<u>Shen et al., 2013c</u>)

- The deadliest and the most destructive TC of 2012 Atlantic hurricane season
- The second-costliest hurricane in United States history ($50 or 75$ billion)
- The largest Atlantic hurricane on record

Major Scenarios in Decadal Survey Missions

Two of Major Scenarios in Decadal Survey missions are:

- **Extreme Event Warnings** (near-term goal): Discovering predictive relationships between meteorological and climatological events and less obvious precursor conditions from massive data sets
- **Climate Prediction** (long-term goal): Robust estimates of primary climate forcing 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.
- Hurricanes, Tropical Cyclones (TCs)



Prediction of Hurricane Tracks and Intensity

Prediction of Hurricane Formation

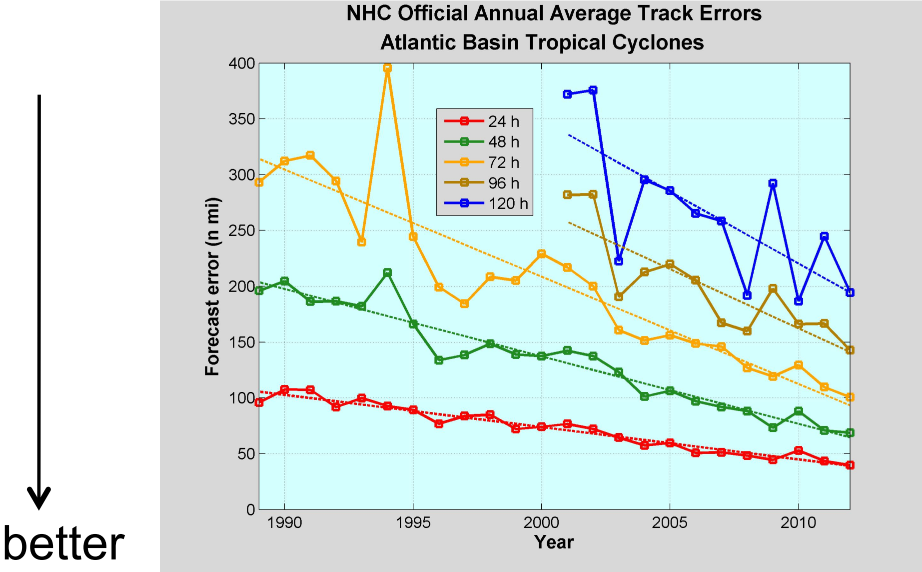
Hurricane Climate Simulation

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

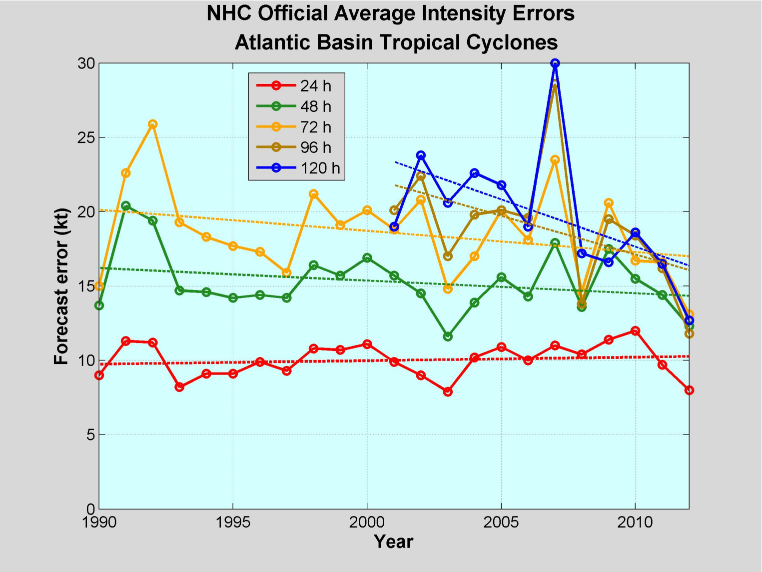
Progress of Hurricane Forecasts

(National Hurricane Center)

Track Errors (1989-2012)



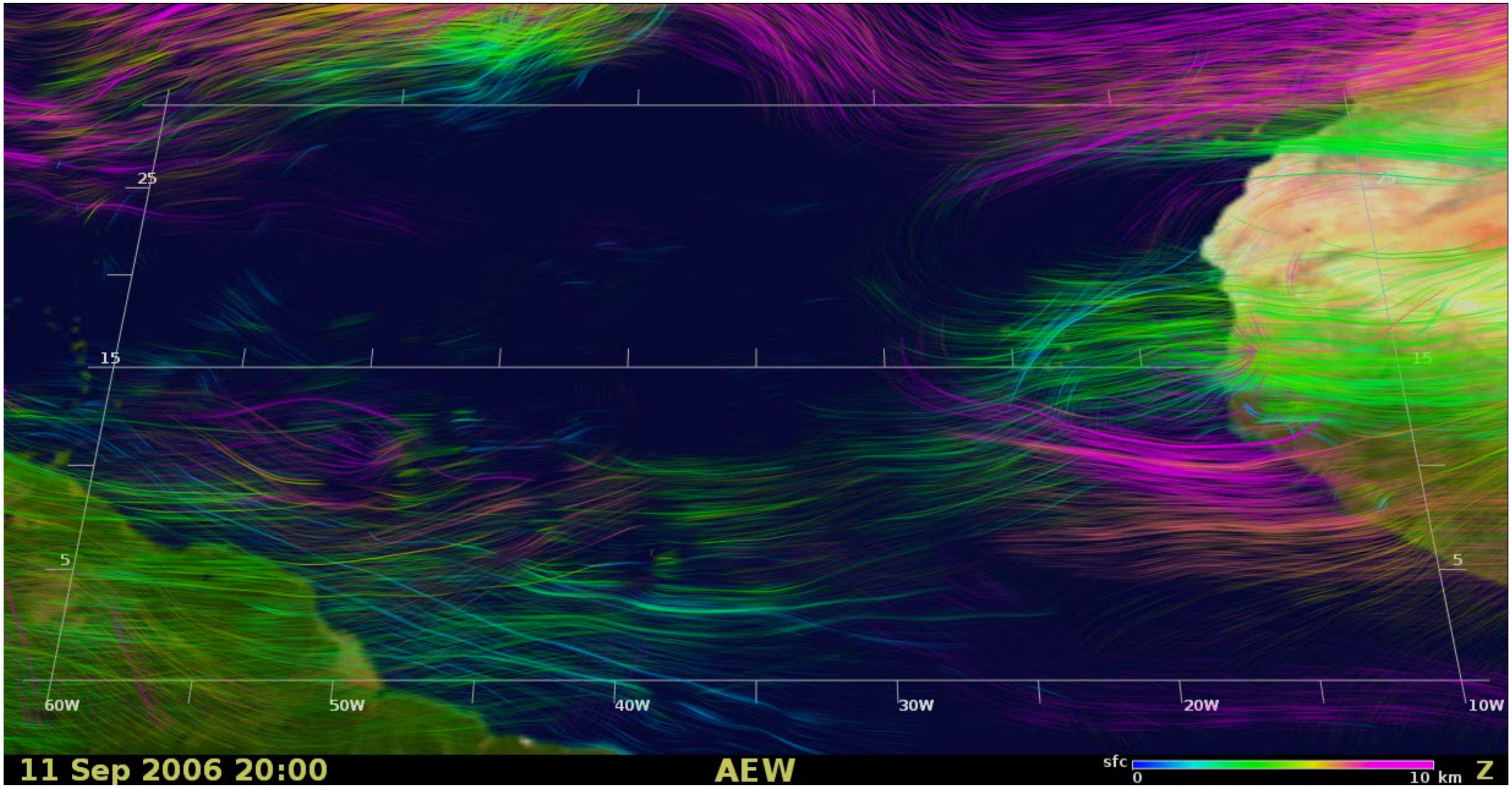
Intensity Errors (1990-2012)



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).*

Formation of Hurricane Helene (2006)

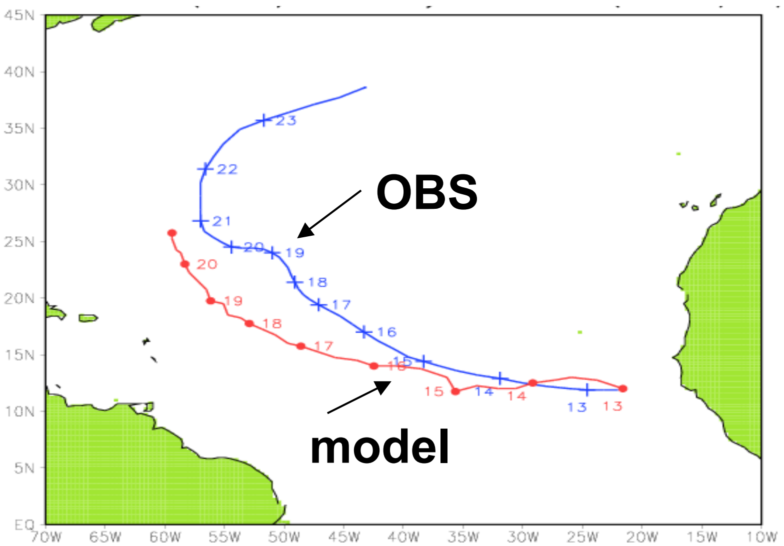


- Simulations from Day 20 to Day 30 in a run initialized at 00Z Aug 22, 2006 http://goo.gl/arWSZ
- Upper-level winds in red; middle-level winds in green; low-level winds in blue
- Low-level CC (cyclonic circulation); Upper-level AC (anticyclonic circulation)
- Shen, B.-W. W.-K. Tao and M.-L. Wu, 2010b: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

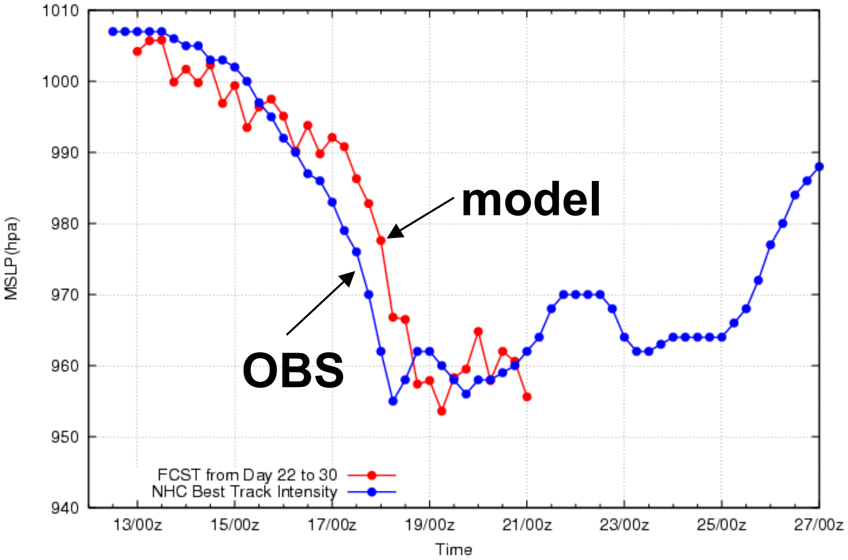
Simulations of Helene (2006) between Day 22-30

(Helene: 12-24 September, 2006)

Track Forecast



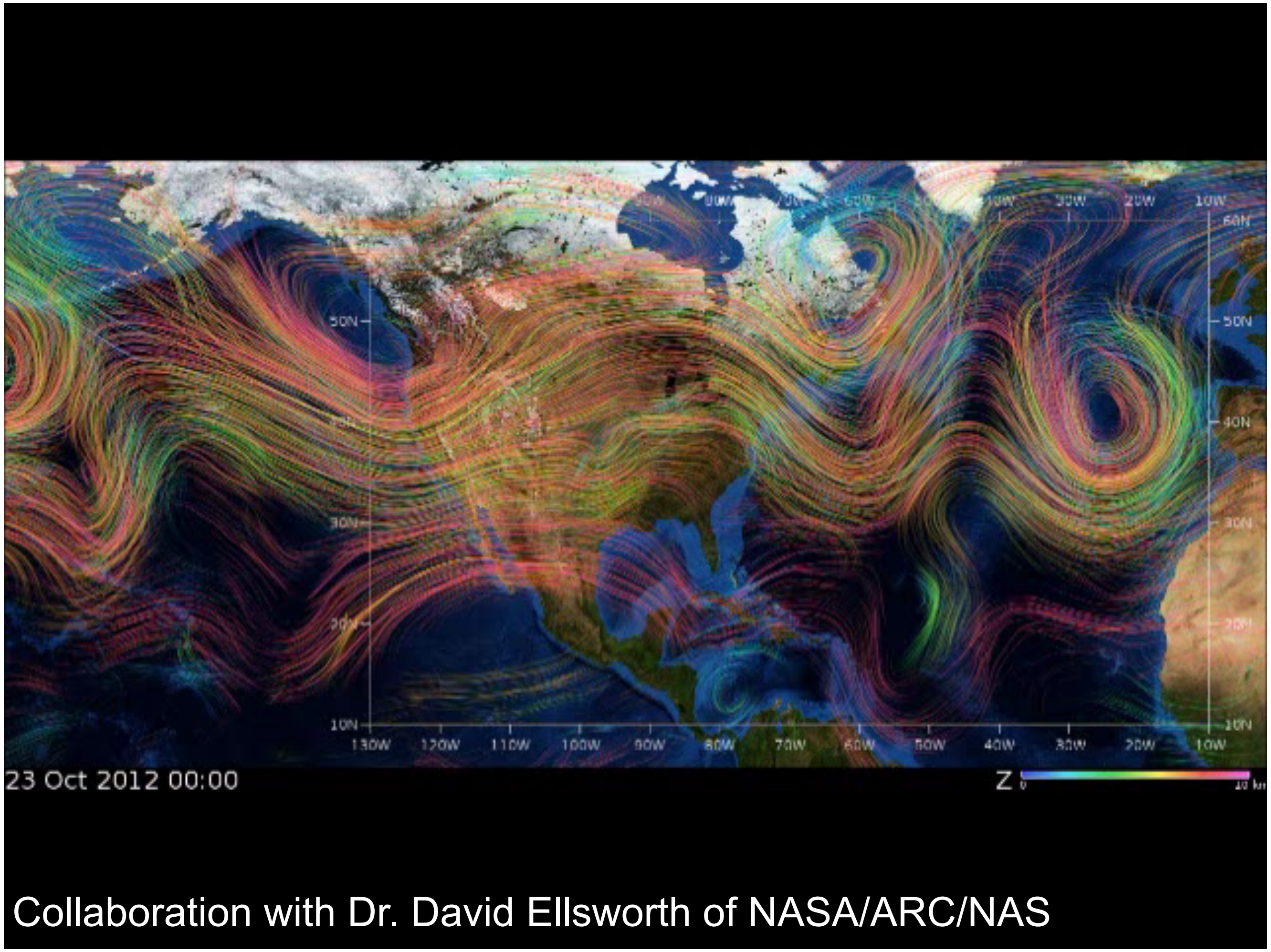
Intensity Forecast



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.

7-day Simulation and Visualization of Sandy



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

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

Questions

- From a modeling perspective, why high-resolution global models have skills?

- From a perspective of chaos (nonlinear) dynamics, are the simulations of TC formation consistent with chaos theory? (e.g., sensitive dependence on initial conditions)? → a high-order Lorenz model (Slide 11, Shen 2014a,b)

- From a perspective of hurricane dynamics, if and how the lead time of hurricane predictions can be extended? → a conceptual model (e.g., Slide 12) and approaches

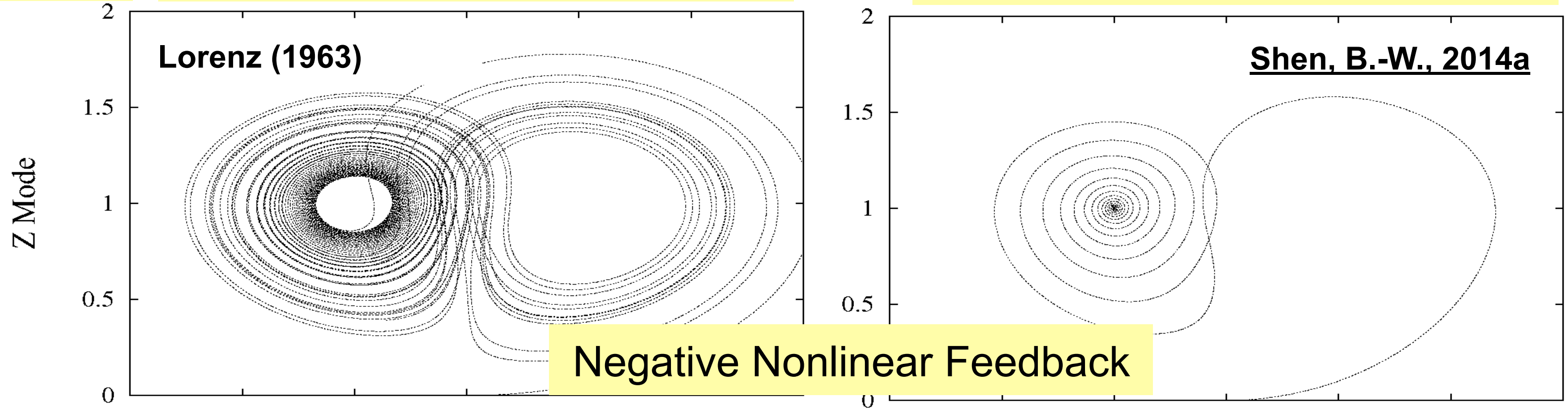
Are the simulations of TC genesis consistent with Chaos theory?

- The butterfly effect of first kind: *sensitive dependence on initial conditions*.
- The butterfly effect of second kind: *a metaphor (or symbol) 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

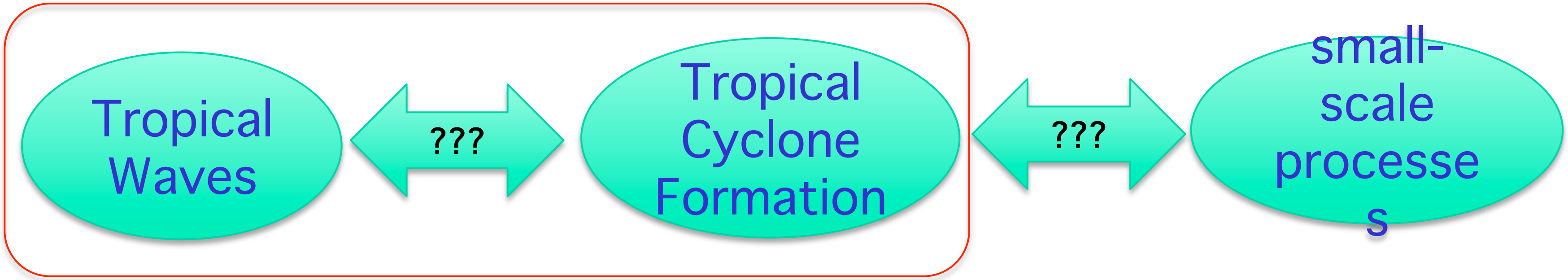
High-order Lorenz Model



Negative Nonlinear Feedback

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).

Scientific Goals



``… *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).*

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

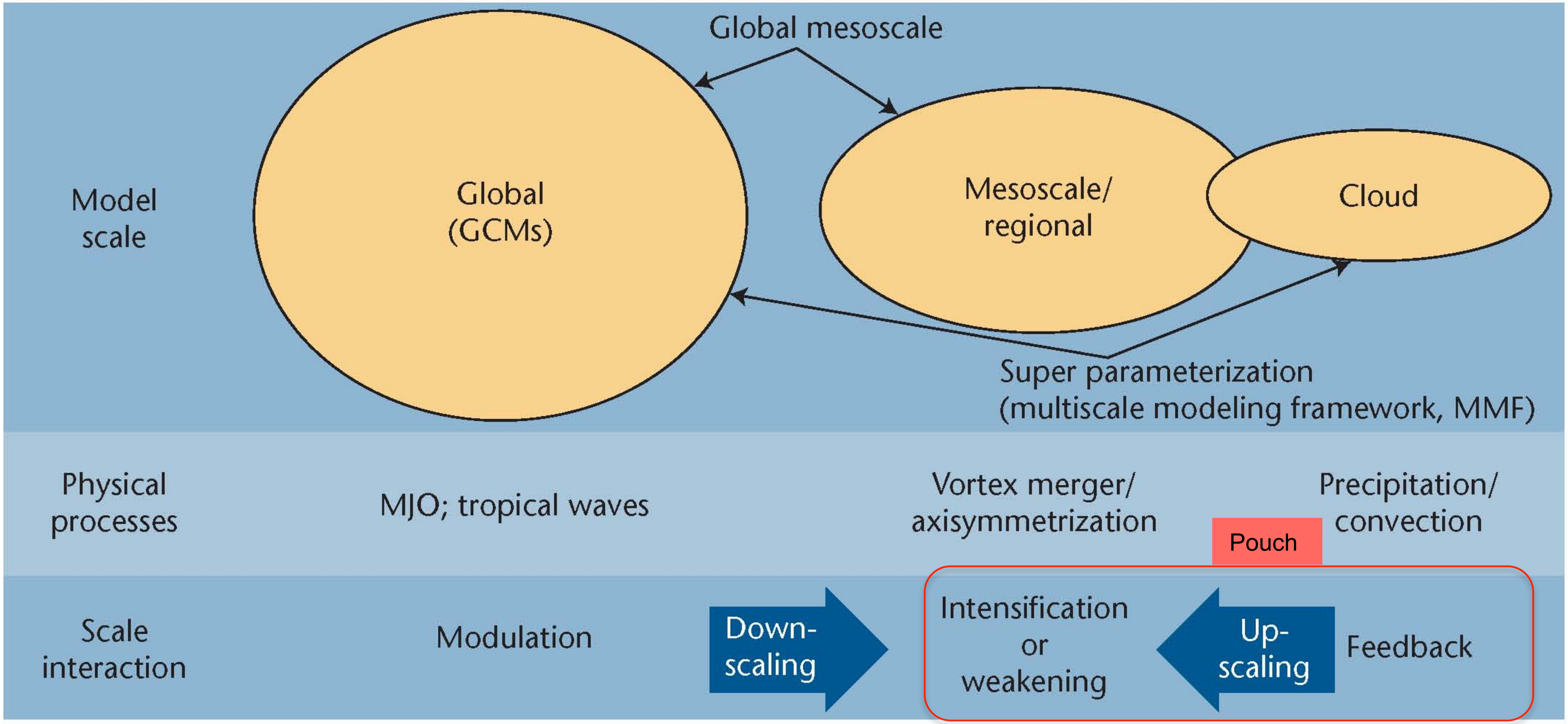
   (e.g., downscaling)

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

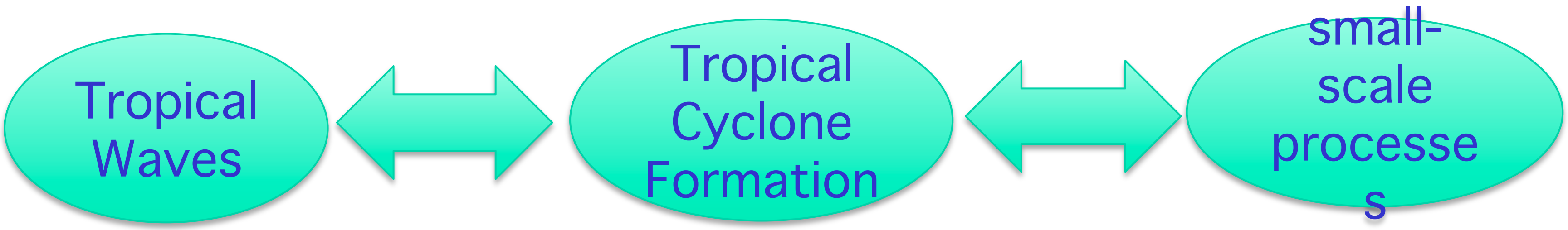
   (e.g., upscaling)

