The Impacts of Numerical Schemes on Asymmetric Hurricane Intensification

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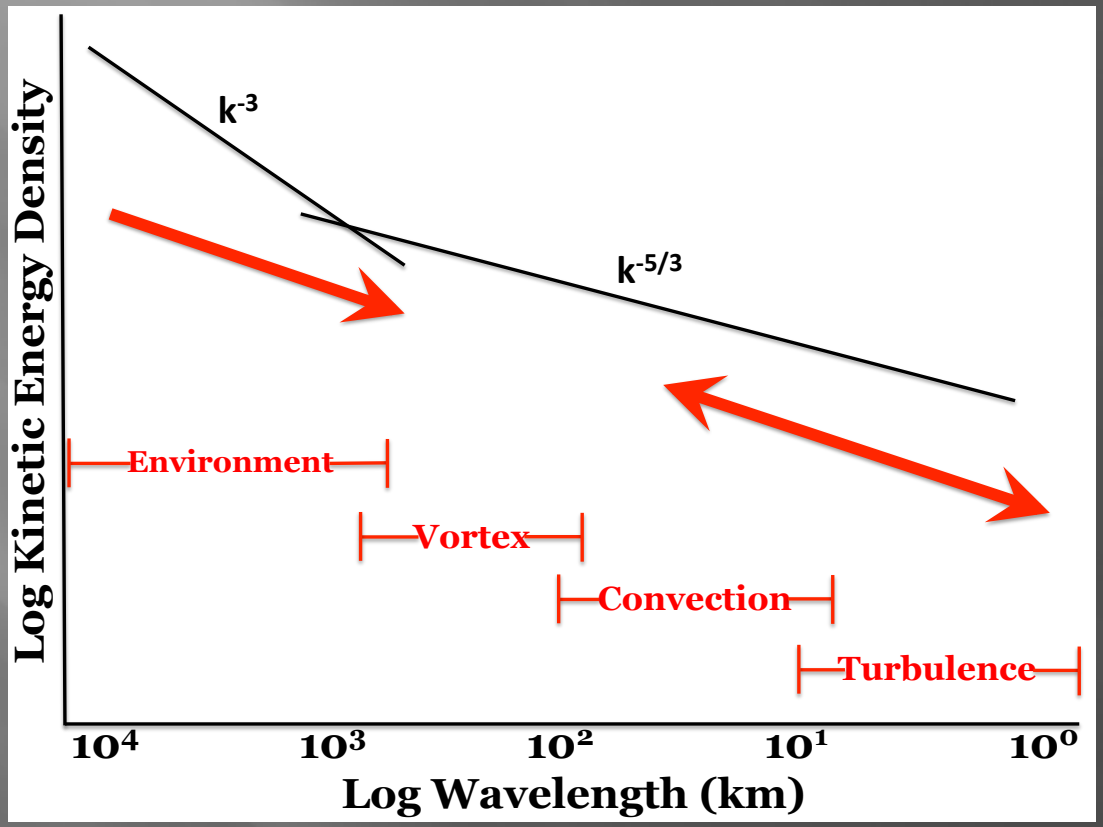
Problem and Motivation

Hurricanes are complex, nonlinear natural systems

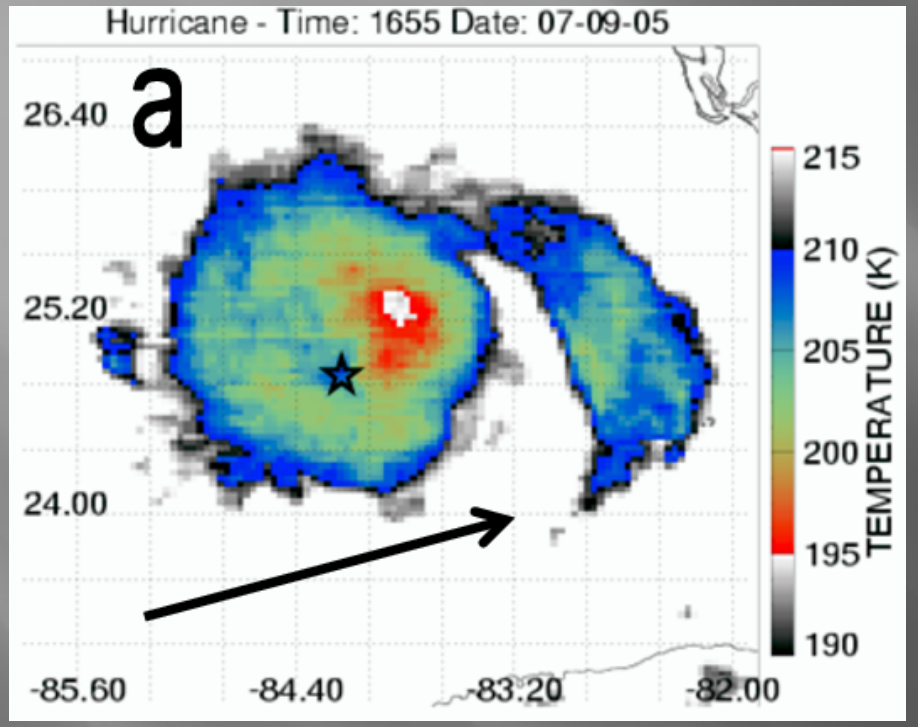
- Physical processes span several orders of magnitude

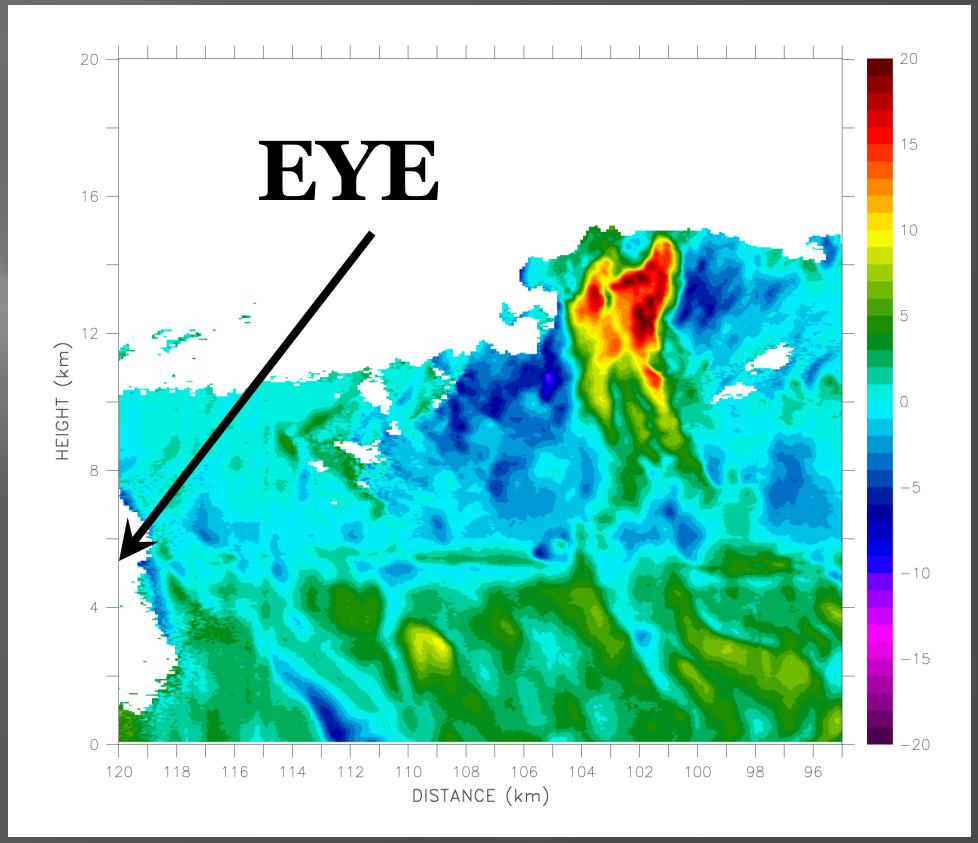


- Predictive capability for intensity is poor
- Interactions between numerics and physics, large errors

Drivers of Hurricane Intensity Change

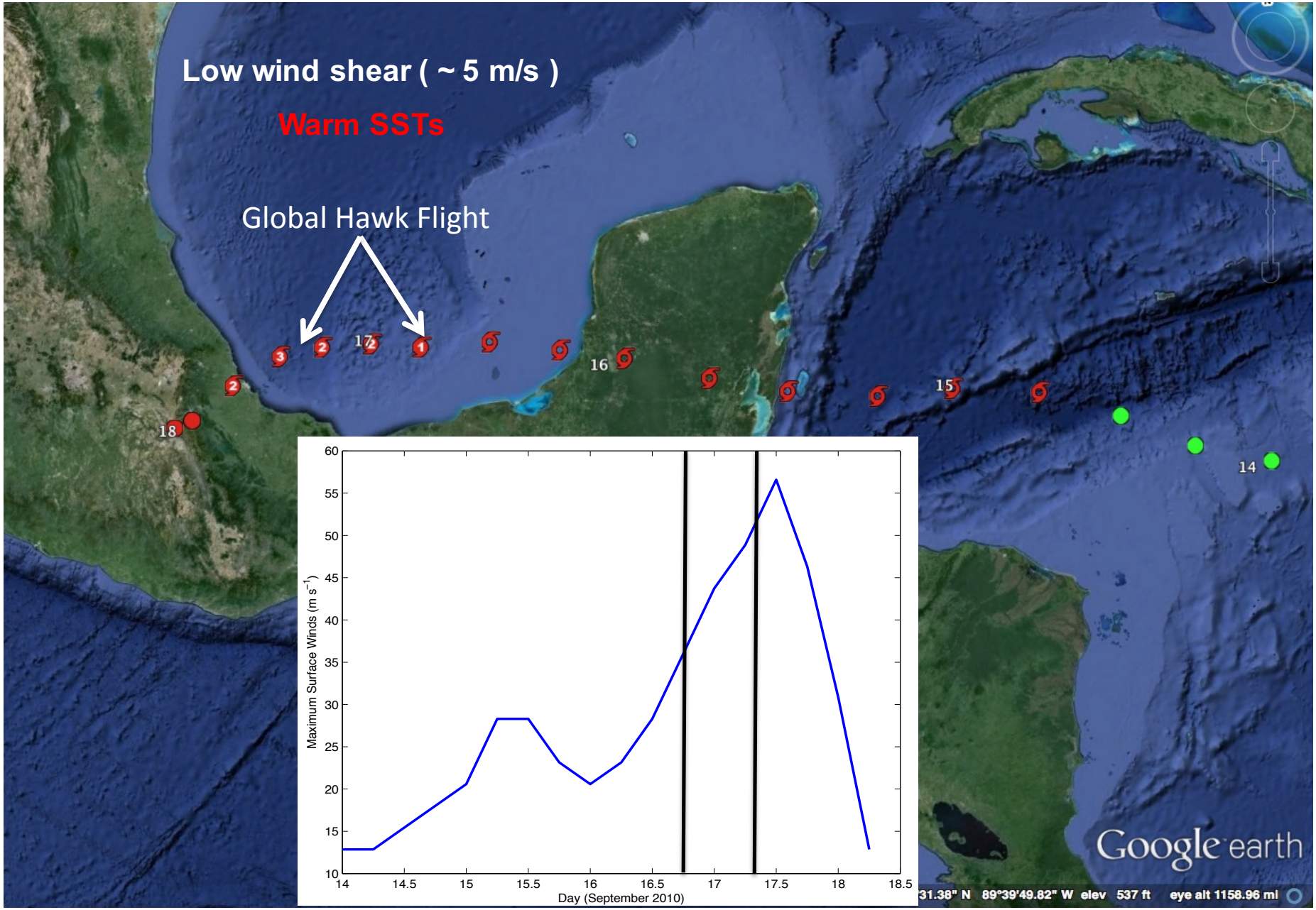
Hurricane Dennis (2005)





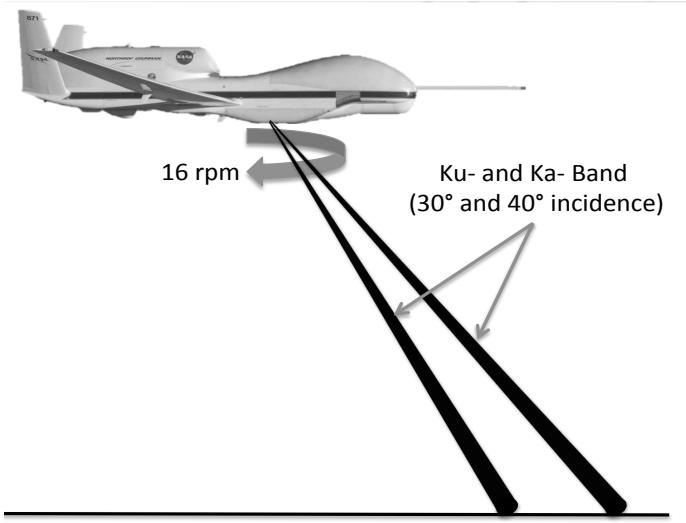
Guimond et al. 2010, J. Atmos. Sci.

