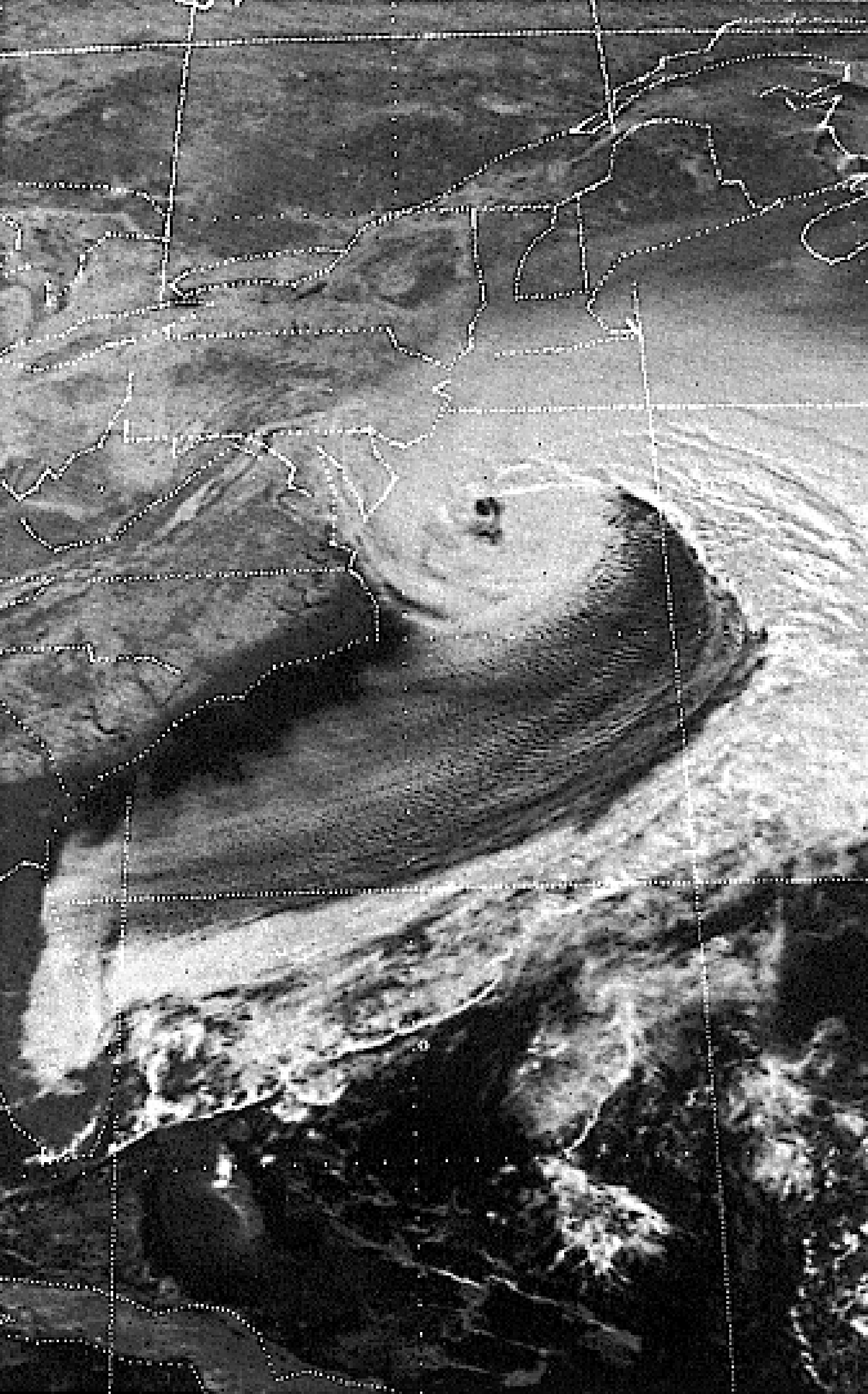
Devil in the Details: Predictability and Dynamics of Winter Cyclones at the Mesoscales

Fuqing Zhang
Penn State University




The Washington Post

Popularity Contest: Lance versus Louis --- most cited papers on Presidents' Day Storm

