# Genesis of Hurricane Sandy (2012)
# Simulated with a Global Mesoscale Model

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# Disclaimer

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**Project Title of AIST-08-0049 (PI: Shen)**
**C**oupling NASA **A**dvanced Multi-Scale **M**odeling and Concurrent **Vis**ualization Systems for Improving Predictions of High-Impact Tropical Weather (**CAMVis**), March 2009 – April 2012
**Project Title of AIST-11-0012 (PI: Shen):**
Integration of the NASA CAMVis and **M**ultiscale **A**nalysis **P**ackage (**CAMVis-MAP**) for Tropical Cyclone Climate Study, May 2012 – April 2015

# Outline

1. Introduction
2. Track Predictions (as model verifications)
3. Genesis Simulations (WWB, ER/MRG Waves)
4. Summary and Future Tasks

Hurricane Sandy (2012)

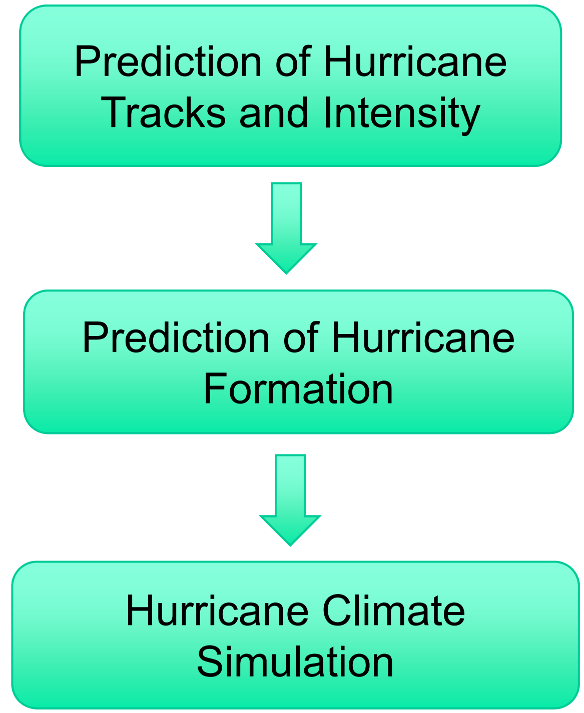
- Formed on Oct 22 and Dissipated on Oct 30
- Category 3 on Oct 25; 940 hPa and 185 km/h
- The deadliest and the most destructive TC of 2012 Atlantic hurricane season
- The second-costliest hurricane in United States history (~$65 billion)
- The largest Atlantic hurricane on record

# Decadal Survey Missions

Two 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 → multiscale interactions; modulations and feedbacks between large/long-term scale and small/short-term scale flows

- **<u>Climate Prediction</u>** (long-term goal): Robust estimates of primary climate forcings for improving 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**

# Published Articles since 2010

**Journal Articles:**

1. **Shen, B.-W., 2014a:** Nonlinear Feedback in a Five-dimensional Lorenz Model. *J. of Atmos. Sci.* in press.
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. posted December 2, 2013.
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:**

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

# Lorenz Models: Stability Analysis

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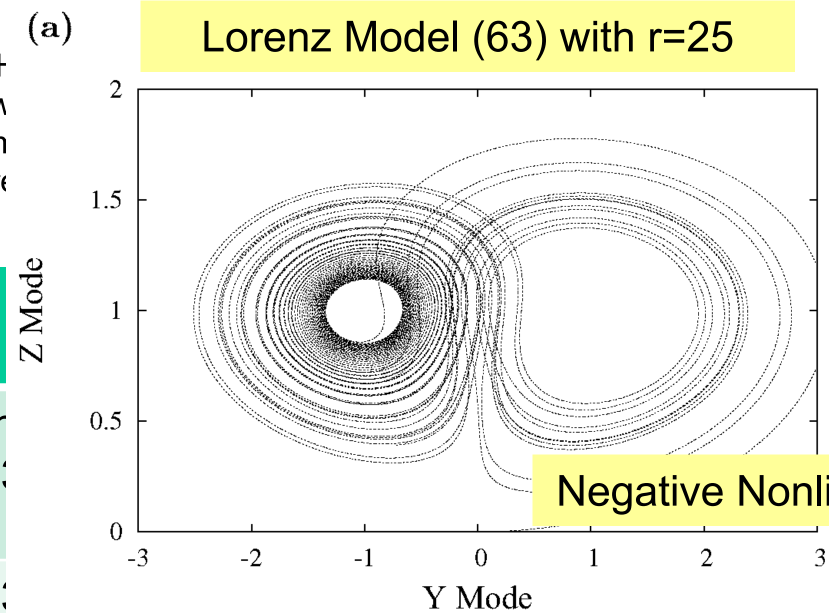


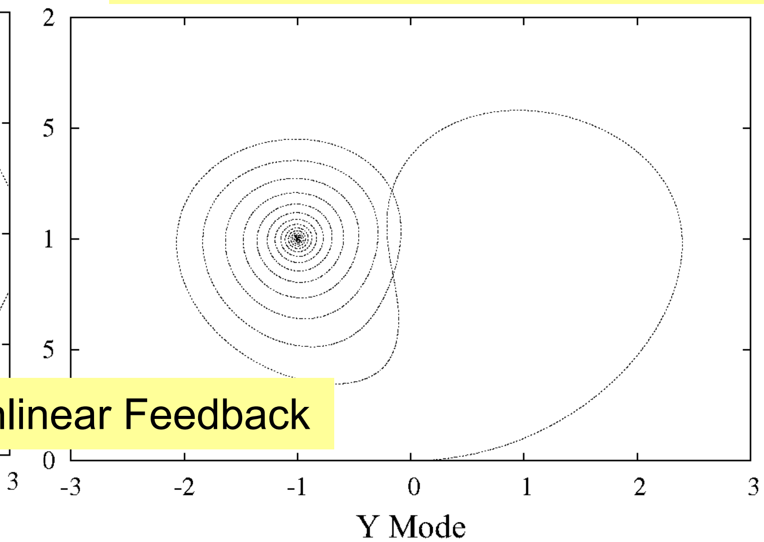


Negative Nonlinear Feedback

strange attractors

stable critical points

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| 3D-NLM | | | | | | | $(X_c, Y_c)$ | | nservative |
| 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. (accepted by NPGD)