Hurricane Karl (2010) during NASA GRIP



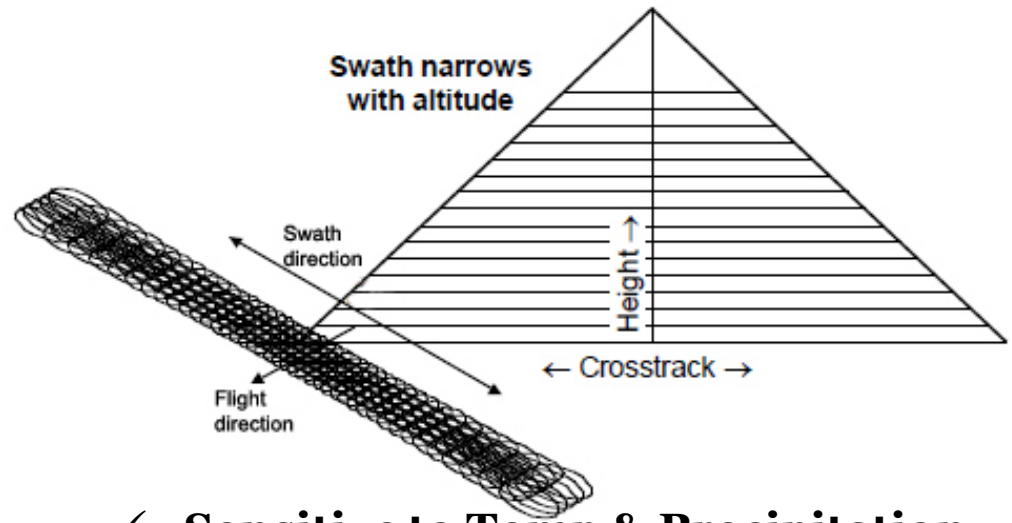
Hurricane Karl (2010) during NASA GRIP

HIWRAP



- ✓ 600 – 700 m (along-track)
- ✓ 150 m (gate spacing)
- ✓ 1 km retrieval products

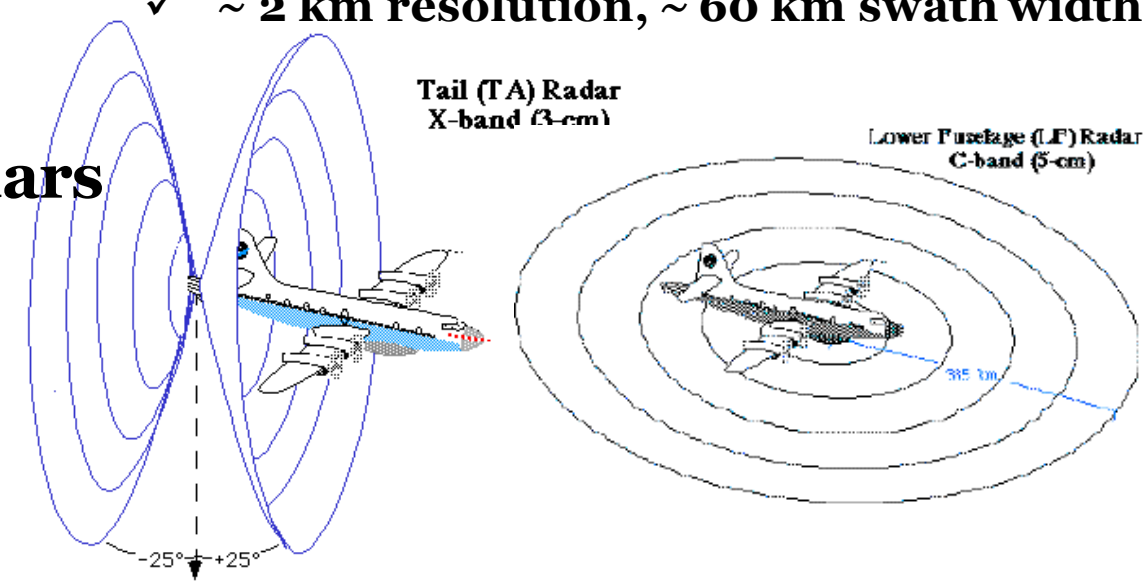
HAMSR



- ✓ Sensitive to Temp & Precipitation
- ✓ ~ 2 km resolution, ~ 60 km swath width

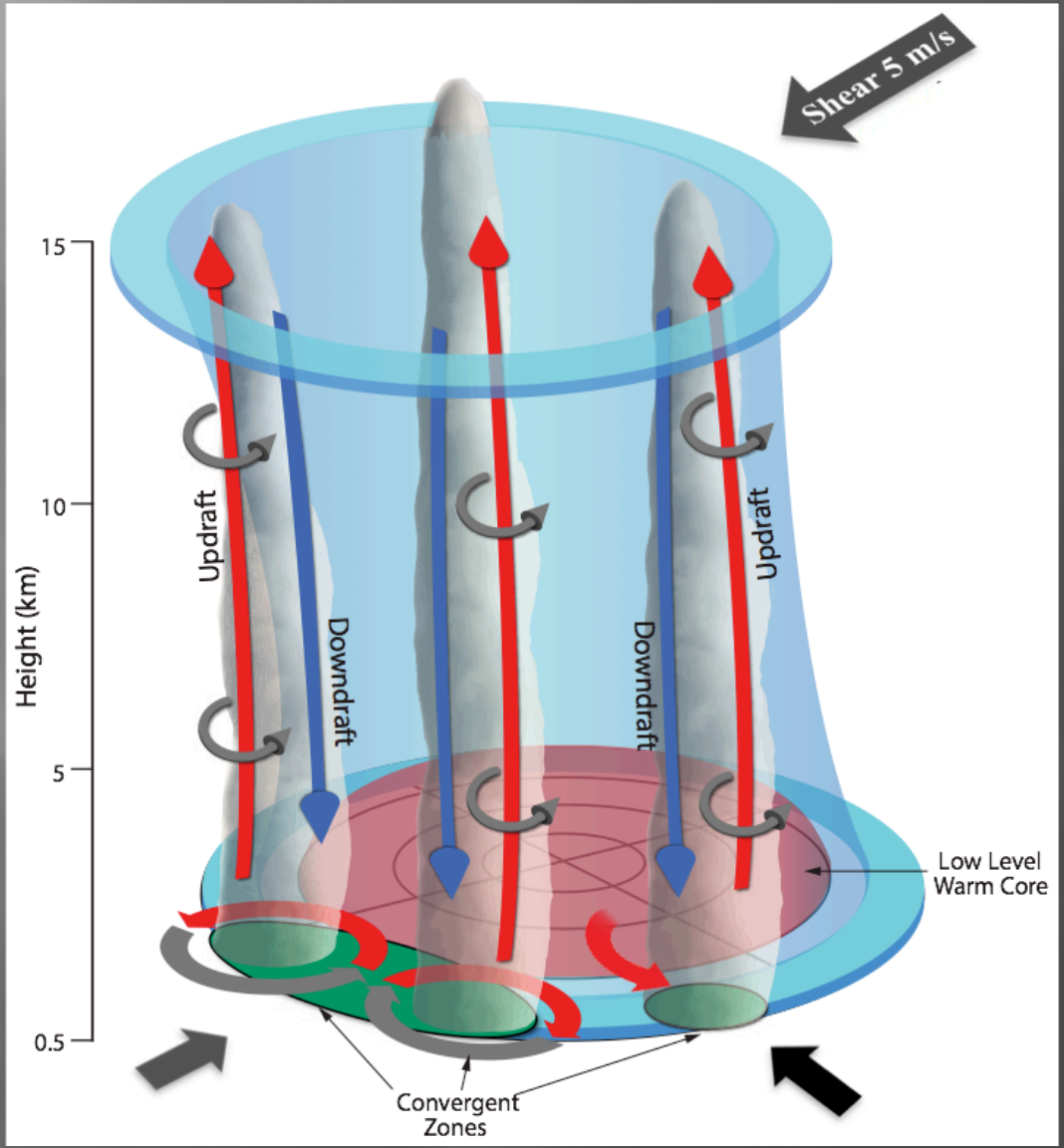
NOAA P3 TA & LF Radars

- ✓ X-band & C-band
- ✓ large coverage area
- ✓ 2 km retrieval products

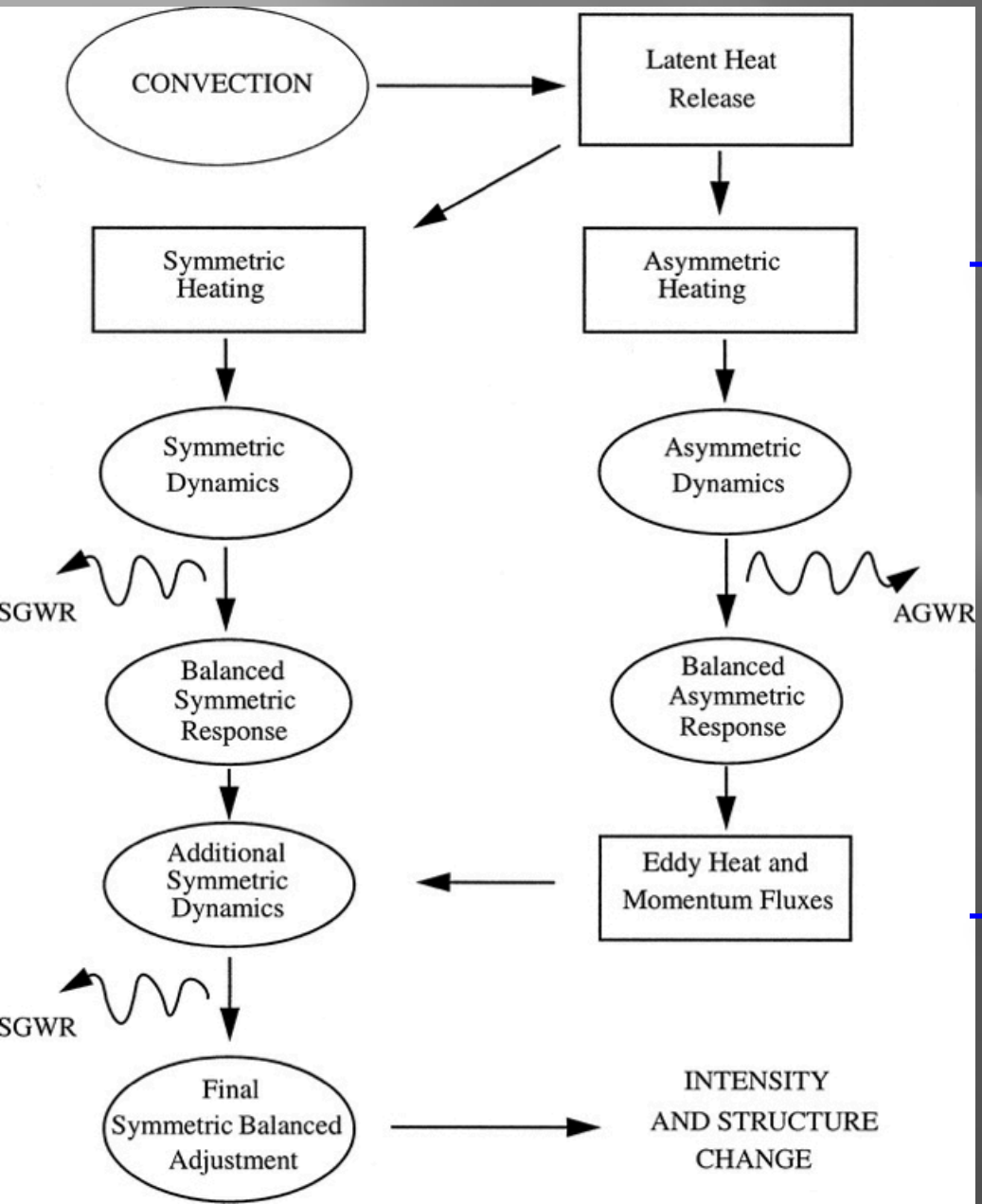


Organization of Stochastic Forcing

Guimond et al. 2016, J. Atmos. Sci.



