Penn State Center for
Advanced Data Assimilation and Predictability Techniques

Intrinsic vs. Practical Limits of Multi-scale Predictability and the Significance of the Butterfly Effect

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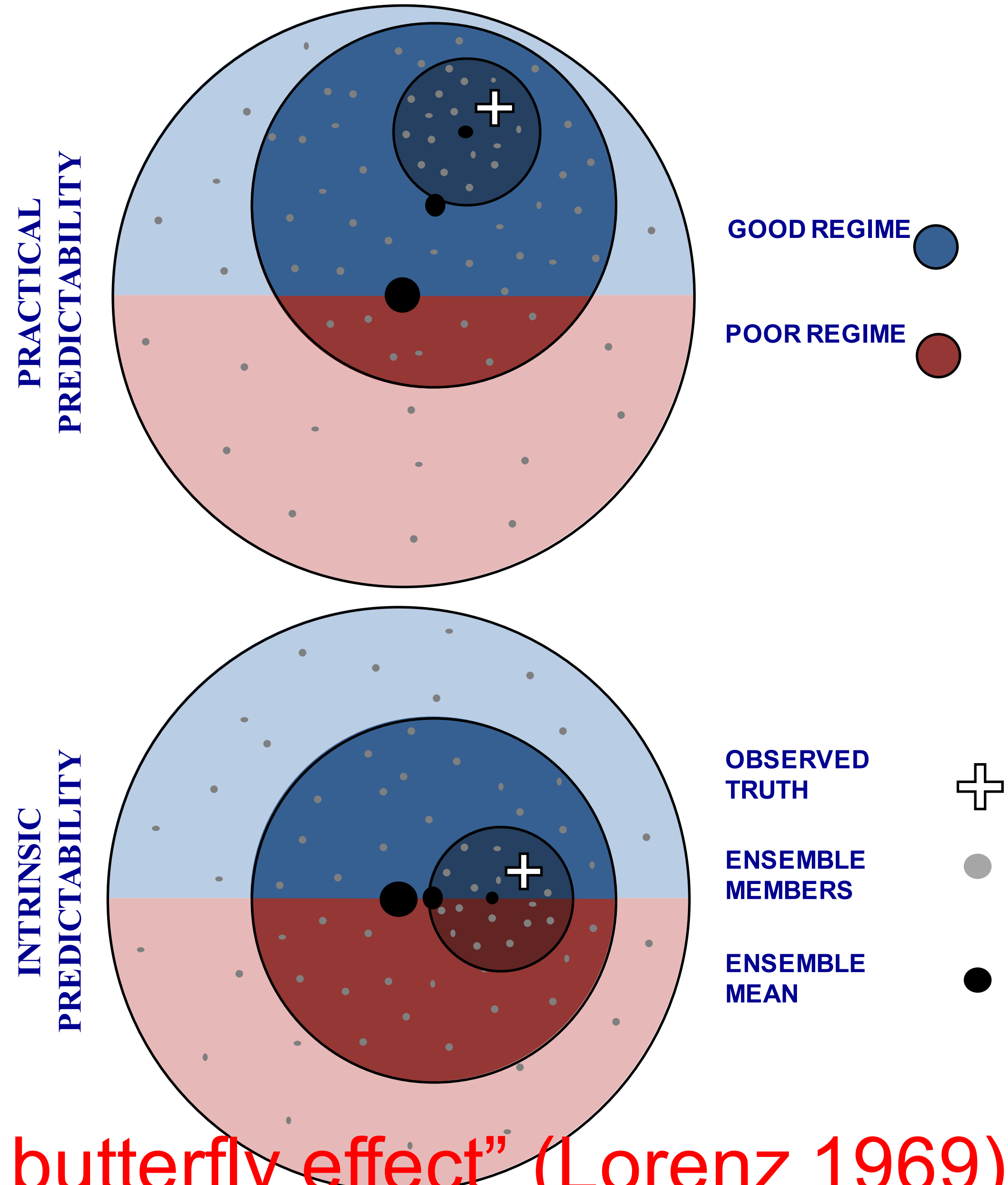
PRACTICAL vs. INTRINSIC PREDICTABILITY

(Lorenz 1995; Melhauser & Zhang 2012 JAS)

Practical predictability: the ability and uncertainty to predict given practical initial condition uncertainties and/or model errors, both of which remain significantly big in the present-day forecast systems.

Intrinsic predictability: the limit to predict given nearly perfect initial conditions and nearly perfect forecast systems, in other words when the initial condition and model errors become infinitesimally small.



"the butterfly effect" (Lorenz 1969)

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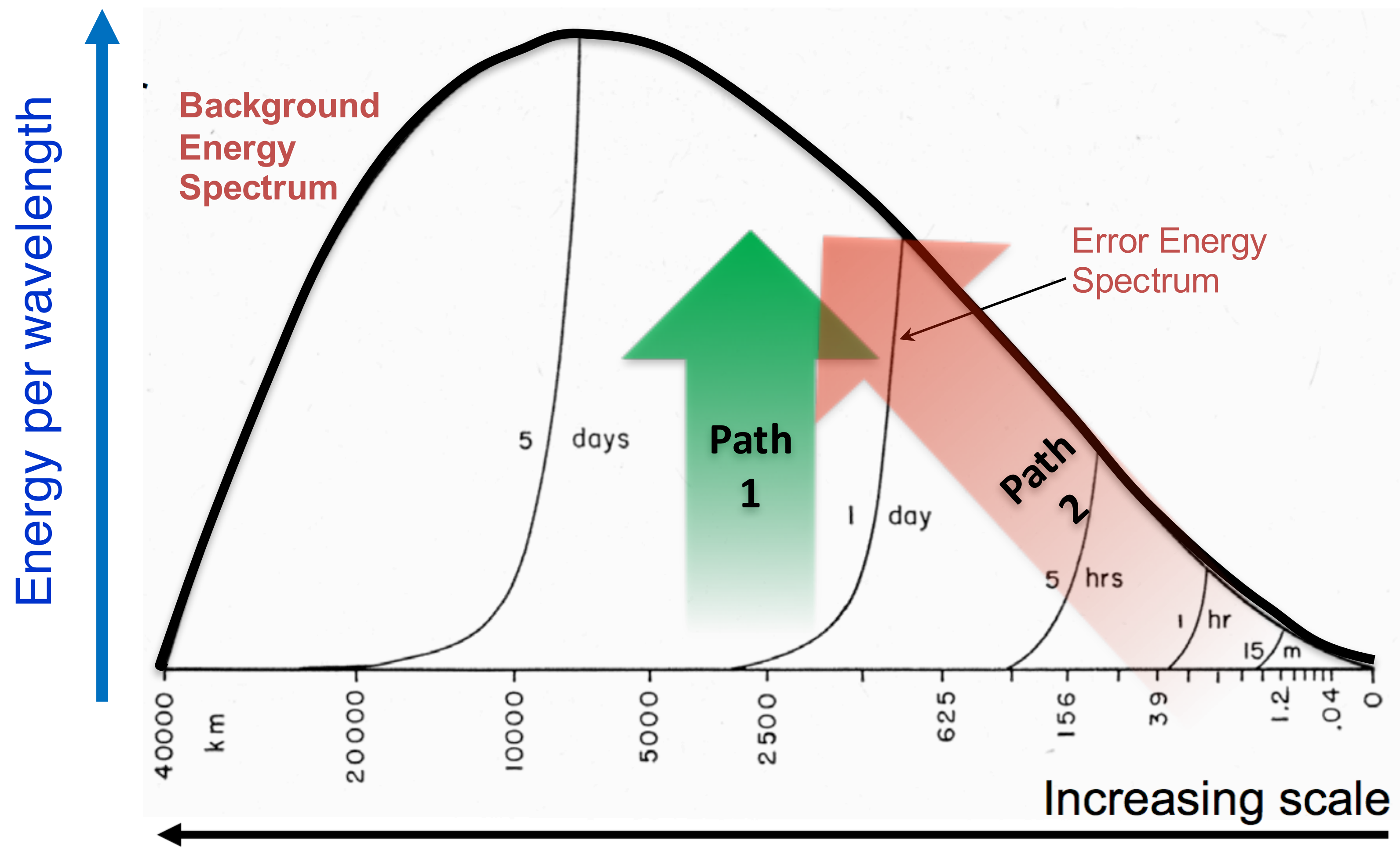


Path 1: error growth under large-scale instability ~ practical predictability

Path 2: error growth via upscale propagation~ depends on the slope

$$Eddy\ turn\ over\ time: \quad \tau(k) \sim \frac{L}{U} \sim k^{-3/2}E^{-1/2}(k)$$

A Multistage Upscale Error Growth Model for Mesoscale Predictability

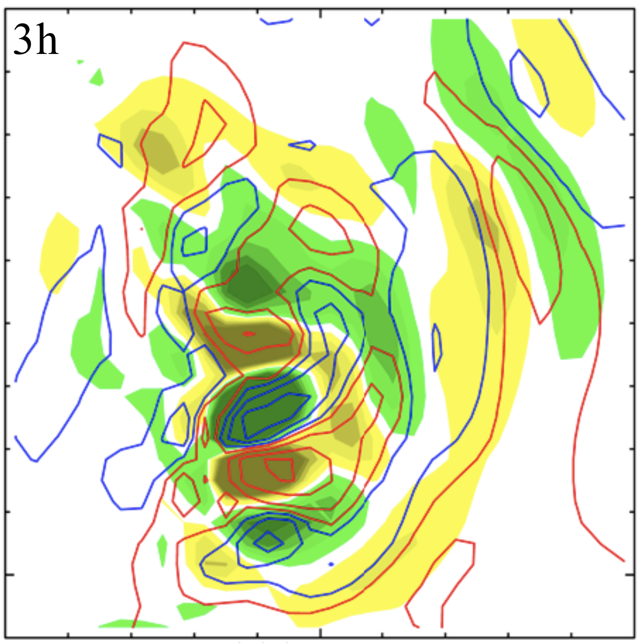
(Zhang et al. 2007, JAS)

Stage I, convective growth: Errors grow mostly from small-scale convective instability and saturate at convective scales on *O(1 h)*. The amplitude of saturation may be a function of CAPE and its areal coverage determined by large-scale flows.

