On the Predictability of 30-day Global Mesoscale Simulations of Multiple African Easterly Waves during Summer 2006: A View with a Generalized Lorenz Model

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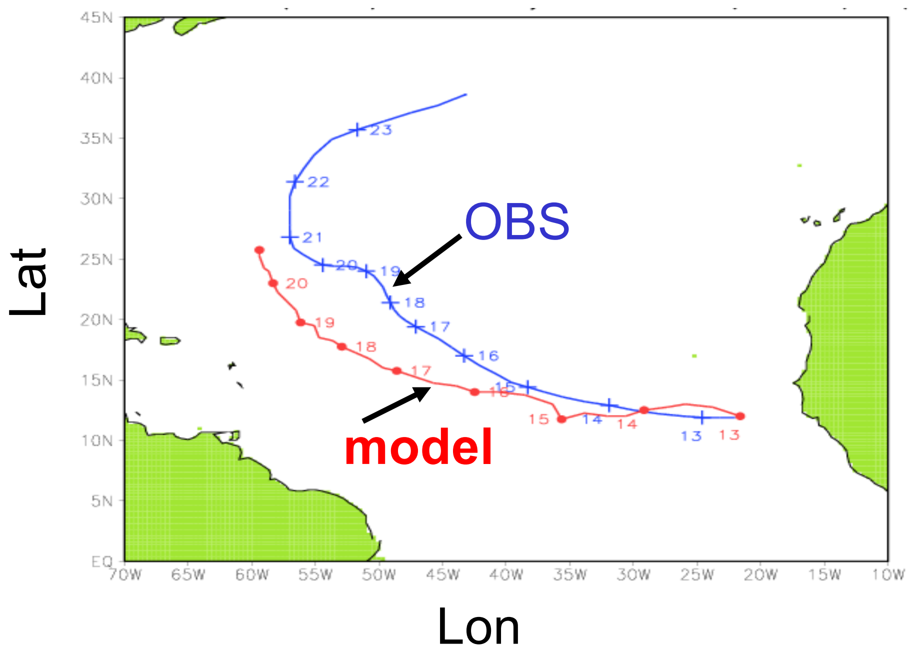
Outline

1. Introduction and Goals
   - Realistic simulation of Hurricane Helene (2006) in 30-day runs
   - Is the theoretical limit of predictability two weeks?
   - Is weather chaotic?
2. Global Model Simulations and Analysis of AEWs
   - A conceptual model with multiscale processes (downscaling vs. upscaling)
   - Simulations of multiple African easterly waves (AEWs)
   - A sensitivity study for the development of an African easterly jet (AEJ)
   - A 10-year analysis of multiscale processes
3. A Generalized Lorenz Model and Various Types of Solutions
   - The Lorenz 1963 model and a generalized Lorenz model
   - Three types of solutions (e.g., steady-state, chaotic and limit cycle orbits)
   - Two kinds of attractor coexistence
   - A hypothetical mechanism for the predictability of the 30-day runs
4. Summary

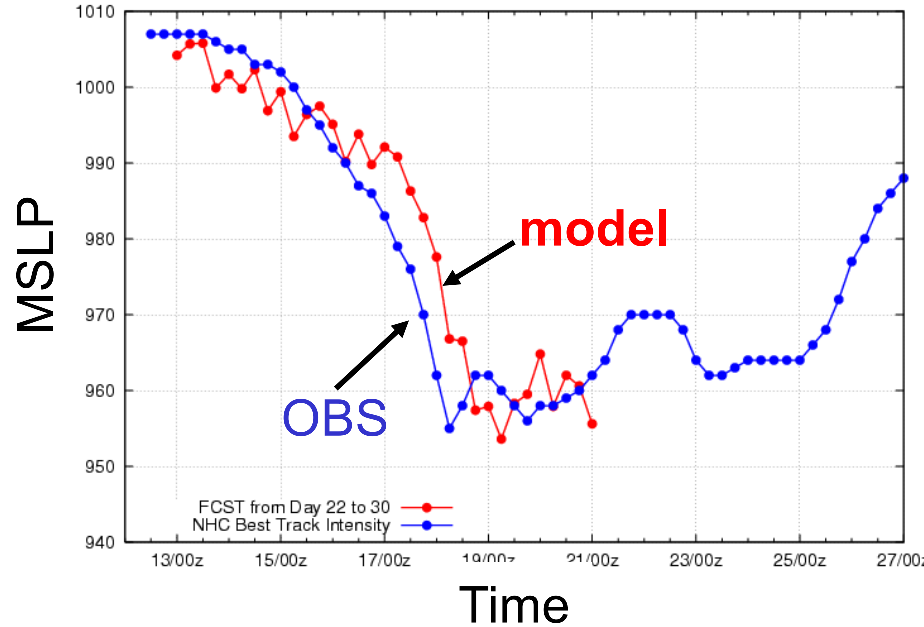
Goals: Predictability, Scale Interactions and Chaos

- We documented realistic simulations of Hurricane Helene (Sep. 12-24, 2006) between Day 22 and 30 (Shen et al., 2010; Shen, 2019b).