Multiscale Processes

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



Scientific Goals


Tropical Waves

Tropical Cyclone Formation

small-scale processes

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

Selected cases in published journal articles

(Shen et al. 2010a,b,2012,2013a,c) include:

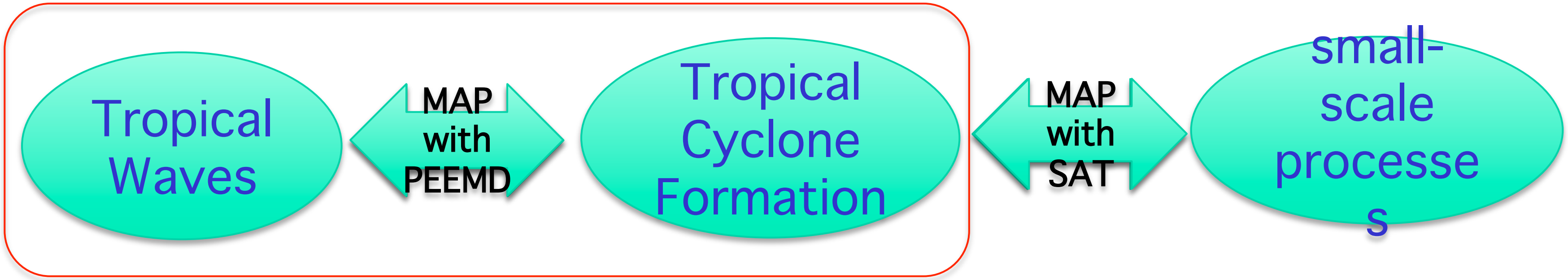
1: TC Nargis (2008) and an Equatorial Rossby (ER) Wave

2: Twin TCs 2002) and a mixed Rossby Gravity (MRG) Wave

3: Hurricane Helene (2006) and an African Easterly Wave (AEW)

4: Hurricane Sandy (2012) and Tropical Waves

Scientific Goals



Tropical Waves

MAP with PEEMD

Tropical Cyclone Formation

MAP with SAT

small-scale processes

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

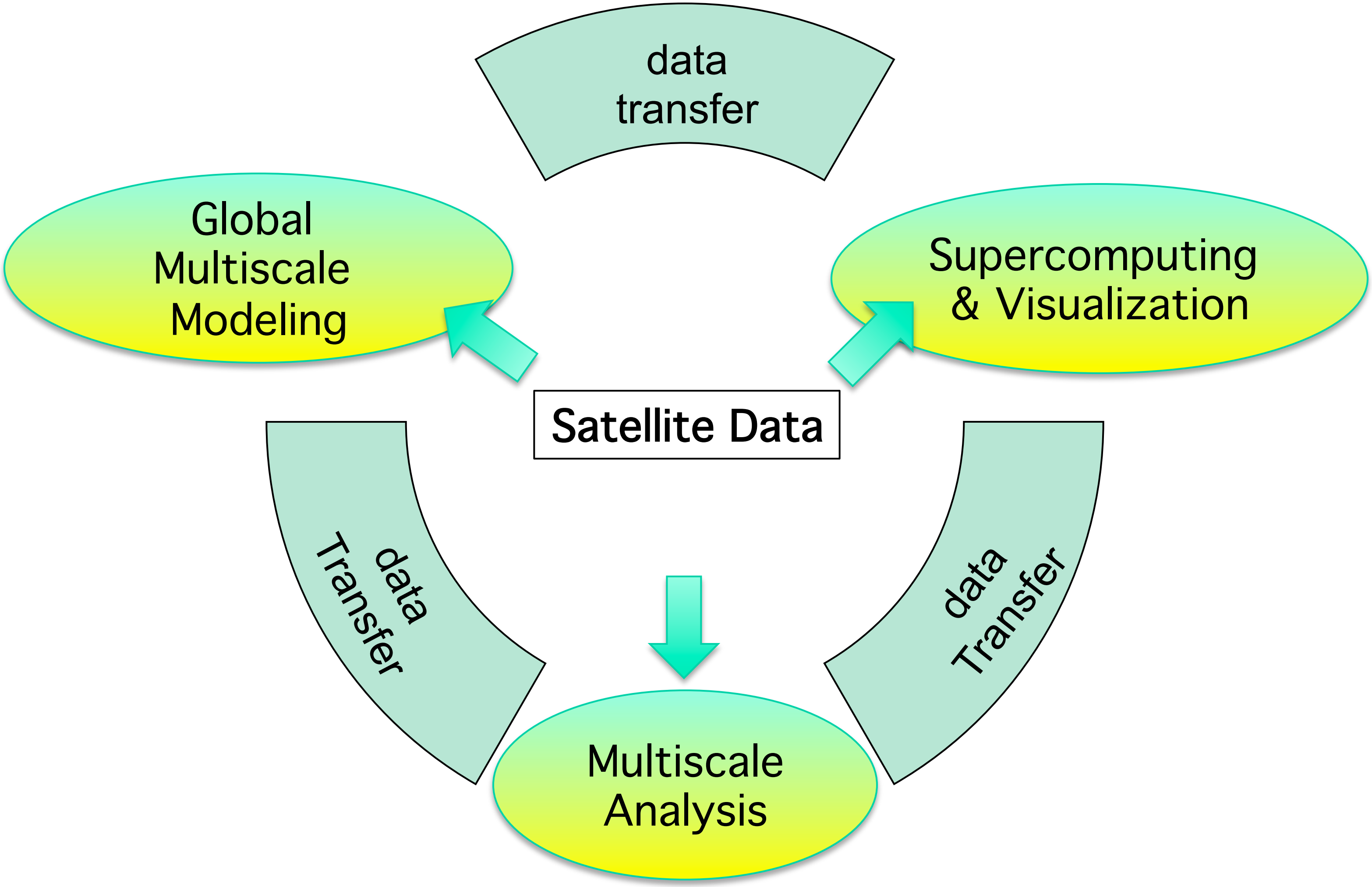
   (e.g., downscaling)

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

Architecture of the CAMVis-MAP


data transfer

Global Multiscale Modeling

Supercomputing & Visualization

Satellite Data

data Transfer

data Transfer

Multiscale Analysis

Scalable Multiscale Analysis Package (MAP)

Published Articles since 2010

Journal Articles:

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
2. **Shen, B.-W.,** M. DeMaria, **J.-L. F. Li and S. Cheung, 2013c:** Genesis of Hurricane Sandy (2012) simulated with a global mesoscale model, *Geophys. Res. Lett., 40,* 4944–4950, *doi:*10.1002/grl.50934.
3. **Shen, B.-W.,** B. Nelson, **S. Cheung,** W.-K. Tao, **2013b:** Improving NASA's Multiscale Modeling Framework for Tropical Cyclone Climate Study. *IEEE Computing in Science and Engineering*, vol. 15, no 5, pp 56-67. Sep/Oct 2013.
4. **Shen, B.-W.,** B. Nelson, W.-K. Tao, and Y.-L. Lin, **2013a:** Advanced Visualizations of Scale Interactions of Tropical Cyclone Formation and Tropical Waves. *IEEE Computing in Science and Engineering*, vol. 15, no. 2, pp. 47-59, March-April 2013, doi: 10.1109/MCSE.2012.64.
5. **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
6. **Shen, B.-W.,** W.-K. Tao, and B. Green, **2011:** Coupling Advanced Modeling and Visualization to Improve High-Impact Tropical Weather Prediction (CAMVis). *IEEE Computing in Science and Engineering (CiSE)*, vol. 13, no. 5, pp. 56-67, Sep./Oct. 2011, doi: 10.1109/MCSE.2010.141.
7. **Shen, B.-W.,** W.-K. Tao, and M.-L. Wu, **2010b:** African Easterly Waves in 30-day High resolution Global Simulations: A Case Study during the 2006 NAMMA Period. Geophys. Res. Lett., 37, L18803, doi:10.1029/2010GL044355.
8. **Shen, B.-W.,** W.-K. Tao, W. K. Lau, R. Atlas, **2010a:** Predicting Tropical Cyclogenesis with a Global Mesoscale Model: Hierarchical Multiscale Interactions During the Formation of Tropical Cyclone Nargis (2008) . J. Geophys. Res.,115, D14102, doi: 10.1029/2009JD013140.

Magazine Articles:

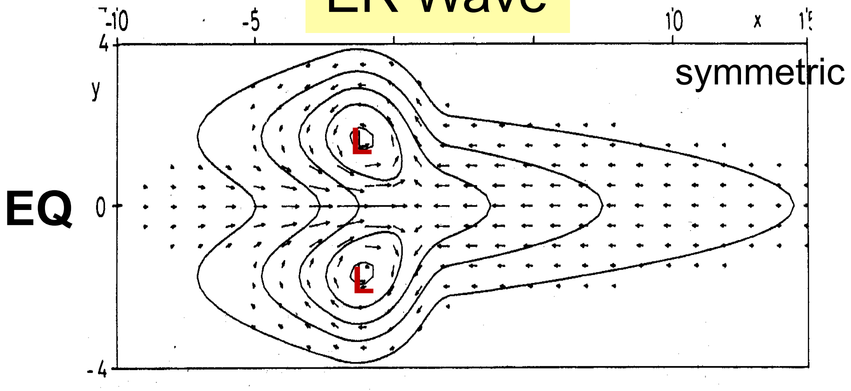
9. **Shen, B.-W., S. Cheung, J.-L. F. Li, and Y.-L. Wu, 2013e:** Analyzing Tropical Waves using the Parallel Ensemble Empirical Model Decomposition (PEEMD) Method: Preliminary Results with Hurricane Sandy (2012), NASA ESTO Showcase . IEEE Earthzine.
10. **Shen, B.-W., 2013f:** Simulations and Visualizations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

Papers under review/preparation:

11. **Shen, B.-W., 2014b:** On the Nonlinear Feedback Loop and Energy Cycle of the Non-dissipative Lorenz Model. (accepted, NPGD)
12. **Shen, B.-W., 2014c:** Nonlinear Feedback in a Six-dimensional Lorenz Model. *Impact of an Additional Heating Term. (to be submitted)*

Tropical Waves and TC Formation

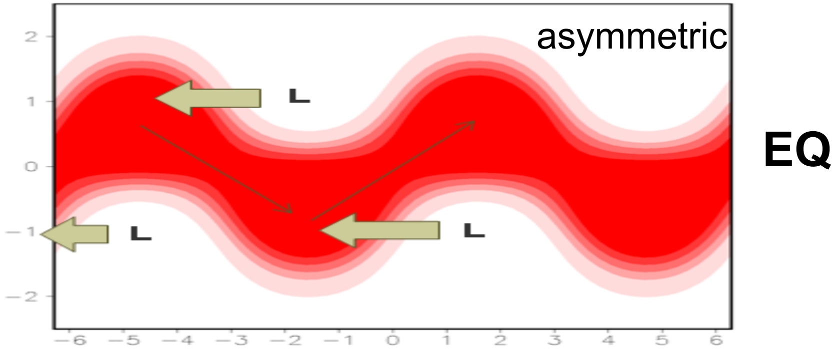
ER Wave



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

TC Nargis (Shen et al., 2010a)

MRG Wave



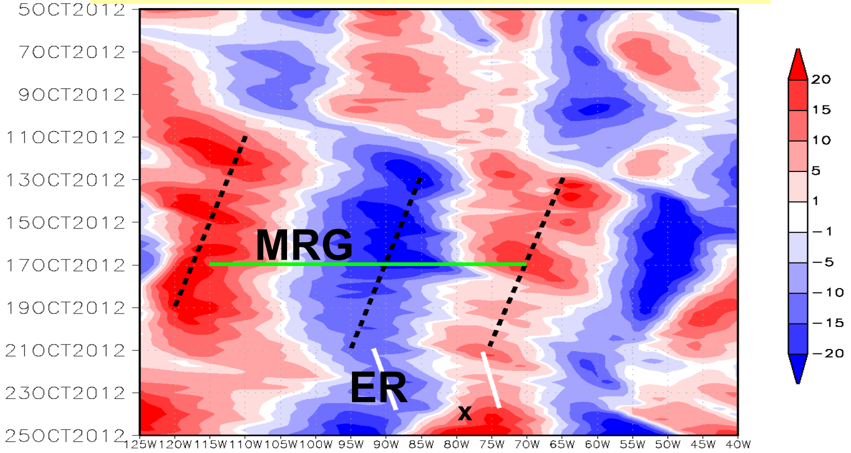
Mixed Rossby Gravity (MRG) waves, asymmetric with respect to to the equator, occasionally appear in Indian Ocean or West Pacific

Twin TC (Shen et al., 2012)

1. to what extent can large-scale flows determine the timing and location of TC genesis?

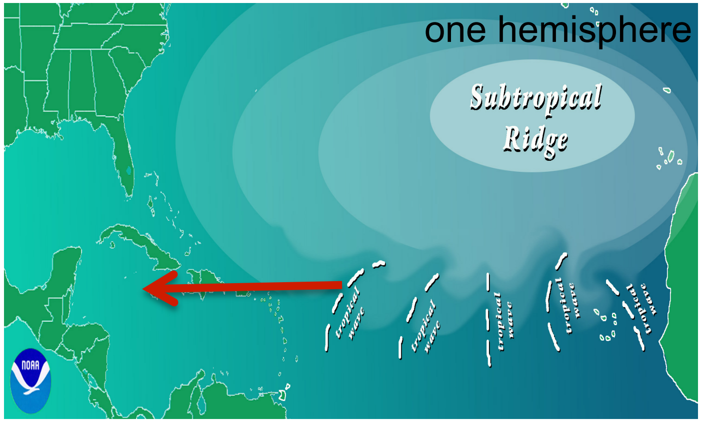
Tropical Waves and TC Formation

Sandy (2012) and Tropical Waves



Time-longitude diagram of V winds at 200 hPa averaged over latitudes 20^{o}N to 30^{o}N. Black dashed (green) lines are used to determine the phase speed (wavelength).

Helene (2006) and an AEW



LAT:5^{o}

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

1. to what extent can large-scale flows determine the timing and location of TC genesis?

Empirical Mode Decomposition (EMD)

1. HHT (Hilbert Huang Transform, Huang et al., 1998) consists of Empirical model 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 model 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.

Fourier, Wavelet and HHT Analysis

	Fourier	Wavelet	Hilbert/EMD
Basis	a priori	a priori	adaptive
Frequency	convolution: global, uncertainty	convolution: regional, uncertainty	differentiation: local, certainty
Presentation	energy-frequency	energy-time-frequency	energy-time-frequency
Nonlinearity	no	no	yes
Nonstationarity	no	yes	yes
Feature extraction	no	discrete: no, continuous: yes	yes
Theoretical base	theory complete	theory complete	empirical

Huang (2005); Huang et al., (1998);

Note: The above table with the major change (highlighted in blue) is updated based on the more recent table of Huang (2005). In addition, the uniqueness of the EMD method is indicated by the recent study of Daubechies et al (2011) who developed the synchrosqueezed wavelet transform, a special kind of wavelet method, to capture the flavor and philosophy of the EMD approach.

Empirical Mode Decomposition (EMD) as a Filter Bank

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).

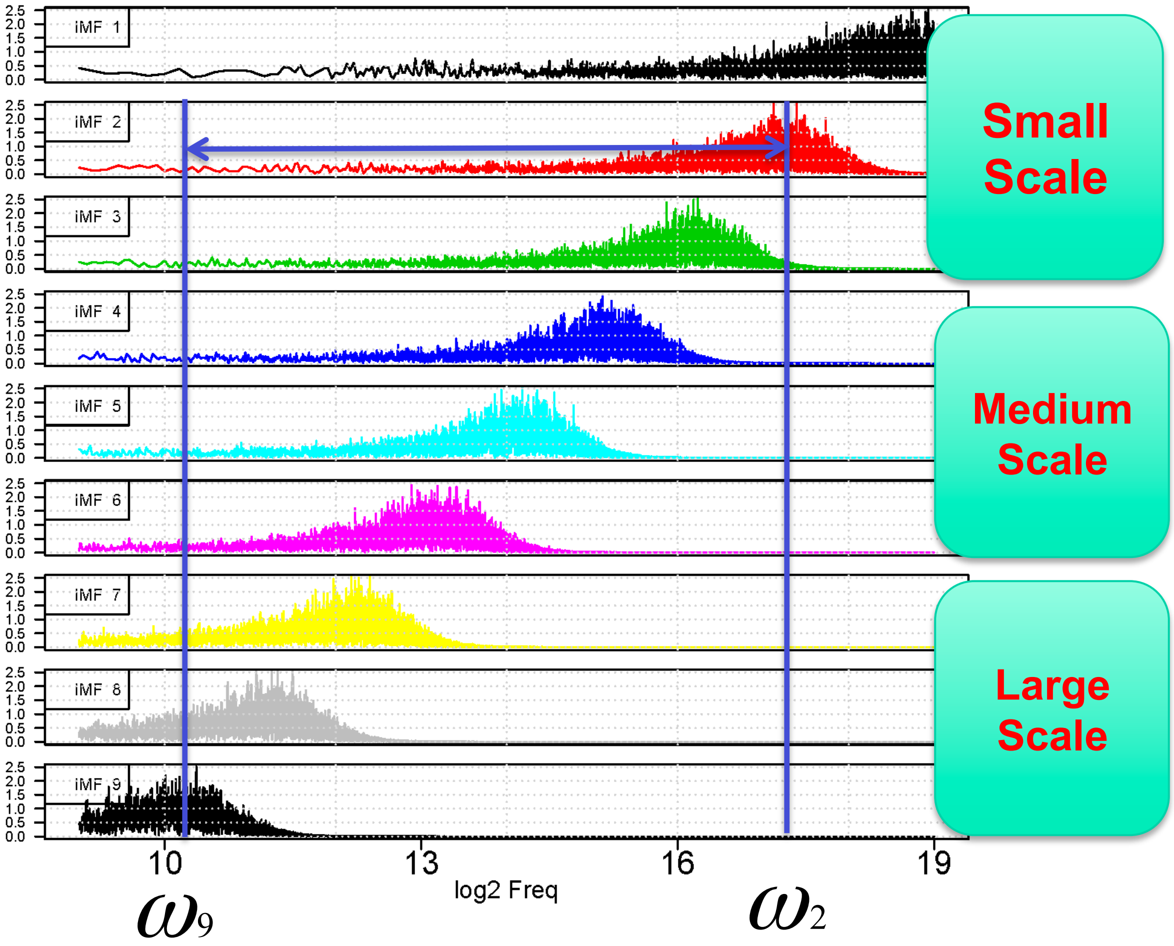
Assume T and ω (=1/T) to be the period and frequency, respectively, we have

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

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

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

which indicates a doubling of the mean period.



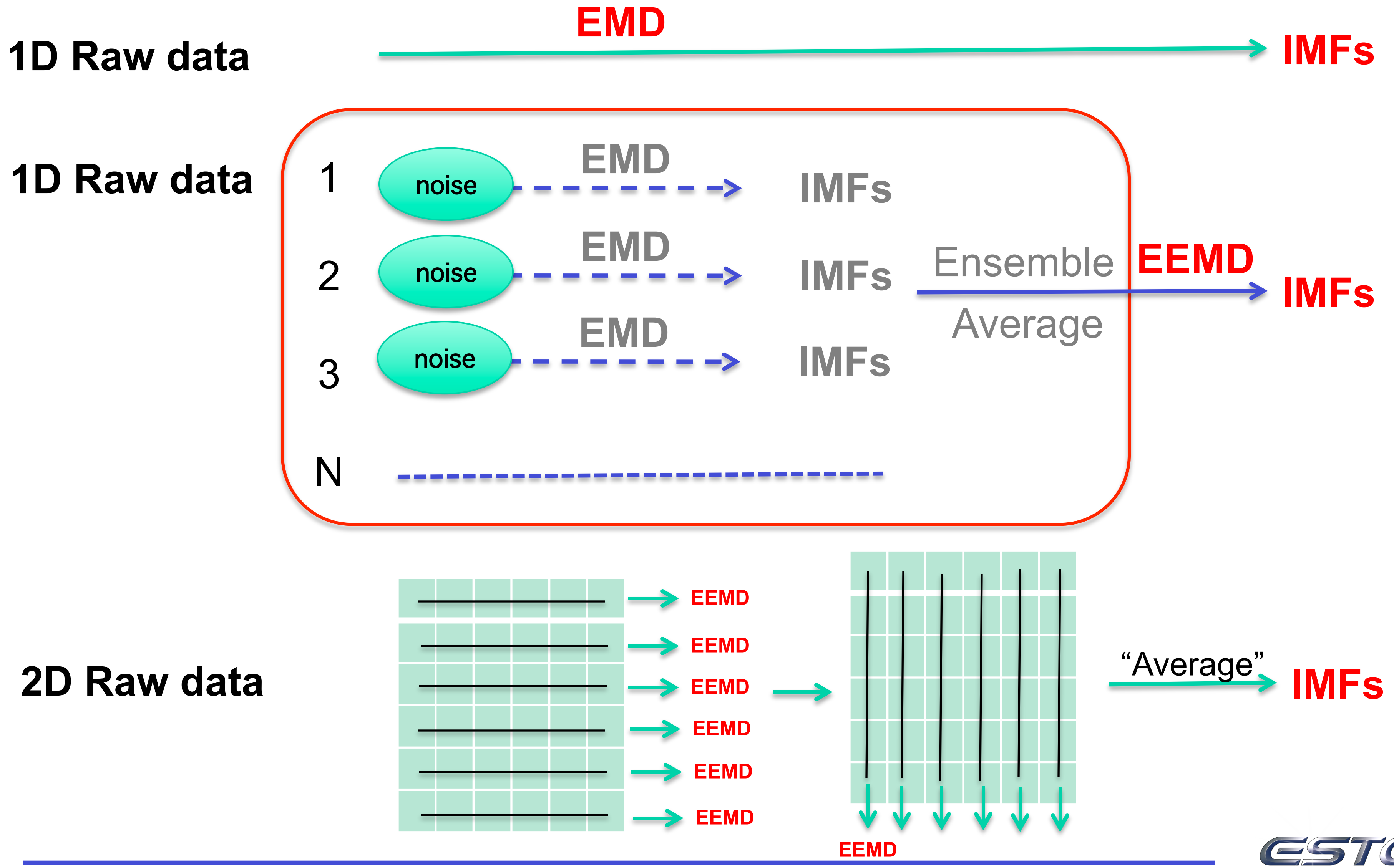
See details in Wu et al. (2004); Reproduced by Shen et al. (2012b).

Ensemble EMD (EEMD): Why?

- Mode mixing is defined as any IMF consisting of oscillations of dramatically disparate scales.
- Mode mixing is a consequence of signal intermittency; it is argued that the time-varying extrema sampling rate is the essential reason of mode mixing (Yang et al., 2009).
- To overcome the issues with mode mixing in the EMD, the ensemble EMD was proposed (Wu and Huang, 2009).

- Ensemble EMD
  - STEP 1: add a noise series to the targeted data
  - STEP 2: decompose the data with added noise into IMFs
  - STEP 3: repeat STEP 1 and STEP 2 again and again, but with different noise series each time
  - STEP 4: obtain the (ensemble) means of corresponding IMFs of the decompositions as the final result

Ensemble EMD and 2D EEMD: How?