Stage II, transient growth: Saturated errors transform from convective-scale unbalanced to larger-scale balanced motions through balance adjustment and GWs at the time scale *O(2π/f)*.

***Stage III, baroclinic growth**:* Balanced components of saturated error project onto the larger-scale flow and grow with background dynamics and instability at the time scale of *O(1day)*.

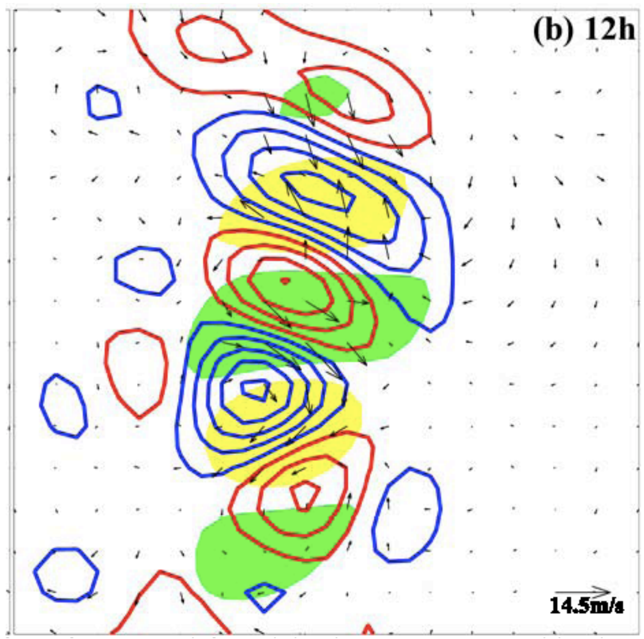
Stage 1



300km

T and w differences

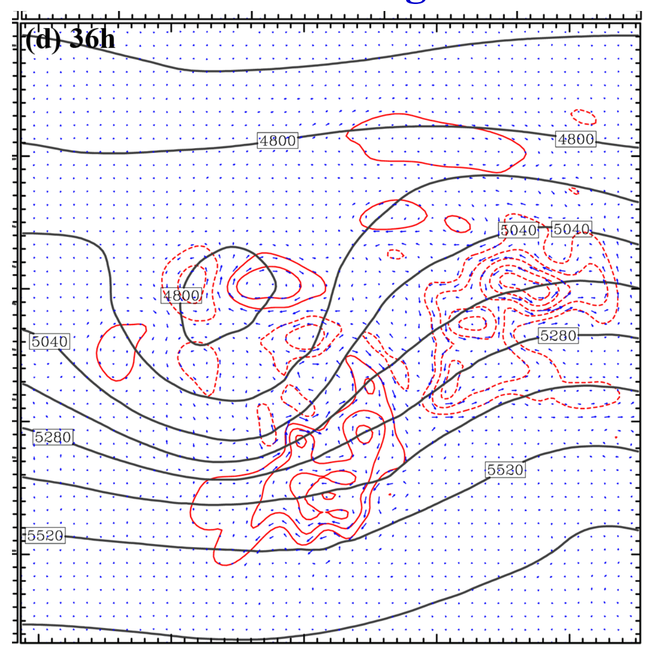
Stage 2



1200km

PV, **Q** and **DIV** differences

Stage 3



4200km

Pressure and **V** differences

Efficiency of Upscale Error Growth (path2)

Suppose we are only interested in predicting some low wavenumber (ie large-scale) k_L

How long before small-scale errors, confined to wavenumbers greater than $2^N k_L$ affect k_L ?

Let the time taken for a small-scale initial error, to grow and nonlinearly infect k_L be given by

$$\Omega(N) = \tau(2^N k_L) + \tau(2^{N-1} k_L) + \ldots \tau(2^0 k_L)$$
$$= \sum_{n=0}^{N} \tau(2^n k_L)$$

If $E(k) \sim k^{-3}$ then $\tau(k) \sim \tau_0$ and

$$\Omega(N) = \sum_{n=0}^{N} \tau(2^n k_L) = (N+1)\tau_0$$

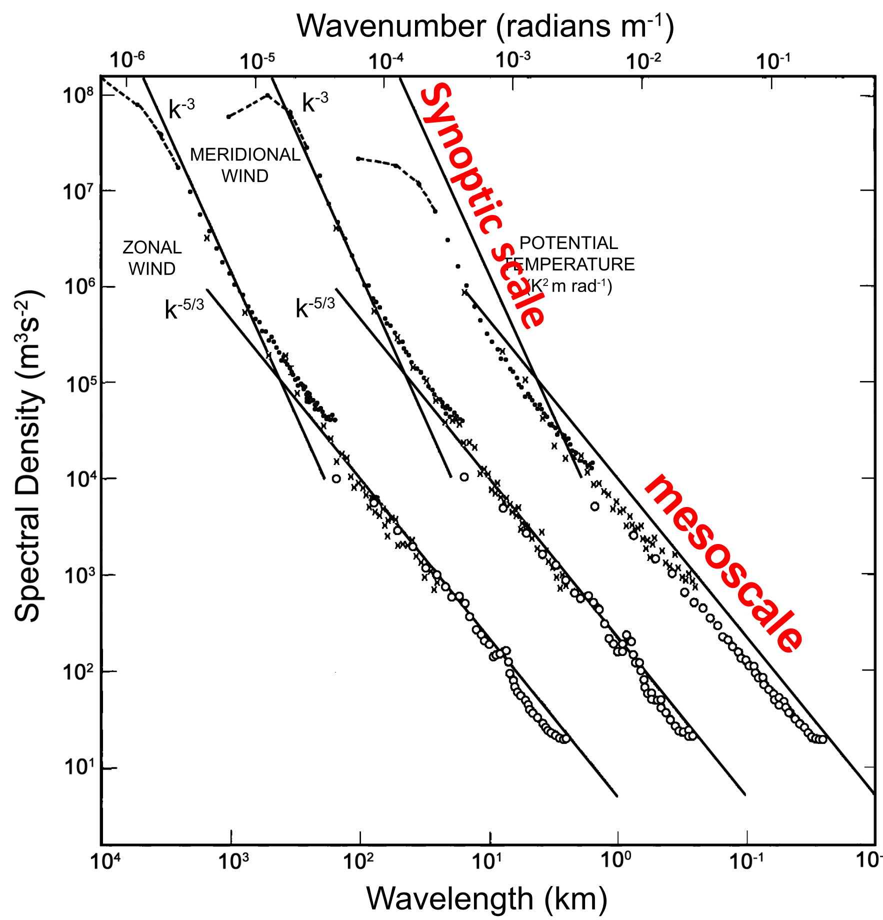
$$\to \infty \text{ as } N \to \infty$$

Large scale will not be affected if
Initial error scale is small enough

If $E(k) \sim k^{-5/3}$ then $\tau(k) \sim k^{-2/3}$ and

$$\Omega(N) = \sum_{n=0}^{N} \tau(2^n k_L)$$

$$= \tau(k_L) \sum_{n=0}^{N} 2^{-2n/3} \sim 2.7\tau(k_L) \text{ as } N \to \infty$$