Track Forecast

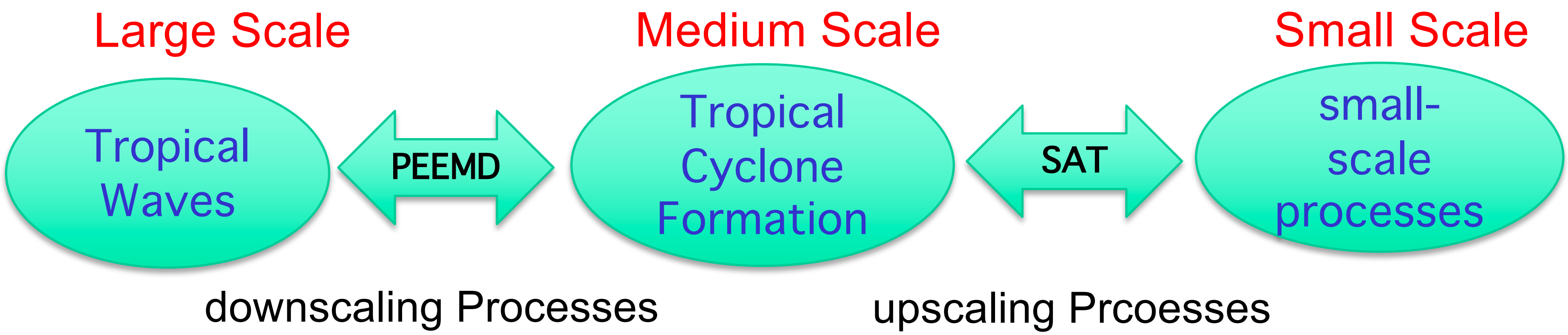


Intensity Forecast

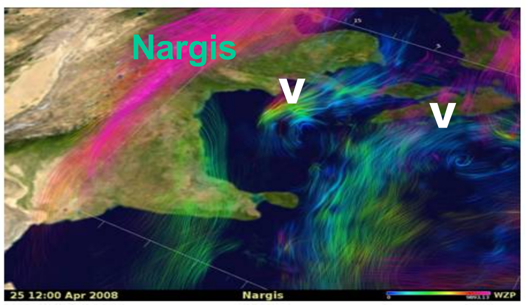


- Is the limit of predictability two weeks?
- Is weather chaotic?
- Are small-scale processes less predictable than large-scale processes?
- Can errors associated with small-scale processes “quickly” contaminate simulations of large-scale flows?

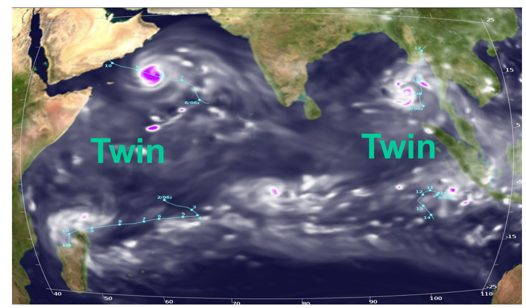
A Conceptual Model with Multiscale Processes



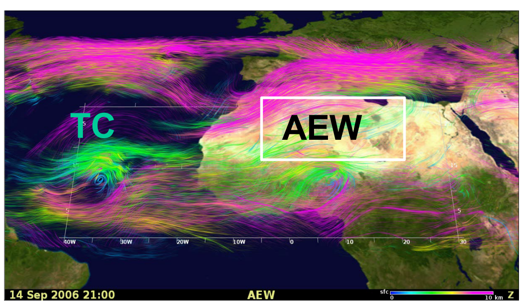
- to what extent can large-scale flows (e.g., AEWs) determine the timing and location of TC genesis? (e.g., downscaling)



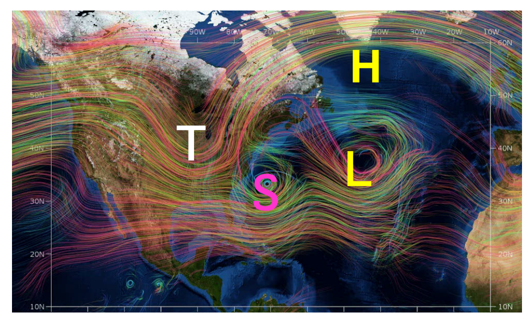
Nargis and an ER Wave (Shen et al. 2010a)



Twin TCs and a MRG Wave (Shen et al., 2012)



Helene and an AEW (Shen et al., 2010b)