1D Raw data

EMD

IMFs

1D Raw data

1 noise EMD IMFs

2 noise EMD IMFs

3 noise EMD IMFs

N

Ensemble

Average

EEMD

IMFs

2D Raw data

EEMD

EEMD

EEMD

EEMD

EEMD

EEMD

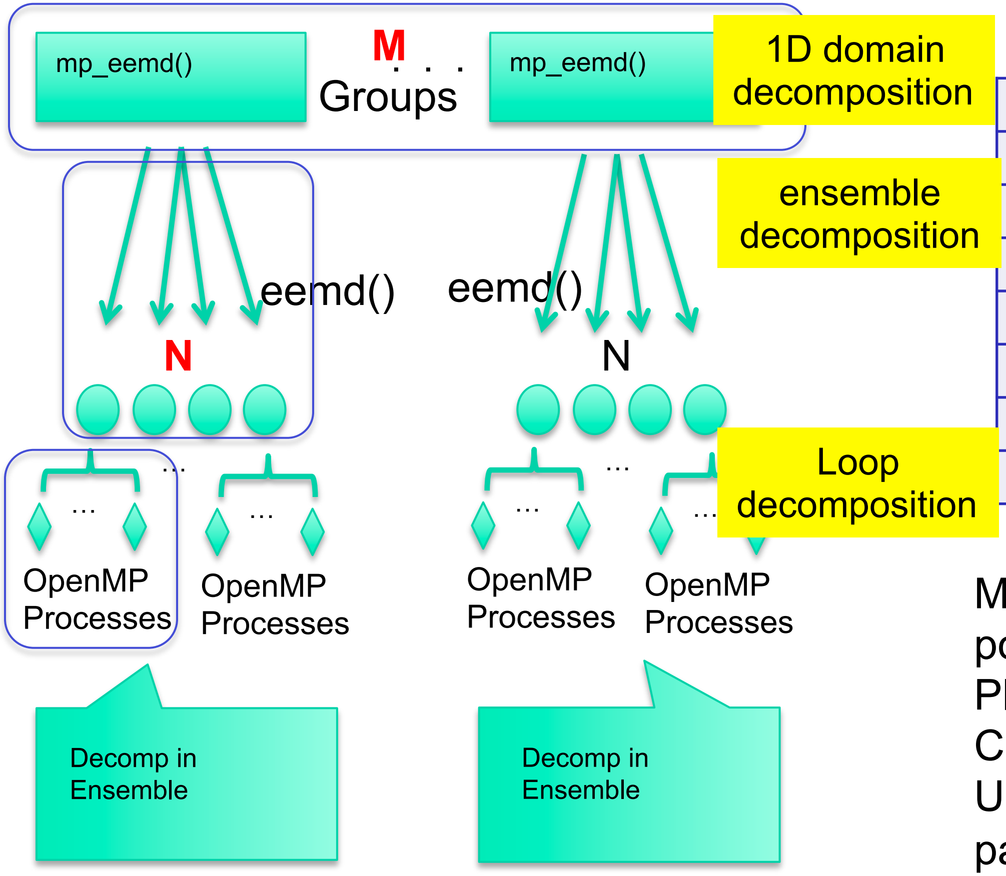
EEMD

“Average”

IMFs

Benchmark with the Three Level Parallelism

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



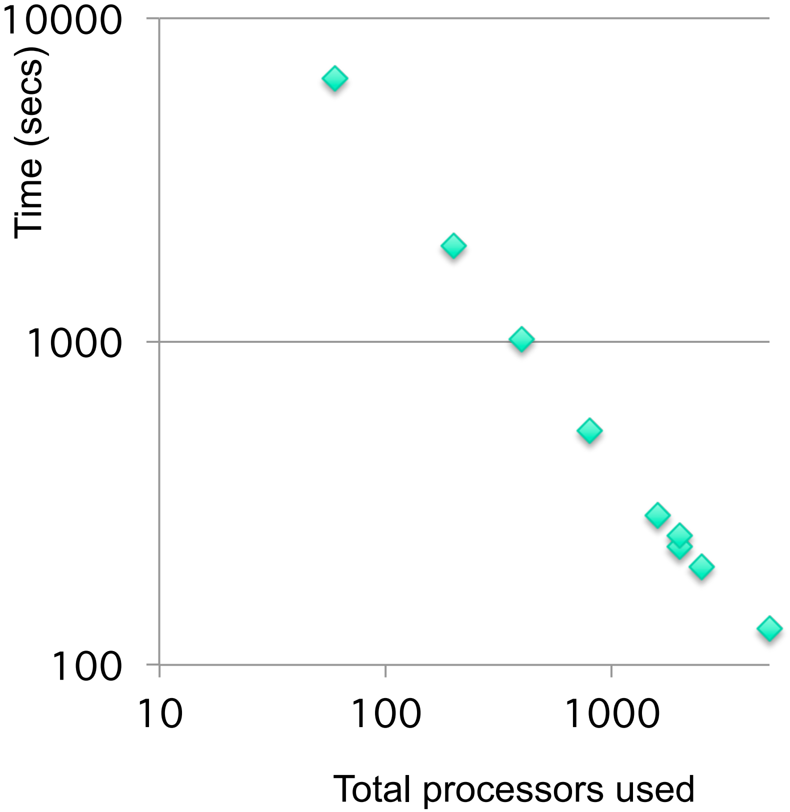
Speedup

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.

Scaling of 5000 Ivy Bridge Processors

MRG Case, Grid:1000x1000 (400MB)



3-Level Parallelization
SGI MPT library is used

Grid DELayout I	Grid DELayout J	Ens	OMP	Total	Time (secs.)	Speed Up
5	6	2		60	6543.56	1.0
10	10	2		200	1983.25	3.3
10	10	4		400	1021.10	6.4
20	20	2		800	531.36	12.3
20	20	4		1600	289.42	22.6
25	40	2		2000	231.69	28.2
25	20	2	2	2000	251.21	26.0
25	25	4		2500	200.60	32.6
25	25	4	2	5000	129.68	50.4
50	50	2		5000	123.85	52.8

Parallel efficiency:
2000 cores, 28.2/(2000/60)=84.6%
5000 cores, 52.8/(5000/60)=63.4%

Parallel Implementation: MP_EEMD

A version of EEMD with multi-level parallelism in MPI, which has been checked into the CVS repository, has the following features:

- Promising Scalability:
  - the serial code (4th case with ERSST Data) takes ~5hours to run; the 32-CPU case takes ~18mins; for the MRG wave case, a speedup of 721.30 is obtained with 100 nodes on Pleiades.
- Bit-by-Bit Consistency:
  - The parallel code produces identical results with different CPU layouts, inclusive of 1 CPU. In addition, a simple code was used to to test the correlation of solutions between the the original serial and parallel codes, showing the correlation coefficient of 0.999.
- Sustainability:
  - As long as the interface of the serial EEMD() is the same, further update of EEMD() would not affect the parallelism nor structure of the code.

Analyzing Idealized Waves with the PEEMD

Design of cases:

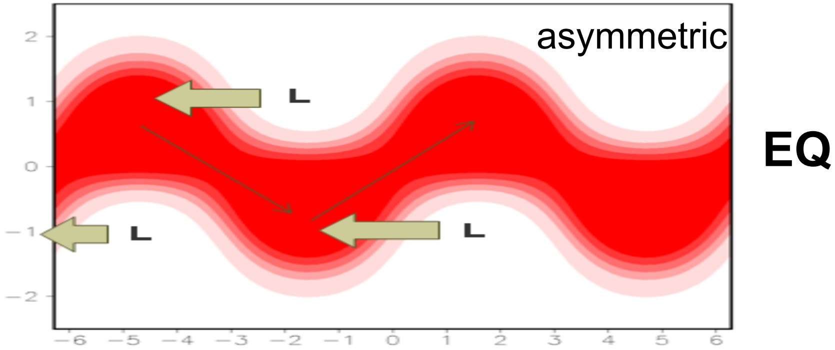
1. Analytical Solutions of an MRG wave and West Wind Burst (WWB)
2. Analytical Solutions of a Kelvin Cat eye's Flow, consisting of an oscillatory mode and non-oscillatory sheared flow.

Approach:

- Verify the decomposed IMFs of the total field against the analytical solutions of individual components (e.g., calculation of correlation coefficients)
- Obtain the same level of accuracy using the parallel EEMD with different parallelisms (e.g., 1, 2 or 3-level parallelism) on different platforms (e.g., different OSs, compilers) and different # of CPUs (associated with different domain decomposition)

Tropical Waves and TC Formation

MRG Wave



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

Twin TC (Shen et al., 2012)

1. to what extent can large-scale flows determine the timing and location of TC genesis?

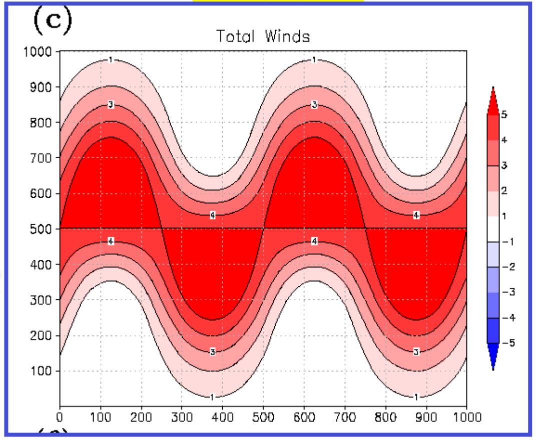
Decompositions of an MRG wave with the PEEMD

Analytical Solutions

U’

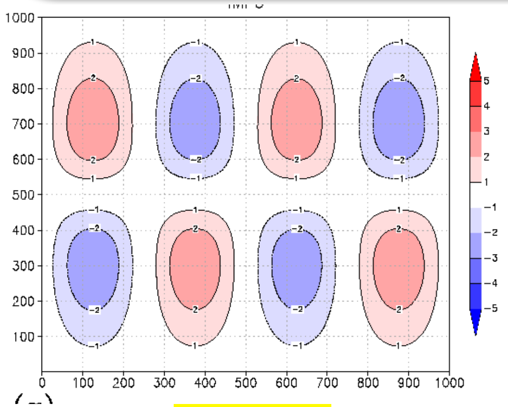
WWB

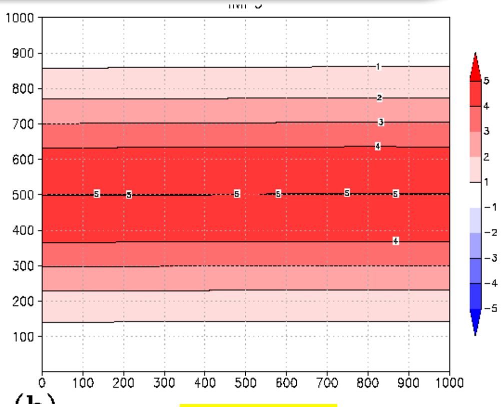
Total



EEMD

IMFs





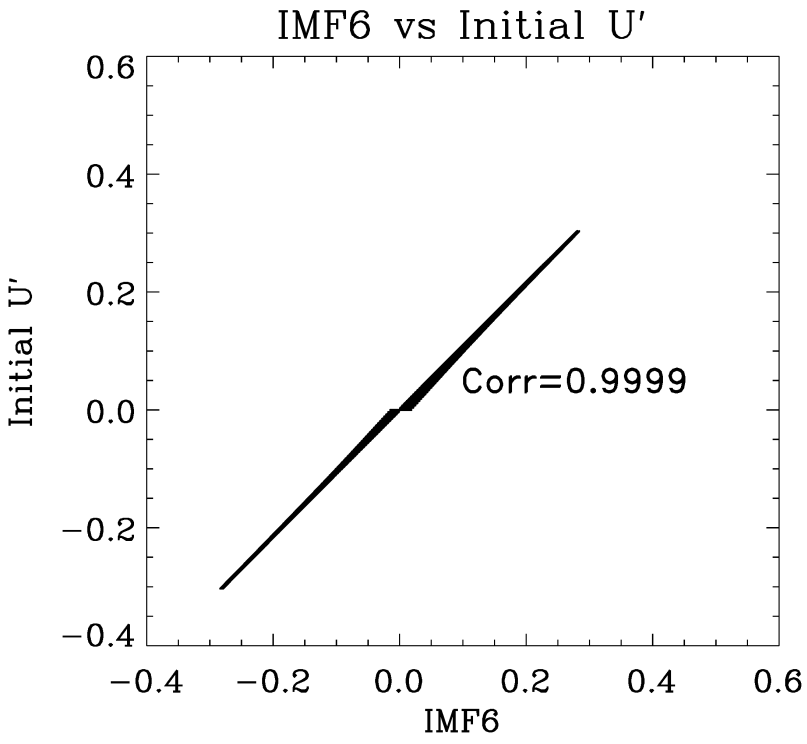
IMF6

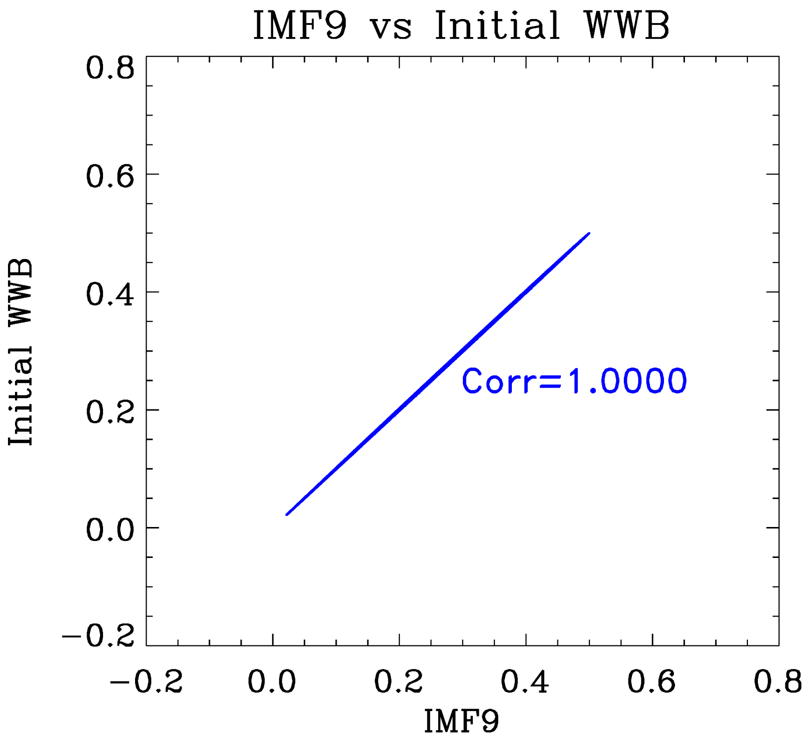
IMF9

(an oscillatory mode)

(a trend mode)

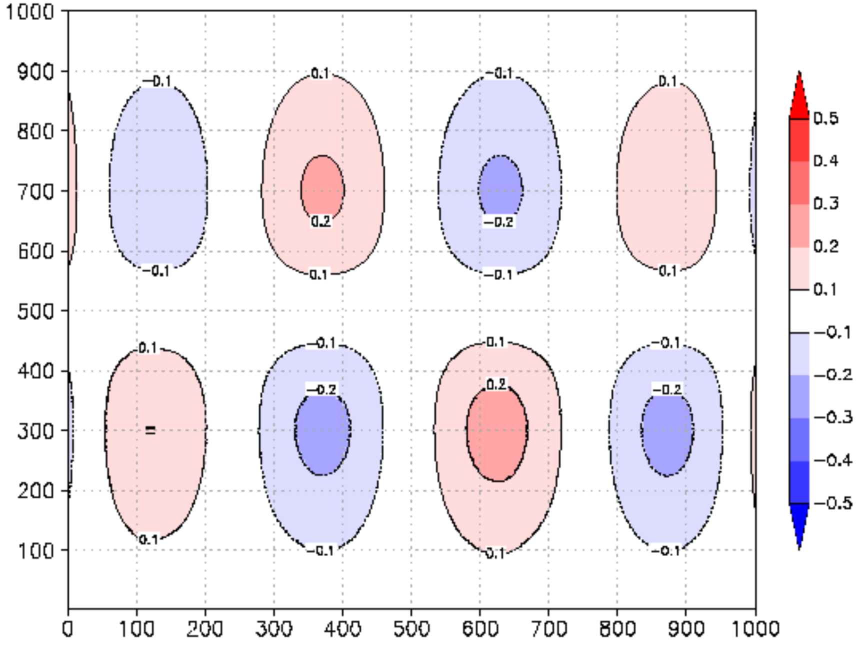
Correlation Plots





Decompositions of MRG wave with the PEEMD

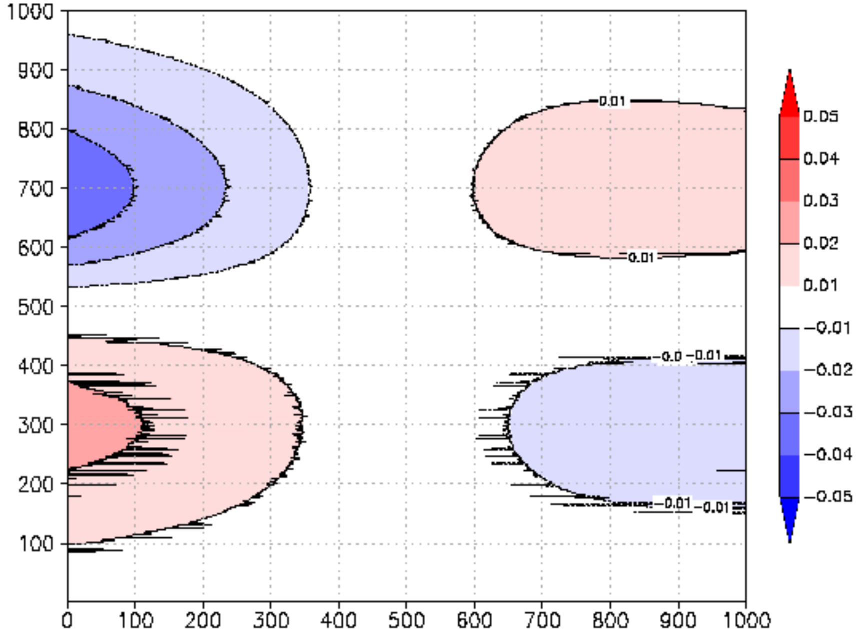
IMF6 - U’



0.10~0.12

(~90%)

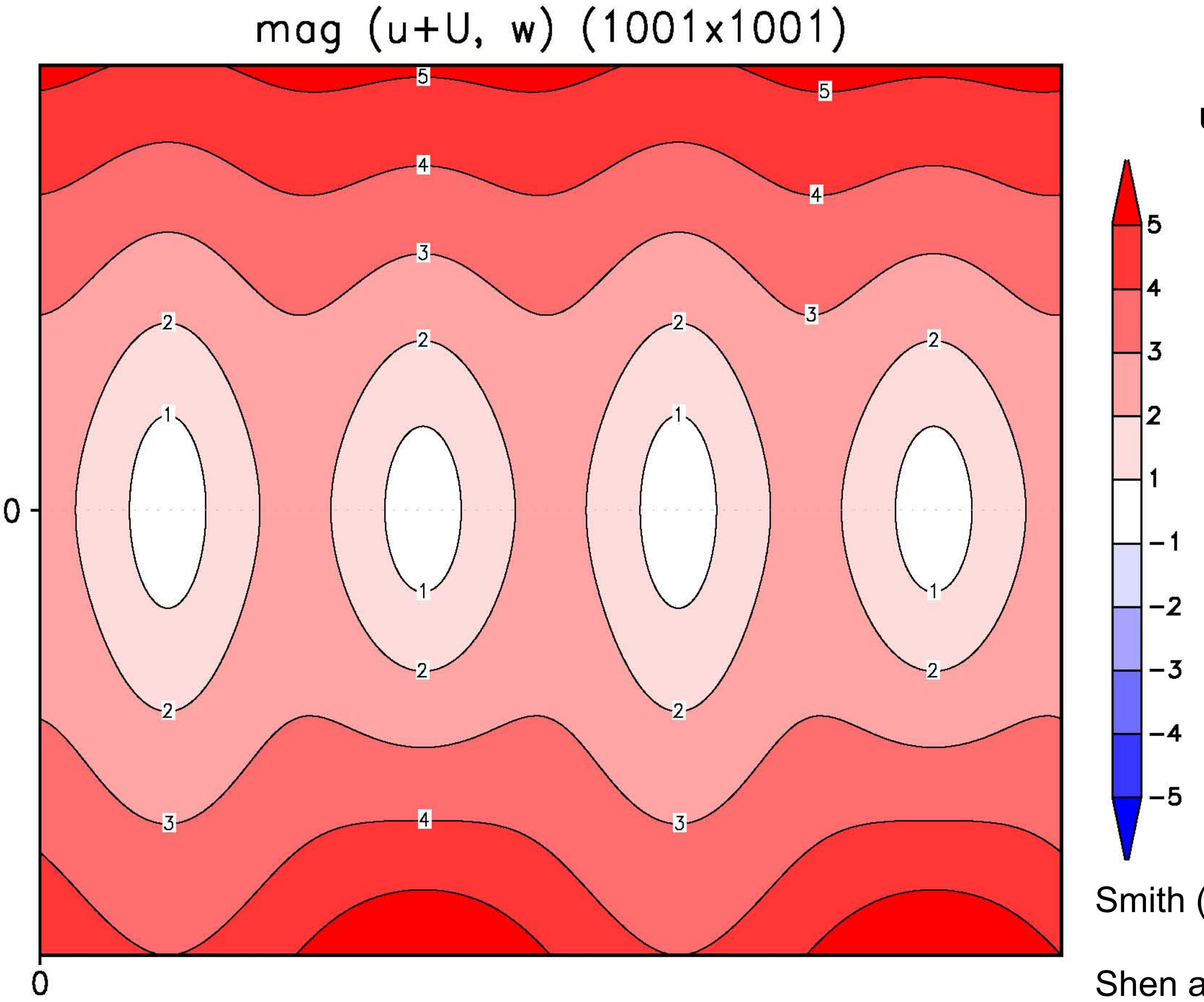
IMF9 - WWB



0.01~0.02

(~99%)

A Kelvin Cat eye's flow



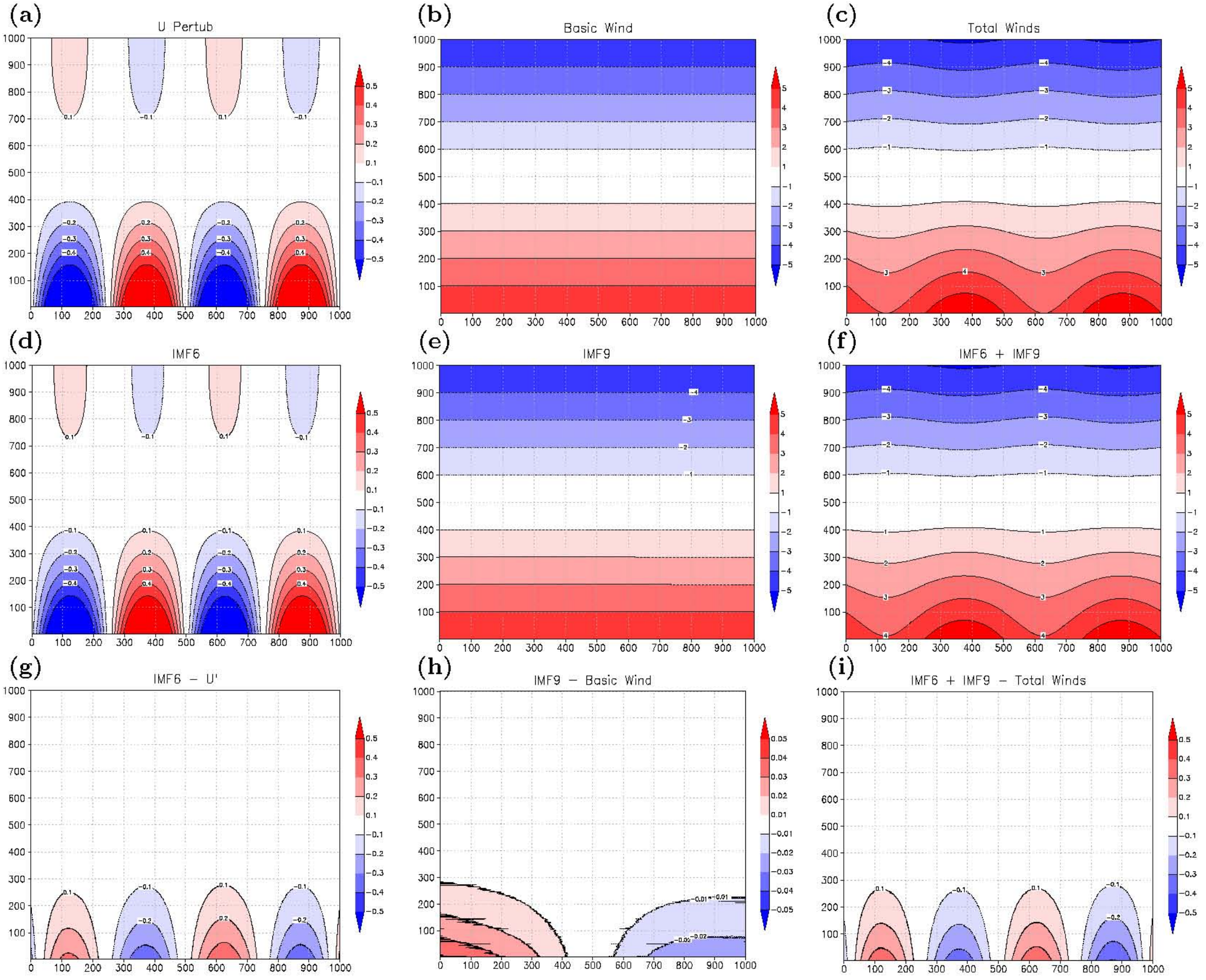
u+U and W

Smith (1986, JAS)

