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The Impacts of Numerical Schemes on Asymmetric Hurricane Intensification

Steve Guimond

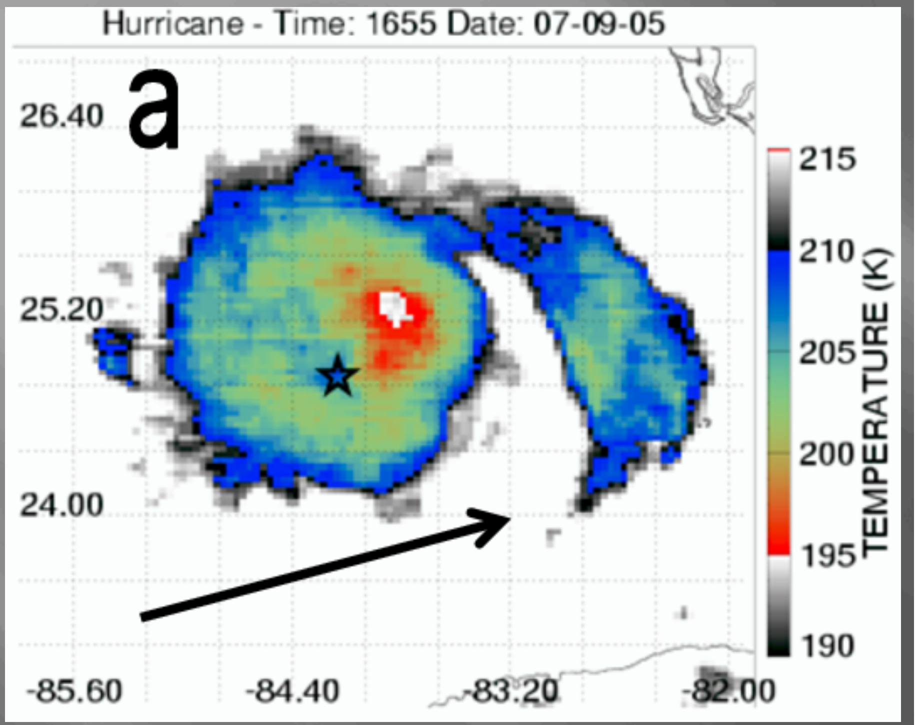
Univ. of Maryland/NASA GSFC

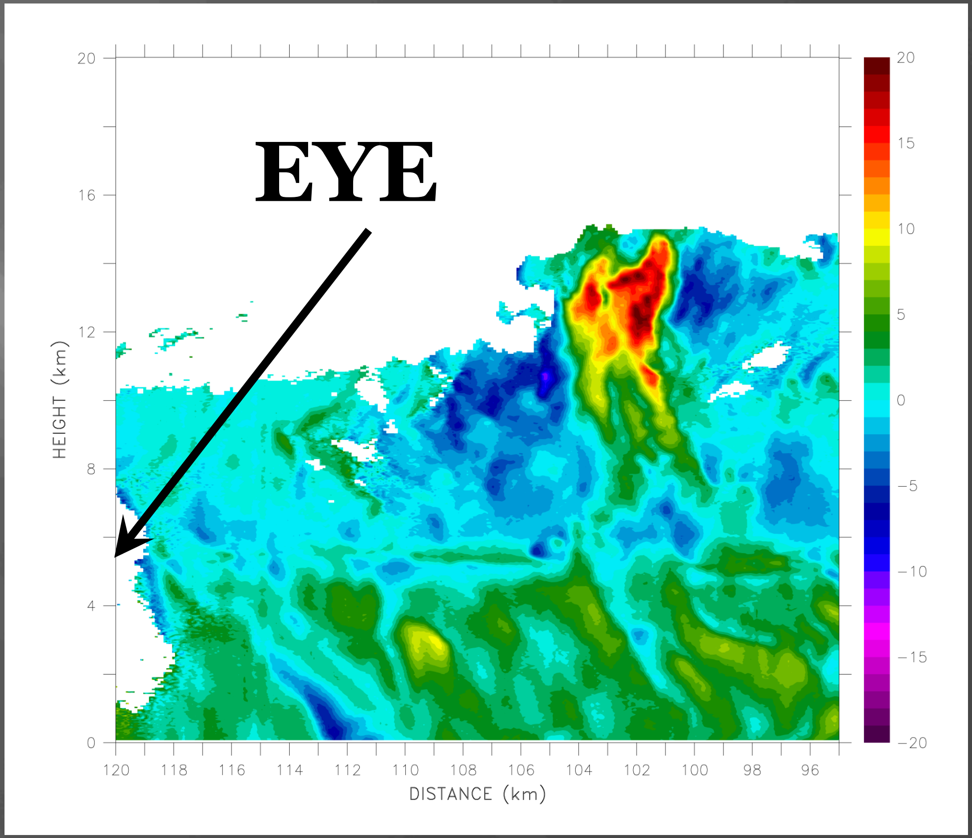
Motivation

Significant coupling between hurricanes and climate

- Downscale impact (Emanuel et al., Vecchi et al.)
  - Global warming → inc. in SST/fluxes of heat & moisture → stronger storms.
  - Global warming → inc. in wind shear → some weaker, some stronger storms.
- Upscale impact (Emanuel et al., Sobel et al.)
  - Hurricane → mixing of upper ocean → affect oceanic transport of heat.
  - Hurricane → poleward migration → affect atmospheric transport of heat.
- Understanding of hurricanes role in climate hinges on:
  - Knowledge of physics governing hurricane intensity.
  - Ability to correctly model nonlinear interactions of scales.