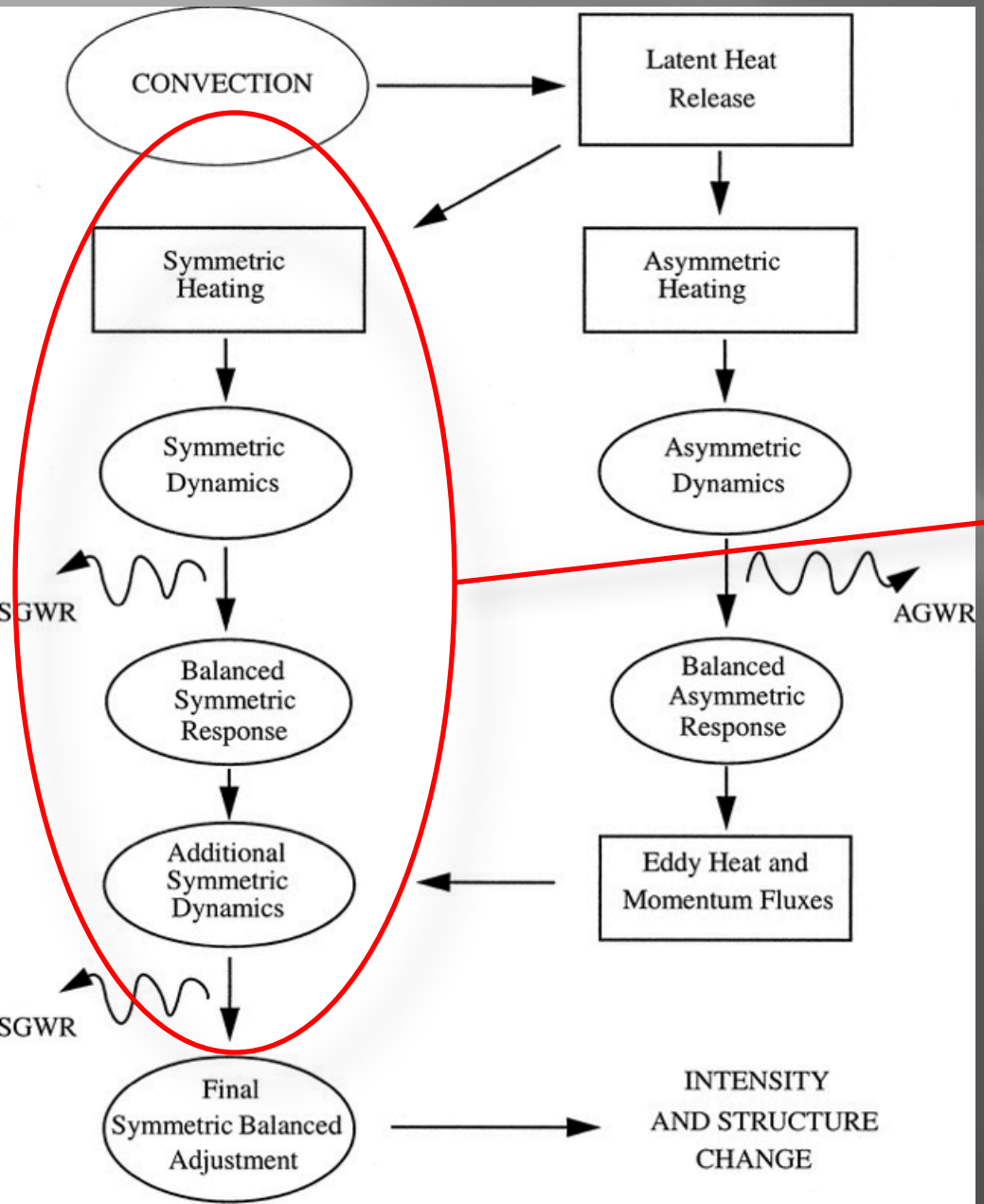
Dynamics of Hurricane Intensity Change



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

"Axisymmetrization"

Dynamics of Hurricane Intensity Change



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

Dominates by 10^2

Dynamical Cores

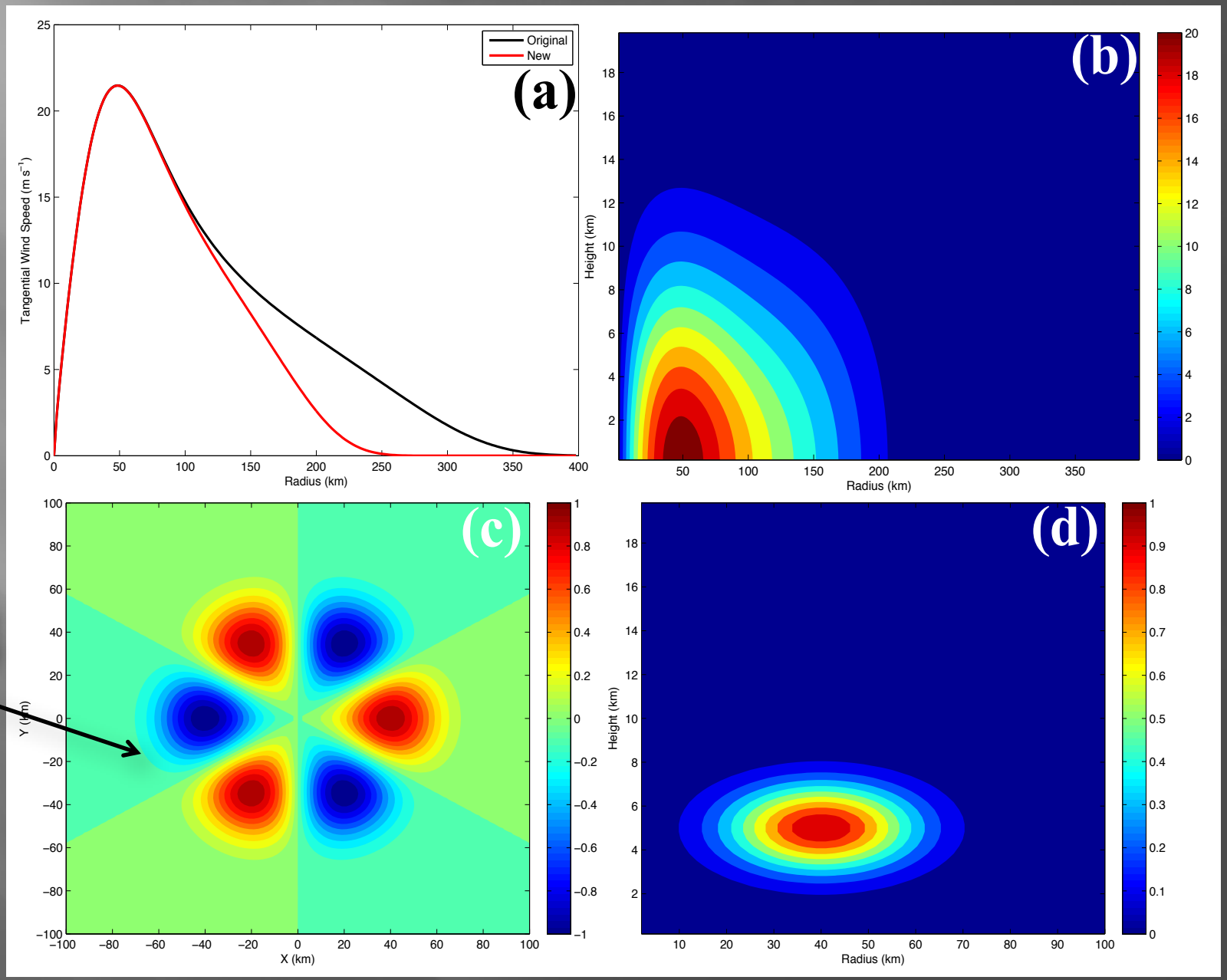
Table 1. Summary of default numerical schemes used in each model for this study. See text for details.

	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	5th order horizontal/ 3rd order vertical	Spectral Element
Explicit Filters	6th order spatial	None	1st order temporal

Numerical Model Setup

- 3D, compressible Euler equation set
- 800 km^2 box, grid spacing of 2 km
  - NUMA (5th 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 ($5.0 \times 10^{-5}\ s^{-1}$)
- 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

