Penn State Center for Advanced Data Assimilation and Predictability Techniques

Gravity Waves from Jets, fronts and Convections: Impacts on Weather and Predictability

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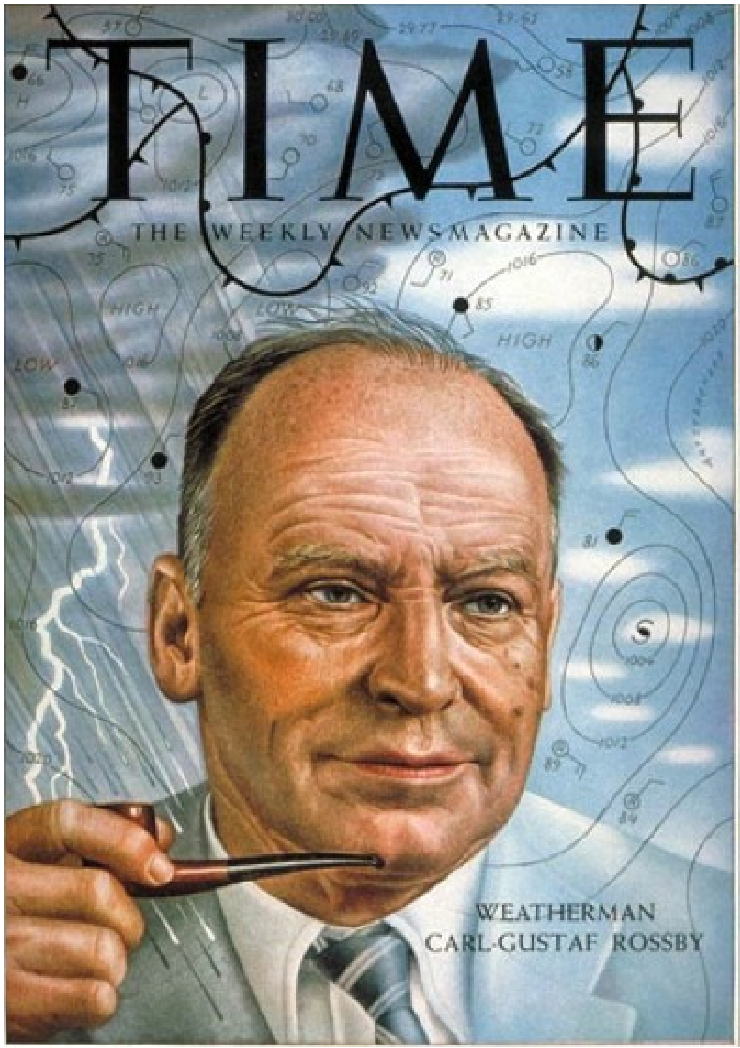
Major contributors: J. Wei, S. Wang, Y. Q. Sun and Y. Ying

Zhang group and visitors August 2014

My Academic Family Tree:
5 Generations under the Great Rossby



Carl-Gustav Rossby (1925)

↓

Horace Byers (1935)

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Roscoe Braham (1951)

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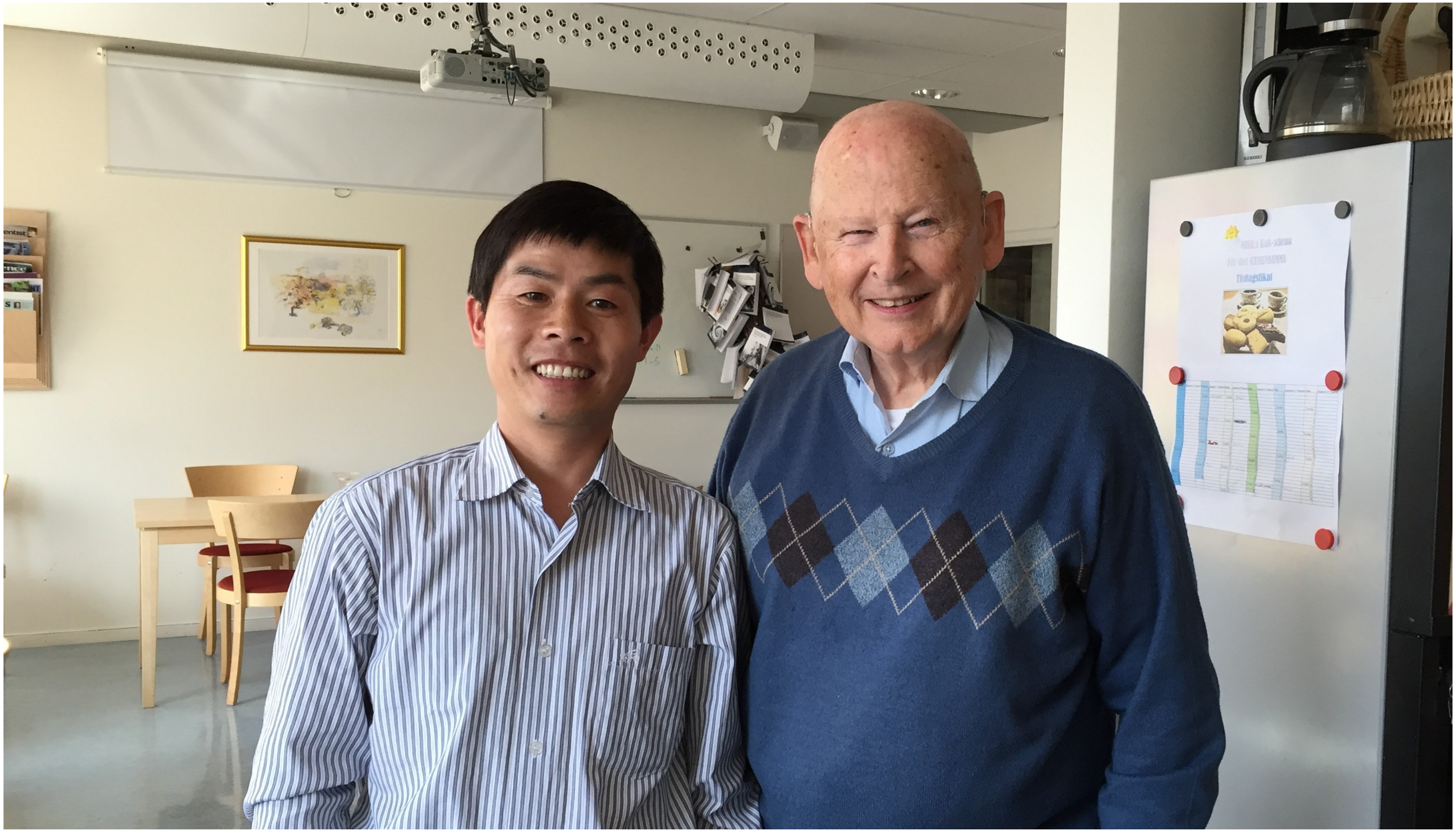
James McCarthy (1973)

↓

Steven Koch (1979)

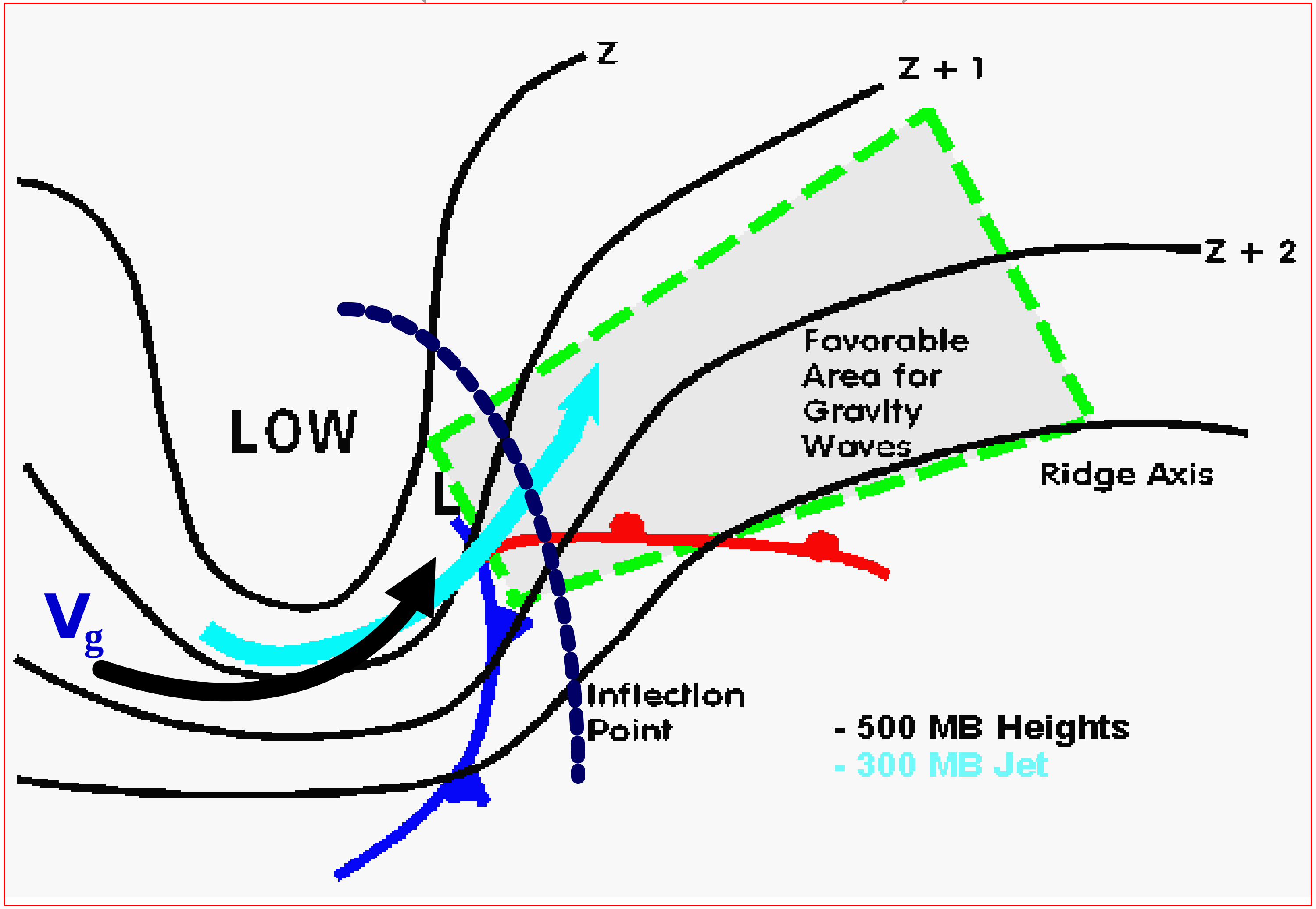
↓

Fuqing Zhang (2000)



Jet/front Gravity Wave: Synoptic Environment

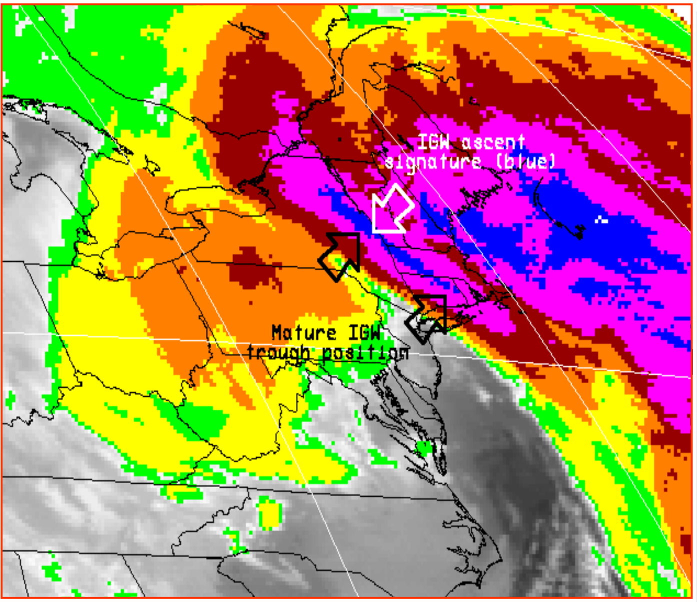
(Uccelini and Koch 1987)

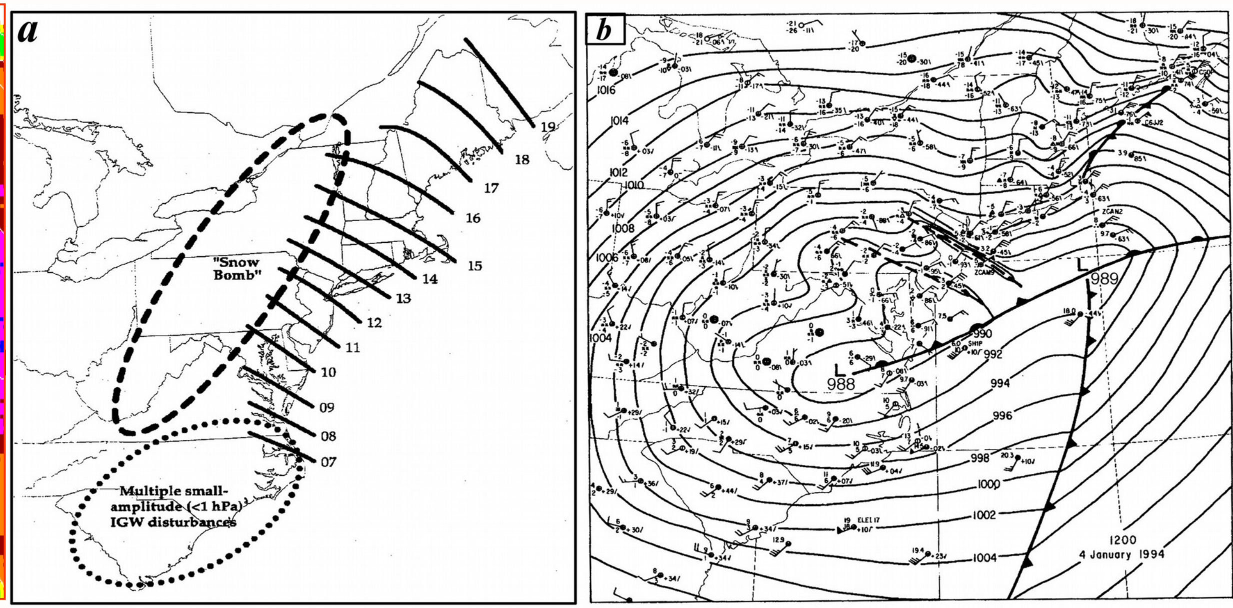


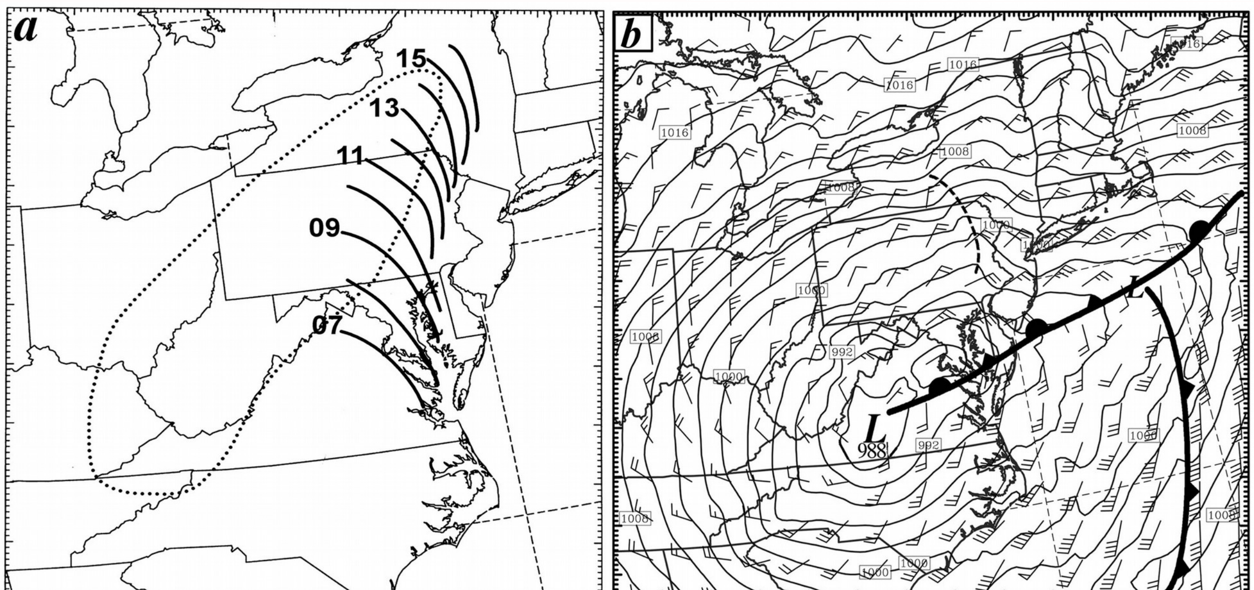
- Observations: 13 documented cases of mesoscale gravity waves; L~50-500km
- Preferred region: exit region of upper jet streak; cold side of surface front
- Leading hypothesis of wave generation: geostrophic adjustment

Large-Amplitude MGW Event of 4 Jan 1994

Bosart et al. (1998 MWR), Zhang et al. (2001QJ; 2003 MAP)







Observations vs. Simulations

Initial Timing: both at 06~07 Z,
wavelength: both ~ 100km,
phase speed: both ~ 25m/s,

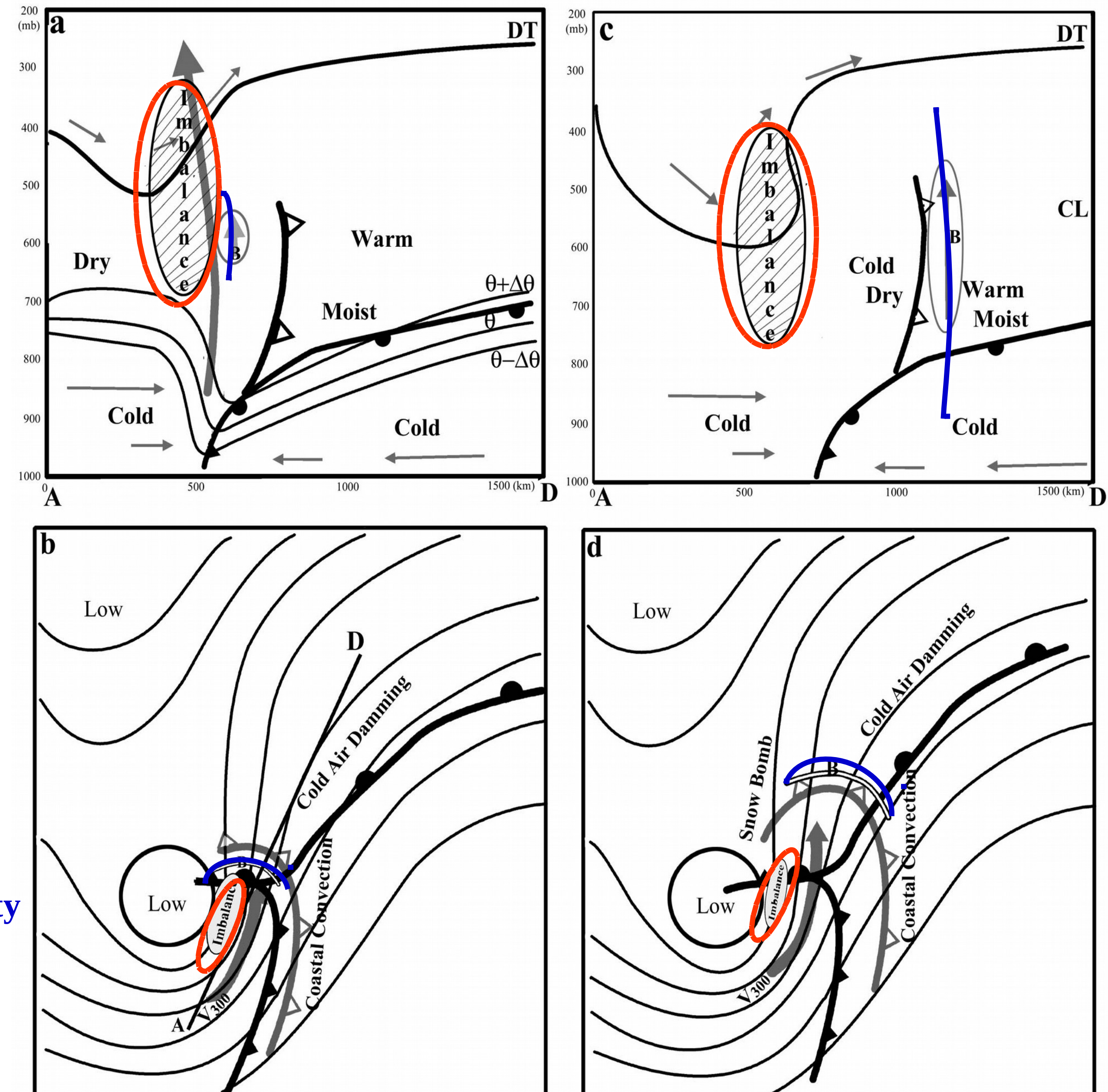
Simulated amplitude: ~ 3-4 mb
Observed amplitude: ~ 7-8 mb

Jet Imbalance + Wave Ducting

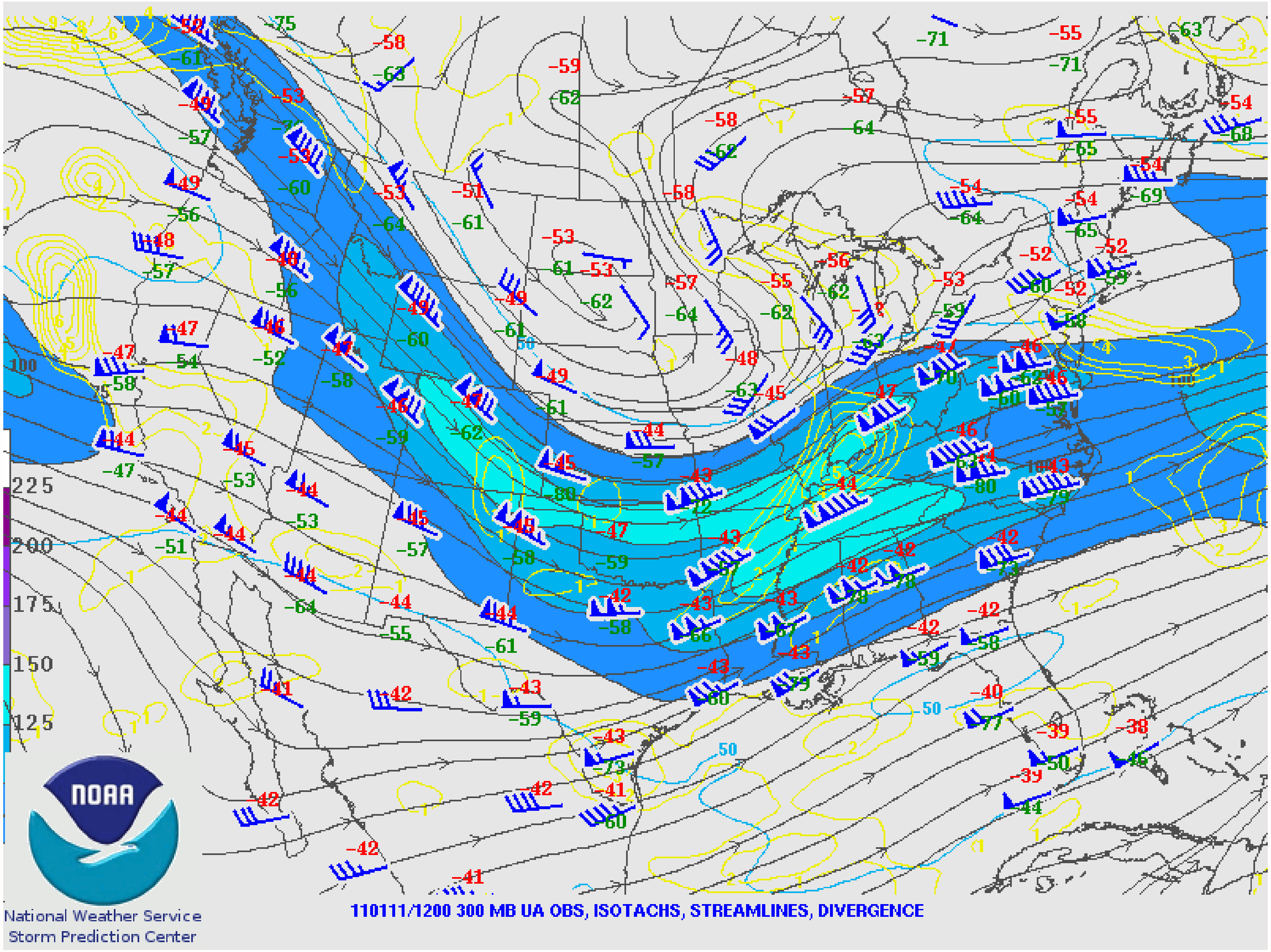
Schematic Wave Generation Model (Zhang et al. 2001, QJ)