Shen and Lin (1999, JAS)

IMFs of the Kelvin Cat eye's flow

Analytical Solutions of a Kelvin Cat eye's flow (e.g., Smith 1986; Shen 1998)



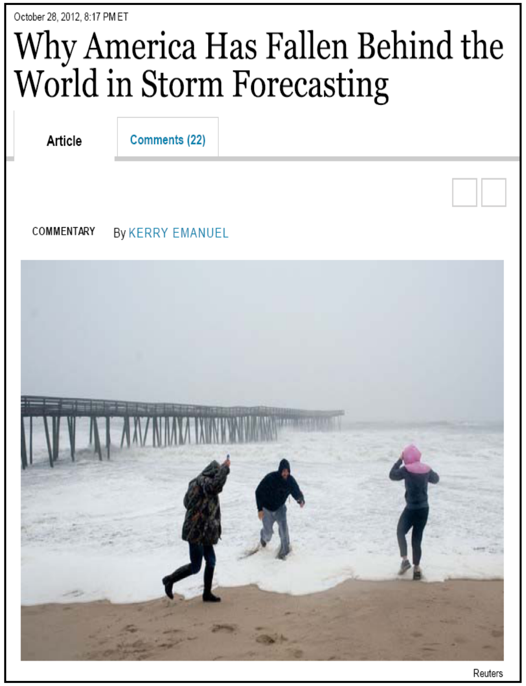
Analyzing Real-world Cases with the PEEMD

1. Hurricane Sandy (2014) and tropical waves (e.g., MRG and ER)
2. Hurricane Helene (2006), AEW and sheared flow.

Hurricane Sandy (2012)

The Wall Street Journal
October 28, 2012

AGU Geophysical Research Letter
September 19, 2013

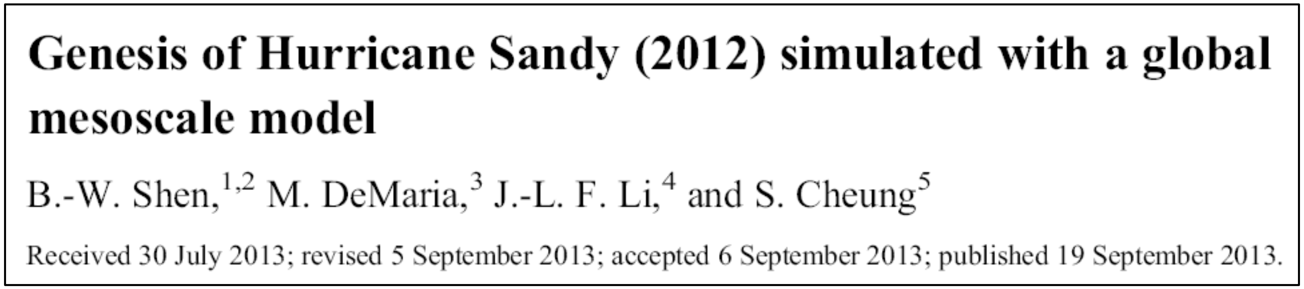


October 28, 2012, 8:17 PM ET

Why America Has Fallen Behind the World in Storm Forecasting

COMMENTARY By KERRY EMANUEL

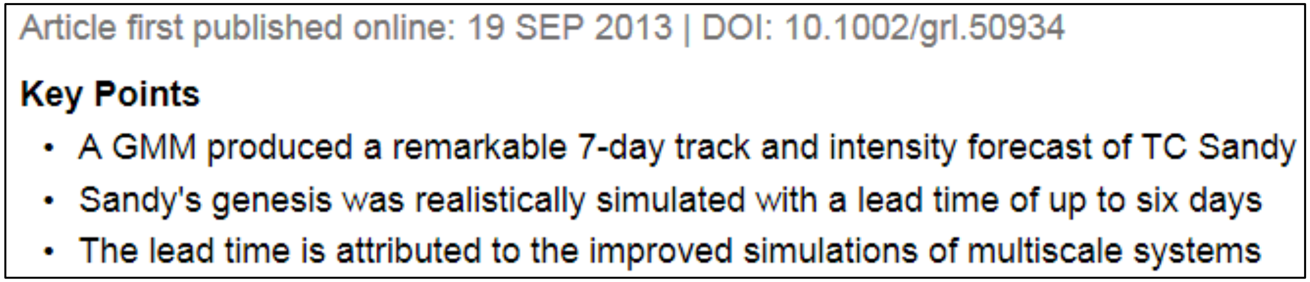
Reuters



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

- Simulations of Track and Intensity (1 slide)
- Simulations of Formation (as model verifications)
- Analysis of Tropical waves (2 slides)

10 Track Predictions of Hurricane Sandy

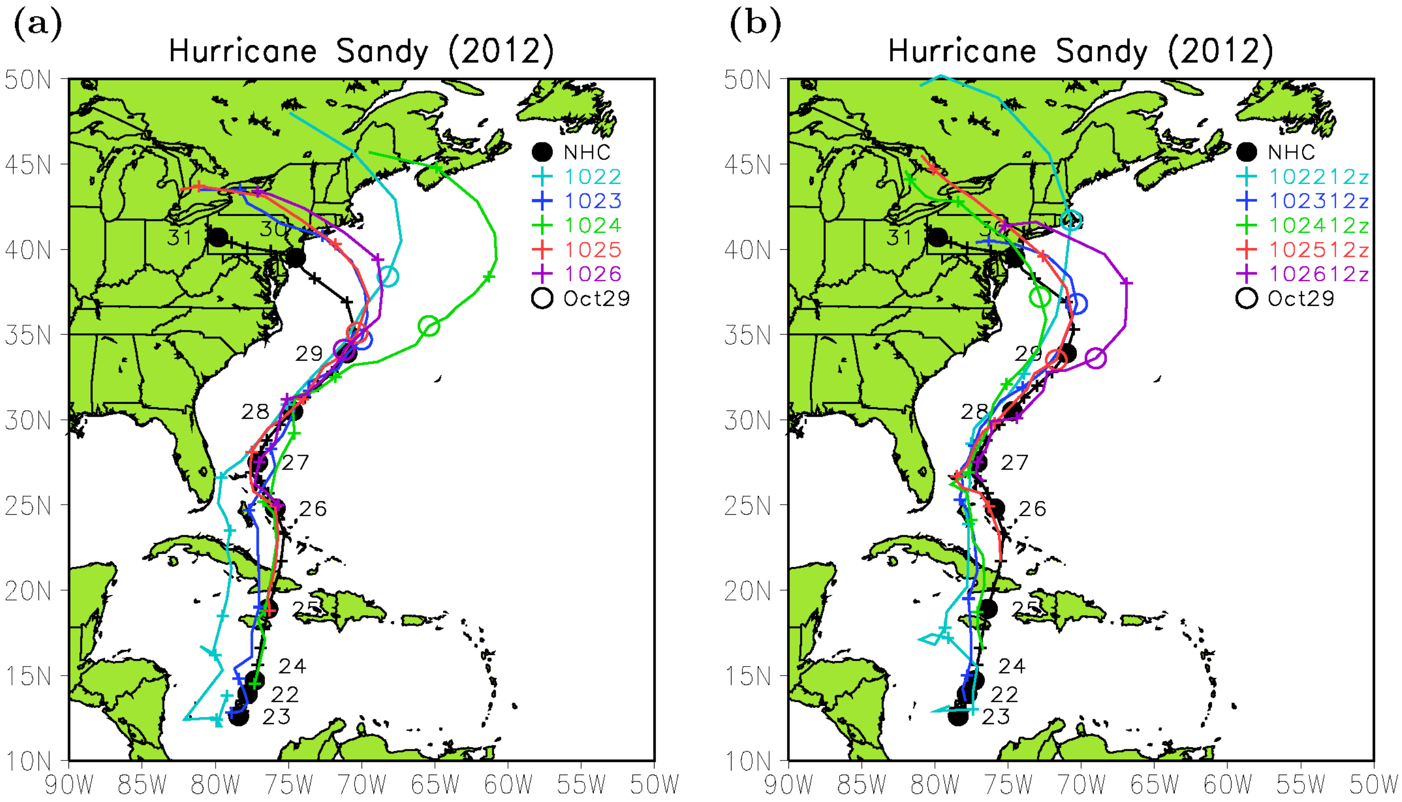


Figure 1: Ten consecutive 5-8 days track predictions of Hurricane Sandy (2012). Panels (a) and (b) show the results initialized at 00Z and 12Z on different days, respectively. Color lines represent model forecasts, while the black line indicates the best track. The light blue, blue, green, red and purple lines represent the forecasts starting from Oct. 22, 23, 24, 25 and 26, respectively. An open circle with the same color scheme indicates the predicted location of Sandy at 00Z Oct. 29 from the corresponding run. (Panel (a) is reproduced from the supplemental materials of Shen et al. 2013c).

Min SLPs and Max Surface Winds

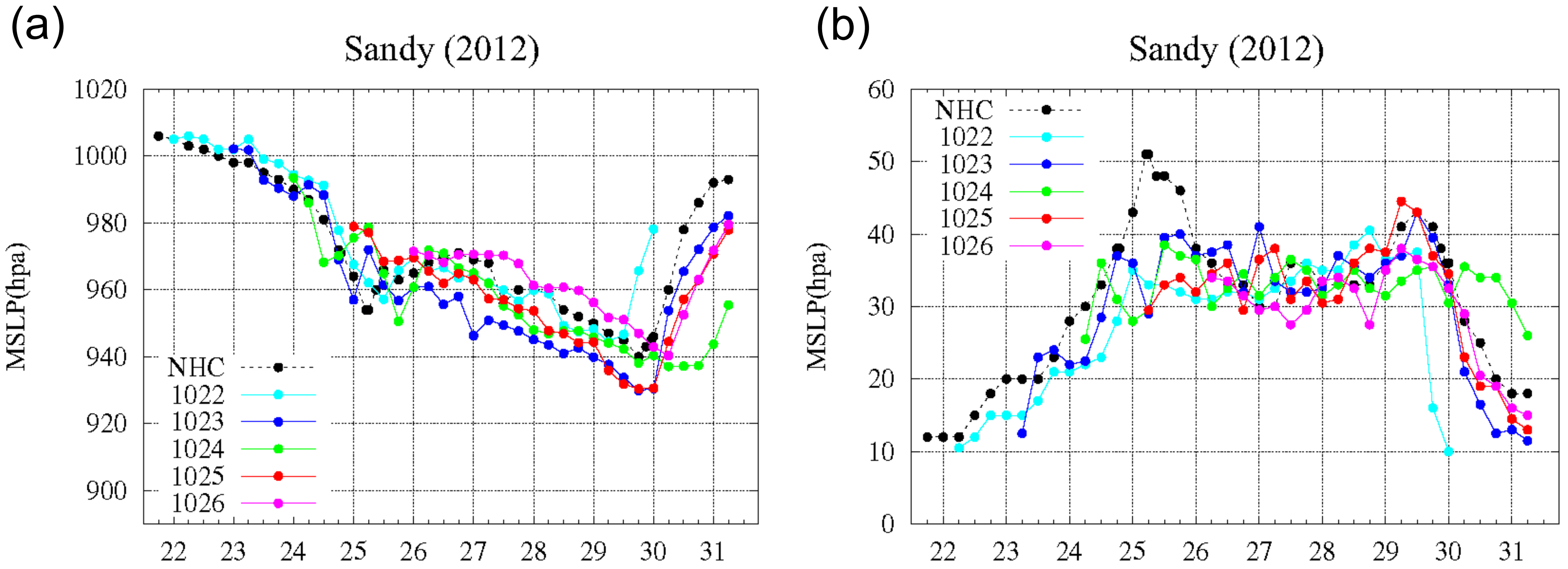


Figure 2: Five consecutive 5-8 days predictions of minimum sea level pressure (MSLP) (a) and 10m winds (b) for Hurricane Sandy (2012) initialized at 00Z on different days. Color lines represent model forecasts, while the black line indicates the intensity of the best track. The light blue, blue, green, red and purple lines represent the forecasts starting from Oct. 22, 23, 24, 25 and 26, respectively.

Track and Intensity after Genesis

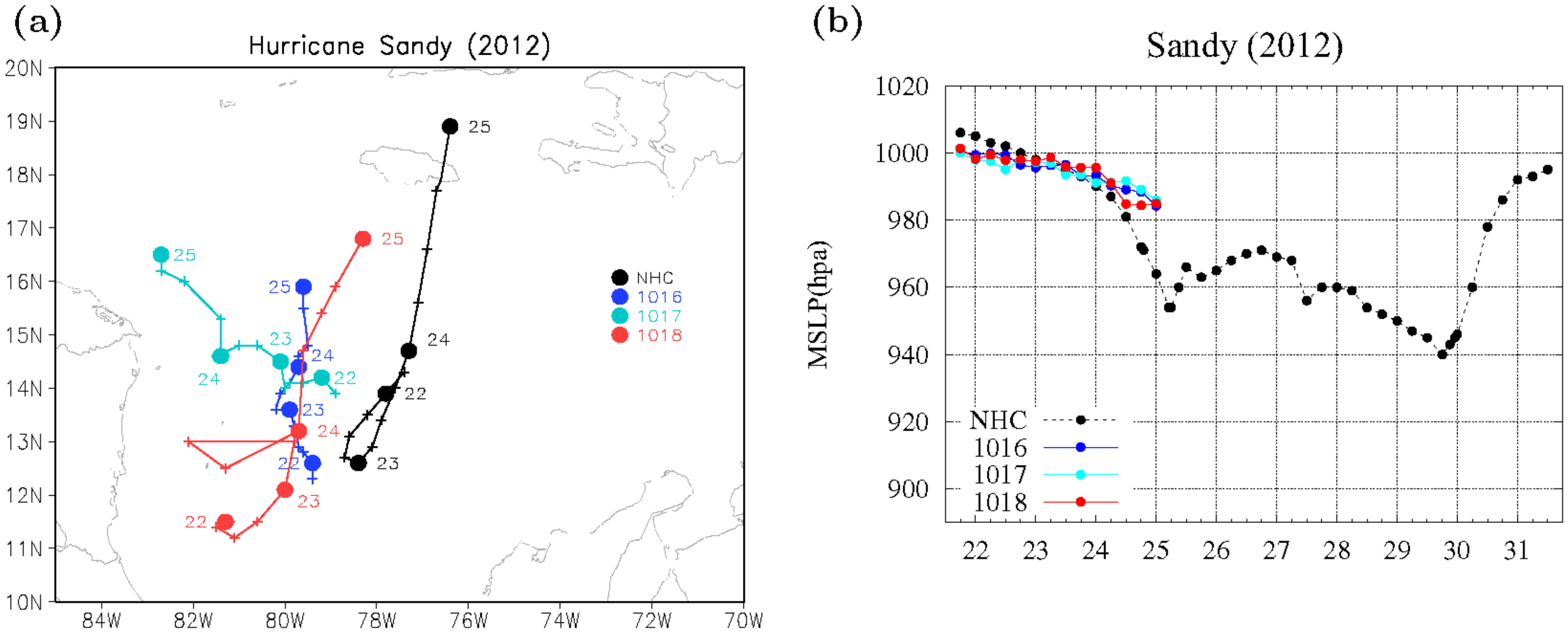


Figure 5: Genesis predictions of Hurricane Sandy in three runs initialized at 00Z Oct. 16-18, shown in blue, light blue, and red, correspondingly. The black line indicates the best track. Panel (a) shows the predicted locations of Sandy after its formation. Panel (b) shows the corresponding minimal sea level pressure from 21Z Oct. 21 to 00Z Oct. 25.

850-hPa Low-level Winds

the ERA-Interim reanalysis

model simulation

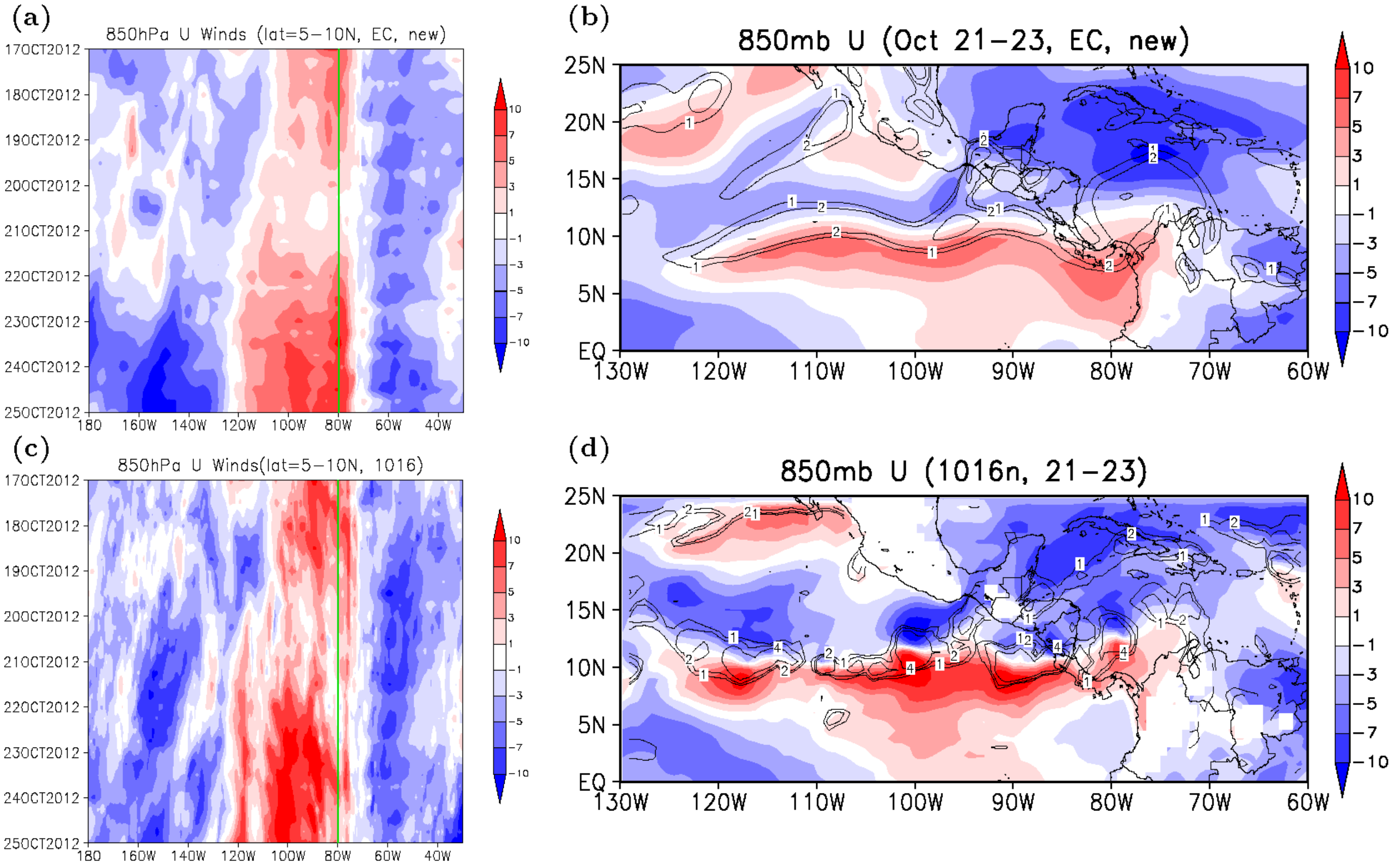


Figure 3: Left: Time-longitudinal diagrams of 850-hPa zonal winds averaged over latitudes 5° to 10°N during the period of Oct. 17 to 25, 2012. Right: Spatial distributions of 850-hPa zonal winds (shaded, m/s) and vorticity (with selected contour lines of 1x, 2x, 4x10^{-5} s^{-1}), which are averaged over a two-day period of 00Z Oct. 21-23. Top panels show ERA-Interim reanalysis while bottom panels show results from the 10/16 run. (Results from other runs can be found in Shen et al. 2013c)

200-hPa Upper-level Winds

the ERA-Interim reanalysis

model simulation

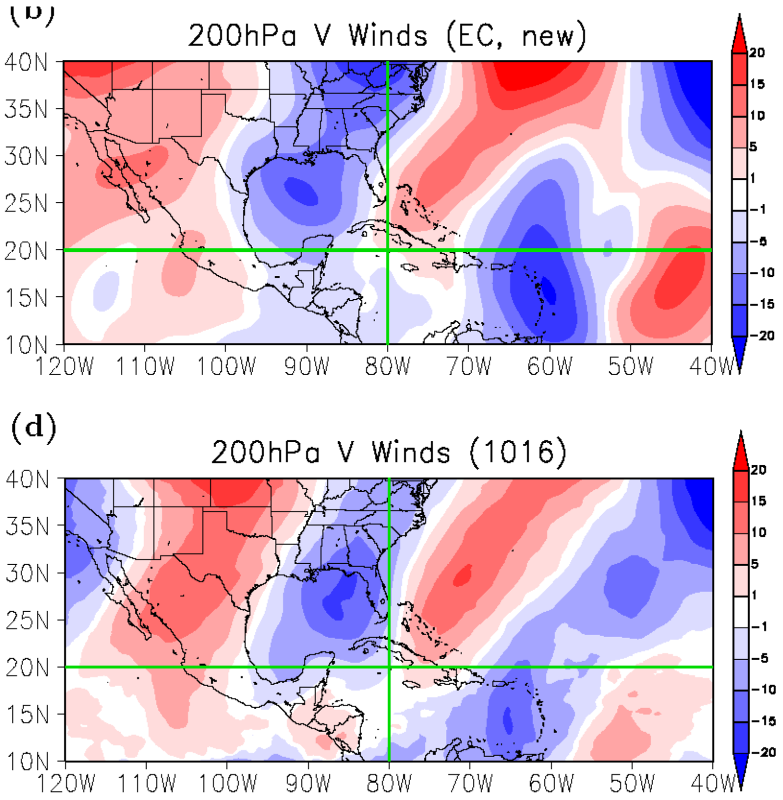
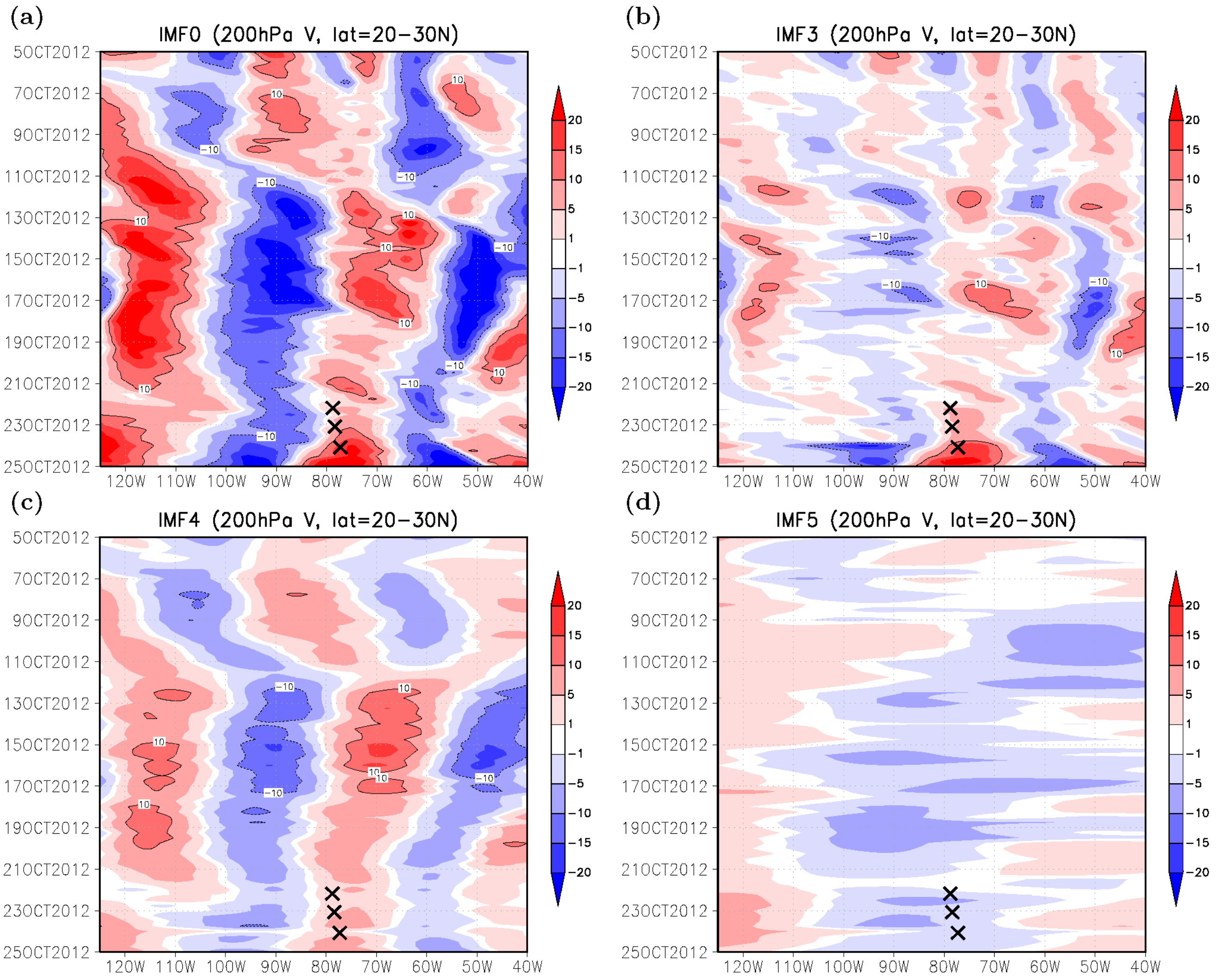