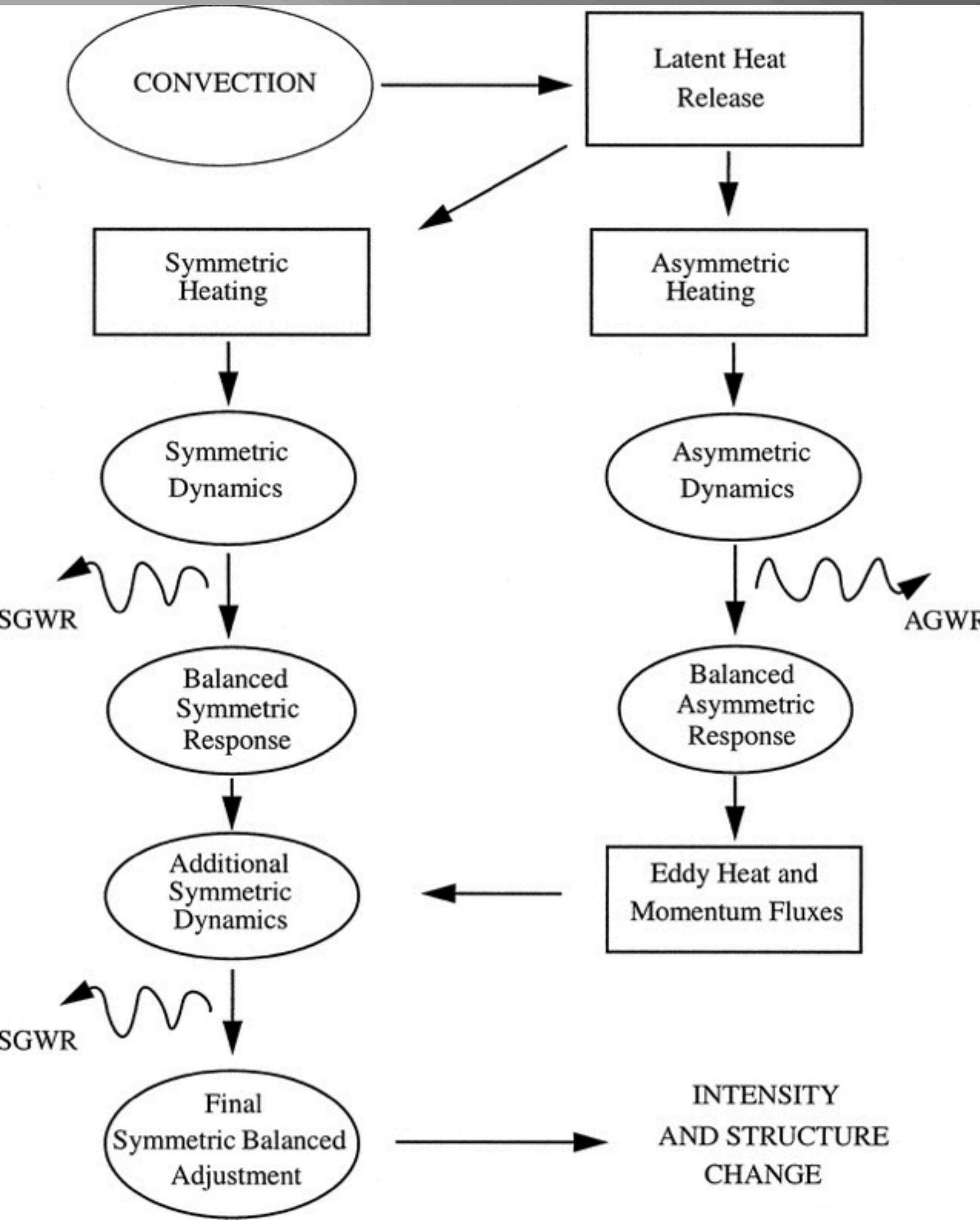
Drivers of Hurricane Intensity Change





Guimond et al. 2010, J. Atmos. Sci.

Dynamics of Hurricane Intensity Change



- ✓ **Nolan and Montgomery (2002;NM02)**
- ✓ **Nolan and Grasso (2003;NG03)**
- ✓ **Nolan et al. (2007)**

"Axisymmetrization"

Dynamical Cores

Table 1. Summary of default numerical schemes used in each model for this study. See text for details.