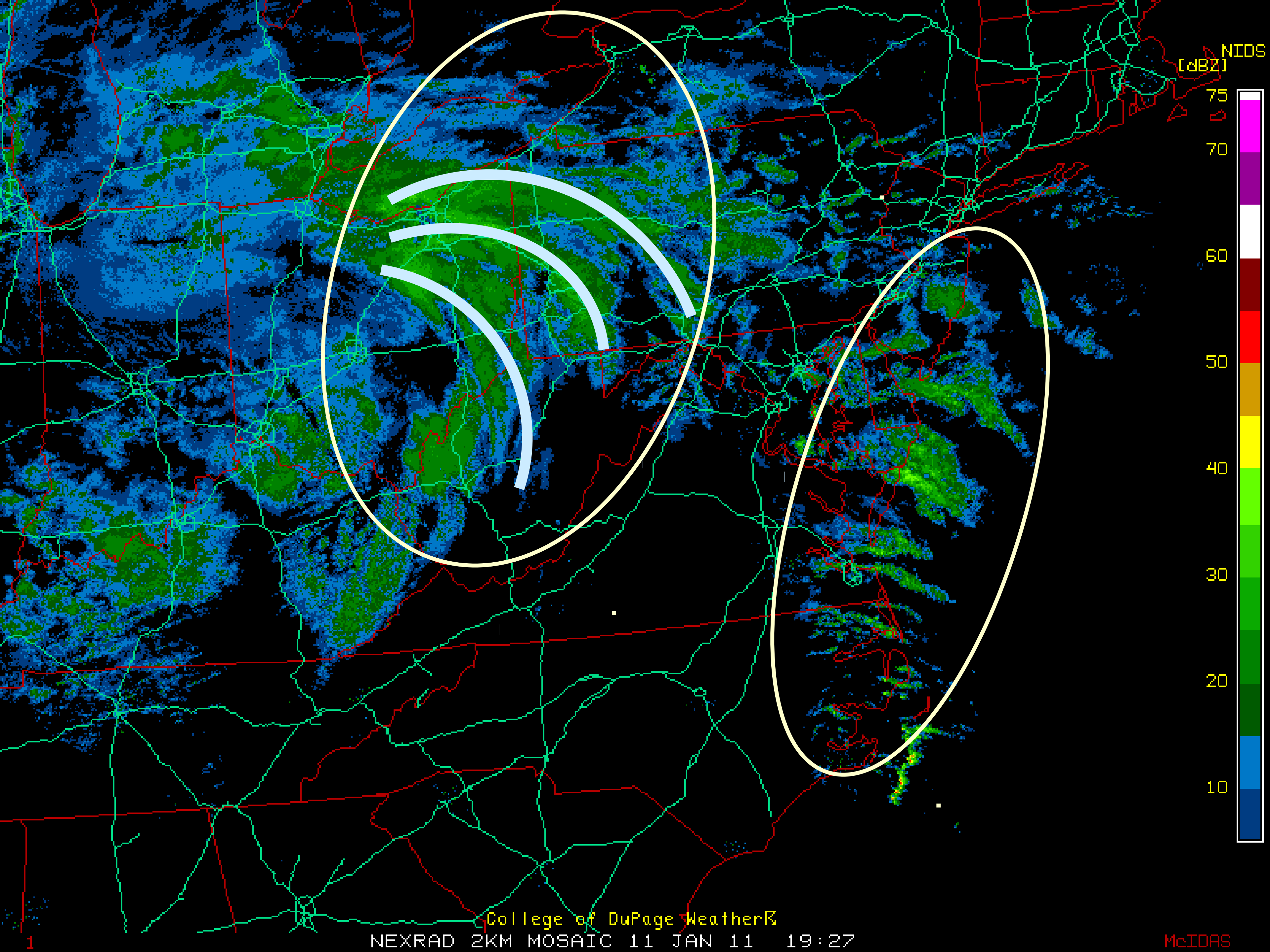
Initiation Stage (left)
Generation of the incipient gravity wave immediately downstream of the maximum imbalance coincide with the development of a split front due to warm occlusion

Development Stage (right)
The incipient wave merges with the split front, resulting in its rapid amplification and scale contraction. Therefore, "localized" convection is triggered and the dominant gravity wave developed at the surface



Gravity Waves in Moist Baroclinic Jets/fronts
Real world examples: Jan 11, 2011

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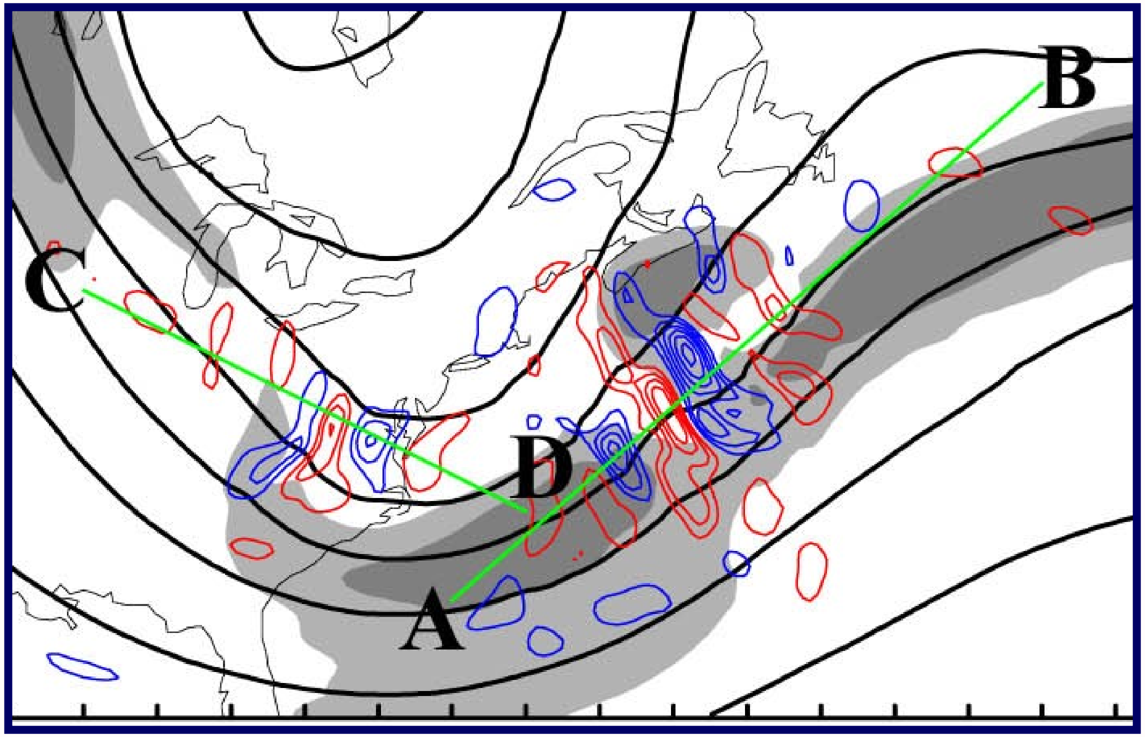
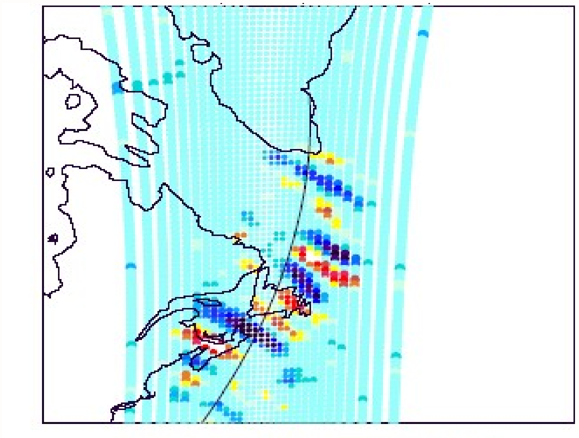
Jet/front Gravity Waves: Real-world example

(Wu and Zhang 2004 JGR)

Mesoscale simulations



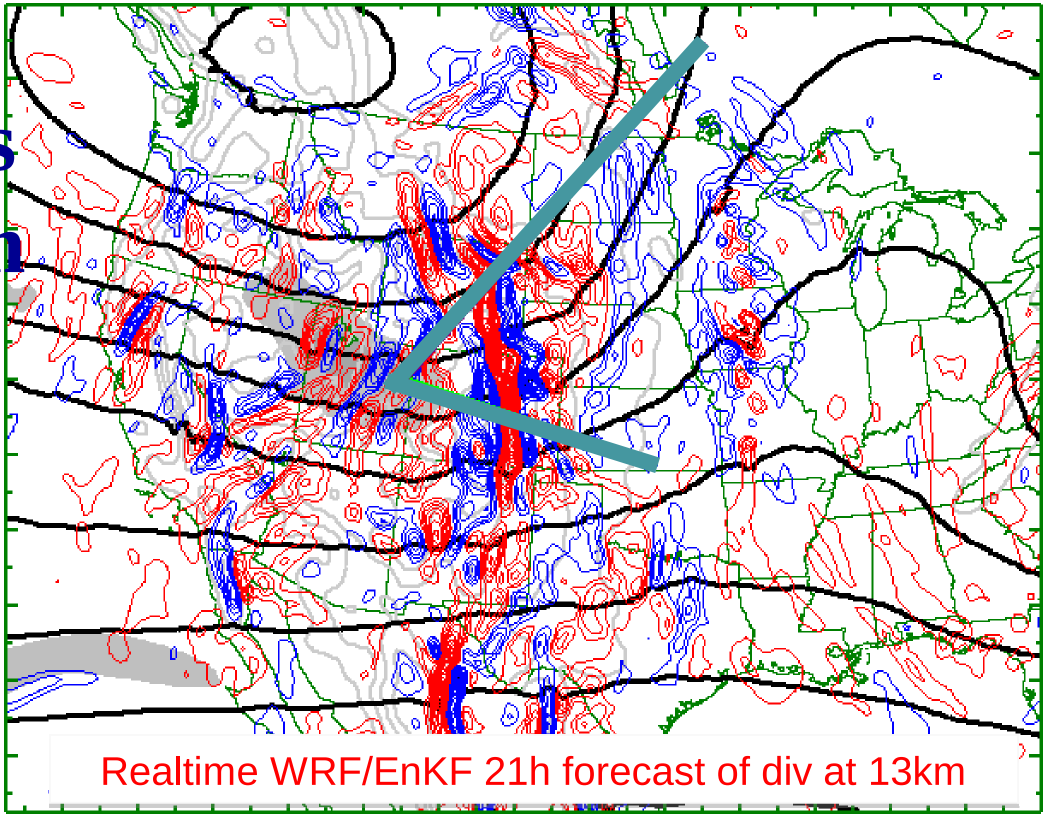
Satellite Radiance

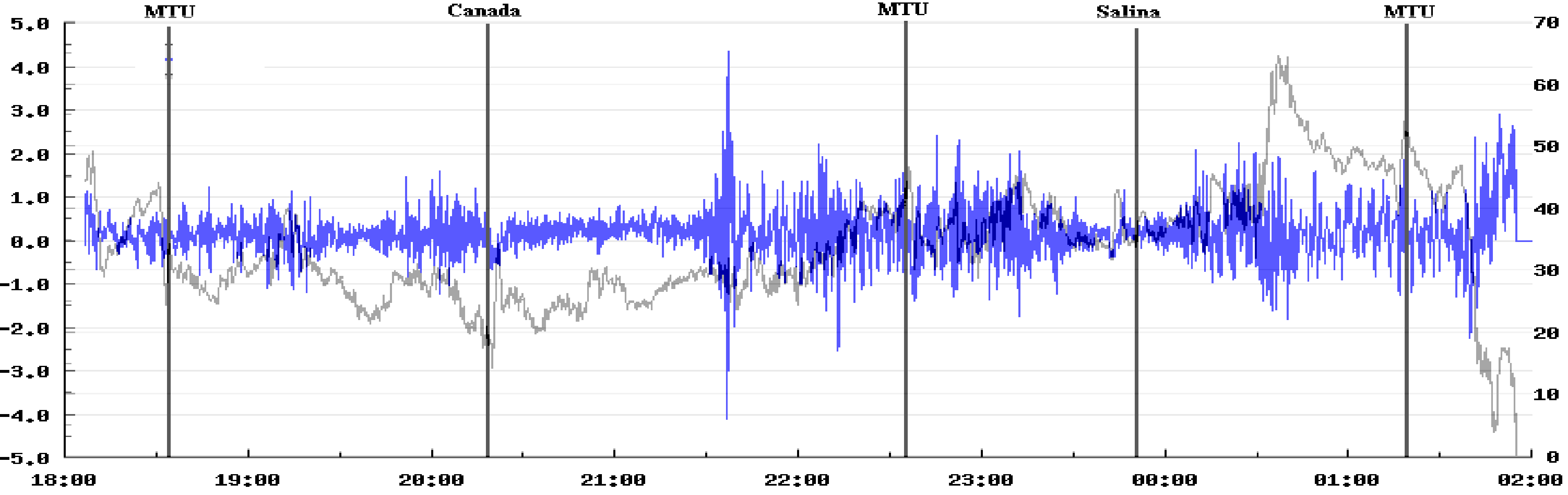


- Jet-exit region gravity waves with λ_x=300-500km; λ_z=6-10km; ω=2-5f
- Wave amplitude at 80mb: u',v'=5-10m/s; T'=3-6K; w'=20-30cm/s
- Similar waves but much weaker amplitude in simulations with no moisture effect

Gravity Wave Forecasts and Measurements from GV Research Flight #2 during START08

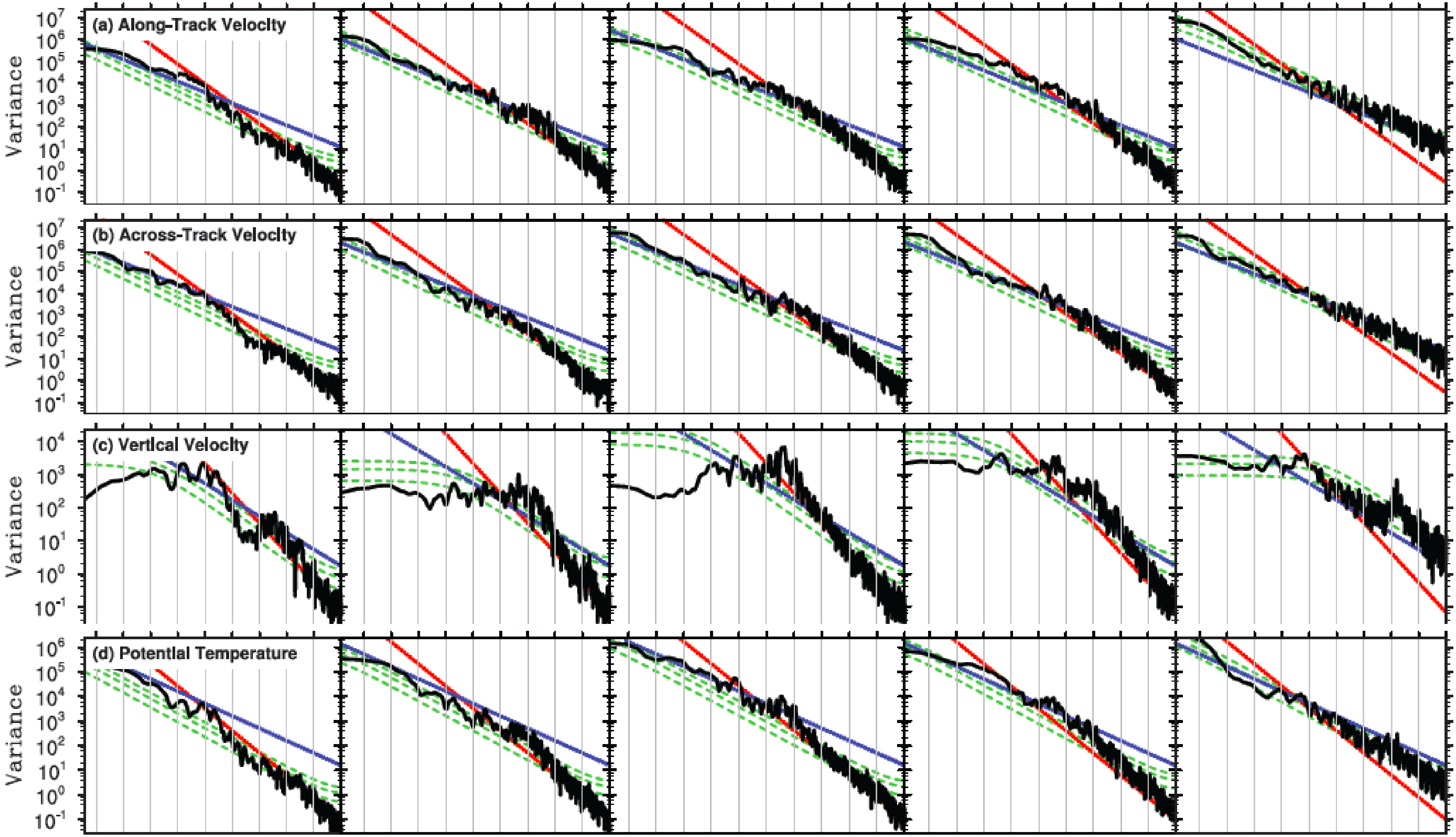
(Pan et al. 2009 BAMS; Zhang et al 2015 ACP)



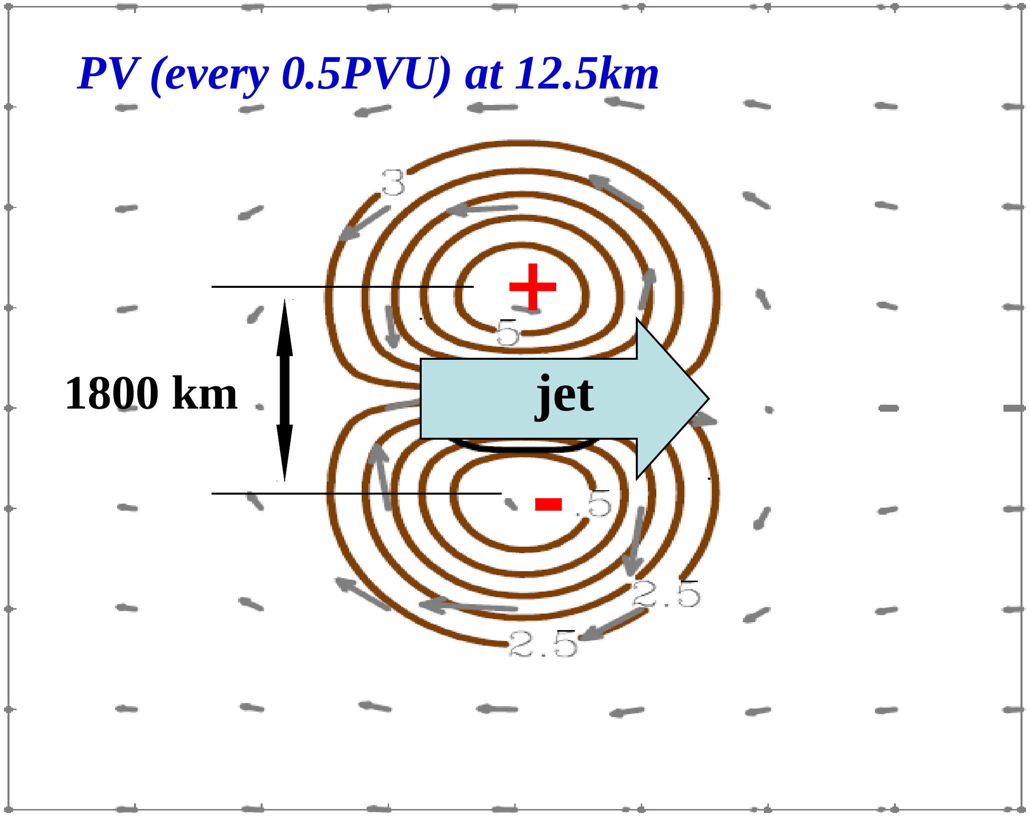


Power Spectra of Gravity Wave Measurements from GV Research Flight #2 during START08

(Zhang et al 2015 ACP)



Localized jets and vortex dipoles
(Wang, Zhang and Snyder 2009 JAS)

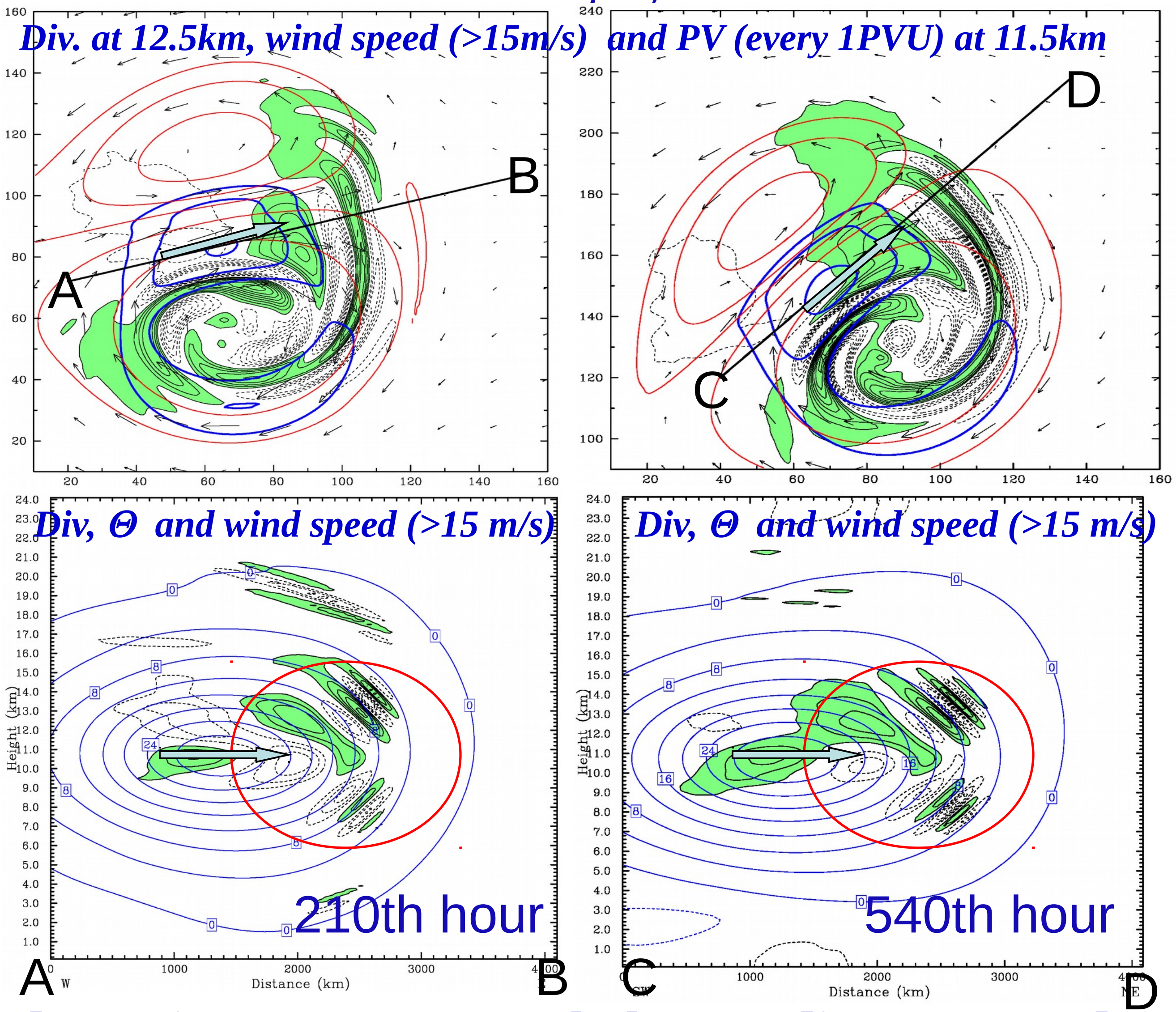


Jet Streak ~ 30 m/s

Translate slowly

- Positive/negative potential vorticity anomalies
- Vortex dipole: two counter rotating vortices
- Potential vorticity inversion to create balanced jet to minimize initial imbalance
- Integrate a mesoscale model (MM5) up to 25 days. Dz=200m, Dx=90,