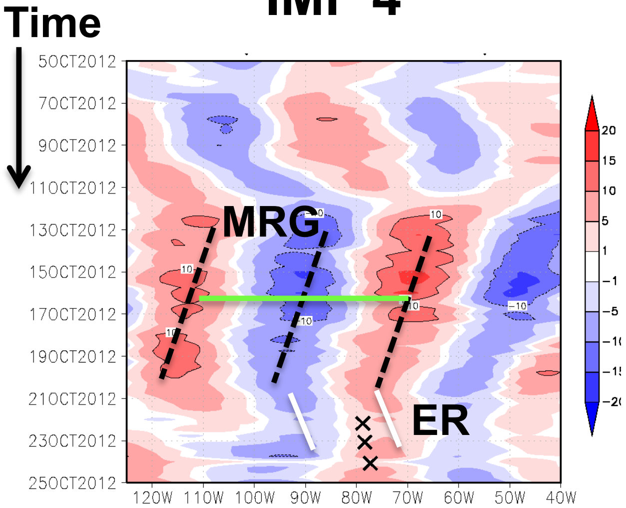
Figure: 200-hpa meridian winds (shaded, m/s) averaged over a two-day period of 00Z Oct. 21 to 23. Top panels show the ERA-Interim reanalysis while bottom panels display results from the 10/16 run. The horizontal (vertical) green reference line is along the latitude of 20^{o}N (the longitude of 80^{o}W). (See details in Shen et al. 2013c)

Decompositions of V winds with the PEEMD

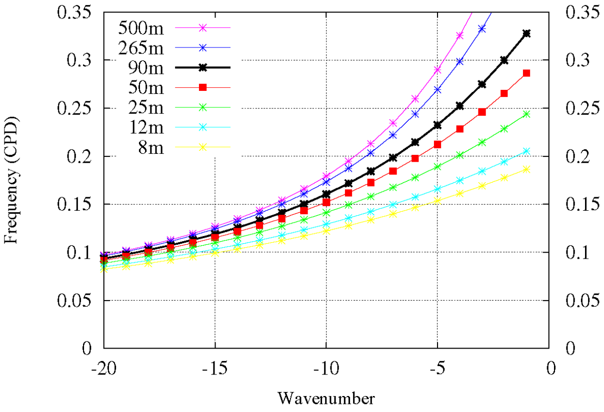
Time



Characteristics of Wave-like Disturbances (200-hPa V winds)

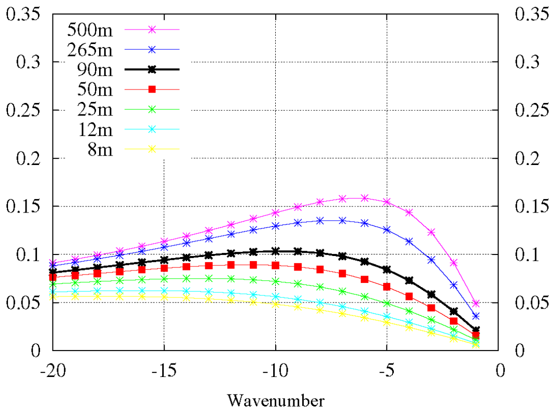


IMF 4



MRG Wave

$$\sigma = \frac{k\sqrt{gH_e}}{2}\left[1-\left(1+\frac{4\beta}{k^2\sqrt{gH_e}}\right)^{1/2}\right].$$



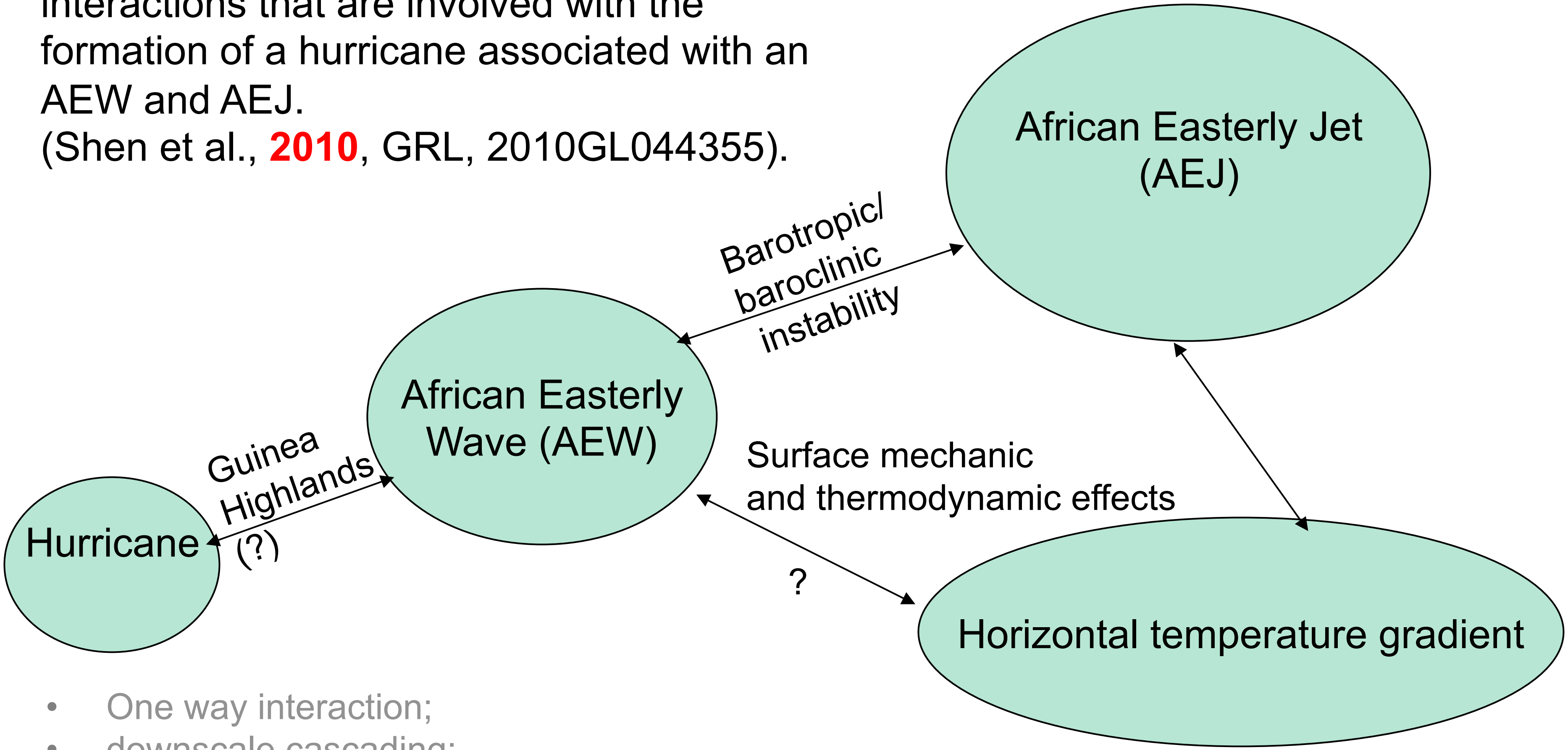
ER Wave

$$\sigma = \frac{-\beta k}{k^2+\beta(2n+1)/\sqrt{gH_e}}.$$

- A dispersion relation describes the relationship between the wavelength and period of a specific wave.
- An MRG wave is indicated by dashed lines in the left panel.
- An ER wave is indicated by white lines in the left panel.

Multiscale Interaction during Hurricane Formation

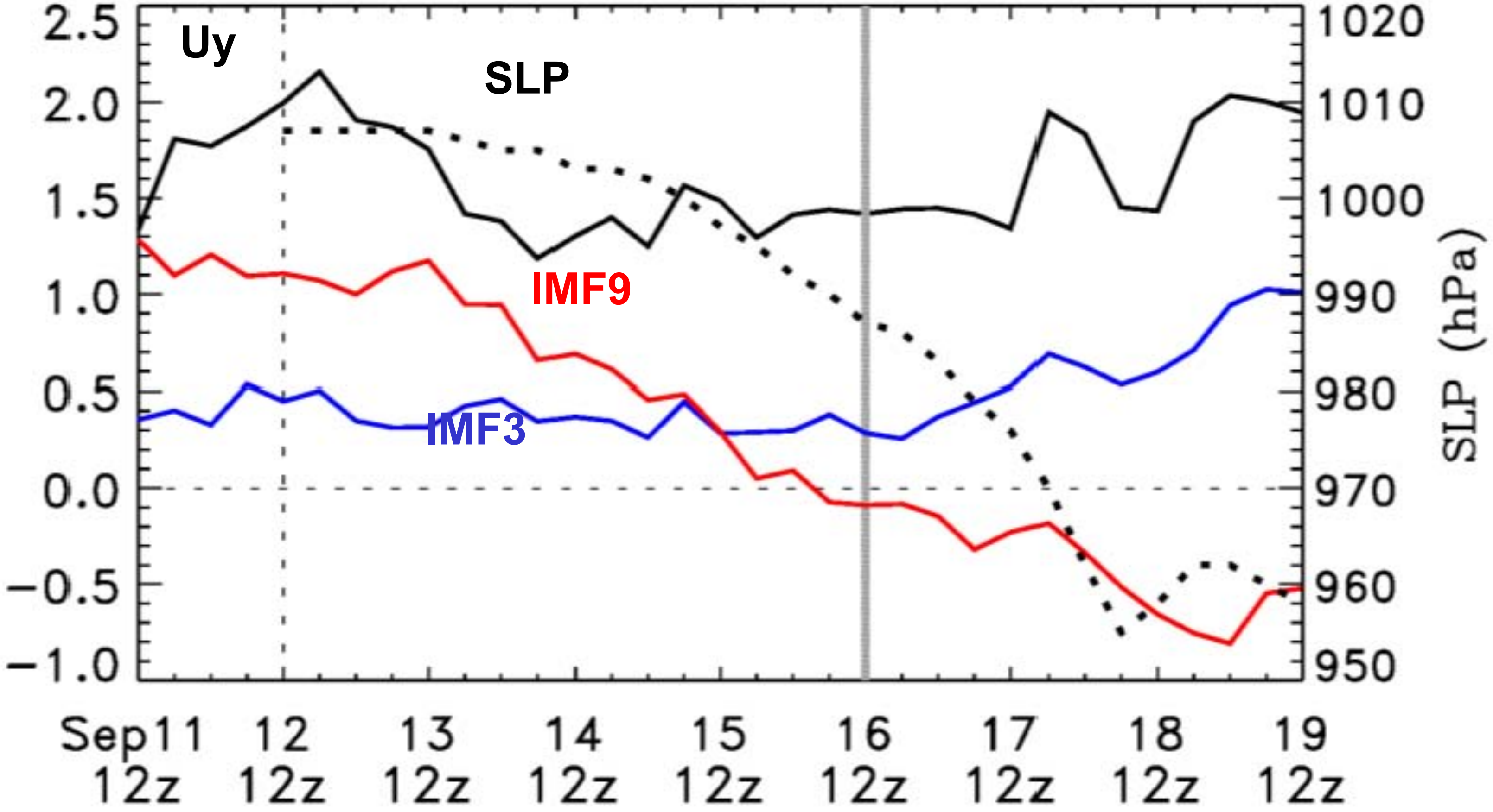
Figure S1. A schematic diagram showing the multiple processes and multi-scale interactions that are involved with the formation of a hurricane associated with an AEW and AEJ.
(Shen et al., **2010**, GRL, 2010GL044355).



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

Downscaling Process illustrated by the PEEMD

IMFs associated with Helene (2006)



Decompose U; Calculate Uy in each of the IMFs

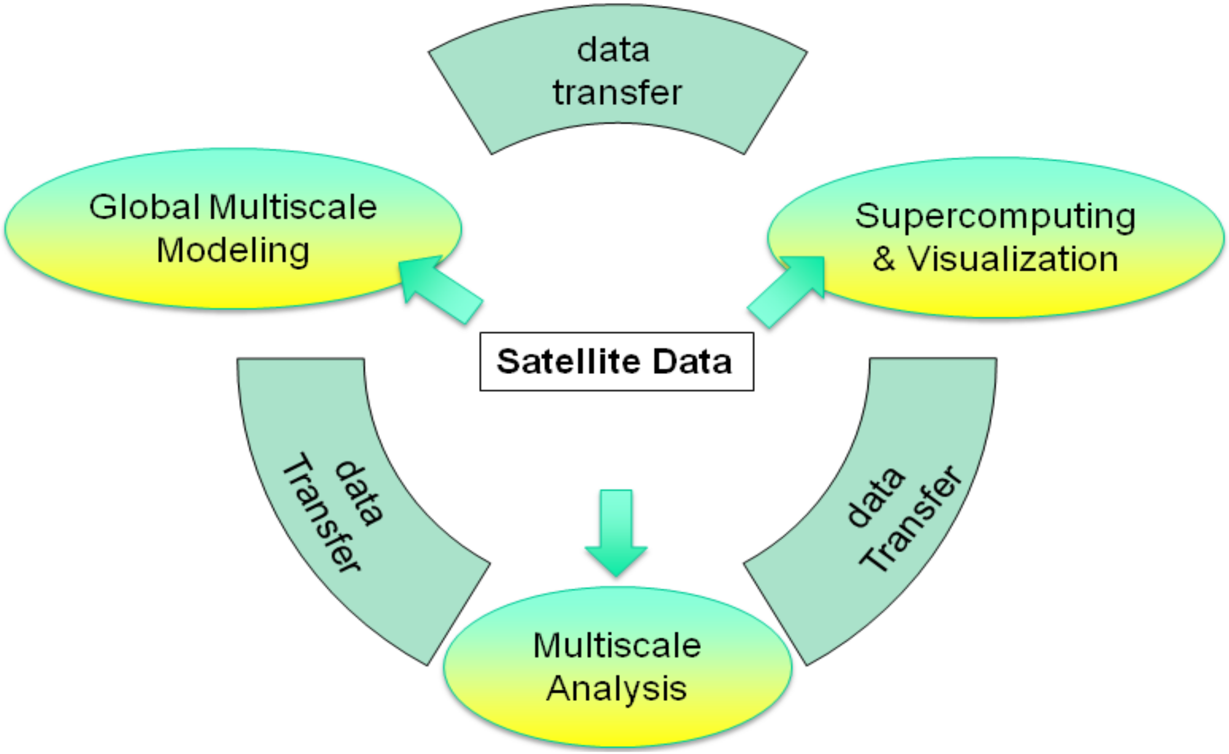
Multiscale Analysis of 10-year Data

Table 1. Named (numbered) storms tracked by NHC that developed in the studied tropical Atlantic domain (longitude: 0—30^0 N and latitude:70^{0}W—15^{0}W) during July-October in 2005-2014 (2013 for now), listed according to the numbering system of NHC. TDs/TSs are storms that have been classified as Tropical Depressions or/Tropical Storms but never intensified into hurricane.

Year	No. of hurricanes	NHC track# of the hurricanes	No. of TDs/TSs	NHC track# of the TDs/TSs
2005	2	14, 17	4	10, 13, 19, 26
2006	2	07, 09	1	05
2007	2	04, 12	2	08, 14
2008	2	02, 09	2	10, 14
2009	1	03	2	02, 10
2010	5	06, 07, 11, 12, 14	3	04, 08, 09
2011	4	09, 12, 14, 17	3	05, 10, 11
2012	2	12, 14	3	06, 10, 15
2013	1	09	3	04, 05, 07

EC Data,
Other types of data?

Summary

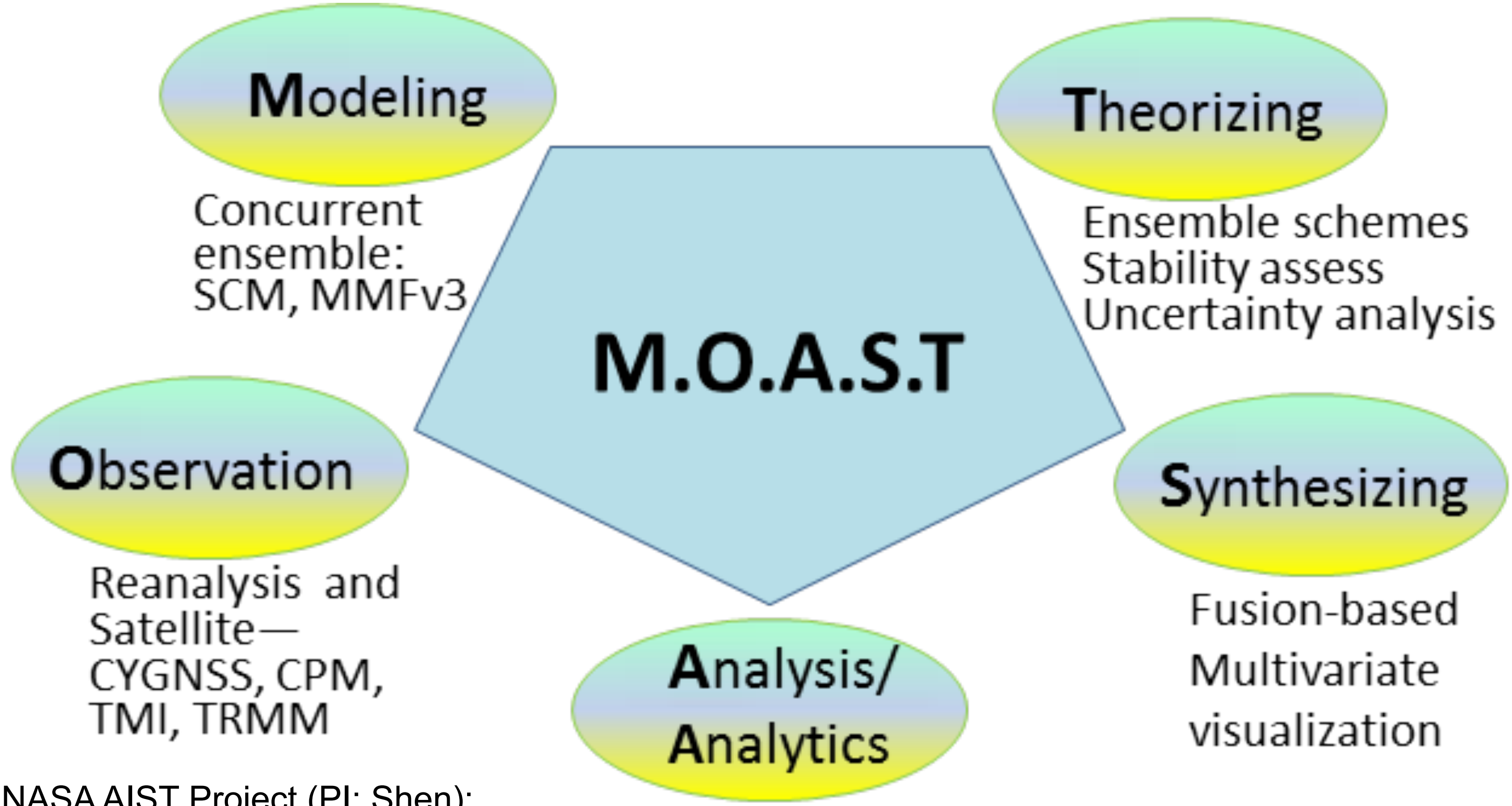


1. to what extent can large-scale flows determine the timing and location of TC genesis? MAP/HHT
2. to what extent can resolved small-scale processes impact solutions stability (or predictability)? MAP/SAT

Summary

- From a modeling perspective, we have published several papers with the high-resolution global model, showing a potential for improving hurricane predictions (i.e., extending the lead time of hurricane predictions)? Examples include Sandy and Helene.
- From a perspective of chaos (nonlinear) dynamics, we have published papers (Shen 2014a,b) to show that (1) chaos can be suppressed via negative nonlinear feedback in a high order Lorenz model; (2) improved degree of nonlinearity can improve simulations.
- From a perspective of hurricane dynamics, we proposed a conceptual model with triple-scale processes to examine the impact of downscaling and upscaling processes on hurricane simulations.
- To examine the scale interactions, we have developed the highly scalable PEEMD and SAT to (1) perform multiscale analysis; (2) to examine the impact of resolved small-scale processes on solution's stability. Preliminary results support our hypothetical model.

