# Characteristics of intensity errors in the HWRF model and predictability implication

Chanh Kieu,
Department of Earth & Atmospheric Sciences
Indiana University, Bloomington

*Collaborators*: *Quan Wang (IU), Kushal Keshavamurty (IU), Allies Downs (IU), Vijay Tallapragada (EMC), Zhan Zhang (EMC), Avichal Mehra (EMC), Sundararaman Gopalakrishnan (HRD)*

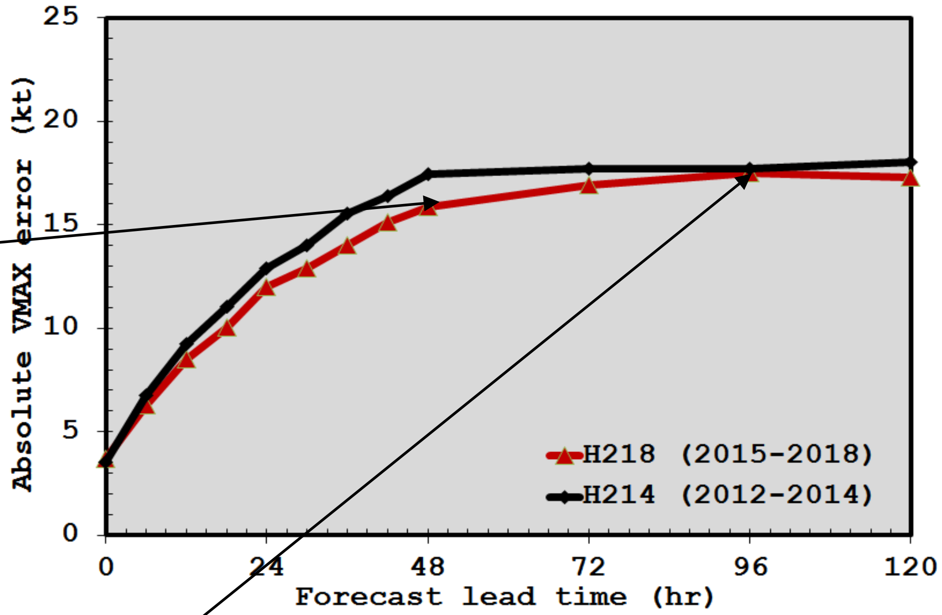
HFIP Telecon, October 2018

# Outline

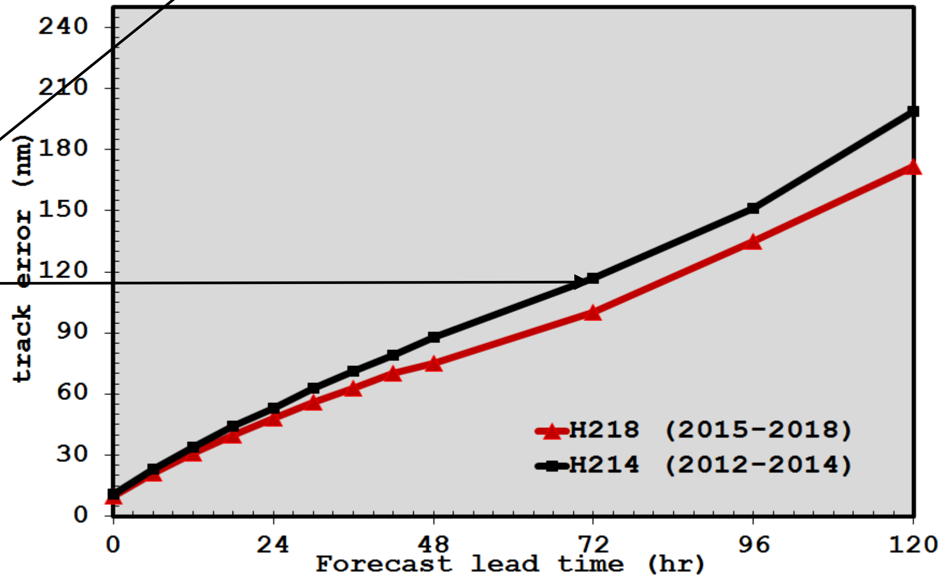
- Introduction
- TC intensity dynamics
- Intensity error characteristics
- HWRF intensity error saturation
- HWRF intensity error growth
- HWRF idealized analyses
- Concluding remarks

# Introduction

Substantial track error improvement over years but not much in intensity!



The intensity error curve looks fundamentally different from the track error curve!



# Scientific questions

The district behaviors of the track and intensity errors bring up several fundamental questions that we wish to address

1. Is the intensity predictability different from track predictability?
2. Are intensity errors due to the intrinsic variability or they are due to the model deficiency?
3. Is there any limit in reducing the intensity errors further?
4. What is the fraction of the intrinsic variability of the TC intensity as compared to the total real-time intensity error in the HWRF model?; and
5. How does the intrinsic variability change with large-scale environment?;

# Approach to TC intensity error problem

There are two approaches to understand the TC intensity error characteristics;

1. Deterministic formalism (or Dynamical framework): Apply for point-like TC intensity metrics by which TC models are treated as a deterministic dynamical system that output TC basic measures:

$$\frac{d\mathbf{X}}{dt} = M(\mathbf{X})$$

where $\mathbf{X} \equiv (V_{max}, U_{max}, W_{max}, P_{min}, RMW, T')$. The predictability now focuses on 1) existence of attractor (boundedness), ii) denseness, and iii) Lyapunov exponent;

2. Statistical formalism: Apply for field-like TC intensity metrics by which TCs are considered as turbulence systems, but then what do we mean by intensity? Is that wind distribution, moisture, temperature ? What observation can we use to verify this intensity and construct climatology? Potential useful in future if satellite obs becomes much more details.

# Deterministic framework

Dynamical systems within the deterministic framework essentially has three different categories:

- Stable systems: $\epsilon\,(t) = \epsilon_0 e^{-\lambda t}$
- Unstable systems: $\epsilon\,(t) = \epsilon_0 e^{\lambda t}$
- Chaotic systems: i) $\epsilon\,(t) = \epsilon_0 e^{\lambda t}$, ii) boundedness, and iii) denseness

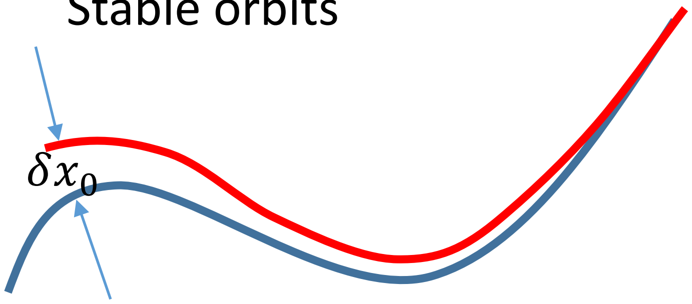
Track errors !!!

Intensity errors !!!

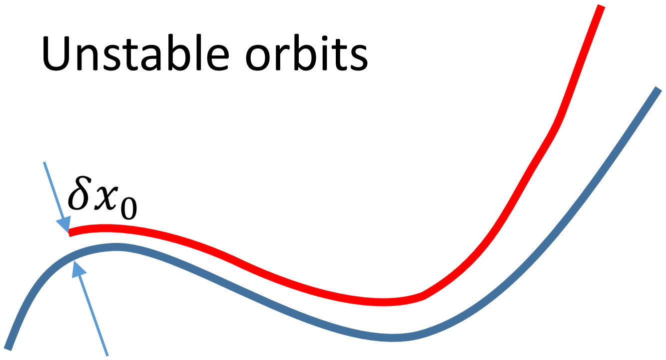
# Deterministic framework

To verify the TC intensity predictability within the deterministic framework , it is important to clearly distinguish several different dynamical behaviors in phase space.