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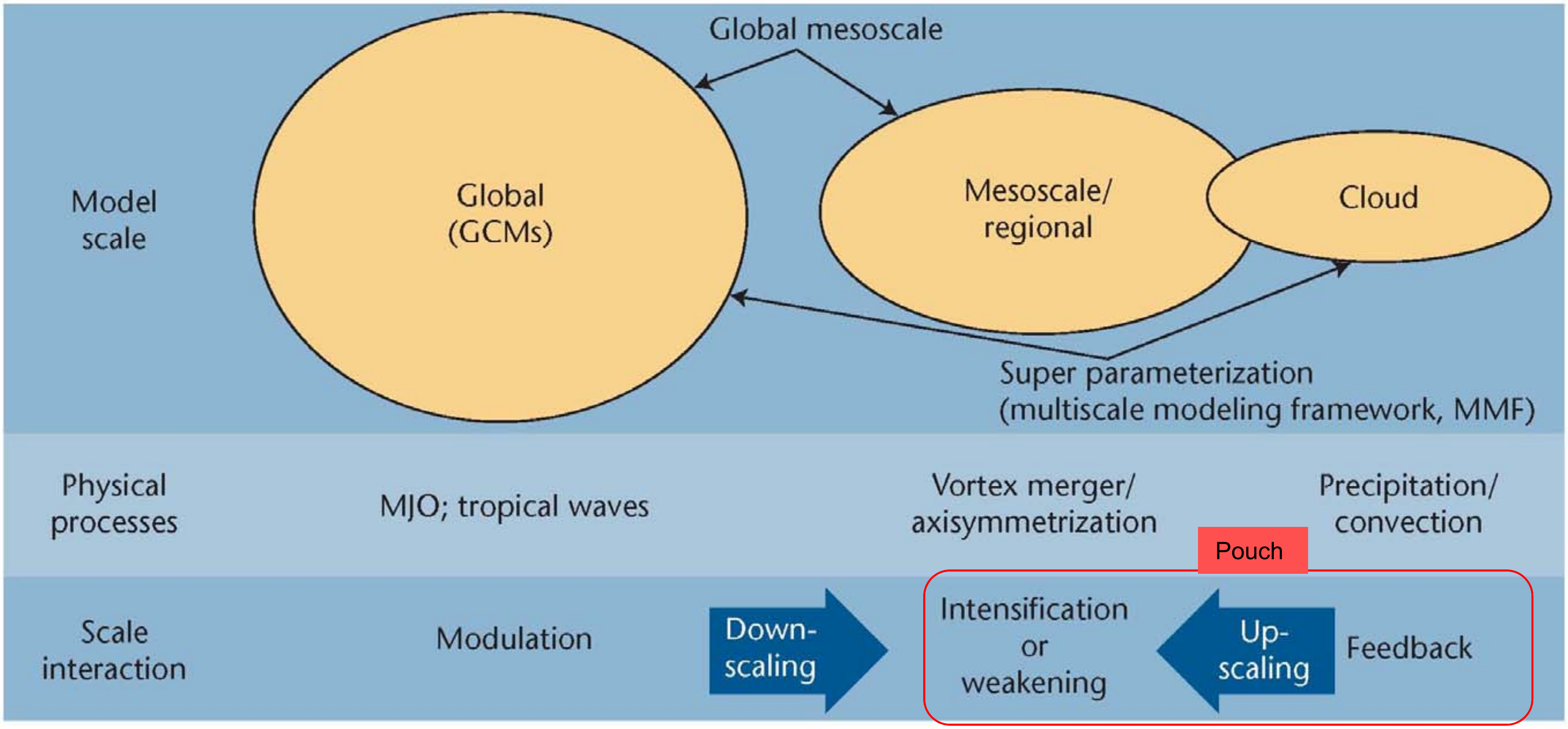
# Multiscale Processes

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).

Hierarchical modeling



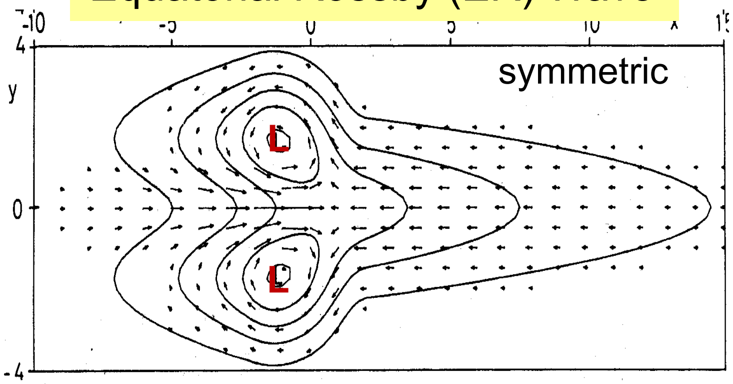

Shen, B.-W., B. Nelson, S. Cheung, W.-K. Tao, **2013b:** Scalability Improvement of the NASA Multiscale Modeling Framework for Tropical Cyclone Climate Study. (Sep/Oct issue of IEEE CiSE)

# 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)

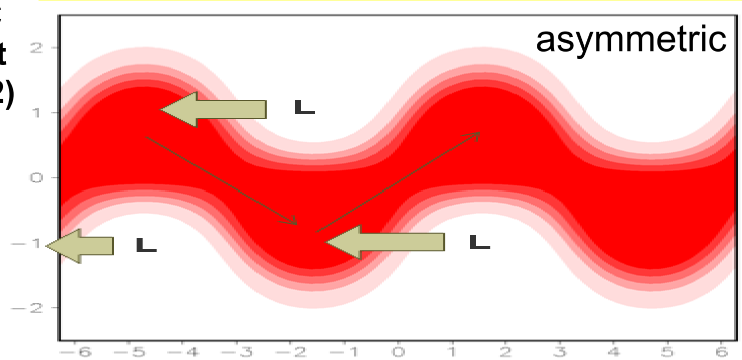
LAT:5º

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

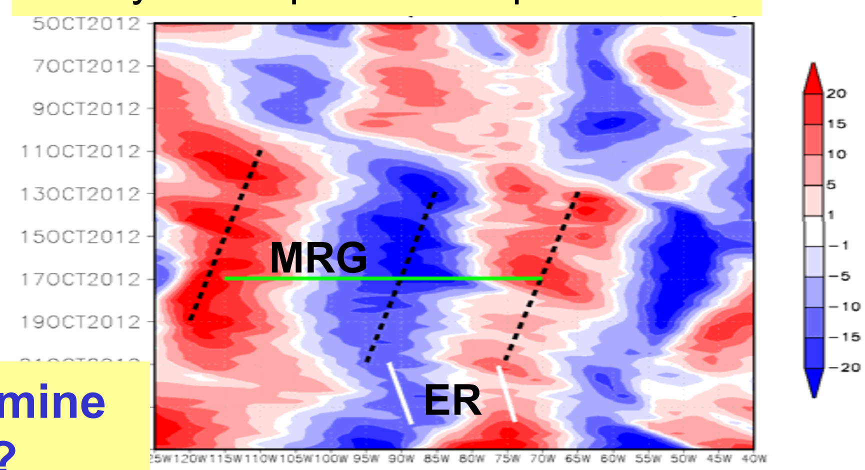
## Mixed Rossby Gravity (MRG) Wave

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?**

# Classification of Predictability

Lorenz, E., **1963b**: The Predictability of Hydrodynamic Flow. Transactions of The New York Academy of Sciences. Ser. II, Volume 25, No. 4, 409-432.

- **Intrinsic predictability**: depending only upon the flow itself;
- **Attainable predictability**: being limited by the inevitable inaccuracies in the measurement → impact of ICs;
- **Practical predictability**: being further limited by our present inability to identify the most suitable formulas → impact of model;

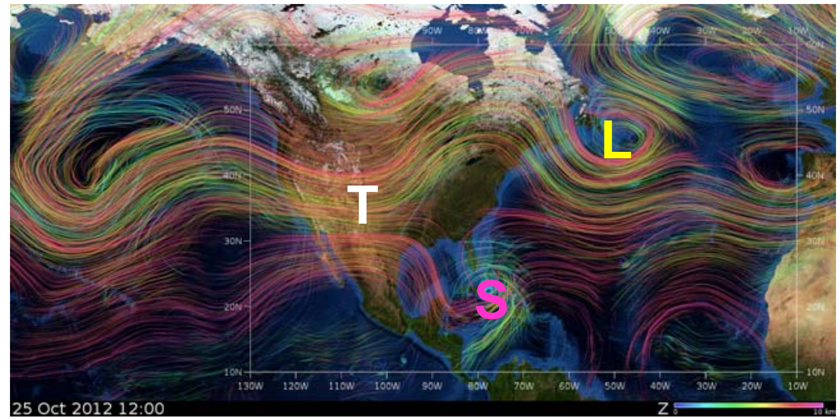
1. *to what extent high intrinsic predictability (of TC genesis) may exist;*
2. *if and how realistic the corresponding practical predictability can be obtained.*