AIST14 (pending)



Concurrent ensemble: SCM, MMFv3

Ensemble schemes
Stability assess
Uncertainty analysis

Reanalysis and Satellite—CYGNSS, CPM, TMI, TRMM

Fusion-based
Multivariate
visualization

CAMVis
MAP/PEEMD
MAP/SAT
Uncertain analysis

NASA AIST Project (PI: Shen):
$957.8K, 05/2015-04/2017 (pending)
Integration of Concurrent Ensemble Hierarchical Modeling and Fusion-Based Multivariate Data Visualization into the NASA CAMVis for Improving Climate Simulations

Summary

- To answer 1, Helene and AEW
- PEEMD
- Chaos study, SAT
- Sandy
- We obtained remarkable 7-day track and intensity forecast of TC Sandy and 6-day prediction of Sandy’s genesis.
- The lead time is attributed to the improved simulations of multiscale systems, including the interaction of an easterly wave (EW) and westerly wind belt (WWB) and impact of tropical waves associated with a Madden-Julian Oscillation (MJO).
- PEEMD, parallel performance,
- Wavelength analysis,
- Trend mode analysis
- Extrema analysis

Questions or Comments? bshen@mail.sdsu.edu

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)

Multiscale Processes associated with Sandy

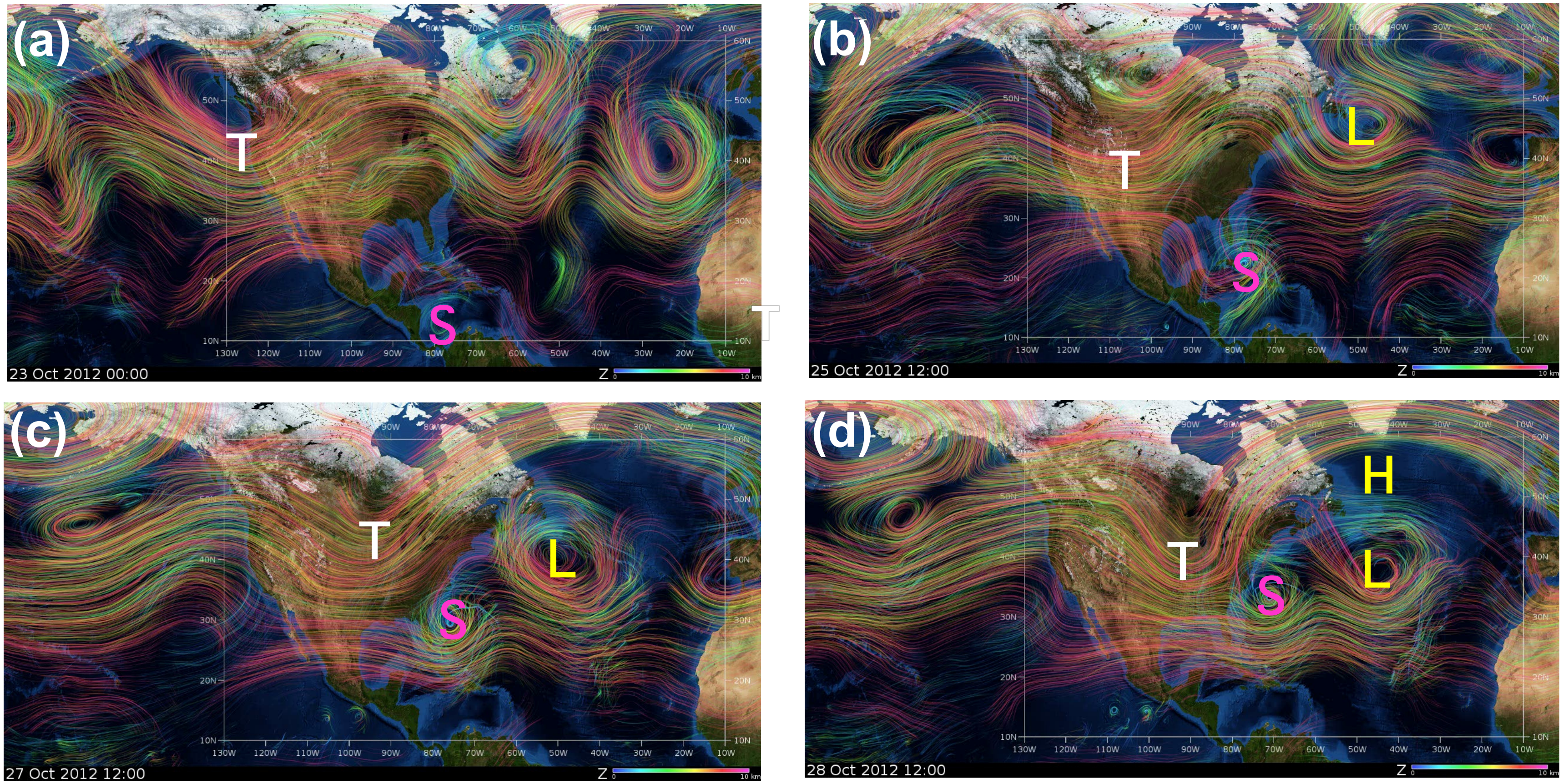


Figure 7: 4D visualizations of Hurricane Sandy (2012) at 00Z Oct. 23 (a), 12Z Oct. 25 (b), 12Z Oct. 27 (c), and 12Z Oct. 28 (d). During the period, Sandy (labeled in a pink ‘S’) moved northward under the influence of the sub-tropical middle- and upper-level trough (to Sandy’s northwest) (a), interacted with the trough that was deepening (b), increased its spatial extent (c), and encountered a pair of high-and-low blocking pattern over the North Atlantic, which prevent Sandy moving eastward further (d).

Decompositions of U winds with the PEEMD

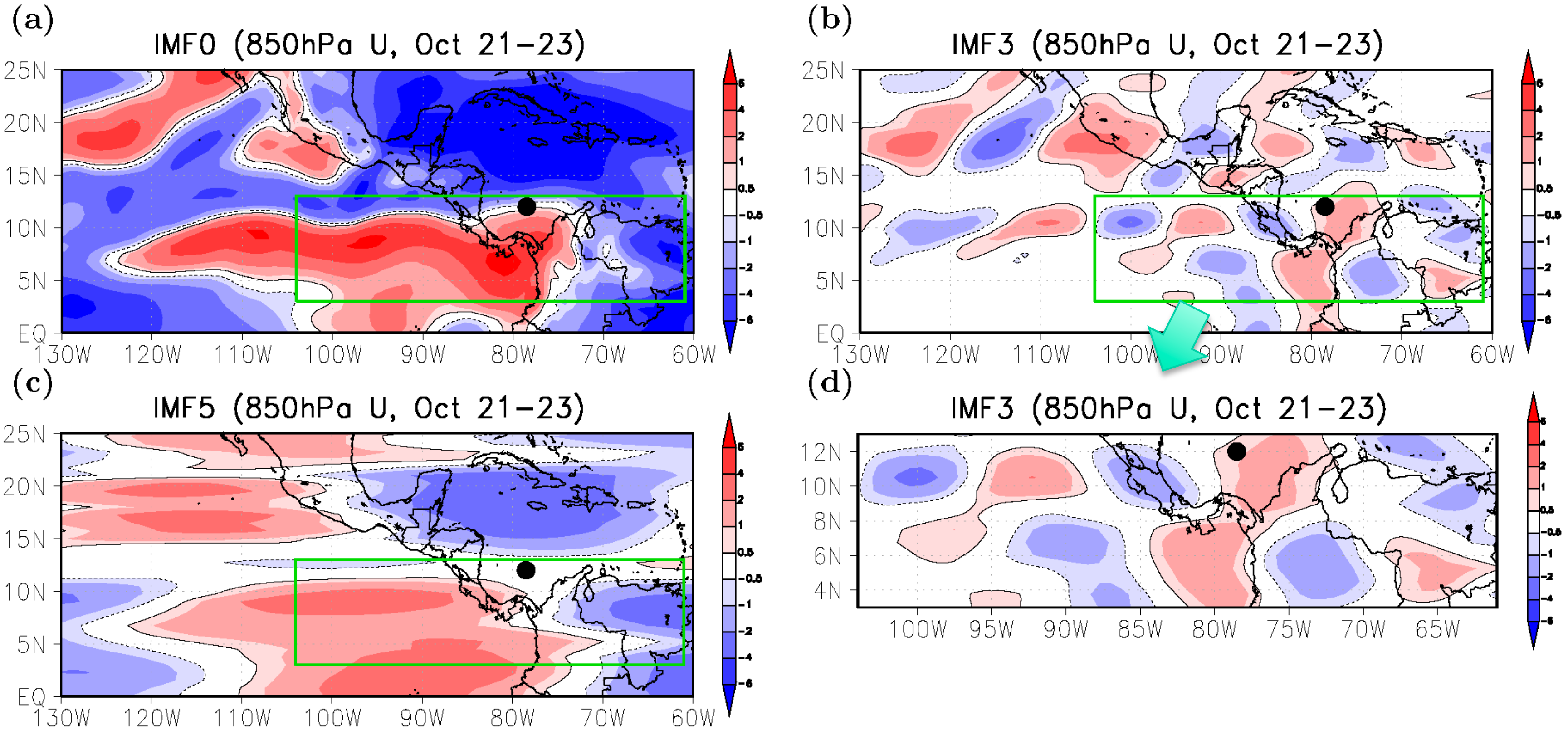


Figure 6: Decompositions of the low-level zonal winds from the ERA-Interim reanalysis data. (a) 850-hPa zonal winds averaged over a two-day period of 00Z Oct. 21-23, 2012. (b, c) The 3rd and 5th IMFs extracted from the zonal wind fields, respectively. (d) A zoomed-in view of IMF3 in a green box. The black dot at (12°N, 78.5°W) indicates the vortex center of the two-day averaged 850-hPa winds.

Visualization of Vortex Interaction

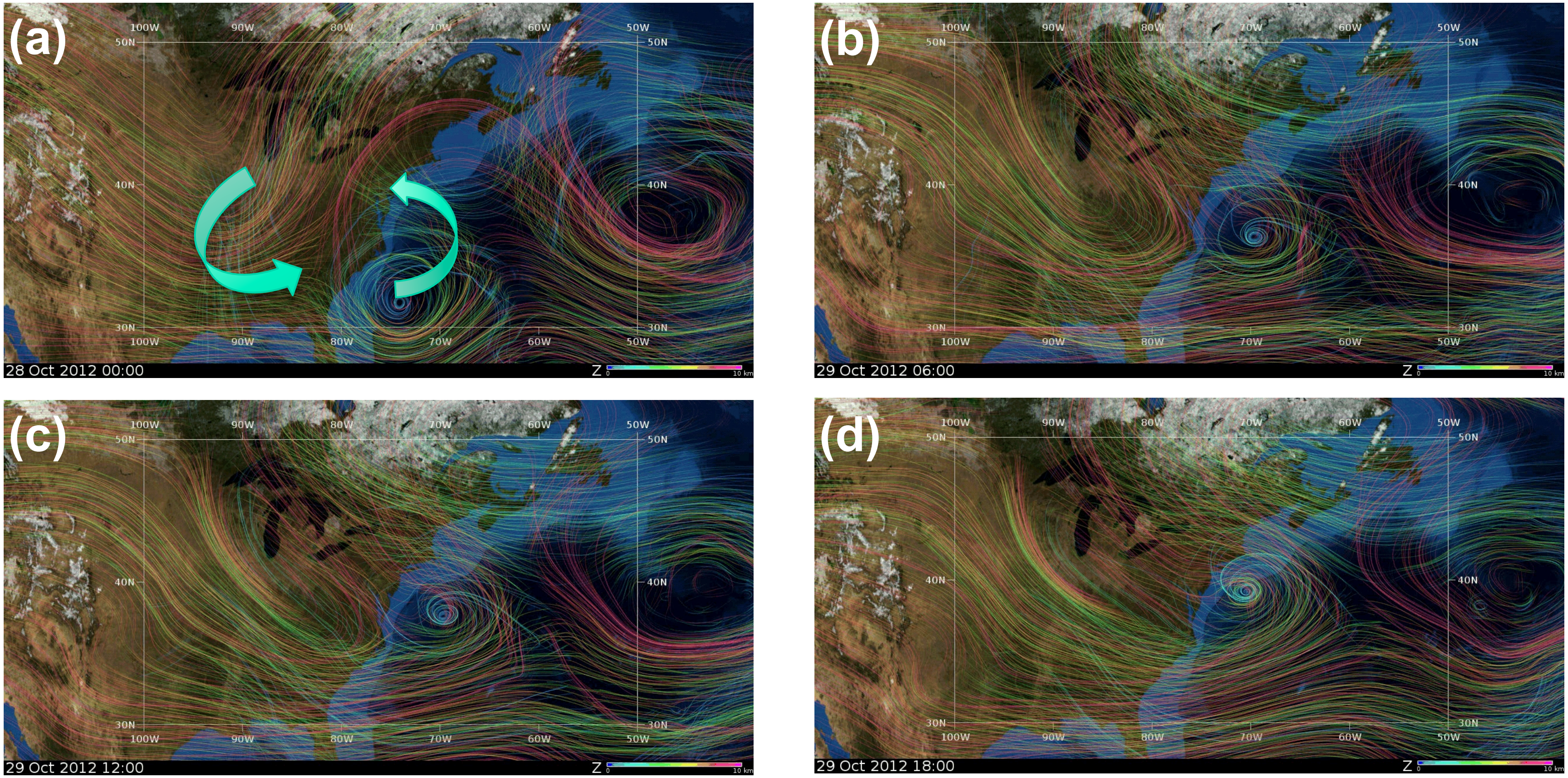


Figure 8: 4D visualizations of the second Sandy-trough interactions prior to its landfall, which are validated at 00Z Oct. 28 (a), 06Z Oct. 29 (b), 12Z Oct. 29 (c), and 18Z Oct. 29, 2012 (d). During this time period, two cyclonic vortices (with positive vorticities), which are associated with Sandy and the trough, rotated cyclonically about each other and eventually merged together. This may be viewed as Fujiwhara effect (e.g., Sobel 2012), Fujiwhara interaction, or binary interaction.

- Among Decadal Survey Missions, “*Extreme Event Warning”* and *“Climate Projections”* have been identified as top-priority scenarios by the advanced data processing group at the ESTO AIST PI workshop (AIST, 2010). In the coming years, *the Global Precipitation Measurement (GPM), the Cyclone Global Navigation Satellite System* (*CYGNSS*) *will provide measured wind fields and precipitation fields for improving the understanding of physical processes for the genesis and intensification of hurricanes.* Our research team has contributed to this objective by developing the NASA Coupled Advanced global multiscale Modeling (Shen et al., 2006a,b; Tao et al., 2008, 2009) and Visualization system (CAMVis) and integrating it with the Multiscale Analysis Packages (MAP) and satellite data modules (e.g., for TRMM data). We have successfully demonstrated that an integrated system, with the capability in revealing sophisticated hierarchical multiscale processes, can improve our understanding of the predictability of mesoscale processes, such as tropical cyclones (TCs) (Shen et al., 2010a,b; 2011; 2012a; 2013a-c). Selected cases in our recent studies include the relationship between (i) TC Nargis (2008) and an Equatorial Rossby (ER) wave; (ii) Hurricane Helene (2006) and an intensifying African Easterly Wave (AEW); (iii) Twin TCs (2002) and a mixed Rossby-gravity wave (MRG) during an active phase of the Madden Julian Oscillation (MJO; Madden and Julian, 1971); (vi) Hurricane Sandy (2012) and upper-level tropical waves associated with an MJO (e.g., Blake et al., 2013; Shen et al., 2013c).

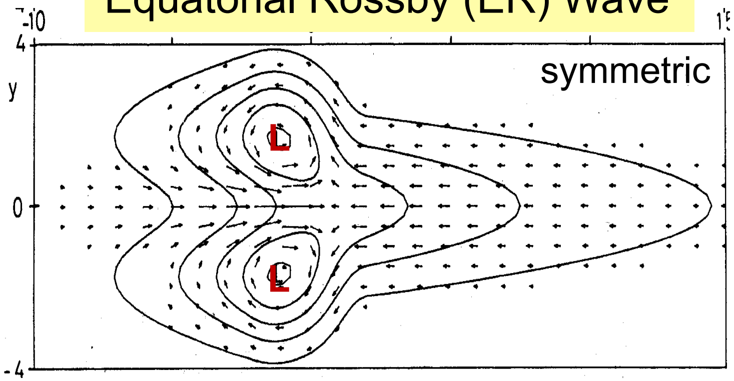
- The MAP includes a parallel version of the ensemble empirical model decomposition (EEMD, Wu and Huang, 2009; Wu et al., 2009) and the stability analysis tool (SAT) with a calculation of the ensemble Lyapunov Exponent (eLE, e.g., Shen et al., 2014a). In this study, we discuss the performance of the parallel ensemble empirical mode decomposition (PEEMD) in the analysis of tropical waves that are associated with tropical cyclone (TC) formation. To efficiently analyze high-resolution, global, multiple-dimensional data sets, we first implement multi-level parallelism into the EEMD and obtain a parallel speedup of 720 using 200 eight-core processors. We then apply the PEEMD to extract the intrinsic mode functions (IMFs) from preselected data sets that represent (1) idealized tropical waves and (2) large-scale environmental flows associated with Hurricane Sandy (2012). Results indicate that the PEEMD is efficient and effective in revealing the major wave characteristics of the data, such as wavelengths and periods, by sifting out the dominant (wave) components. This approach has a potential for hurricane climate study by examining the statistical relationship between tropical waves and TC formation. As of July 2014, the PEEMD can scale up to 5000 CPUs using a high resolution MRG wave case study with 1000x1000 grid points, suggesting that it can efficiently process high-resolution global data at a resolution of 0.25 degrees or higher. It is being applied to perform tropical wave analysis for multi-year data.

Tropical Waves and TC Formation

Equatorial Rossby (ER) Wave

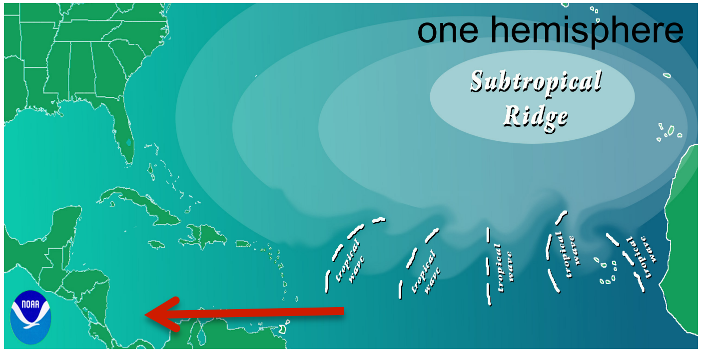
TC Nargis (Shen et al., 2010a)

EQ



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

African easterly waves (AEWs)



Helene (Shen et al., 2010b)

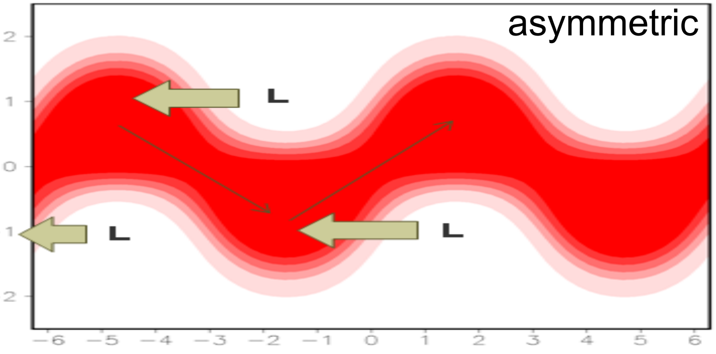
LAT:5o

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

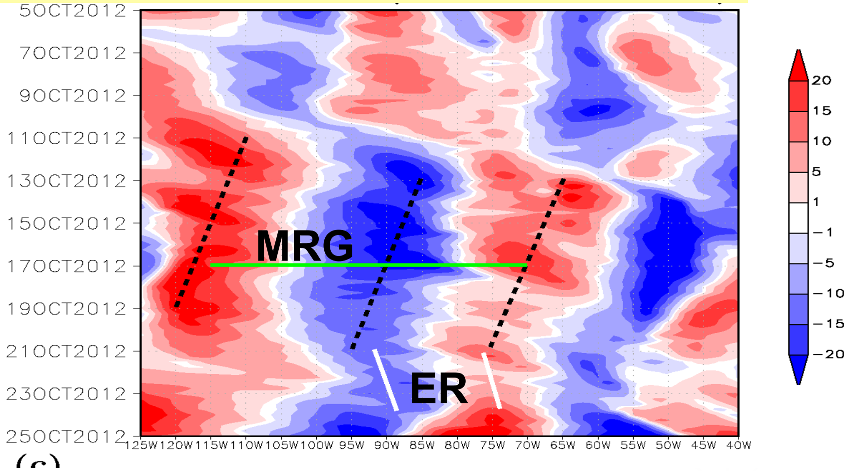
Mixed Rossby Gravity (MRG) Wave

Twin TC (Shen et al., 2012)

EQ



Sandy and Equatorial Tropical Waves



to what extent can large-scale flows determine the timing and location of TC genesis?

Scientific Goals

- Different scale flows may have different intrinsic predictability (or "persistence");
- Larger-scale flows are more predictable (in general), so it may provide determinism on the simulations of smaller-scale flows;
- Small-scale moist processes are believed to be more chaotic, so it may pose uncertainties during the numerical integration;

1. To what extent can large-scale flows determine the timing and location of TC genesis;
2. To what extent can small-scale flows resolved by increased resolution have significant (negative or positive) feedback on the simulations of TC genesis;
3. If and how realistically can a high-resolution global model depict those processes.

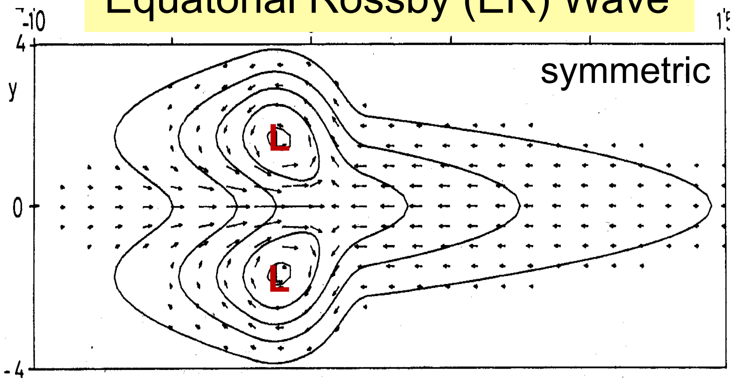
- To address (1), we need tools to detect and analyze wave-like disturbances, such as spectral analysis method or HHT/EEMD methods;
- To address (2), we need to understand the impact of small-scale processes on solution's stability, which requires stability analysis tools (SAT) to calculate nonlinear growth rate (Lyapunov exponent);
- To address (3), we will need an integrated system, e.g., CAMVis-MAP.

Tropical Waves and TC Formation

Equatorial Rossby (ER) Wave

TC Nargis (Shen et al., 2010a)

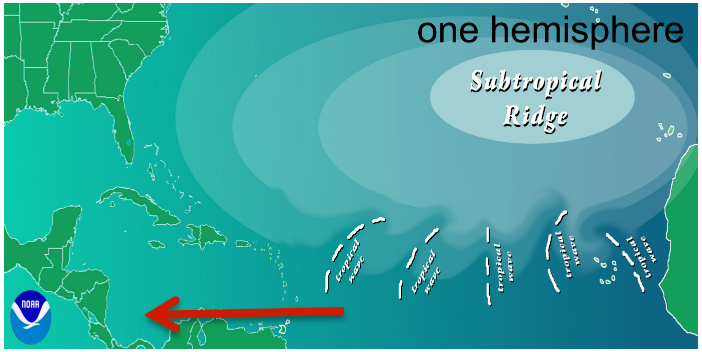
EQ



symmetric

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

African easterly waves (AEWs)



one hemisphere

Helene (Shen et al., 2010b)

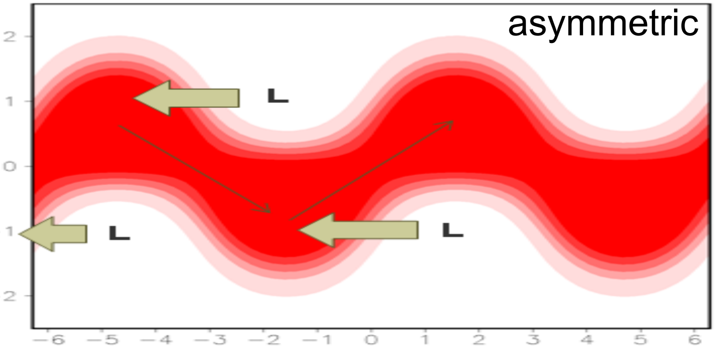
LAT:5°

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

Mixed Rossby Gravity (MRG) Wave

Twin TC (Shen et al., 2012)

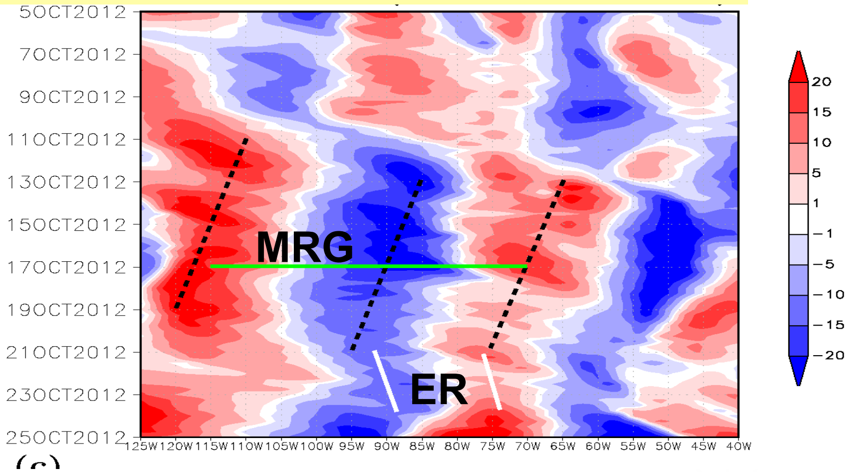
EQ



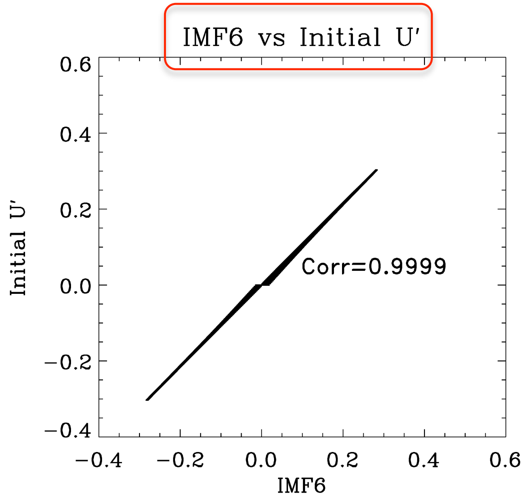
asymmetric

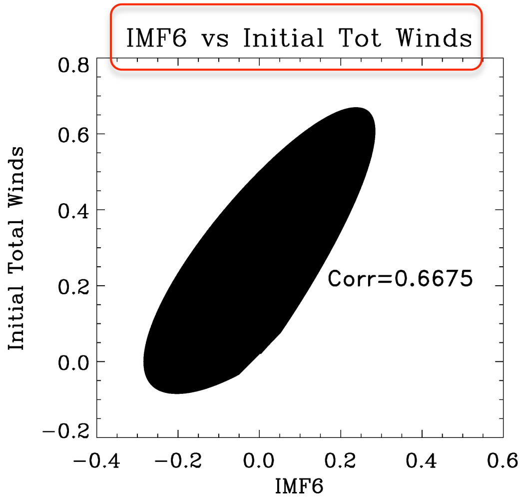
to what extent can large-scale flows determine the timing and location of TC genesis?