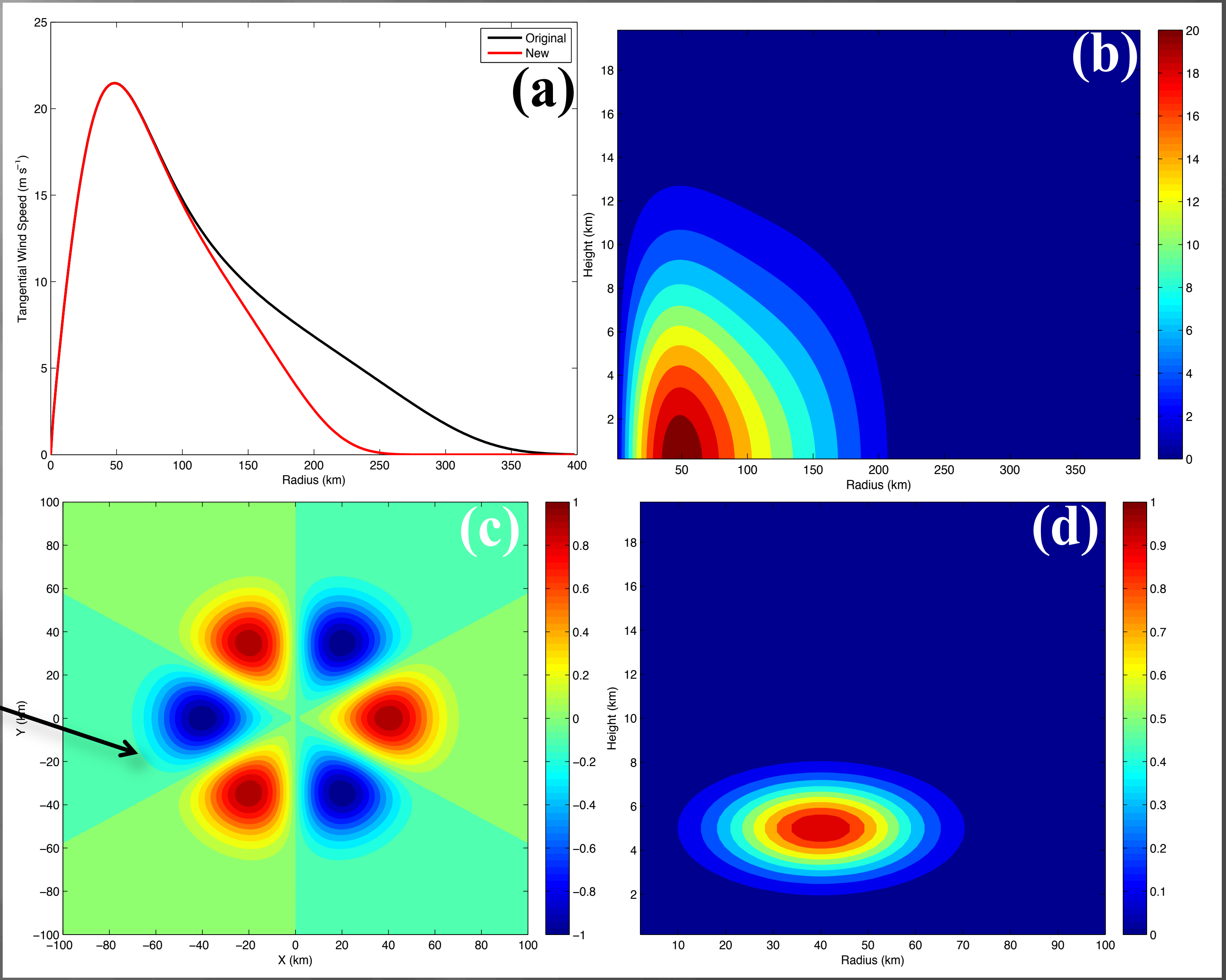
	HIGRAD	WRF	NUMA
Time Integration	Semi-implicit w/ Forward Euler	Split-explicit w/ Runge Kutta	Semi-implicit w/ Leap Frog
Spatial Discretization	Finite Difference on A-grid	Finite Difference on C-grid	Spectral Element
Advection	QUICK	5^{th} order horizontal/ 3^{rd} order vertical	Spectral Element
Explicit Filters	6^{th} order spatial	None	1^{st} order temporal

Numerical Model Setup

- 3D, compressible Euler equation set
- 800 km^2 box, grid spacing of 2 km
  - NUMA (5^{th} order polynomials, 80 elem in x/y, 12 in z)
- 60 vertical levels at ~ 333 m resolution
- WRF upper damping layer added to HIGRAD and NUMA
- Same Coriolis frequency (5.0×10^{-5} s^{-1})
- No dissipation of momentum at lowest level
- Doubly Periodic BCs
- Turbulent diffusion – very simple
  - Laplacian operator
  - Eddy viscosity/diffusivity = 150 m^2/s in x/y/z