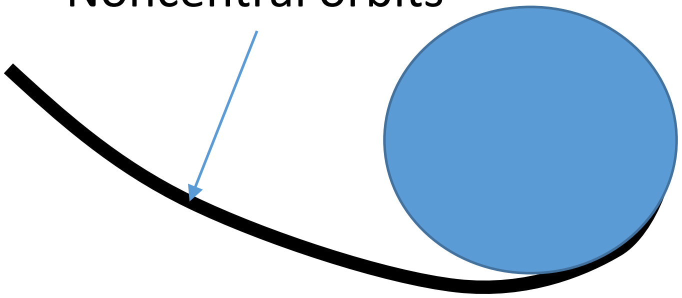
Stable orbits



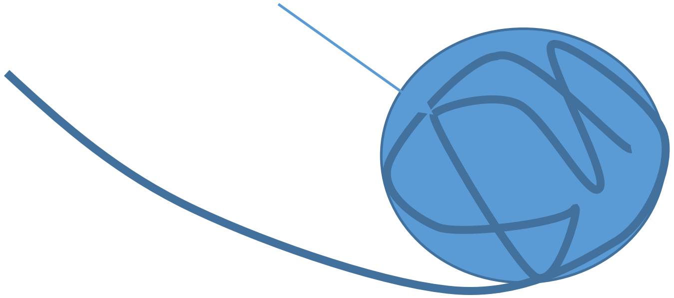
Unstable orbits



Noncentral orbits



Central orbits



Remarks:

- For chaotic attractors, noncentral orbits are unstable (because central orbits are unstable)
- Nonperiodic orbits are unstable

# Deterministic framework: A low-order model

A low-order model based on the TC-scale dynamics was recently presented to examine the TC development in a reduced phase space (U,V,B) (Kieu 2015 QJ, Kieu and Wang 2017a,b, JAS)

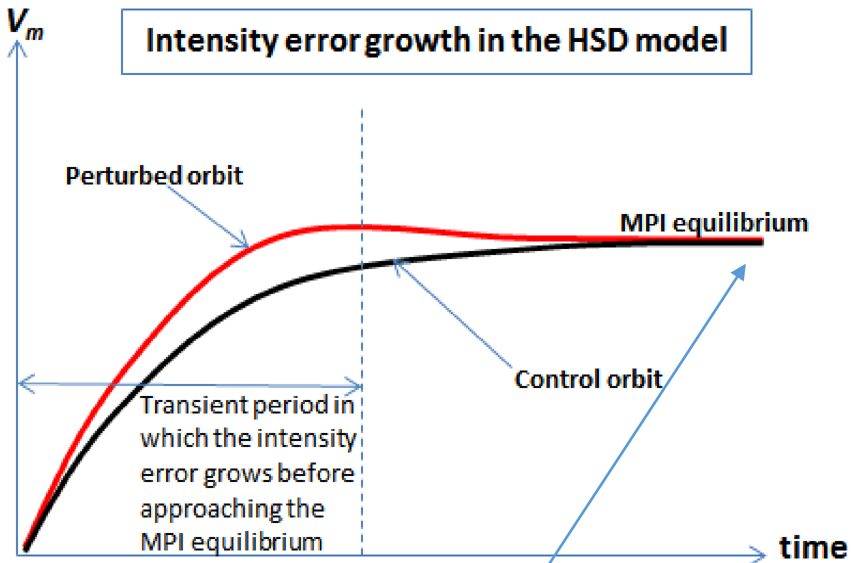
$$\dot{U} = \gamma V^2 - \frac{\gamma}{\alpha} B - \beta U V$$

$$\dot{V} = -\gamma U V - \beta V^2$$

$$\dot{B} = \gamma U B + \delta V$$

V: maximum surface wind
U: maximum radial wind
B: warm core

- The MPI is structurally stable and unique;
- The MPI is characterized by (U,V,B);
- The WISHE hypothesis is consistent with the MPI's stability ;

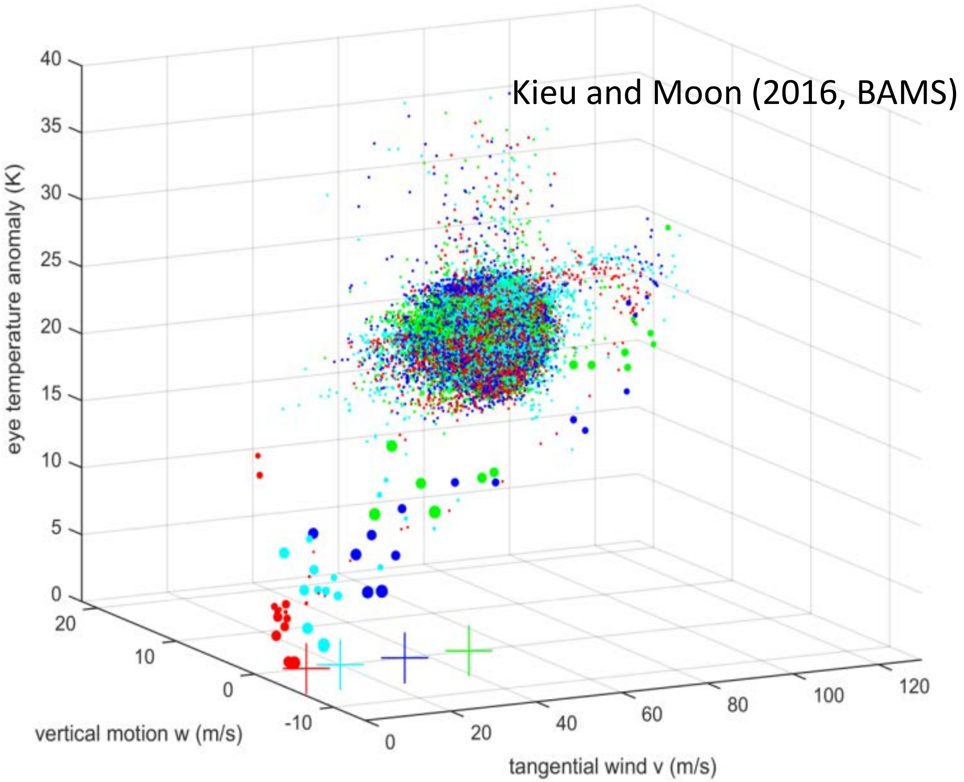


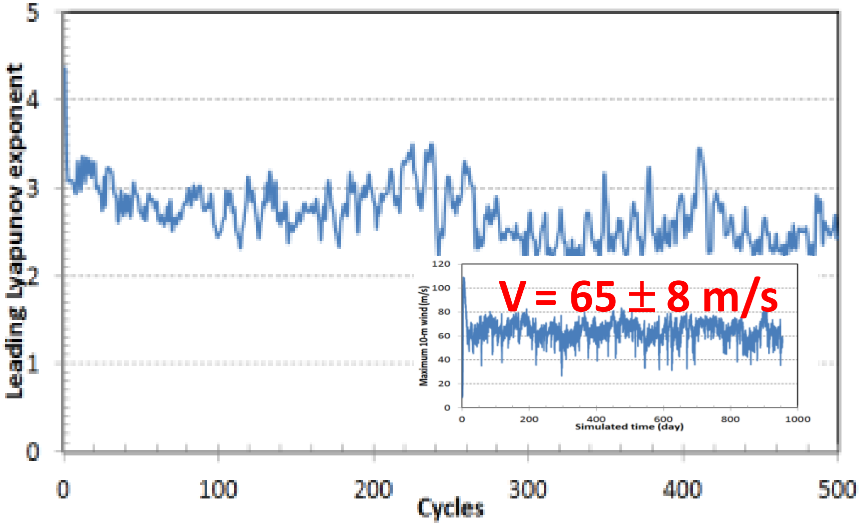
All TC intensity will approach the same MPI limit (assuming the same environment) $\rightarrow$ all intensity errors will go to zero?