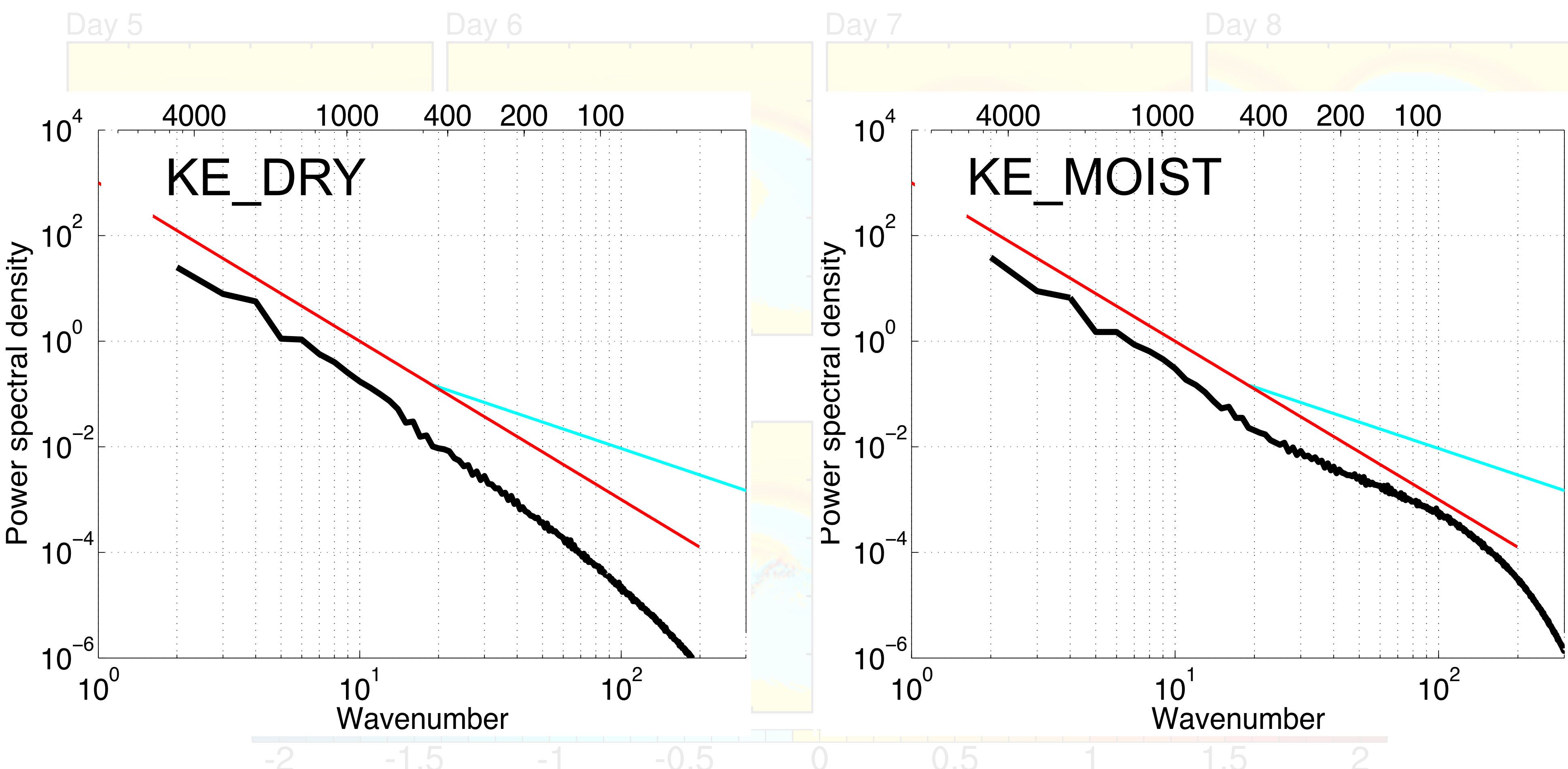


Nastrom and Gage (1985)

Does not depend on initial error scale!

Baroclinic wave simulations: Dry vs. Moist

Sun and Zhang (2016 JAS)

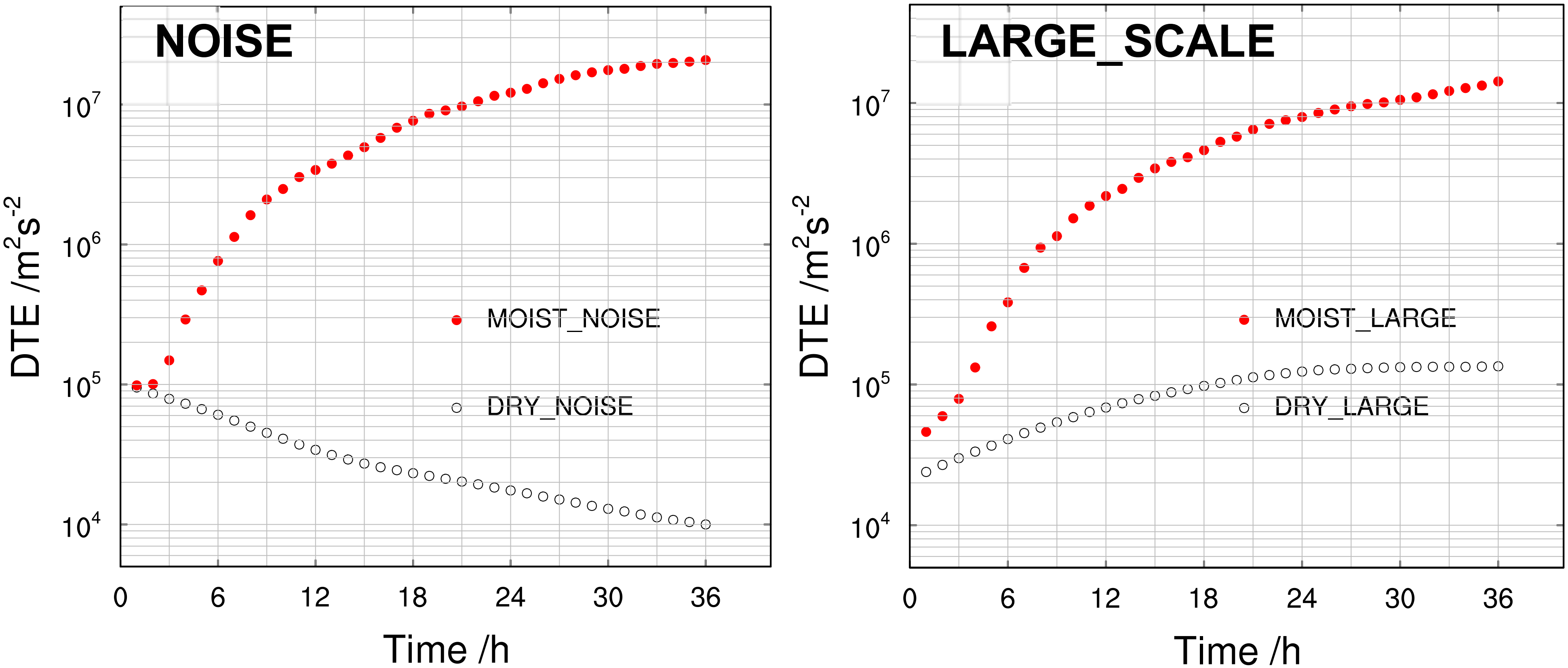


Simulated dry baroclinic Jets have a -3 slope, while moist experiments show a transition at mesoscale.

DTE Growth: Dry vs. Moist, random vs. large-scale IC error

$$DTE = \frac{1}{2}\sum[(\delta u)^2 + (\delta v)^2 + \kappa(\delta T)^2]$$

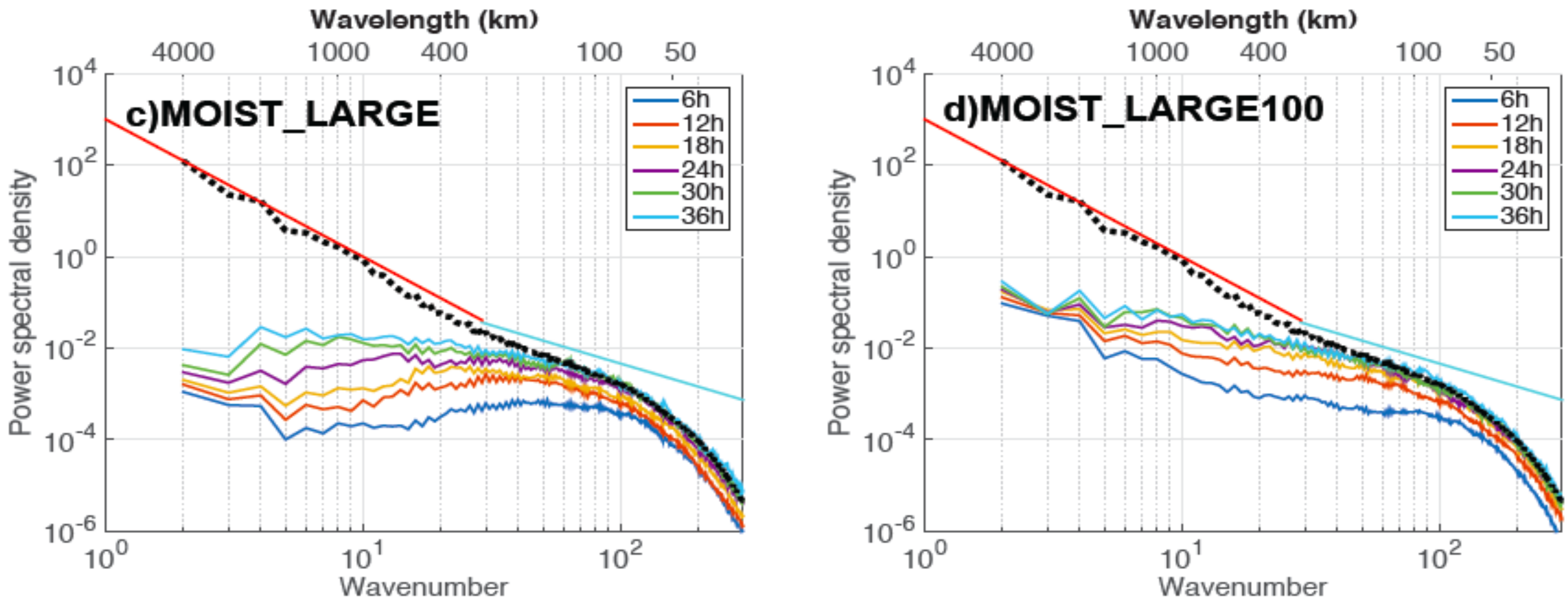
(Sun and Zhang 2016 JAS)



NOISE: As in Zhang et al. (2007), grid point Gaussian white noises of 0.2K, pridominantly small scales

LARGE: normal mode at the large-scale baroclinic wave scale (4000 km) with peak amplitude of 0.25m/s