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

# Multiscale Processes associated with Sandy

0000 UTC Oct 23 2012


1200 UTC Oct 25 2012




1200 UTC Oct 27 2012

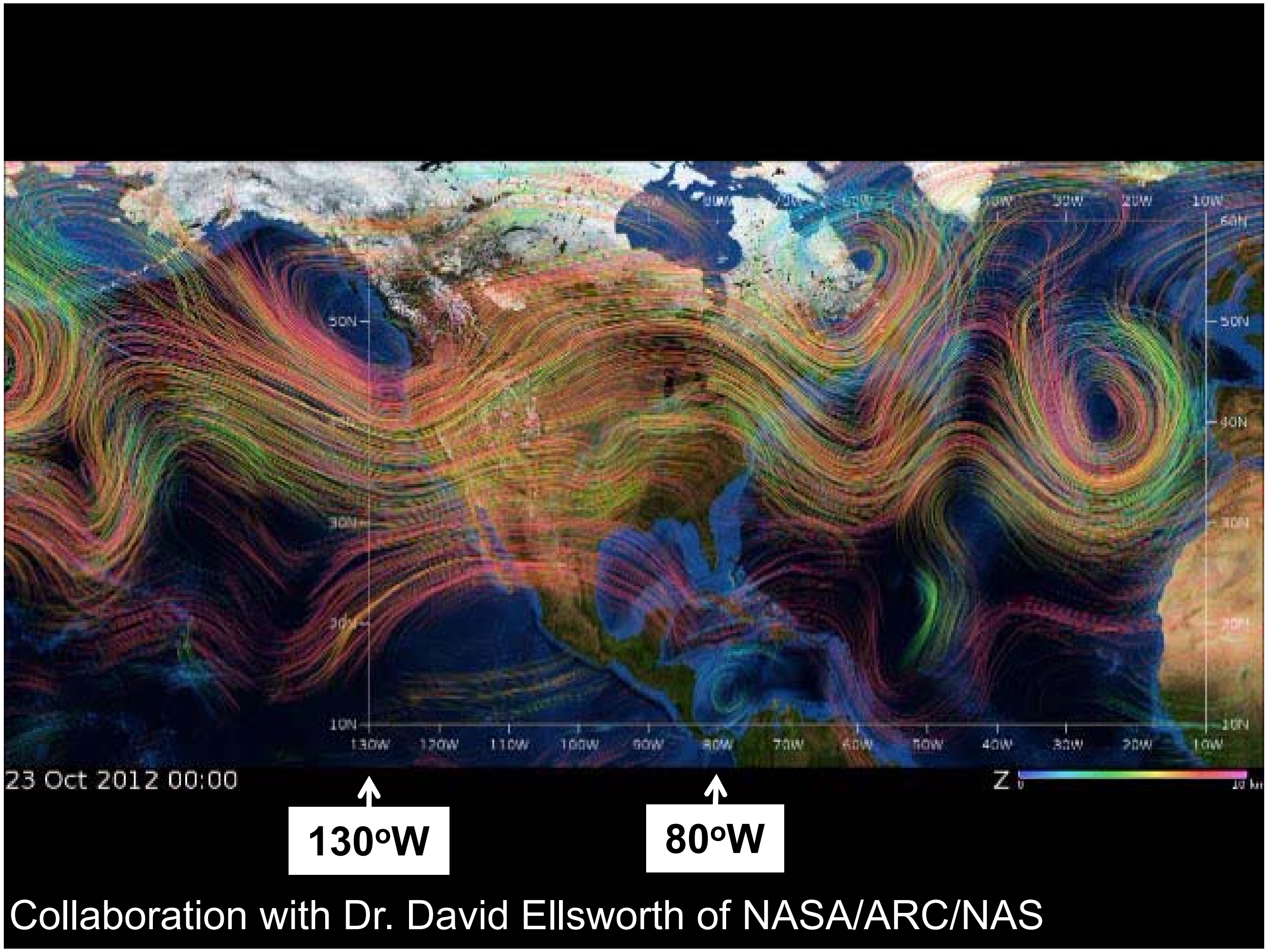

1200 UTC Oct 28 2012


**130°W** **80°W**

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

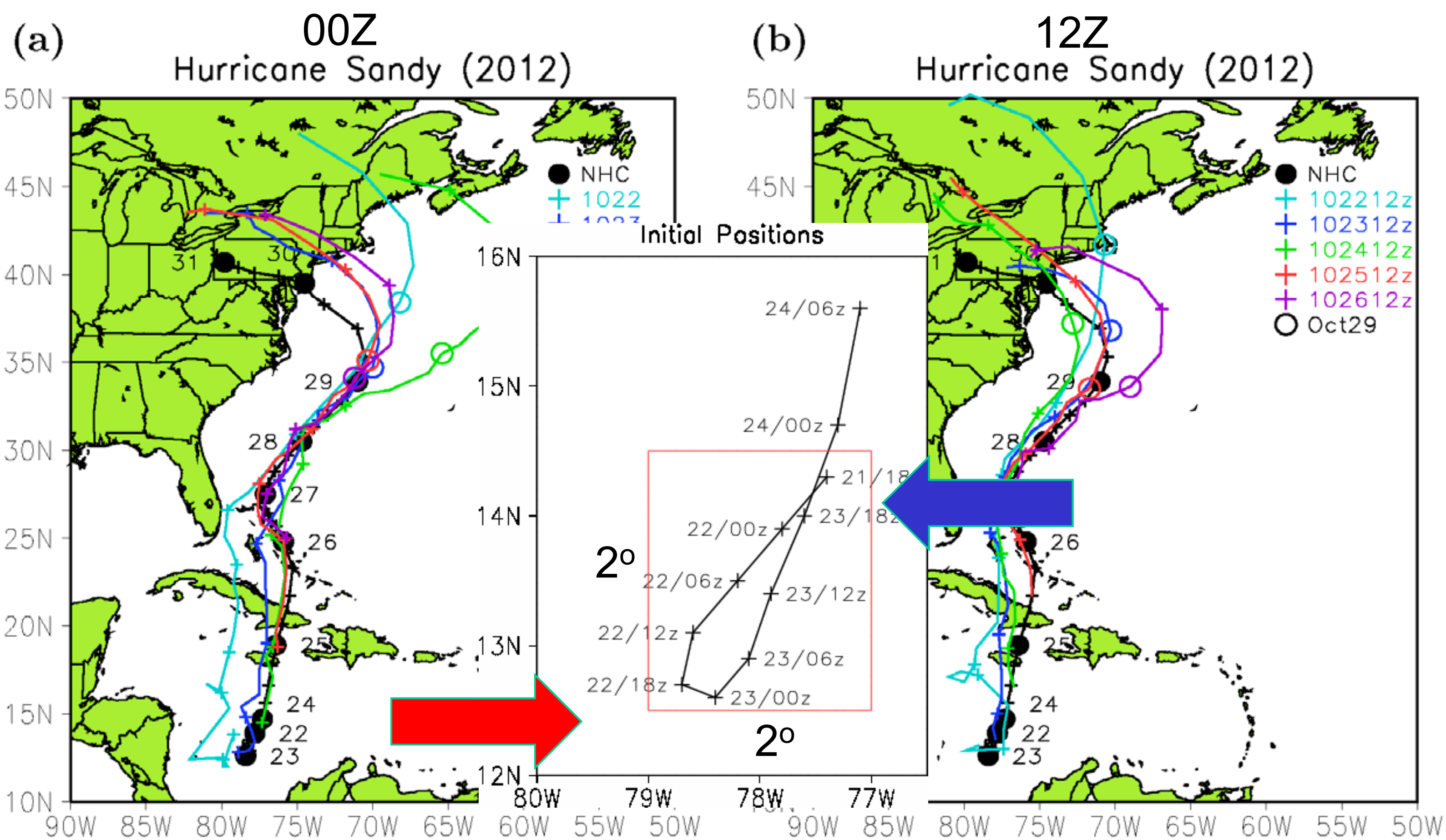
Pink: upper-level winds
Green: middle-level winds
Blue: low-level winds

