Predictability Limit of the HWRF model in Forecasting Hurricane Intensity at the 4-5 day Lead Times

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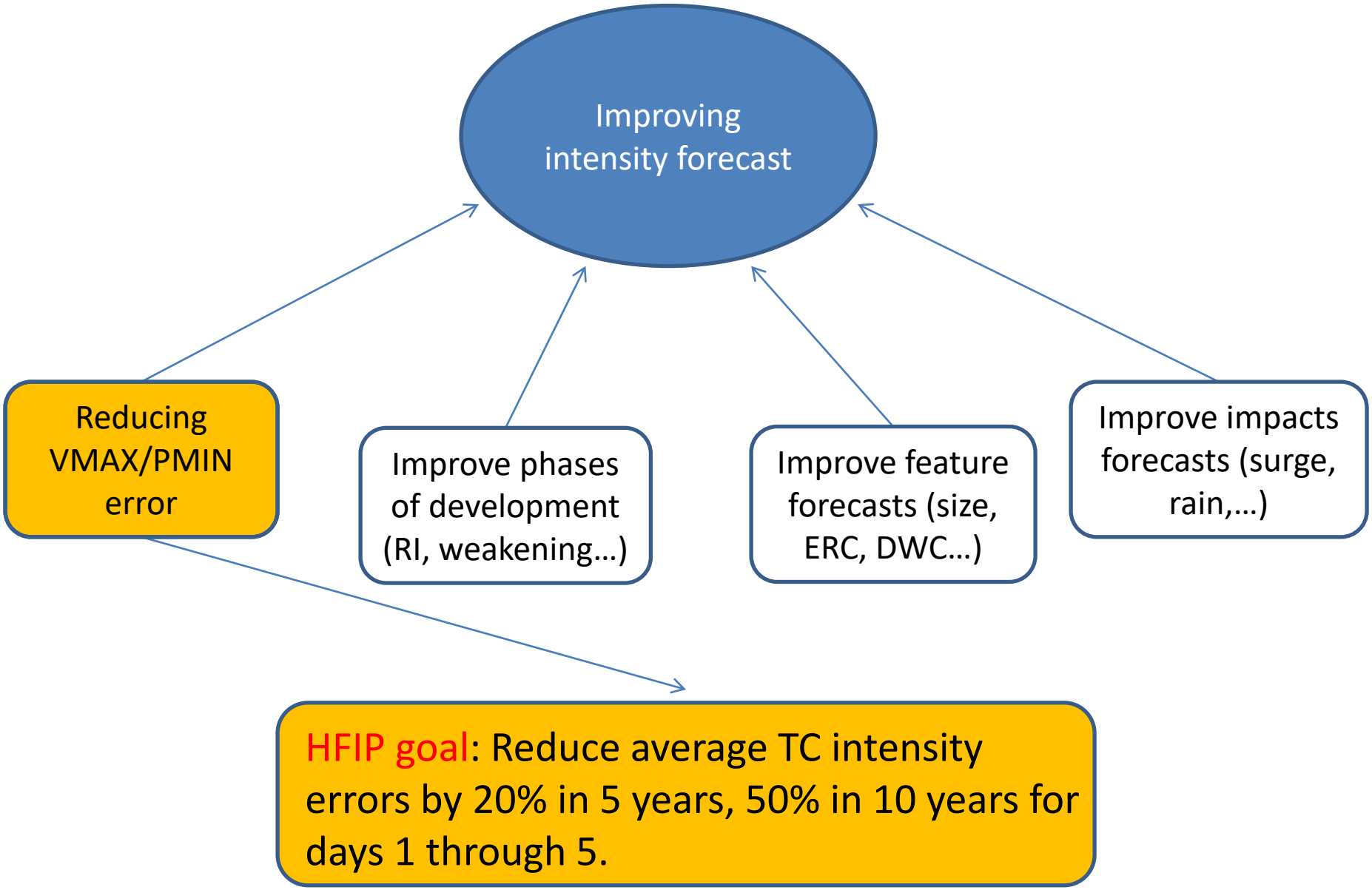
Outline

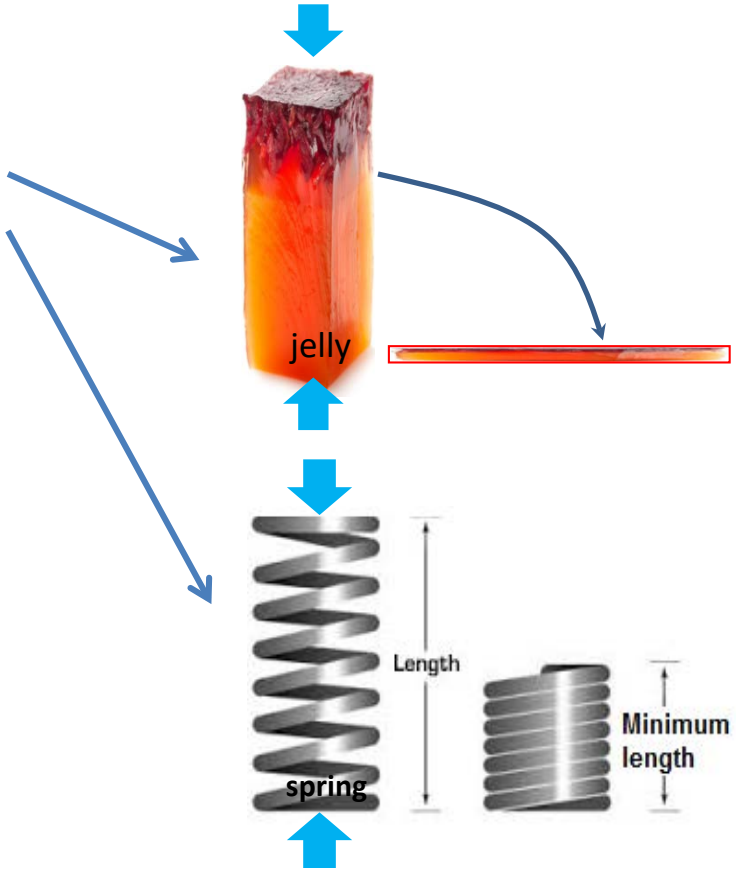
- Motivation/objectives
- Real-time intensity error
- HWRF intensity error growth
- Conclusions
- Upcoming plans

Motivation


Improving intensity forecast
Reducing VMAX/PMIN error
Improve phases of development (RI, weakening…)
Improve feature forecasts (size, ERC, DWC…)
Improve impacts forecasts (surge, rain,…)
HFIP goal: Reduce average TC intensity errors by 20% in 5 years, 50% in 10 years for days 1 through 5.

Proposal objectives

- Quantify characteristics of intensity error growth and conditions under which the HWRF's TC intensity forecast errors can be most reduced during RI;



- Estimate a practical predictability limit of TC intensity forecasts in the HWRF model

How far ahead can we predict the TC intensity with the HWRF model?

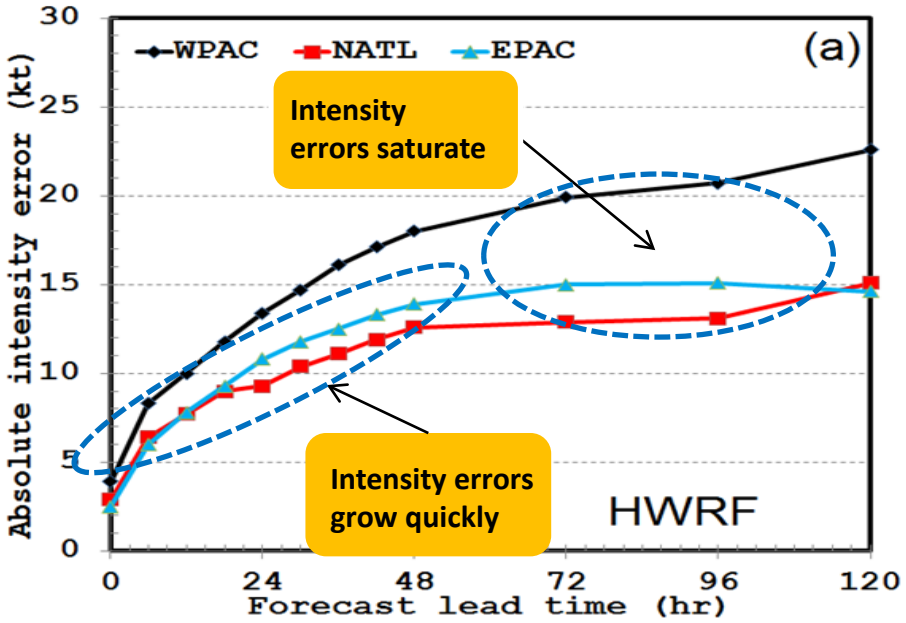
Working hypothesis

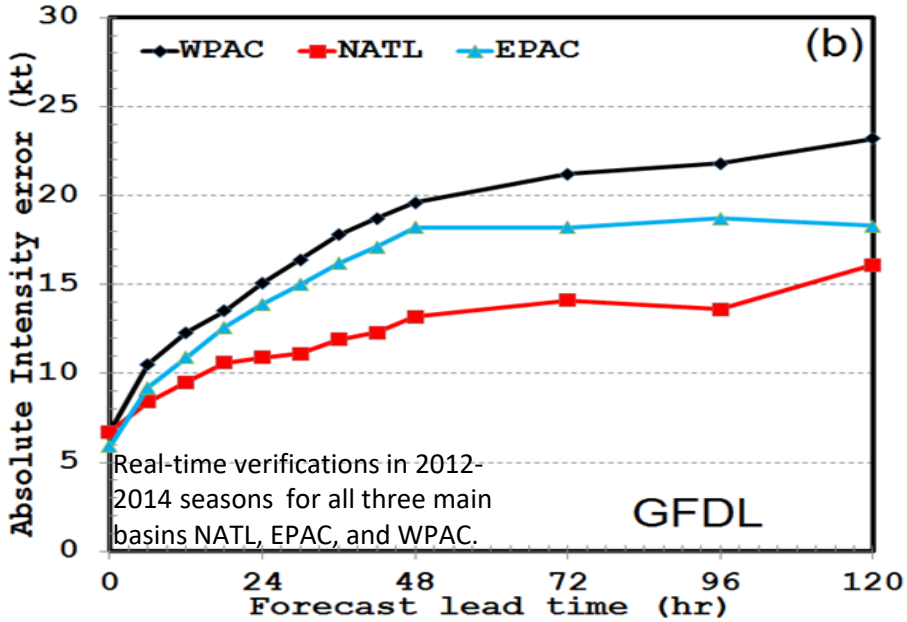
- **Working hypothesis 1**: HWRF's intensity error growth depends on the vortex initial strength during RI; the intensity error growth is faster for strong storms.
- **Working hypothesis 2**: At the MPI limit, HWRF possesses a saturated intensity error threshold that is statistically determined by large-scale conditions.