Gravity Waves from Mid-level Dipole Jet (Wang, Zhang and Snyder 2009 JAS)

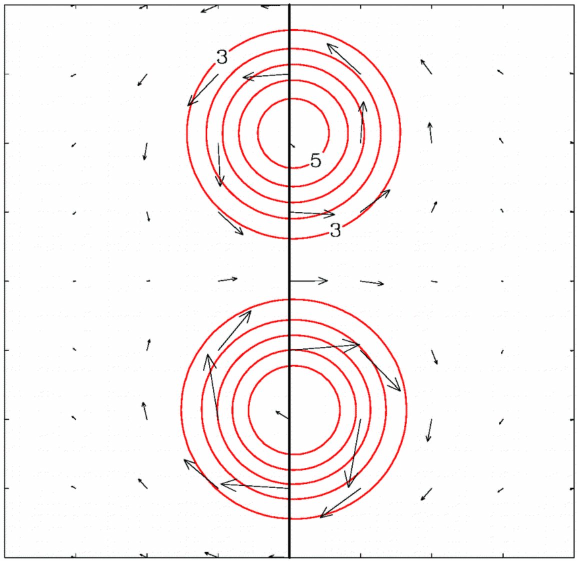


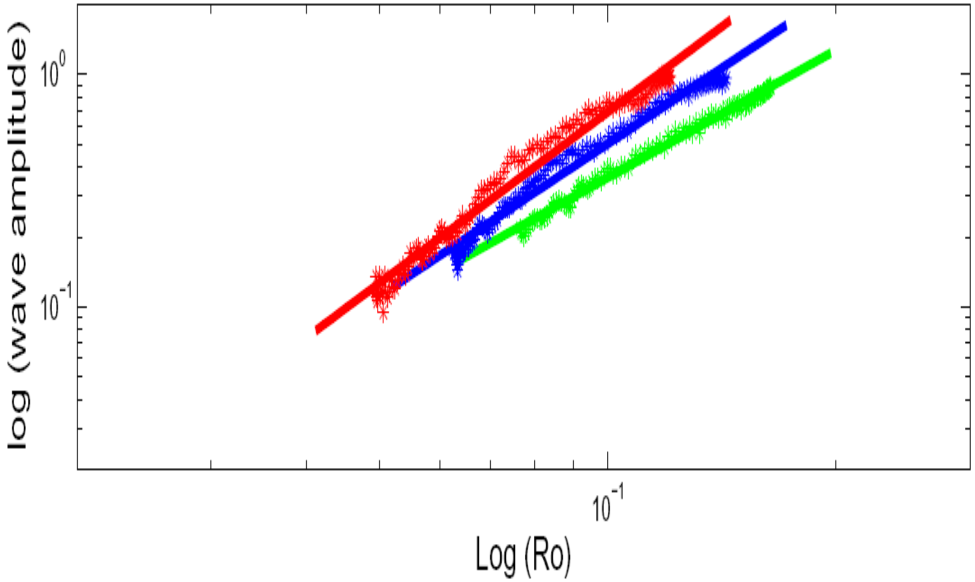
L_h~300km,
L_z~2km
ω_i~1.4f

Governing dynamics: Spontaneous balance adjustment and wave capture

(Wang and Zhang 2010 JAS; Wang, Zhang & Epifanio 2010 QJ)

Amplitude dependence on the jet strength (Rossby number)

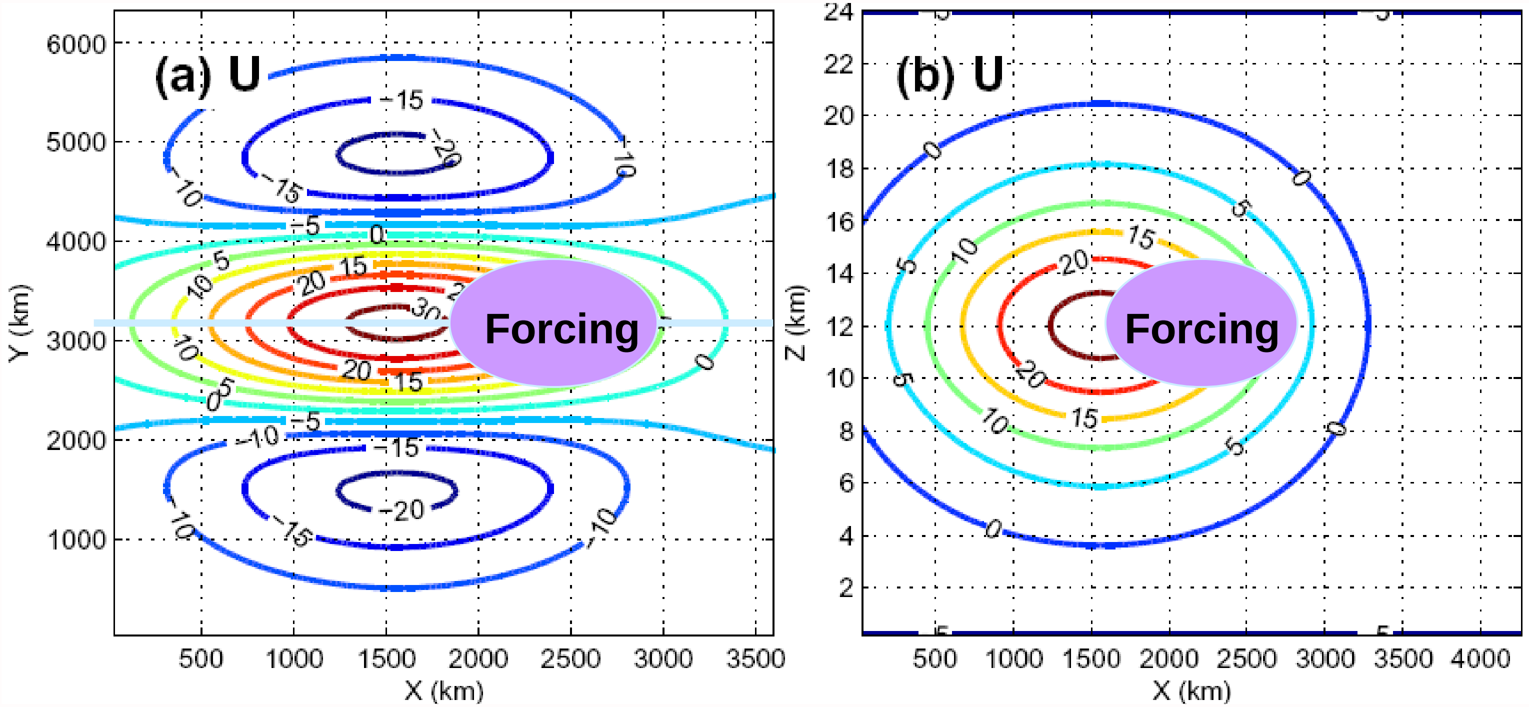




Distant vortex dipoles

- Wave amplitude is weak
- Power law relation: wave amplitude ~ Ro^2

Wave responses to specified forcing from a QG dipole jet



- Localized jet within a quasi-geostrophic (QG) vortex dipole
- Impose Gaussian shape divergence forcing: horizontal scale 112-450 km, vertical scale 0.75-4.5 km

Wang, Zhang & Epifanio (2010 QJ
Wang, Zhang & Snyder (2009 JAS

Propagating Effects: Ray tracing (Marks and Eckermann 1995) and Wave capture (Buhler and McIntyle 2005)

Ray Solution: Consider slowly varying flow $\psi(\vec{x},t) = A(\vec{x},t)e^{i\psi(\vec{x},t)}$

- Wave numbers and frequency $\vec{k} = \nabla\psi, \omega = \frac{\partial\psi}{\partial t}$
- Dispersion relation $\omega = \Omega(x_j, k_i, t)$ and group velocity $c_{g_j} = \frac{\partial\Omega}{\partial k_j}$
- Wave frequency and wave number change following a wave

$$\frac{\partial \vec{k}}{\partial t} + (c_{g_j} \cdot \nabla)\vec{k} = -\nabla\Omega, \quad \frac{\partial\omega}{\partial t} + (c_{g_j} \cdot \nabla)\omega = -\frac{\partial\Omega}{\partial t}, \quad \frac{dx_j}{dt} = c_{g_j},$$

- Wave amplitude are governed by conservation of wave action along ray tube

$$A = Energy/\omega_i, \quad \int_{V(t)} A dV = AJ = c$$

Wave Capture: When wave packets propagate to flow of strong horizontal deformation,

- horizontal wave number increases to near infinity: a.k.a. horizontal critical level
- wave vectors align with the local contraction axis: k/m=Ux/Uz
- intrinsic group velocity vanishes and wave packets are advected by the mean wind

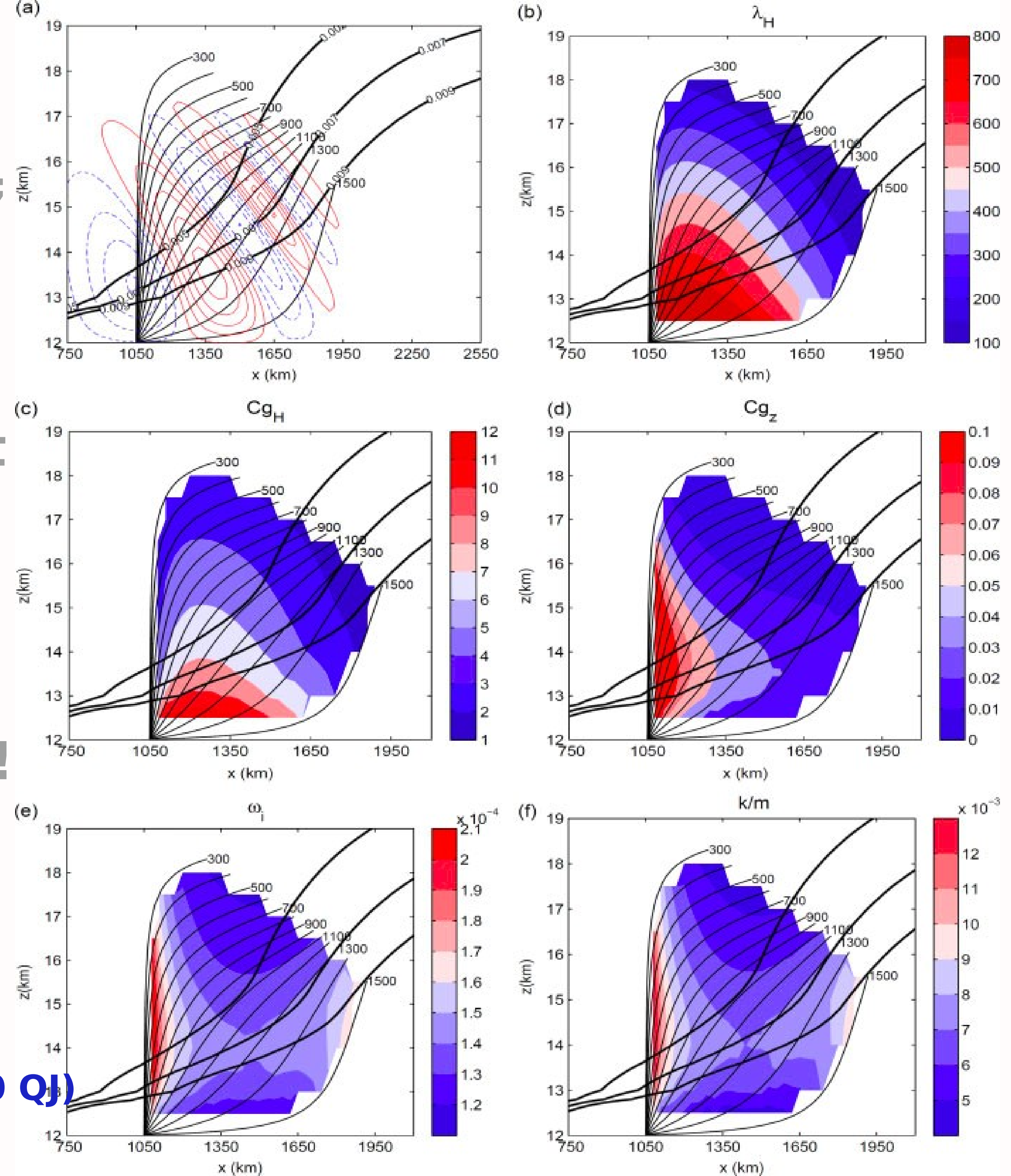
deformation: result with ray tracing

(Lin and Zhang 2008 JAS; Marks/Eckermann 1995 JAS)

releasing rays at jet exit with initial Lx=300-1500km

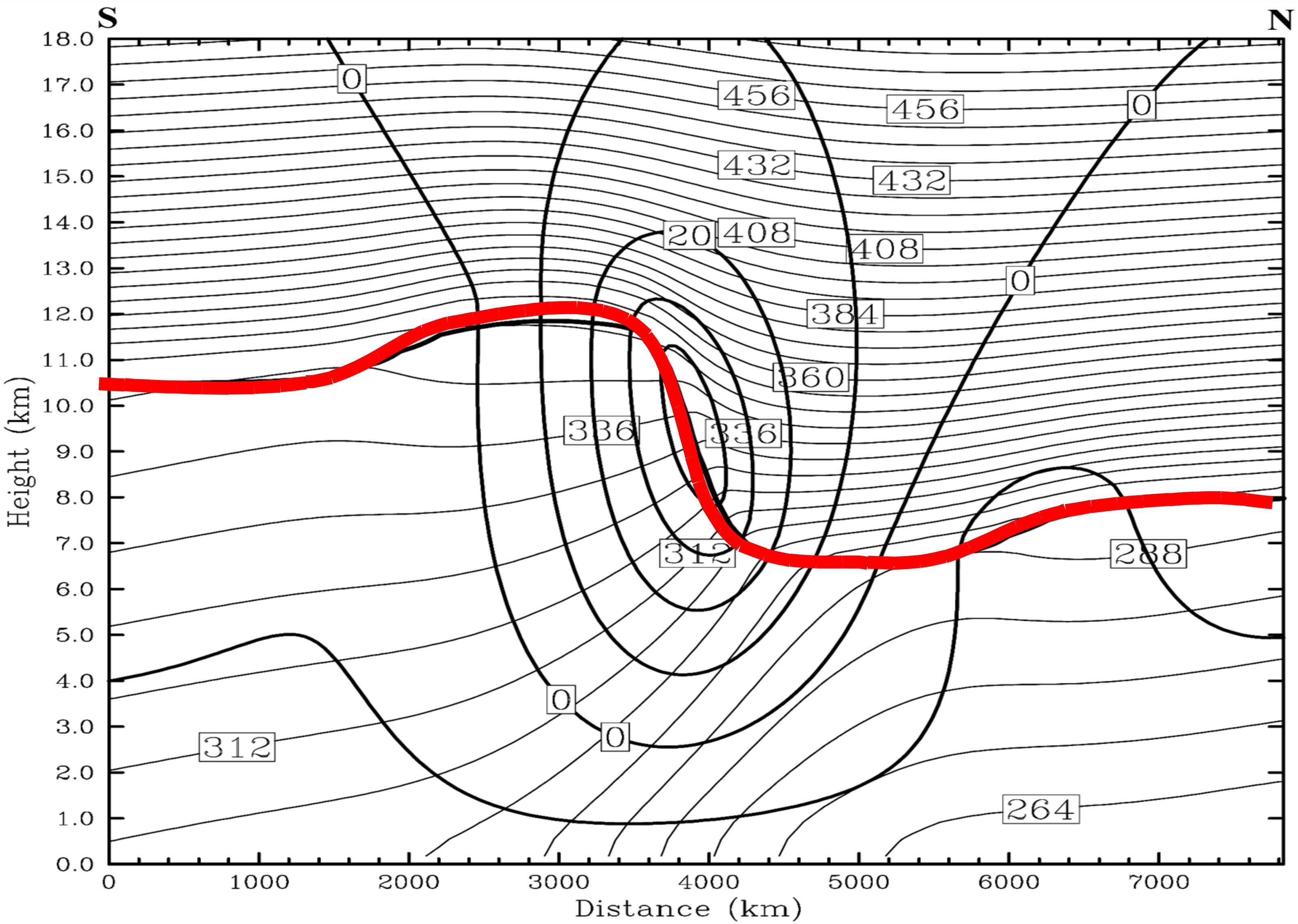
wave capturing?!

mid thick line: k/m~Ux/Uz ~f/N~0.007 s^{-1}



Wang, Zhang, Epifanion 2010 QJ)

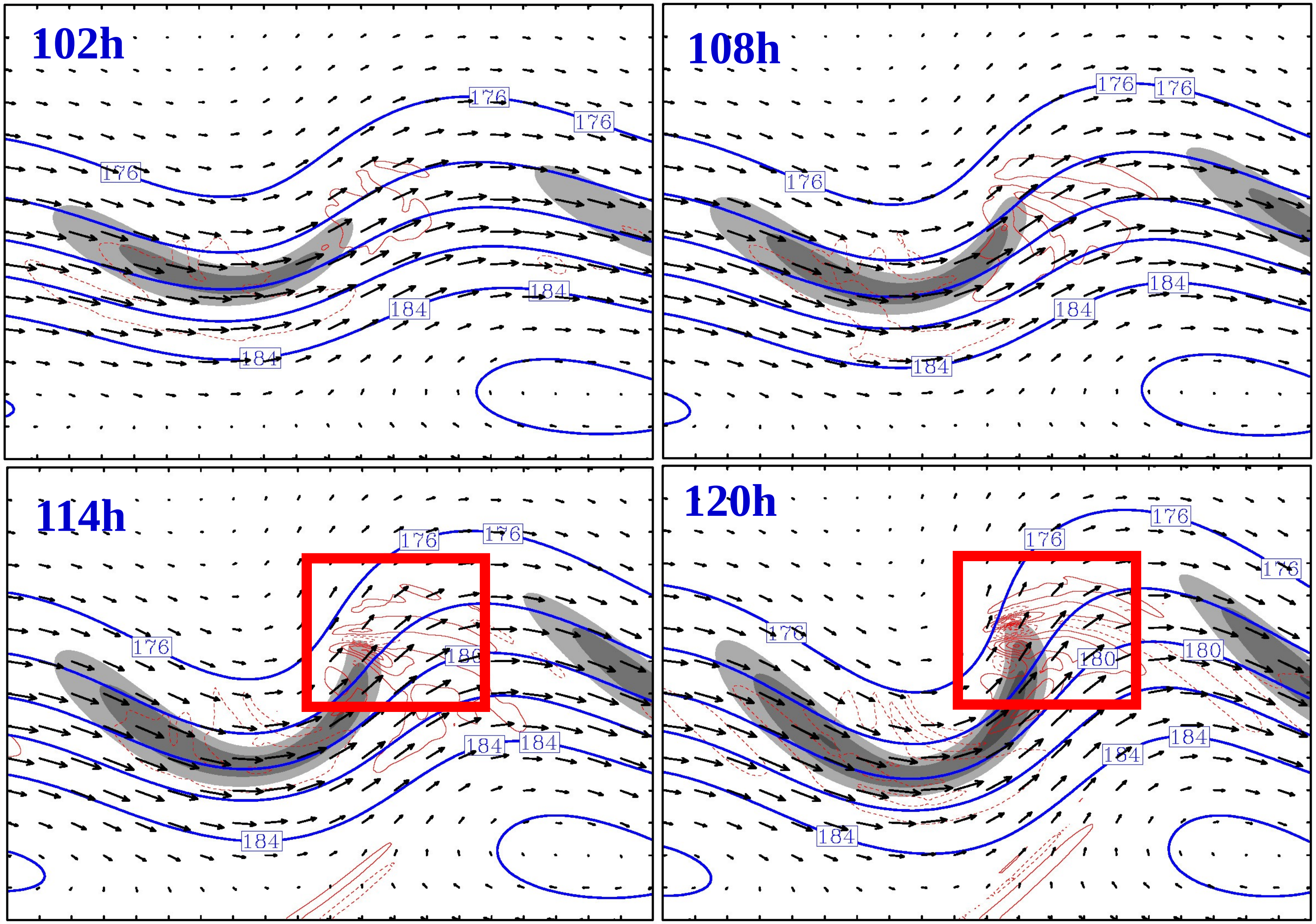
Initial 2-D Baroclinic Jet



Red: tropopause; thick: isotachs, D=10m/s; thin: potential temperature, D=8K

(Zhang 2004 JAS)

Upper-tropospheric Jet and Lower-Stratospheric Gravity Waves



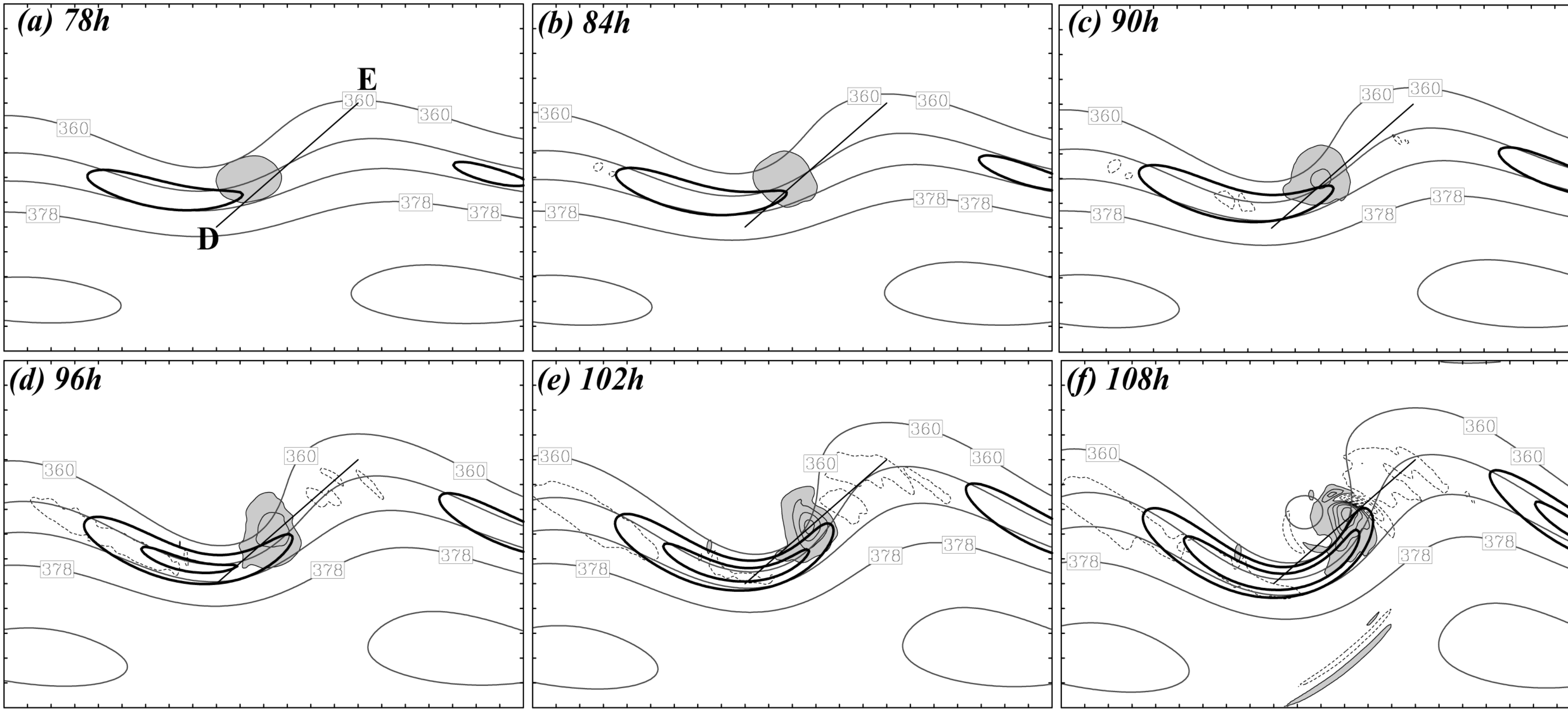
Thick lines: 13-km pressure, D=2hPa; thin lines: divergence, negative, dashed; shaded: 8-km jet>55m/s

(Zhang 2004 JAS)

w imbalance diagnosed with nonlinear balance equat

(Gray: pressure, every 5hPa; Bold: winds>55m/s; Thin: ΔNBE, positive, solid & shaded, negative, dashed)

$$\Delta NBE = 2J(u,v) + f\varsigma - \nabla^2\Phi$$



- Increasingly larger imbalance maximized at jet exit region, near strong tropopause fold
- Gravity waves are continuously initiated downstream of the maximum imbalance
- Faster BW growth rate → higher frequency and strong amplitude of gravity waves

(Zhang 2004 JAS; Wang and Zhang 2007 MWR)

Balance, Imbalance, Adjustment and Wave Emission

Balance: Physically reliable state which is free of static, inertial and symmetric instability as well as gravity waves (Hoskins et al. 1985)

Geostrophic balance (Ro<<1) vs. Nonlinear balance (Ro<=1)

Imbalance: The extent away from the balance state

Geostrophic adjustment: The process leads the flow from imbalance to (geostrophic) balance through radiating gravity waves; typically treated as an initial value problem (e.g., Rossby 1938; Blumen 1972)

What if nonlinear balance is the most appropriate balance and what if the flow is continuously producing balance while being adjusted?