Initial Conditions

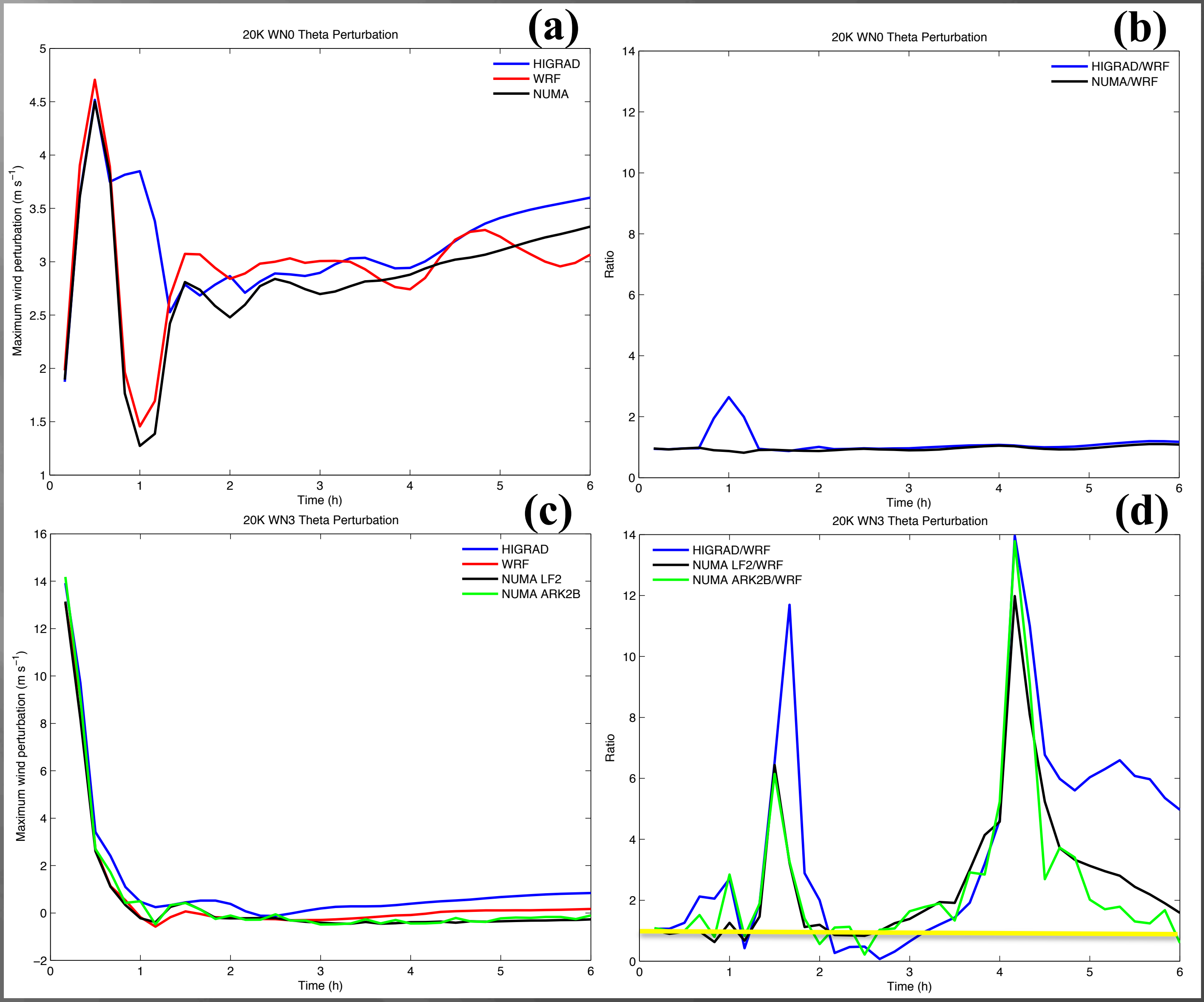
WN3



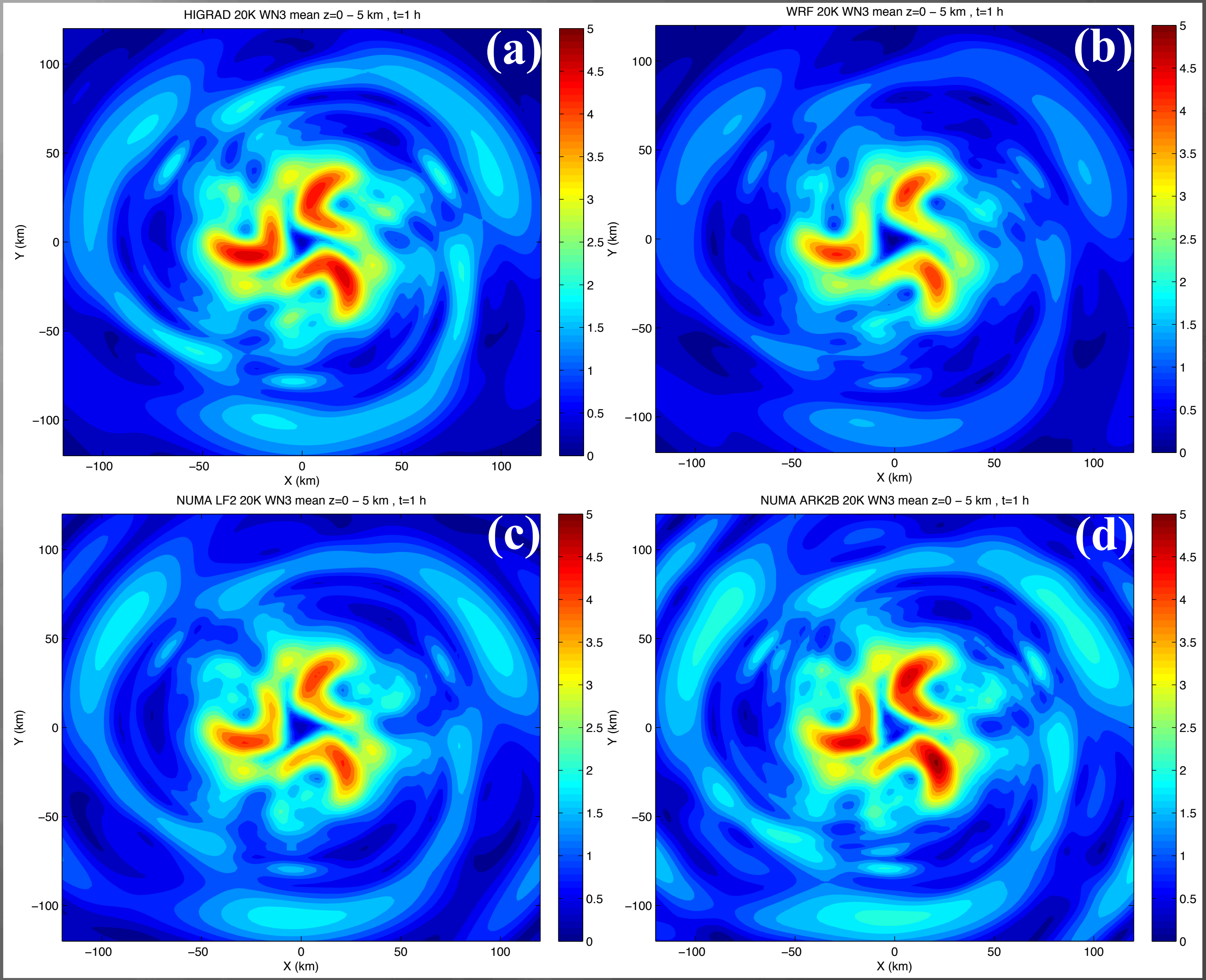
20 K Perturbation Results

WN0

WN3



20 K WN3 Perturbation Results



WN3 Perturbation Results

Table 2. Absolute value of the impact ratio, $\left|\frac{WN0}{WN3}\right|$, for impulsive thermal perturbations in each numerical model for various amplitudes. The ratio is listed as a 2 h average over the 4 – 6 h period rounded to the nearest whole number. This is reported in terms of either perturbation maximum wind speed or perturbation integrated kinetic energy. The format is: wind ratio / kinetic energy ratio. The "I" and "W" letters indicate whether intensification or weakening, respectively, was observed during this time period. The NUMA results use the LF2 time integrator, but similar results were obtained with the ARK2B scheme during this period.

Amplitude	HIGRAD	WRF	NUMA
1 K	4^{I} / 7^{I}	20^{I} / 1562^{I}	24^{I} / 583^{I}
10 K	3^{I}/ 13^{I}	1596^{I} / 40^{I}	17^{W} / 36^{I}
20 K	5^{I} / 13^{I}	36^{I} / 39^{I}	9^{W} / 16^{I}

Testing other Asymmetries

Table 4. As in Table 2, only replacing the denominator in the impact ratio with various asymmetric wavenumber perturbations.