# Visualizations of Sandy (10/23)



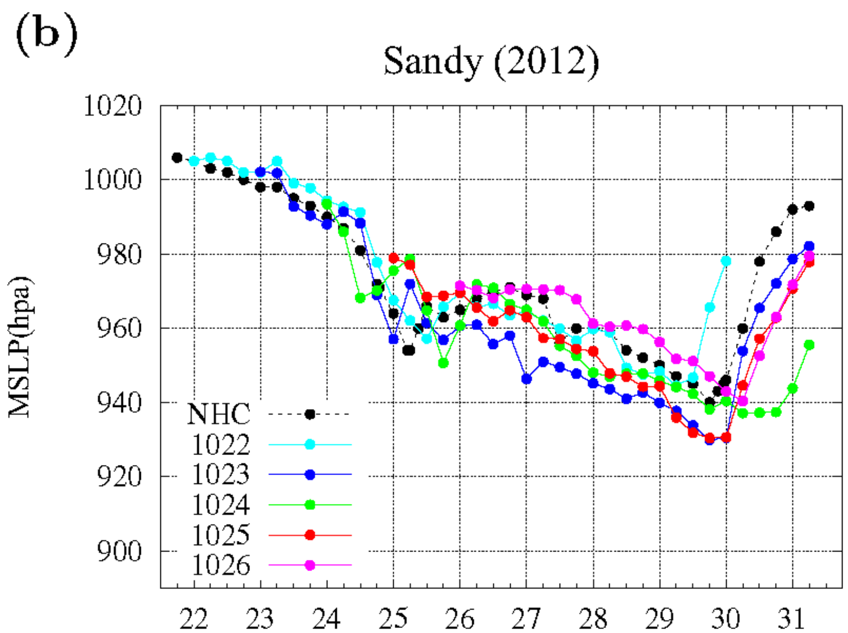

Shen, B.-W., B. Nelson, W.-K. Tao, and Y.-L. Lin, 2013a: Advanced Visualizations of Scale Interactions of Tropical Cyclone Formation and Tropical Waves. *IEEE Computing in Science and Engineering*, vol. 15, no. 2, pp. 47-59, March-April 2013, doi:10.1109/MCSE.2012.64.

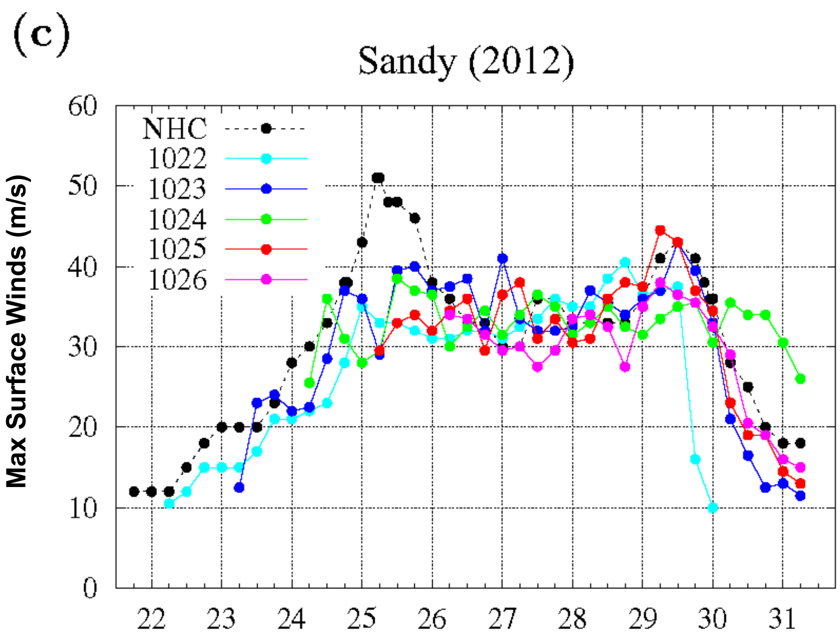
# 10 Track Predictions of Hurricane Sandy




The initial counter-clockwise loop within a 2°x2° domain is very likely due to the competing impact between the WWB and easterly wave. Therefore, the initial erratic track of the 10/22 run may be associated with the inaccurate simulations of the complicated large-scale flows.

# Min SLPs and Max Surface Winds

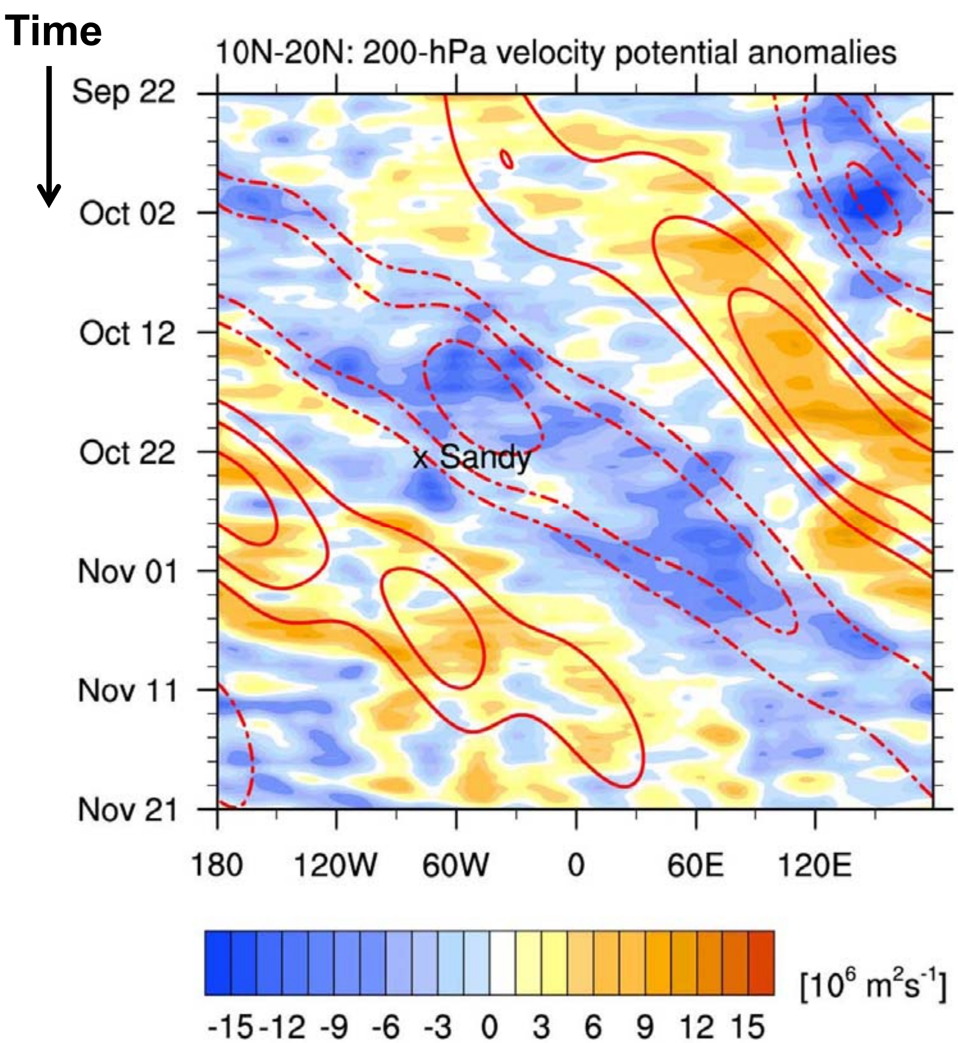


# Genesis Predictions

- Analysis of environmental flows with NCEP Reanalysis and EC ERA-Interim data
- Simulations of initial vortex circulation and subsequent location and intensity
- Comparisons of model simulations with NCEP Reanalysis and EC ERA-Interim data