Hypothesis: Spontaneous Balance Adjustment

- ***Adjustment***: imbalance → gravity waves
- ***Balance adjustment***: generalization of geostrophic adjustment

  Geostrophic balance (Ro<<1) → **Nonlinear balance** (Ro<=1)
- ***Spontaneous balance adjustment***: flow can become increasingly unbalanced if production of imbalance by background baroclinic waves greater than reduction of imbalance due to wave emission
- ***Similarity to convective adjustment***: convection sustained due to destablization by background environment while CAPE is continuously released in a faster time scale

(Zhang 2004 JAS)

A perturbation model linearized on nonlinear balanced state

(Plougonven and Zhang 2007 JAS; Wang and Zhang 2010 JAS; Wang, Zhang & Epifanio 2010 QJ)

- A linear disturbance model in a nonhydrostatic, compressible, Boussinesq flow on f plane

$$\partial_t \delta' + \overrightarrow{U_B} \nabla \delta' + \overrightarrow{u'} \nabla \bar{\delta} + \Delta \Phi' - f \cdot \varsigma' + [\ldots] = F_\delta$$

$$\partial_t \varsigma' + \overrightarrow{U_B} \nabla \varsigma' + f \cdot \delta' + [\ldots] = F_\varsigma$$

$$\partial_t \theta' + \overrightarrow{U_B} \nabla \theta + w' \frac{\partial \bar{\Theta}}{\partial z} + [\ldots] = F_\theta$$

Forcing

$$(\partial_t + \overrightarrow{U_B} \nabla) w' = -\Phi'_z + \frac{g}{\bar{\bar{\Theta}}} \theta' \qquad (\Phi'_z = \frac{g}{\bar{\bar{\Theta}}} \theta')$$

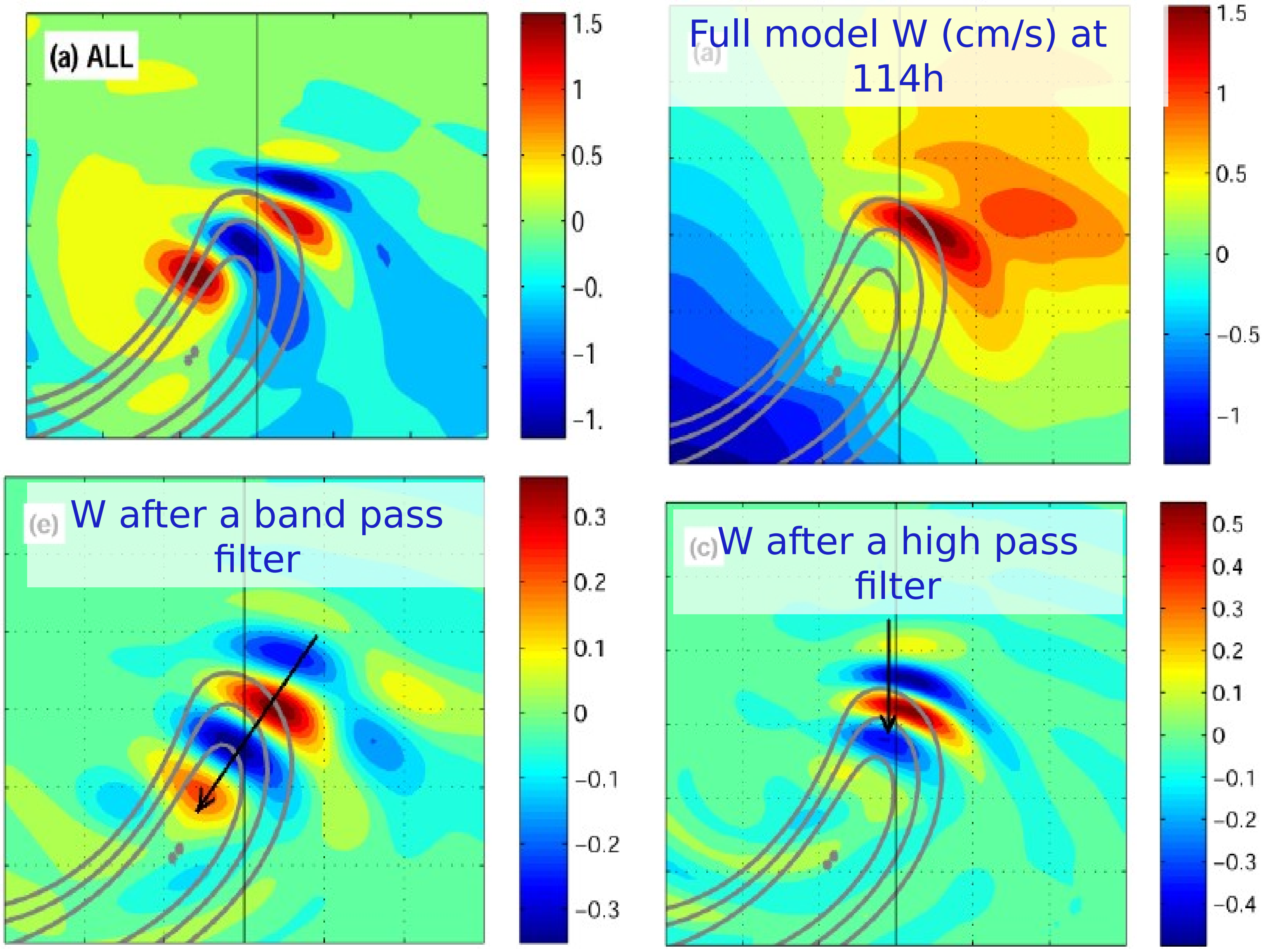
$$(\partial_t + \overrightarrow{U_B} \nabla) \Phi' + \delta' + \partial_z w' = 0 \qquad (\partial_x u' + \partial_y v' + \partial_z w' = 0)$$

$$L(w') = G_\delta + G_\varsigma + G_\theta$$

$$G_\delta = D_\gamma \frac{\partial F_\delta}{\partial z} \qquad G_\varsigma = f \frac{\partial F_\varsigma}{\partial z} \qquad G_\theta = -\frac{g}{\bar{\bar{\Theta}}} \Delta F_\theta$$

G_δ, G_θ and G_ζ are *normalized forcing terms* and can be compared directly

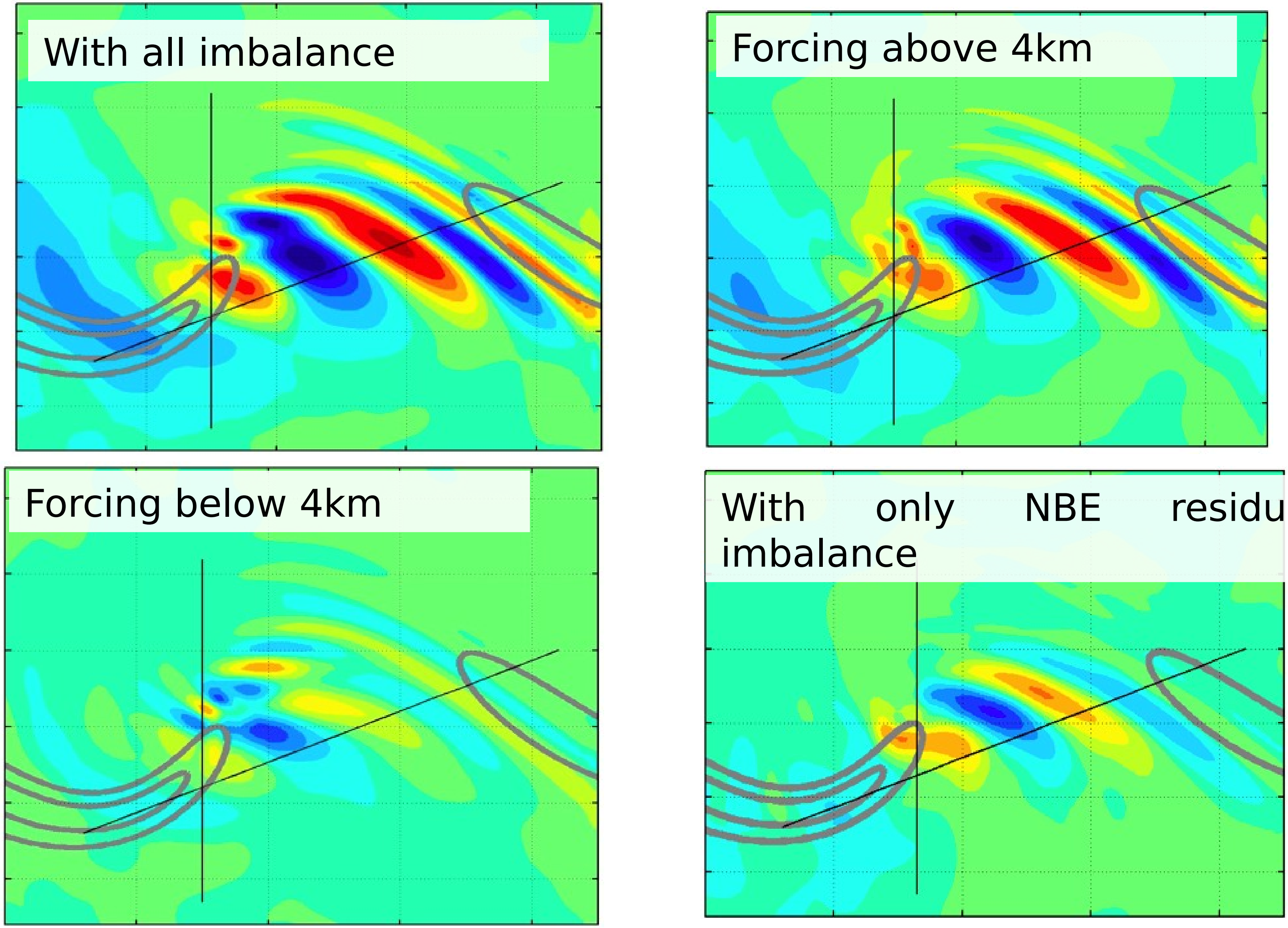
Linearly forced waves versus full nonlinear model simulated waves



Gravity wave response to imbalance forcing in the dry jet

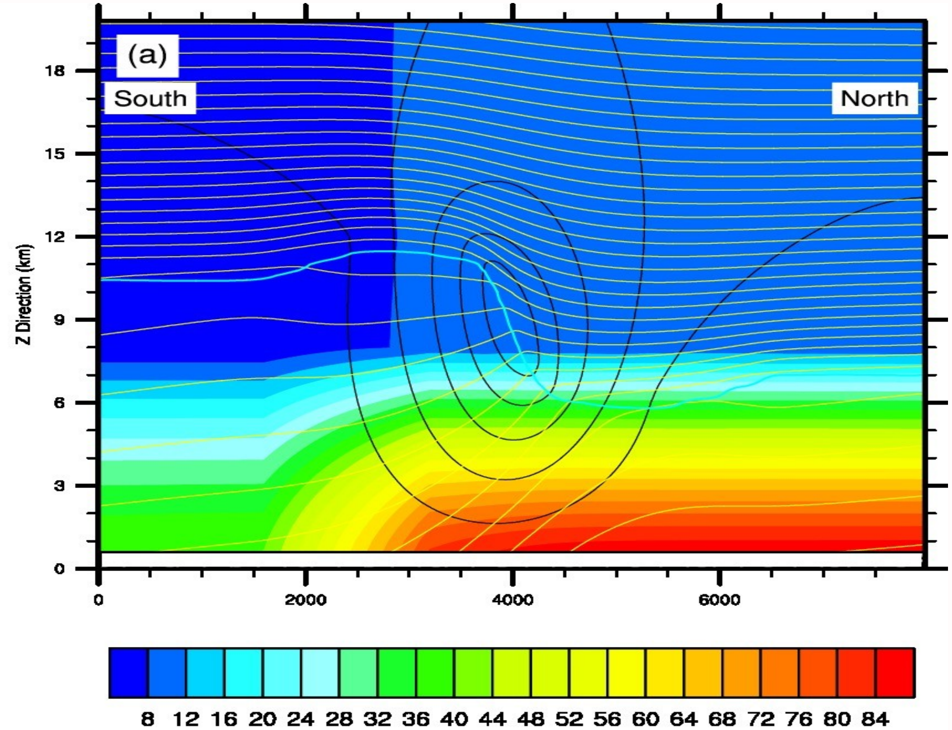
Linear numerical model solution verification

(Wang and Zhang 2010 JAS; Zhang and Wang, in preparation)

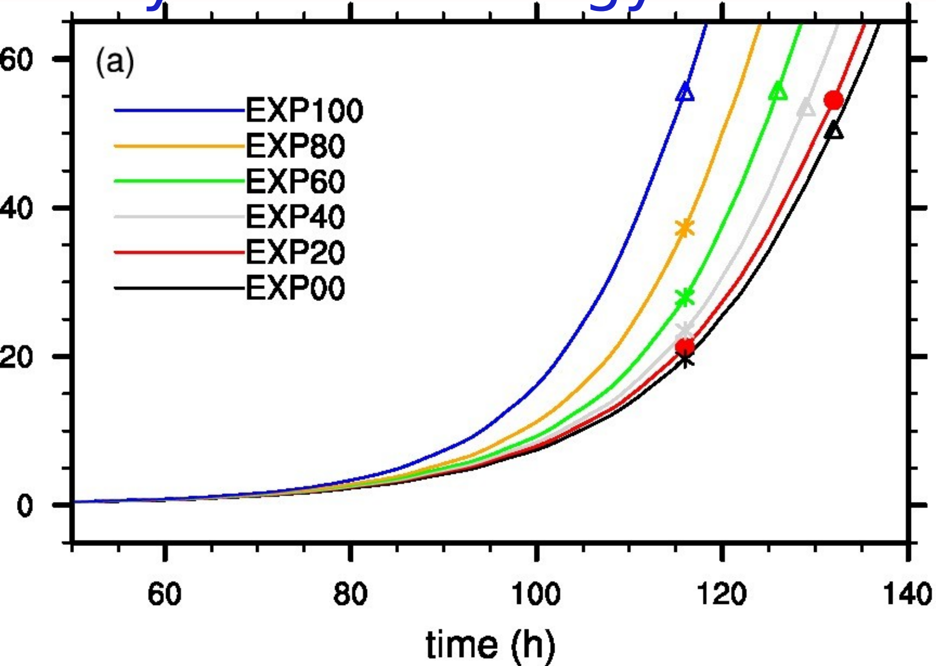


Gravity Waves from Moist Baroclinic Jets

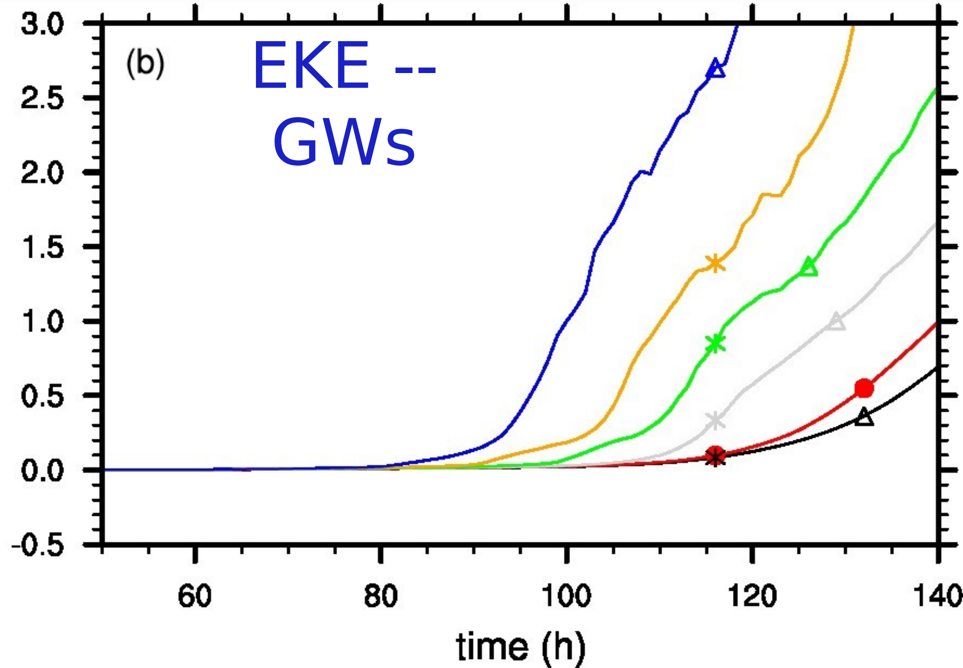
(Wei and Zhang 2014 JAS, Wei and Zhang 2015 JAMES)



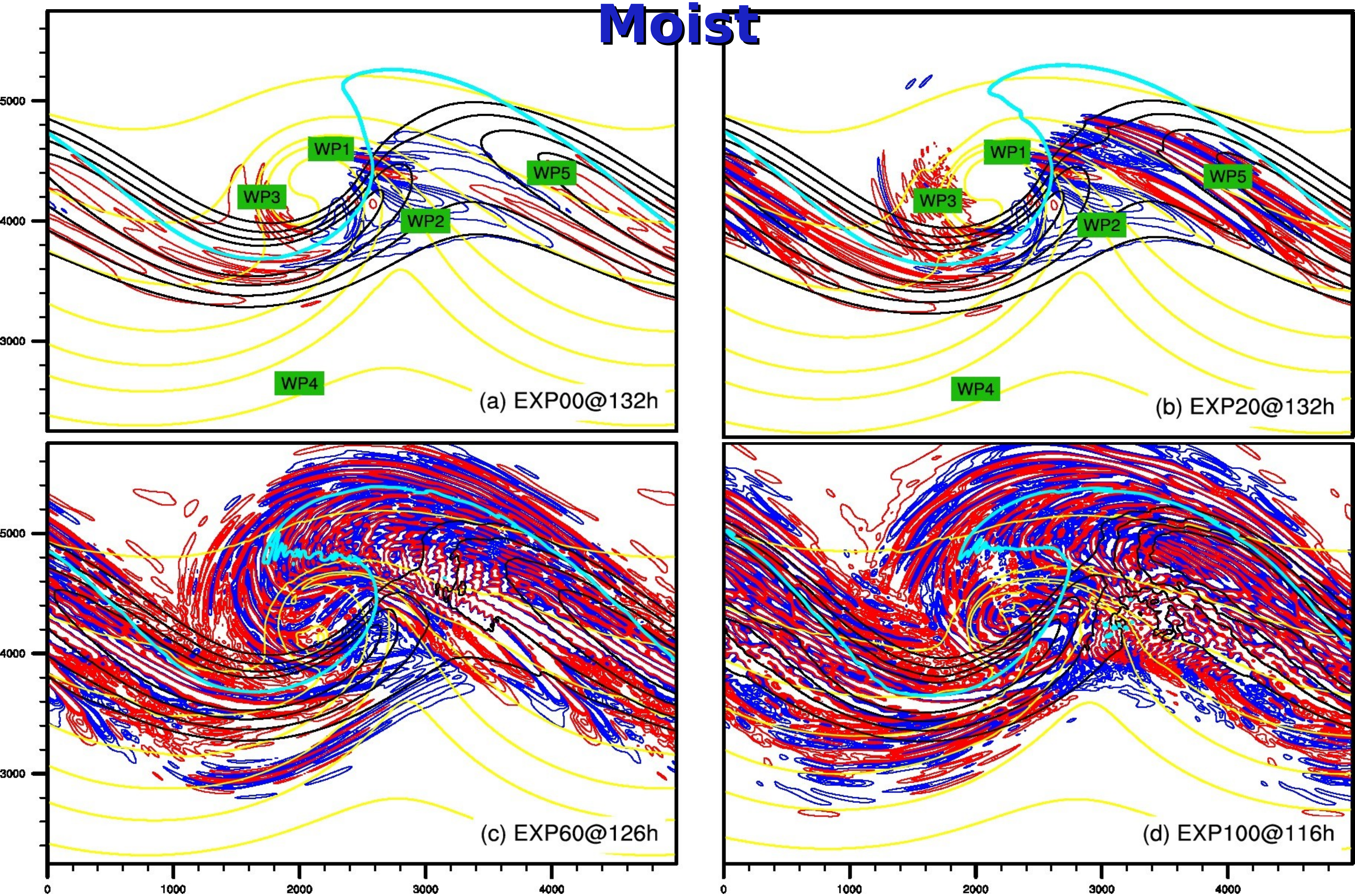
Eddy Kinetic Energy -- BWs



EKE -- GWs

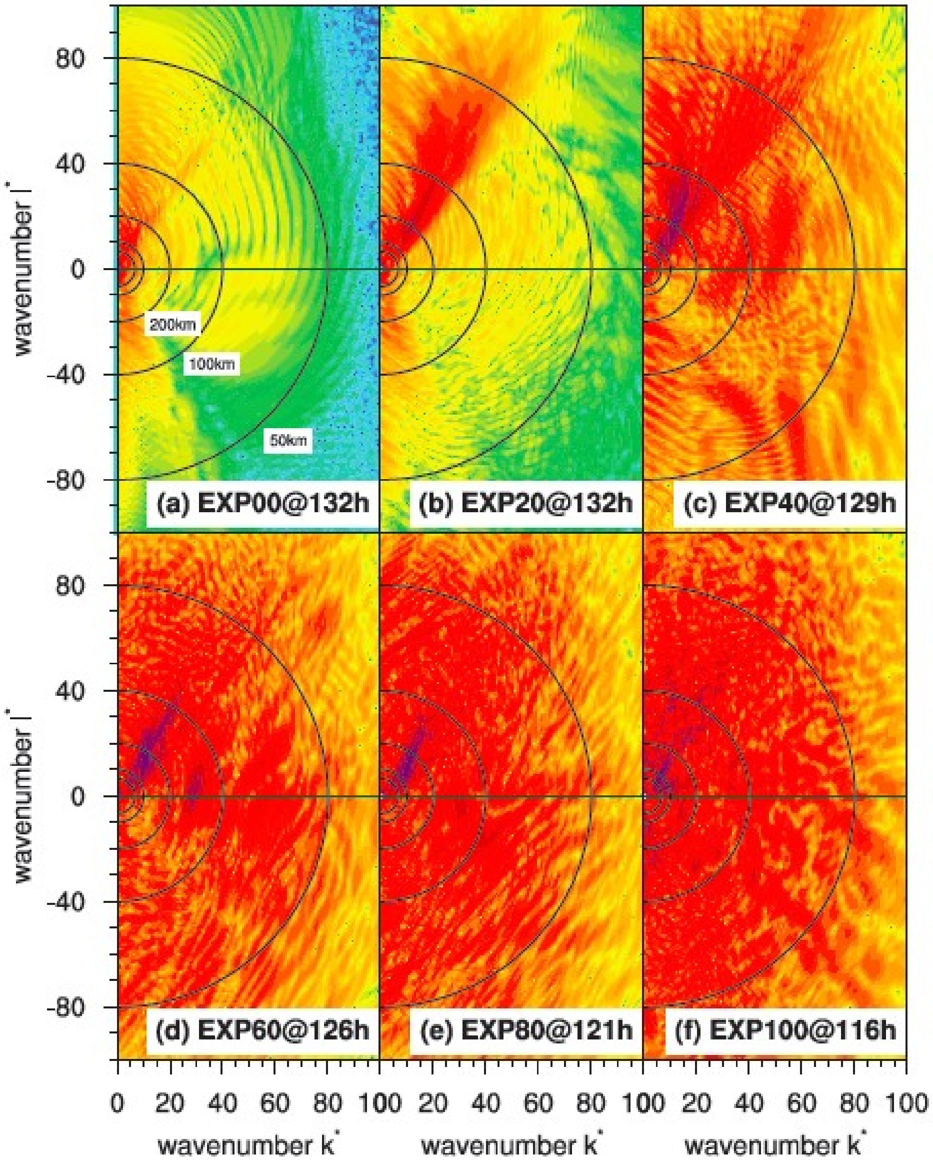


Gravity Waves in Baroclinic Jets: Dry vs. Moist



(Wei and Zhang 2014 JAS; 2015 JAMES)