1.	**THE PRESIDENTS DAY SNOWSTORM OF 18-19 FEBRUARY 1979 - A SUBSYNOPTIC-SCALE EVENT** By: BOSART, LF MONTHLY WEATHER REVIEW Volume: 109 Issue: 7 Pages: 1542-1566 Published: 1981	2	2	0	2	2	210
2.	**THE PRESIDENTS DAY CYCLONE OF 18-19 FEBRUARY 1979 - INFLUENCE OF UPSTREAM TROUGH AMPLIFICATION AND ASSOCIATED TROPOPAUSE FOLDING ON RAPID CYCLOGENESIS** By: UCCELLINI, LW; KEYSER, D; BRILL, KF; et al. MONTHLY WEATHER REVIEW Volume: 113 Issue: 6 Pages: 962-988 Published: 1985	4	1	3	5	0	139
3.	**THE PRESIDENTS DAY CYCLONE OF 18-19 FEBRUARY 1979 - SYNOPTIC OVERVIEW AND ANALYSIS OF THE SUB-TROPICAL JET STREAK INFLUENCING THE PRE-CYCLOGENETIC PERIOD** By: UCCELLINI, LW; KOCIN, PJ; PETERSEN, RA; et al. MONTHLY WEATHER REVIEW Volume: 112 Issue: 1 Pages: 31-55 Published: 1984	4	0	0	1	0	116
4.	**A DIAGNOSTIC-ANALYSIS OF THE PRESIDENTS DAY STORM OF FEBRUARY 1979** By: BOSART, LF; LIN, SC MONTHLY WEATHER REVIEW Volume: 112 Issue: 11 Pages: 2148-2177 Published: 1984	2	2	0	2	0	108
5.	**THE LIFE-CYCLE OF AN EXTRATROPICAL MARINE CYCLONE .1. FRONTAL-CYCLONE EVOLUTION AND THERMODYNAMIC AIR-SEA INTERACTION** By: NEIMAN, PJ; SHAPIRO, MA MONTHLY WEATHER REVIEW Volume: 121 Issue: 8 Pages: 2153-2176 Published: AUG 1993	3	3	1	2	2	78
6.	**A MODEL-AIDED STUDY OF THE ORIGIN AND EVOLUTION OF THE ANOMALOUSLY HIGH-POTENTIAL VORTICITY IN THE INNER REGION OF A RAPIDLY DEEPENING MARINE CYCLONE** By: REED, RJ; STOELINGA, MT; KUO, YH MONTHLY WEATHER REVIEW Volume: 120 Issue: 6 Pages: 893-913 Published: JUN 1992	1	2	1	0	1	75
7.	**TROPOPAUSE UNDULATIONS AND THE DEVELOPMENT OF EXTRATROPICAL CYCLONES .1. OVERVIEW AND OBSERVATIONS FROM A CYCLONE EVENT** By: HIRSCHBERG, PA; FRITSCH, JM MONTHLY WEATHER REVIEW Volume: 119 Issue: 2 Pages: 496-517 Published: FEB 1991	0	1	0	0	0	49
8.	**THE ROLE OF ANTECEDENT SURFACE VORTICITY DEVELOPMENT AS A CONDITIONING PROCESS IN EXPLOSIVE CYCLONE INTENSIFICATION** By: GYAKUM, JR; ROEBBER, PJ; BULLOCK, TA MONTHLY WEATHER REVIEW Volume: 120 Issue: 8 Pages: 1465-1489 Published: AUG 1992	0	2	2	1	0	38
9.	**STRATOSPHERIC TROPOSPHERIC MASS-EXCHANGE DURING THE PRESIDENTS DAY STORM** By: SPAETE, P; JOHNSON, DR; SCHAACK, TK MONTHLY WEATHER REVIEW Volume: 122 Issue: 3 Pages: 424-439 Published: MAR 1994	0	0	0	1	0	32
10.	**A survey of unbalanced flow diagnostics and their application** By: Zhang, FQ; Koch, SE; Davis, CA; et al. ADVANCES IN ATMOSPHERIC SCIENCES Volume: 17 Issue: 2 Pages: 165-183 Published: 2000	2	3	0	2	1	26