# MJO and Sandy

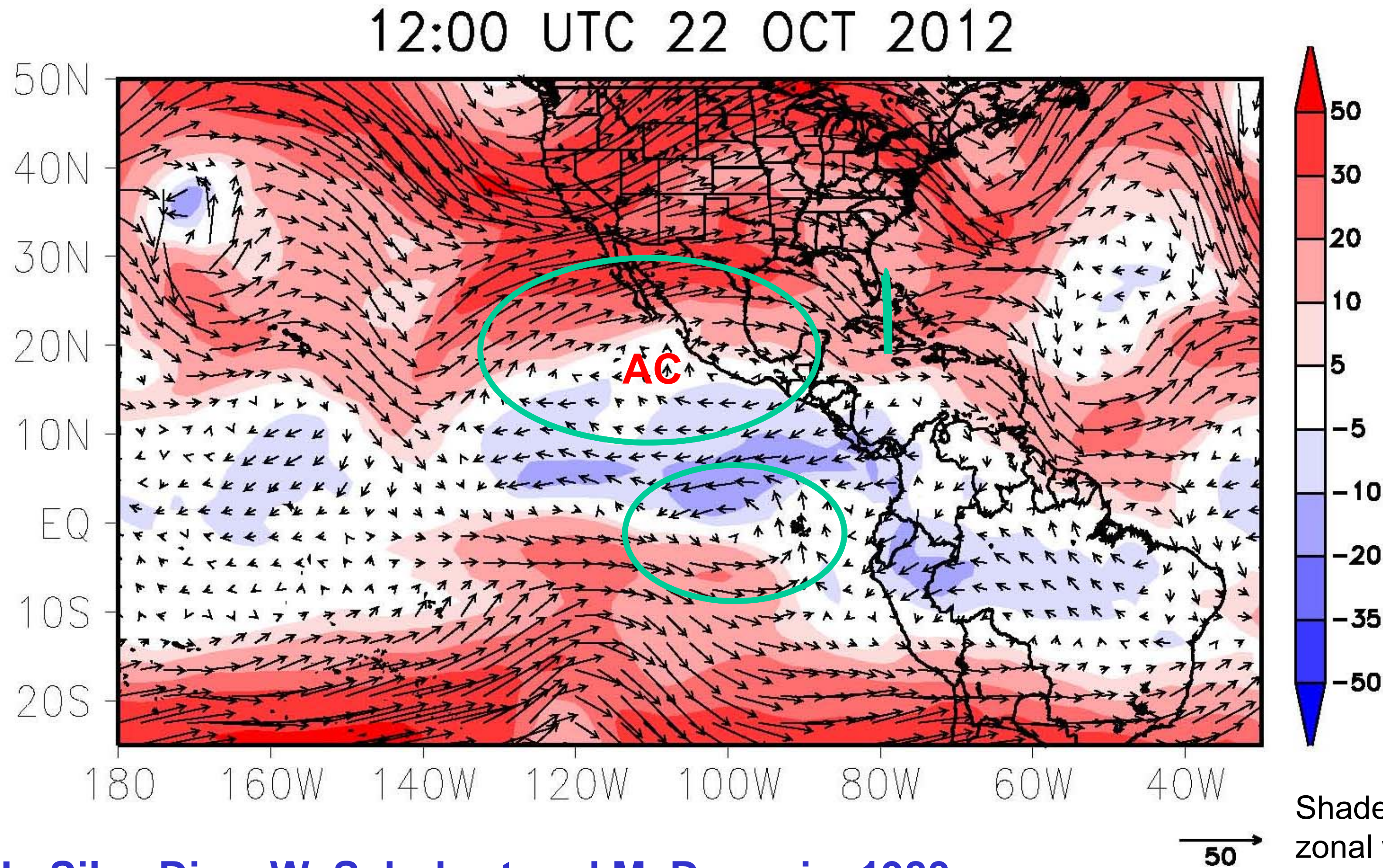



Blake, E. S., T. B. Kimberlain, R. J. Berg, J. P. Cangialosi and J. L. Beven II, 2012: Tropical Cyclone Report: Hurricane Sandy, Rep. AL182012. Natl. Hurricane Cent., Miami, Fla.

X: timing and location of Sandy's genesis

Velocity potential anomalies at 200 mb (VP200) from 10°N-20°N. The shading shows unfiltered VP200 anomalies (negative values [in blue] represent mass divergence). Red contours show MJO-filtered VP200 anomalies; dashed lines represent the upper-level divergent (convectively active) phase of the MJO. The contour interval begins at 1 standard deviation and is in 0.5 standard deviation increments thereafter. Figure courtesy of Michael Ventrice (SUNY-Albany).

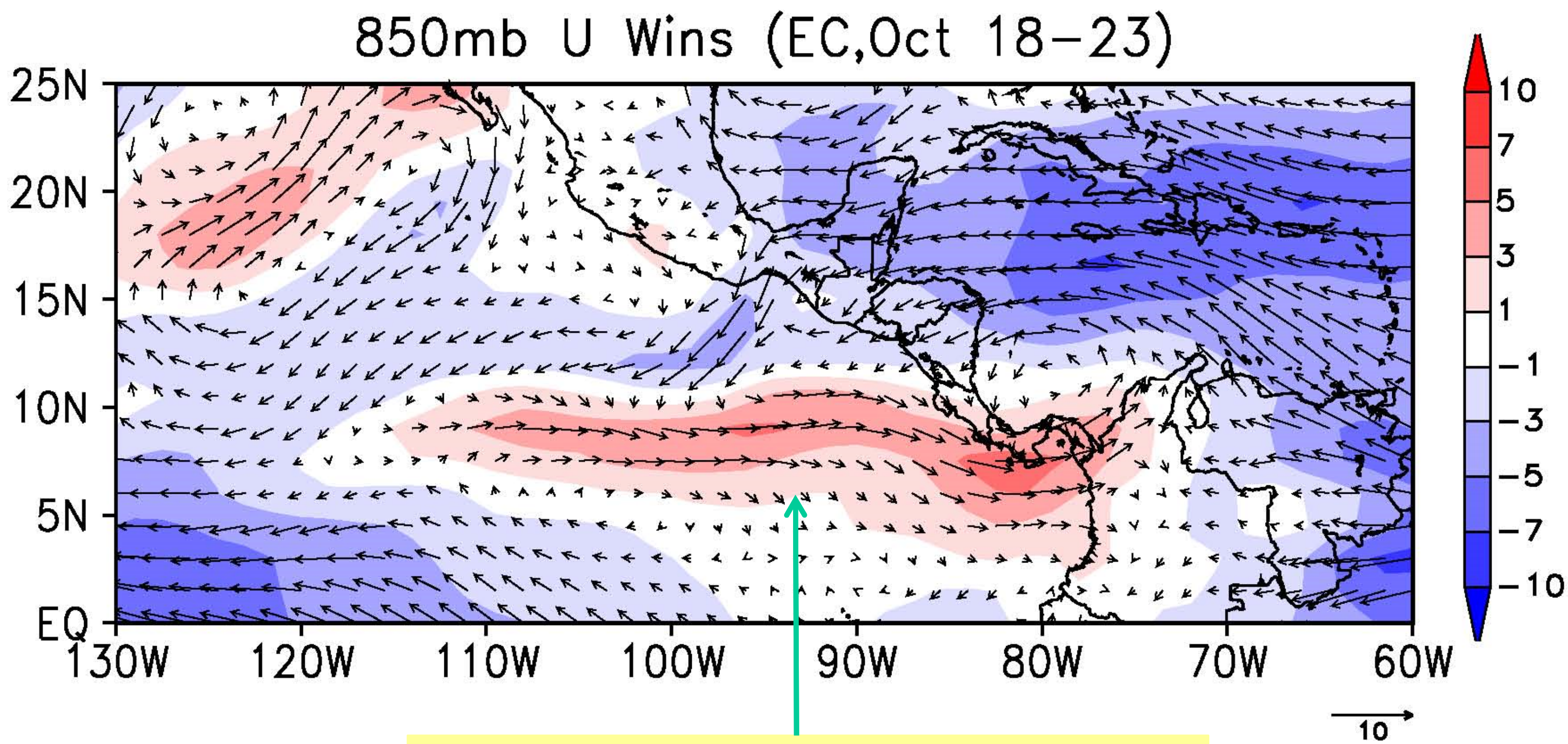
# An AC and Trough at 200 mb
# (Sandy first appeared on Oct 22)