Two necessary conditions to examine the limited predictability for TC intensity forecasts

1) existence of a stationary saturated error limit Γ; and
2) a faster intensity error growth for a stronger initial storm.

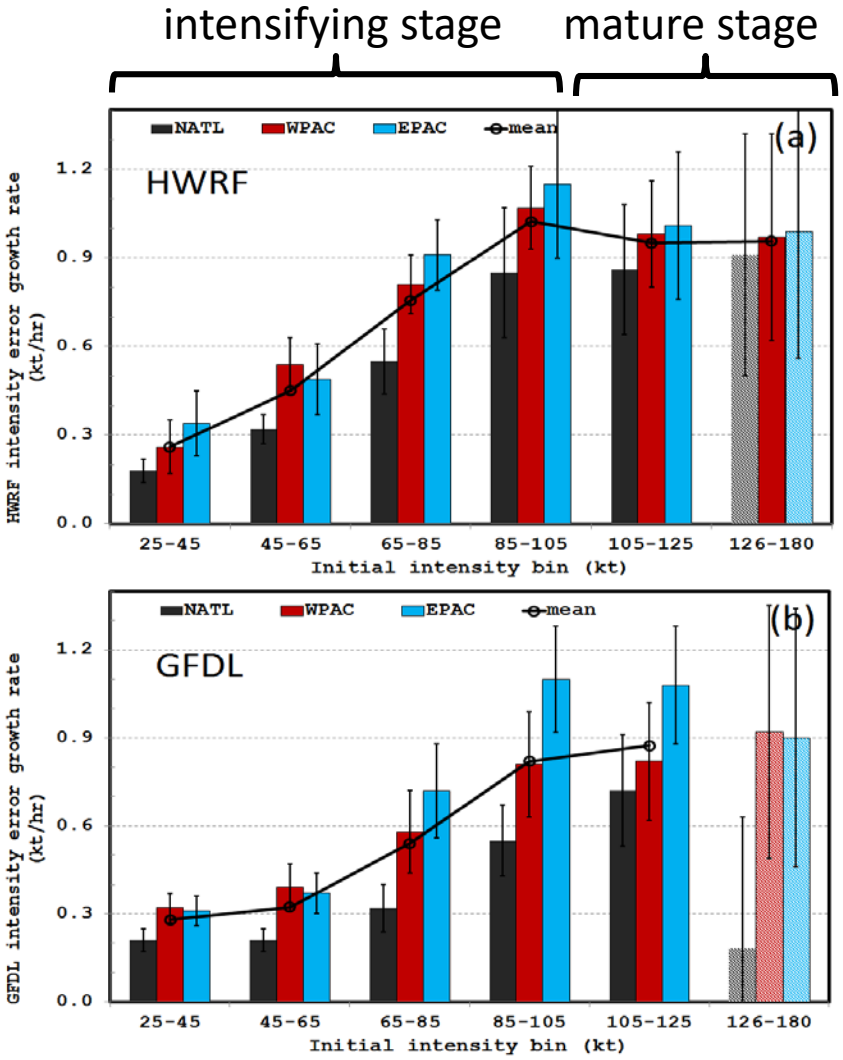
Real-time intensity error saturation





- Real-time verifications show a consistent TC intensity error saturation after 72-h in all basins/models → indication of existence of Γ;
- Γ depends on the basin with the largest amplitude in WPAC (18 m/s), smallest in EPAC (~ 13 m/s) for both HWRF/GFDL → Γ depends on environment;
- The exact value of Γ is still not conclusive as models are imperfect;
- Remark: the existence of Γ is only necessary for limited predictability

Real-time intensity error growth rate



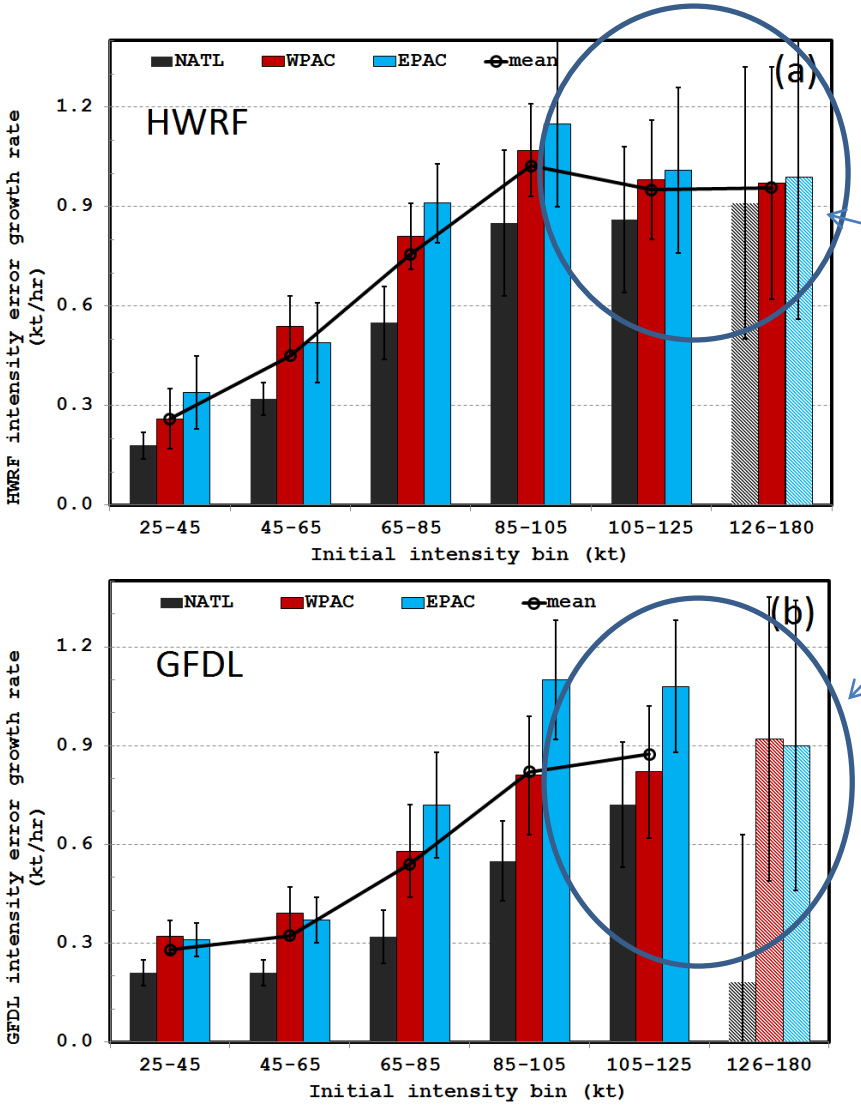
Real-time intensity **error growth rate** for the HWRF and GFDL models. Solid line denotes the mean of all basins, and error bars denote 95% confidence intervals.

1. A consistent trend of a faster error growth rate for stronger intensity in all basins;

2. Both GFDL/HWRF show similar trends of error growth rate (fastest in EPAC, WPAC, then NATL) → TC intensity has limited predictability (see proof in Appendix)

3. This result suggests that it is difficult to reduce TC intensity errors for strong storms, not just because of the model errors or physics, but because of the intrinsic dynamics of TCs.

Real-time intensity error issues



Intensity forecasts errors due to:

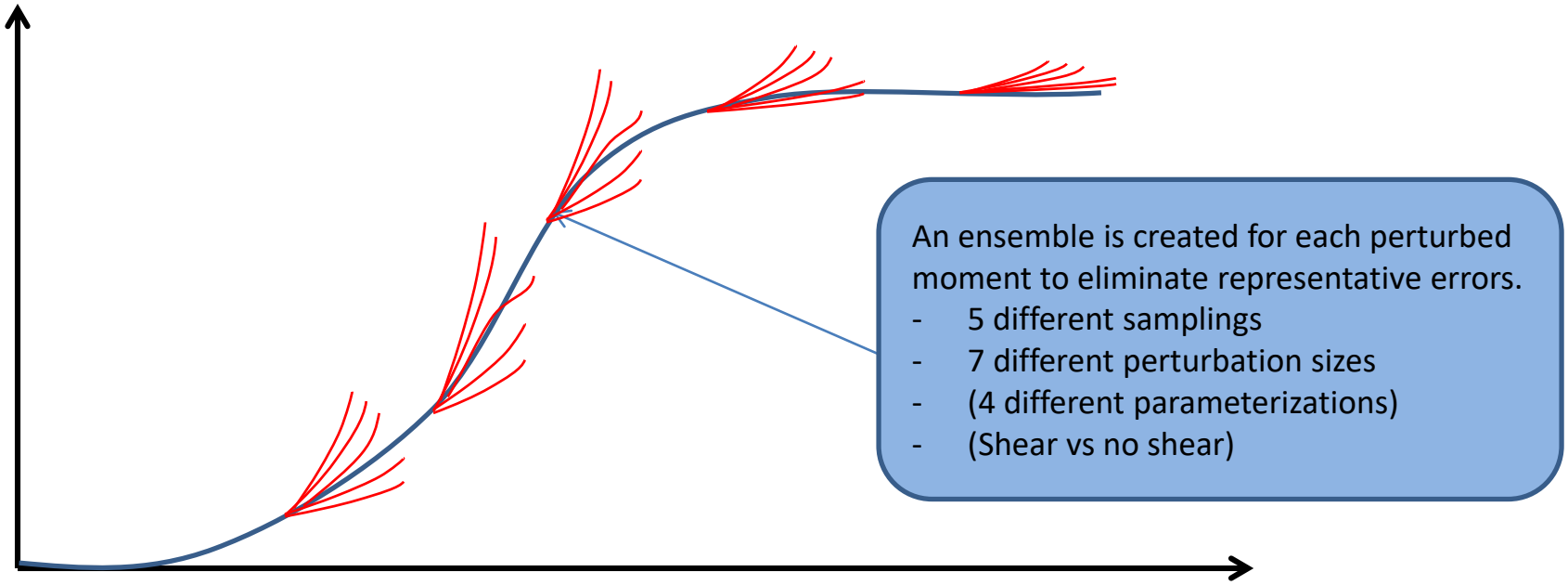
1. **Model errors (random forcings)**
2. **Boundary condition errors**
3. **Initial conditions errors**
   - **Strength errors**
   - **Structure errors**
   - **Random errors**