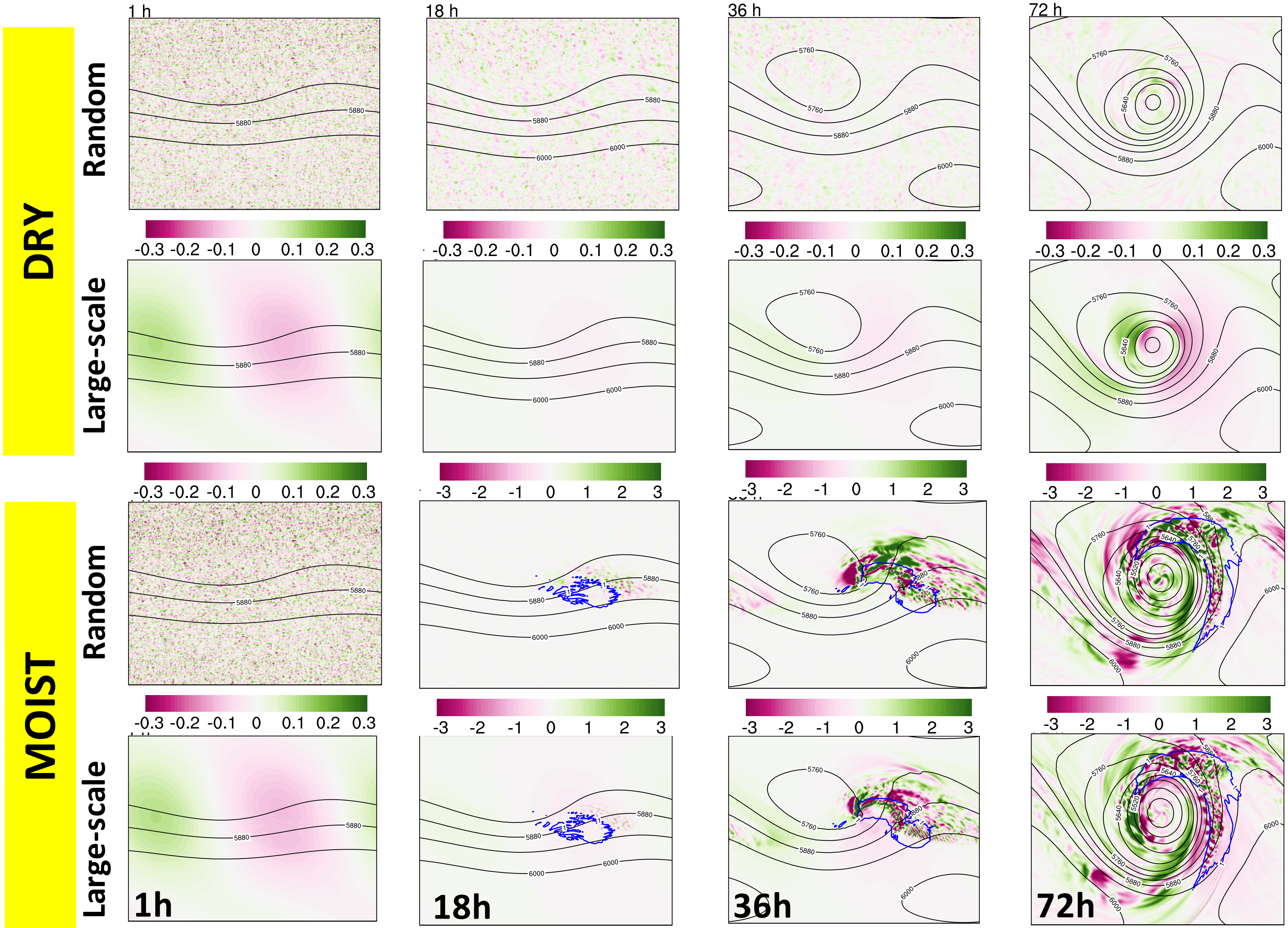
What happens we have large IC error?



LARGE: large-scale baroclinic scale (4000 km) IC error with peak amplitude of 0.25m/s
LARGE100: 100 times IC error energy but 10 times wave amplitude peaks at 2.5m/s

Predictability: Random vs. large-scale IC error, dry vs. moist BWs

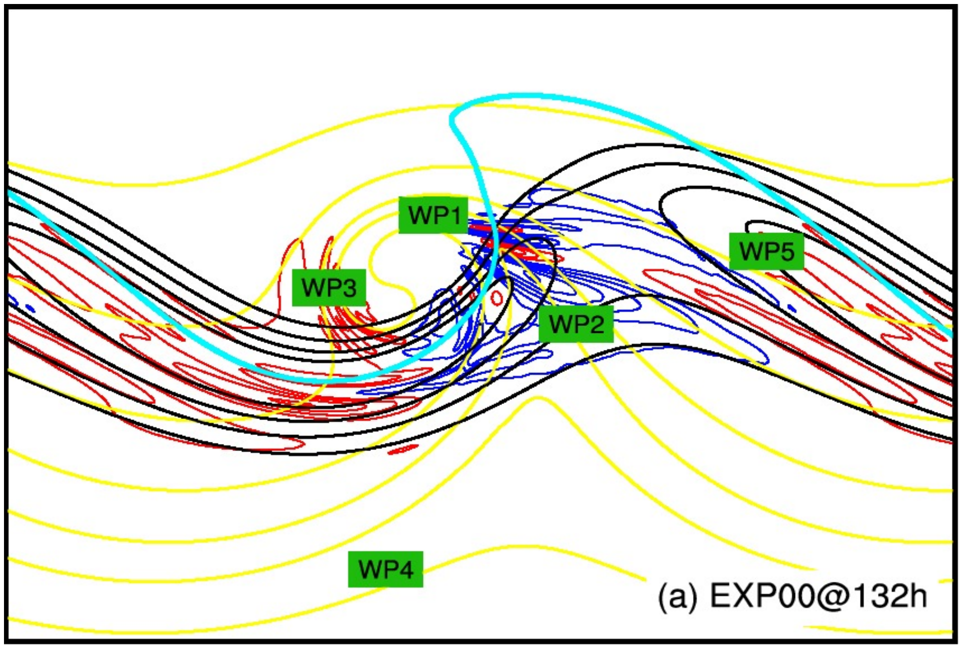
(Sun and Zhang, 2016, JAS)



Gravity waves in baroclinic wave simulations: Dry vs. Moist

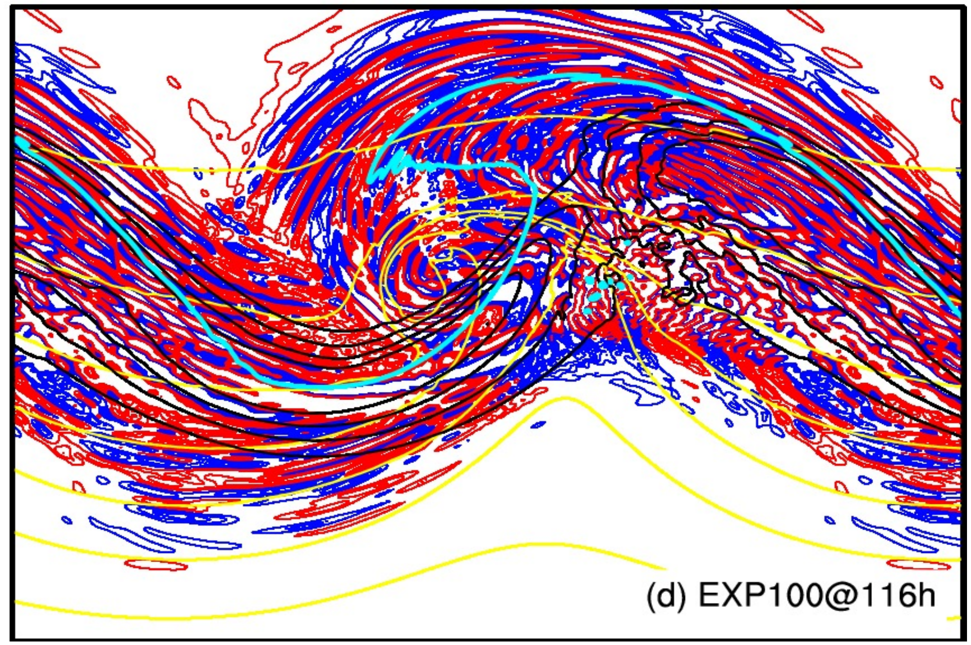
DRY

(Zhang 2004 JAS)