# Deterministic framework: Axisymmetric model

### Idealized experiment

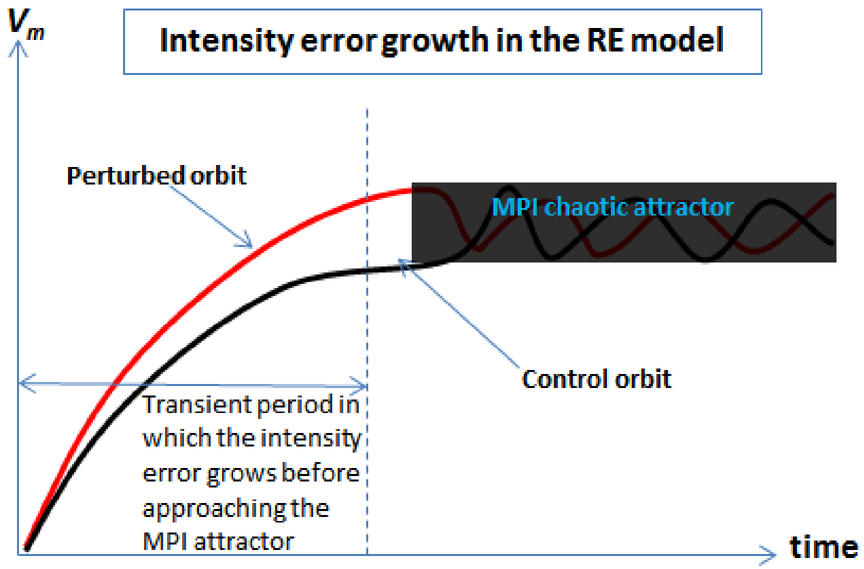
- Use Rotunno and Emanuel (1987) TC axisymmetric model;
- A bounded system;
- 1000-day simulation;
- 5 x $10^4$ DOF → examine stability in a reduced phase space of (V,W,B);


Kieu and Moon (2016, BAMS)



- Boundedness;
- Denseness (ergodic);
- Positive leading Lyapunov exponent;
- The MPI attractor depends on large-scale environment

# Axisymmetric model: intensity predictability



- Intensity errors grow quickly during noncentral (transient) orbits, but eventually converge towards the MPI attractor regardless of initial conditions;

- Inside the MPI attractor, a slight perturbation at the maximum intensity limit will drift the systems quickly → no way to control intensity errors at the mature stage ~ 8 m/s;

# Real-time HWRF forecasts: methodology

So how can we realize the intensity predictability from real-time HWRF forecast, given various inferences related to obs errors, mixed cycles, landfalling, weakening/intensifying cycles, model errors…?

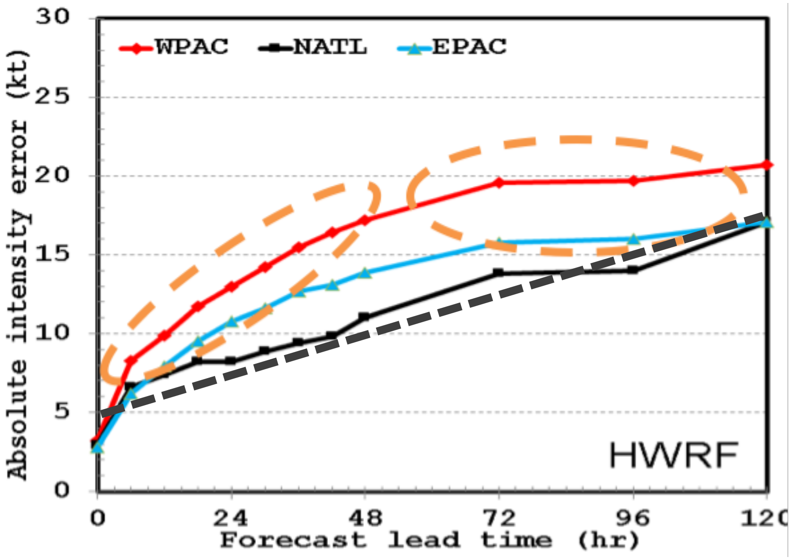
Two criteria to extract the intensity intrinsic variability from real-time intensity forecasts are (Kieu et al. 2018, QJ)

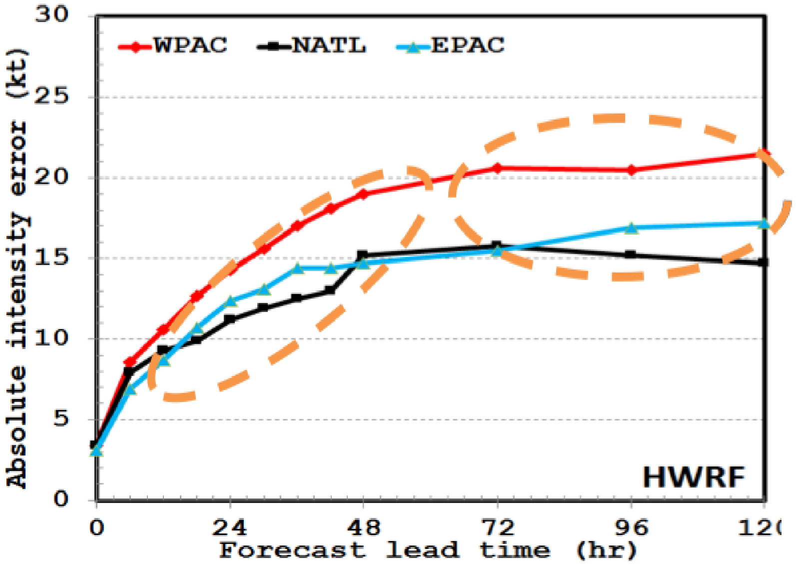
1. Quantifying the error saturation based on real-time errors: this is a must for any chaotic system
2. Verifying that an intensity noncentral orbit is unstable: Stratifying the error growth rate for intensifying cycles to see the error growth at different stages of TC development;

# Real-time HWRF intensity error saturation

- TC intensity errors grow and approach a saturation limit after 4-5 day lead times;
- Different basins have different intensity error saturation → dependence of intensity variation with large-scale environment;
- The saturation is most apparent in the WPAC and EPAC basin, but not in NATL basin due to the dominance of weaker storms

But how can we extract the intrinsic intensity variability from this real-time errors, given various obs, model, track errors?



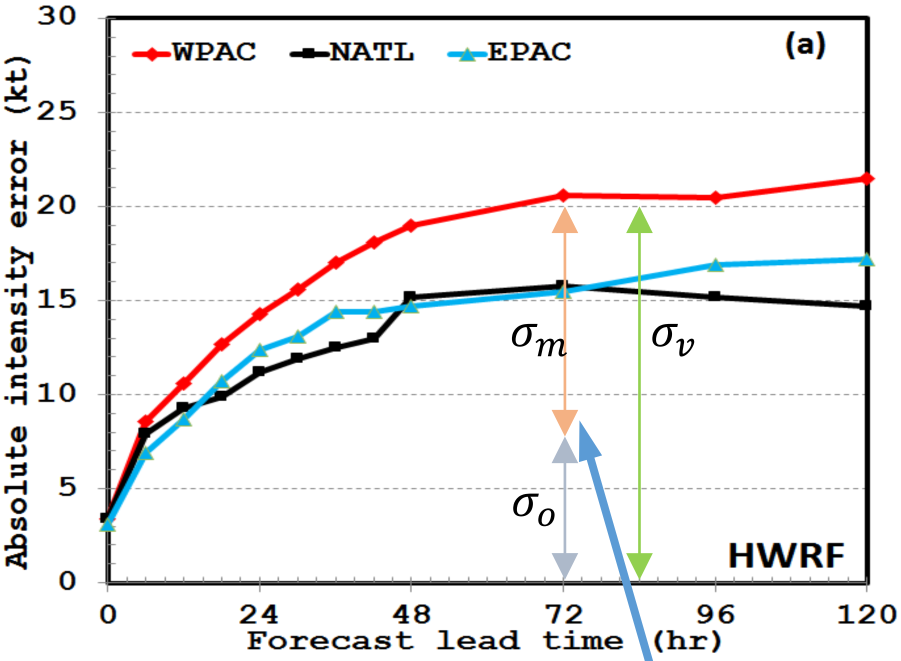


# Real-time HWRF intensity error saturation

Let $\epsilon(\tau) = V_m(\tau) - V_o(\tau)$ the VMAX error at lead time $\tau$,

$$\sigma_v(\tau) = \sigma_m(\tau) + \sigma_o - 2E[V_m(\tau)V_o(\tau) - V_t^2(\tau)]$$

$$\boxed{\sigma_v \to \sigma_m + \sigma_o}$$



But $\sigma_m$ still includes TC intrinsic dynamic errors and the model errors !!!