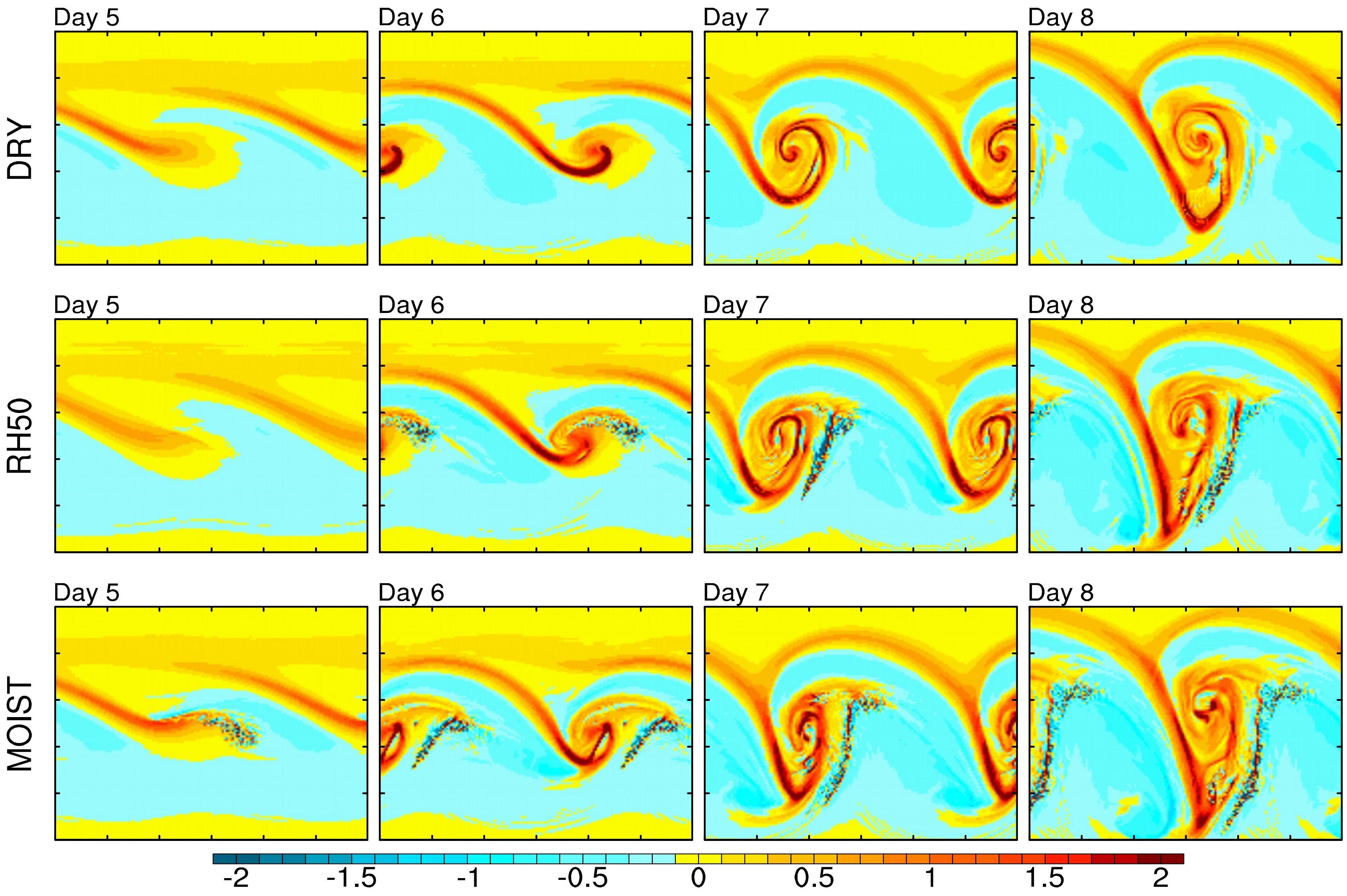
Gravity Waves in Baroclinic Jets: Dry vs. Moist



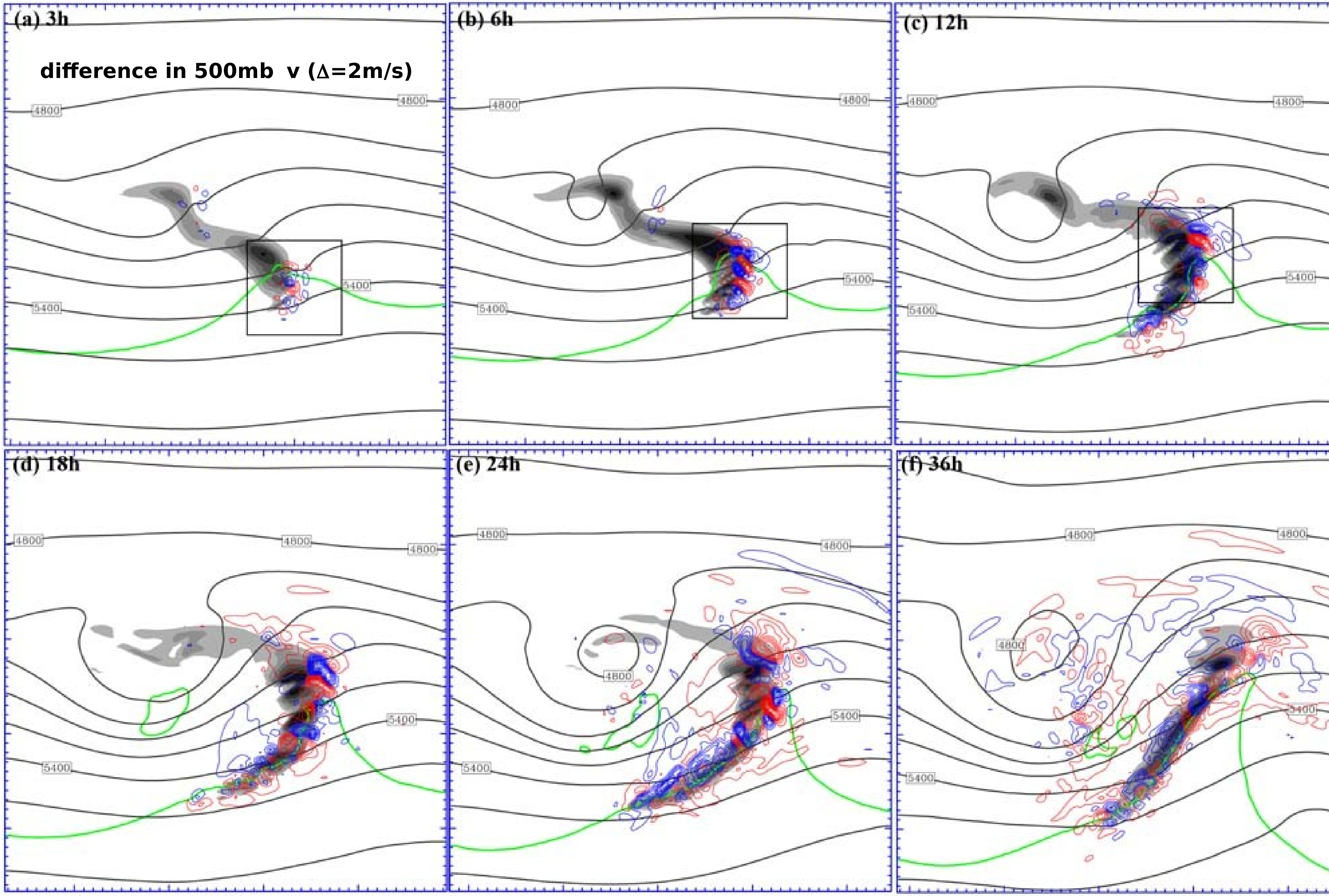
- For the short scales between 50 km and 200 km, the weak moist run of EXP20 has significant enhance of power along approximate 45 degree (relative to dry run).
- The distribution of power in strong convective cases (e.g., EXP80 and EXP100) appears to be more homogeneous along all angles (relative to EXP00 and EXP20)

(Wei, Zhang and Richter, 2016 JAS)

Dry versus Moist Baroclinic Waves: 500hPa Vorticity



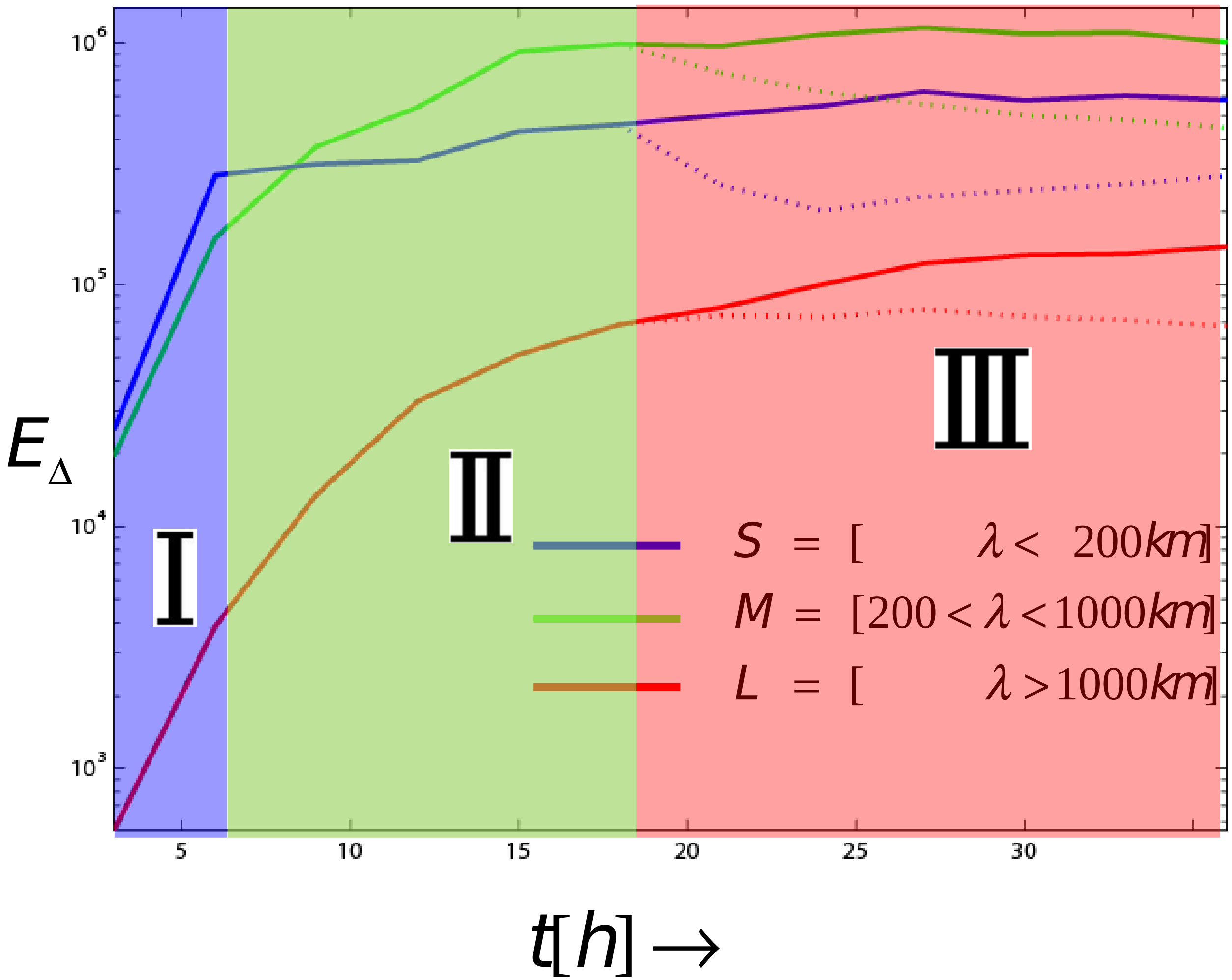
Mesoscale Predictability of Moist Baroclinic Waves



(Zhang et al. 2007, JAS)

A Multi-stage Conceptual Error Growth Model

Zhang et al. (2007 JAS)



Difference Energy of Band-Pass Filtered Fields

A Multistage Error Growth Model for Mesoscale Predictability

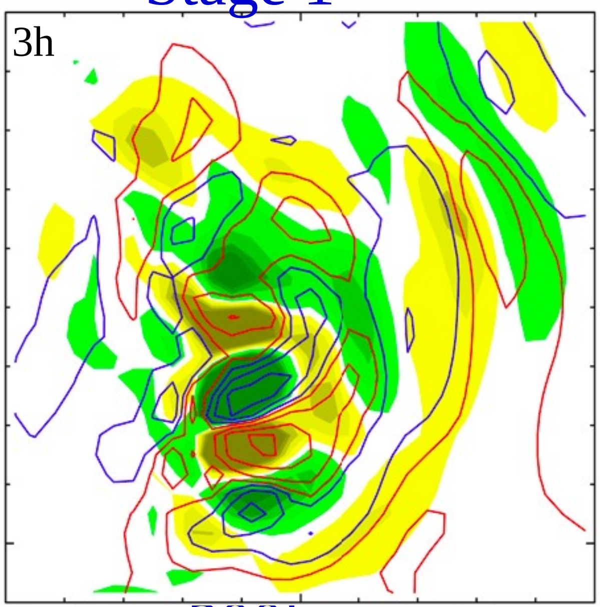
(Zhang et al. 2007, JAS)

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)*.

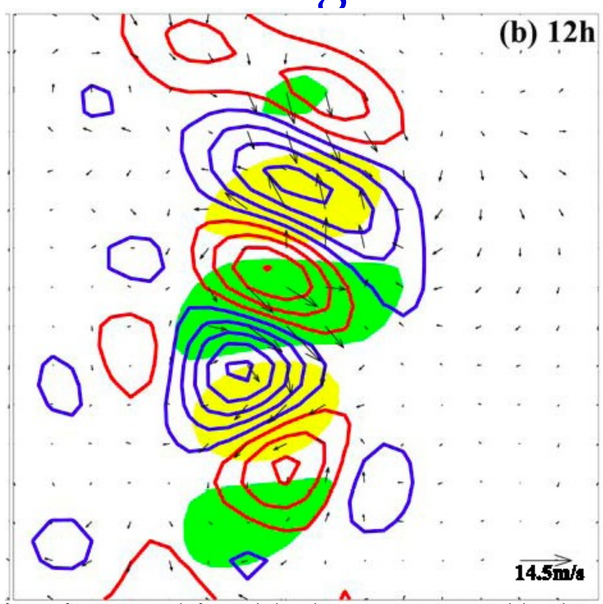
Stage 1



300km

T and w differences

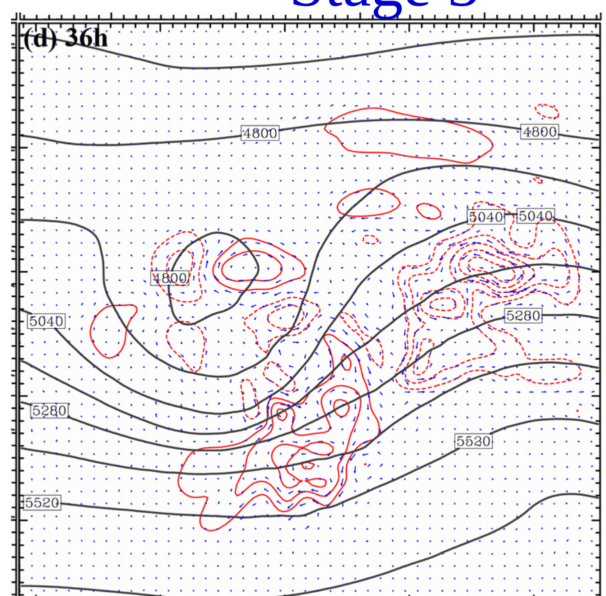
Stage 2



1200km

PV, Q and DIV differences

Stage 3

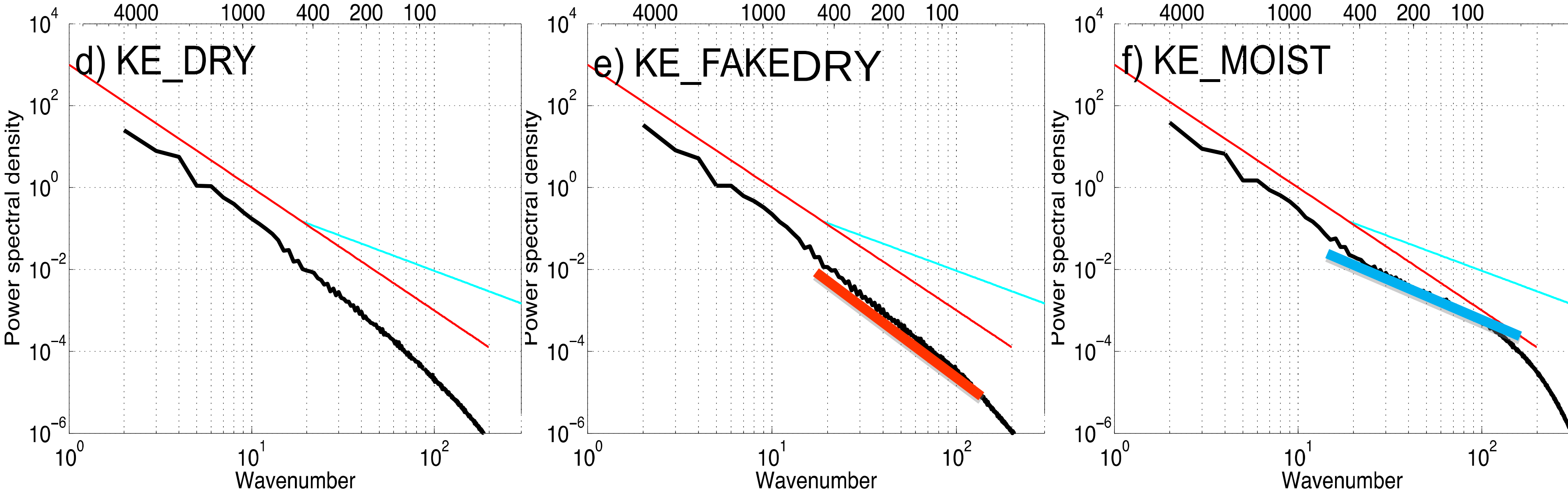


4200km

Pressure and V differences

Kinetic Energy Spectra with and without Moisture

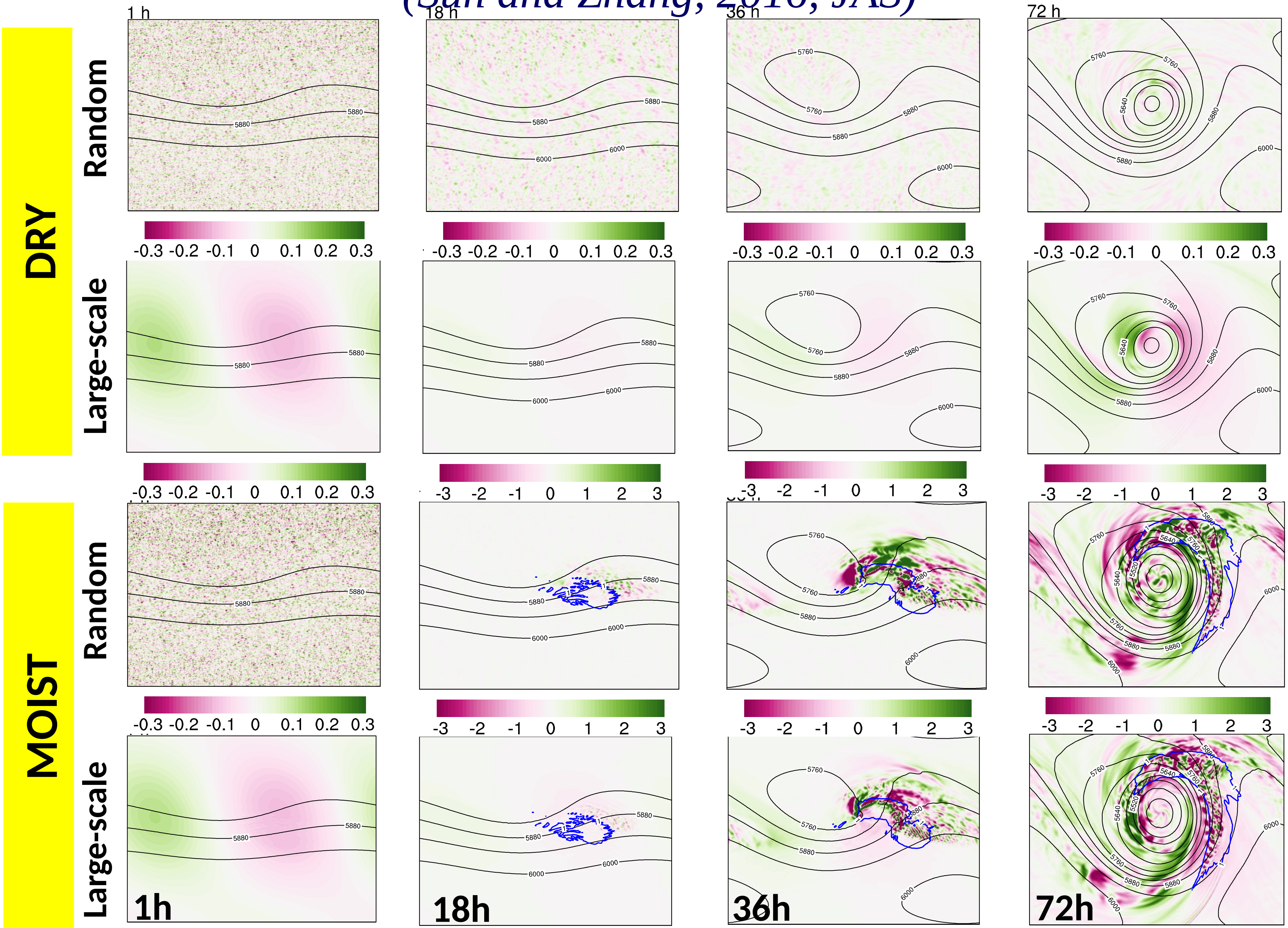
(Sun and Zhang 2016 JAS)



- Moist convection is the key to mesoscale predictability; dry and "fakedry" have -3 spectral slope, moist run has -5/3 at L<400km.
- Implication of spectral slopes on intrinisc predictability consistent with the recent study of Rotunno and Snyder (2008 JAS).
- Convection and gravity waves are key processes that lead to the flattened meso/small-scale spectral slope close to -5/3. HOW?