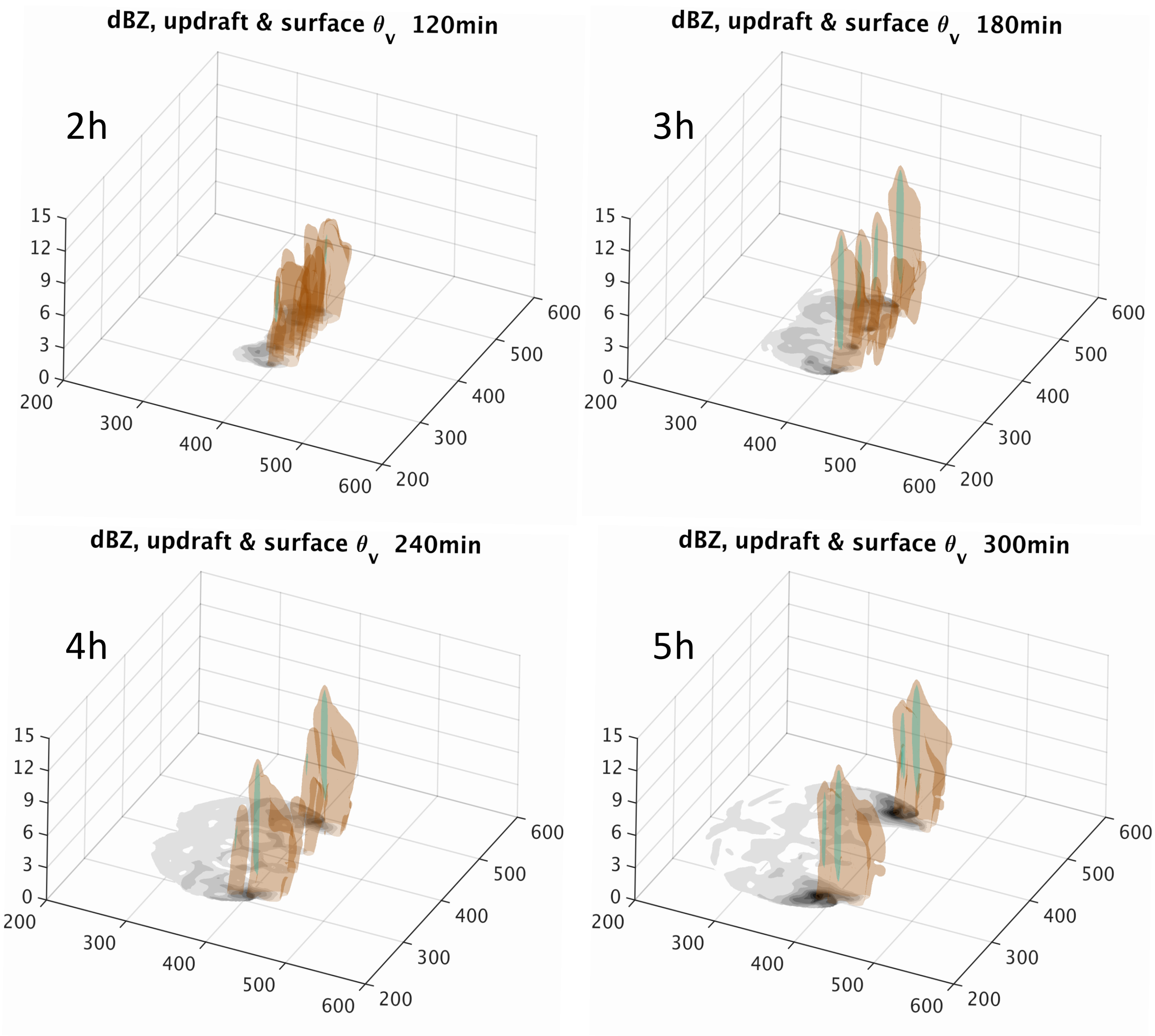
MOIST

(Wei and Zhang 2014 JAS; 2015 JAMES)



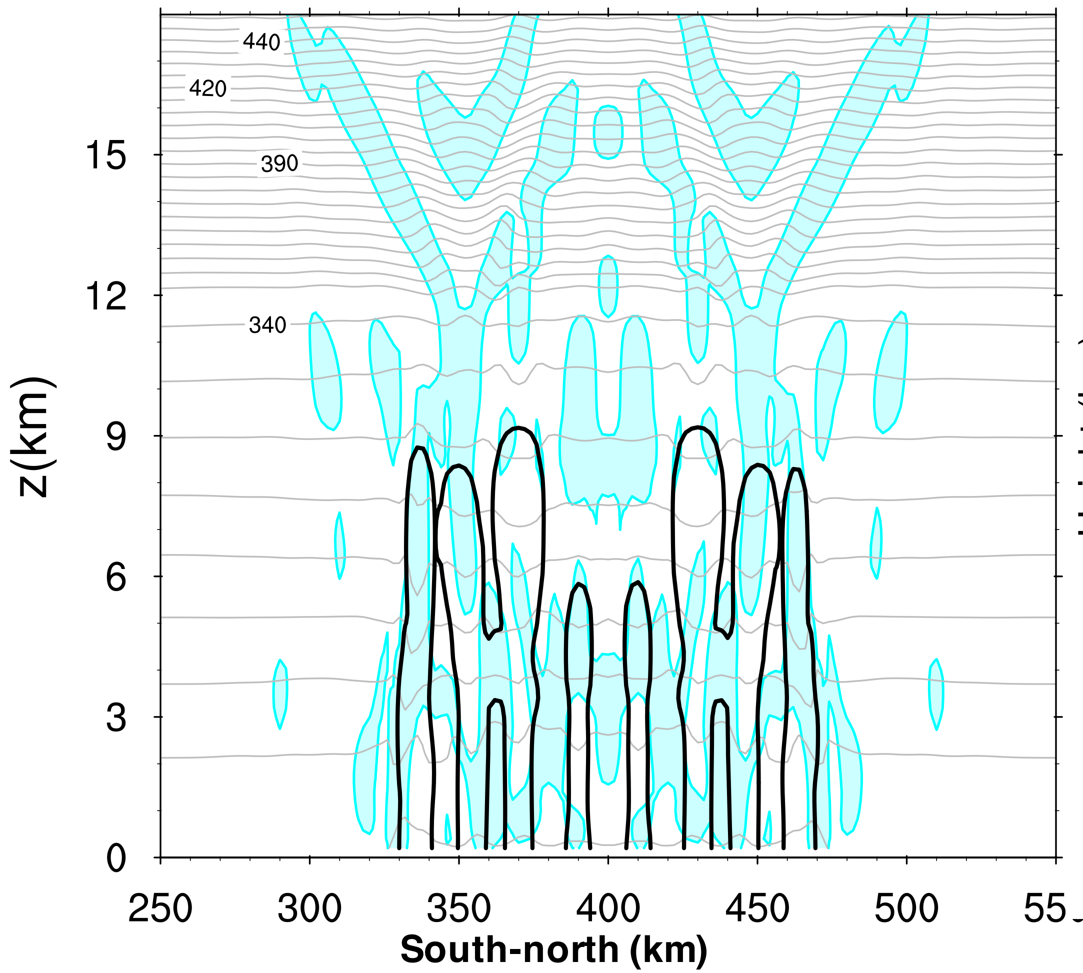
- ✓ Adjustment and gravity waves likely play a key role in the error propagation across scales, as hypothesized in Zhang et al. (2007 JAS).
- ✓ Convection and gravity waves key to flatten the meso/small-scale spectral slope.

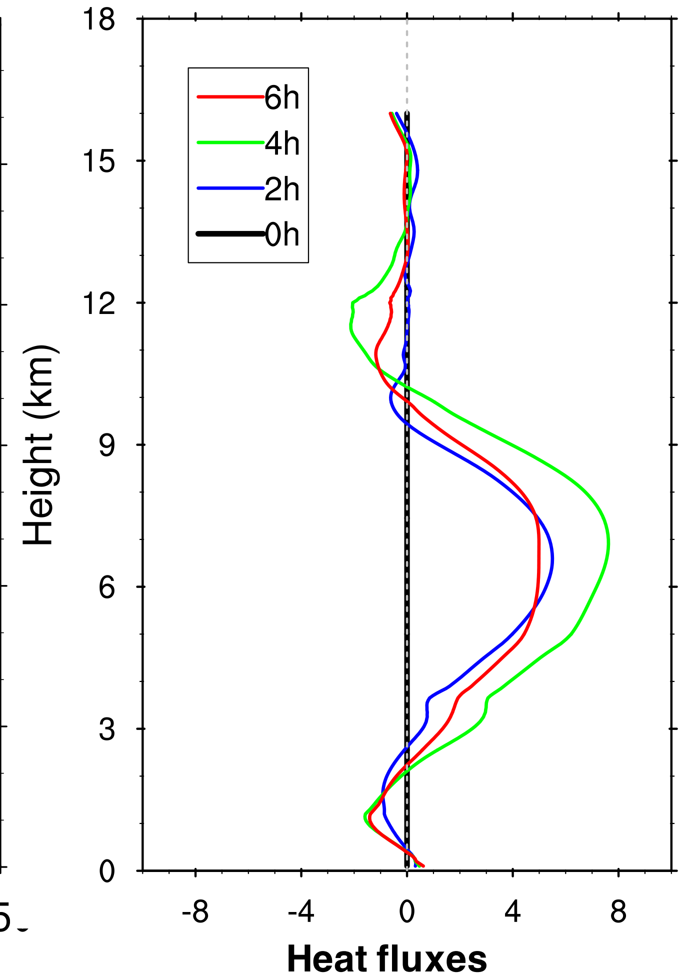
Why -5/3 mesoscale KE spectra with moist convection?