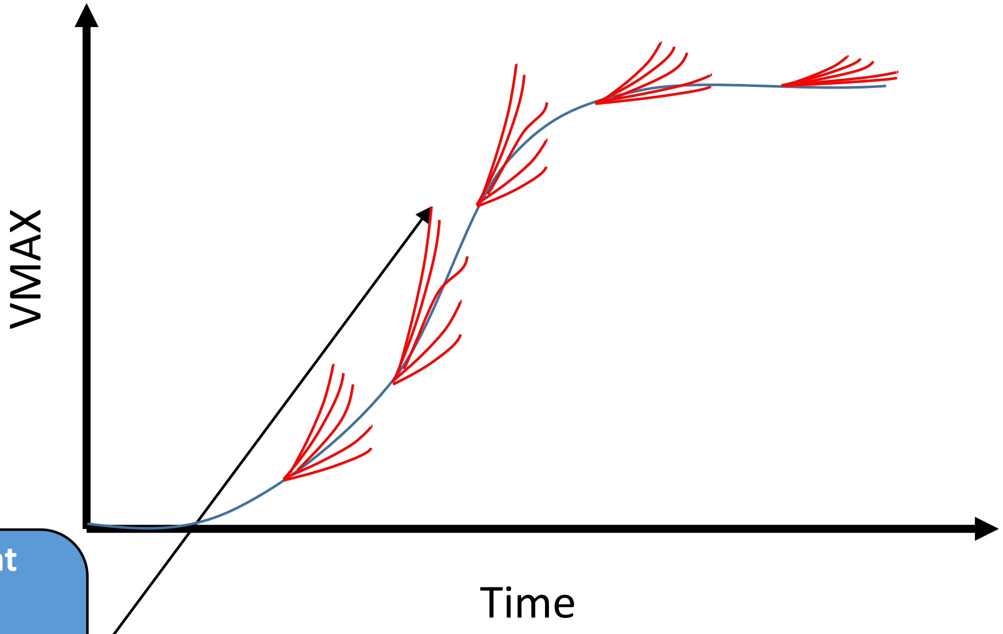
Given $\sqrt{\sigma_o} = 7.5$ kt (Torn and Snyder (2012), we then have

- For NATL: $\sqrt{\sigma_v}$= 15 kt, $\sqrt{\sigma_o}$= 7.5 kt → $\sqrt{\sigma_m}$= 12.9 kt,
- For EPAC: $\sqrt{\sigma_v}$= 16 kt, $\sqrt{\sigma_o}$= 7.5 kt → $\sqrt{\sigma_m}$= 14.1 kt,
- For WPAC: $\sqrt{\sigma_v}$= 20 kt, $\sqrt{\sigma_o}$= 7.5 kt → $\sqrt{\sigma_m}$= 18.5 kt,

# Idealized HWRF simulation

## Idealized experiments: perfect model scenario

- Use of idealized HWRF (V3.7)
- Implement a scheme to add random perturbation at different stages of intensification
- (9/3/1km) setup, but the test so far were only for 9/3km configuration
- Focus on the rapid intensification (RI) and mature stage period every 3 hours
- Varying SST and shear to determine how large-scale environment change the error saturation



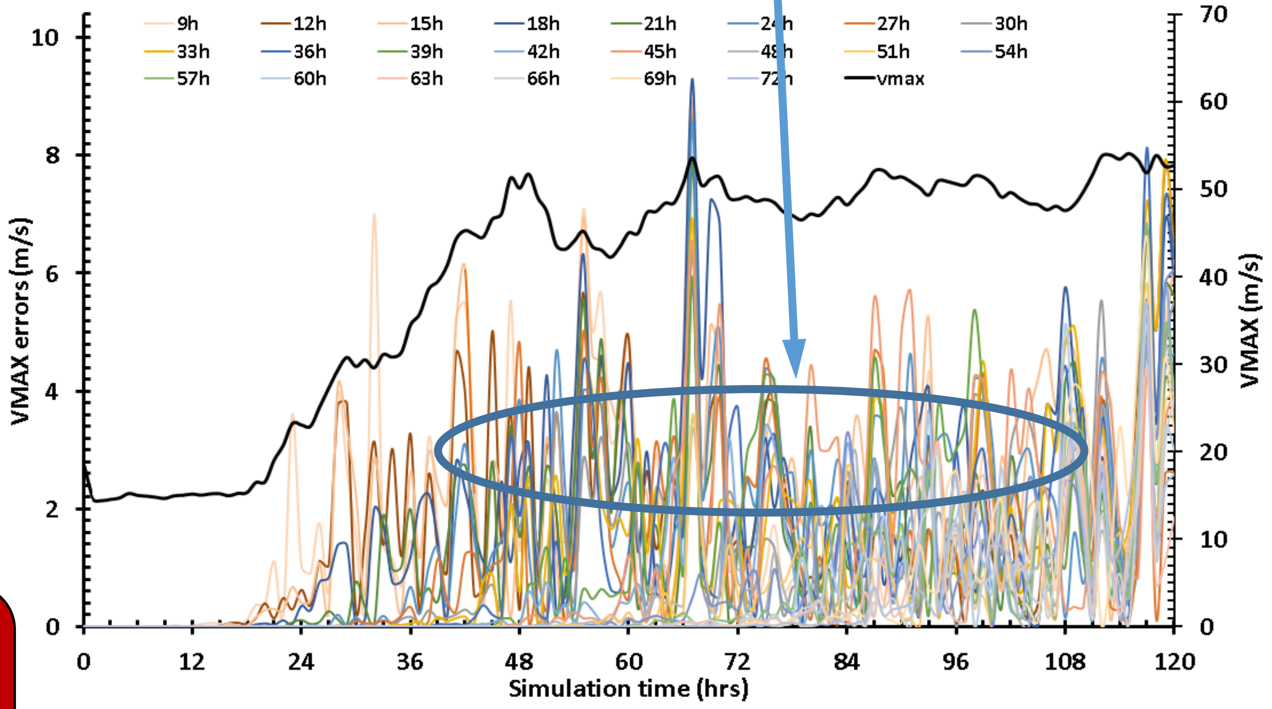
**An ensemble is created for each perturbed moment to eliminate representative errors.**
- **5 different samplings**
- **7 different perturbation sizes**
- **(4 different parameterizations)**
- **(Shear vs no shear)**

# Idealized HWRF simulation

**Perfect model scenarios**:

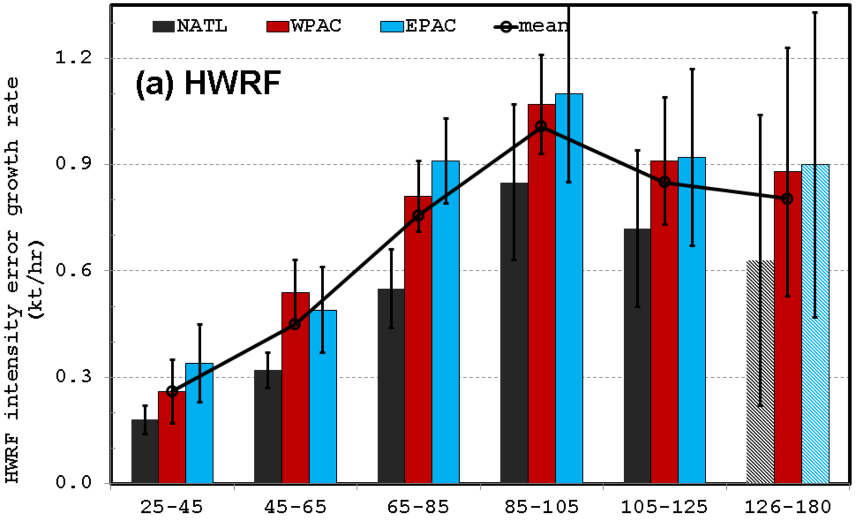
- Idealized experiments at 900 m resolution
- Perturbations added at different stages of development
- An ensemble of 10 random realizations is added at each stage of development to increase representativeness