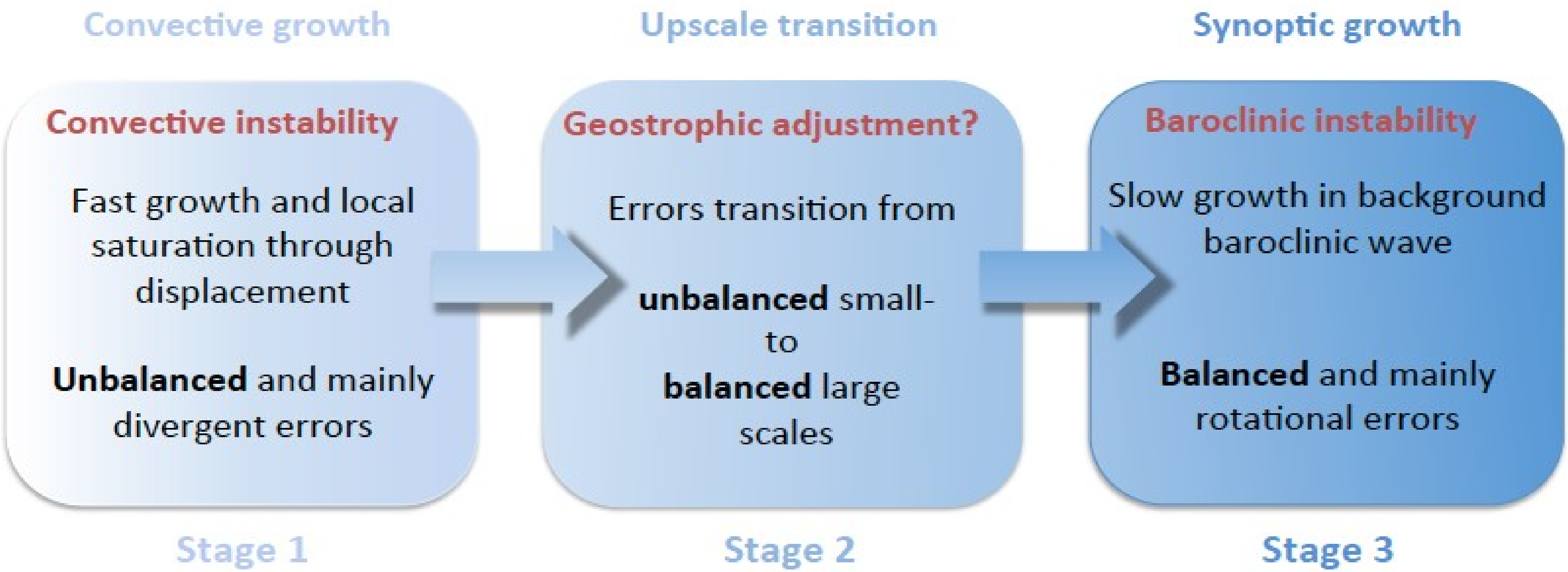
Predictability: Random vs. large-scale IC error, dry vs. moist BWs

(Sun and Zhang, 2016, JAS)



A Multistage Error Growth Model for Mesoscale Predictability

(Zhang et al. 2007, JAS)

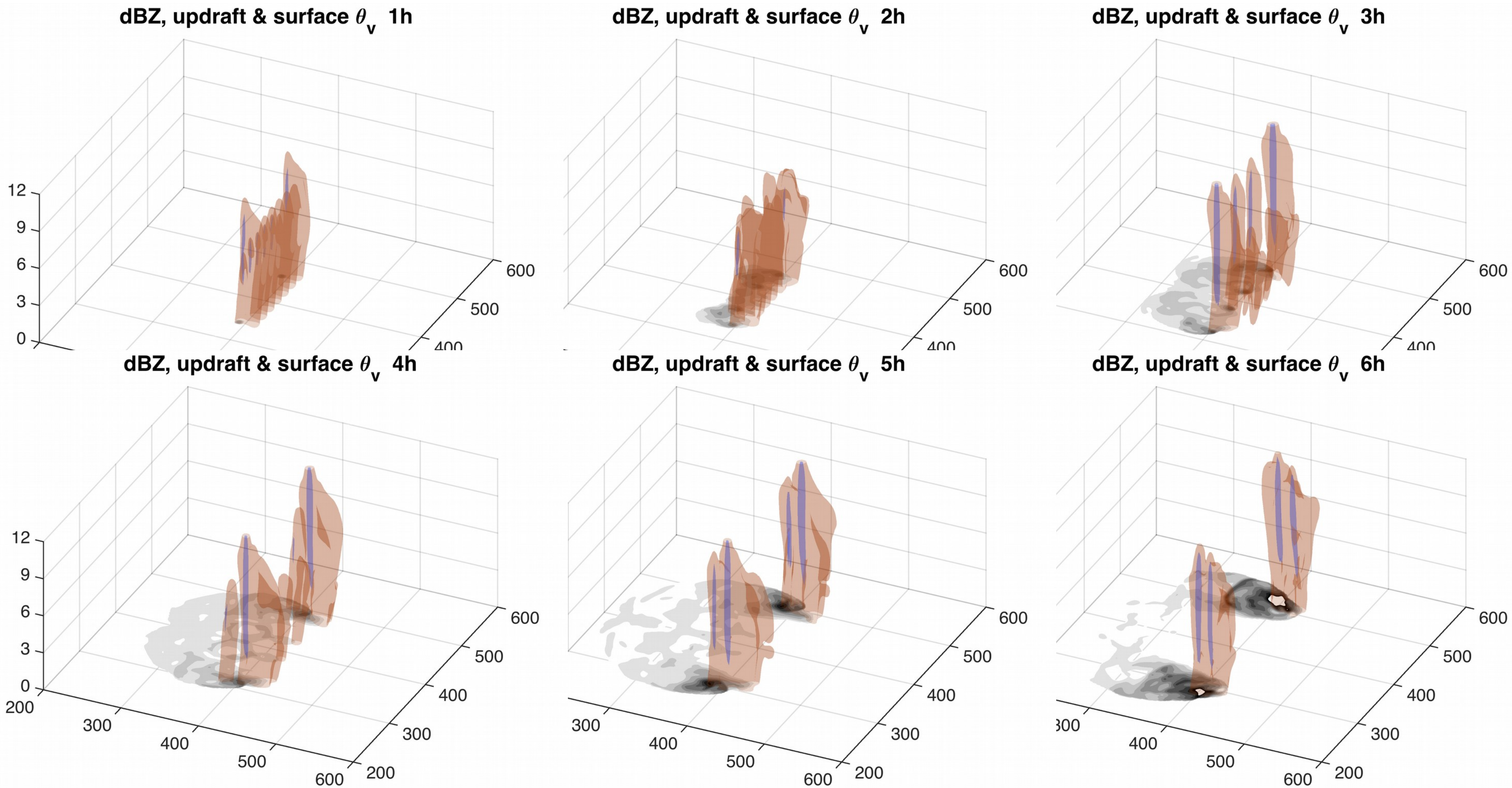


 (Lotte Bierdel, 2017 Ph.D. Dissertation)

and contains the full temporal evolution of all transient and balanced flow components. Characteristic spatial and temporal scales of the geostrophic adjustment mechanism are deduced and three diagnostics that can be used to identify this process in numerical simulations are proposed. These predictions are then tested in the framework of error growth experiments in highly idealized numerical simulations of a convective cloud field in a rotating environment. The error growth characteristics feature a high level of agreement with the analytical predictions. The results of this thesis suggest that the geostrophic adjustment following convective heating governs upscale error growth through the atmospheric mesoscales.

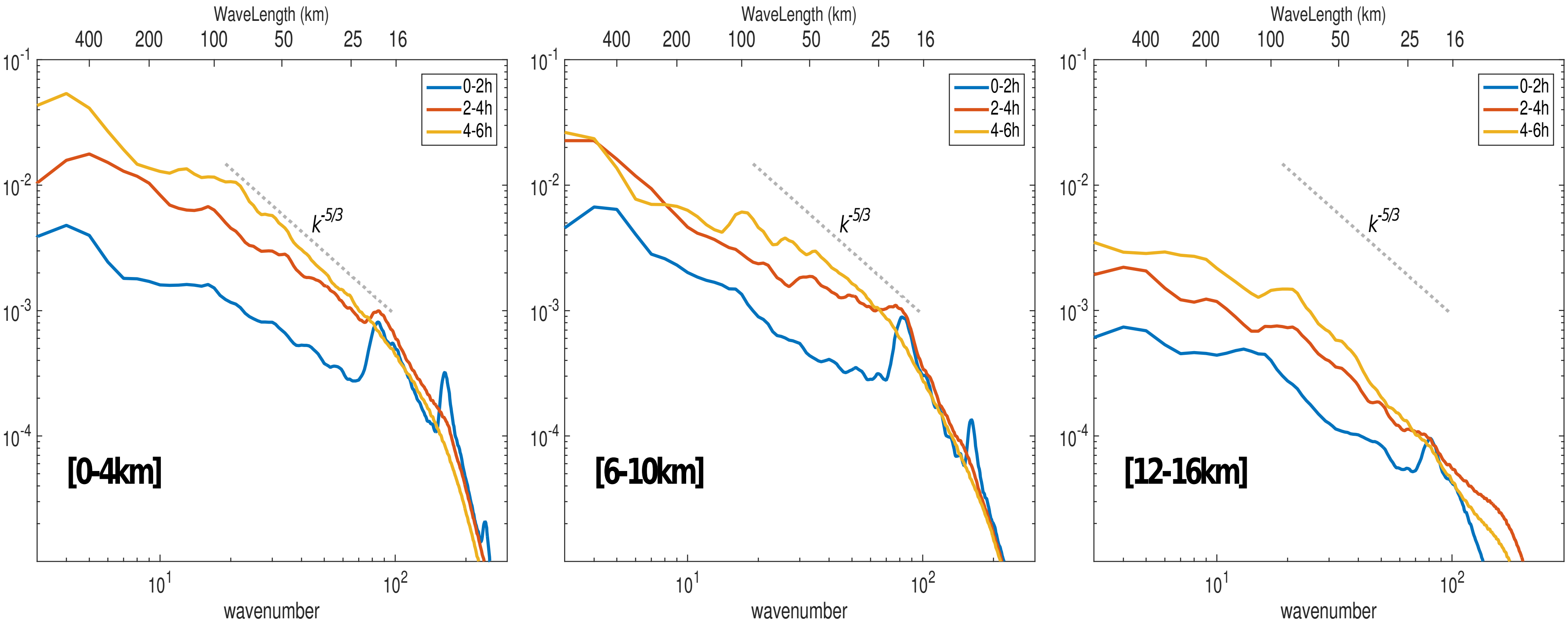
Why -5/3 mesoscale KE spectra with moist convection?

key physical processes: convection and gravity waves



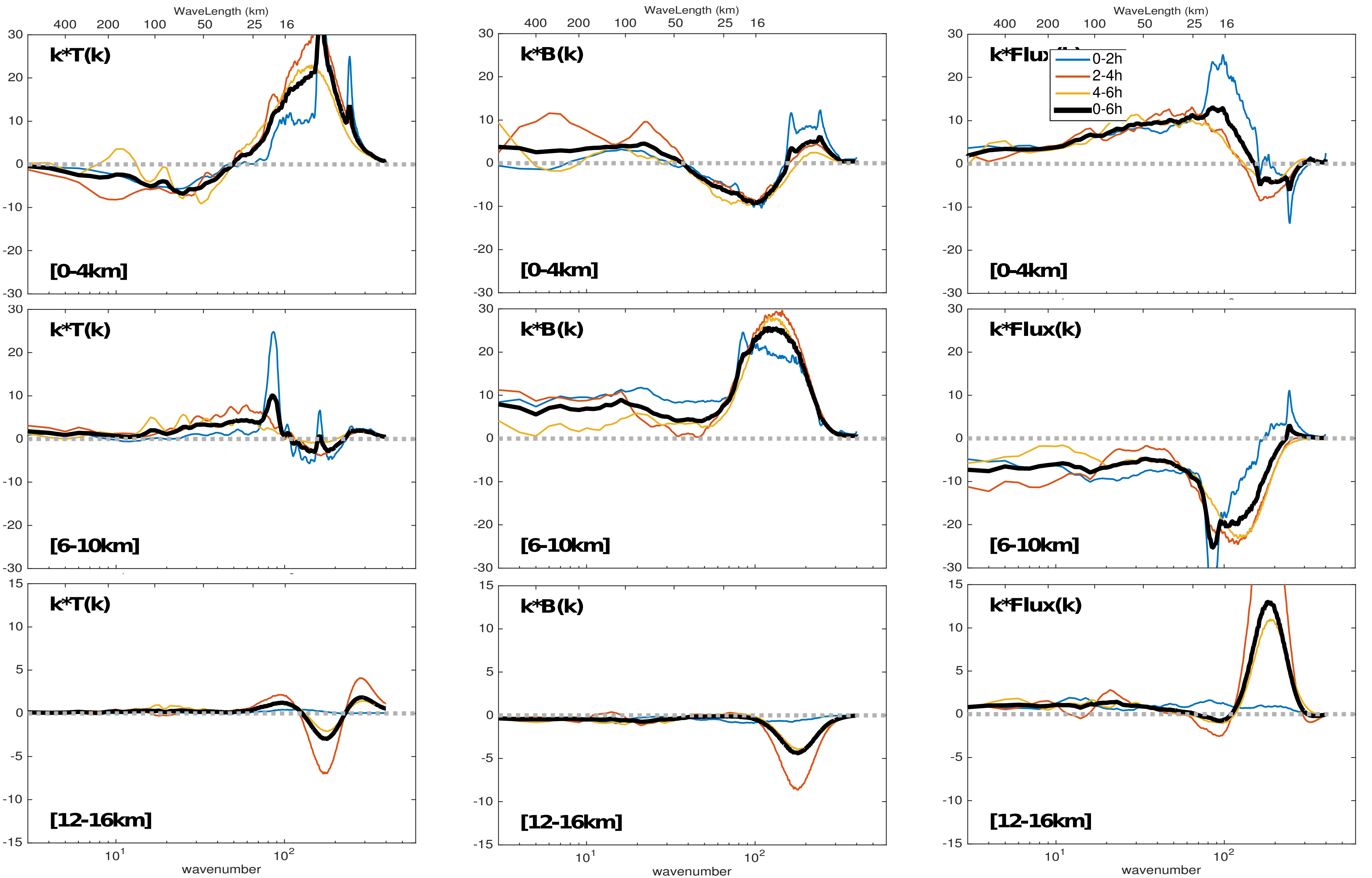
(Sun, Rotunno and Zhang 2017 JAS)

Kinetic Energy Spectra at different altitude



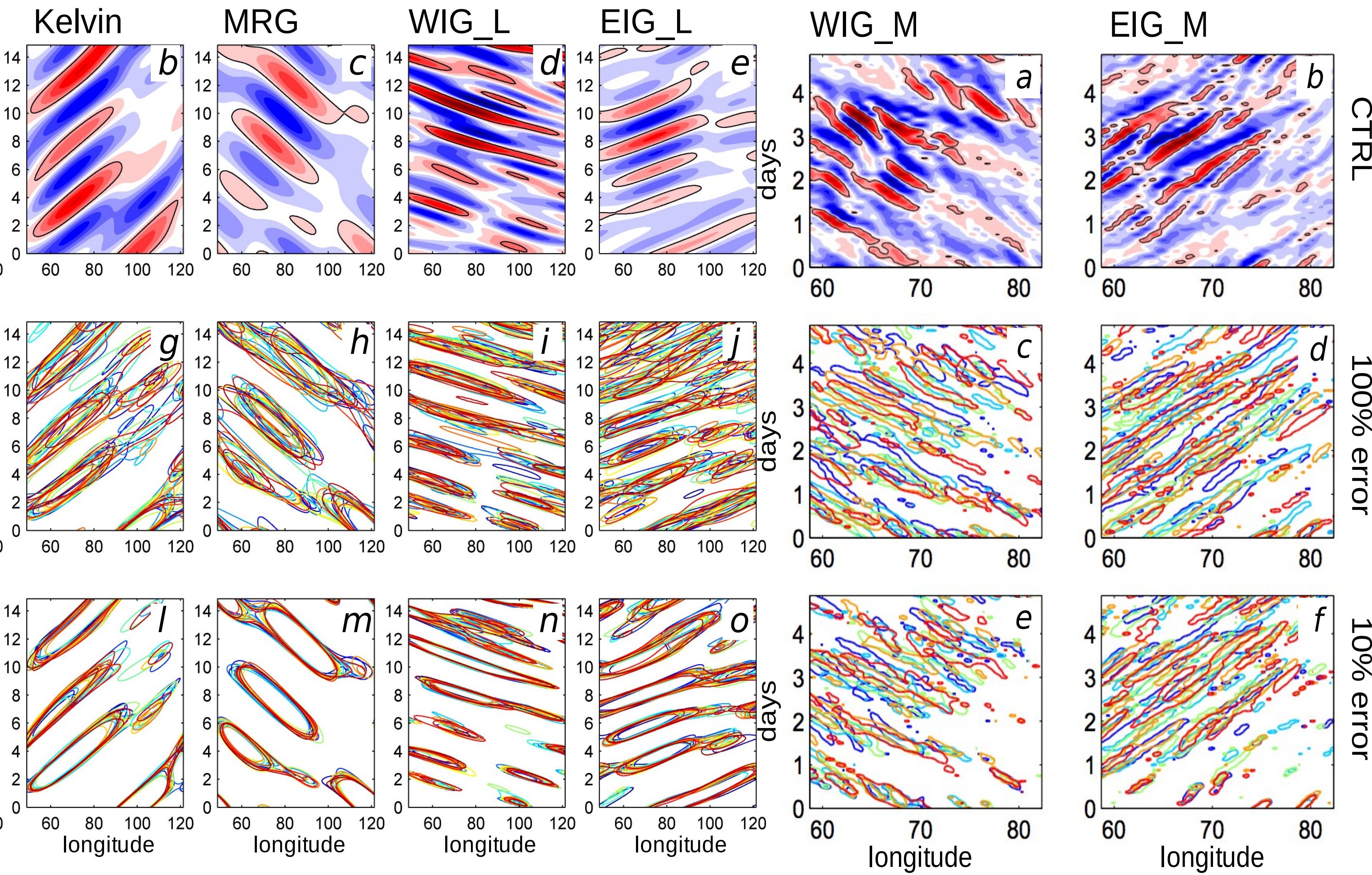
lower troposphere upper troposphere lower
stratosphere

KE Spectra budget across scales at different altitudes

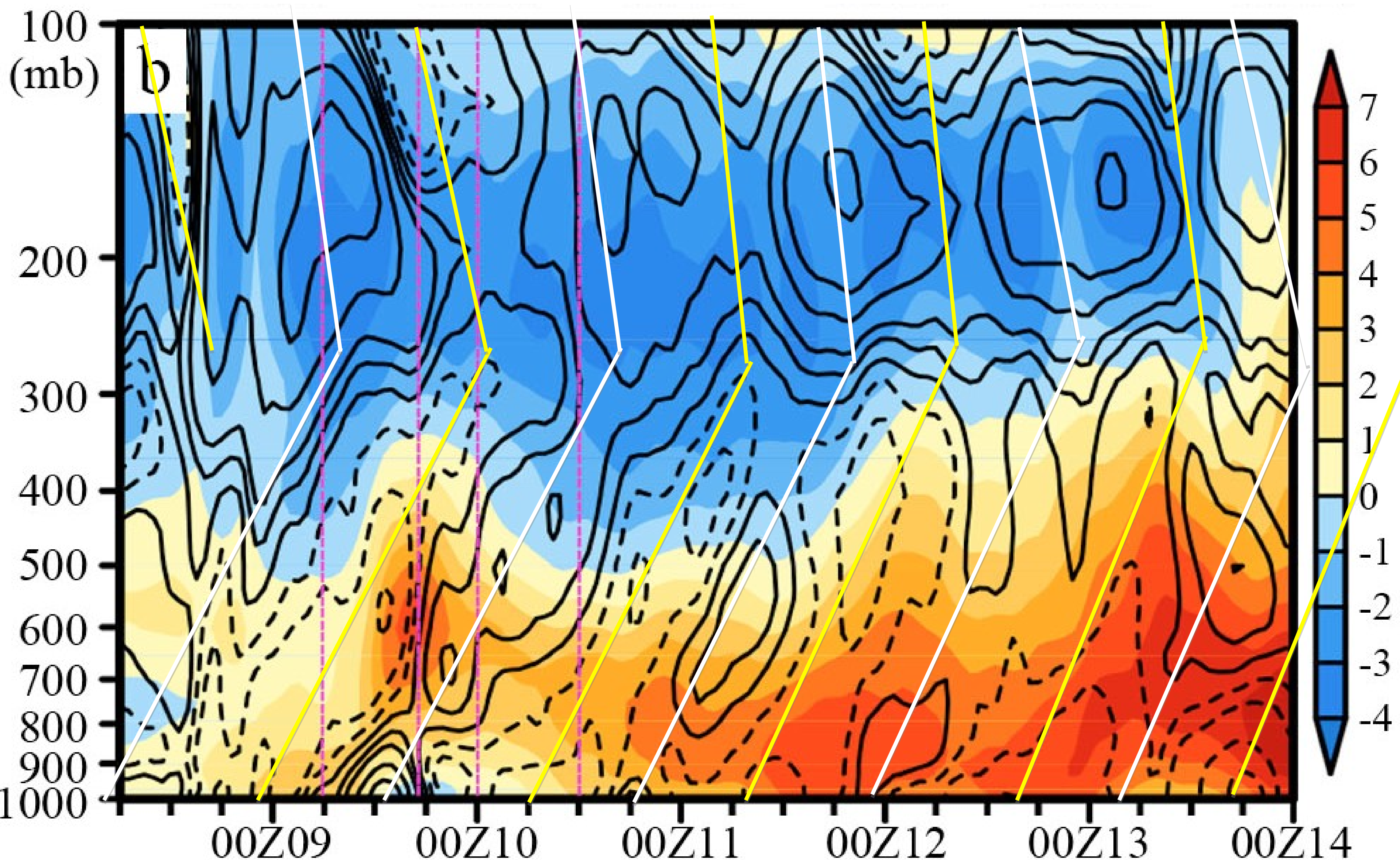


T(k): nonlinear transfer term across scales; B(k) buoyancy term; Flux(k): vertical transport

Predictability of convectively coupled waves in the tropics (Ying and Zhang 2017 JAS, minor revision)