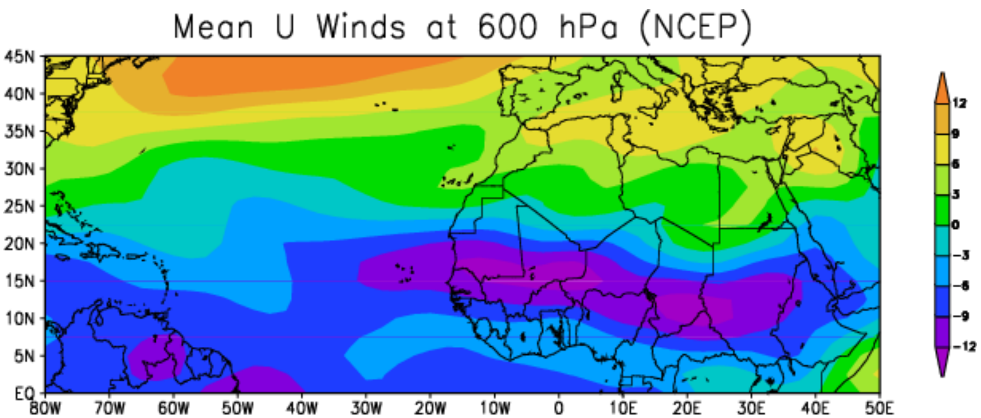


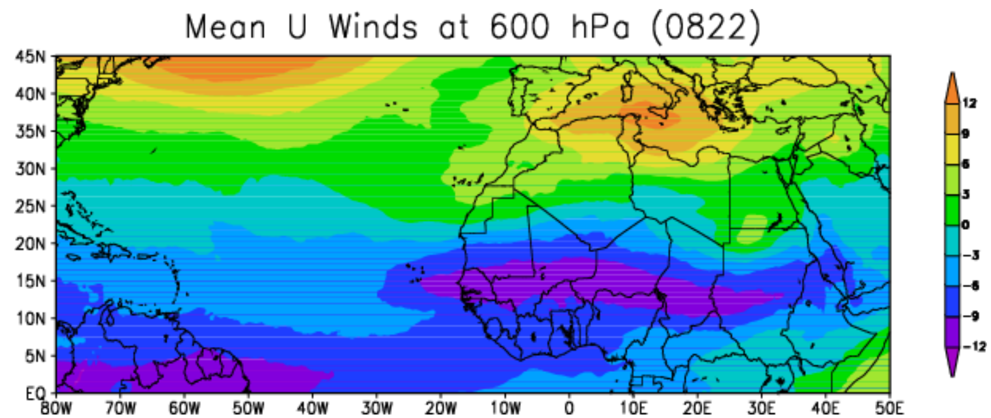
Sandy and Multiscale Systems (Shen et al., 2013)

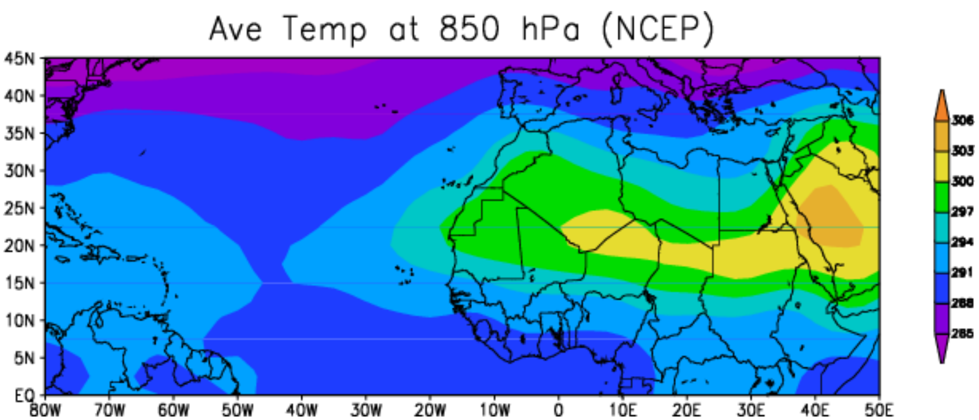
30-day Averaged U Winds and Temp

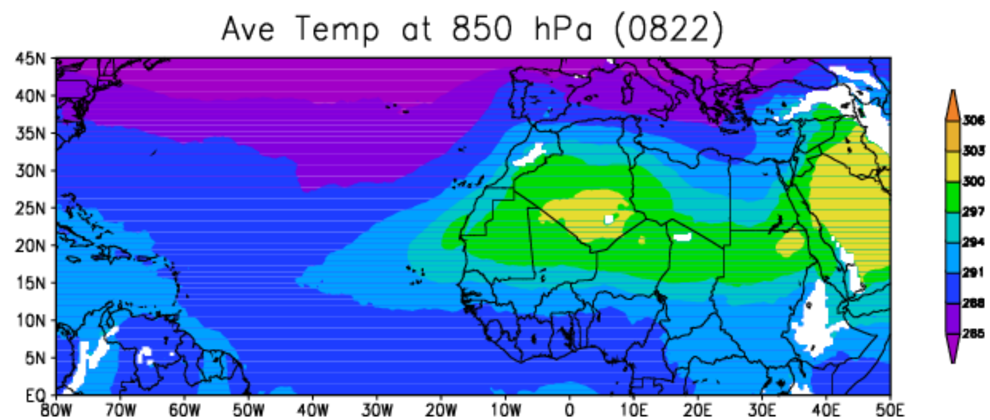
NCEP Reanalysis

Model Simulations (CNTL)