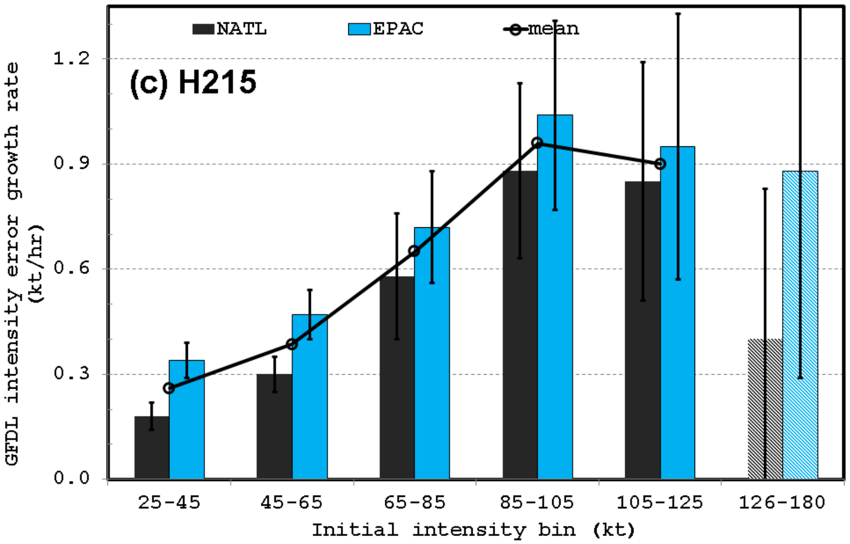
**All intensity errors w.r.t. control shows a bounded error ~ 8 kt (4 ms$^{-1}$)**

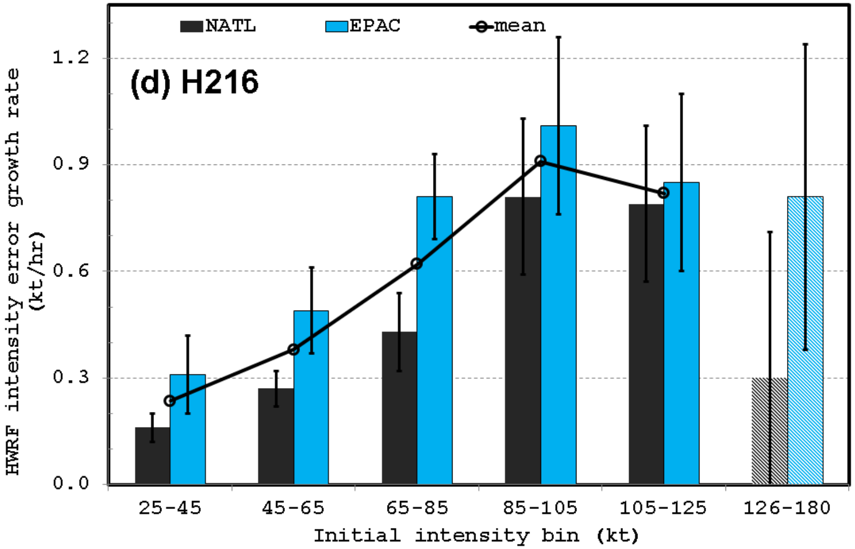


**The difference between real-time $\sigma_m$ (12-19kt) and idealized $\sigma_c$ (~8 kt) appears to be due to the model errors?**

# Real-time HWRF error growth





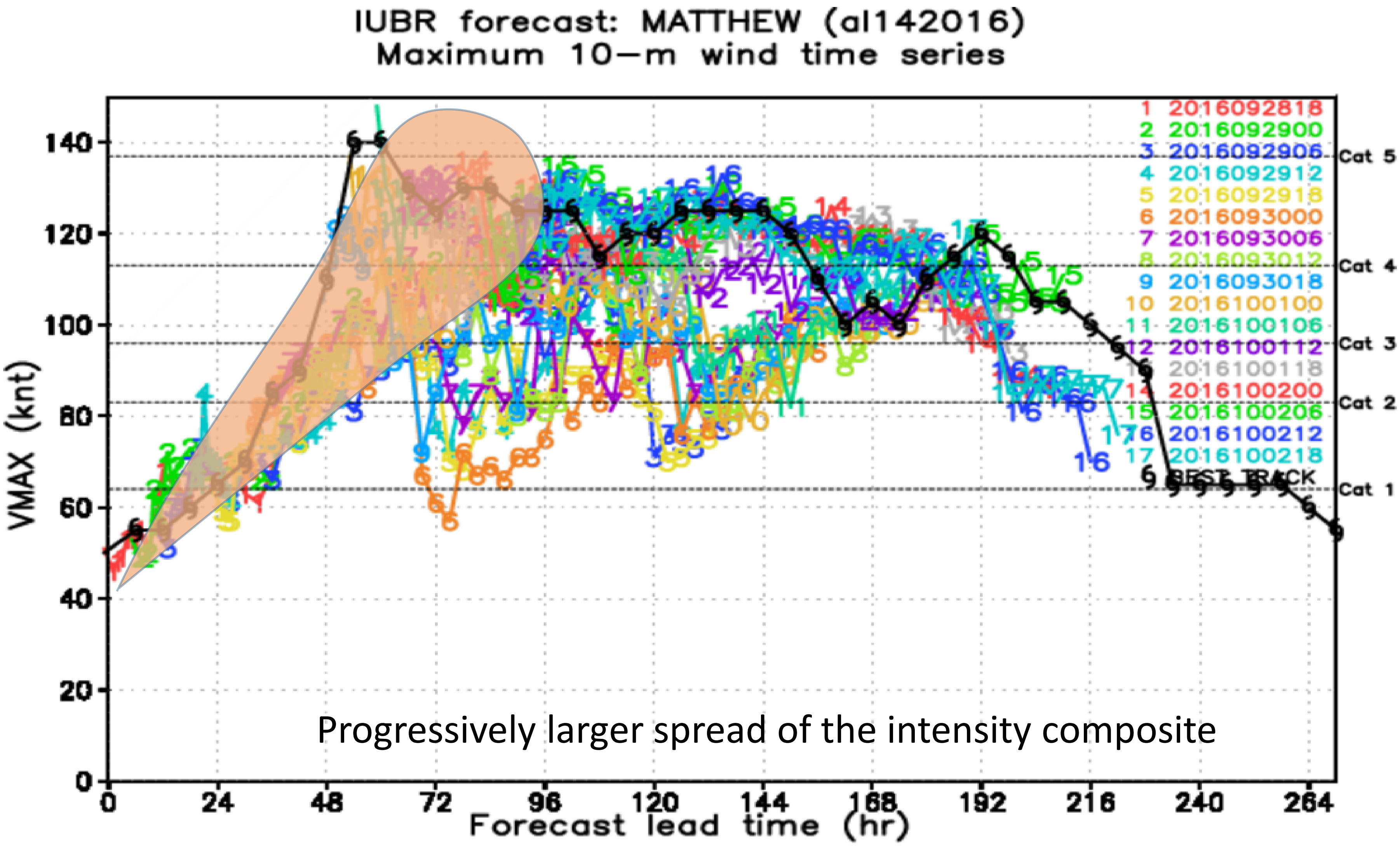


- $\epsilon = \frac{(Vmax - Vobs)_{t=18h} - (Vmax - Vobs)_{t=0}}{18\ hours}$

- Faster error growth during the intensification → indication of unstable noncentral orbit that support the chaotic MPI attractor.

- Error growth rate subsides once attaining the mature stage, representing the growth rate (positive leading Lyapunov exponent) inside the chaotic attractor;

# Real-time HWRF error growth



Progressively larger spread of the intensity composite

# Discussions

So what have we learned from all of these analyses?

- Unlike track errors, we are closer to confirming that the TC intensity has an intrinsic variability due to the TC dynamics rather than the model issues;

- The error saturation limit is not universal, but changes with the large scale environment. So the goal of reducing intensity error must be basin-wide dependent;

- Intensity errors will grow faster during the TC development -> intensity forecasts of the early cycles are more reliable, and so it is progressively harder to predict as TCs intensify;

- The HWRF hurricane intensity forecast errors based on the absolute VMAX metric will have a limited threshold of 8 kt, but this is still not actual intrinsic yet.