Perturbation	HIGRAD	WRF	NUMA
10 K WN1	1^{I} / 7^{I}	2^{I} / 21^{I}	3^{I} / 16^{I}
10 K WN2	2^{I}/ 9^{I}	6^{I} / 51^{I}	146^{I} / 31^{I}
10 K WN4	3^{I} / 9^{I}	29^{W} / 377^{I}	15^{W} / 34^{I}
10 K WN5	3^{I} / 8^{I}	26^{W} / 306^{I}	19^{W} / 28^{I}
20 K WN4	4^{I} / 10^{I}	341^{I} / 37^{I}	13^{W}/15^{I}
20 K WN5	3^{I}/ 10^{I}	195^{I} / 34^{I}	21^{W}/13^{I}

Understanding Differences

- ✓ Model configuration sensitivity tests
  - ➢ Grid spacing, domains, boundary conditions, gravity wave absorption, initialization, perturbation magnitude and location, explicit diffusion, etc.
- ✓ Angular and Radial Momentum Budgets
- ✓ Model Solution Sensitivity Analysis
- ✓ Spectral Kinetic Energy Budgets and Analysis

Spectral Dynamics

- Compare kinetic energy (KE, per unit mass) spectra

$$E(k) = \frac{1}{2}\left(|\hat{u}|^2 + |\hat{v}|^2\right)$$

  - *X*-direction FFTs for velocity (perturbations)
  - Average in *y*-direction and up to damping layer
  - Decomposed into rotational and divergent modes

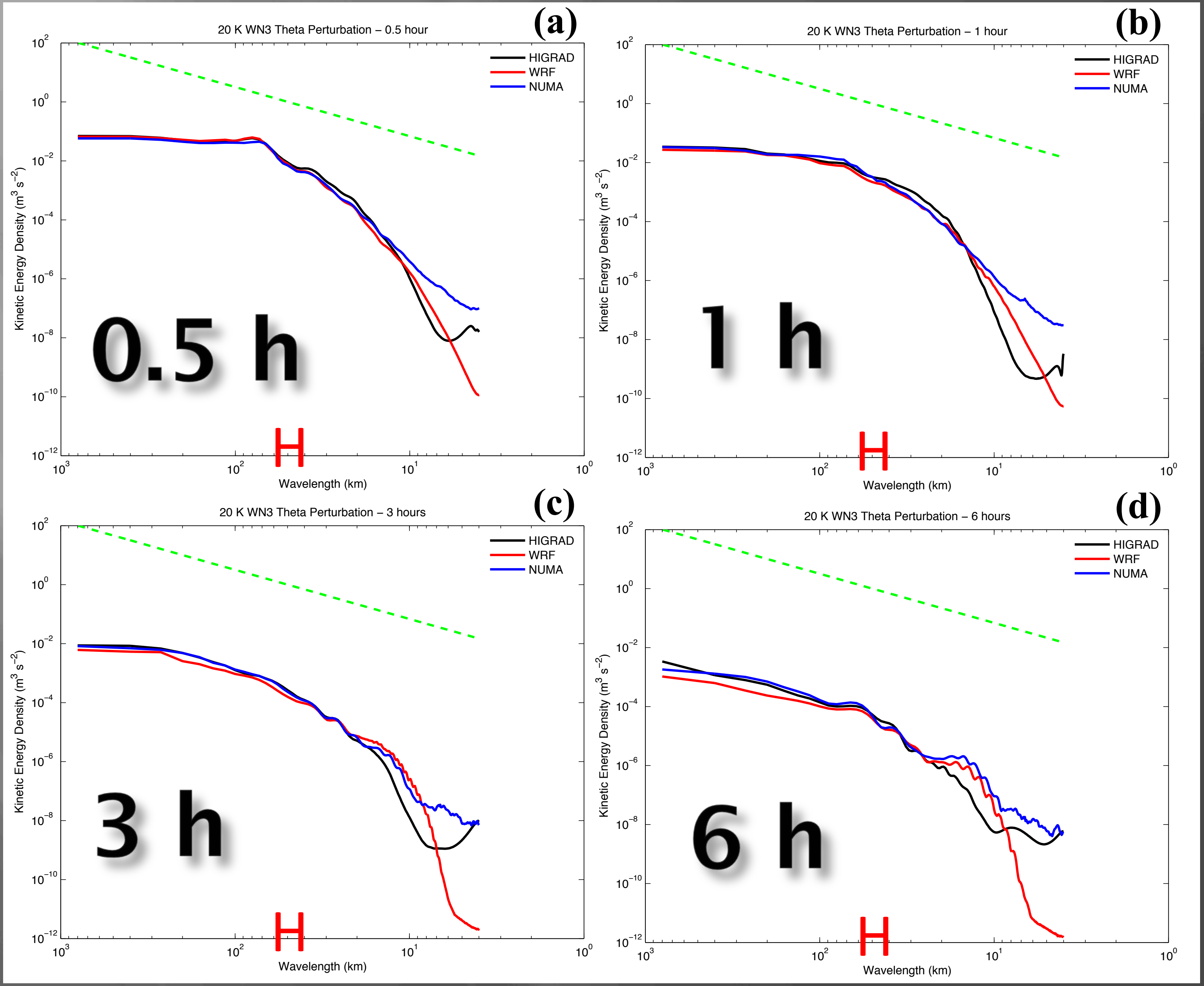
$$\vec{V}_h = k \times \nabla\psi + \nabla\chi$$