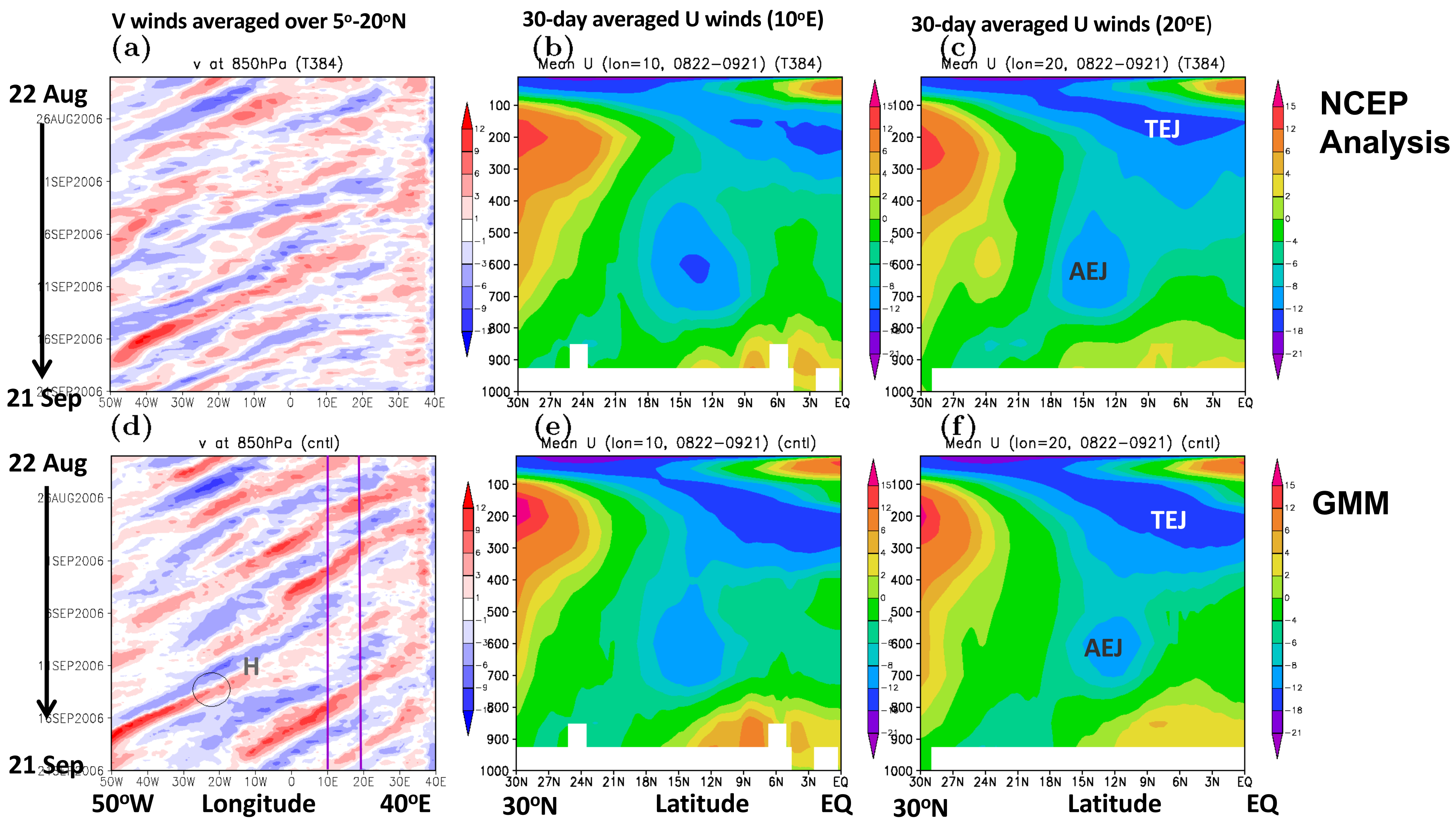




Shen, B.-W. et al., 2010b: African Easterly Waves and African Easterly Jet in 30-day High-resolution Global Simulations. A Case Study during the 2006 NAMMA period. Geophys. Res. Lett., L18803, doi:10.1029/2010GL044355.

Five AEWs in 30-day Simulations

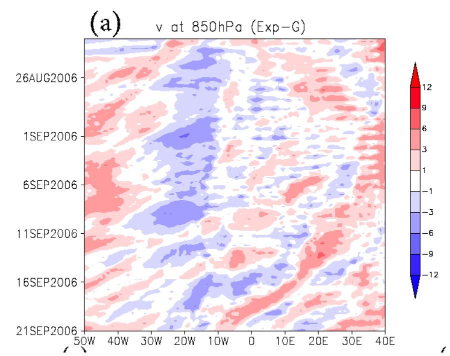
- Initial conditions: at 00zz Aug 22, 2006
- Study period: August 22 – September 21, 2006



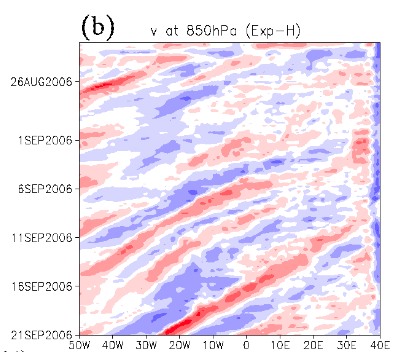
A Sensitivity Study with Parallel Experiments

Case ID	Dynamic IC	CLM and Physics IC	Remarks
CNTL	08/22	08/22	
P1	04/22	08/22	for AEJ development
P2	06/22	08/22	for AEJ development
P3	08/22	08/22	A factor of 0.6 in heights