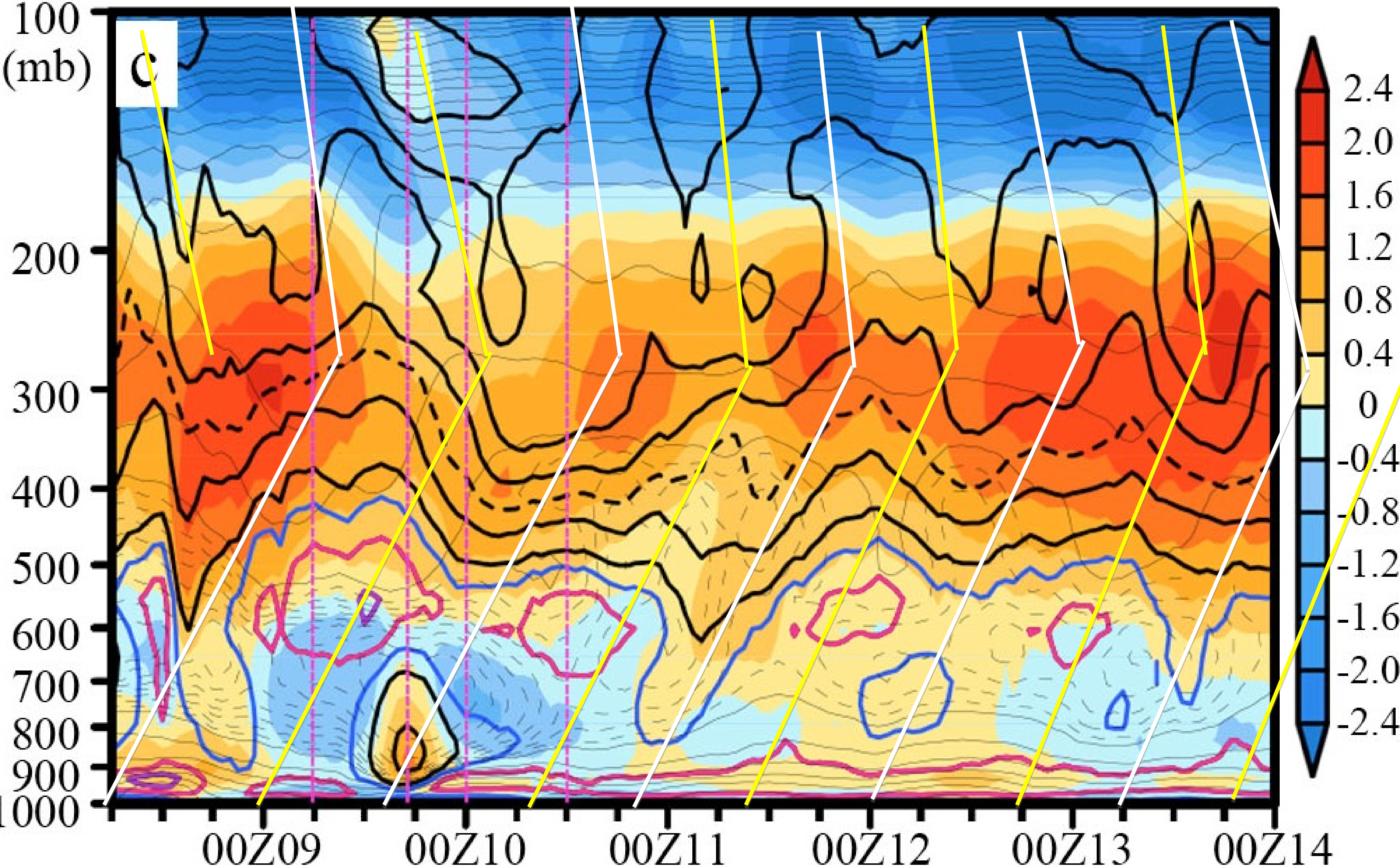


Gravity waves, diurnal cycle and tropical cyclogenesis



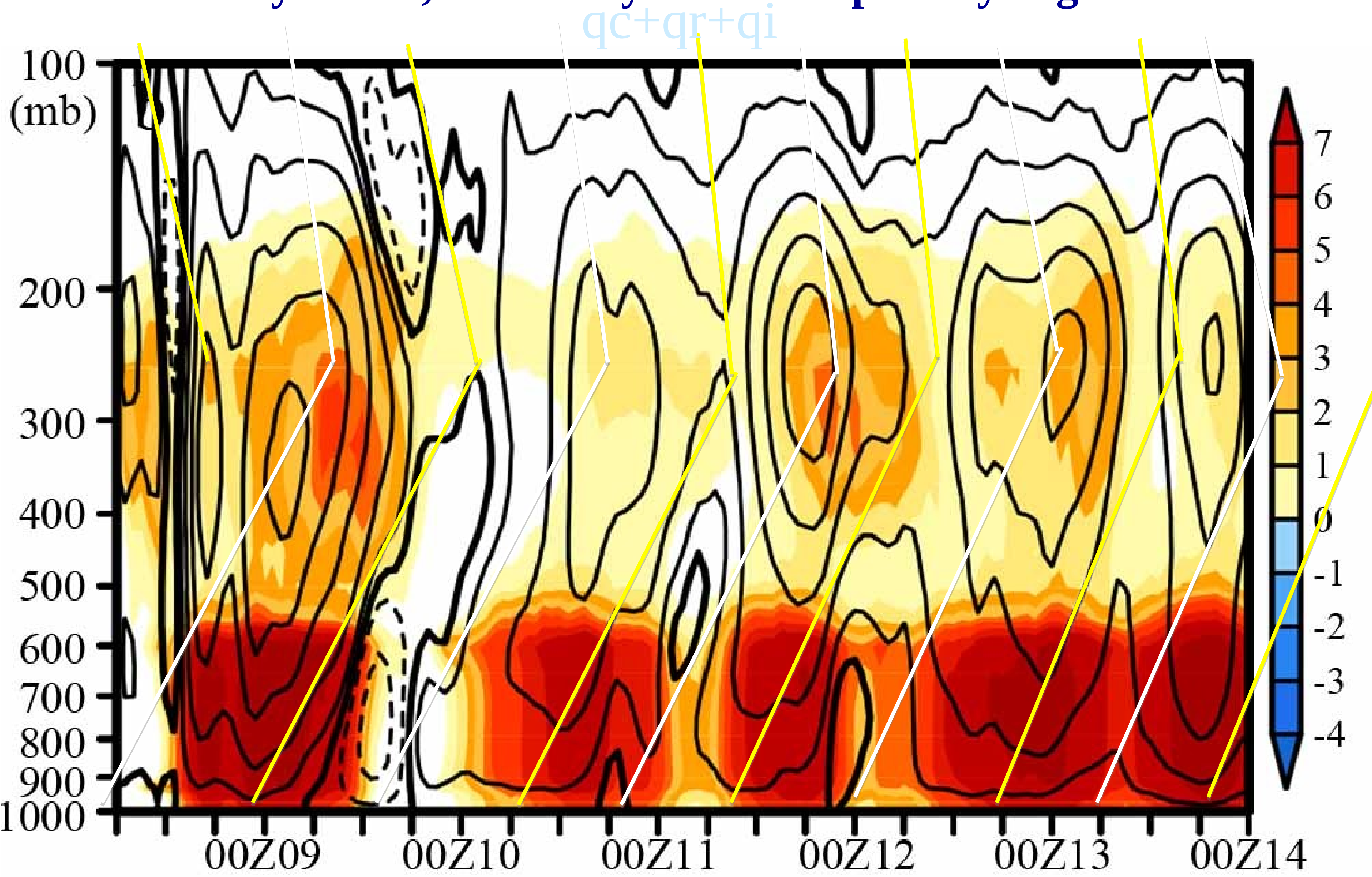
_(Melhauser and Zhang 2014 JAS; Tang and Zhang 2016 JAS; Fang and Zhang, in prep)

Gravity waves, diurnal cycle and tropical cyclogenesis



_(Melhauser and Zhang 2014 JAS; Tang and Zhang 2016 JAS; Fang and Zhang, in prep)

Gravity waves, diurnal cycle and tropical cyclogenesis



_(Melhauser and Zhang 2014 JAS; Tang and Zhang 2016 JAS; Fang and Zhang, in prep)

Concluding Remarks

- **Gravity waves are simulated to originate from jet streak exit region during idealized baroclinic life cycles, and in real weather, w/ and w/o moisture**
- **These gravity waves are hypothesized to be generated through *spontaneous balance adjustment* (as a generalization of geostrophic adjustment) in which imbalance continuously produced by large-scale flows are spontaneously adjusted through radiating gravity waves**
- **Inclusion of moist convection add complexity to the jet-front gravity waves but the dry dynamics appears to be essential in selecting the wave modes while fundamentally altering the atmospheric energy spectrum slope**

http://rammb.cira.colostate.edu/ramsdis/online/loop.asp?data_folder=loop_of_the_day/himawari/20170731000000&number_of_images_to_display=300&loop_speed_ms=80

- **Balance adjustment, gravity waves coupled with moist convection may play an important role in limiting the predictability of multiscale weather**

Full review at Plougoven and Zhang (2014, Review of Geophysics)

http://rammb.cira.colostate.edu/ramsdis/online/loop.asp?data_folder=loop_of_the_day/himawari/20170731000000&number_of_images_to_display=300&loop_speed_ms=80

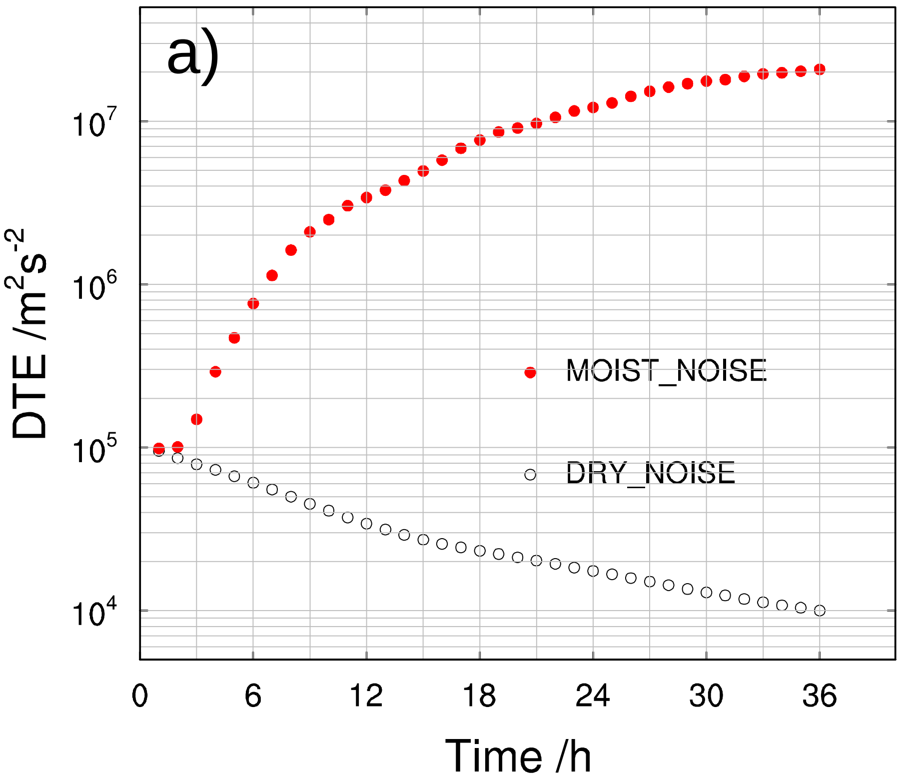
http://cimss.ssec.wisc.edu/goes/blog/wp-content/uploads/2017/07/170719_goes16_visible_spc_storm_reports_SD_severe_anim.mp4

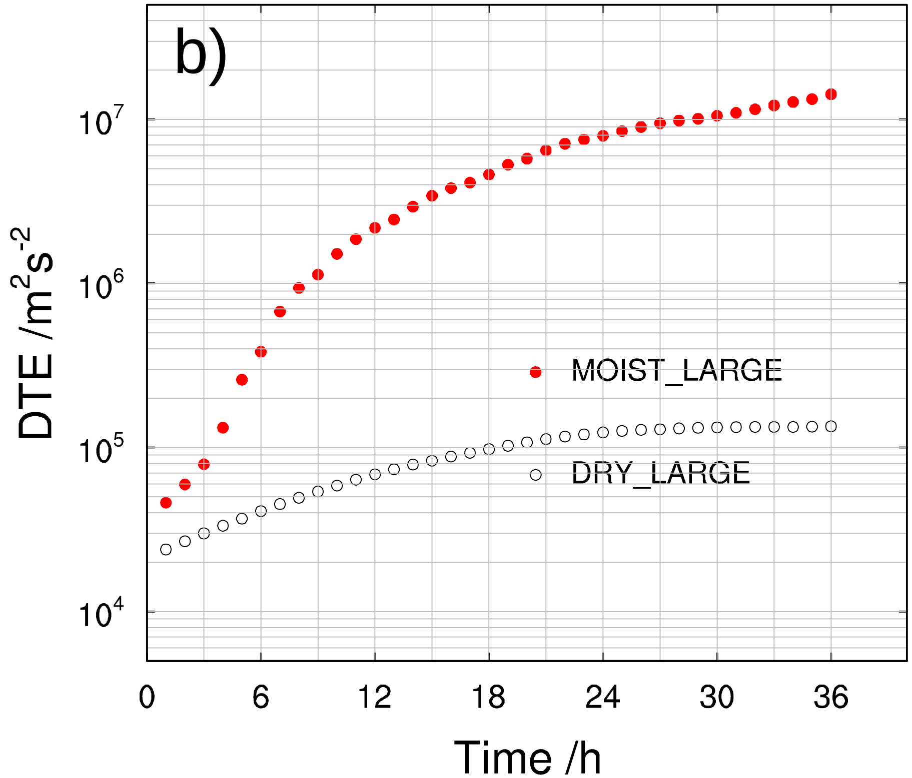
http://rammb-slider.cira.colostate.edu/?sat=himawari&sec=mesoscale_01&x=1000&y=1000&z=0&im=60&ts=2&st=0&et=0&speed=130&motion=loop&map=1&lat=0&p%5B0%5D=15&opacity%5B0%5D=1&hidden%5B0%5D=0&pause=0&slider=-1&hide_controls=0&mouse_draw=0&s=rammb-slider

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

(Sun and Zhang 2016 JAS)

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



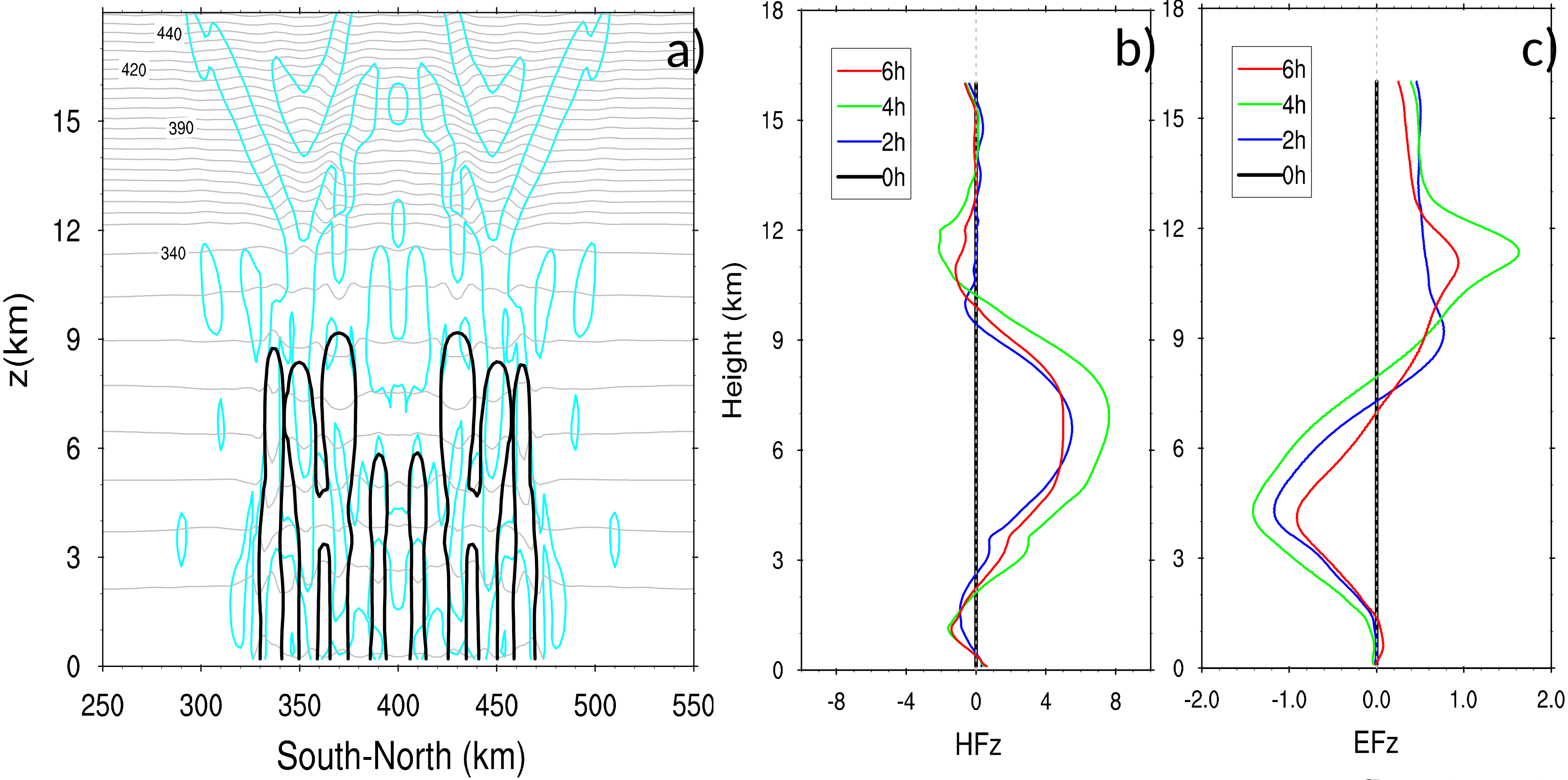


NOISE: As in Zhang et al. (2007), grid point Gaussian white noises of 0.2K, predominantly small scales

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

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

key physical processes: convection and gravity waves

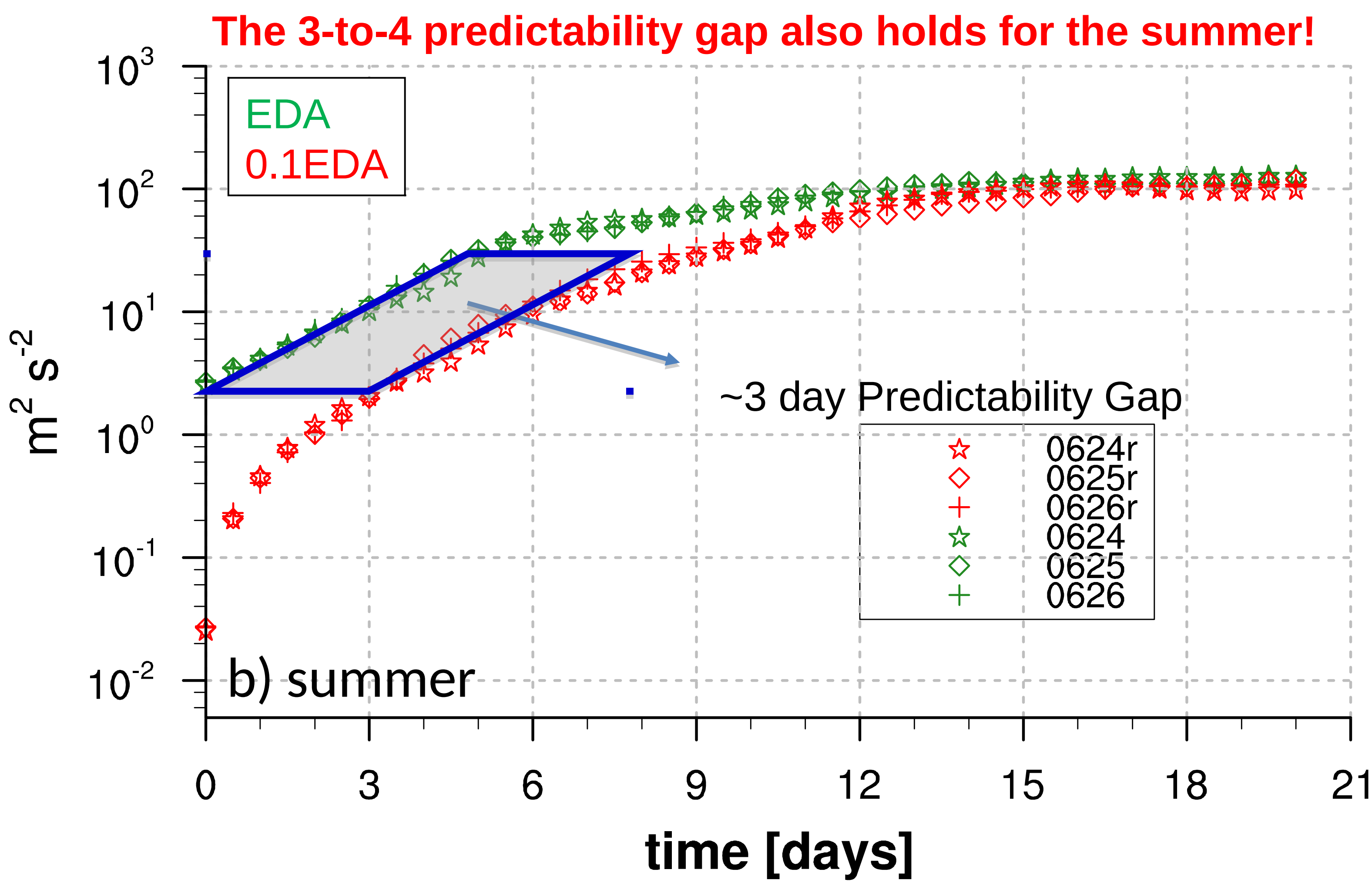


w > 0.1m/s, cyan; dbz > 25, black line; theta, gray

Heat flux (w'T')

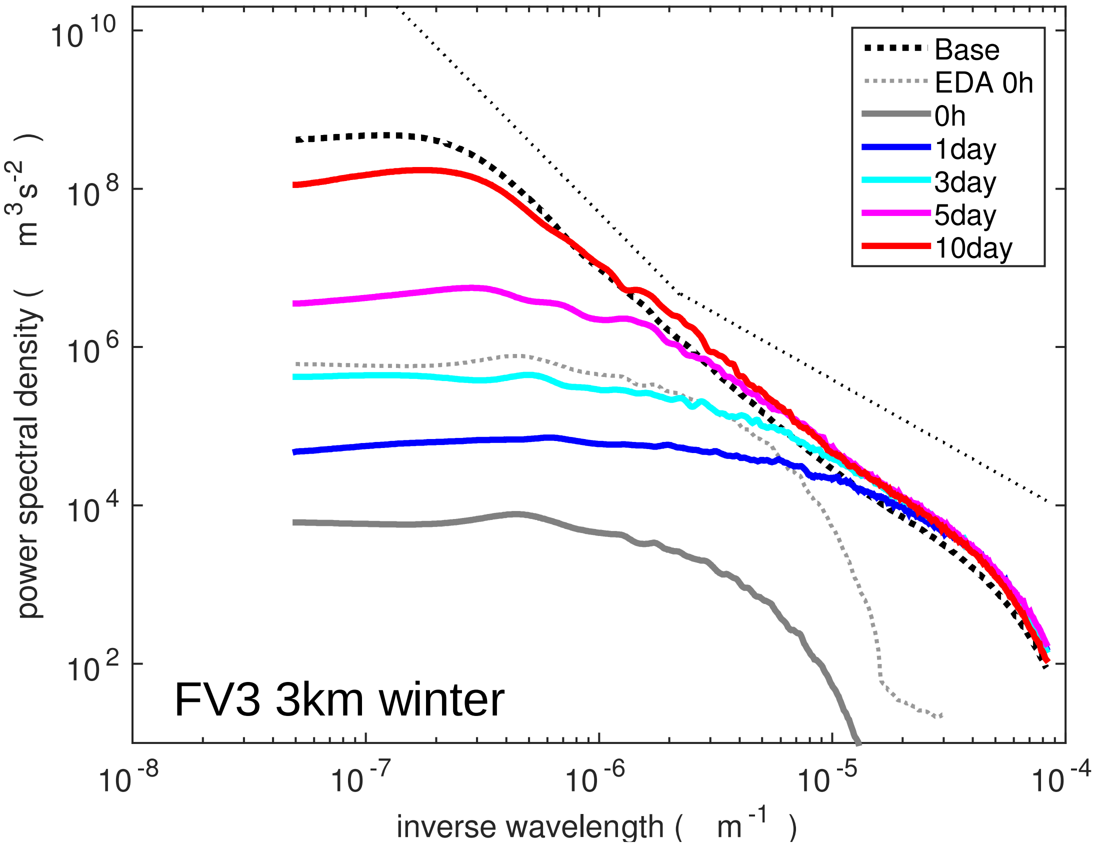
Energy flux (w'p')