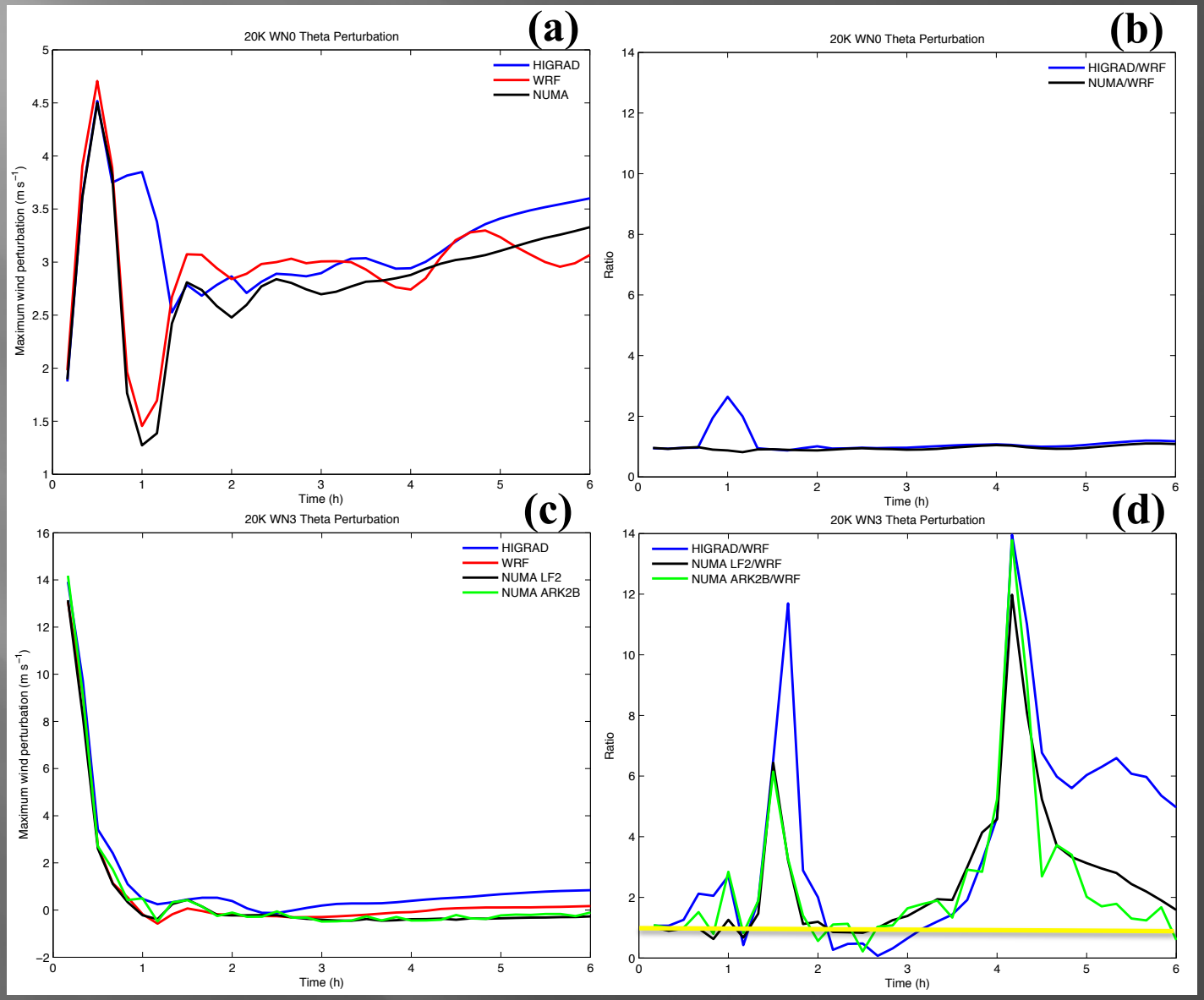


WN3

20 K Perturbation Results

WN0

WN3



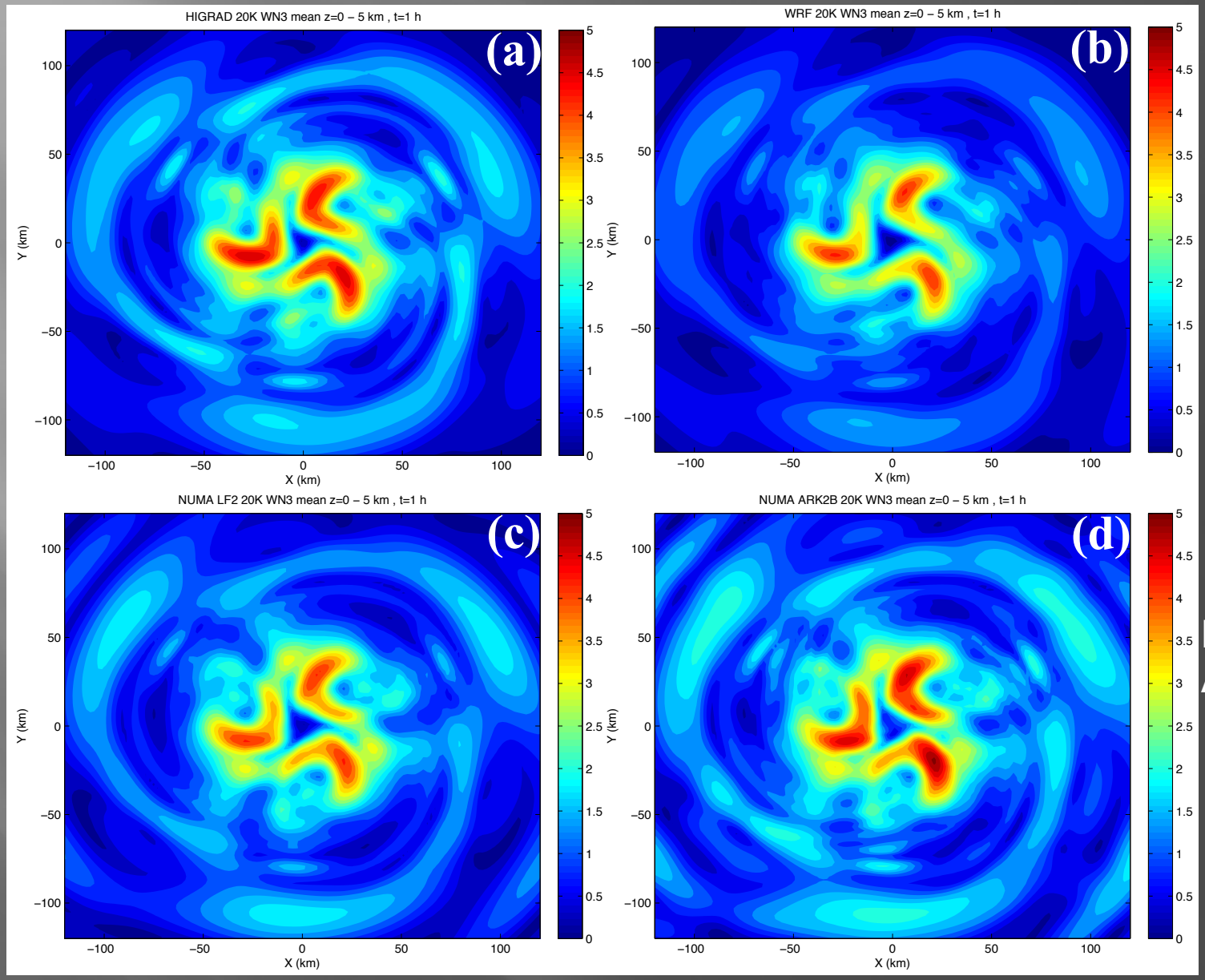
20 K WN3 Perturbation Results

HIGRAD

WRF

NUMA LF2

NUMA ARK2B



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

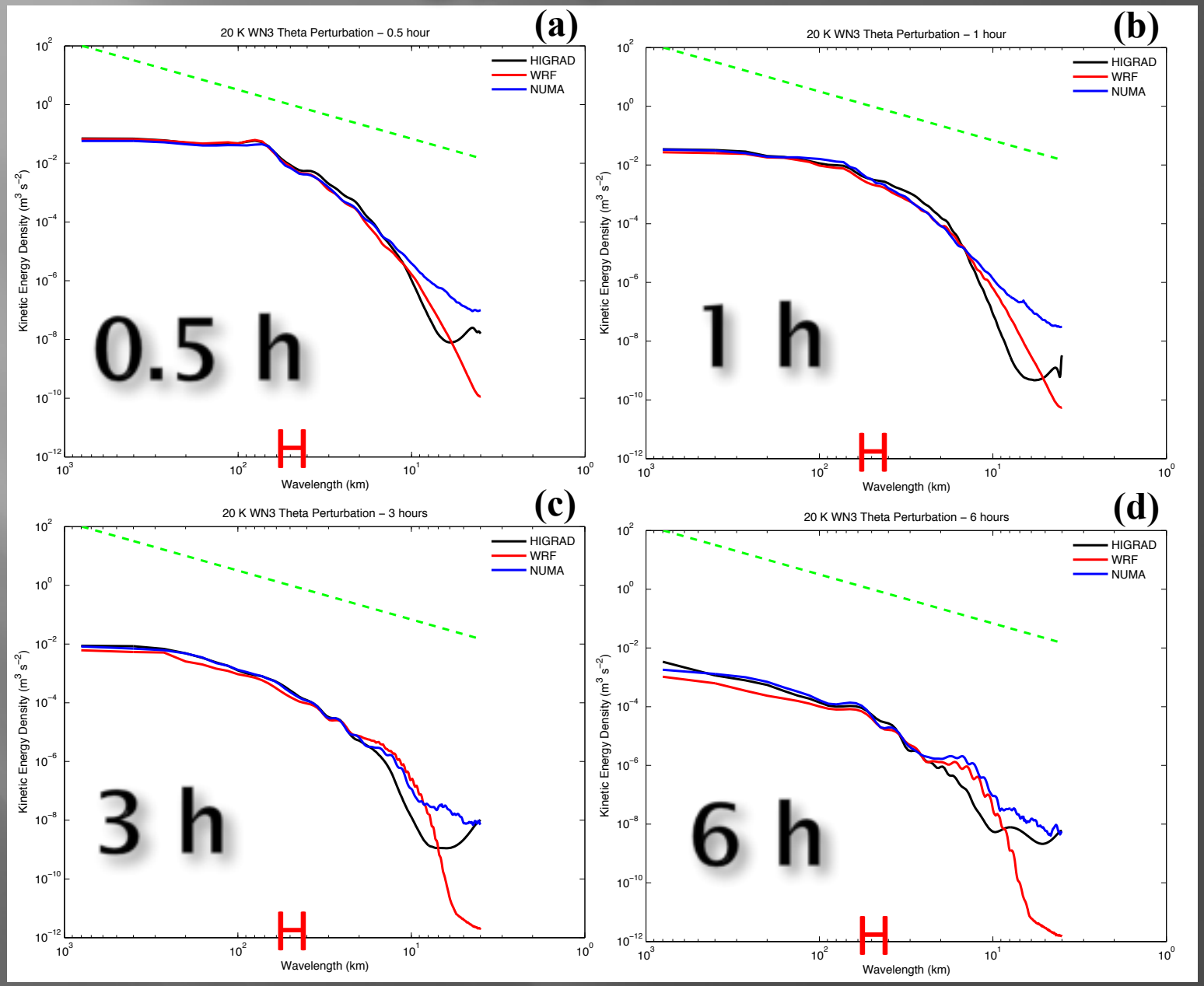
$$\vec{V}_h = k \times \nabla\psi + \nabla\chi$$

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

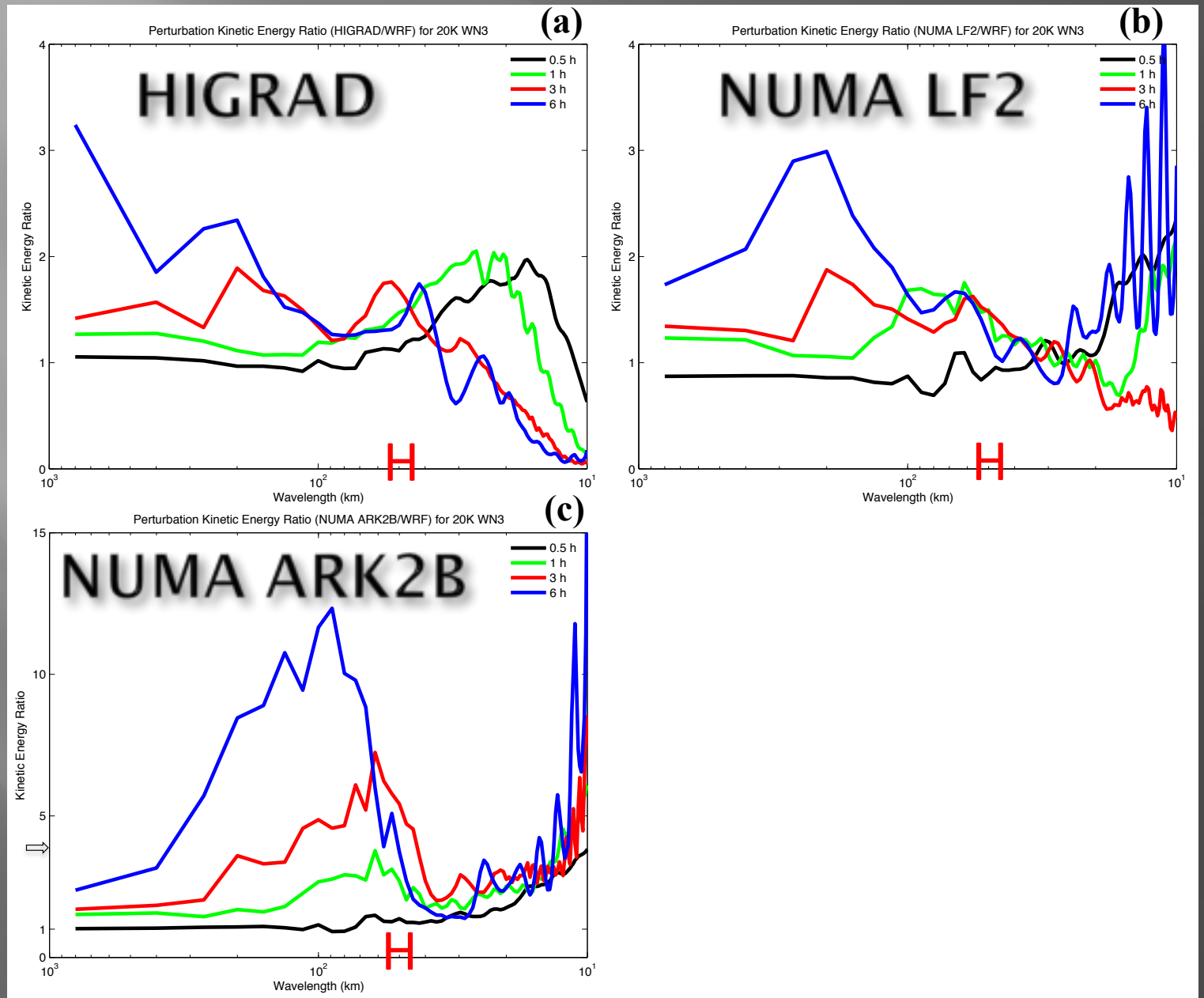
- Compare spectral KE budgets (shown later)