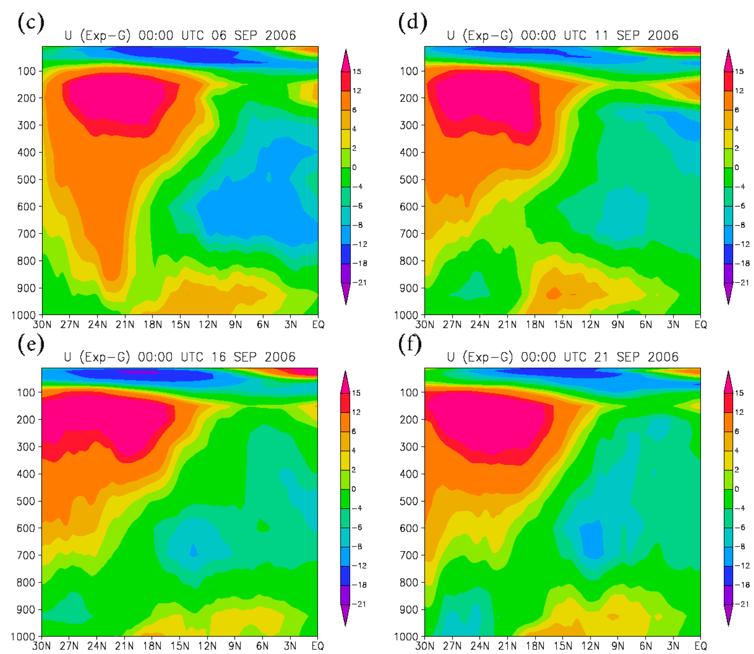
P1



P2

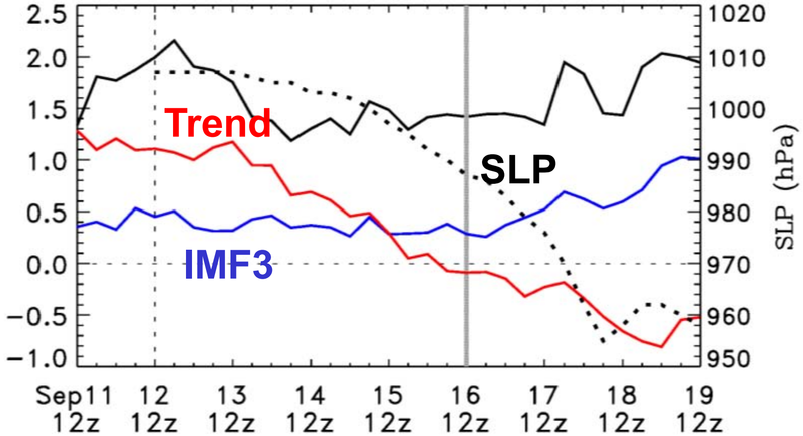


P1



A10-year Analysis of Multiscale Processes

Downscale Transfer (Helene)



In the mid-east Main Development Region (MDR, 7^o-20^o N and 60^o W - 15^o E.)

- 42 TD/TSs appeared in association with AEWs,
- 25 of these TDs/TSs eventually turned into hurricanes,
- 13 hurricanes showed the features of downscaling processes.

Approach using the PEEMD:

1. Decompose U (and V) winds at 700 hPa into a set of IMFs
2. Calculate the wind shear, Uy (and Vx), in each of the IMFs
3. Calculate spatial average Uy (and Vx) as a function of time

Physical interpretations of decomposed components

- ❖ Uy in the trend mode indicates the magnitude of shear of the basic state, a potential indicator of (barotropic) shear instability.
- ❖ Uy in the IMF3 indicates the strength of a TC or an AEW (as vorticity).

• Wu, Y.-L.,and B.-W. Shen, **2016:** An Evaluation of the Parallel Ensemble Empirical Mode Decomposition Method in Revealing the Role of Downscaling Processes Associated with African Easterly Waves in Tropical Cyclone Genesis. J. Atmos. Oceanic Technol. 33, 1611-1628, DOI: 10.1175/JTECH-D-15-0257.1.

The Lorenz Model and A Generalized Lorenz

The Lorenz 1963 Model (3DLM, Lorenz, 1963) Three Dimension

$$\frac{dX}{d\tau} = -\sigma X + \sigma Y,$$

$$\frac{dY}{d\tau} = -XZ + rX - Y,$$

$$\frac{dZ}{d\tau} = XY - bZ.$$

primary scale modes

A Generalized Lorenz Model (GLM, Shen, 2019a) Any Odd Dimension

$$\frac{dX}{d\tau} = -\sigma X + \sigma Y,$$

$$\frac{dY}{d\tau} = -XZ + rX - Y,$$

$$\frac{dZ}{d\tau} = XY - XY_1 - bZ,$$

smaller scale modes

$$\frac{dY_j}{d\tau} = jXZ_{j-1} - (j+1)XZ_j - d_{j-1}Y_j, \quad j \in [1, N],$$

$$\frac{dZ_j}{d\tau} = (j+1)XY_j - (j+1)XY_{j+1} - \beta_j Z_j, \quad j \in [1, N],$$

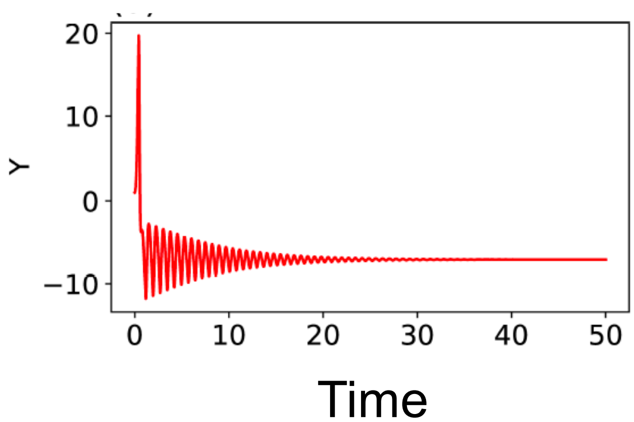
$$N = \frac{M-3}{2}; \quad d_{j-1} = \frac{(2j+1)^2 + a^2}{1+a^2}; \quad \beta_j = (j+1)^2 b.$$

- r – Rayleigh number
- σ – Prandtl number
- b – Physical proportion

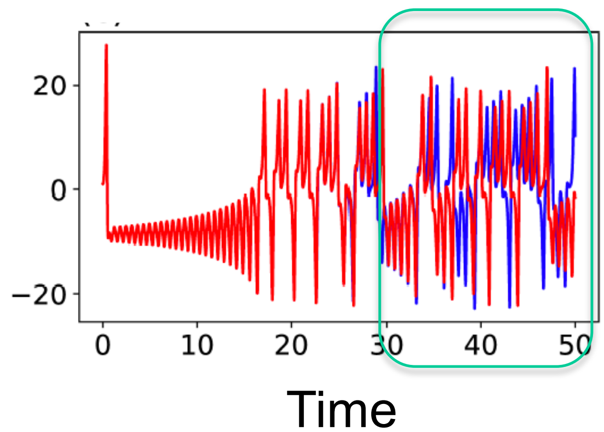
Three Kinds of Attractors and Butterfly Effect