Shaded: zonal wind speeds

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

# Interactions of Westerly and Easterly Winds




Westerly Wind Belt (WWB, shaded in red)

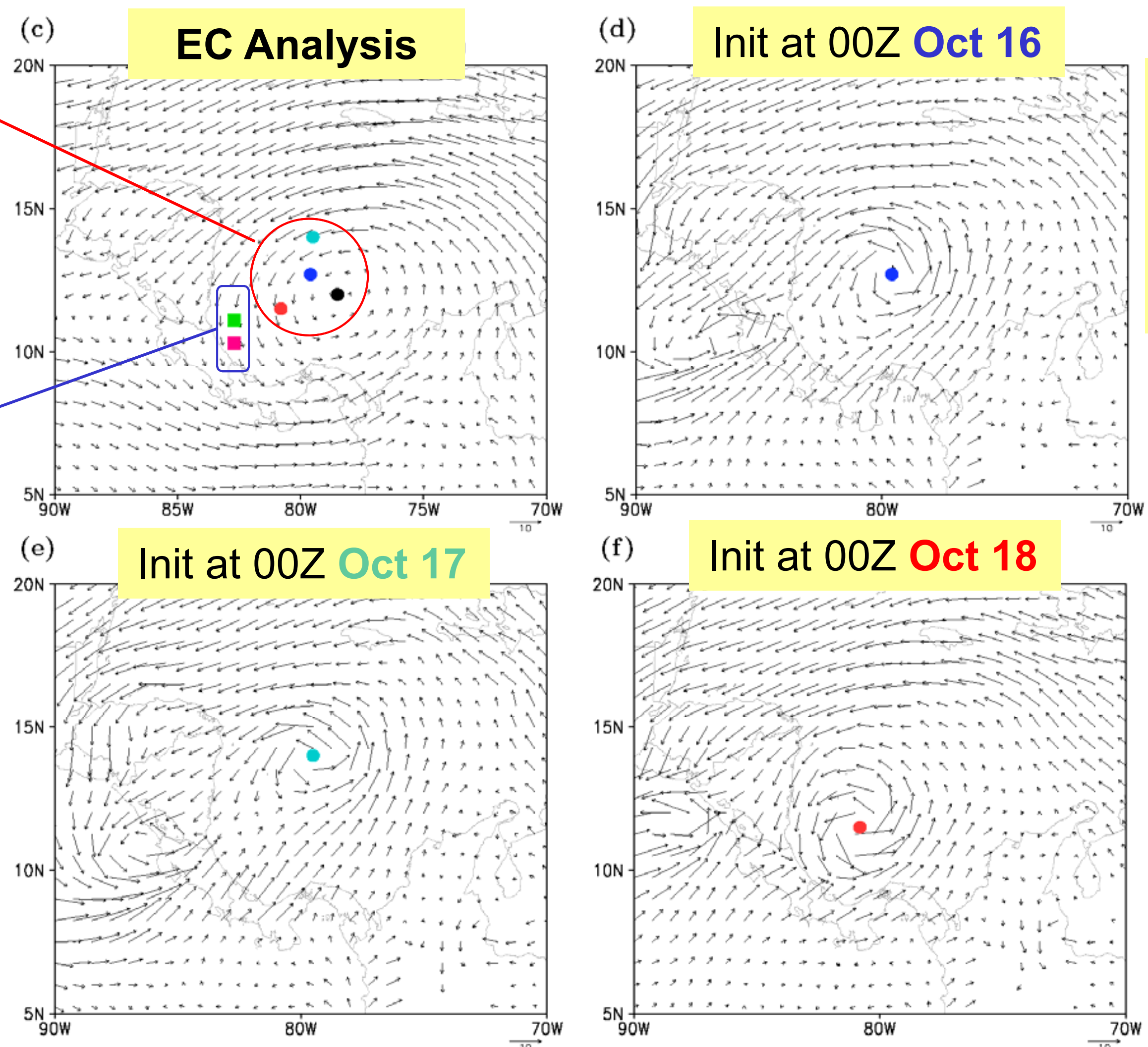
EC ERA-Interim T255 (~0.75$^o$ or 79 km) reanalysis (e.g., Dee et al. 2011) .

Dee, D. P., et al., 2011: The ERA-Interim reanalysis: configuration and performance of the data assimilation system. Q.J.R. Meteorol. Soc., 137: 553–597.

# Simulations of Initial Sandy Circulation

good forecasts (init at 00Z Oct 16, 17, and 18).

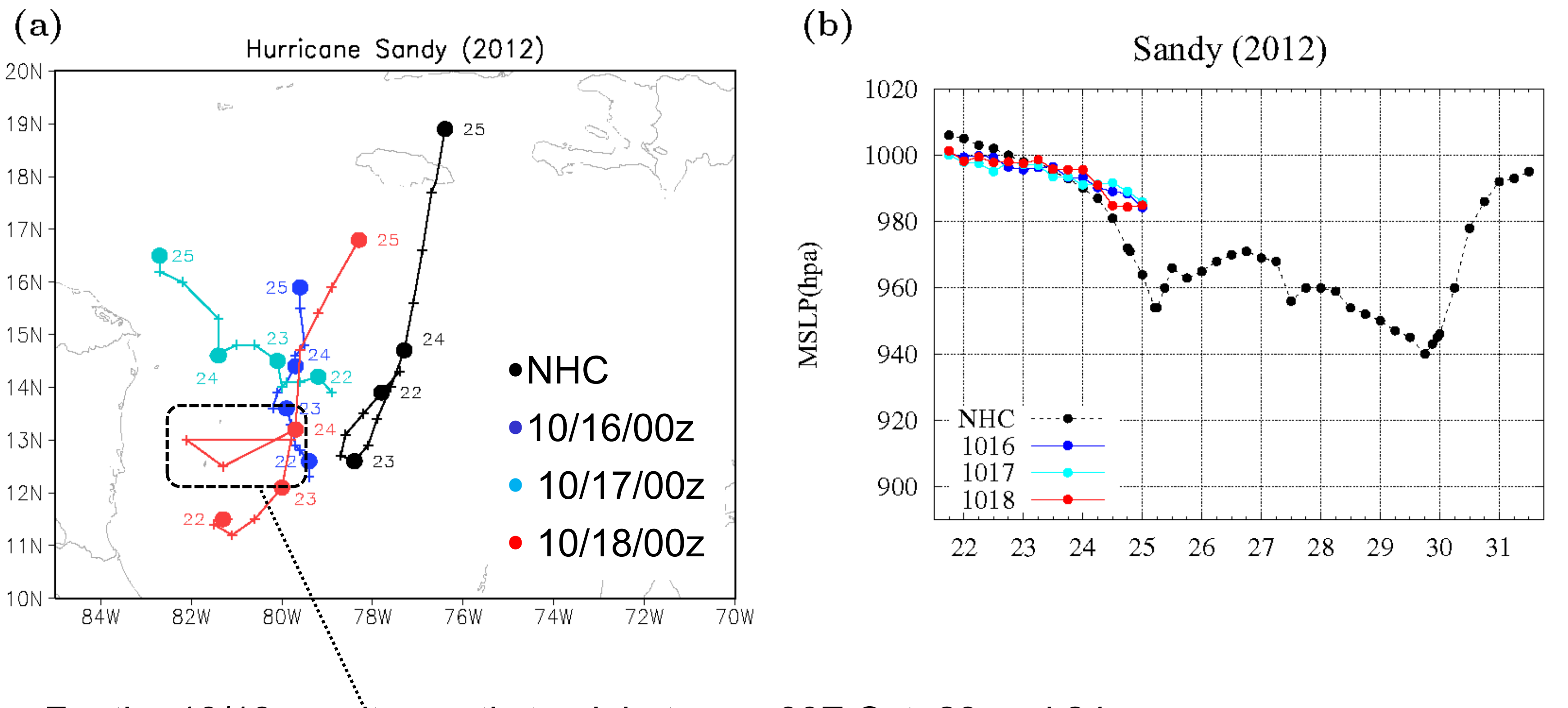
No good forecasts (init at 00Z Oct 14 and 15).