This type of errors is the intrinsic limit that we can never get rid of

HWRF intensity error growth exp

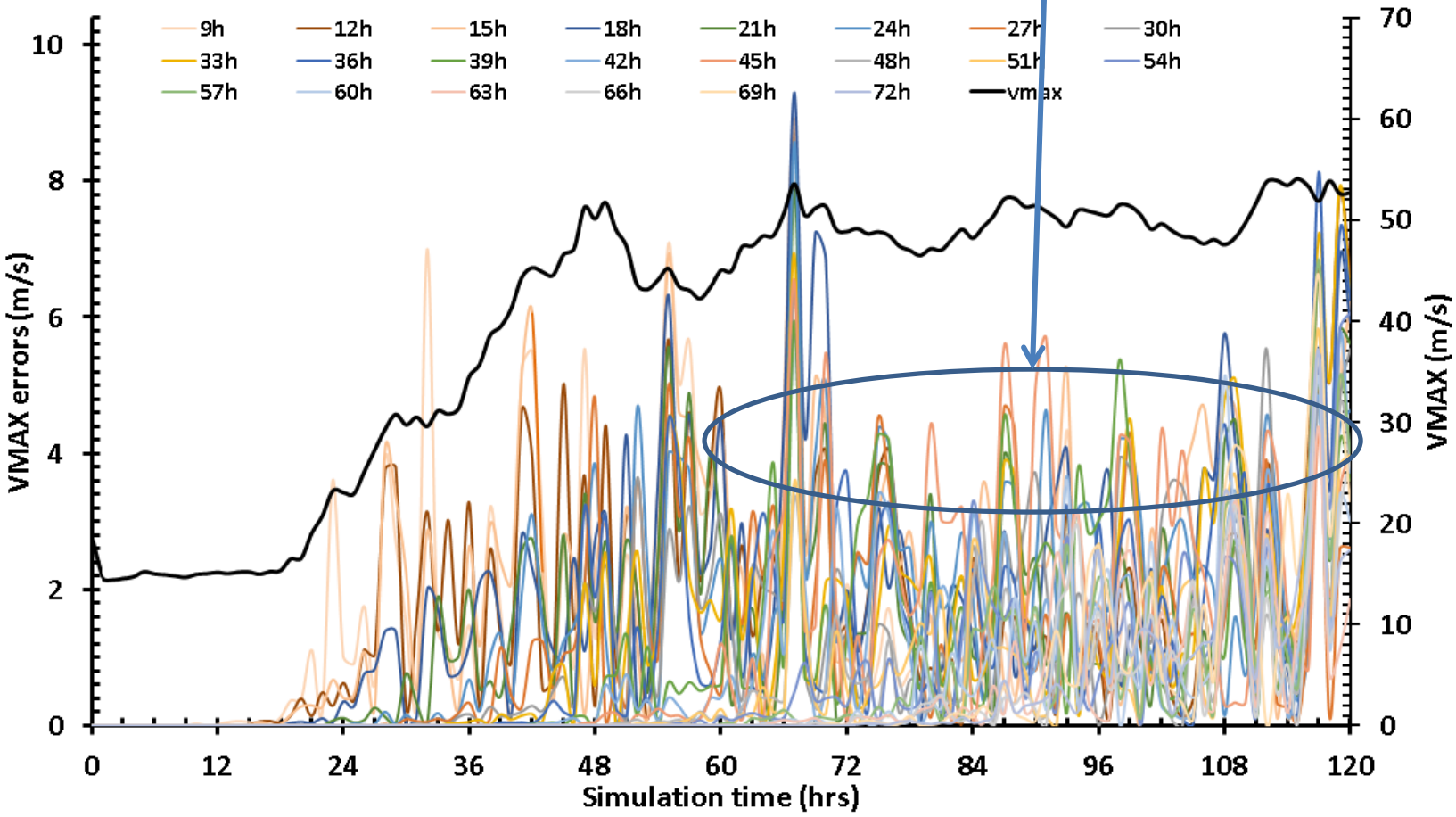
How to get grid of the initial adjustment?

- Use of idealized HWRF (V3.7)
- Implement a scheme to add random perturbation at different stages of intensification
- Isolate the intrinsic error growth from other environmental influences
- (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
- No vertical wind shear



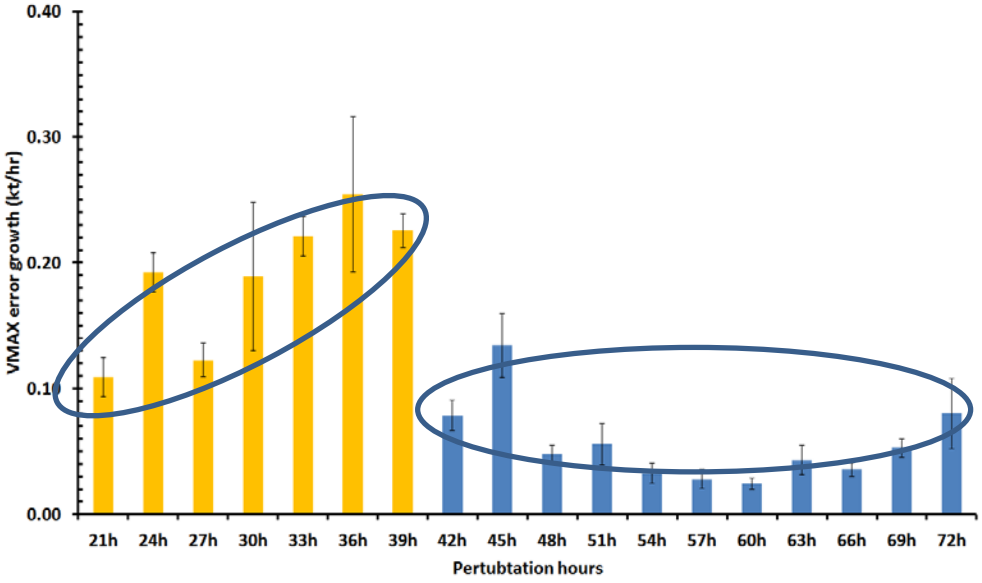
HWRF intensity error growth

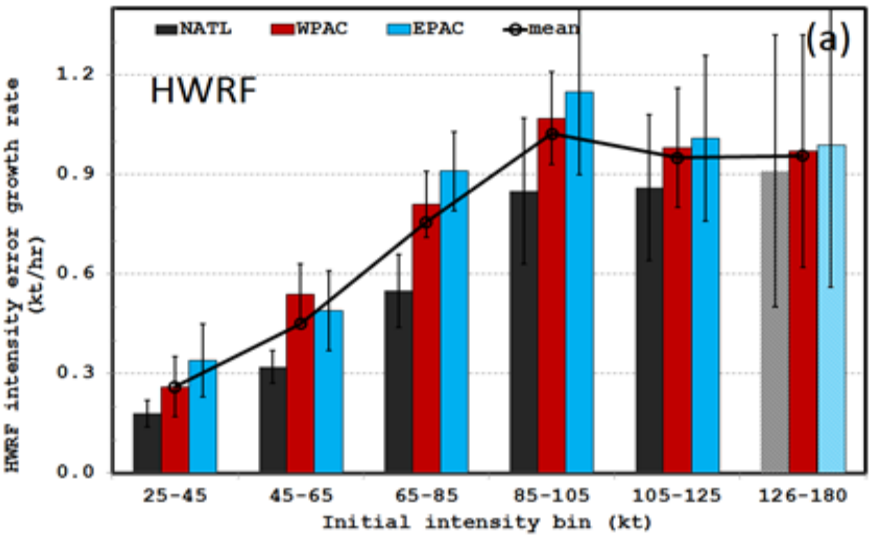
All intensity errors w.r.t. control shows a bounded error ~ 9 kt (4 ms^{-1}) < 15 kt in real-time -> hope to improve TC intensity further



HWRF intensity error growth

- ✓ Much smaller growth rate during the RI in idealized exps → real-time growth rate contains something else (vortex initialization, wrong landfalling time) → some hope to improve intensity …
- ✓ The same saturated error growth for the mature stage, albeit much less -> again there is a problem with vortex structure errors





Conclusion

- There exits a saturated error limit for TC intensity forecast. The lowest absolute intensity errors in the HWRF model under idealized environment is 4-5 m/s (9kt), a cap at 4-5 days lead time that is basin-wise dependent;

- Real-time/idealized exps showed that intensity errors grow faster during RI, and quickly saturated at the mature stage. The stronger an initial vortex is, the faster error growth rate will be.

- Idealized experiment show significantly weaker growth rate/saturation limit as compared to real-time $\rightarrow$ TC intensity has some room to be improved;

- The range of predictability limit for TC intensity is ~ 3 days, and reduced to about 1 days for Cat 1+. This range is entirely on the VMAX metric of VMAX, and could be longer for other measures.

Timelines		Products
Year 1: Quantify characteristics of TC intensity error growth in the HWRF model during the rapid intensification stage.		
√	Quarter 1	Obtain the newest version of the HWRF code; configure and modify the dynamical core of the HWRF to allow for experiments that can quantify the TC intensity error growth at different stages of the TC development in the HWRF model;
√	Quarter 2	Conduct sensitivity experiments to evaluate the roles of different environmental factors and the vortex initial structure in the growth of intensity errors during the rapid intensification period;
	Quarter 3	Conduct real-data experiments to examine how the results obtained from idealized simulations can be realized in real-data RI forecasts in the operational mode with the HWRF model;
	Quarter 4	Analyze real-time intensity forecasts during 2010-2015 period across different ocean basins for different modeling systems to further quantify general conditions for the predictability of RI and to examine how the intensity error growth depends on the vortex strength during the RI period; Writing reports and publications;
Year 2: Estimate the practical predictability limit of intensity forecasts at 4-5 day lead times in the HWRF model.		
	Quarter 1	Establish existence of an intensity attractor at the maximum intensity equilibrium in the HWRF model. The existence and the properties of the MPI attractor in the HWRF model will be also verified with axisymmetric models to supplement the finding of the HWRF model;
	Quarter 2	Quantify intensity variations at the MPI limit and the sensitivity of the intensity error growth at the MPI limit in the HWRF model, especially how sensitive the MPI equilibrium is to various environmental factors and initial conditions;
	Quarter 3	Diagnose the spectrum of TC basic and error energy to establish the intensity forecast limit at 4-5 day lead times in the HWRF model;
	Quarter 4	Complete a diagnostic tool/tabular to aid EMC and NHC in warning the potential rapid intensity error growth and intensity error saturation in operational intensity forecasts. Writing reports and publications.