# Future HWRF development?

So if we cannot bring the absolute intensity error down below a threshold, then how can we improve TC intensity errors in future TC models?

1. Focus on the VMAX bias. There may have a limit on the absolute errors, but the VMAX bias for different stratifications can really tell a model is good or not;
2. Change the metric of the TC intensity by, e.g., the phase of development, RI, RW, or introduce new 3D metric or 2D metric such as radar reflectivity, rain or wind swath;

# Appendix

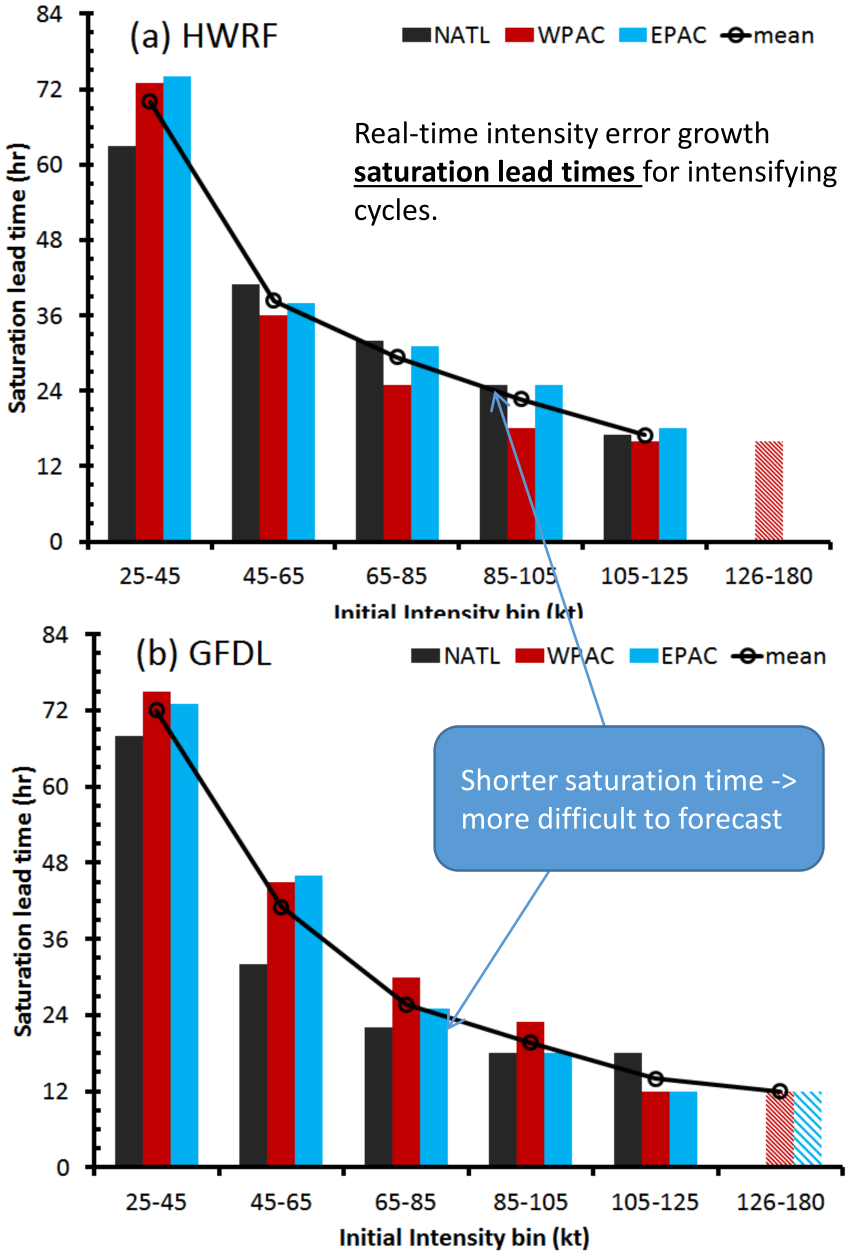
# Real-time intensity error growth

We have seen from real-time intensity errors analyses that:

1. Existence of a saturated error Γ
2. Faster growth rates (indication of positive leading Lyapunov exponent)

Question: can we say anything about the predictability limit here?

Answer: yes, it is likely, and so the range of TC intensity predictability becomes shorted for stronger storms. If so, the saturation time must be shortened as a consequence



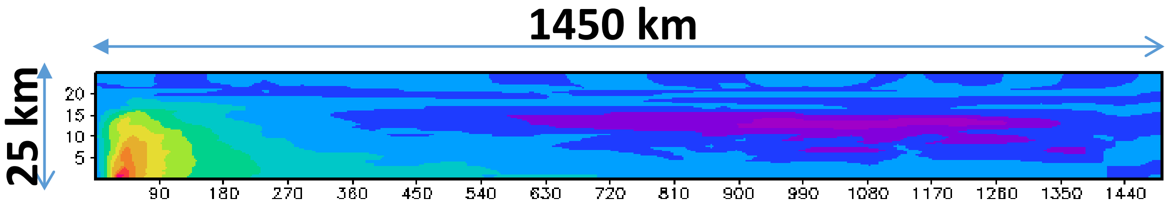
Real-time intensity error growth **saturation lead times** for intensifying cycles.

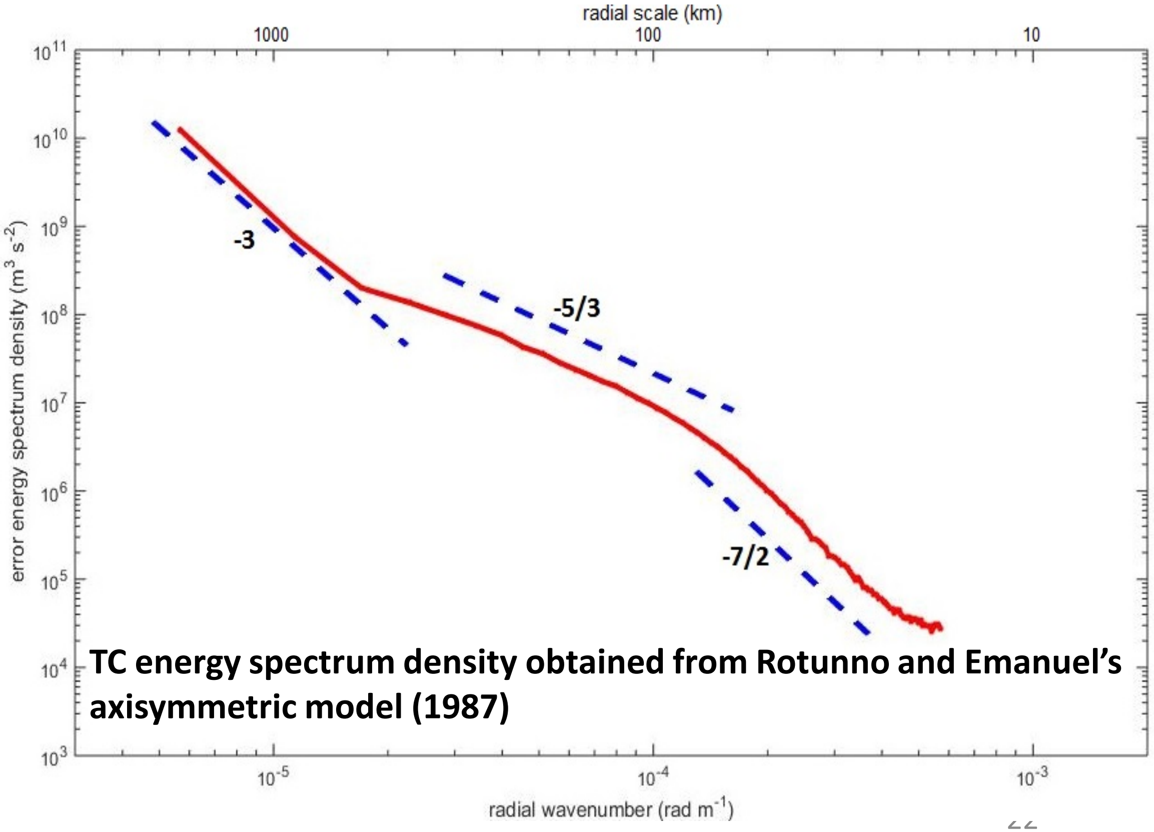
Shorter saturation time -> more difficult to forecast

- Analysis of the energy error spectrum for TC radius-height band shows several spectrums at different scales!