- Depending on the relative strength of heating, as compared to $r_c = 24.74$ and $R_c = 313$, three types of solutions within the 3DLM are:
  - ✓ control run (blue): $(X, Y, Z) = (0, 1, \quad 0)$
  - ✓ parallel run (red): $(X, Y, Z) = (0, 1 + \epsilon, 0)$, $\epsilon = 1e - 10$

A steady-state solution
$(\, r < r_c)$

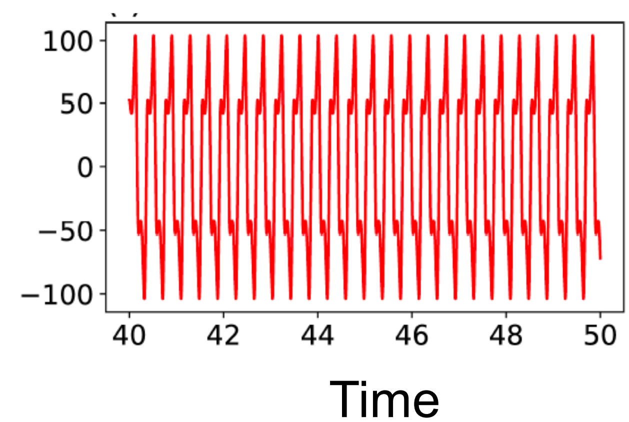


A chaotic solution
$(r_c < \mathrm{r} < R_c)$



sensitive dependence

A limit cycle
$(R_c < r)$



The LC, except for its phase, has no long term memory regarding ICs.

- Butterfly effect of the first kind (BE1)
- appearing within a finite range of parameters

Major Features of the GLM

As discussed in Shen (2019a) and Shen et al. (2019a), the GLM with many M modes possesses the following features:

(1) any odd number of M greater than three; a conservative system in the dissipationless limit;

(2) three types of solutions (that also appear within the 3DLM);

(3) energy transfer across scales by the nonlinear feedback loop (NFL);

(4) slow and fast variables across various scales;

(5) aggregated negative feedback;

(6) increased temporal complexities of solutions associated with additional (incommensurate) frequencies that are introduced by the extension of the NFL (i.e., spatial mode-mode interactions);

(7) hierarchical scale dependence;

(8) two kinds of attractor coexistence;

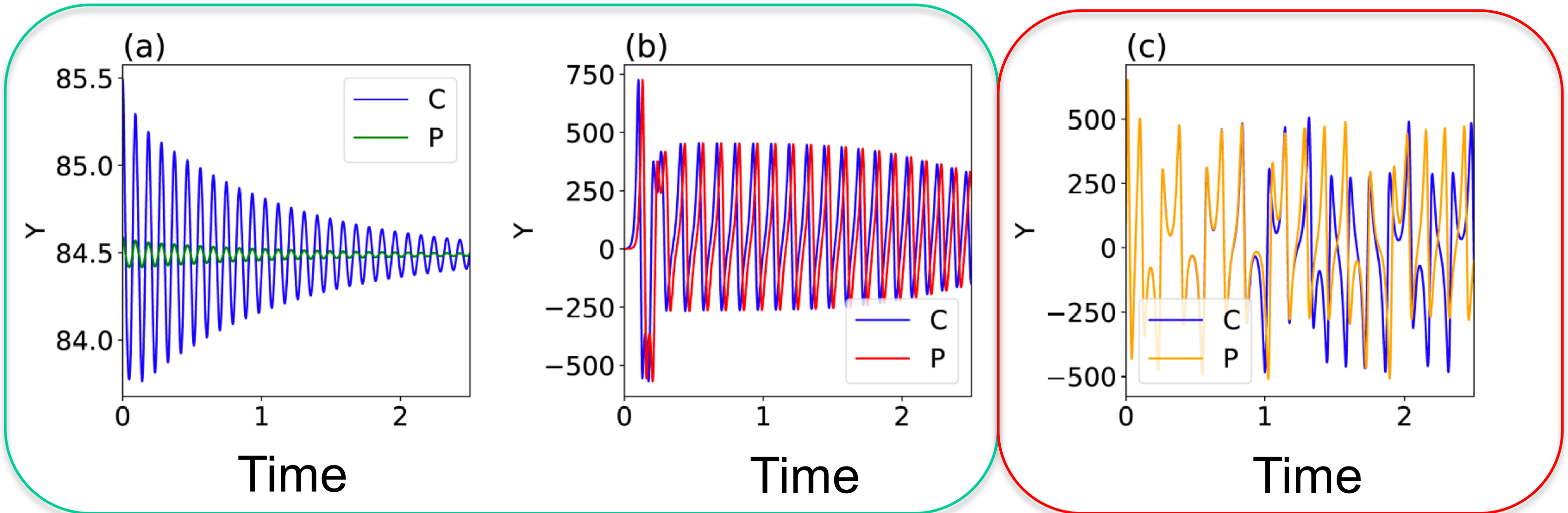
- The 1st kind of Coexistence for Chaotic and Steady-state Solutions,
- The 2nd kind of Coexistence for Limit Cycle and Steady-state Solutions.