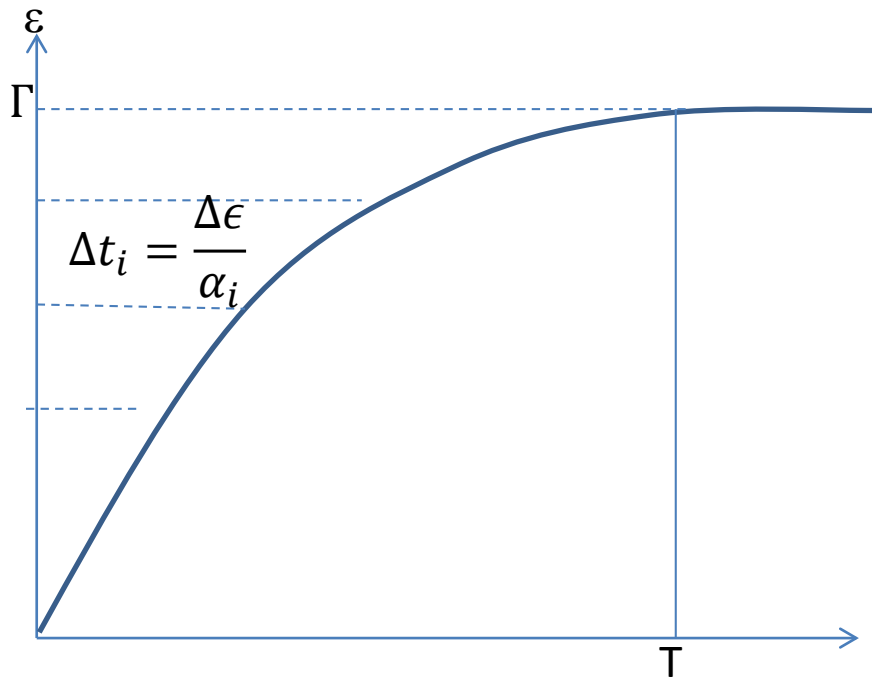
Appendix

Proof of the TC limited predictability during the transient orbit

Assume there exists a saturated error limit Γ, we will prove that the error growth rate has to increase with time during the transient orbit so that the time interval T required for an initial error to approach the limit Γ is finite. Indeed, let divide the range $[0, \Gamma]$ into N intervals with an increment of error change $\Delta\epsilon = \frac{\Gamma}{N}$, then the time interval Δt_i that the error growth in the interval i at the growth rate α_i will be $\Delta t_i = \frac{\Delta\epsilon}{\alpha_i}$. The total time for the initial error ϵ_0 to reach Γ is therefore:

$$T = \frac{\Delta\epsilon}{\alpha_i} + \frac{\Delta\epsilon}{\alpha_2} + \cdots \frac{\Delta\epsilon}{\alpha_N} = \frac{\Delta\epsilon}{\alpha_0} \sum_{i=1}^{i=N} \frac{1}{\lambda^i} \qquad (1)$$

where we assume that the successive growth rate $\alpha_i = \lambda\alpha_{i-1} = \lambda^n\alpha_0$. Apparently, the geometrical series (1) will converge to a finite value iff $\frac{1}{\lambda} < 1$ or equivalently $\lambda > 1$. This implies that the growth rate at the later time has to be faster time than the growth rate at the previous time. Otherwise, the series will not converge and it would take infinite amount of time, i.e., $T \to \infty$, to approach the saturated limit Γ.



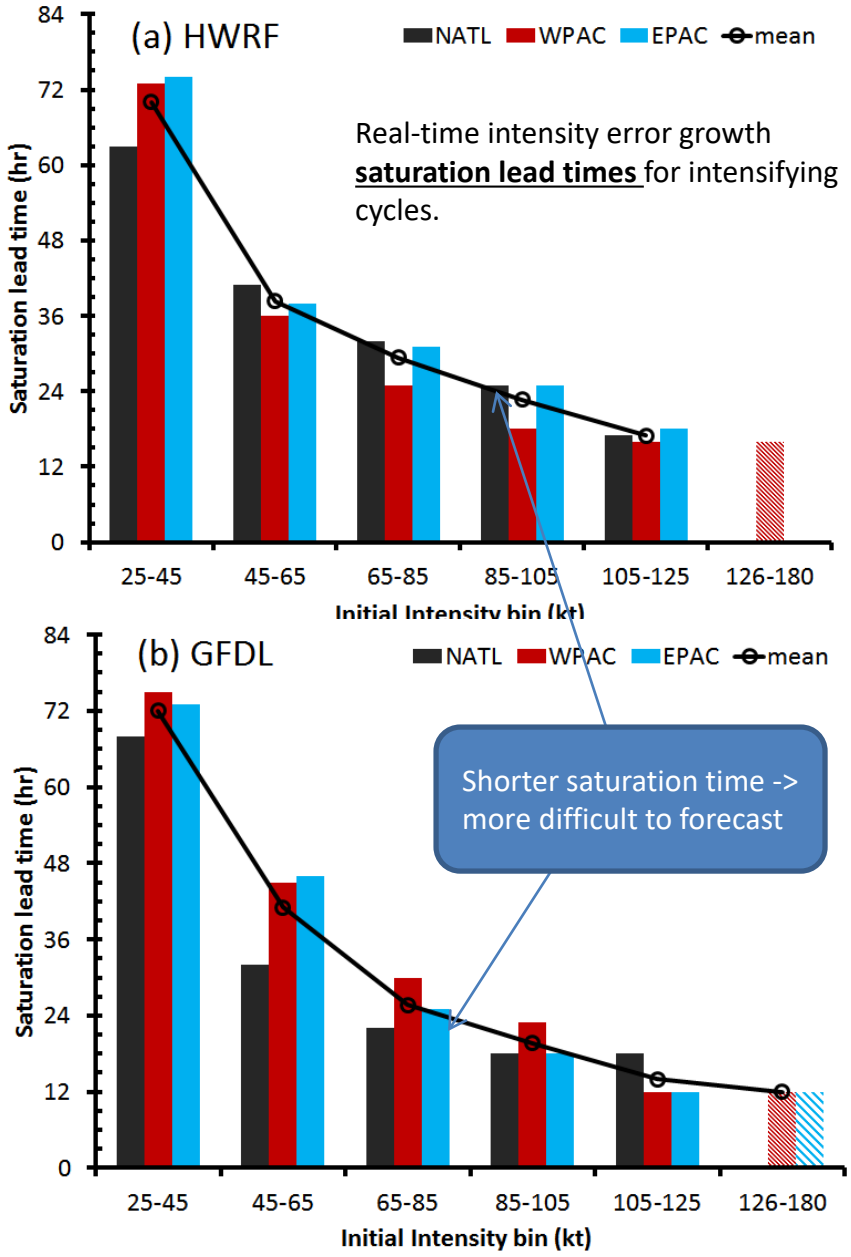
Real-time intensity error growth

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)

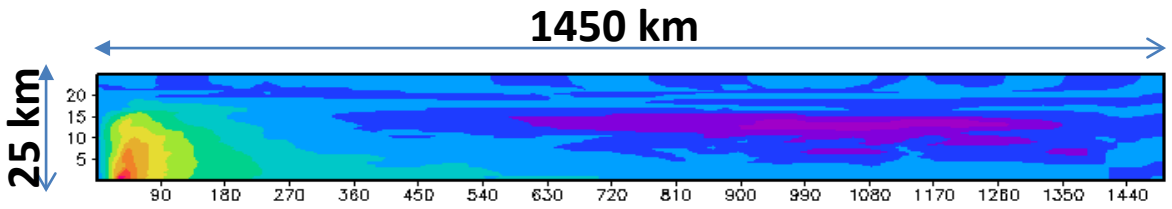
Question: can we say anything about the predictability limit here?

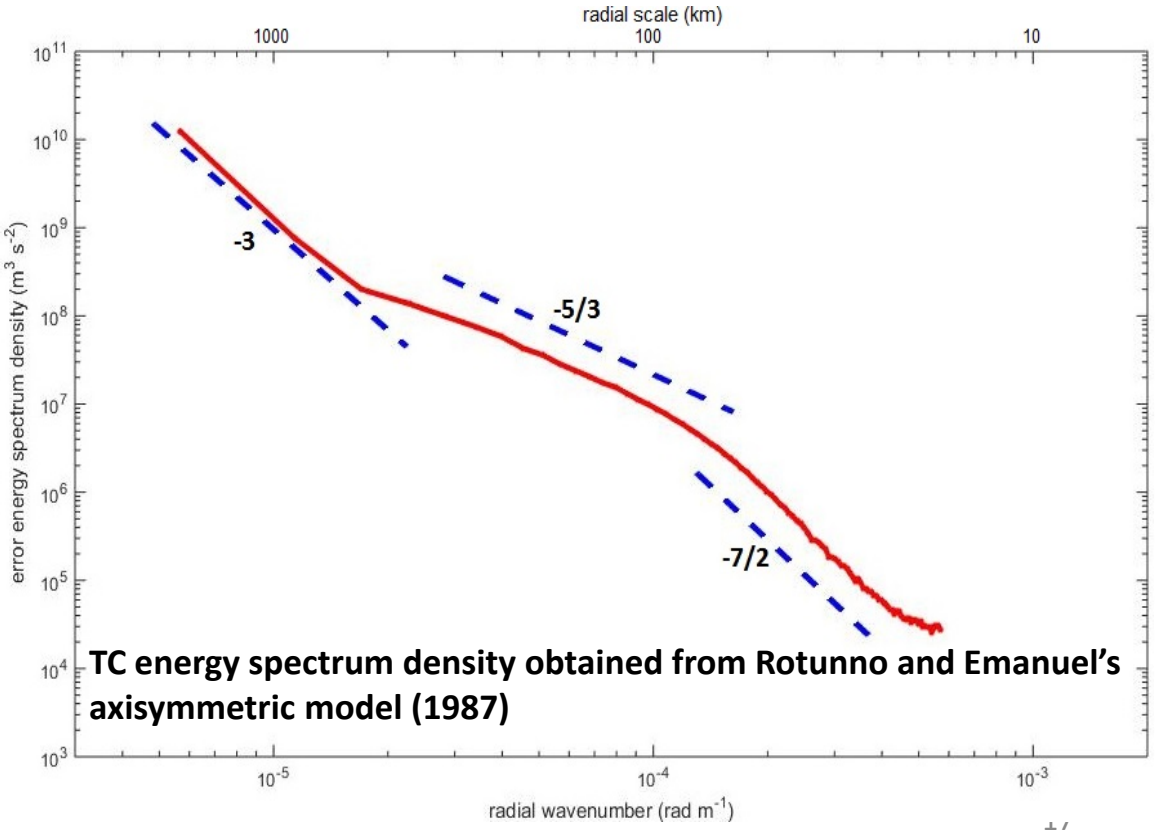
Answer: yes, it is likely, and so the range of TC intensity predictability becomes shorted for stronger storms. If so, the saturation time must be shortened as a consequence