THE NEWS&OBSERVER

WEDNESDAY, JANUARY 26, 2000

Stuck fast in North Carolina

'We really need some help from Mother Nature'

Snow buries the record

Triangle isn't expected to thaw out until weekend

The Washington Post

WEDNESDAY, JANUARY 26, 2000

High-Tech Tools Fooled Forecasters

Blindsided and Snowed Under

Colorized IR Image
January 25, 2000 @ 0715 UTC

My personal story:

Car stuck; store closed, no eggs, milk (my wife was 7 months pregnant)

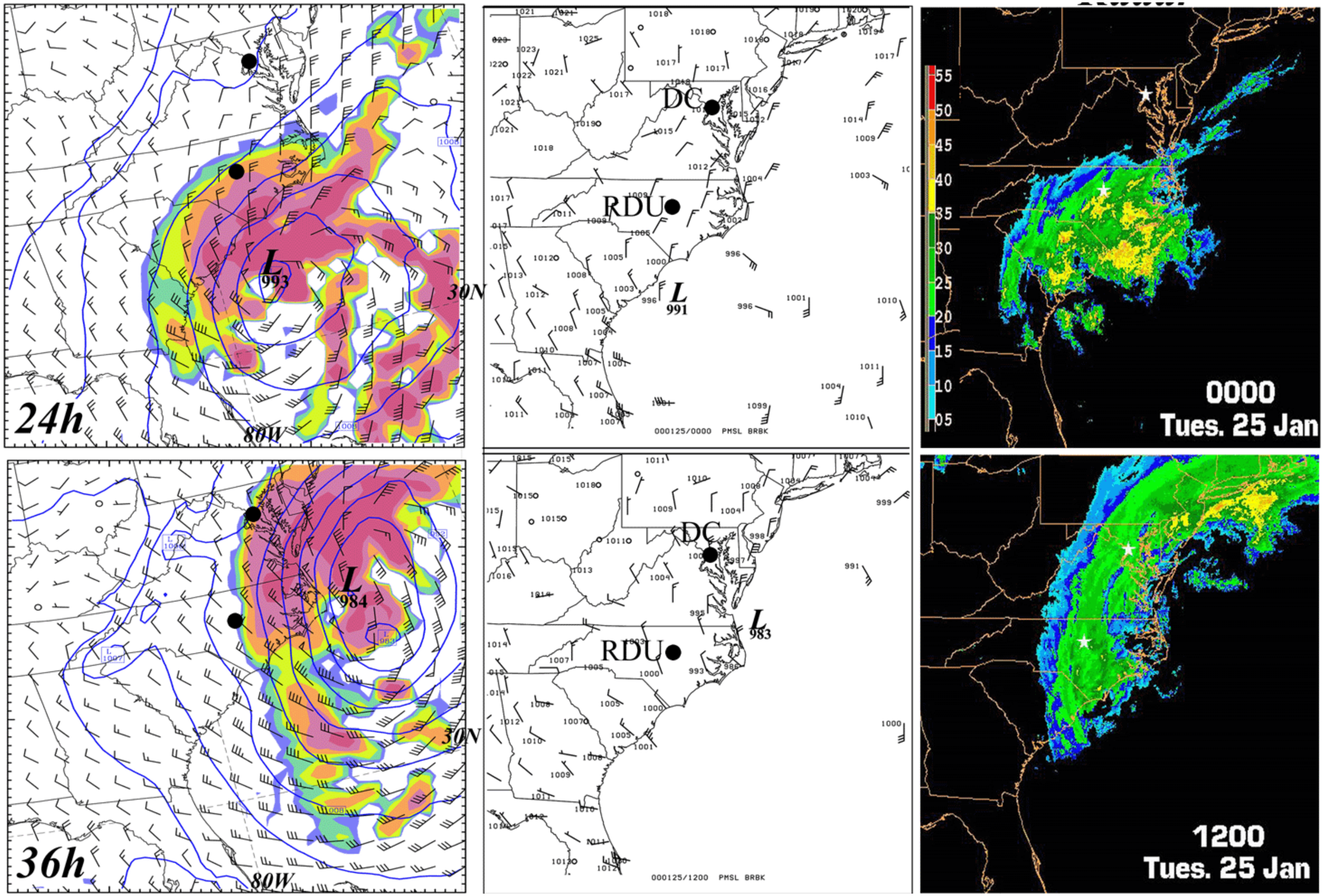
Class cancelled for the week (defense in 8 days; thesis to print; travel for two out-of-town members; new job at NCAR in 2.5 weeks)