The First Kind of Attractor Coexistence

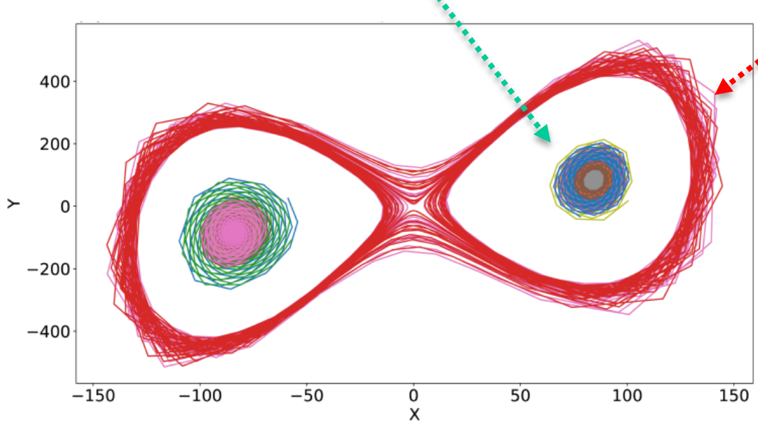
- The 1st kind of attractor coexistence within the GLM using 9 modes (referred to as the 9DLM) indicates final state sensitivity to ICs.

non-chaotic orbits

chaotic orbit



r=680



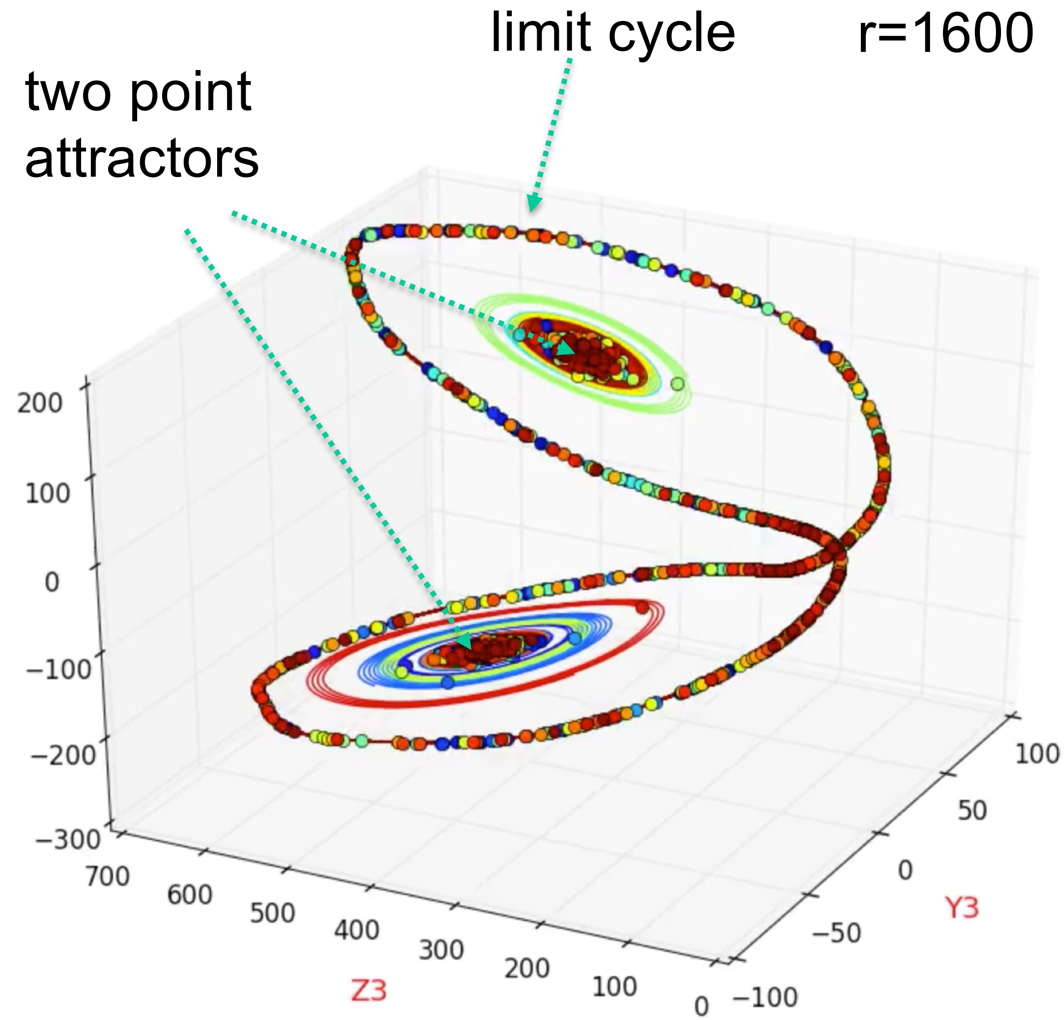
The coexistence of chaotic and non-chaotic orbits displays distinct regions of attraction.

(Note that the figure displays 128 orbits with different ICs)

The Second Kind of Attractor Coexistence

- For the 2nd kind of attractor coexistence, a limit cycle (LC) that is an isolated closed orbit coexists with point attractors within a GLM.