TC energy spectrum at the MPI limit

- 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)

Proof of a stable MPI equilibrium

The hurricane-scale dynamics in a reduced phase space V,W,B (Kieu, 2015 QJ)

- Gradient wind balance
- Non-hydostatic approximation

$$\dot{V} = \alpha VW - \beta V^2$$

$$\dot{W} = -\alpha V^2 + B$$

$$\dot{B} = -\alpha BW + \delta V + \zeta r$$

$$V_c^2 = \frac{\delta}{\alpha\beta}$$

V: maximum surface wind
W: maximum vertical motion in eyewall
B: warm core

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

Modified hurricane-scale dynamics in a reduced phase space (U,V,B)

- Gradient wind imbalance
- Hydostatic approximation

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

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

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

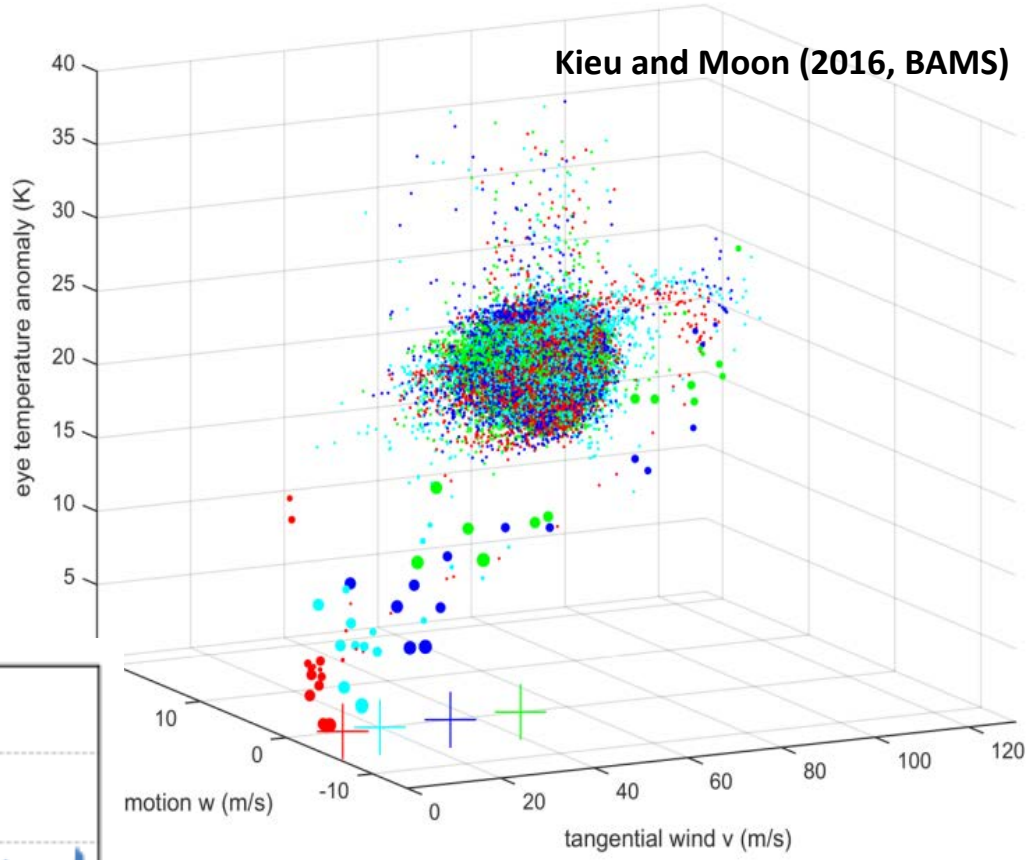
$$V_c^2 = \frac{\delta}{\alpha\beta}\frac{\gamma^2}{\gamma^2 - \beta^2}$$

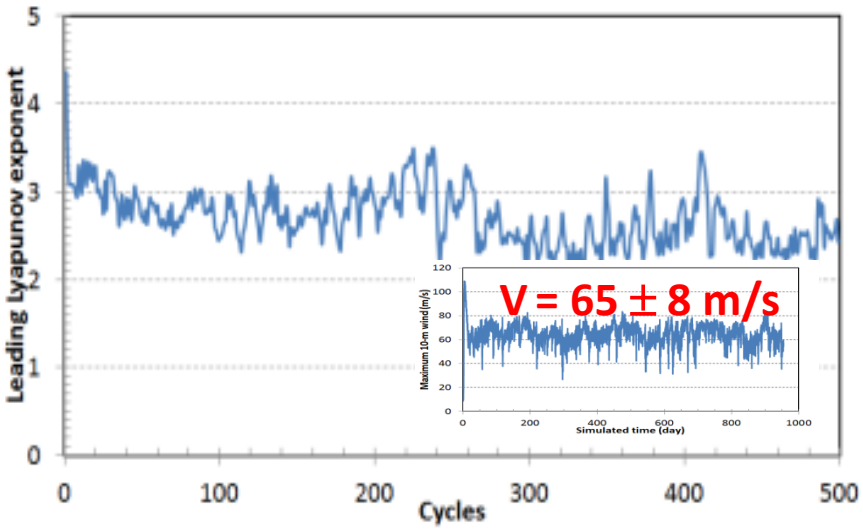
V: maximum surface wind
U: maximum radial wind
B: warm core

- 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 ;

Characteristics of the MPI attractor

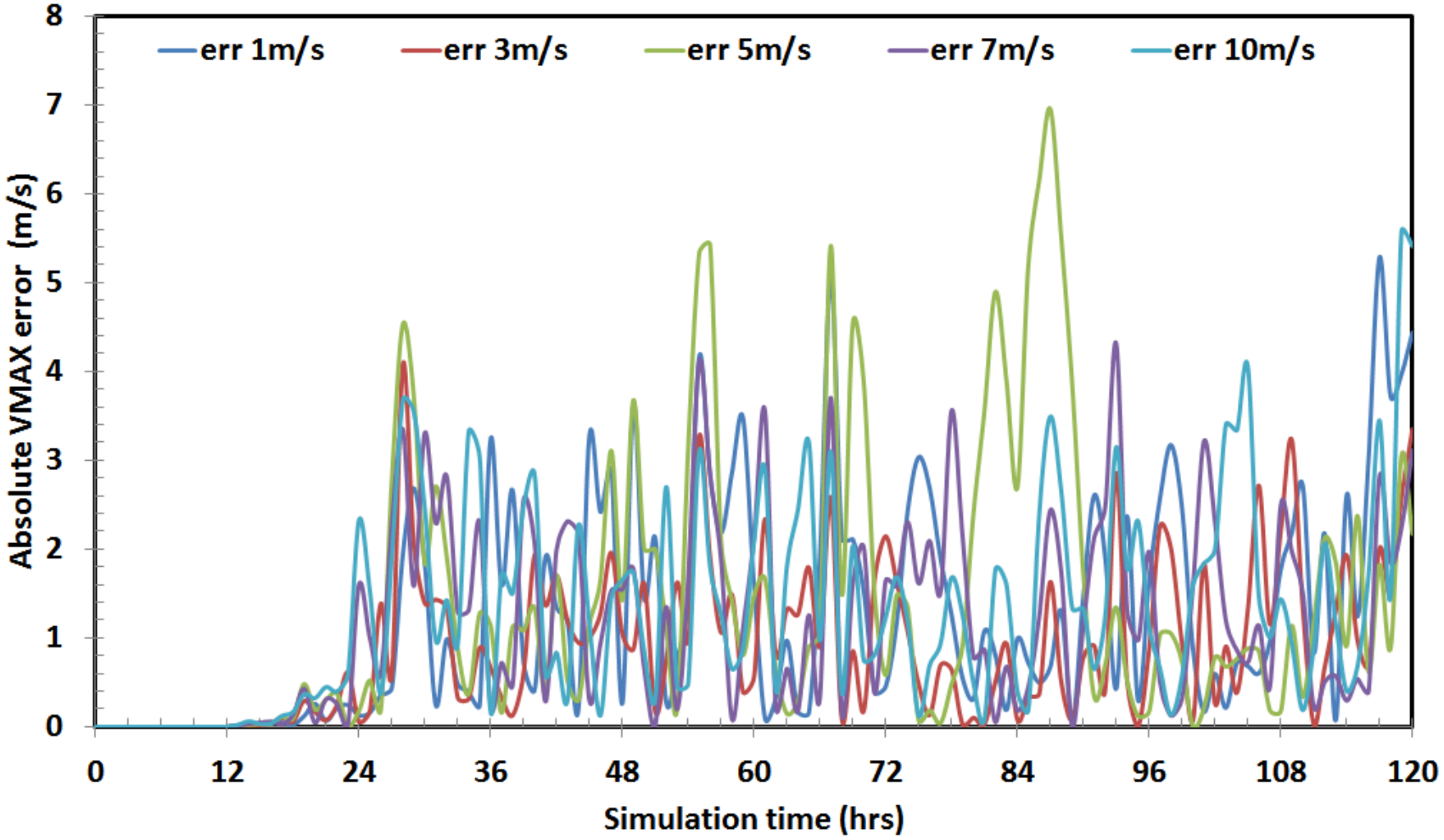
- Boundedness property
- Denseness property
- Positive leading Lyapunov exponent
- The MPI attractor depends on large-scale environment