$$\nabla^2\psi = k \bullet \nabla \times \vec{V}_h, \quad \nabla^2\chi = \nabla \bullet \vec{V}_h$$

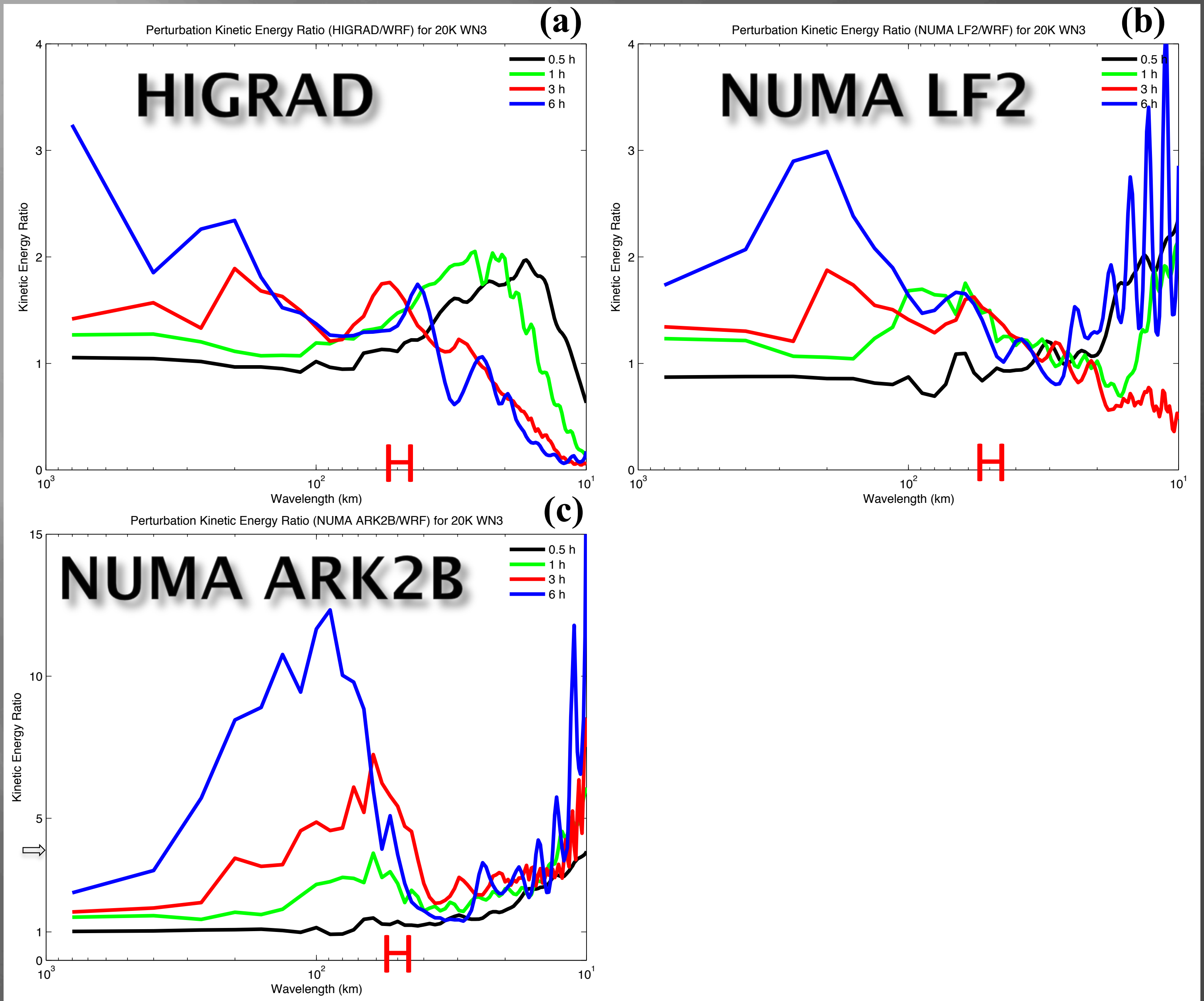
- Compare spectral KE budgets (shown later)

$$\frac{\partial}{\partial t}E(k) = A(k) + P(k) + D(k)$$

Kinetic Energy Spectra: 20 K WN3



Kinetic Energy Spectra: 20 K WN3



Spectral Kinetic Energy Budgets

$$\frac{\partial}{\partial t}E(k) = A(k) + P(k) + D(k)$$

$$A(k) = -\frac{1}{2}\left(\hat{\mathbf{u}}^{*} \bullet \overbrace{\mathbf{ADV}_f}^{\wedge} + \hat{\mathbf{u}} \bullet \overbrace{\mathbf{ADV}_f}^{\wedge}{}^{*}\right)$$