Sun, Rotunno and Zhang (2016, JAS, in review)

What key processes: convection and gravity waves

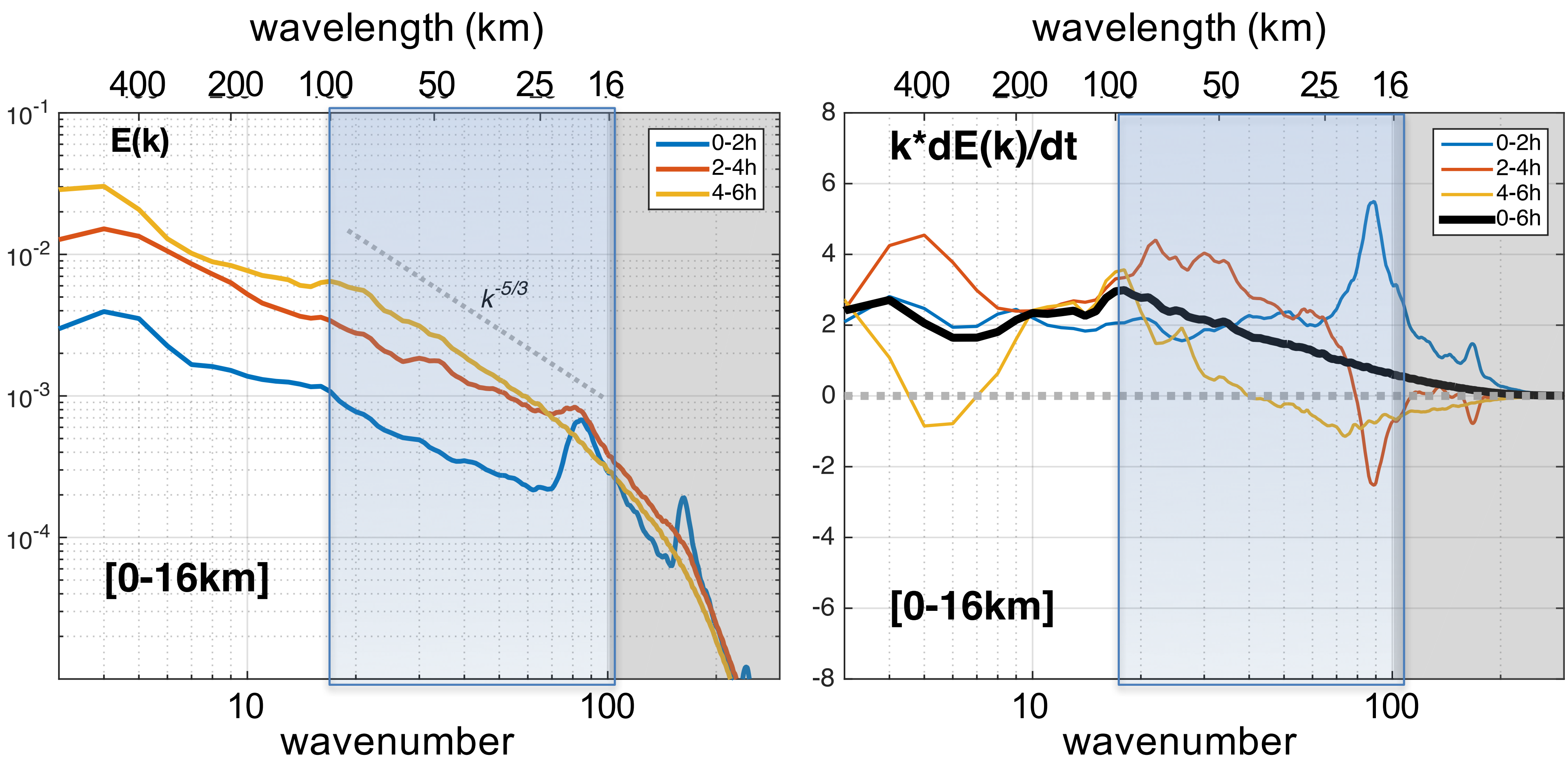




w > 0.1m/s, cyan; dbz > 25, black line;
potential temperature, gray

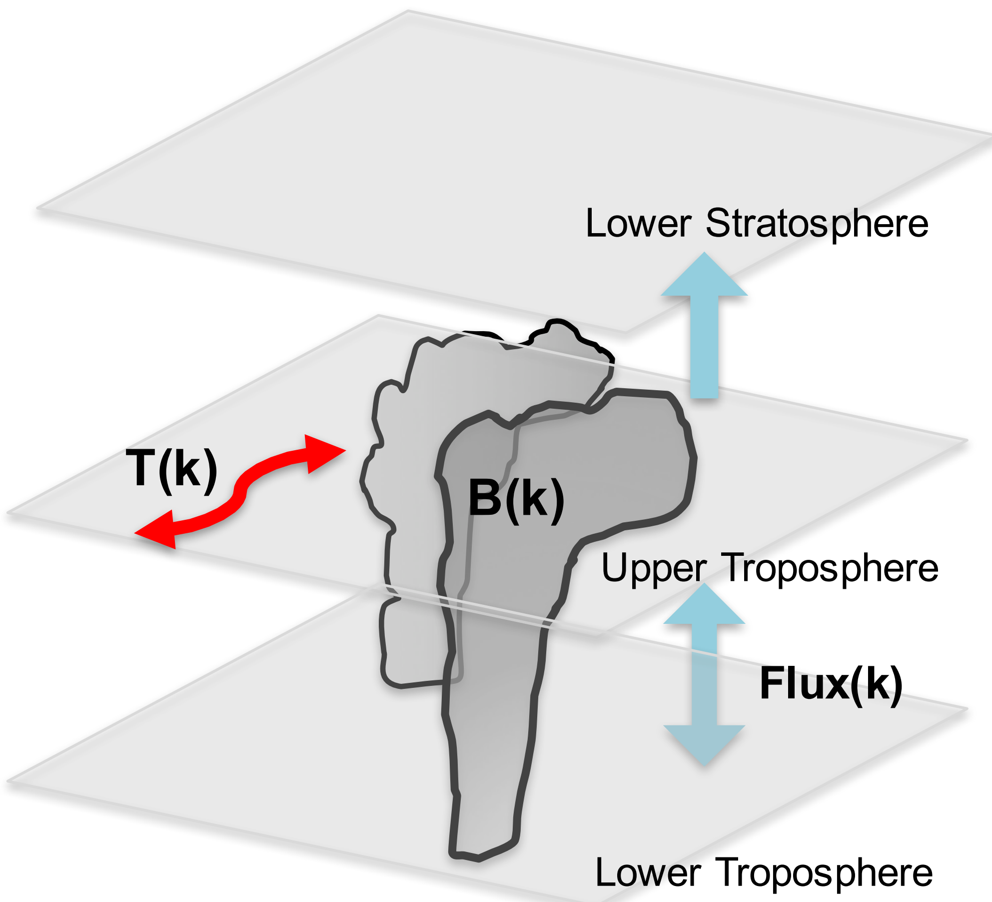
w'T'

Kinetic Energy Spectra in our Simulation



Spectra Budget Analysis for Kinetic Energy

$$\frac{\partial E(k)}{\partial t} = T(k) + B(k) + Flux(k) + D(k)$$



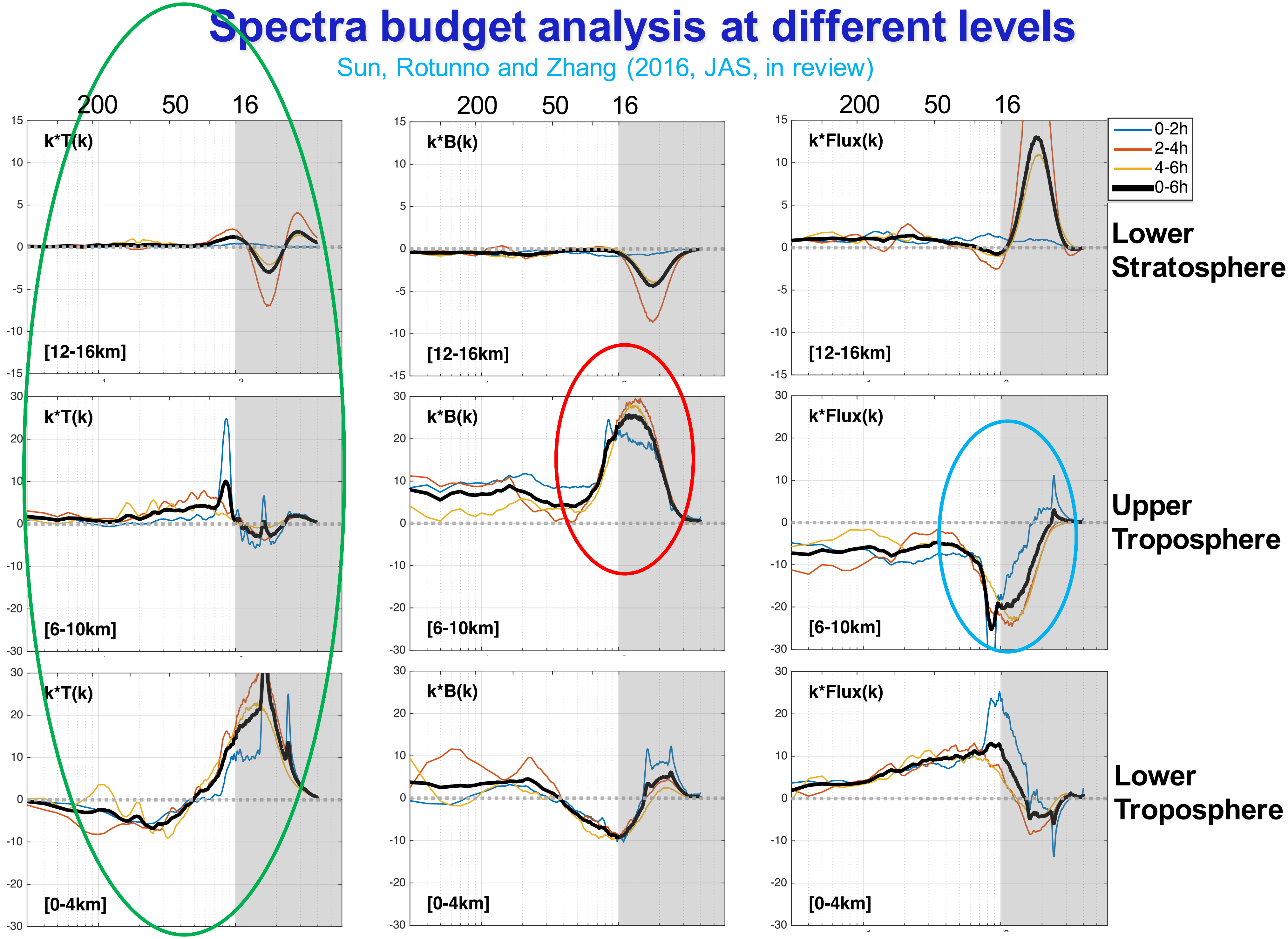
T(k): Energy transfer between different scales