Most cited papers on the January 2000 Surprise Snowstorm

1.	**Effects of moist convection on mesoscale predictability** By: Zhang, FQ; Snyder, C; Rotunno, R JOURNAL OF THE ATMOSPHERIC SCIENCES Volume: 60 Issue: 9 Pages: 1173-1185 Published: MAY 2003	15	14	12	13	4	113
2.	**Mesoscale predictability of the "surprise" snowstorm of 24-25 January 2000** By: Zhang, FQ; Snyder, C; Rotunno, R MONTHLY WEATHER REVIEW Volume: 130 Issue: 6 Pages: 1617-1632 Published: JUN 2002	6	4	8	8	3	78
3.	**Tests of an ensemble Kalman filter for mesoscale and regional-scale data assimilation. Part II: Imperfect model experiments** By: Meng, Zhiyong; Zhang, Fuqing MONTHLY WEATHER REVIEW Volume: 135 Issue: 4 Pages: 1403-1423 Published: APR 2007	7	10	13	16	0	63
4.	**Tests of an ensemble Kalman filter for mesoscale and regional-scale data assimilation. Part I: Perfect model experiments** By: Zhang, FQ; Meng, ZY; Aksoy, A MONTHLY WEATHER REVIEW Volume: 134 Issue: 2 Pages: 722-736 Published: FEB 2006	2	9	10	10	1	55
5.	**Initial condition sensitivity and error growth in forecasts of the 25 January 2000 east coast snowstorm** By: Langland, RH; Shapiro, MA; Gelaro, R MONTHLY WEATHER REVIEW Volume: 130 Issue: 4 Pages: 957-974 Published: APR 2002	1	4	1	6	1	48
6.	**Winter storms in the central Himalayas** By: Lang, TJ; Barros, AP JOURNAL OF THE METEOROLOGICAL SOCIETY OF JAPAN Volume: 82 Issue: 3 Pages: 829-844 Published: JUN 2004	7	1	9	8	4	47
7.	**Mesoscale predictability of moist baroclinic waves: Experiments with parameterized convection** By: Tan, ZM; Zhang, FQ; Rotunno, R; et al. JOURNAL OF THE ATMOSPHERIC SCIENCES Volume: 61 Issue: 14 Pages: 1794-1804 Published: JUL 2004	1	3	8	4	3	39
8.	**Understanding Utah winter storms - The intermountain precipitation experiment** By: Schultz, DM; Steenburgh, WJ; Trapp, RJ; et al. BULLETIN OF THE AMERICAN METEOROLOGICAL SOCIETY Volume: 83 Issue: 2 Pages: 189-+ Published: FEB 2002	2	0	1	3	1	31
9.	**Spatial-temporal features of intense snowfall events in China and their possible change** By: Sun, Jianqi; Wang, Huijun; Yuan, Wei; et al. JOURNAL OF GEOPHYSICAL RESEARCH-ATMOSPHERES Volume: 115 Article Number: D16110 Published: AUG 24 2010	0	2	9	10	1	22
10.	**Interpretation of the structure and evolution of adjoint-derived forecast sensitivity gradients** By: Kleist, DT; Morgan, MC MONTHLY WEATHER REVIEW Volume: 133 Issue: 2 Pages: 466-484 Published: FEB 2005	1	3	0	4	1	18