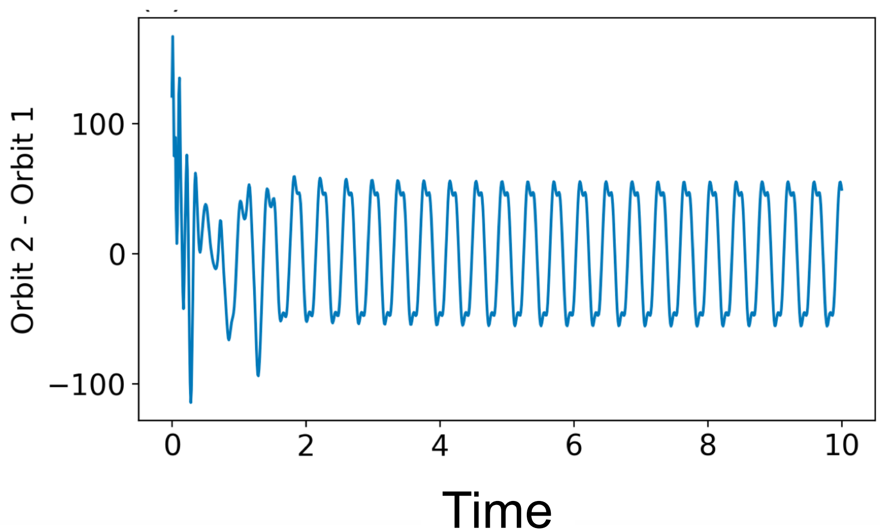
- Time evolution of 2,048 orbits in the X-Y_3-Z_3 space using the 9DLM.
- The total simulation time is τ = 3.5.
- Transient orbits are only kept for the last 0.25 time units, i.e. for the time interval of [max (0, T-0.25), T] at a given time T.

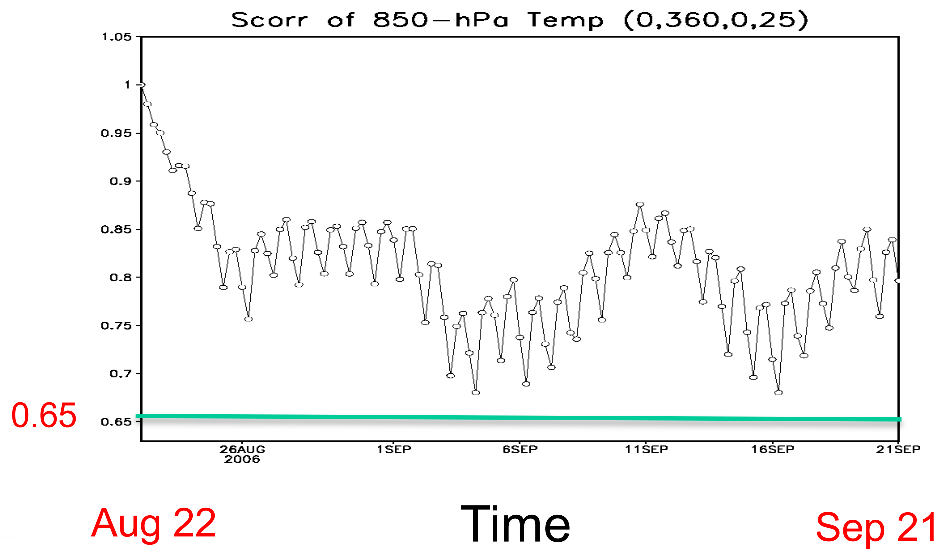


- The animation is available from https://goo.gl/sMhoUb.

A Hypothetical Mechanism for the Predictability of the 30-day Runs

Limit Cycle	African Easterly Waves (AEWs)
oscillatory errors	oscillatory correlation coefficients
strong heating + nonlinearity	during summer (JAS)





➢ The realistic simulation of Hurricane Helene (2006) from Day 22 to 30 became possible as a result of the realistic simulation of the

1. periodicity (or recurrence) of AEWs and
2. downscaling process of the 4th AEW.

Summary

1. Using a global mesoscale model, we showed promising 30-day simulations of multiple AEWs and formation of hurricanes. High but oscillatory correlation coefficients were obtained for the 30-day period (see (5) for explanations).
2. By developing a new tool for nonlinear multiscale analysis, we showed that the downscaling processes contributed to the high predictability of Helen's predictions.
3. In a 10-year analysis study using the EC reanalysis data, we showed that (i) 42 TCs were associated with AEWs; (ii) 25 TCs intensified into hurricanes; and (iii) 13 of intense hurricanes showed downscaling processes.
4. Our results provides the view, which is consistent with Prof. Arakawa's, that the theoretical limit of predictability should not be a fixed number of two weeks.
5. Using Lorenz model, we suggested a collective role of nonlinearity and strong heating in producing nonlinear oscillatory solutions, leading to oscillatory divergence between the control and parallel runs.
6. In Lorenz (1969), experiments that examined the impact of downscale and upscale transfer of errors produced comparable predictability limits.
7. We suggest that the entire weather possesses a dual nature of chaos and order that consists of chaotic and non-chaotic processes (Shen et al., 2019a, b and references therein).

Takeaway Messages

- Is weather chaotic?
  - Shen et al. (2019a, b) propose that the entire weather possesses a dual nature of chaos and order associated with chaotic and non-chaotic processes, respectively.
  - The above refined view is neither too optimistic nor pessimistic as compared to the Laplacian view of deterministic unlimited predictability and the Lorenz view of deterministic chaos.
- Is the limit of predictability two weeks?
  - ”*there is no reason that it is a fixed number*” as suggested by Prof. Arakawa (Lewis, 2005, MWR)
- Are small-scale processes less predictable than large-scale processes? Not all of them
- Can errors associated with small-scale processes “quickly” contaminate simulations of large-scale flows? Not always
- References and additional information can be found in the following link: https://bwshen.sdsu.edu.