B(k): Energy converted from potential energy, buoyancy production

Flux(k): Energy exchange between different vertical levels, induced by convection and vertical propagating **gravity waves**

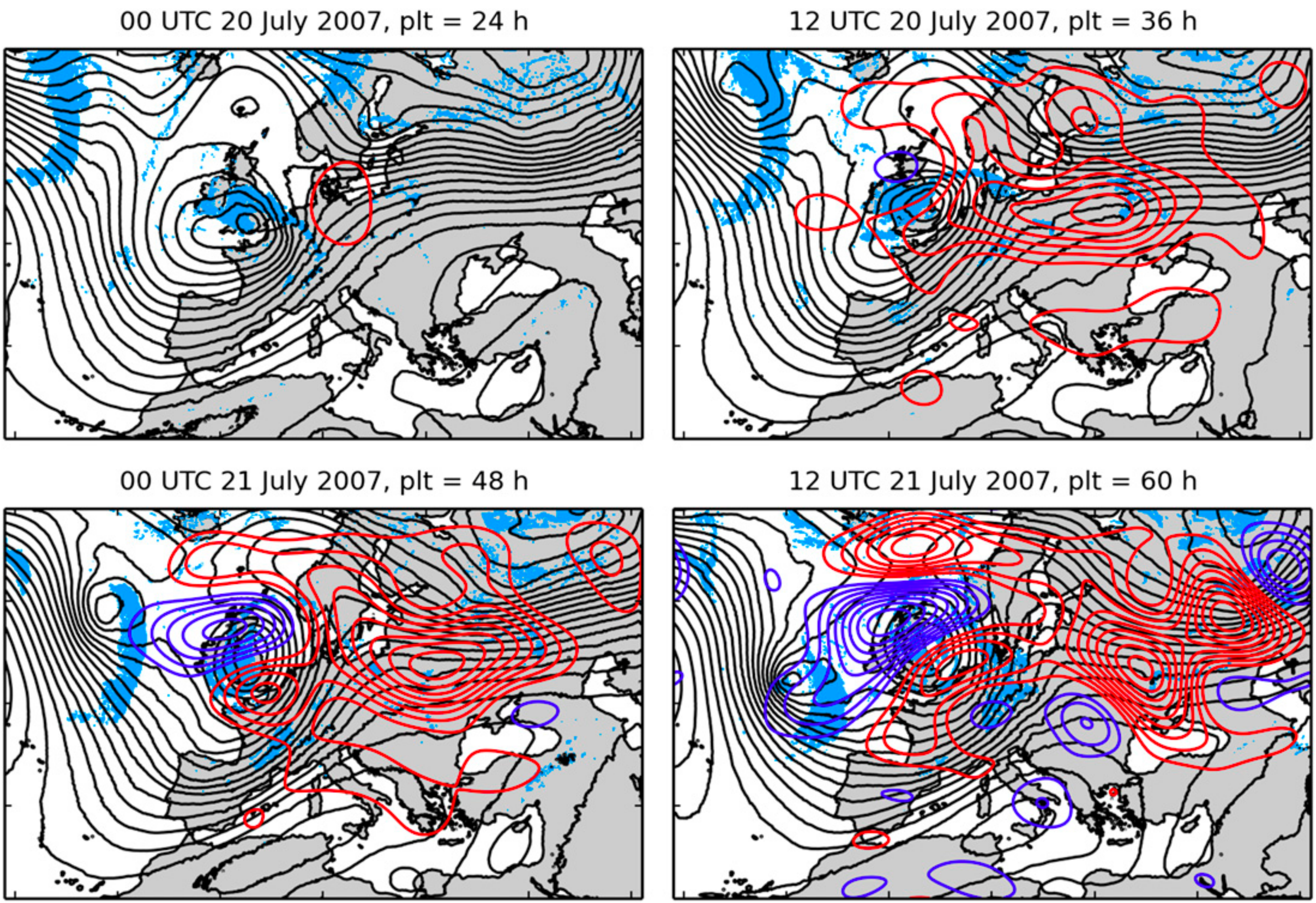
Spectra budget analysis at different levels

Sun, Rotunno and Zhang (2016, JAS, in review)



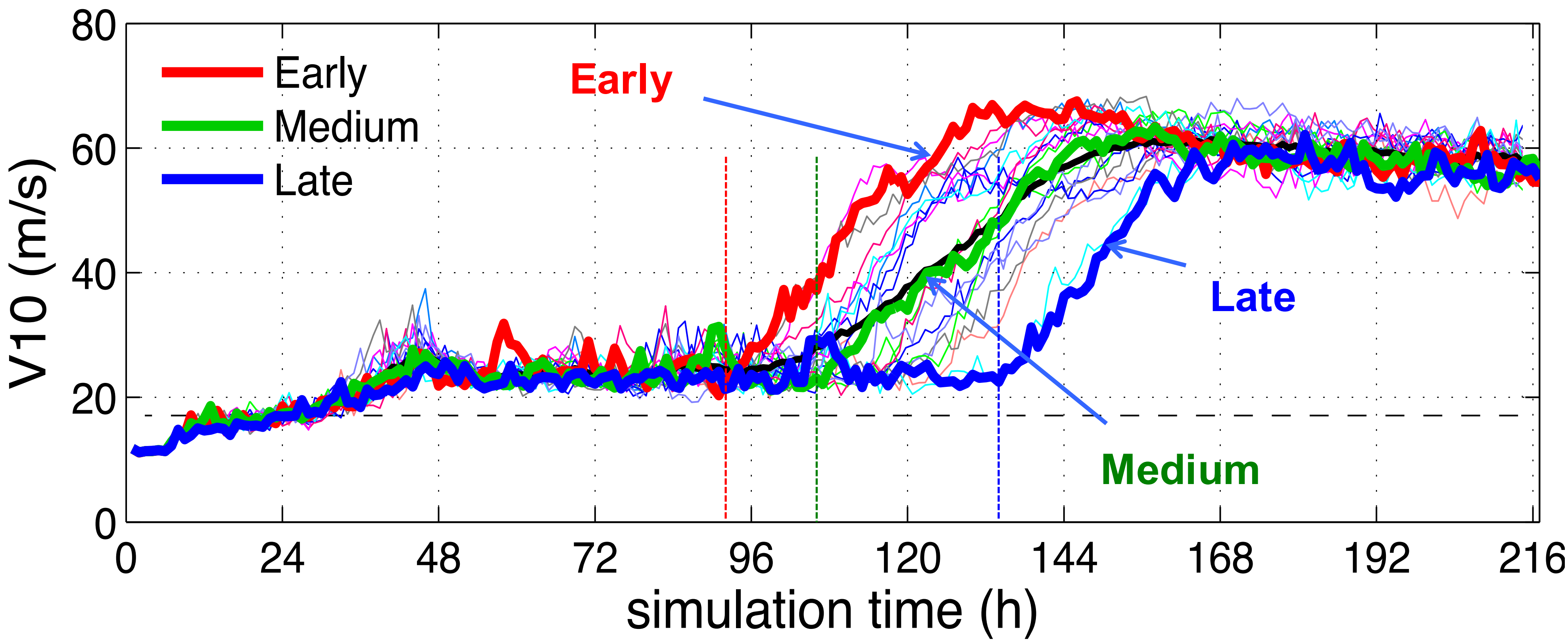
Conceptual Model Fits for A Summertime Event

Selz and Craig (2015, MWR)