850 hPa winds Averaged over a two-day period of 00Z Oct 21-23.

Dependence on Initial Conditions

# Track and Intensity after Genesis



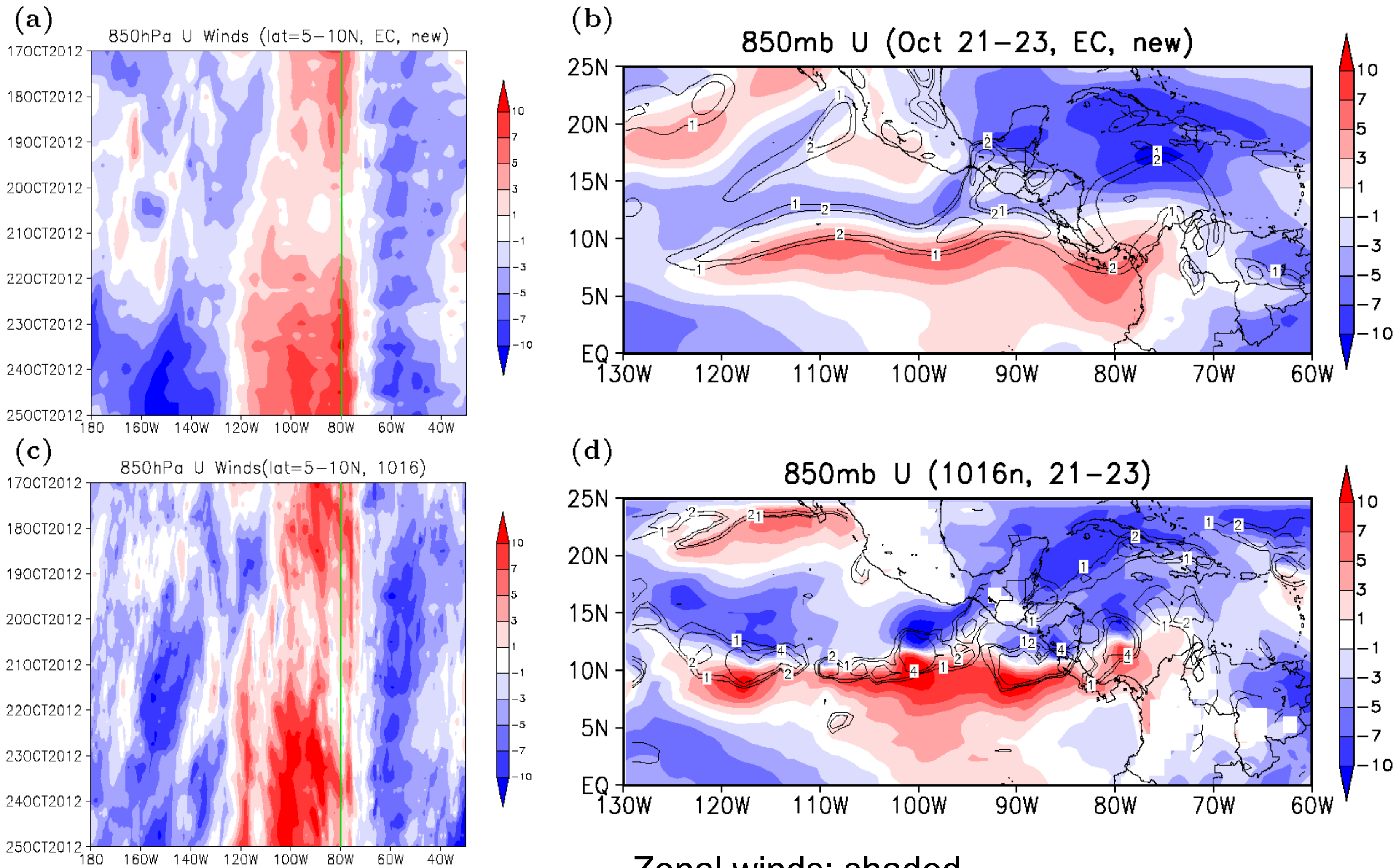

For the 10/18 run, its erratic track between 00Z Oct. 23 and 24 appears as a result of the occurrence of two low pressure centers which later merged.

# 850-hPa Zonal Winds

Time ↓

ERA-Interim T255

Model run init at 00Z Oct 16



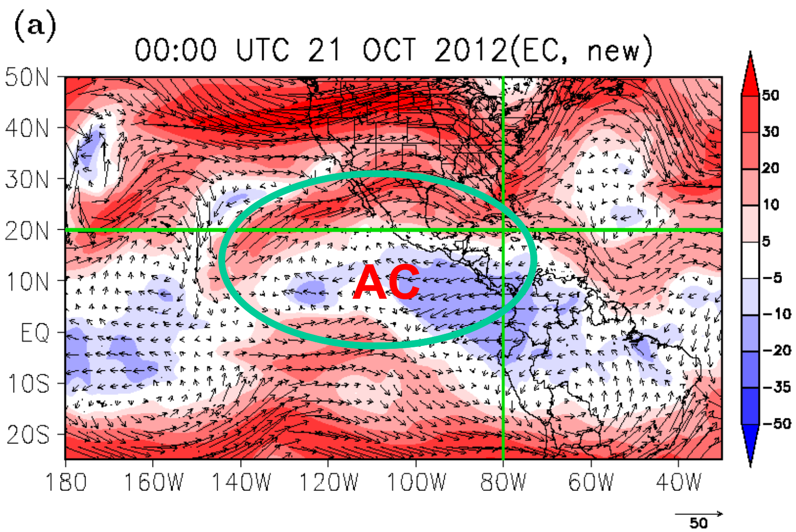

Zonal winds: shaded
Vorticity: contour lines

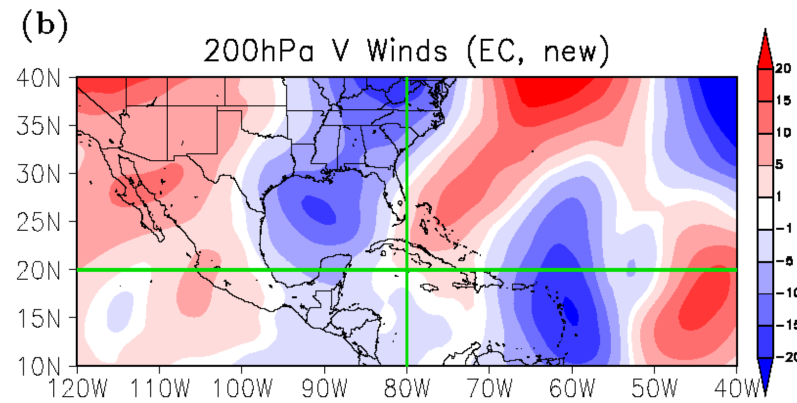
# 200-hPa Upper-level Winds

Wind vector and Zonal winds (shaded)

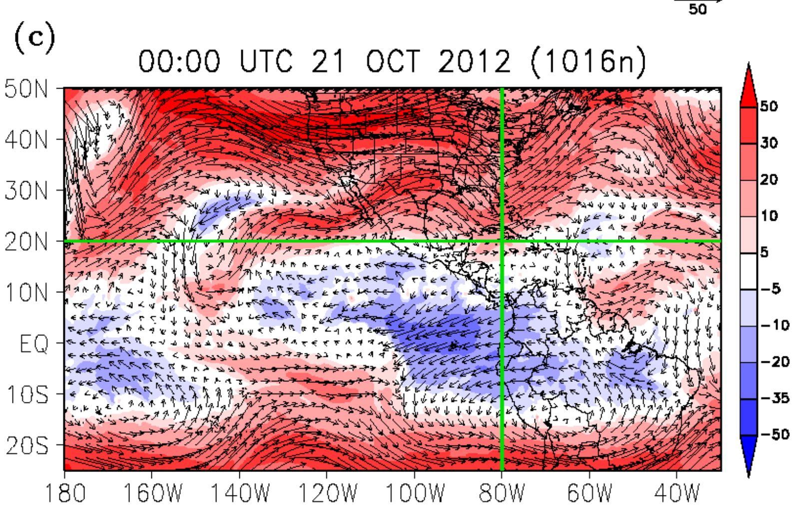
Meridional winds (shaded)