- At < 30 km, -7/2 spectrum emerges -> unlimited predictability!

- Is this representative or model dependence?

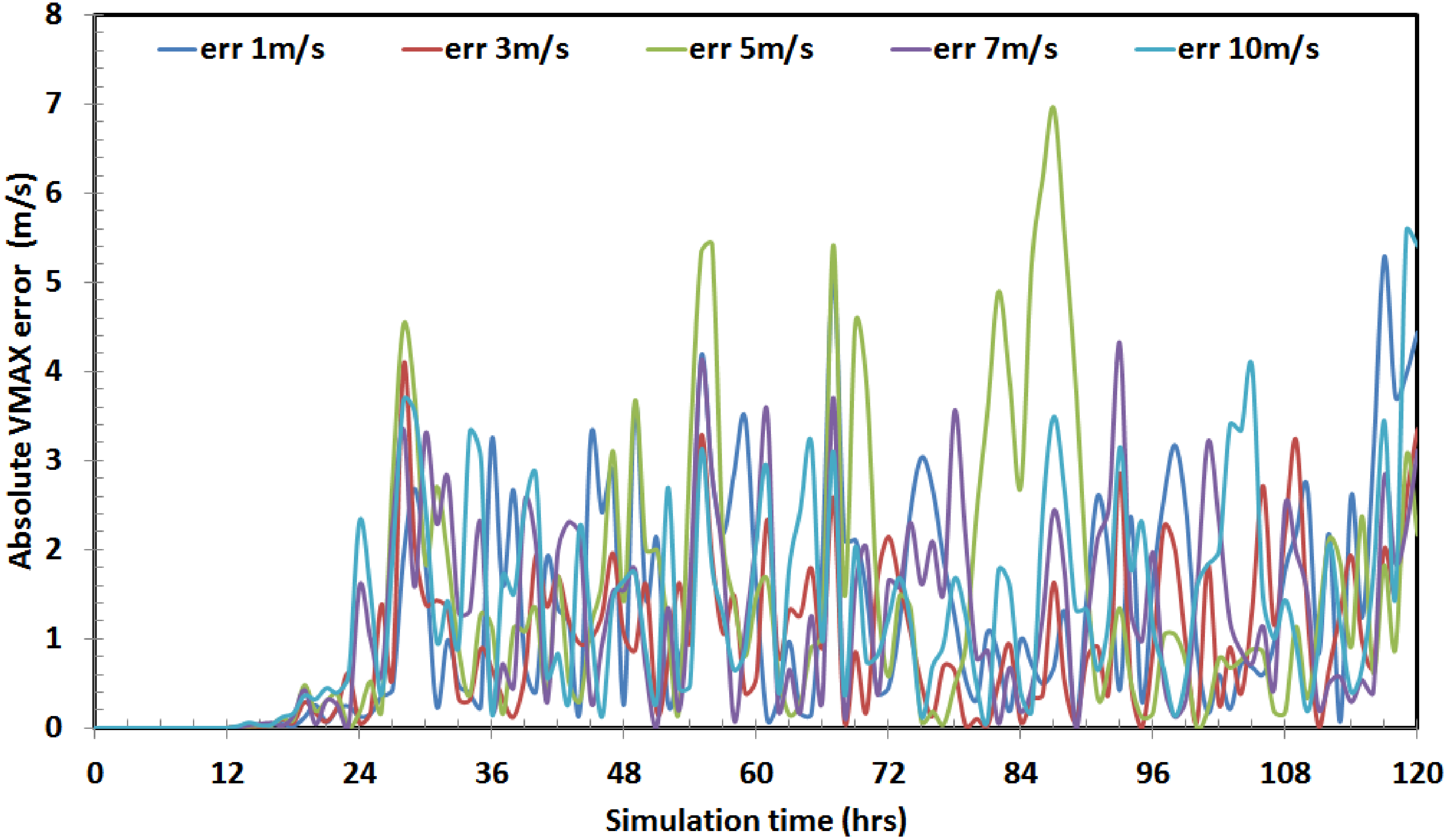




**TC energy spectrum density obtained from Rotunno and Emanuel's axisymmetric model (1987)**

# HWRF intensity error growth sensitivity

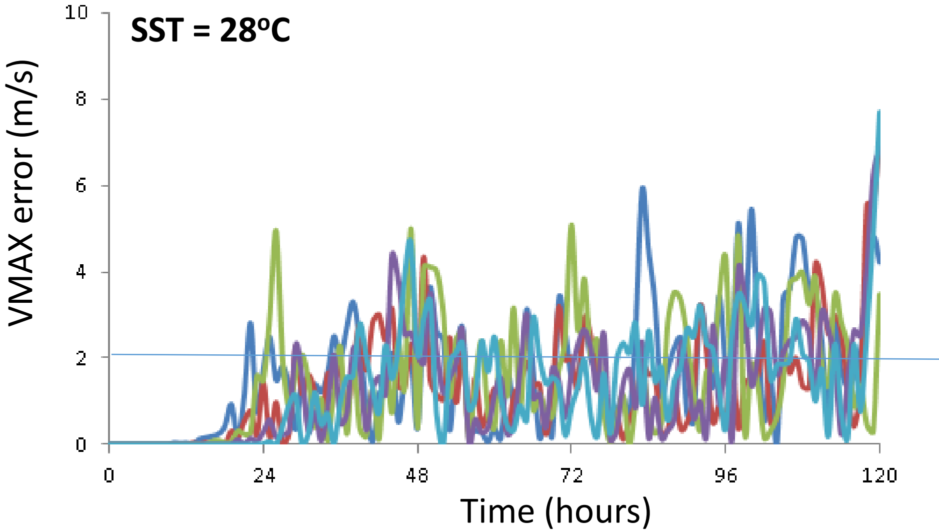
Sensitivity experiments with different initial perturbation amplitudes