Tropical Cyclone Predictability Under 5m/s Shear

10m maxWSP from ensemble with minute initial perturbations

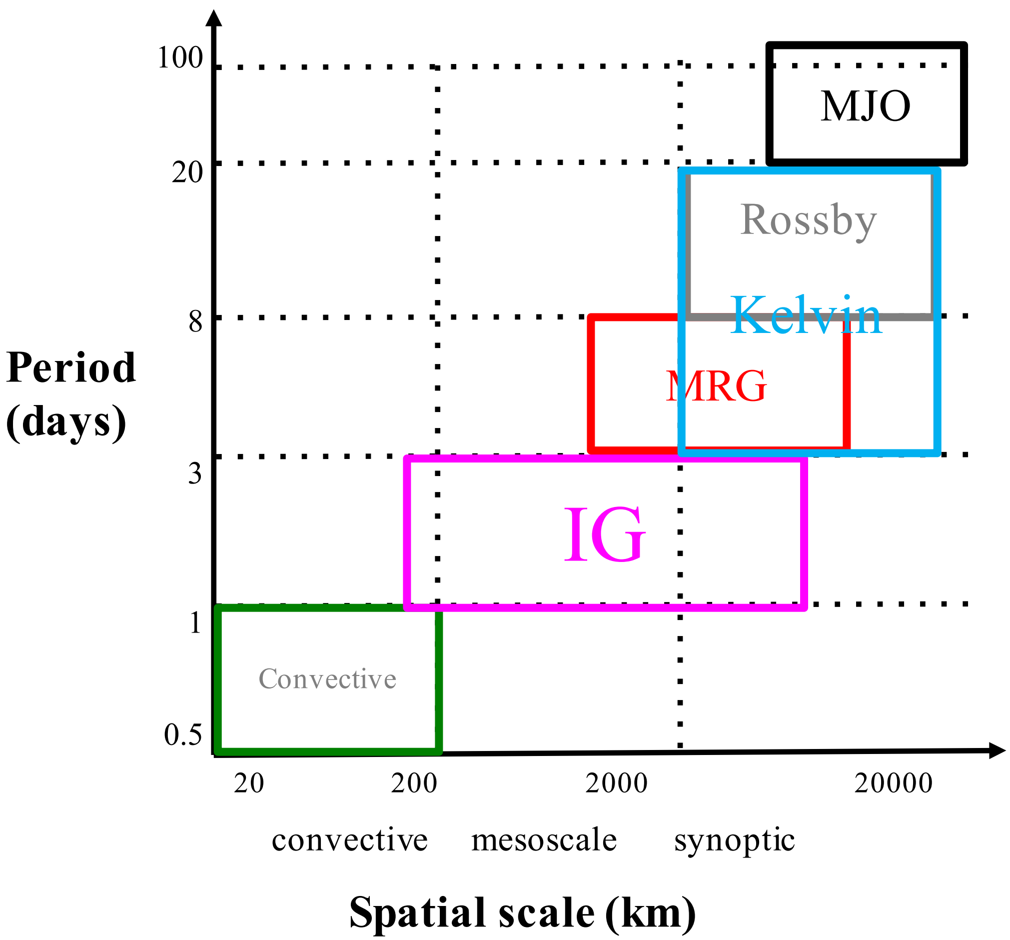


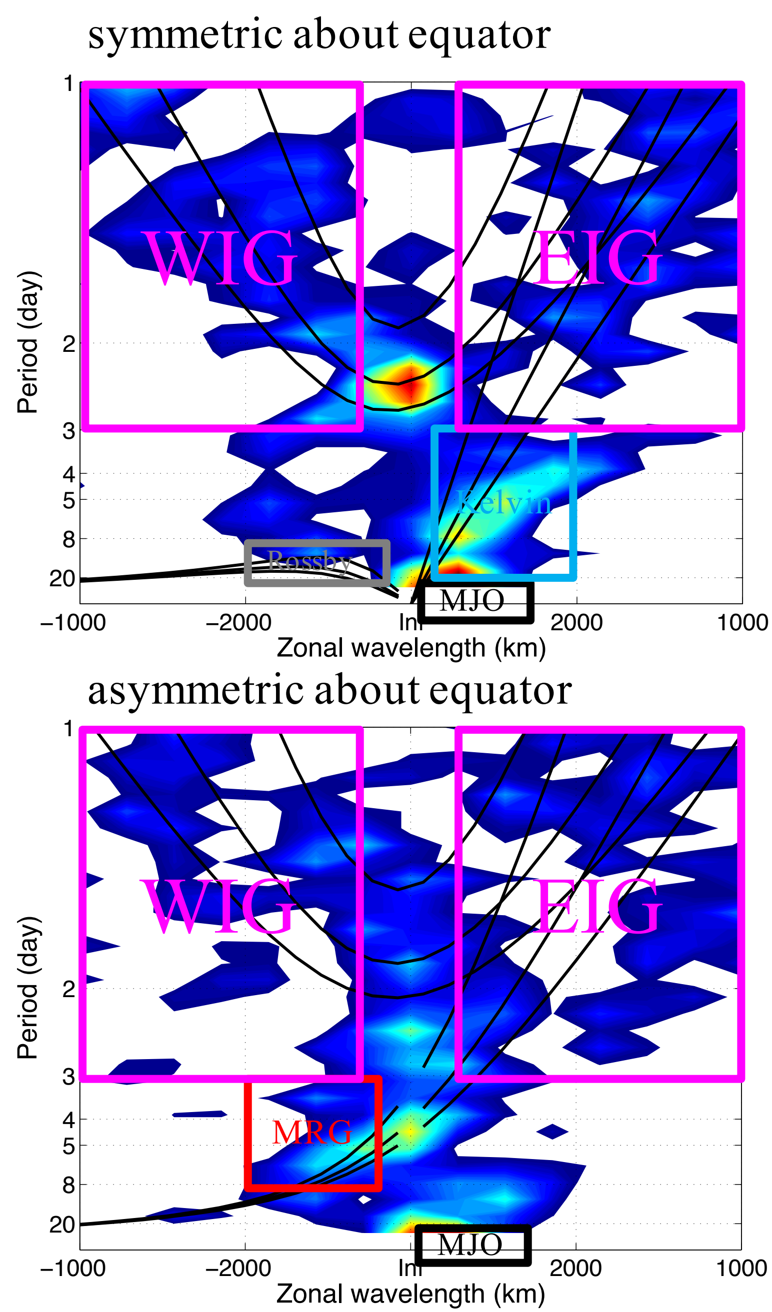
(Zhang and Tao 2013, JAS; Tao and Zhang 2014 2015, JAME

Courtesy of Ying

Space-time filtering (Wheeler-Kiladis) of multi-scale convective systems

convectively coupled equatorial waves (CCEW)

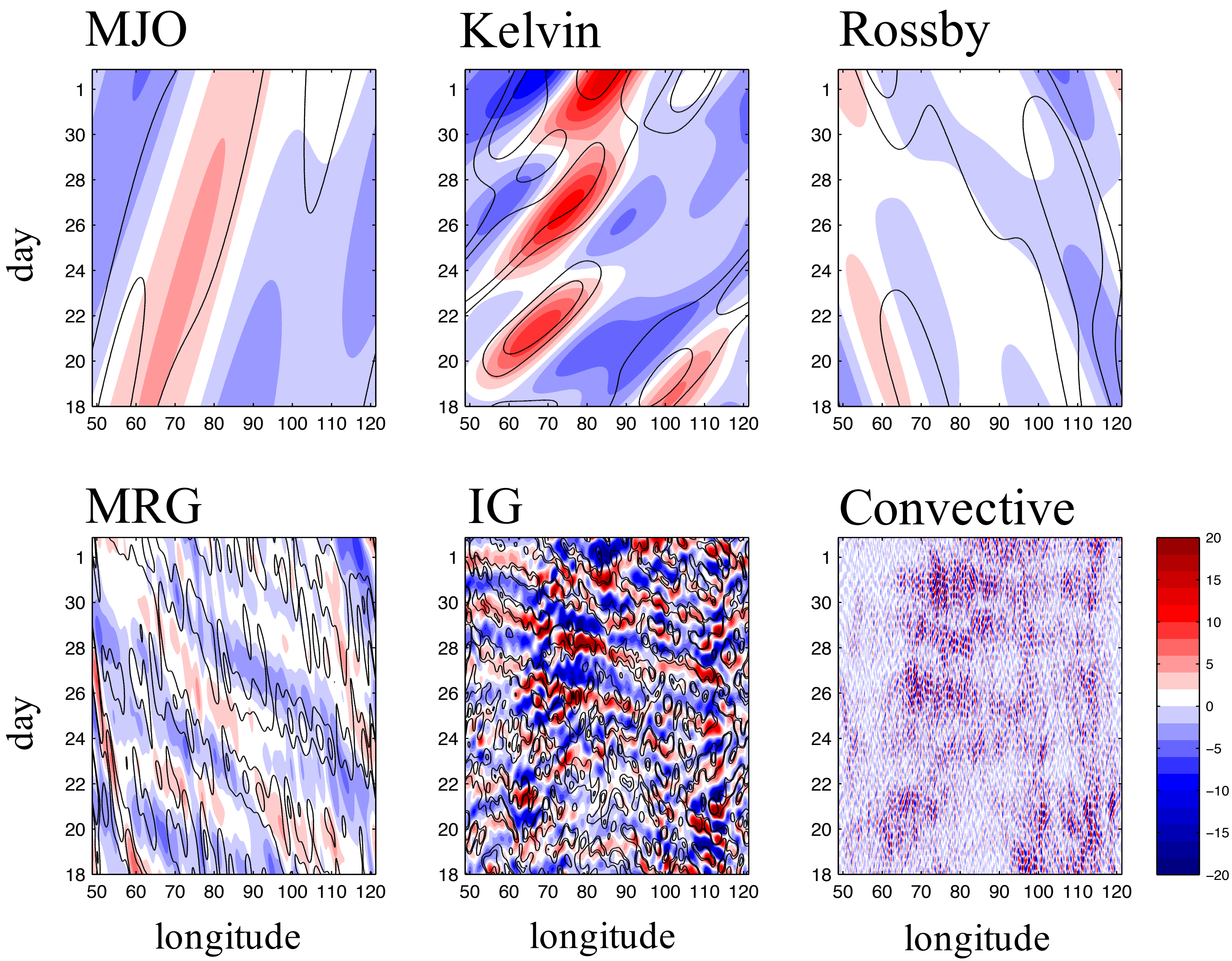




Courtesy of Ying

Synopsis of Oct 2011 MJO active phase

time-longitude plots of precipitation (color) and 200-mb zonal wind divergence (contours)



Concluding Remarks

- Predictability of multiscale weather with moist convection can be intrinsically limited.
- Moist convection and gravity waves are the key processes that lead to the -5/3 mesoscale KE spectrum slope.
- However, most of the current forecast error likely still dominates by large IC and/or model deficiencies that can be reduced through advanced DA techniques with high-resolution observations and an improved cloud-resolving NWP model.
- Nevertheless, it is of key importance to understand and estimate the flow-dependent intrinsic predictability limit for multi-scale weather and climate that is not a function of IC and model error.
- The idea of intrinsic predictability does not mean we can do nothing, but rather that all predictions must be considered probabilistic.