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

Kinetic Energy Spectra: 20 K WN3



Kinetic Energy Spectra: 20 K WN3



Spectral Kinetic Energy Budgets

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

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

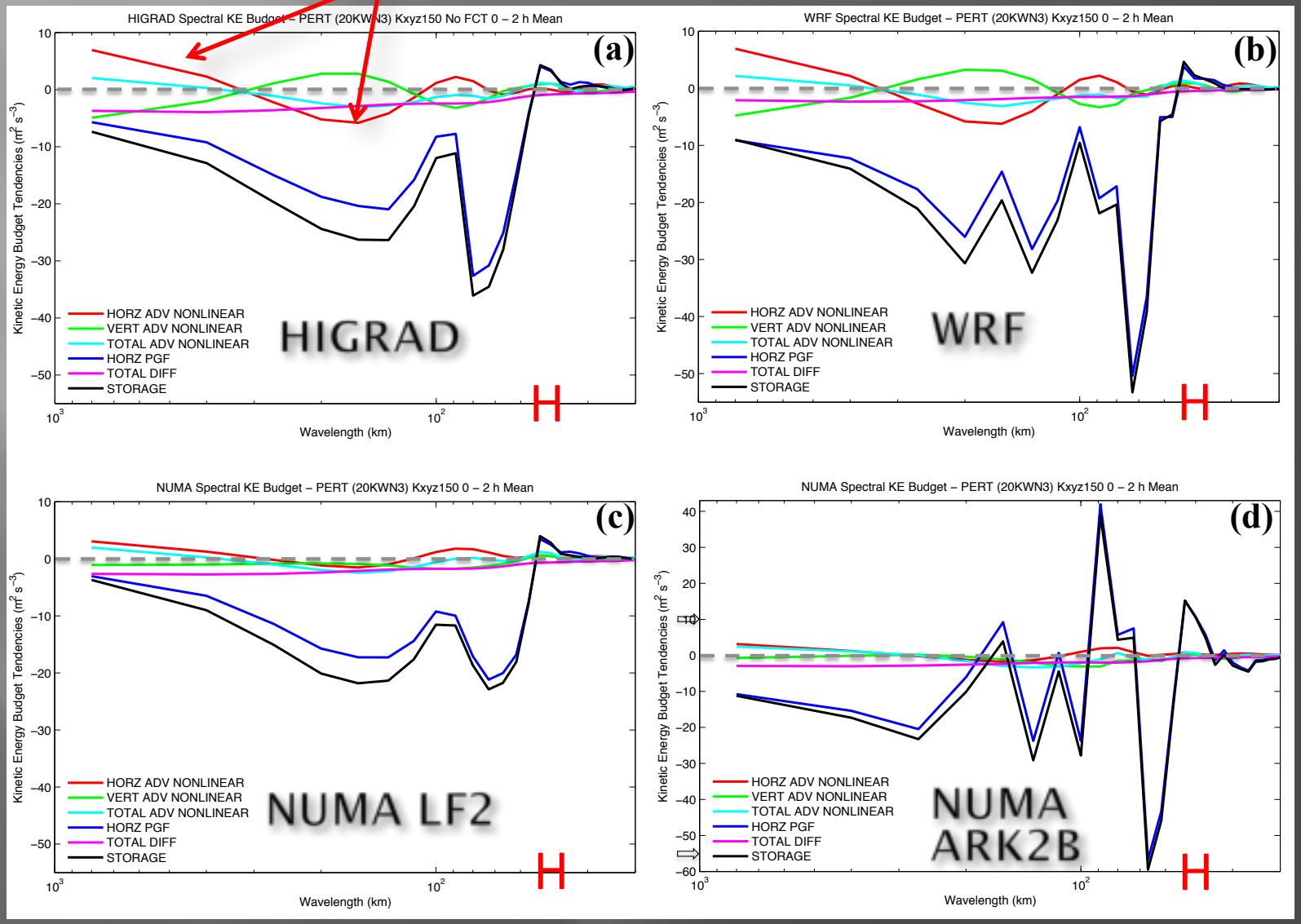
$$P(k) = -\frac{1}{2}\left(\hat{\mathbf{u}}^* \bullet \widehat{\mathbf{PGF}} + \hat{\mathbf{u}} \bullet \widehat{\mathbf{PGF}}^*\right)$$

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

Spectral Kinetic Energy Budgets

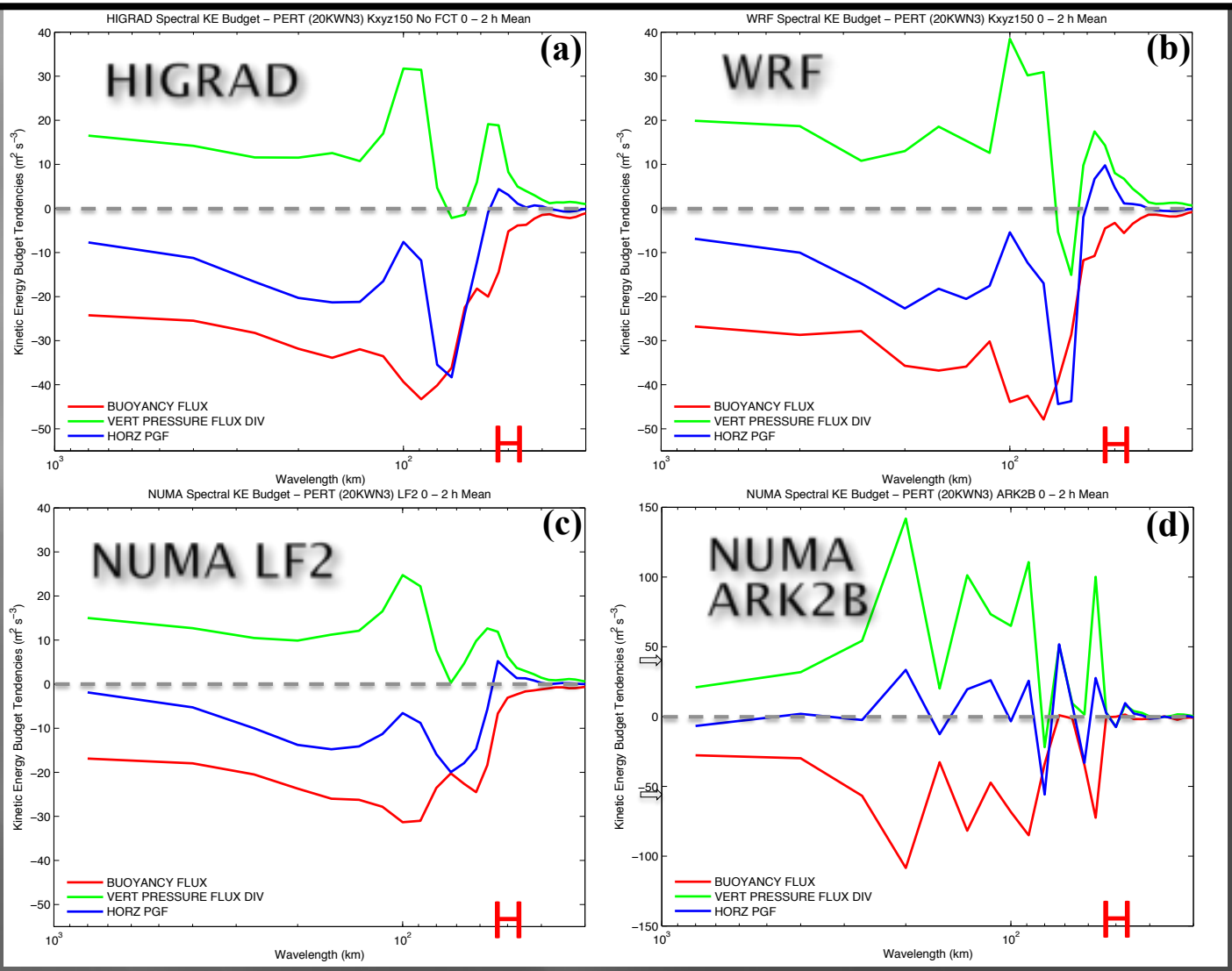
For 20K WN3 theta perturbation

upscale transfer



Spectral Kinetic Energy Budgets

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



Summary

- 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.

Guimond, S., J. Reisner, S. Marras and F. Giraldo 2016: The impacts of dry dynamic cores on asymmetric hurricane intensification. *J. Atmos. Sci.,* in review.

Implications

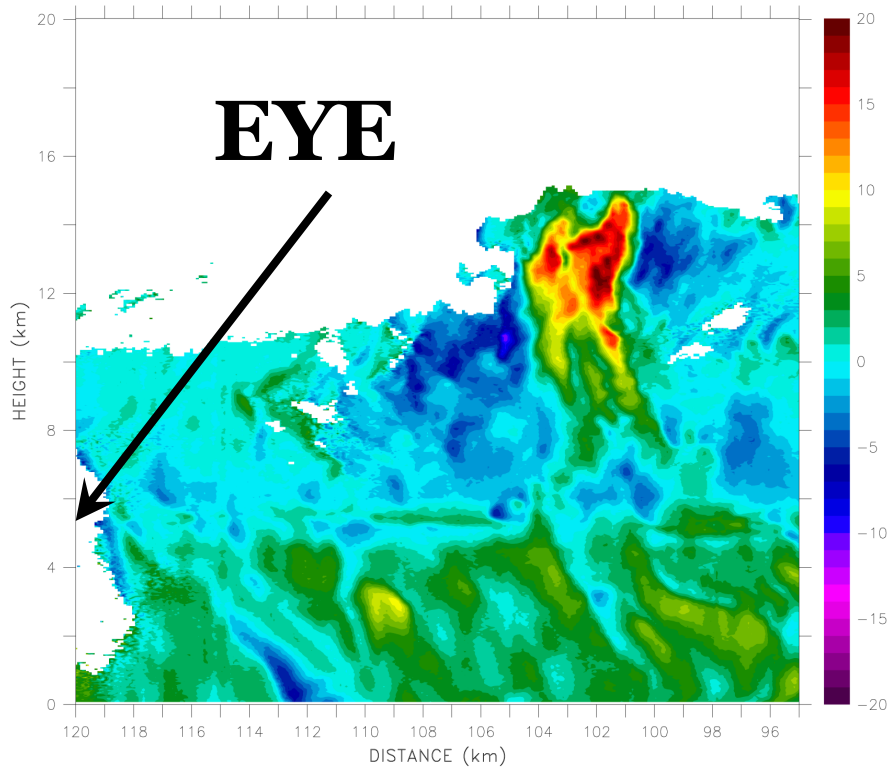
- WRF has more numerical dissipation than HIGRAD/NUMA for this problem.

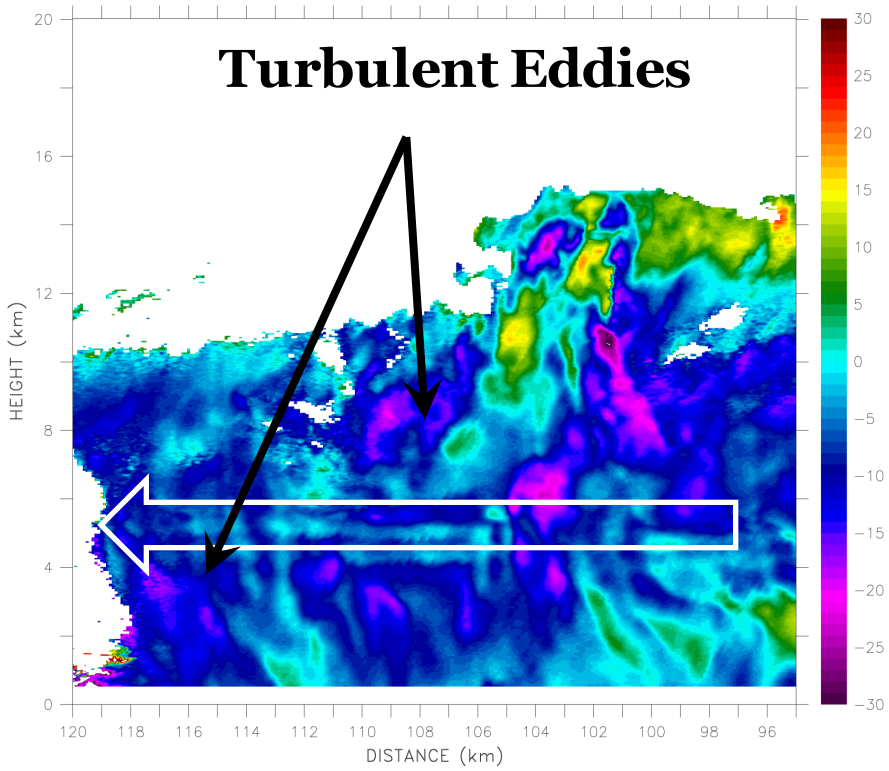
- Indicates significant uncertainty in hurricane intensification understanding and potentially prediction.