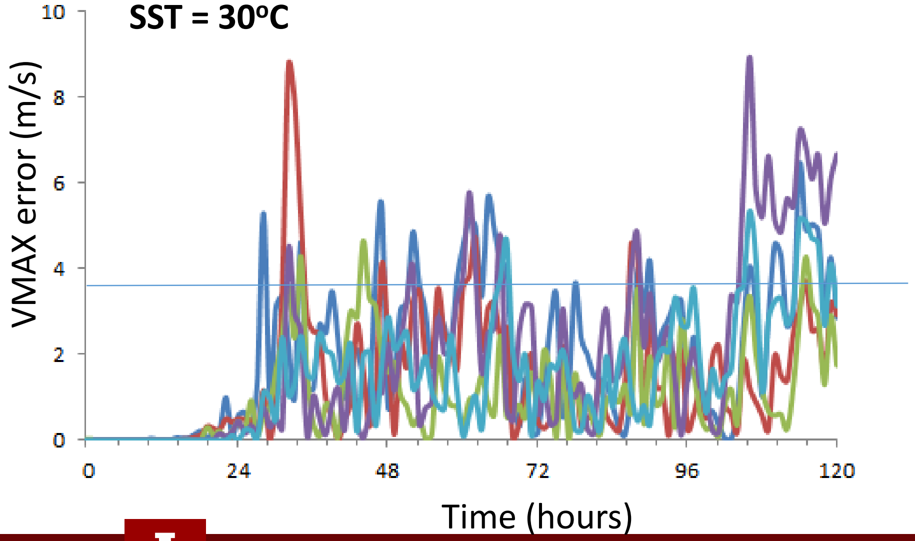
# Environment-controlled predictability

**SST Sensitivity:**

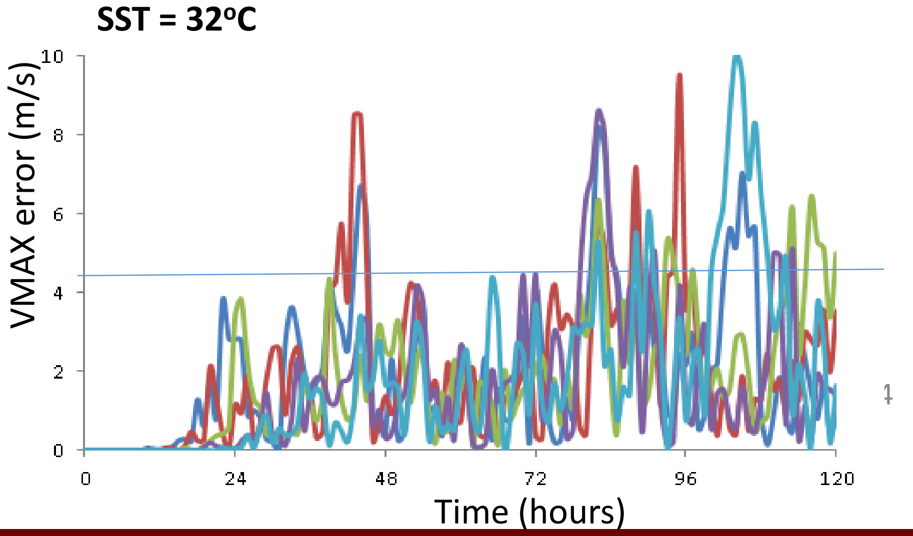
- MPI increases with SST;
- $\sigma_c$ is still small 4-8 kt, but it increases with SST, indicating the large-scale control on intensity variability



SST = 28°C



SST = 30°C

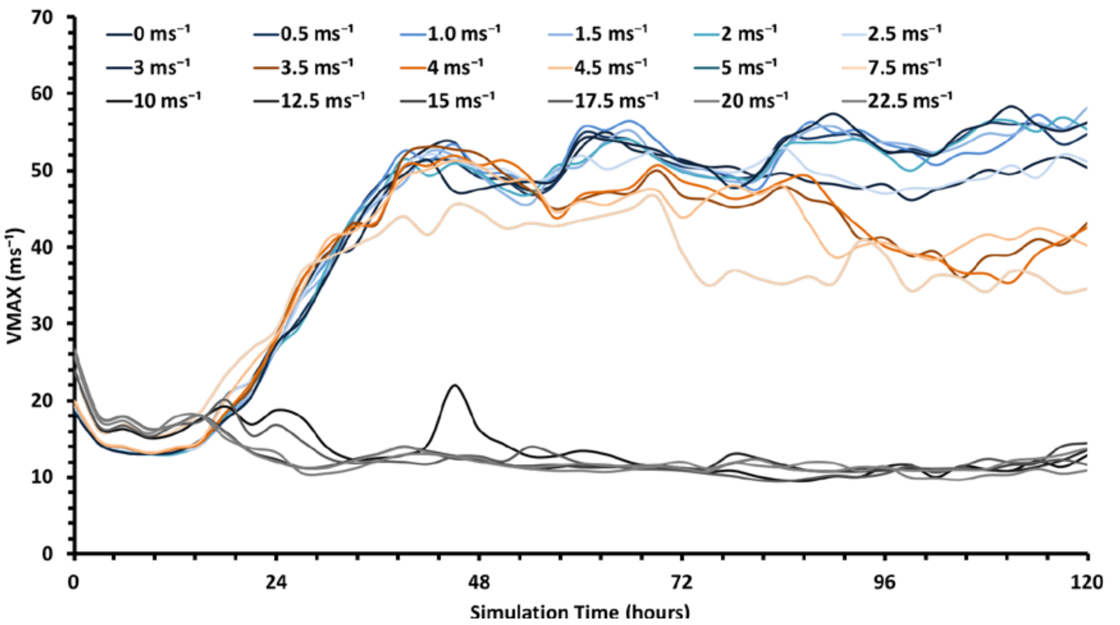


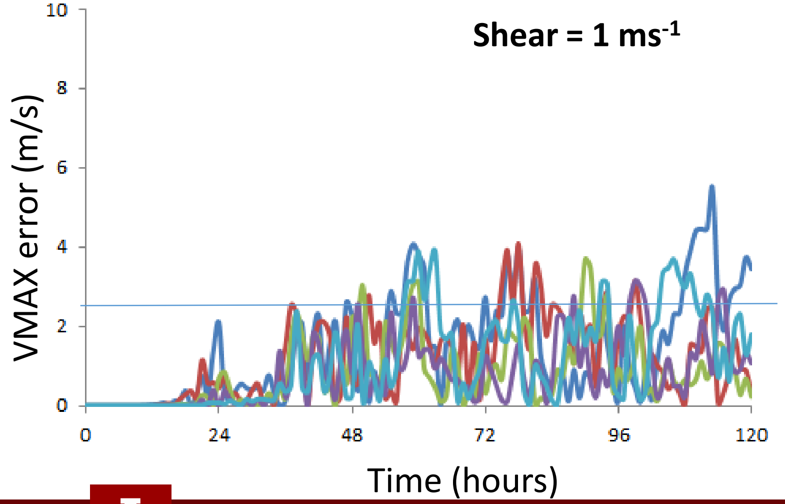
SST = 32°C

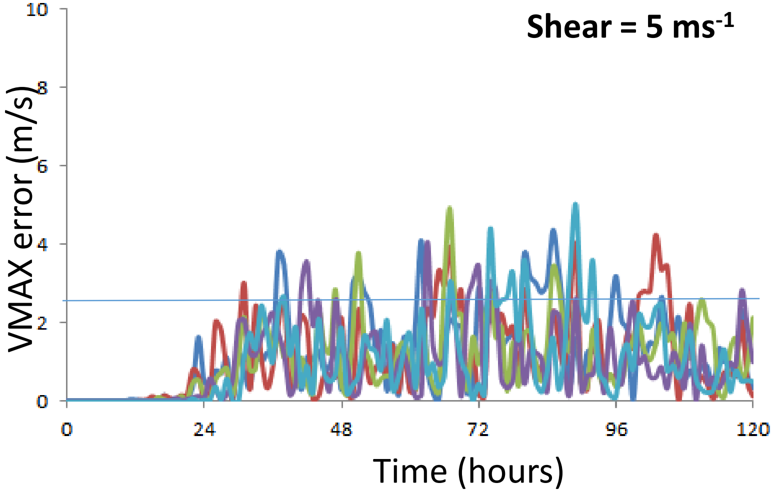
# Environment-controlled predictability

**Shear sensitivity**

- MPI decreases with shear
- $\sigma_c$ shows no change with shear







# Real-time HWRF forecasts: methodology

**Error saturation analyses:** Quantify the practical predictability for real-cases during the mature stage under the following assumption

- TC development reaches maximum intensity in 4-5 days
- Dynamic errors and observational errors are uncorrelated after long lead time
- No landfalling effects (only intensifying stage)
- SST in each basin are statistically different
- Errors are random
- All weak storms eliminated

Let $\epsilon(\tau) = V_m(\tau) - V_o(\tau)$ the VMAX error at lead time $\tau$, then we will have

$$\sigma_v(\tau) = \sigma_m(\tau) + \sigma_o - 2E[V_m(\tau)V_o(\tau) - V_t^2(\tau)]$$

# Real-time HWRF forecasts: methodology

**Error growth analyses**: Quantify the practical predictability for real-cases during noncentral orbit period (i.e., intensifying period)

- Using NHC/JTWC best track database for three basins (NATL, EPAC and WPAC)

Compute 18-h intensity error growth rate as follows:

$$\epsilon = \frac{(Vmax - Vobs)_{t=18h} - (Vmax - Vobs)_{t=0}}{18\ hours}$$

- Stratifying the error growth rate based on different initial intensity bins: 25-45 kt, 46- 65 kt, 66-85 kt, 86- 105 kt, 106-120 kt, and 121-185 kt.
- Select only intensifying cycles in all 3 basins NATL, EPAC, and WPAC
- Note: small sample size for 121-185 kt.