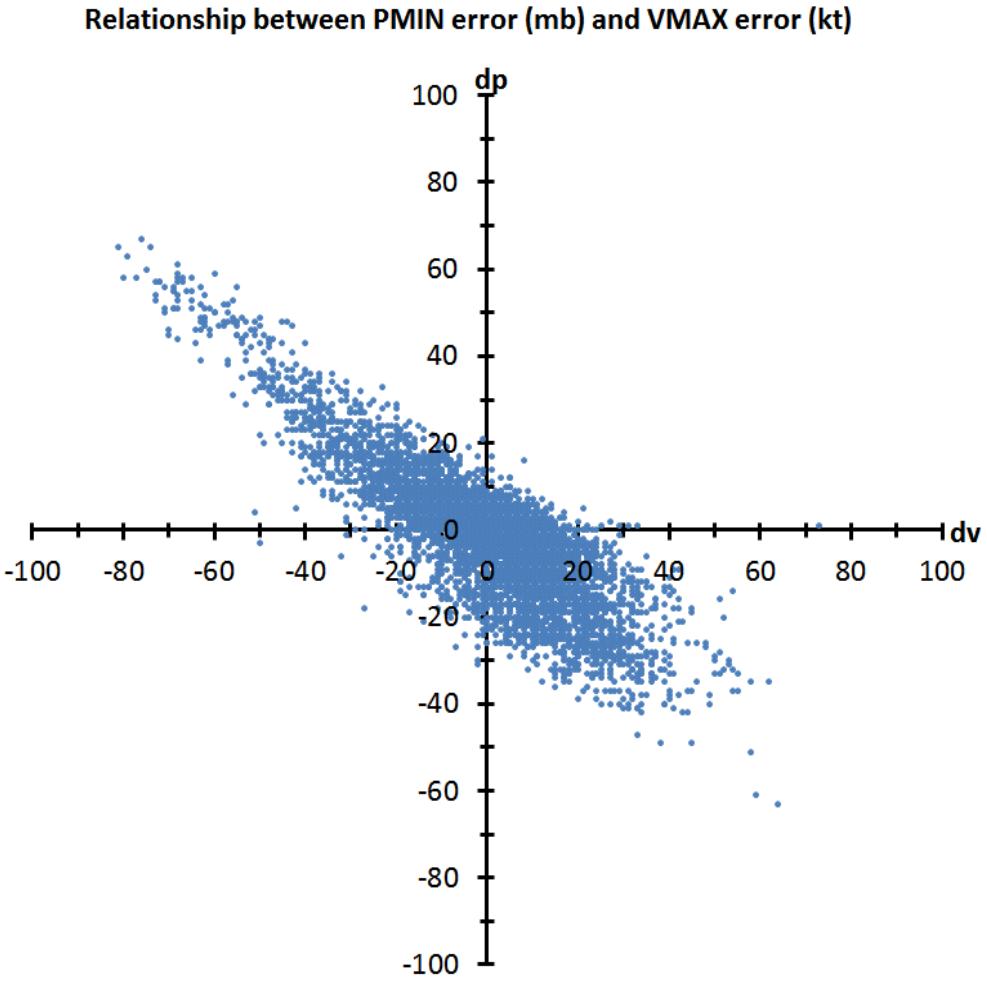
HWRF intensity error growth sensitivity

Sensitivity experiments with different initial perturbation amplitudes



Pmin vs Vmax error growth

Scatter plot of PMIN and VMAX errors for the HWRF model during 2012-2014 seasons in the WPAC basin.

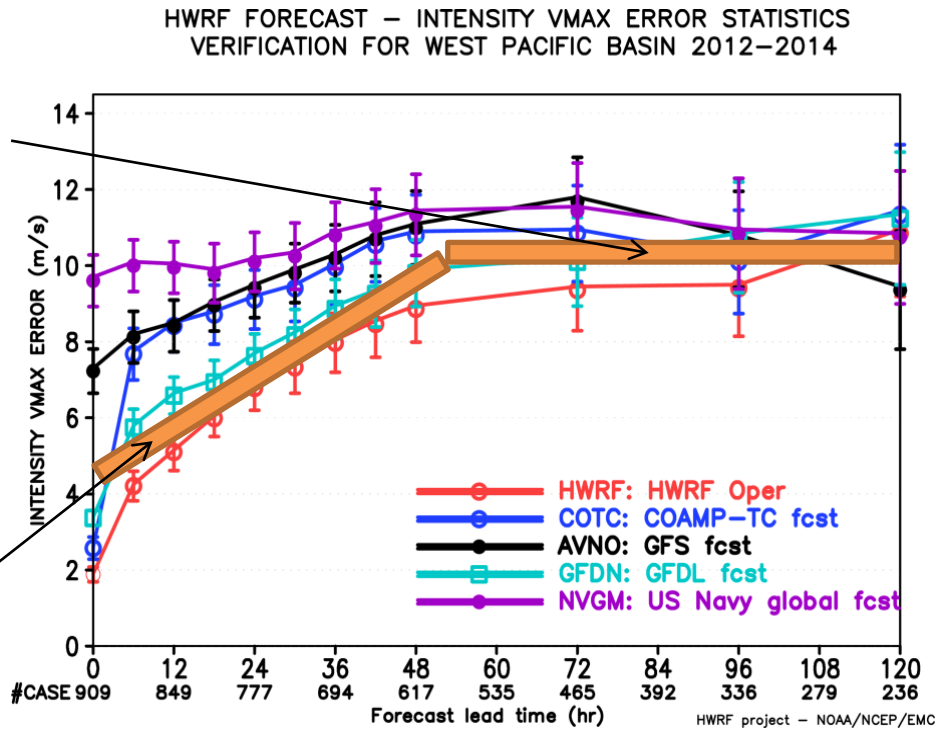


Remarks:

1. Consistent linear relationship between VMAX and PMIN errors → saturation of VMAX errors implies saturation of PMIN errors;

Real-time intensity verification

Intensity errors saturate

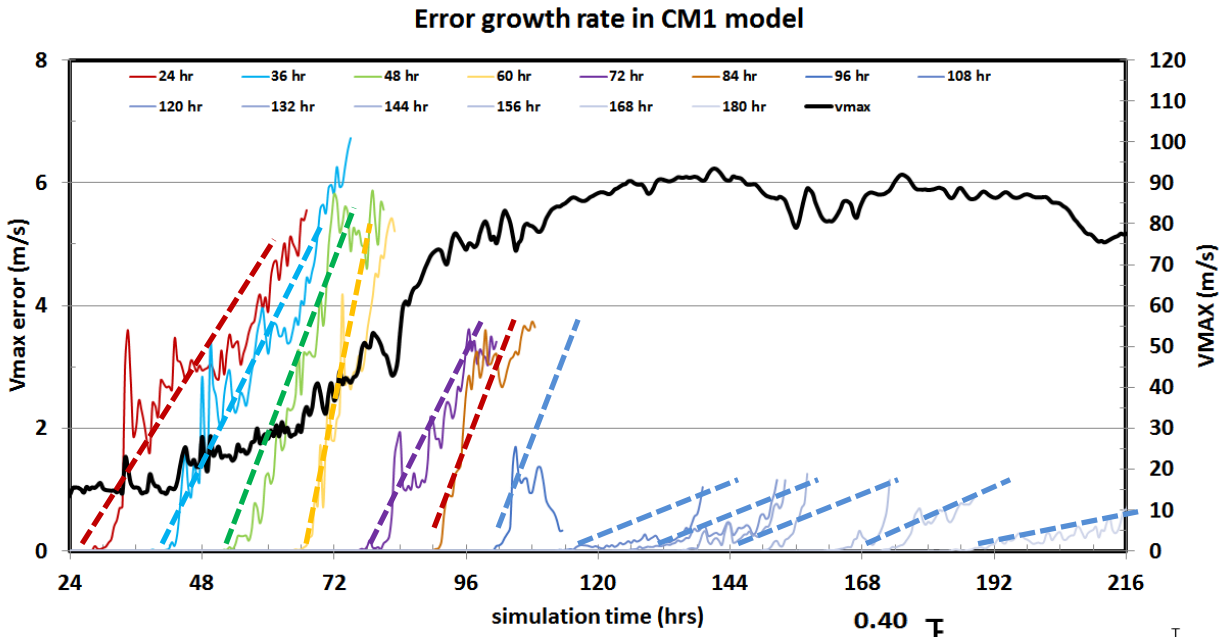


Intensity errors grow quickly

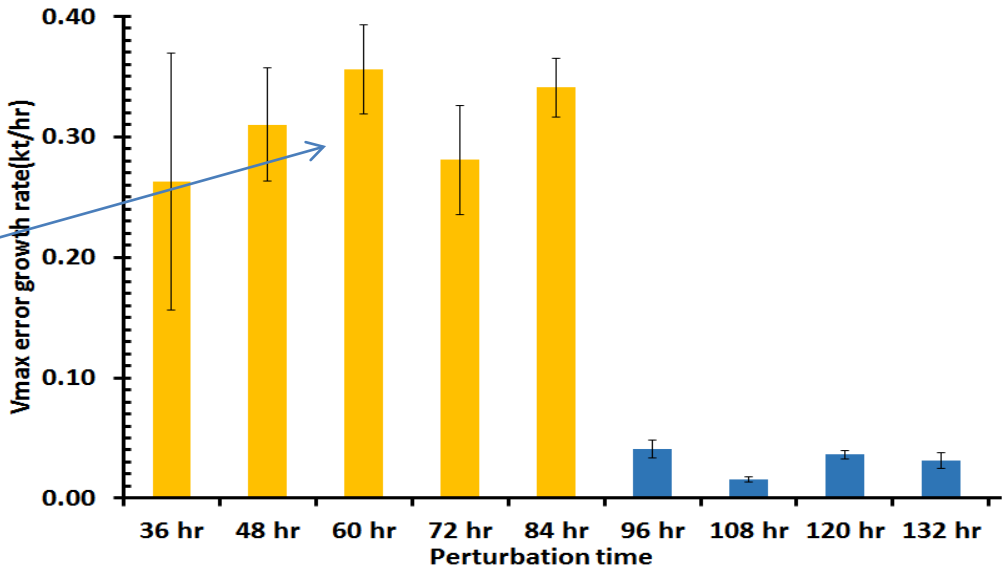
Remark 1: Intensity errors are saturated after 3 days;

Remark 2: The errors are saturated at 8-10 m s^{-1}.