- What about more realistic regime?
  - Realistic heating, moisture, turbulence
- What about HWRF (NMM dynamic core)?
  - Evaluate forecasts with spectral dynamics/scale interactions
    - Use higher resolution/re-analysis/obs for truth
    - Various physics packages and data assimilation

Ongoing Work: Impact of Asymmetric Mode in Turbulent, Observational Regime

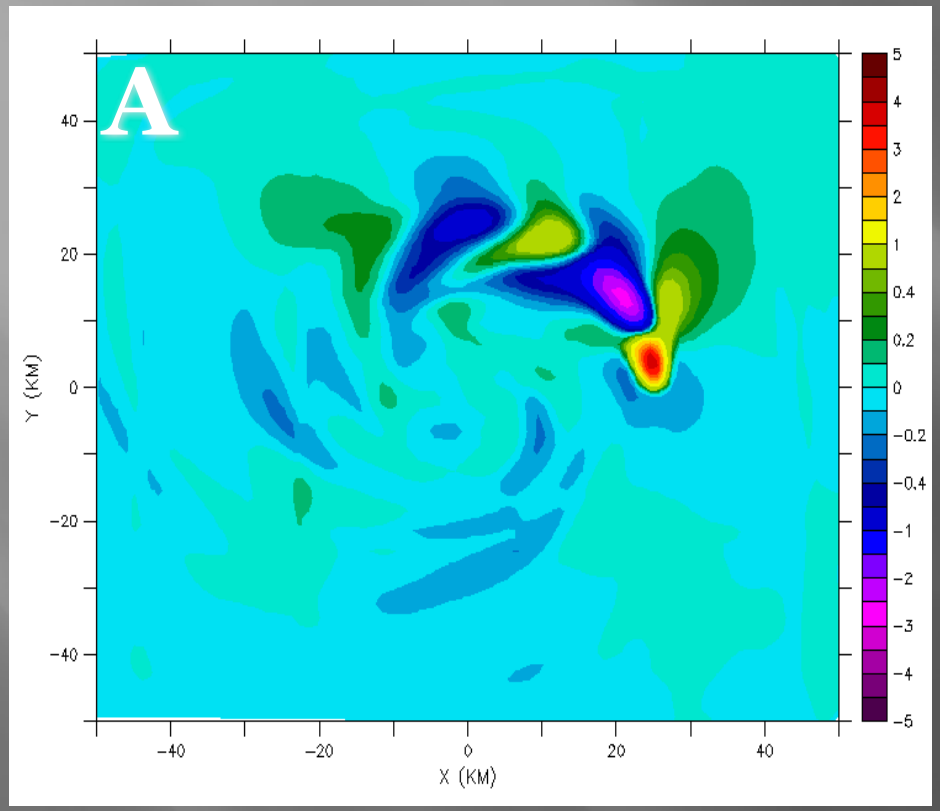
EDOP Observations (Guimond et al. 2010)
100 m horizontal, 37.5 m vertical sampling

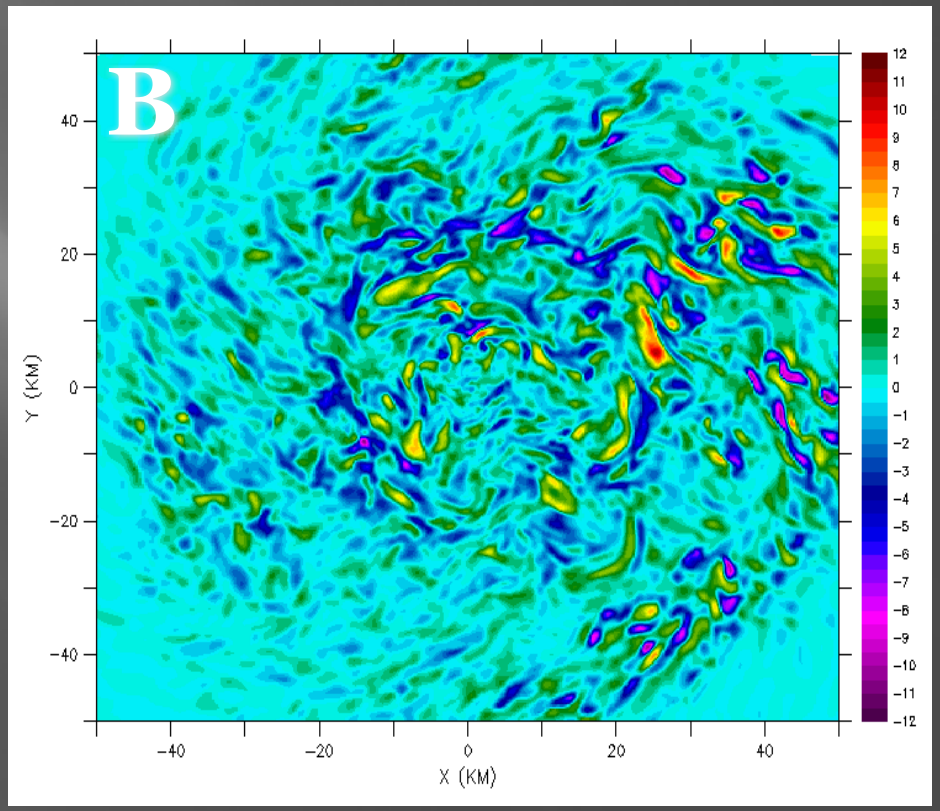




Ongoing Work: Impact of Asymmetric Mode in Turbulent, Observational Regime

Vertical velocity at 10 km height using EDOP heating pulse for (A) 1 km resolution and (B) 200 m resolution





- Will LES runs produce -5/3 spectral slope and up-scaling effects? What is the role of symmetric/asymmetric processes in this regime?

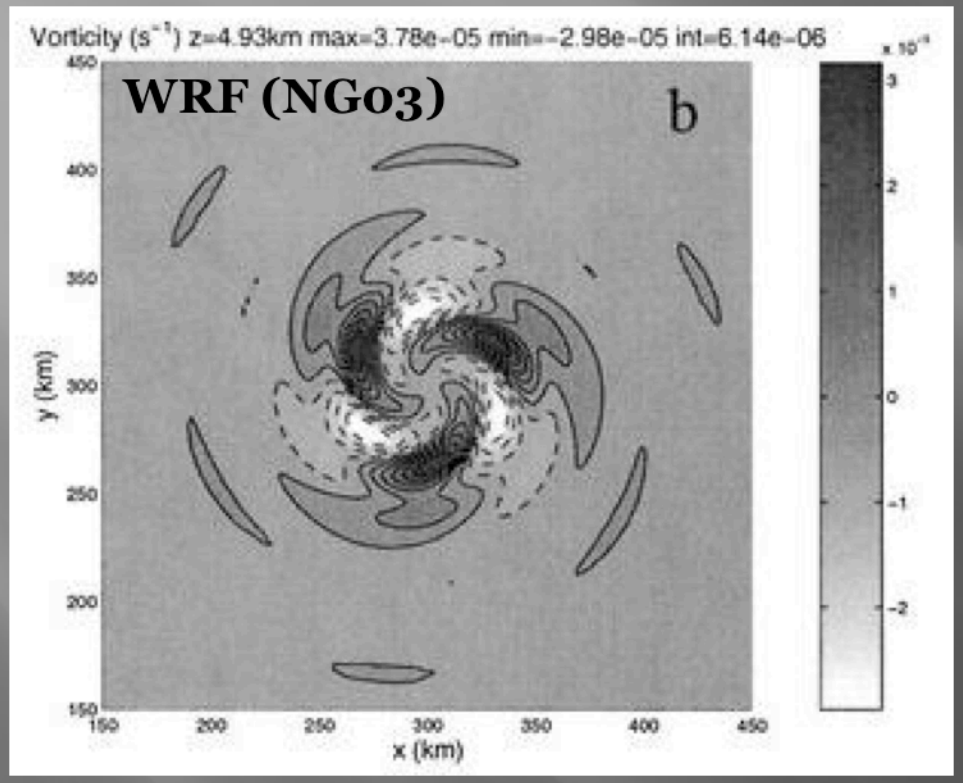
Acknowledgements

- I am grateful to Institute of Geophysics, Planetary Physics and Signatures (IGPPS) at LANL for support.
- Jon Reisner for many discussions and support.
- Simone Marras and Frank Giraldo for NUMA help.
- Dave Nolan (Univ. Miami) for initial conditions and discussions.
- Discussions with Michael Waite, Paul Reasor, George Bryan, Bill Skamarock and Mike Montgomery.
- Three anonymous JAS reviewers.