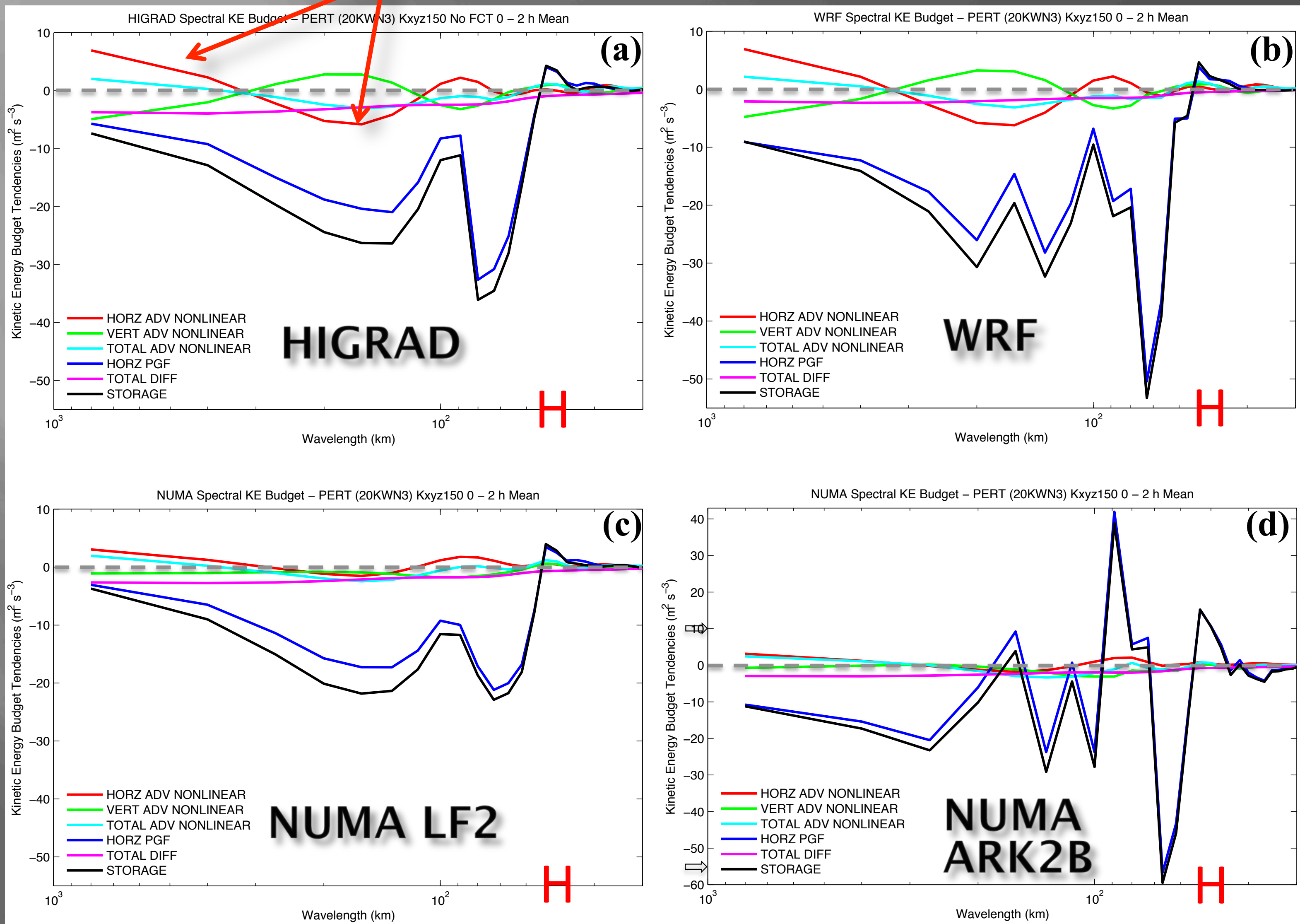
$$P(k) = -\frac{1}{2}\left(\hat{\mathbf{u}}^{*} \bullet \overbrace{\mathbf{PGF}}^{\wedge} + \hat{\mathbf{u}} \bullet \overbrace{\mathbf{PGF}}^{\wedge}{}^{*}\right)$$

$$D(k) = -\frac{1}{2}\left(\hat{\mathbf{u}}^{*} \bullet \overbrace{\mathbf{DIFF}_L}^{\wedge} + \hat{\mathbf{u}} \bullet \overbrace{\mathbf{DIFF}_L}^{\wedge}{}^{*}\right)$$