CM1 intensity error growth rate



Similar slower growth rate as HWRF. Intrinsic errors will grow ~0.3 kt/hours even with perfect model or vortex structure/Vmax



Range of predictability

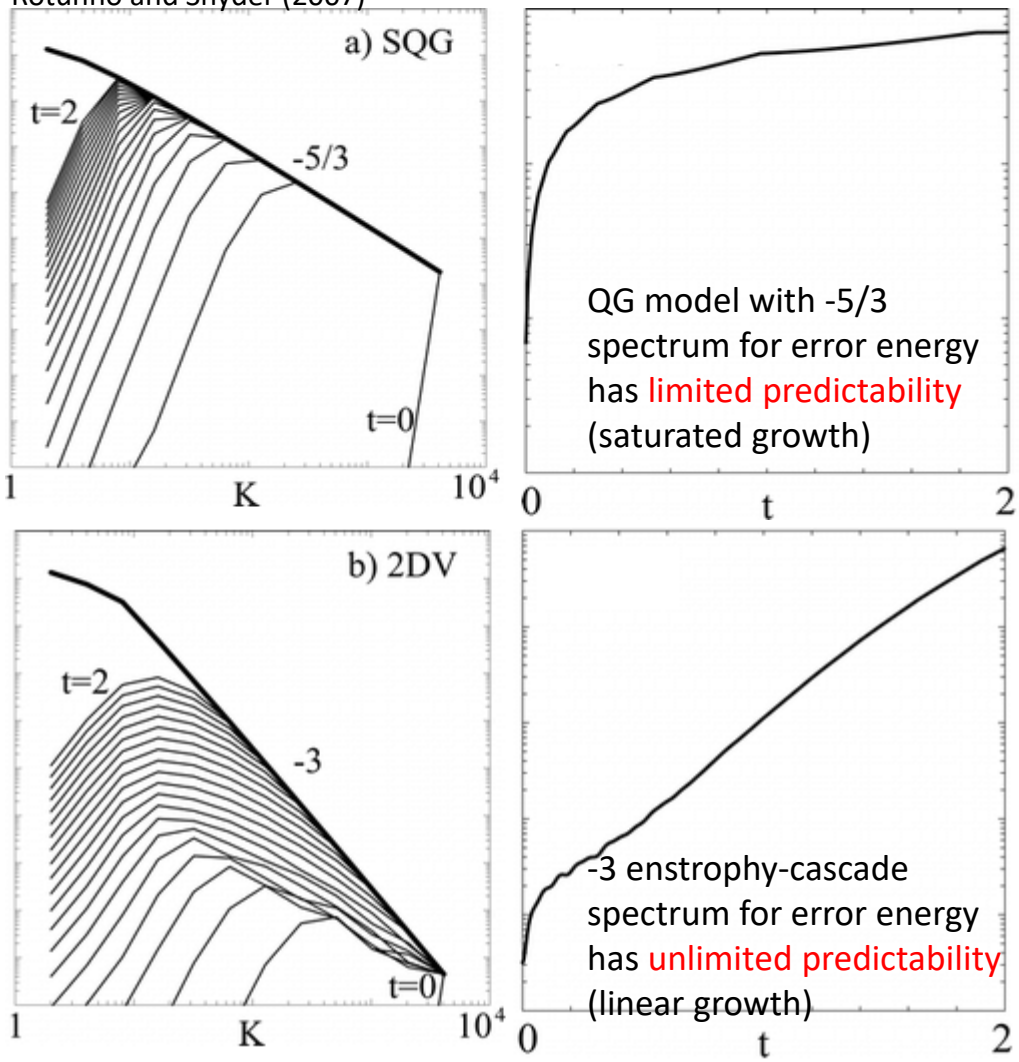
- **Range of predictability***: a time interval T such as $\epsilon_0 < \epsilon_0 e^{\lambda T} \leq \Gamma$, where Γ is the magnitude of the difference between randomly chosen initial states.

- For TCs, how can we know Γ? Is there any quasi-stationary stage for hurricanes to approach in the longer run so that Γ can be defined?

***Remark**: a predictability limit can be defined in terms of a statistical decorrelation time for multi-scale homogenous turbulence systems (see, e.g., Orszag 1970, Metais and Lesieur 1986…). We will choose the above dynamical-based definition for the predictability range, as it is more relevant to the operational TC forecast practice.

Role of underlying dynamics

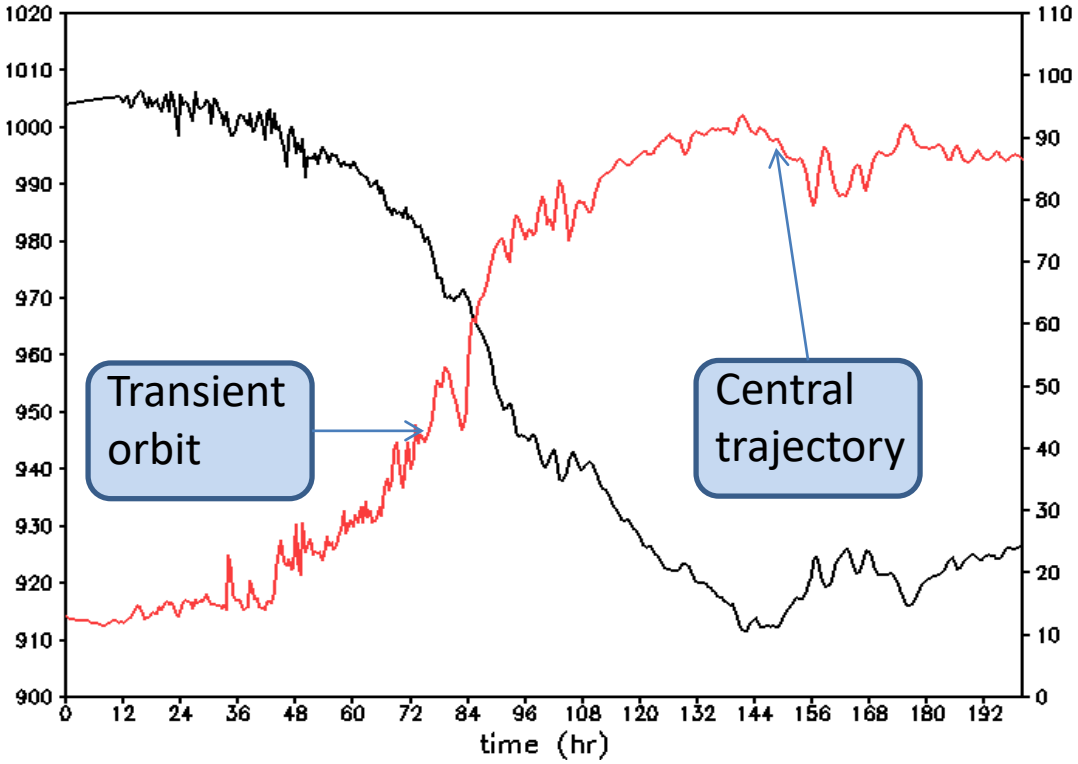
Rotunno and Snyder (2007)

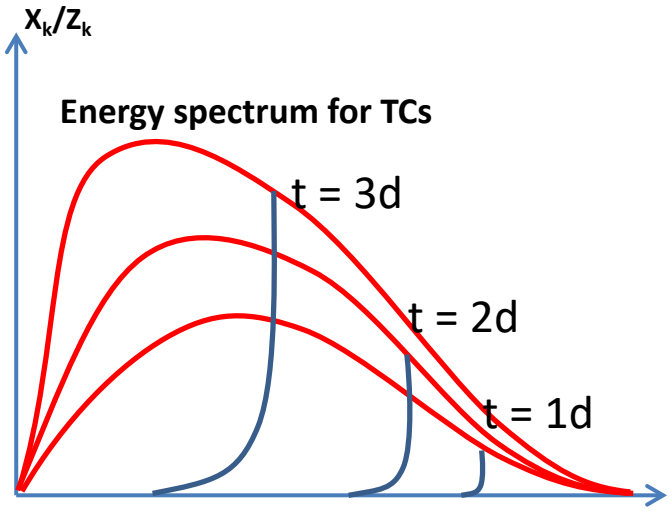


- Background dynamics plays a fundamental role in predictability limit that a dynamical system possesses.
- Existence of a finite stationary error saturation limit is fundamental so that the errors can be saturated (boundness)

Role of underlying dynamics

Lorenz (1963): a central trajectory that is non-periodic will be unstable → the sensitive dependence on the initial condition;





TCs possess a background spectrum X_k changing with time (red curve) → what is the range of predictability for the TC intensity under evolving background…?

Real-time intensity error growth rate

Approach:

- ✓ Compute 18-h intensity error growth rate as follows:

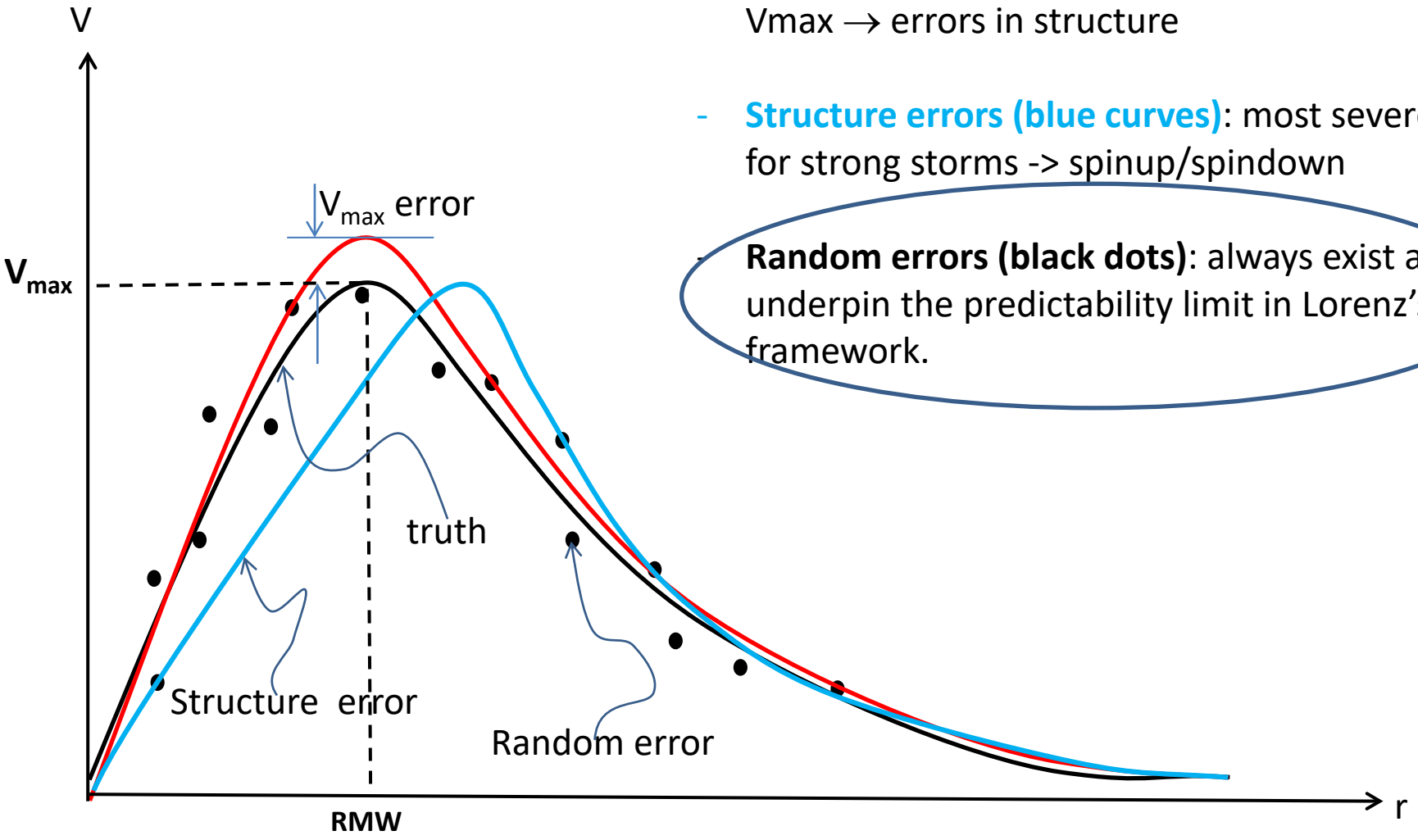
$$\epsilon = \frac{(Vmax - Vobs)_{t=18h} - (Vmax - Vobs)_{t=0}}{18\ hours}$$