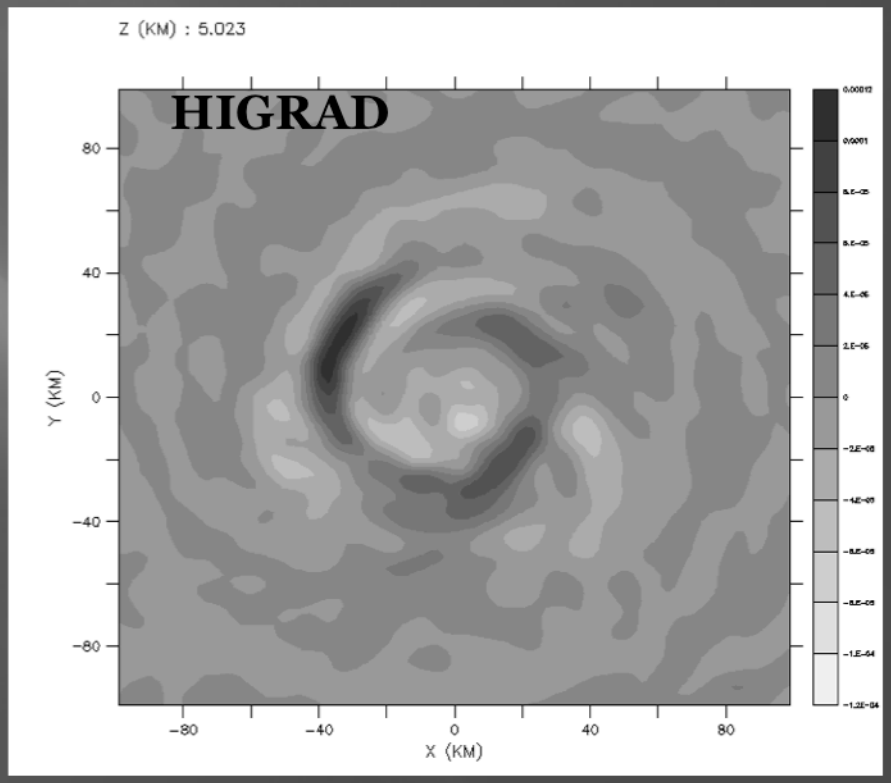
Backup Slides

Vorticity: HIGRAD and WRF

$K = 40\ m^2\ s^{-1}$



$K = 40\ m^2\ s^{-1}$

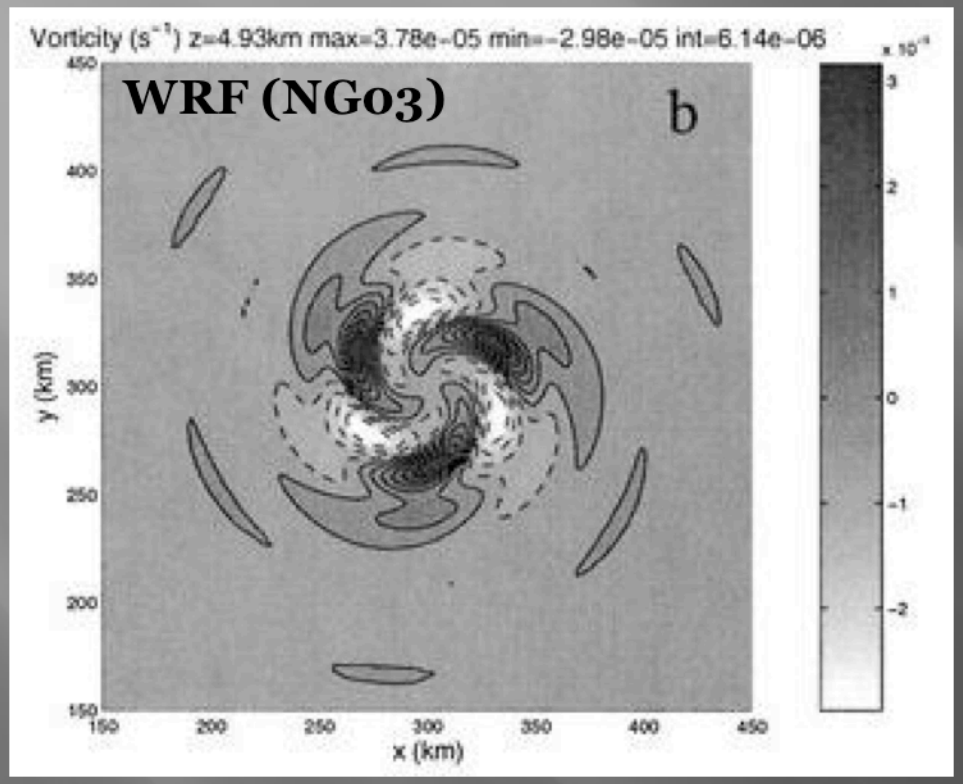


Max = ~ $4 \times 10^{-5}\ s^{-1}$

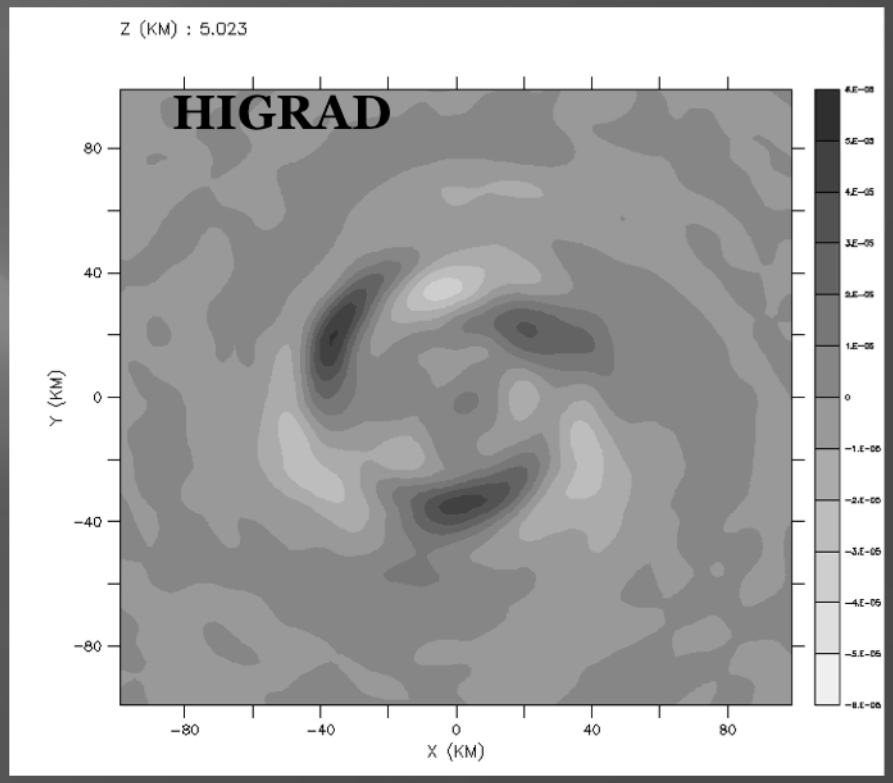
Max = ~ $2 \times 10^{-4}\ s^{-1}$

Vorticity: HIGRAD and WRF

K = 40 $m^2 s^{-1}$



K = 100 $m^2 s^{-1}$

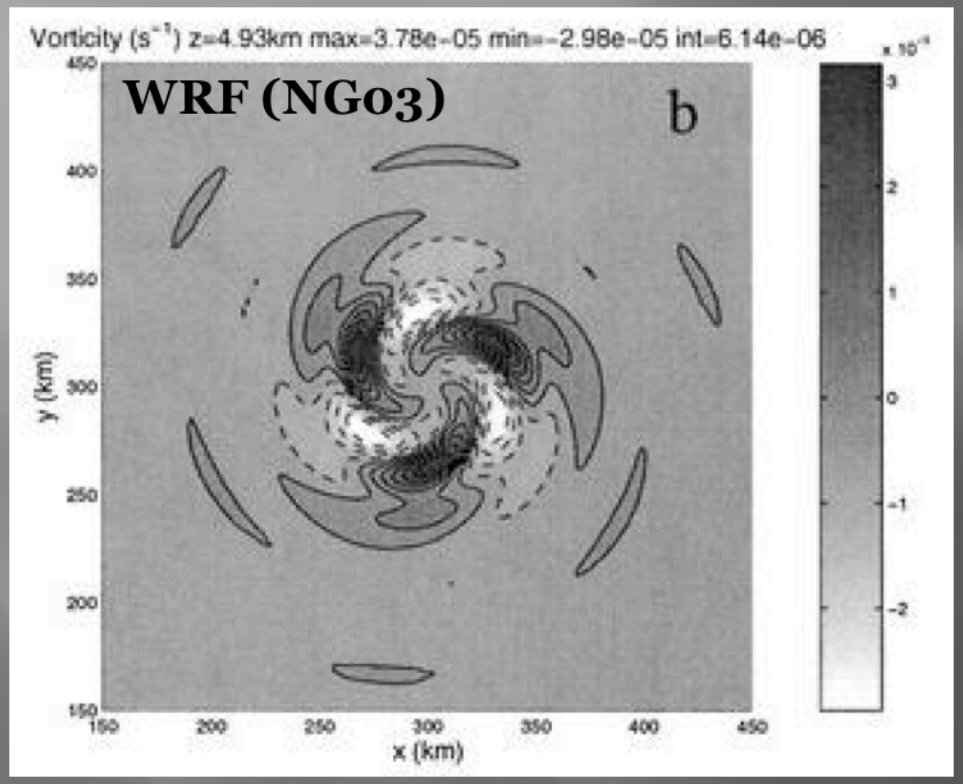


Max = ~ 4 x 10^{-5} s^{-1}

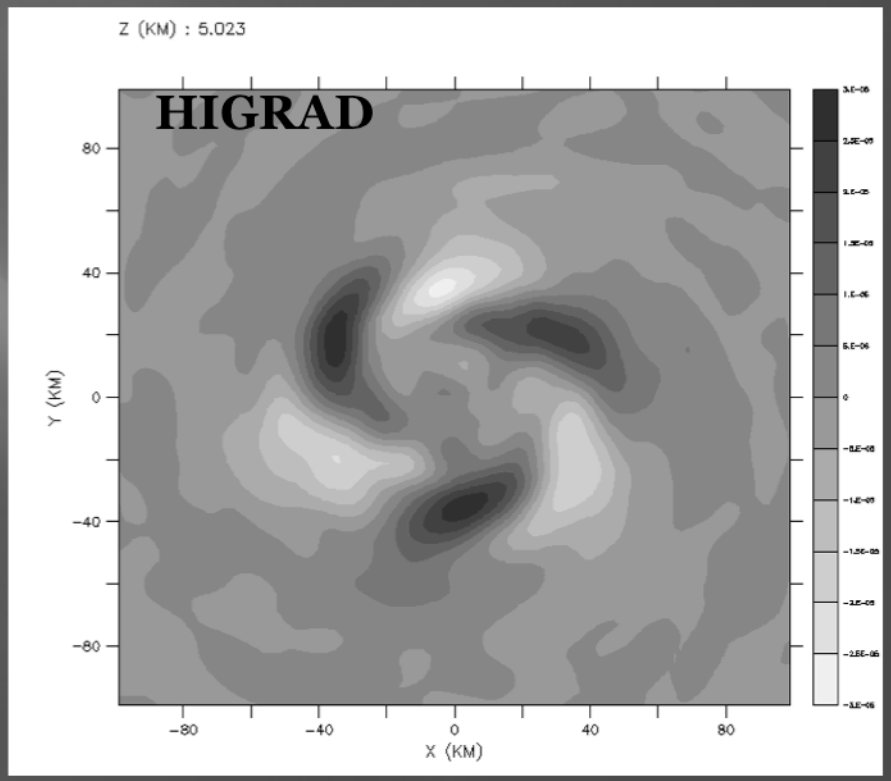
Max = ~ 7 x 10^{-5} s^{-1}

Vorticity: HIGRAD and WRF

K = 40 $m^2 s^{-1}$



K = 200 $m^2 s^{-1}$



Max = ~ 4 x 10^{-5} s^{-1}

Max = ~ 3 x 10^{-5} s^{-1}

Numerical Model

- HIGRAD (Reisner et al. 2005; Reisner and Jeffery 2009)
- Equation set…

$$\frac{\left(u^i \quad\right)}{t} + \frac{\left(u^i u^j \quad\right)}{x^j} = \quad \frac{p}{x^j} \quad g \quad {}_{i3} \quad 2 \quad {}_{ijk} \quad {}_j\left(u^k \quad u_e^k\right) + \frac{\left(\quad {}^{ij}\right)}{x^j}$$

$${}^{ij} = \frac{u^i}{x^j} + \frac{u^j}{x^i} \quad \frac{2}{3}\frac{u^k}{x^k} \quad {}^{ij}$$

$$= 1.8\left(C_s \quad\right)^2 |S|$$

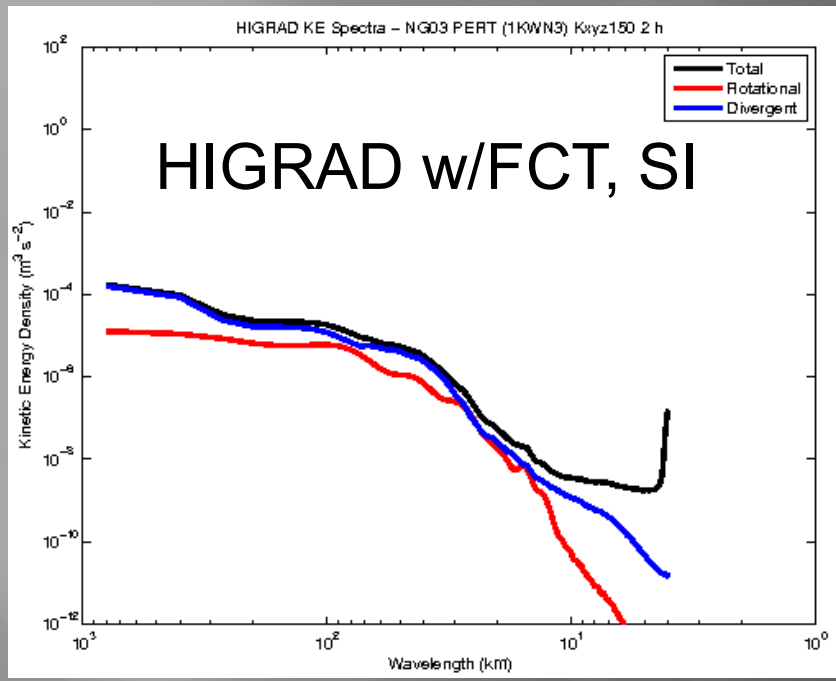
where $C_s \quad 0.1, \quad = (Volume)^{1/3}, S = \sqrt{2 \quad {}^{ij} \quad {}^{ij}}$

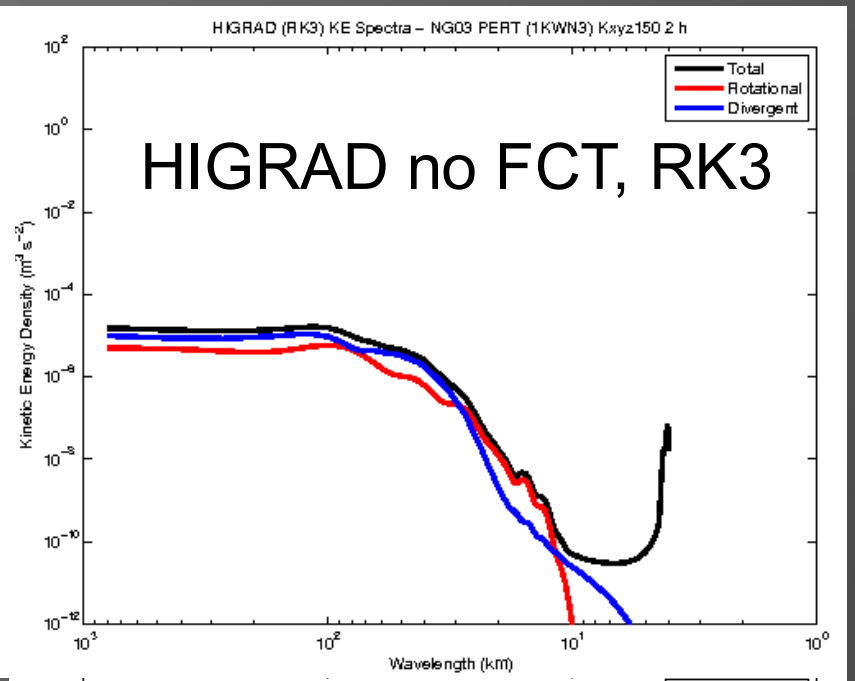
$$\frac{\left(\quad\right)}{t} + \frac{\left(u^i \quad\right)}{x^i} = \frac{}{x^i} \qquad \frac{}{x^i}$$

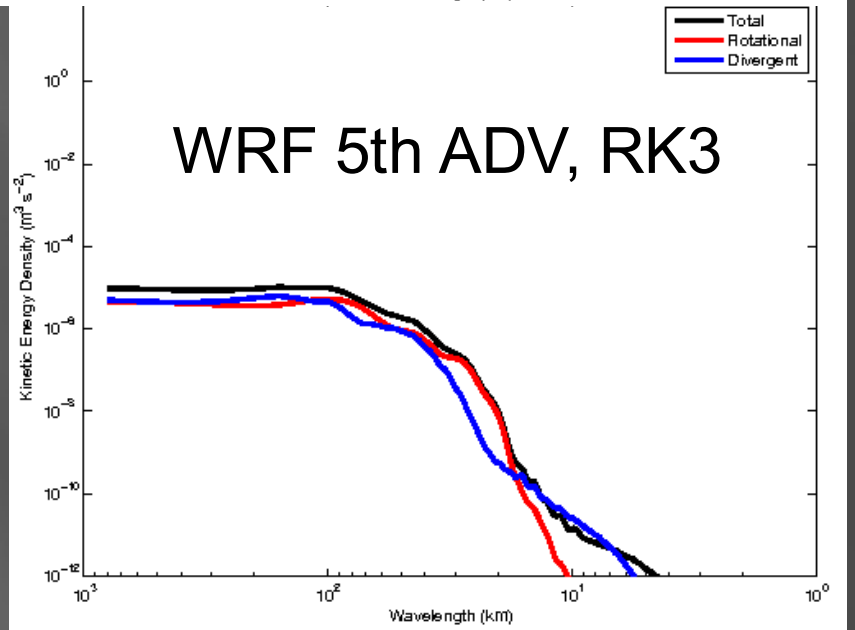
$$\frac{}{t} + \frac{u^i}{x^i} = 0$$

- Discretization
  - Temporal →semi-implicit (higher order an option)
  - Space → finite volume on A-grid (non-staggered)
  - No filters or damping added to numerics