Predictability of the 24-25 January 2000 Snowstorm

3.3-km MM5 Simulation vs. Observations

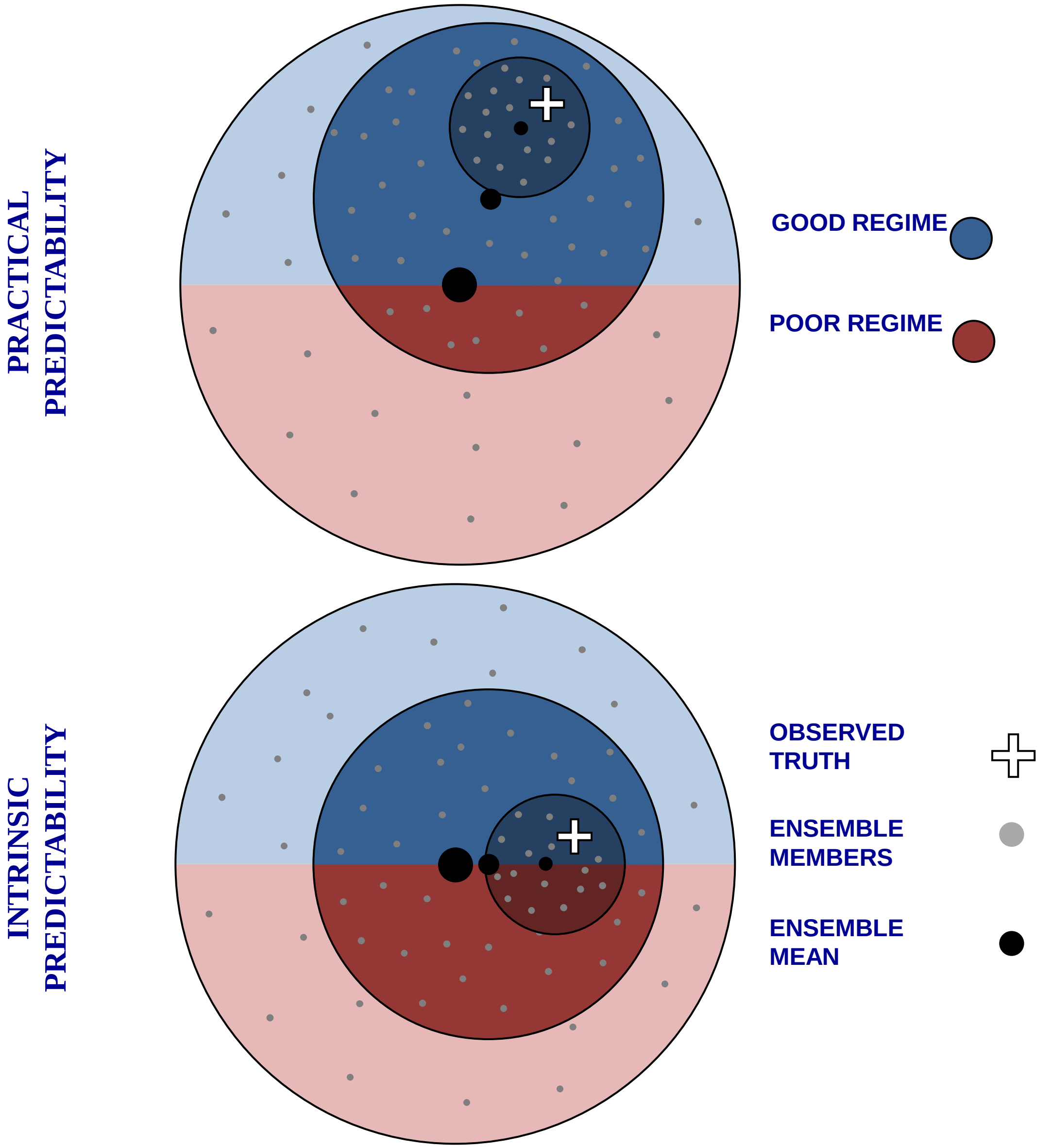


Practical Predictability: IC error matters, resolution matters (Zhang et al. 2002 MWR)