- ✓ 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: a small sample size for 121-185 kt.

HWRF initial intensity error

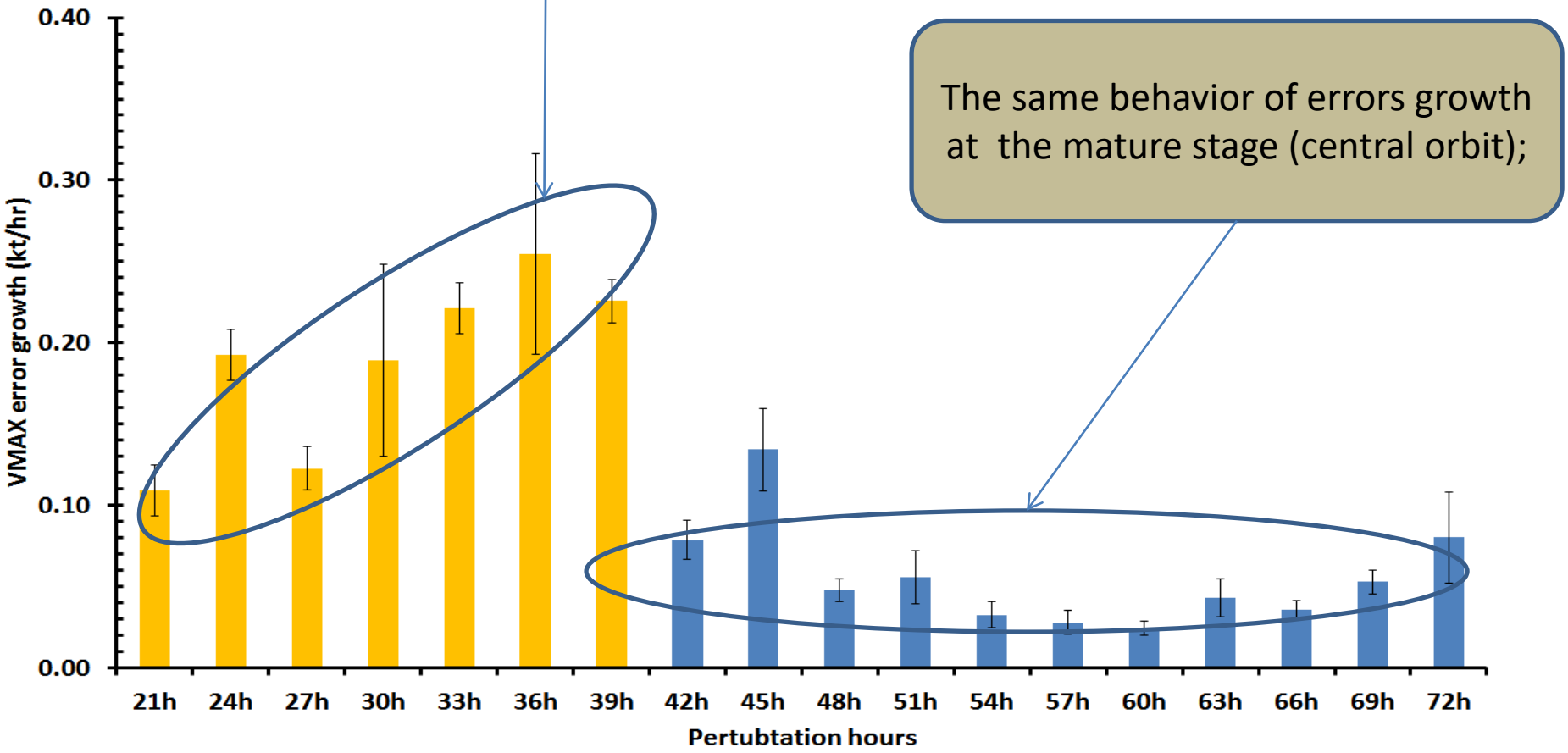


- **Strength or V_{max} errors (red curves)**: errors in Vmax → errors in structure
- **Structure errors (blue curves)**: most severe for strong storms -> spinup/spindown
- **Random errors (black dots)**: always exist and underpin the predictability limit in Lorenz's framework.

HWRF intensity error growth rate

The same behavior of a faster error growth rate for stronger storm during RI (transient orbit);

The same behavior of errors growth at the mature stage (central orbit);

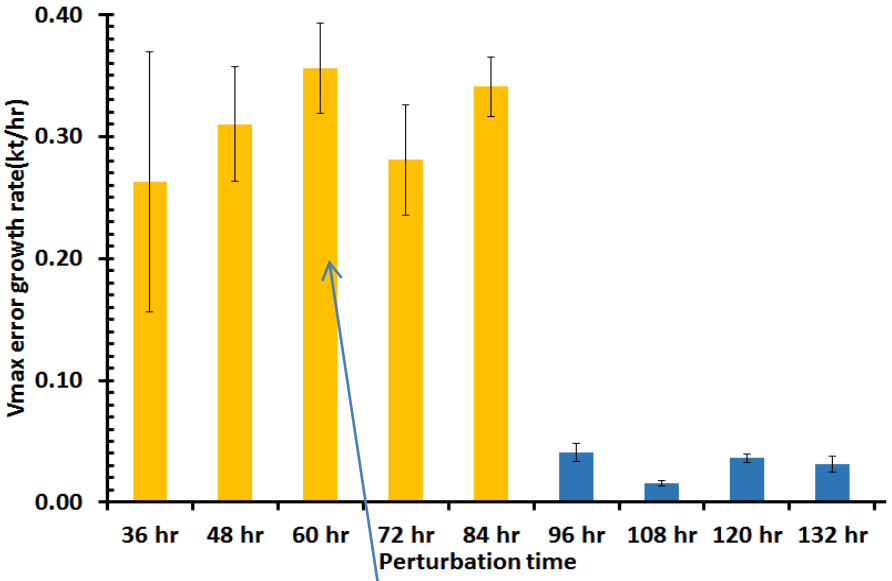


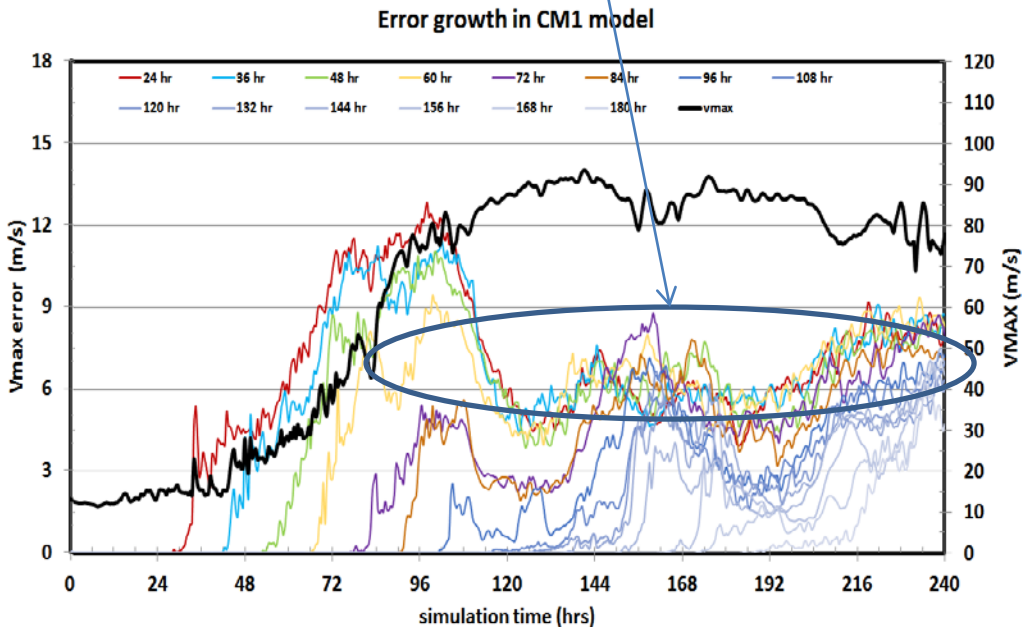
CM1 intensity error growth

Is the HWRF's growth unique?

- Use of idealized CM1 (George Bryan)
- Implement a perturbation at different stages of intensification
- Isolate the common intrinsic error growth between HWRF and CM1 model

Regardless of time to perturbations, intensity errors w.r.t. control show bounded error at ~ **13kt** (6.5 ms^{-1})





Similar slower growth rate as HWRF. Intrinsic errors grow ~0.3 kt/hours even with perfect model or vortex structure/Vmax

What next?

- Redo the analyze all statistics for the H217 to evaluate the saturation error limit of the new upgrades;

- Quantifying how the error saturation limit depends large-scale environment (a range of the saturation limit from 9-16 kt has been seen so far)

- Determine the intensity error growth rate during RI, and how the growth rate depends on environmental factors and model parameterizations;

- Estimate the error energy spectrum at the MPI limit;