The Impact of Numerics: 2 hours



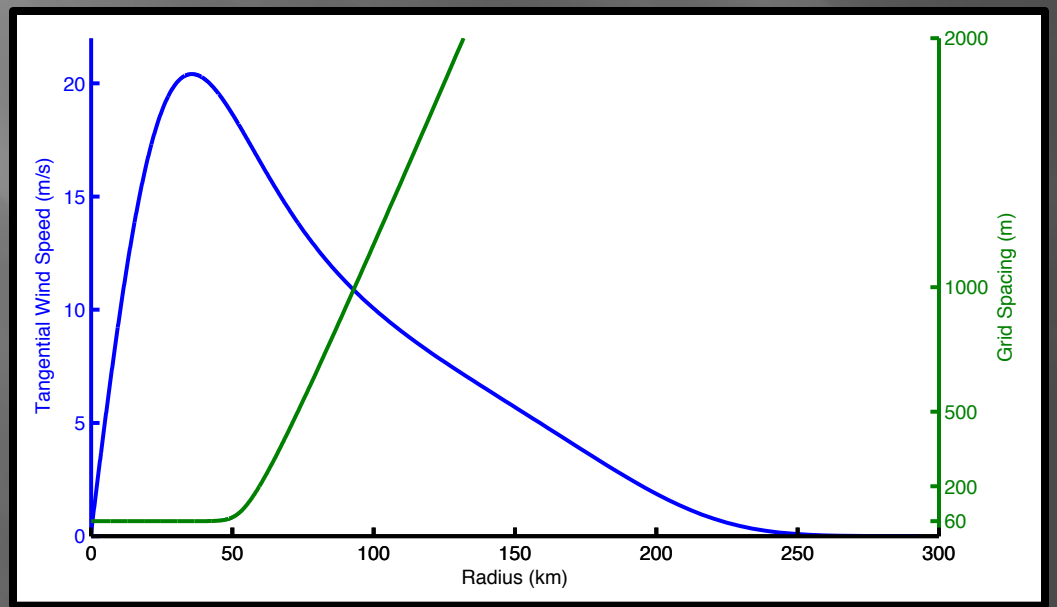




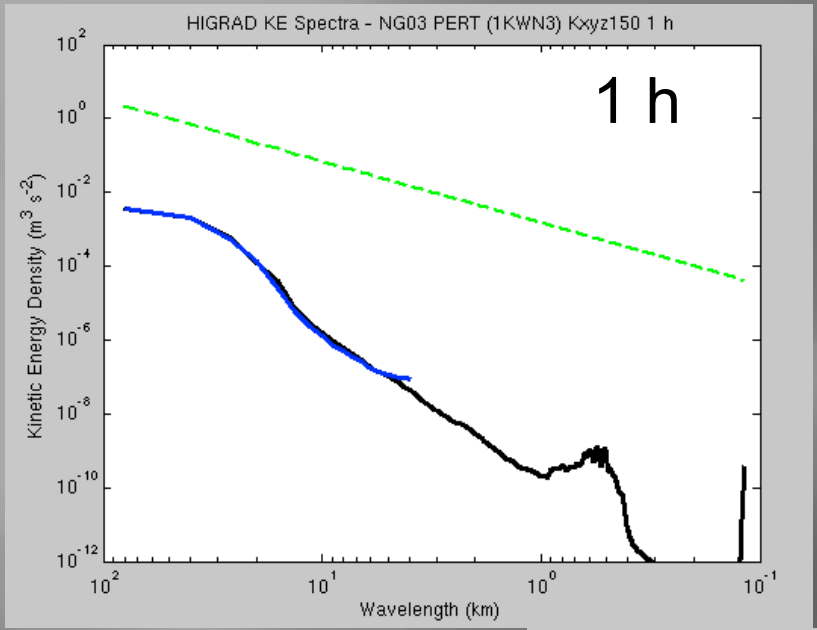
- *Very similar results to WRF using NO FCT and RK3 in HIGRAD*

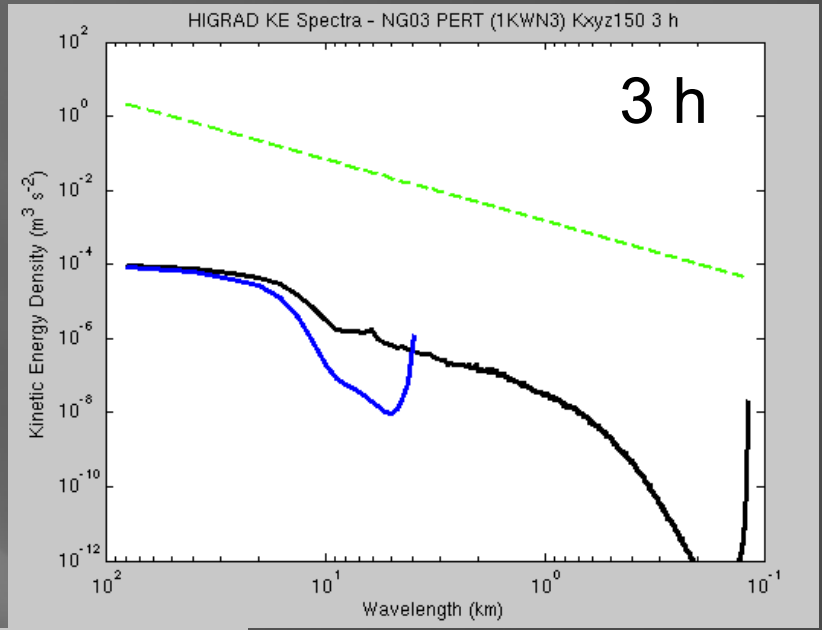
Which Results are Correct?

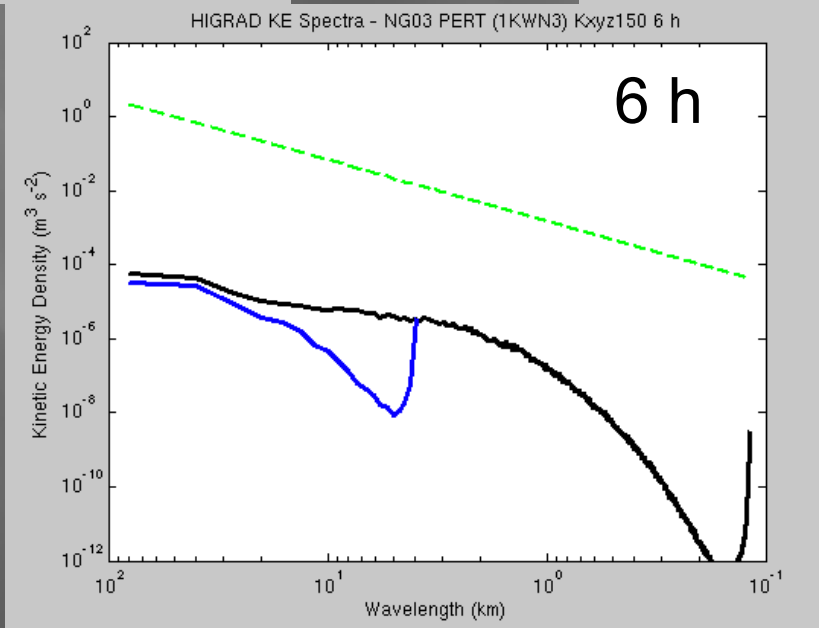
- HIGRAD FCT results produce -5/3 spectrum and up-scaling of energy
- HIGRAD NO FCT and WRF produce steep/damped energy spectrum
- What is correct energy spectrum for this problem?
- LES simulation using HIGRAD with NO FCT
  - dx = 60 m, dt = 0.25 s, semi-implicit
  - Slightly modified vortex/heating



LES Results



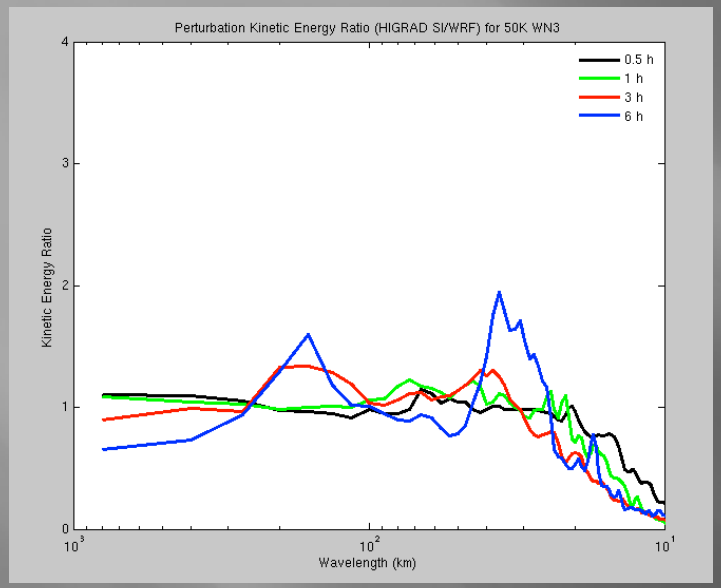




Blue = 2 km

Black = 60 m

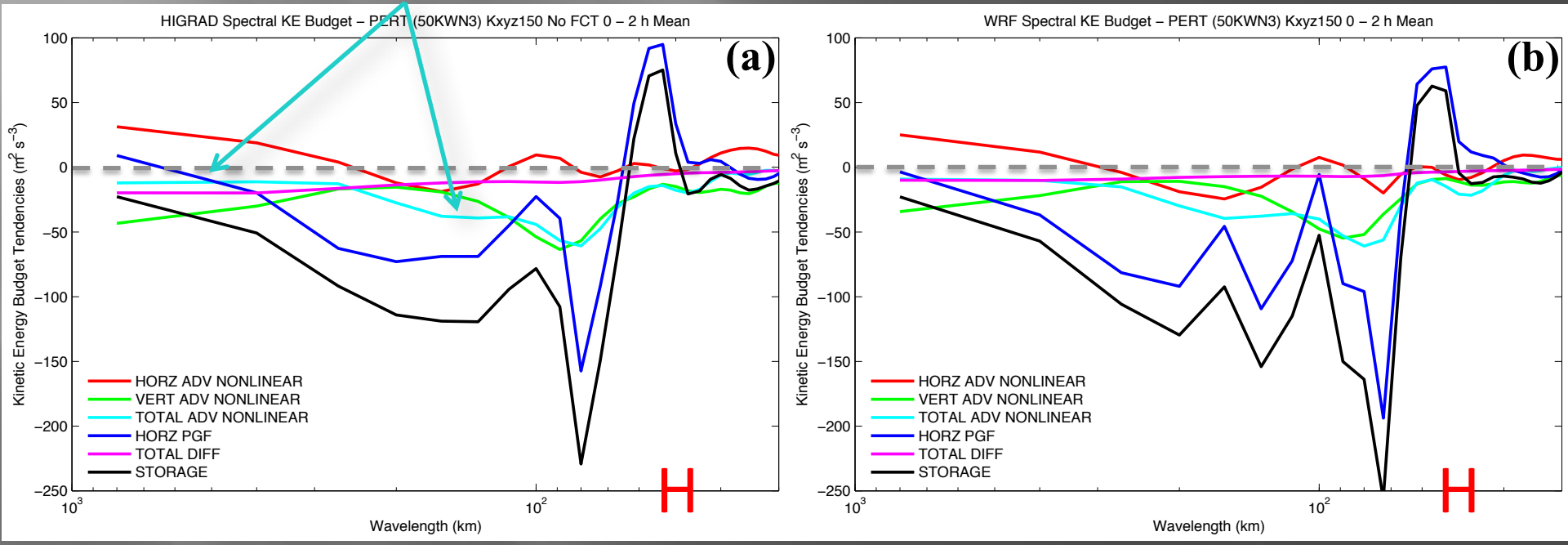
Kinetic Energy Evolution: 50K WN3 in HIGRAD/WRF/NUMA



Spectral Kinetic Energy Budgets

For 50K WN3 theta perturbation

Net removal of energy



HIGRAD WRF