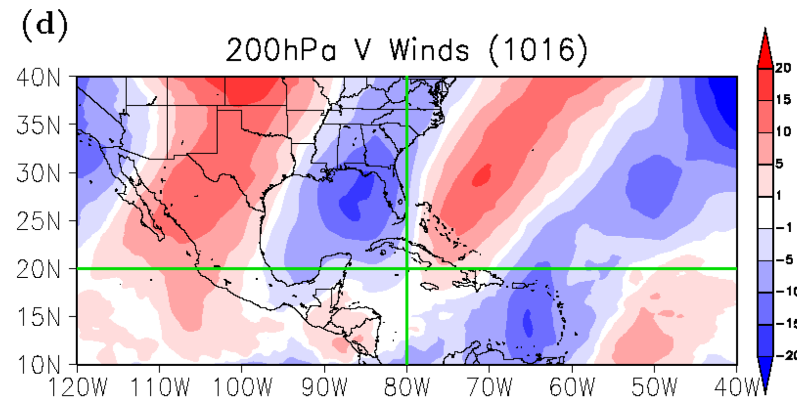
ERA-Interim T255



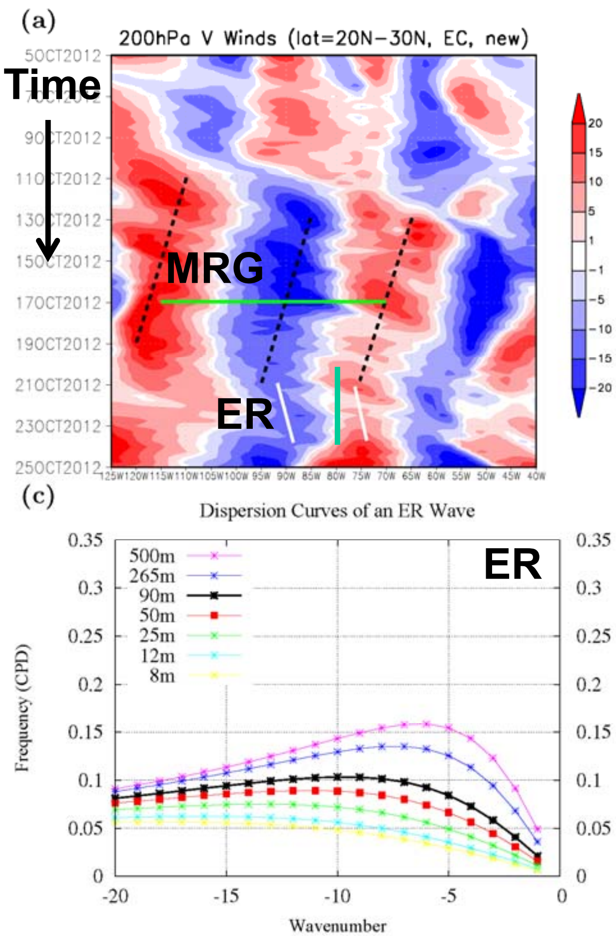



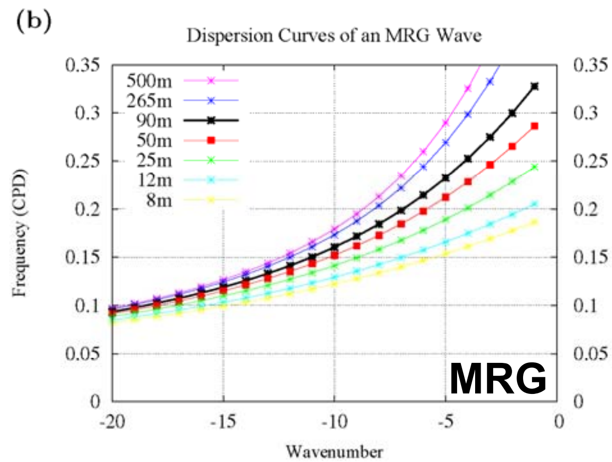

Model run init at 00Z Oct 16



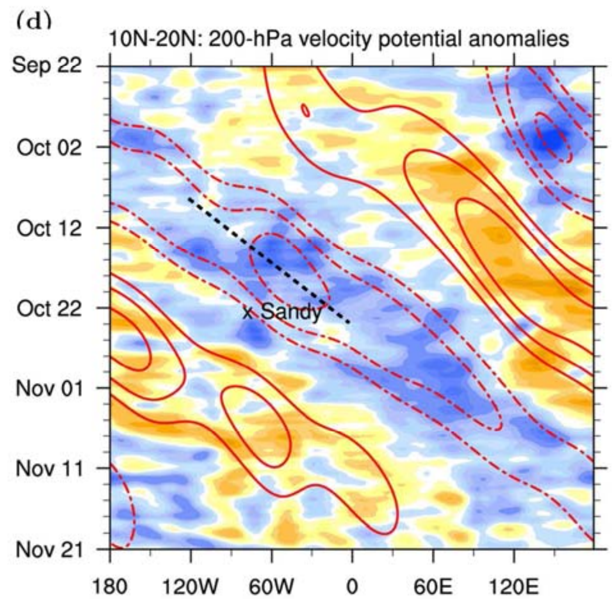



# Characteristics of Wave-like Disturbances (200-hPa V winds)



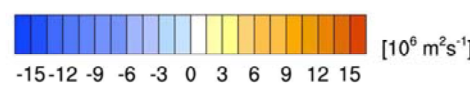




$$\sigma = \frac{-\beta k}{k^2 + \beta(2n+1)/\sqrt{gH_e}}.$$




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

- the wavelength ~ 45 degrees (K=-8)
- 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.



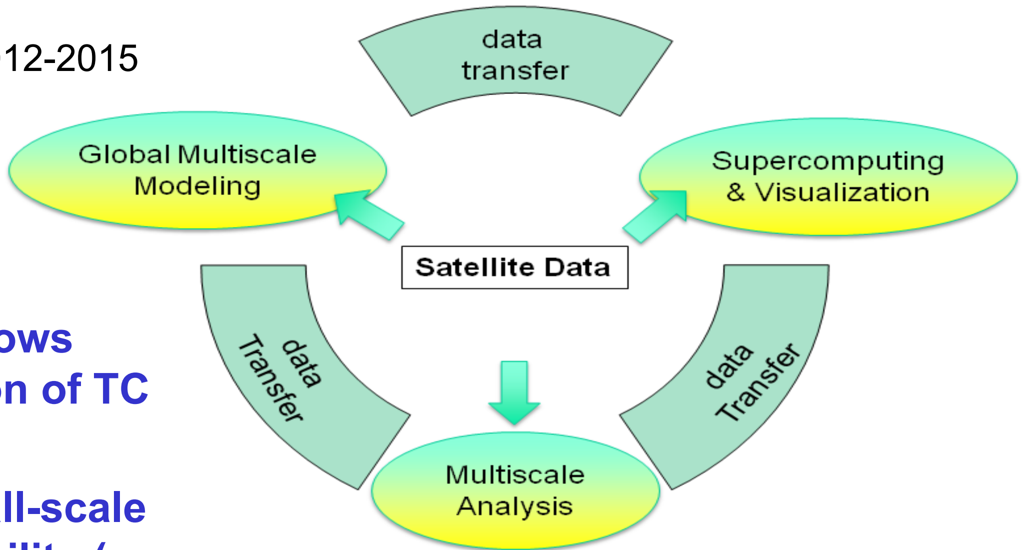
# Summary

- 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, 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).

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**




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