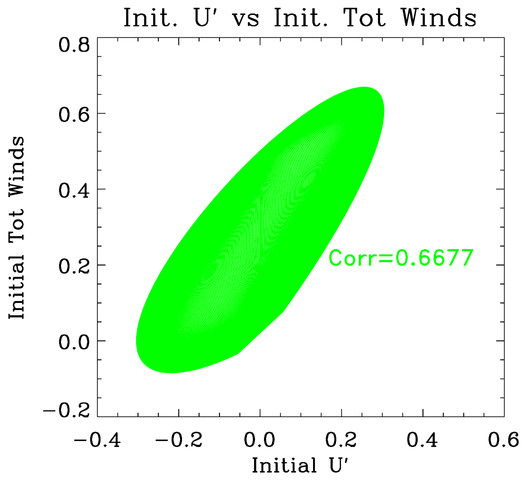
Sandy and Equatorial Tropical Waves

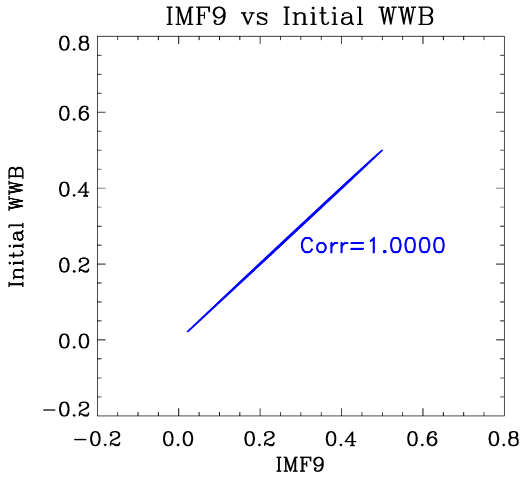


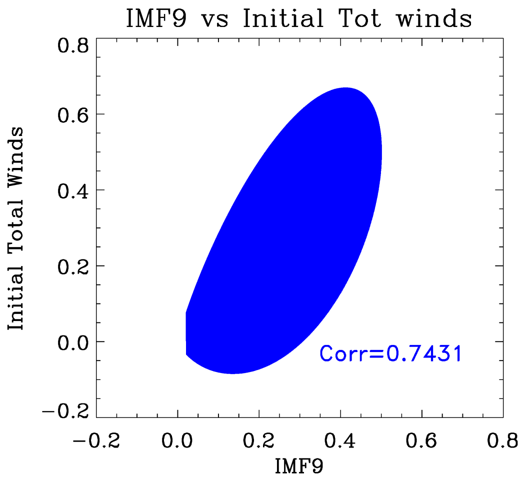
Correlation and Scatter Plots

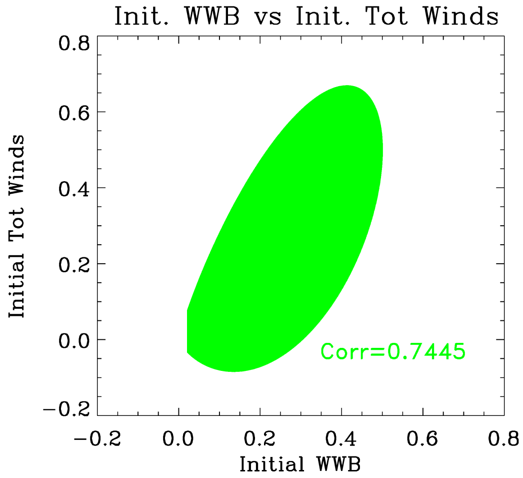

IMF6 vs Initial U′


IMF6 vs Initial Tot Winds


Init. U′ vs Init. Tot Winds


IMF9 vs Initial WWB


IMF9 vs Initial Tot winds


Init. WWB vs Init. Tot Winds

Ensemble EMD (EEMD): Why?

- Mode mixing is defined as any IMF consisting of oscillations of dramatically disparate scales; Mode mixing is a consequence of signal intermittency; it is argued that the time-varying extrema sampling rate is the essential reason of mode mixing (Yang et al., 2009). To overcome the issues with mode mixing in the EMD, the ensemble EMD was proposed (Wu and Huang, 2009).
- Ensemble EMD
  - STEP 1: add a noise series to the targeted data
  - STEP 2: decompose the data with added noise into IMFs
  - STEP 3: repeat STEP 1 and STEP 2 again and again, but with different noise series each time
  - STEP 4: obtain the (ensemble) means of corresponding IMFs of the decompositions as the final result
- Effects
  - In the mean IMFs, the added noise canceled with each other
  - The mean IMFs stays within the natural filter period windows (significantly reducing the chance of scale mixing and preserving dyadic property)

200-hPa Upper-level Winds

the ERA-Interim reanalysis

model simulation

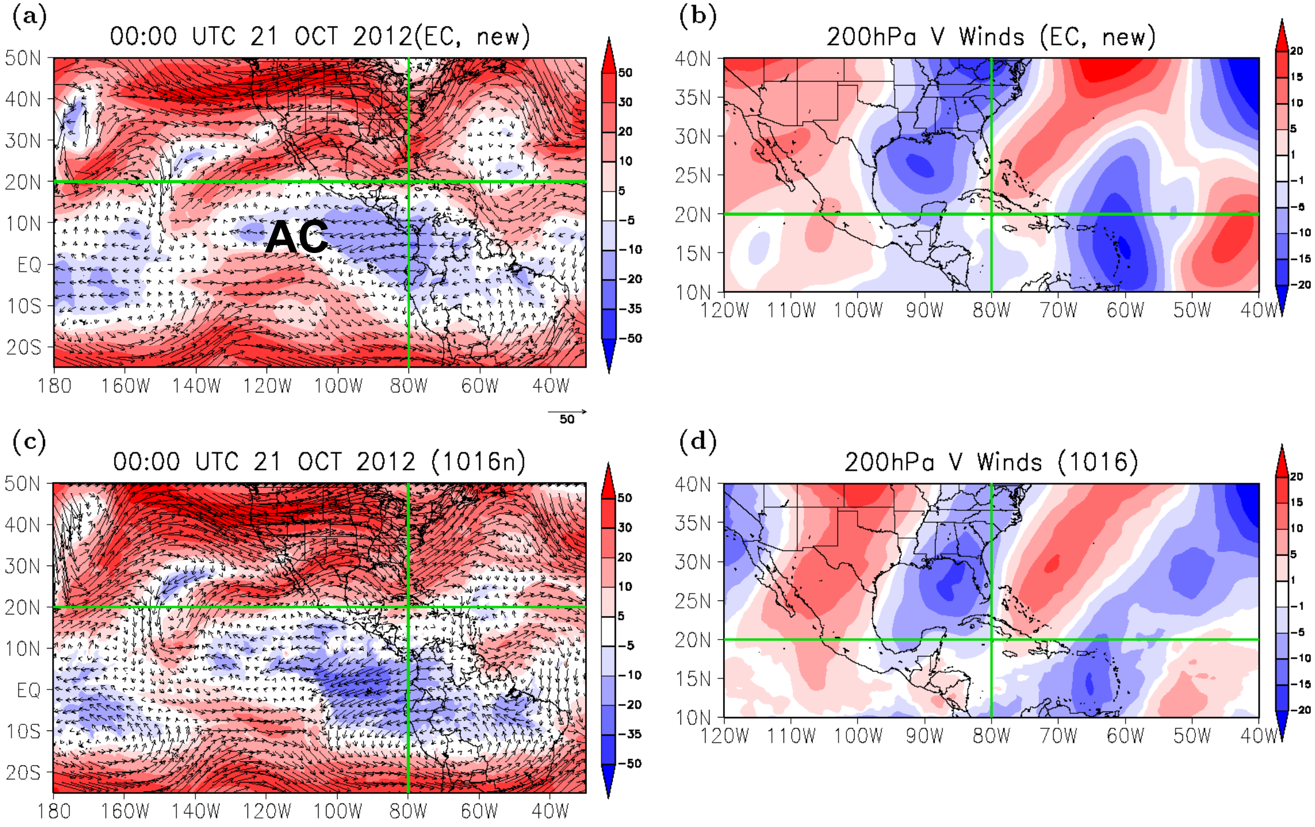
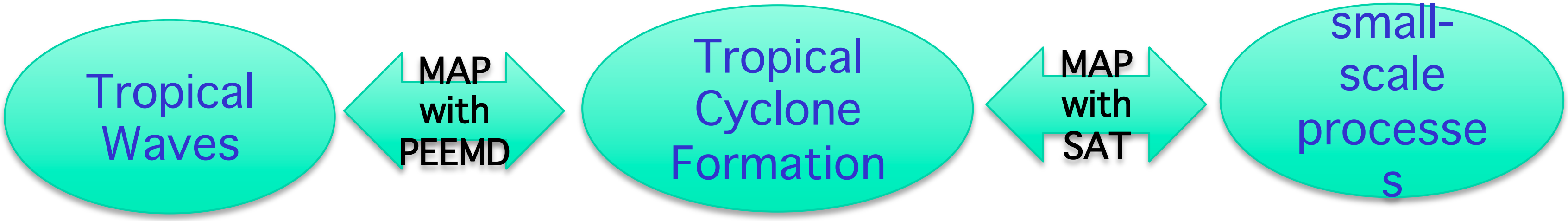


Figure 4: Left: 200-hPa wind vectors and zonal winds (shaded, m/s) at 00Z Oct. 21 2012. Right: 200-hpa meridian winds (shaded, m/s) averaged over a two-day period of 00Z Oct. 21 to 23. Top panels show the ERA-Interim reanalysis while bottom panels display results from the 10/16 run. The horizontal (vertical) green reference line is along the latitude of 20°N (the longitude of 80°W). The label 'AC' indicates an anti-cyclonic circulation. (Results from other runs can be found in Shen et al. 2013c)

Advanced Data Analysis and Model Verification

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



Tropical Waves

MAP with PEEMD

Tropical Cyclone Formation

MAP with SAT

small-scale processes

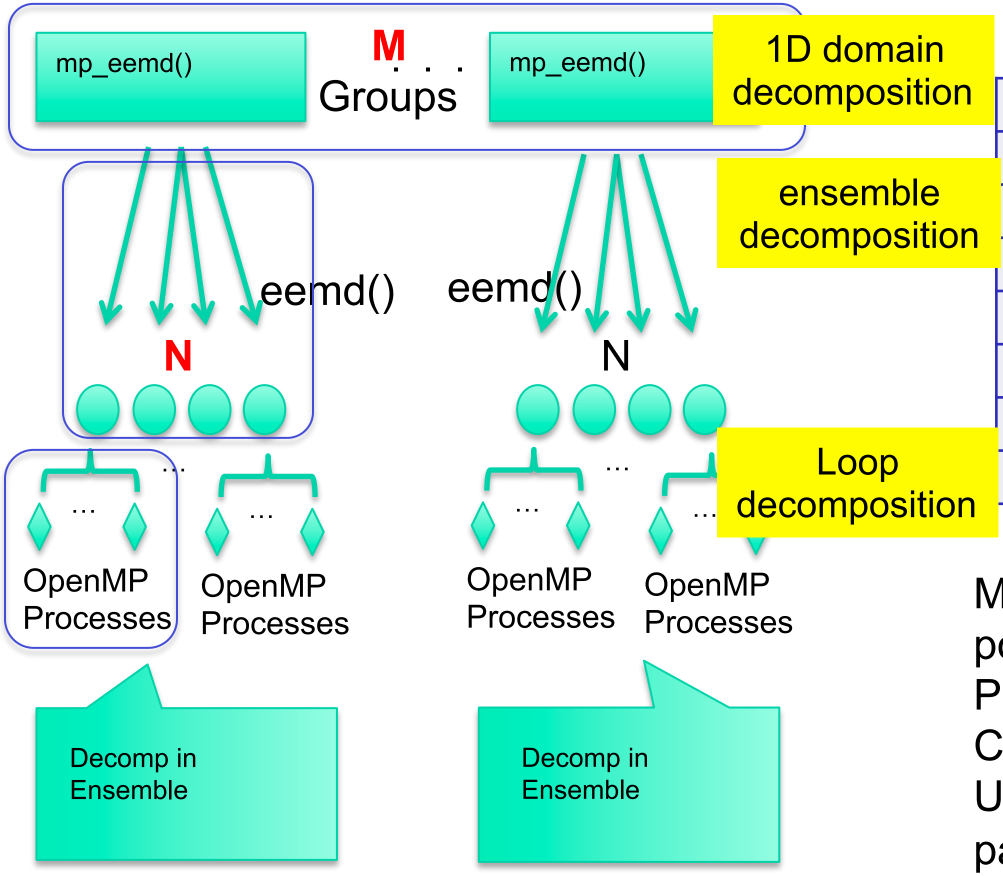
1. Extension of the EEMD to the two spatial dimensions
2. Parallelization of the EEMD (PEEMD)
3. Performance of the PEEMD in idealized cases
4. Analysis of AEWs and TC Helene with the PEEMD
5. Multiscale (multi-level) visualization

1. Implementation of ensemble Lyapunov exponent (eLE) calculation (which has been tested with Lorenz models)
2. Application of the EMD to determining the local growth rate and local period[which is inter-compared with the results in (1)];
3. Derivations of analytical solutions for linear stability analysis in a high-order Lorenz model

Demonstration with Hurricane Sandy (2012)

Benchmark with the Three Level Parallelism

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



mp_eemd()
M Groups . . .
mp_eemd()
1D domain decomposition
ensemble decomposition
eemd()
eemd()
N
N
…
…
Loop decomposition
OpenMP Processes
OpenMP Processes
OpenMP Processes
OpenMP Processes
Decomp in Ensemble
Decomp in Ensemble

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.

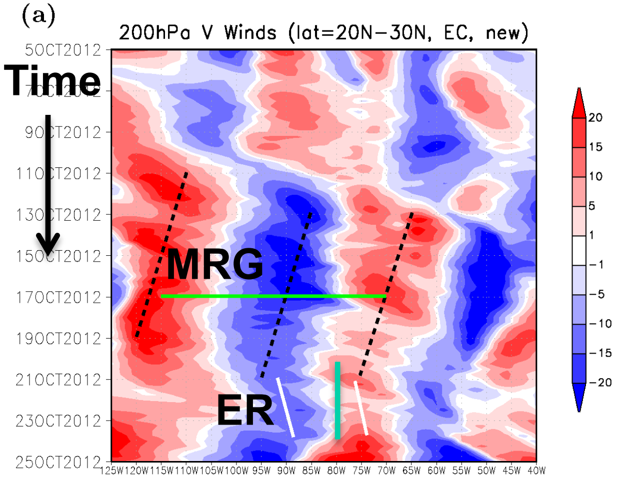
Introduction

In late October 2012, Storm Sandy made landfall near Brigantine, New Jersey, devastating surrounding areas and causing tremendous economic loss and hundreds of fatalities (Blake et al., 2013). An estimated damage of $50 billion made Sandy become the second costliest tropical cyclone (TC) in US history, surpassed only by Hurricane Katrina (2005).

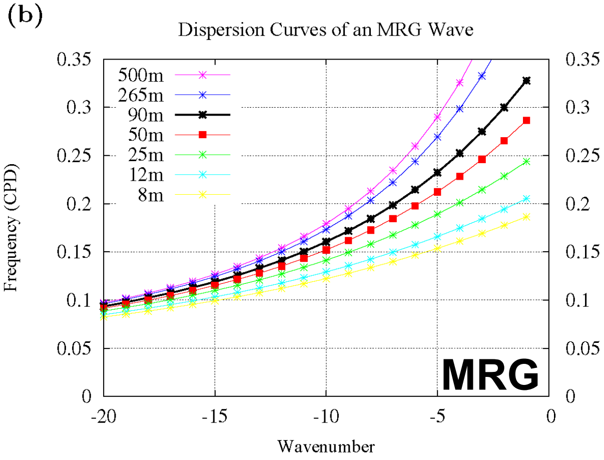
In this study, we analyze the multiscale processes associated with Sandy using a global mesoscale model and multiscale analysis package (MAP) and focus on short-term (or extended-range) genesis prediction as the first step toward the goal of understanding the relationship between extreme events, such as Sandy, and the current climate. We first present five track and intensity forecasts of Sandy initialized at 00Z October 22-26, 2012, realistically producing its movement with a northwestward turn prior to its landfall. We then show that three experiments initialized at 00Z October 16-18 captured the genesis of Sandy with a lead time of up to six days and simulated reasonable evolution of Sandy's track and intensity in the next two-day period of 18Z October 21-23. Results suggest that the extended lead time of formation prediction is achieved by realistic simulations of multi-scale processes, including (1) the interaction between an easterly wave and a low-level westerly wind belt (WWB); (2) the appearance of the upper-level trough at 200-hPa to Sandy's northwest. The low-level WWB and upper-level trough are likely associated with a Madden-Julian Oscillation.

Characteristics of Wave-like Disturbances (200-hPa V winds)

(a)

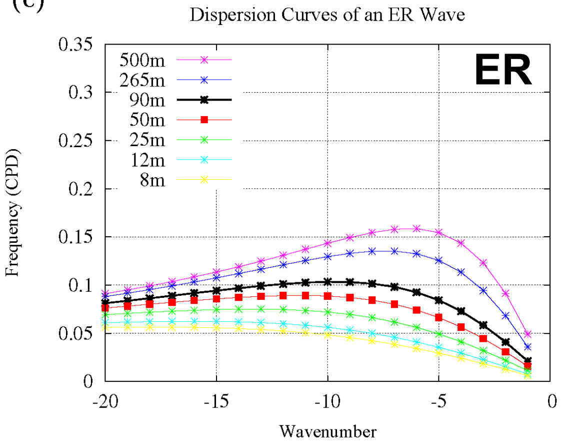


(b)



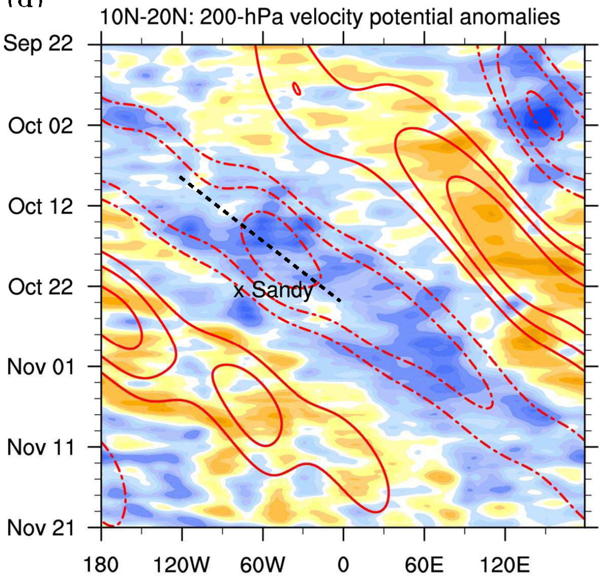
$$\sigma = \frac{k\sqrt{gH_e}}{2}\left[1-\left(1+\frac{4\beta}{k^2\sqrt{gH_e}}\right)^{1/2}\right].$$

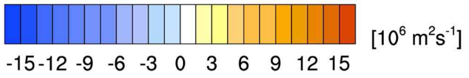
(c)



$$\sigma = \frac{-\beta k}{k^2+\beta(2n+1)/\sqrt{gH_e}}.$$

(d)

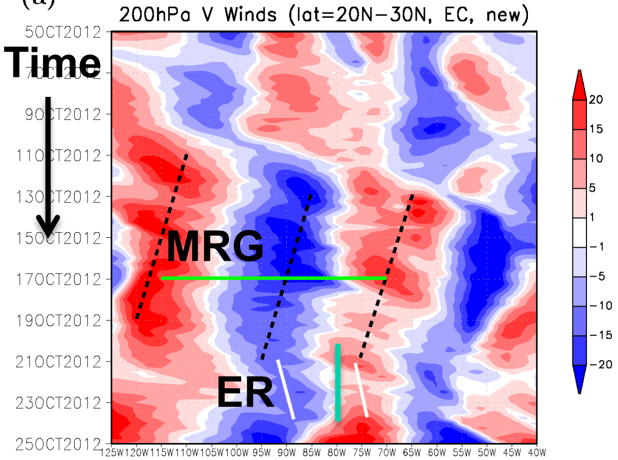




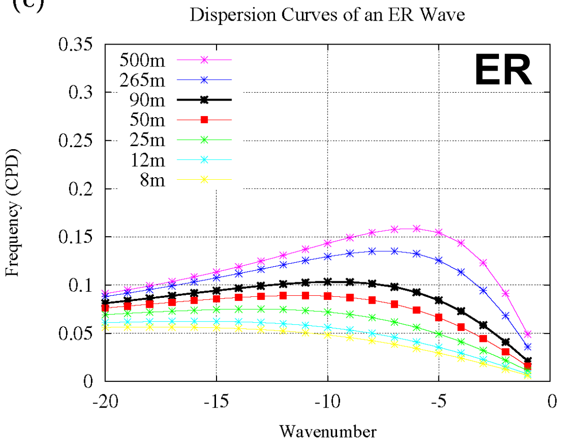
- the wavelength ~ 45 degrees (K=-8)
- The corresponding phase speed is roughly equal to the reciprocal of the slope of a constant phase line, leading to a (total) phase speed of -1.46 m/s.
- the frequency of the MRG (ER) wave is 0.2035 (0.135) CPD (cycles per day), which corresponds to a period of 4.914 (7.407) days.
- the intrinsic phase speed of the MRG (ER) wave with a wavelength of 45 degrees (~4535.1 km) and a period of 4.914 (7.407) days is about -10.68 (-7.09) m/s.
- the "basic" wind speed is about 9.32 m/s, from panel (d).
- the Dopper-shifted phase speed with K=-8 is about -1.36 m/s (=-10.68+9.32) for the MRG wave and 2.23 m/s (=-7.09 + 9.32) for the ER wave.