(Sun, Rotunno and Zhang 2017 JAS)

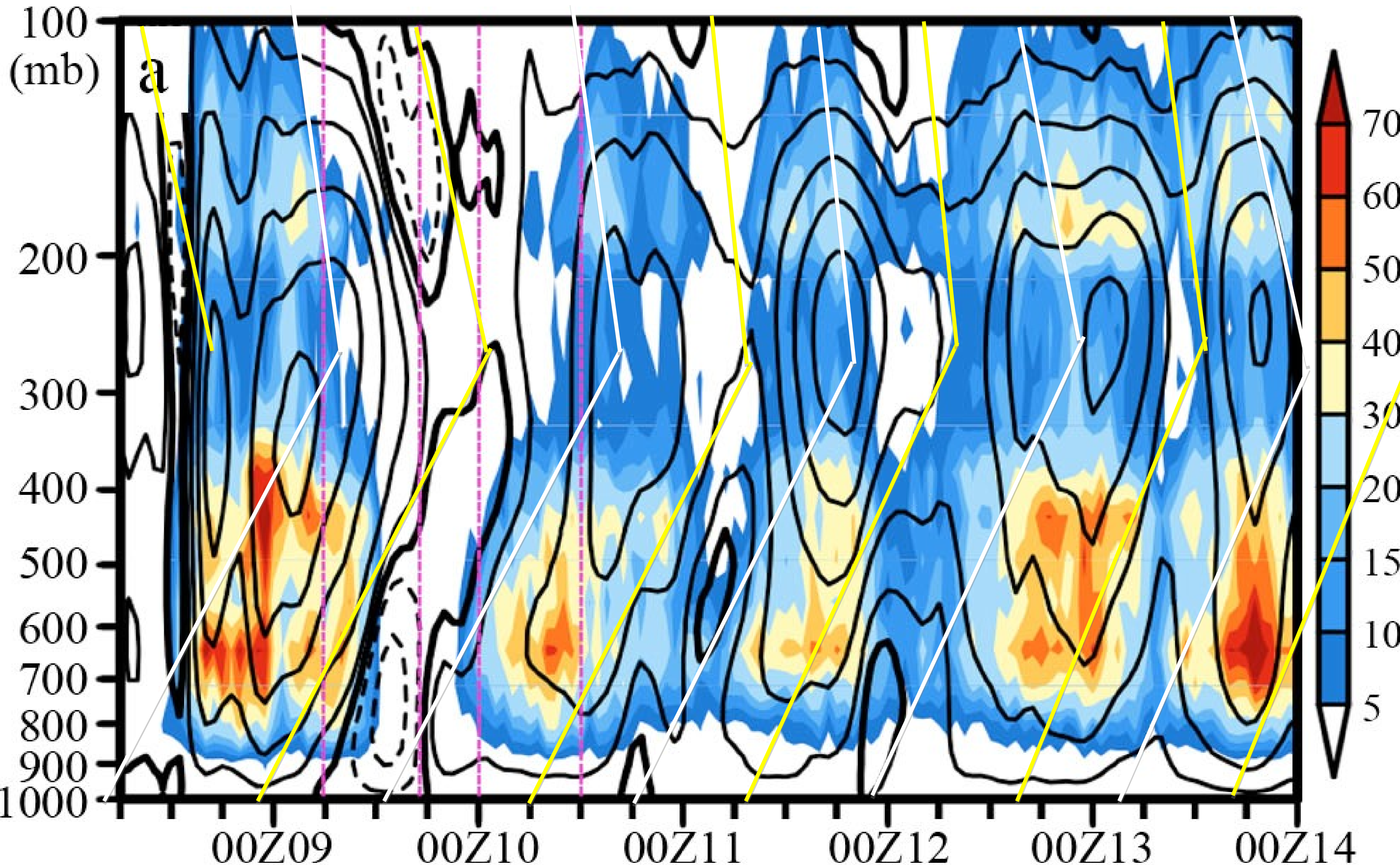


The 3-to-4 predictability gap also holds for the summer!
EDA
0.1EDA
~3 day Predictability Gap
0624r
0625r
0626r
0624
0625
0626
b) summer
$m^2 s^{-2}$
10^3
10^2
10^1
10^0
10^{-1}
10^{-2}
0
3
6
9
12
15
18
21
time [days]

Consistency in error growth from 9-km EC ensemble vs 3-km FV3 runs

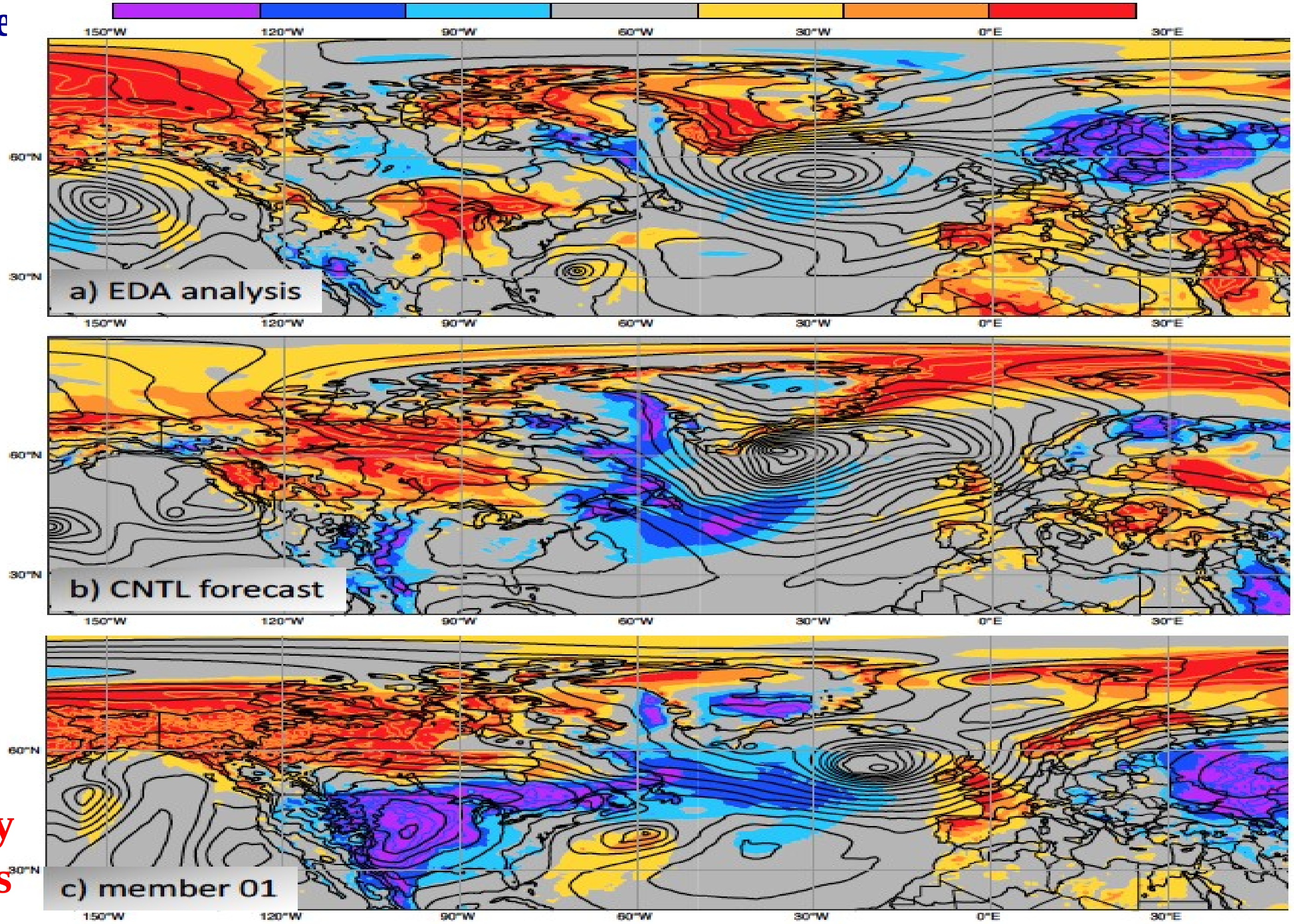


Gravity waves, diurnal cycle and tropical cyclogenesis



_(Melhauser and Zhang 2014 JAS; Tang and Zhang 2016 JAS; Fang and Zhang, in prep)

ECMWF operational analysis, CNTL forecast, and #1 of the 0.1EDA ensemble valid at 15-day lead time



Member #1 of the 0.1EDA ensemble 10% of IC uncertainty of current EC analysis

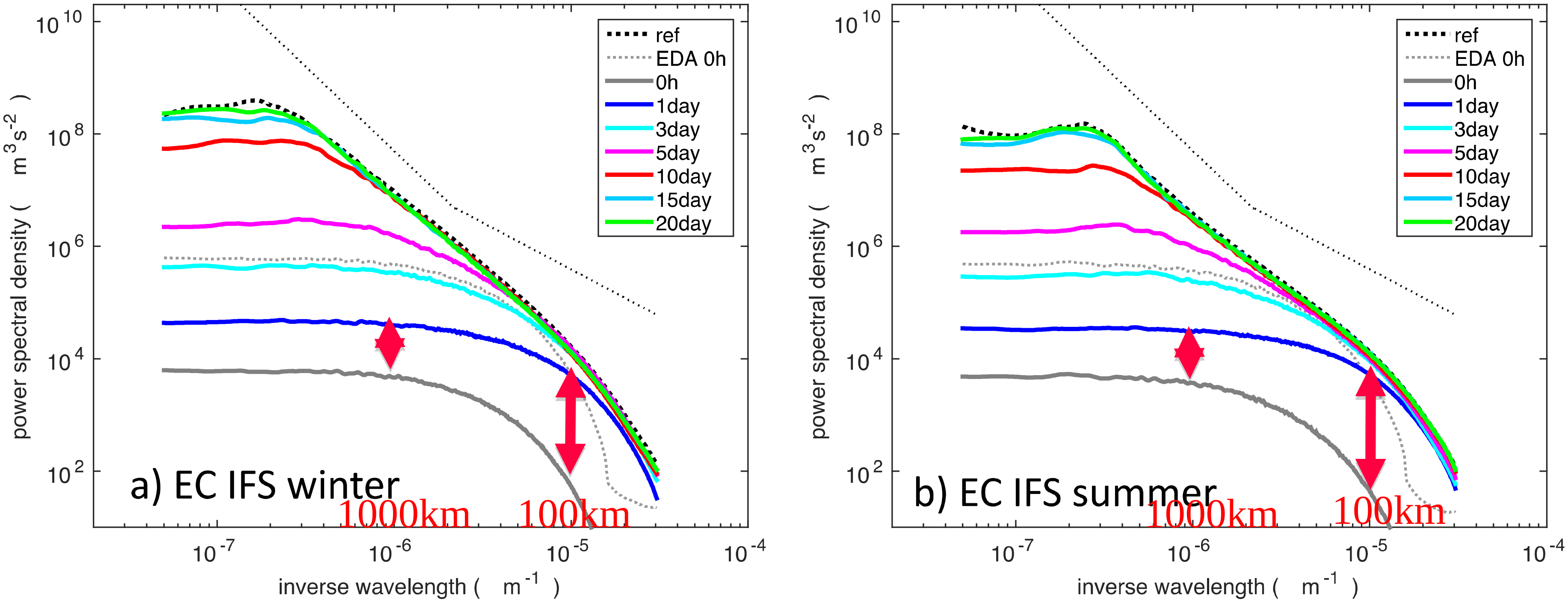
How much more can the current forecast lead time can be extended?

Reducing IC error to 70% of the current level will lead to a gain of ~1 day

Reducing IC error to 30% of the current level will lead to a gain of ~2 day

Reducing IC error to 10% of the current level will lead to a gain of ~3 days

(10% of the current level is unlikely achievable if not impossible)



Ultimate Limit of Multi-scale Weather Predictability?

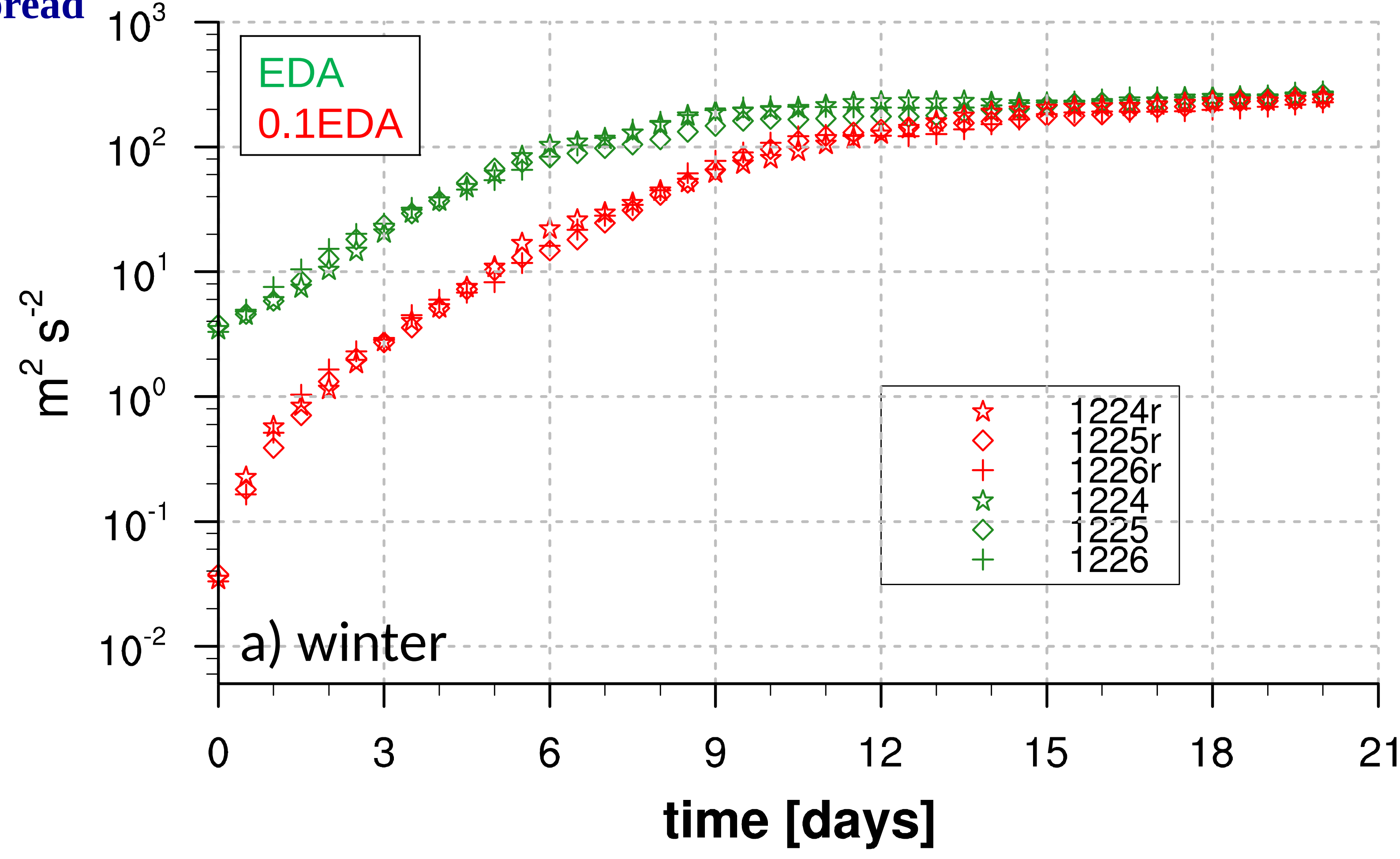
Ongoing collaborative research with ECMWF and GFDL

with state-of-the-art global NWP models

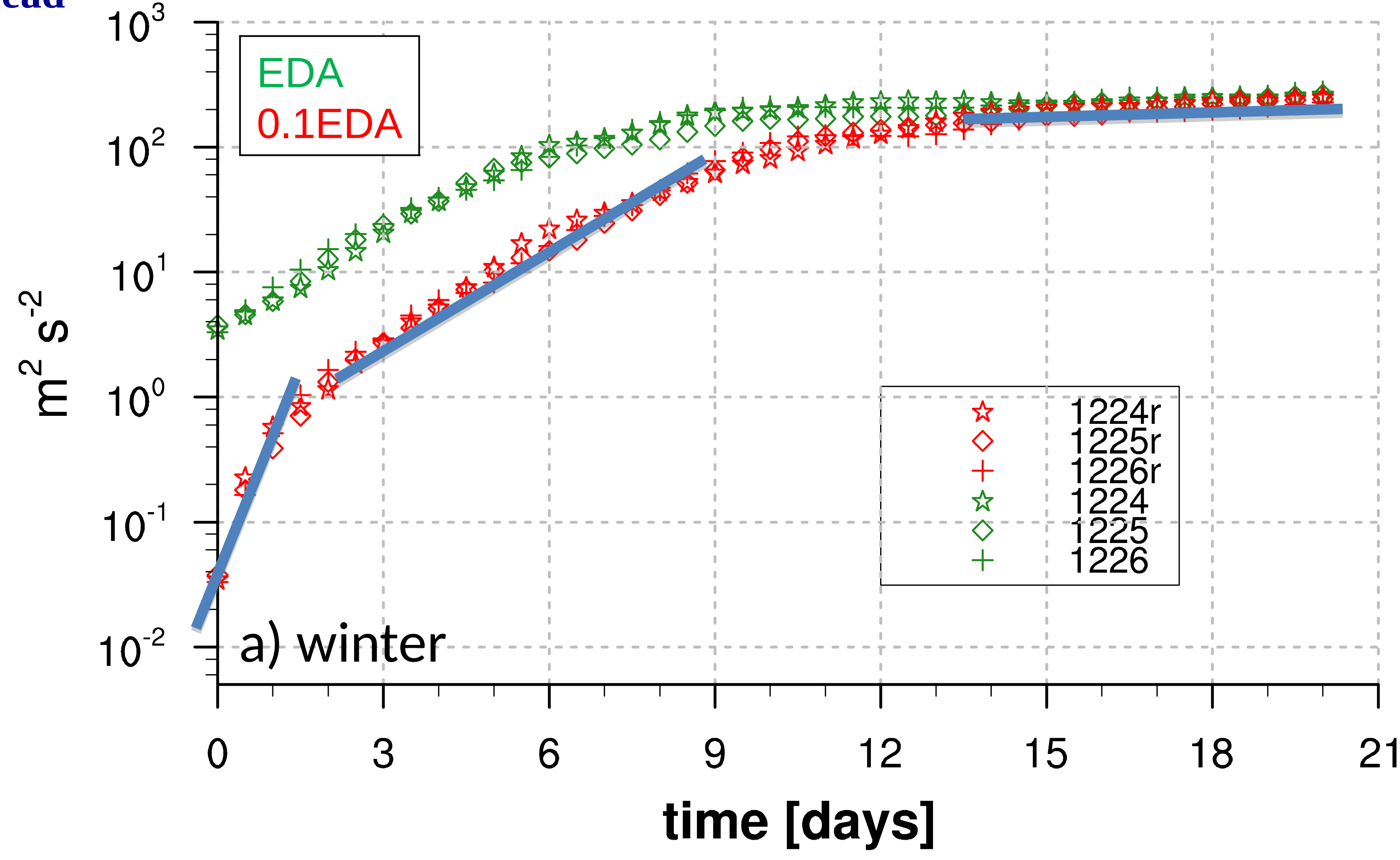
- **ECMWF IFS:**
  - **Operational 9-km global model but 10-member 20-day ensembles, 6 different times**
  - **EDA ensemble: Initial perturbations from each EDA analysis (1.0 x EDA)**
  - **0.1EDA ensemble: initial perturbation 10% of EDA ensemble (centered on EC CNTL)**

- **US NGGPS GFDL/FV3:**
  - **3-km convection-permitting simulations initialized with ECMWF CNTL and 0.1EDA interpolated initial condition and perturbations (so far only 1 pair of 10-day runs)**
  - **13-km runs that mimic the current US GFS operational models**

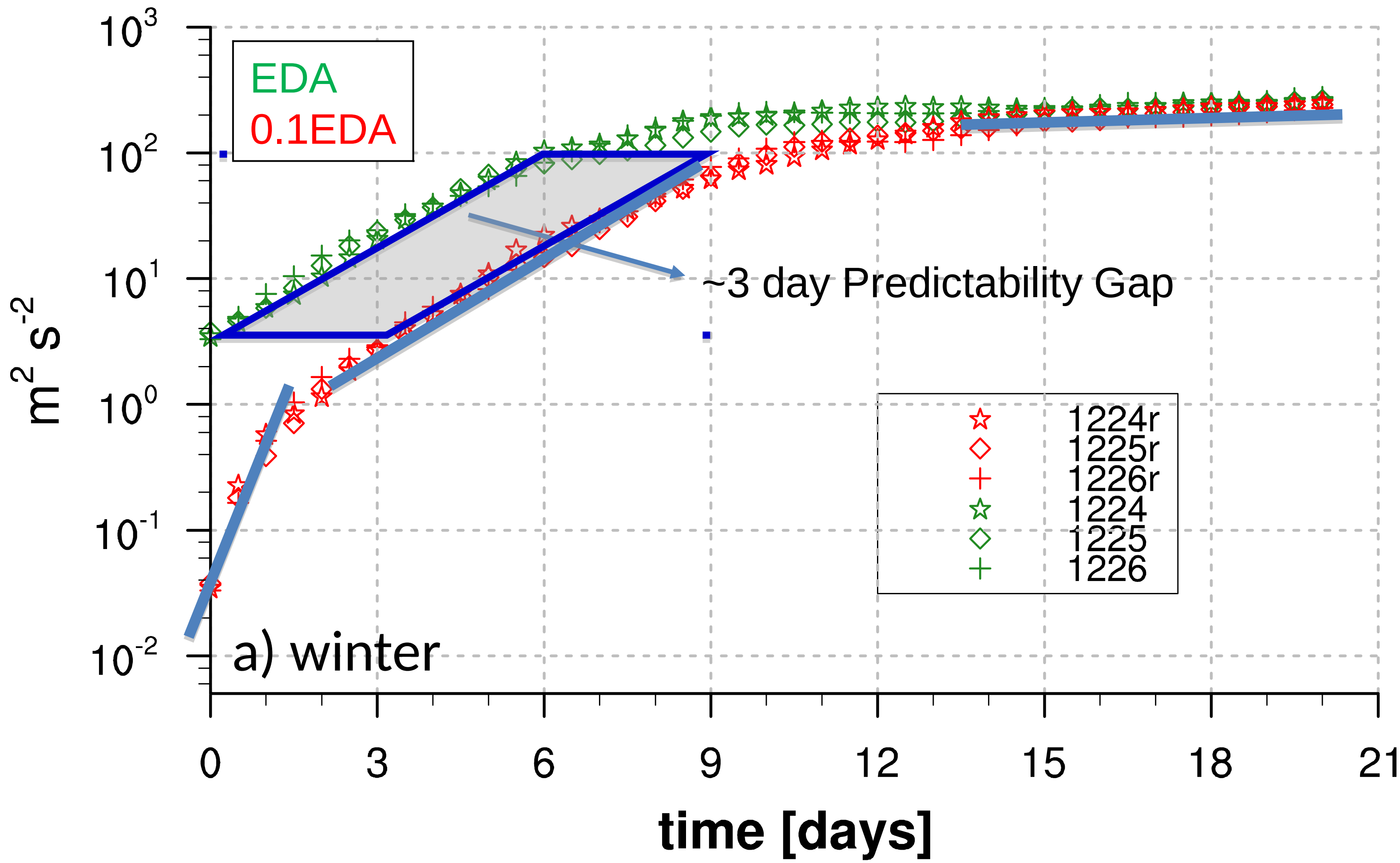
Time evolution of midlatitude (40-60N) averaged ensemble error kinetic energy spread



Time evolution of midlatitude (40-60N) averaged ensemble error kinetic energy spread



Likely 3-to-4 more days can be gained through better ICs!



Flow imbalance from jet/fronts calculated from full nonlinear model