Spectral Kinetic Energy Budgets

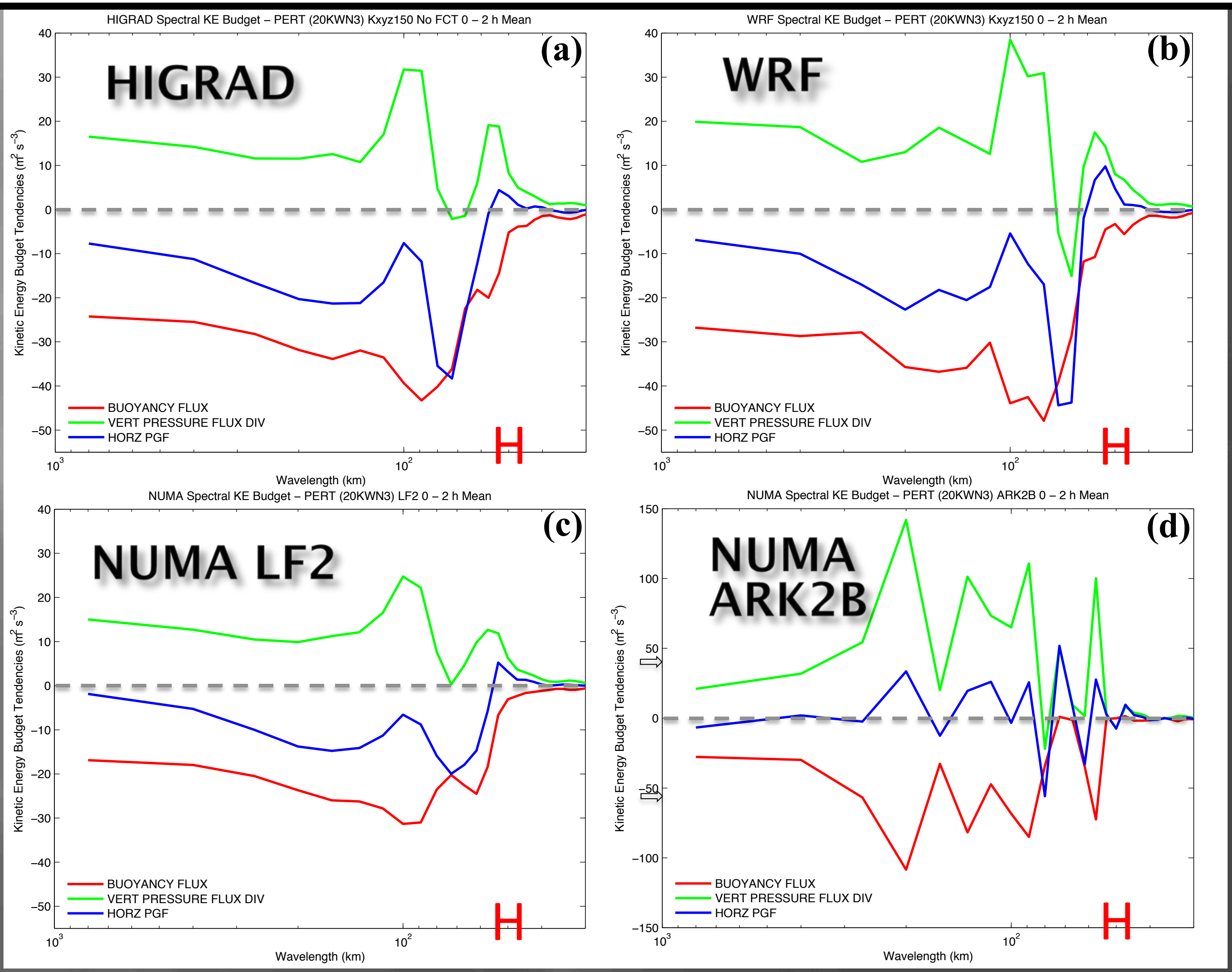
For 20K WN3 theta perturbation

upscale transfer



Spectral Kinetic Energy Budgets

$$P(k) = -\frac{1}{2}\left(\hat{\mathbf{u}}^{*} \bullet \widehat{\mathbf{PGF}} + \hat{\mathbf{u}} \bullet \widehat{\mathbf{PGF}}^{*}\right) \cong -\frac{1}{2\bar{\rho}}\left(\boxed{\frac{1}{\bar{\rho}}\frac{\partial}{\partial z}\left(\bar{\rho}\hat{w}^{*}\hat{p}\right)} + \boxed{g\hat{w}^{*}\hat{\rho}} + \frac{1}{\bar{\rho}}\frac{\partial}{\partial z}\left(\bar{\rho}\hat{w}\hat{p}^{*}\right) + g\hat{w}\hat{\rho}^{*}\right)$$



Summary

- Large differences in vortex response to asymmetric heating between dynamic cores (HIGRAD/NUMA >> WRF).

- Impulsive thermal asymmetries in vortex intensification…
  - Important, largely positive impact in HIGRAD/NUMA.
  - Negligible impact in WRF.

- Spectral dynamics
  - WRF removes more kinetic energy than HIGRAD/NUMA due to pressure term (inertia-gravity wave activity).
  - Energy moves upscale with time from nonlinear effects.

Implications

- WRF has more numerical dissipation than HIGRAD/NUMA for this problem.
- Possible culprits…
  - Time integration for fast modes.
  - Spatial discretization (C-grid).
- Indicates significant uncertainty in hurricane intensification understanding and possibly prediction.
- What about more realistic regime?
  - Realistic heating, moisture, turbulence

Guimond, S., J. Reisner, S. Marras and F. Giraldo 2016: The impacts of numerical schemes on asymmetric hurricane intensification. *J. Atmos. Sci.*, accepted pending revision.

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