Characteristics of Wave-like Disturbances (200-hPa V winds)

(a)

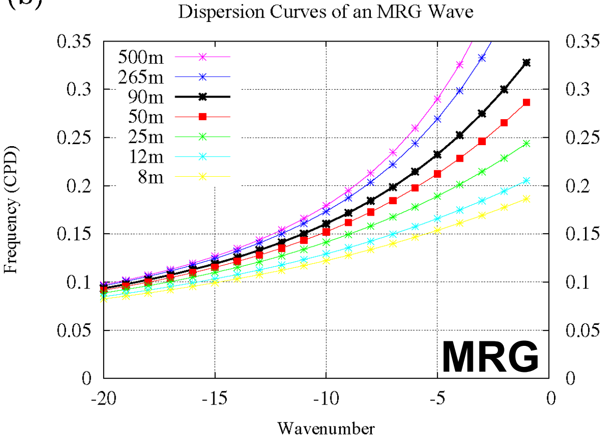


(c)

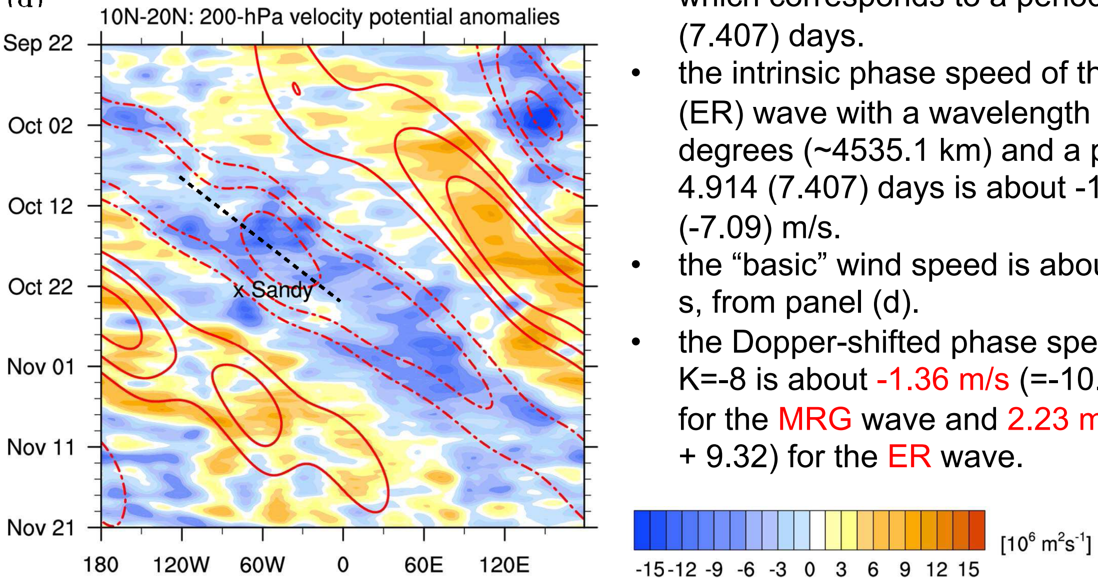


$$\sigma = \frac{-\beta k}{k^2 + \beta(2n+1)/\sqrt{gH_e}}.$$

(b)



(d)



$$\sigma = \frac{k\sqrt{gH_e}}{2}\left[1 - \left(1 + \frac{4\beta}{k^2\sqrt{gH_e}}\right)^{1/2}\right].$$

- the wavelength ~ 45 degrees (K=-8)
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Analyzing a Kelvin cat eye's flow with the PEEMD

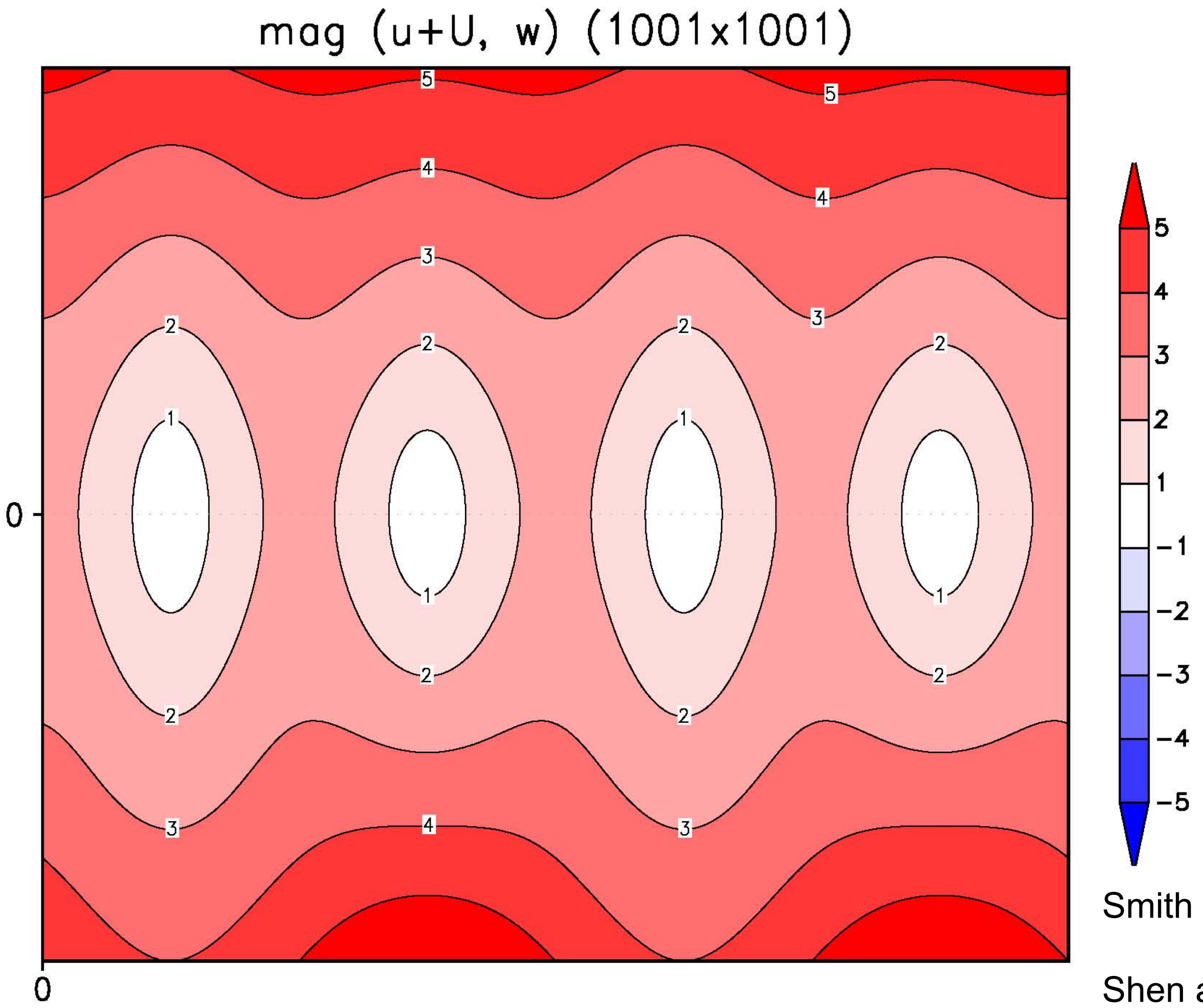
“Protected Upscaling” in Marsupial Paradigm
(Dunkerton, Montgomery and Wang, 2008)

- The so-called Marsupial Paradigm states the parent large-scale disturbance contains a small-scale sub-region within which small-scale processes can develop and efficiently provide upscale feedback. The favored “sub-region” for TC genesis is analogous to the pouch of a mother kangaroo. The development of “pouch” is accompanied by the critical layer/level (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, ar (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 my 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.

A Kelvin Cat's flow



u+U and W

Smith (1986, JAS)

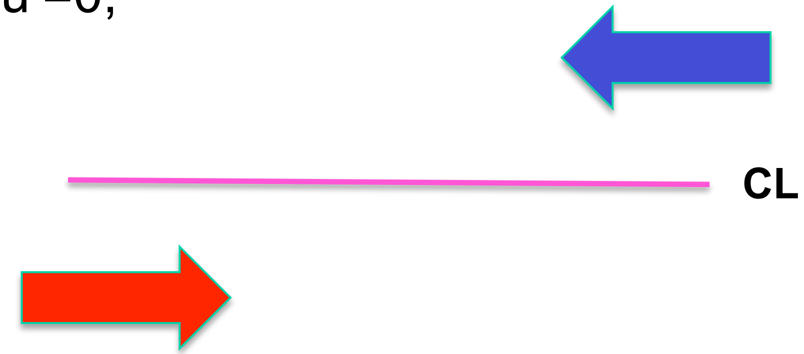
Shen and Lin (1999, JAS)

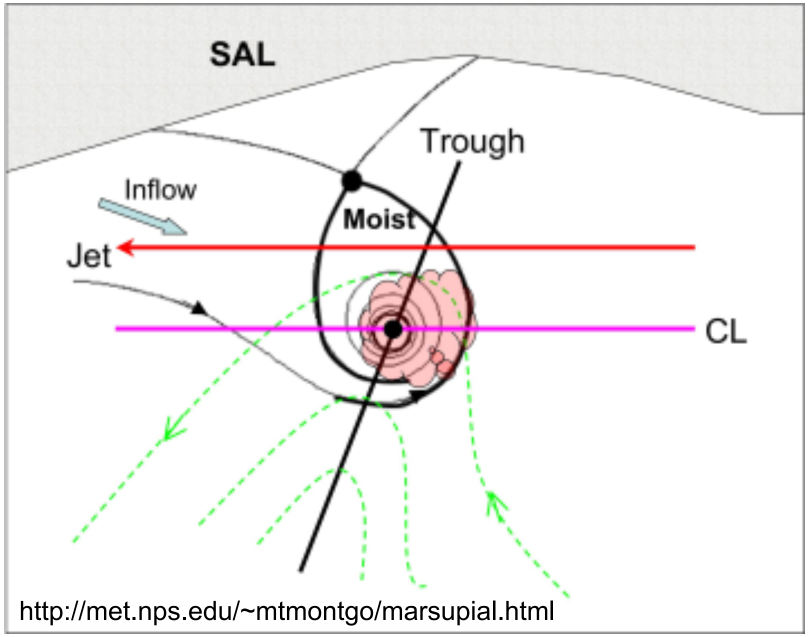
Marsupial Paradigm

(Dunkerton, Montgomery and Wang, ACP, 2009)

- u' = U – c, here "c" is a phase speed of an AEW, i.e., a reference wind speed;

  ➔ a local mean speed?
- u'=0;





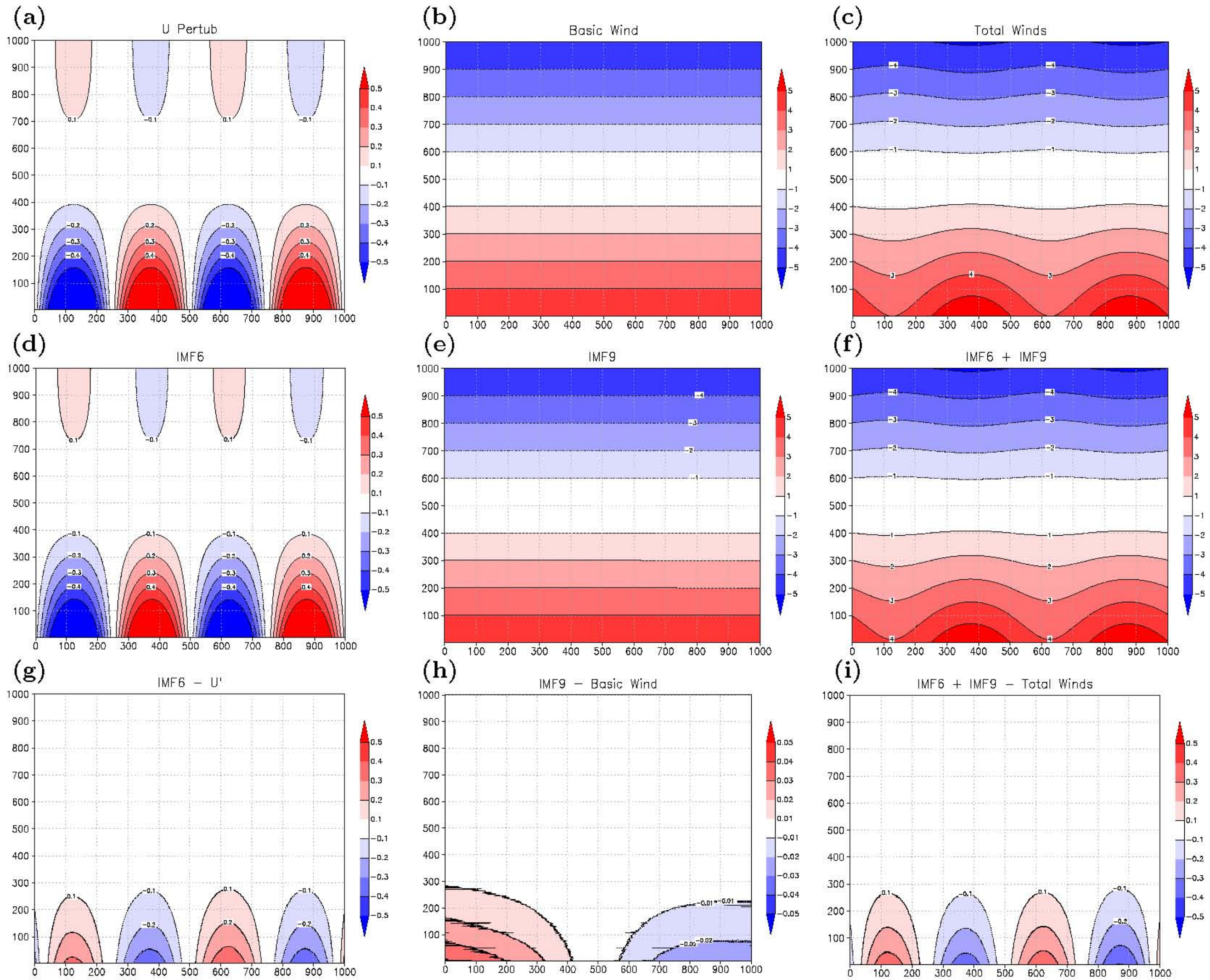
http://met.nps.edu/~mtmontgo/marsupial.html

- Role by the large scale flows: providing a protective environment, (→ no explicit downscaling transfer)

How to determine the phase speed or "basic wind"?

IMFs of the Kelvin Cat eye’s flow

Analytical Solutions of a Kelvin Cat eye’s flow (e.g., Smith 1986; Shen 1998)



Analysis of an AEW and Hurricane Helene (2006)

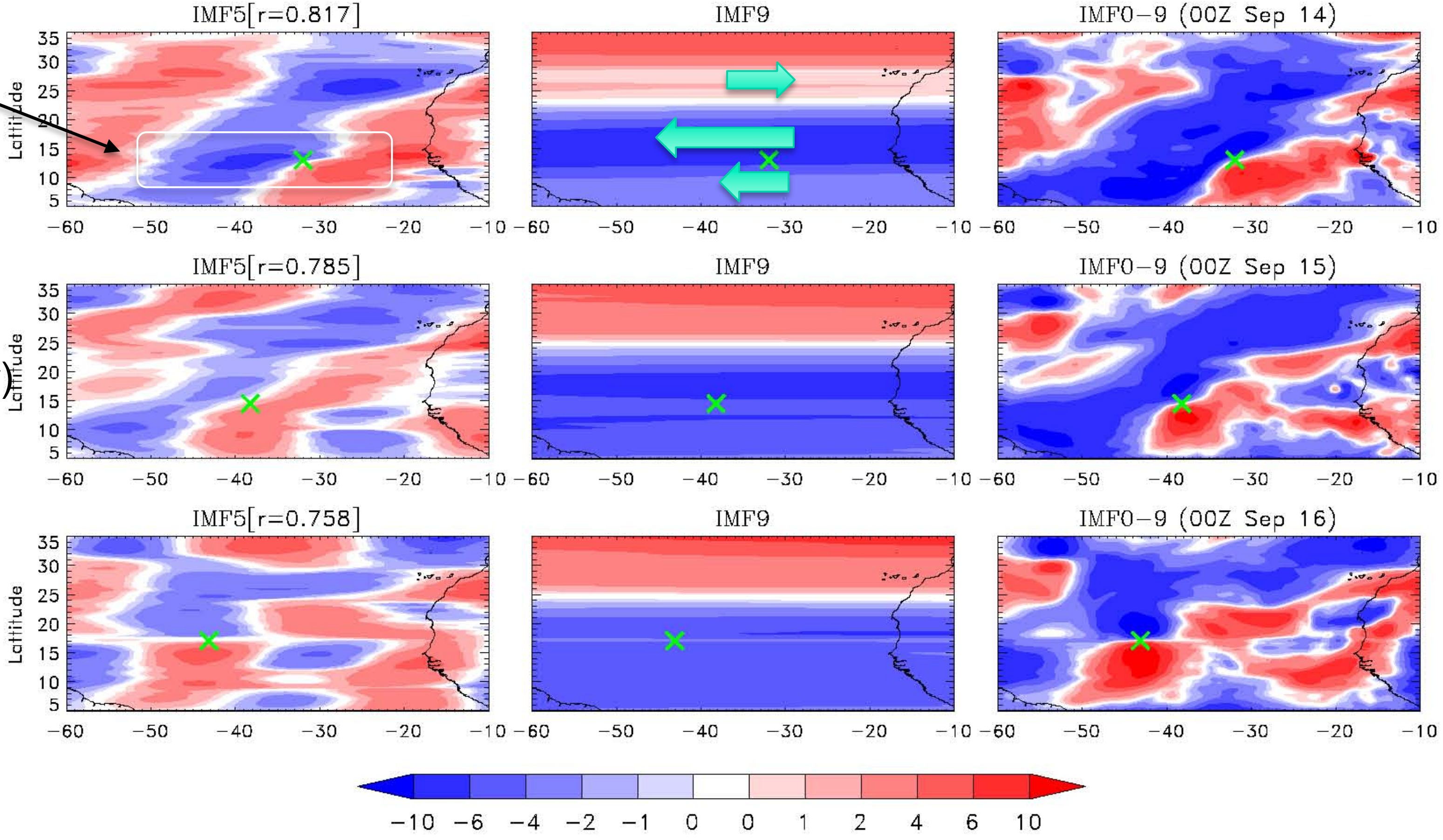
barotropic unstable flow

with phase lines that tilt upshear (in an opposite direction of shear vector)

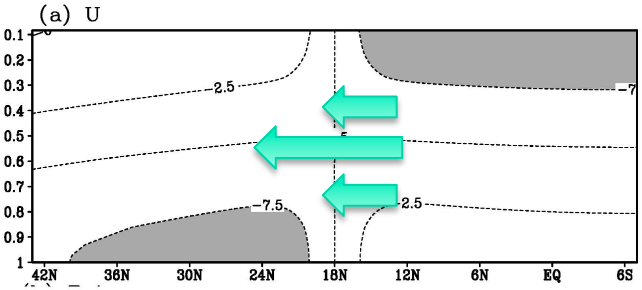
Kelvin cat eye's flow

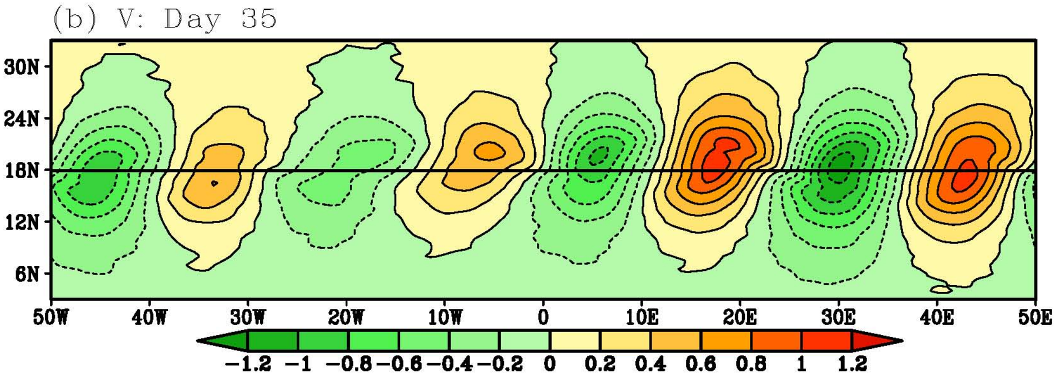
with phase lines that nearly have no tilt.

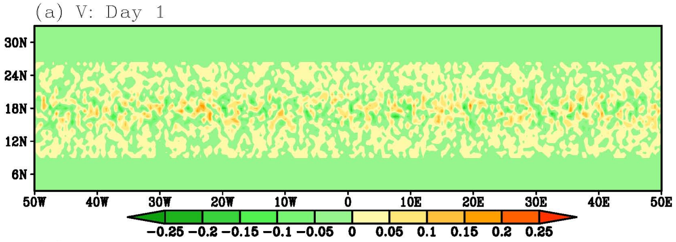
700 mb Zonal winds

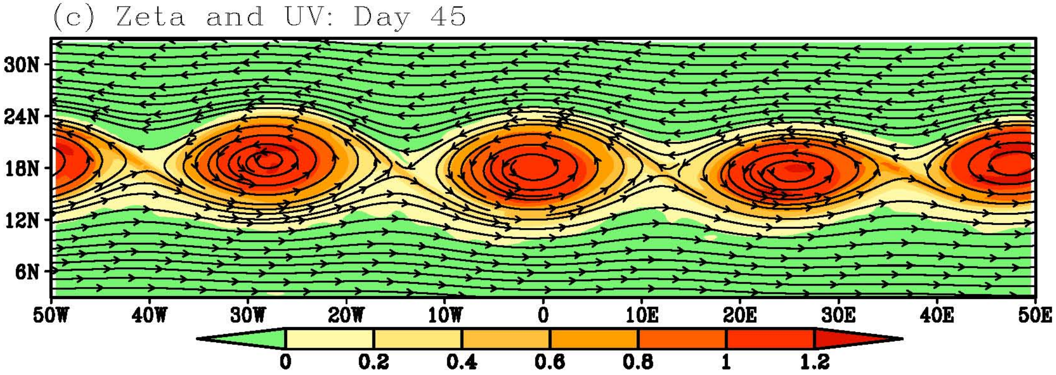


Model Simulation


(a) U

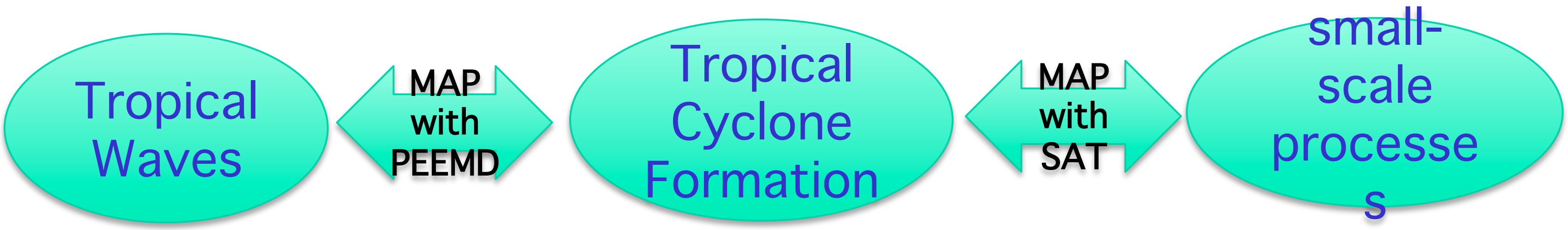

(b) V: Day 35


(a) V: Day 1


(c) Zeta and UV: Day 45

Montgomery, Wang, and Dunkerton (2012): Atmos. Chem. Phys., 10, 10803–10827, 2010

Scientific Goals



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

Selected cases in published journal articles

(Shen et al. 2010a,b,2012,2013a,c) include:

1: TC Nargis (2008) and an Equatorial Rossby (ER) Wave

2: Twin TCs 2002) and a mixed Rossby Gravity (MRG) Wave

3: Hurricane Helene (2006) and an African Easterly Wave (AEW)

4: Hurricane Sandy (2012) and Tropical Waves