PRACTICAL vs. INTRINSIC PREDICTABILITY

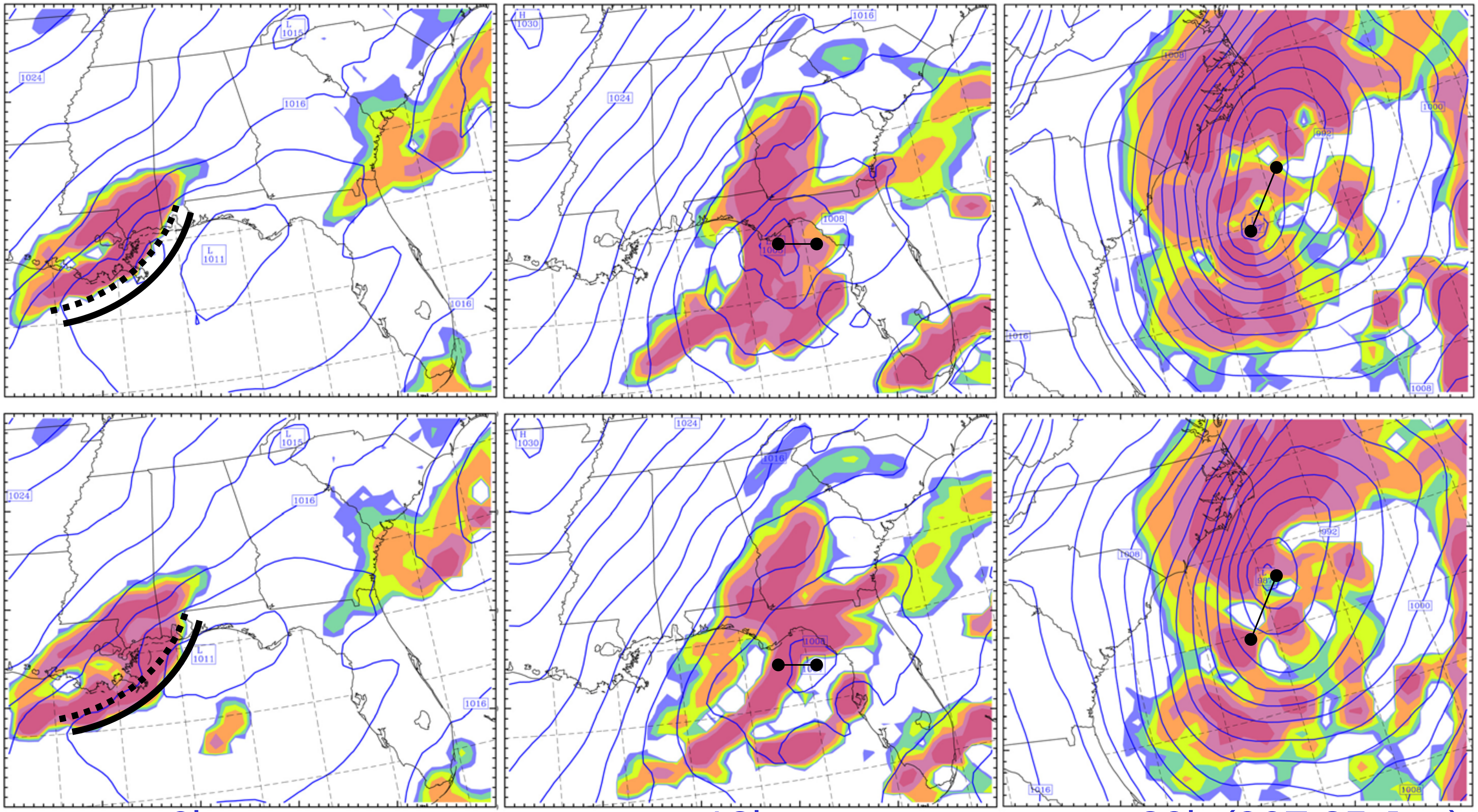
(Lorenz 1996; Melhauser & Zhang 2012 JAS)

- Where the members lie in relation to the truth and within which flow regime determines the evolution of that member
- If truth lies almost entirely in a flow regime
  - reducing the initial perturbations will hone in on the truth
  - increase the practical predictability of the event
- If truth lies near bifurcation
  - Reducing initial perturbations will contain both regimes/solutions
  - No increase in predictability
  - Intrinsic limit



Intrinsic Predictability of 2000 *Surprise* Snowstorm

MSLP and reflectivity for w/ and w/o small random white noise in initial temperature

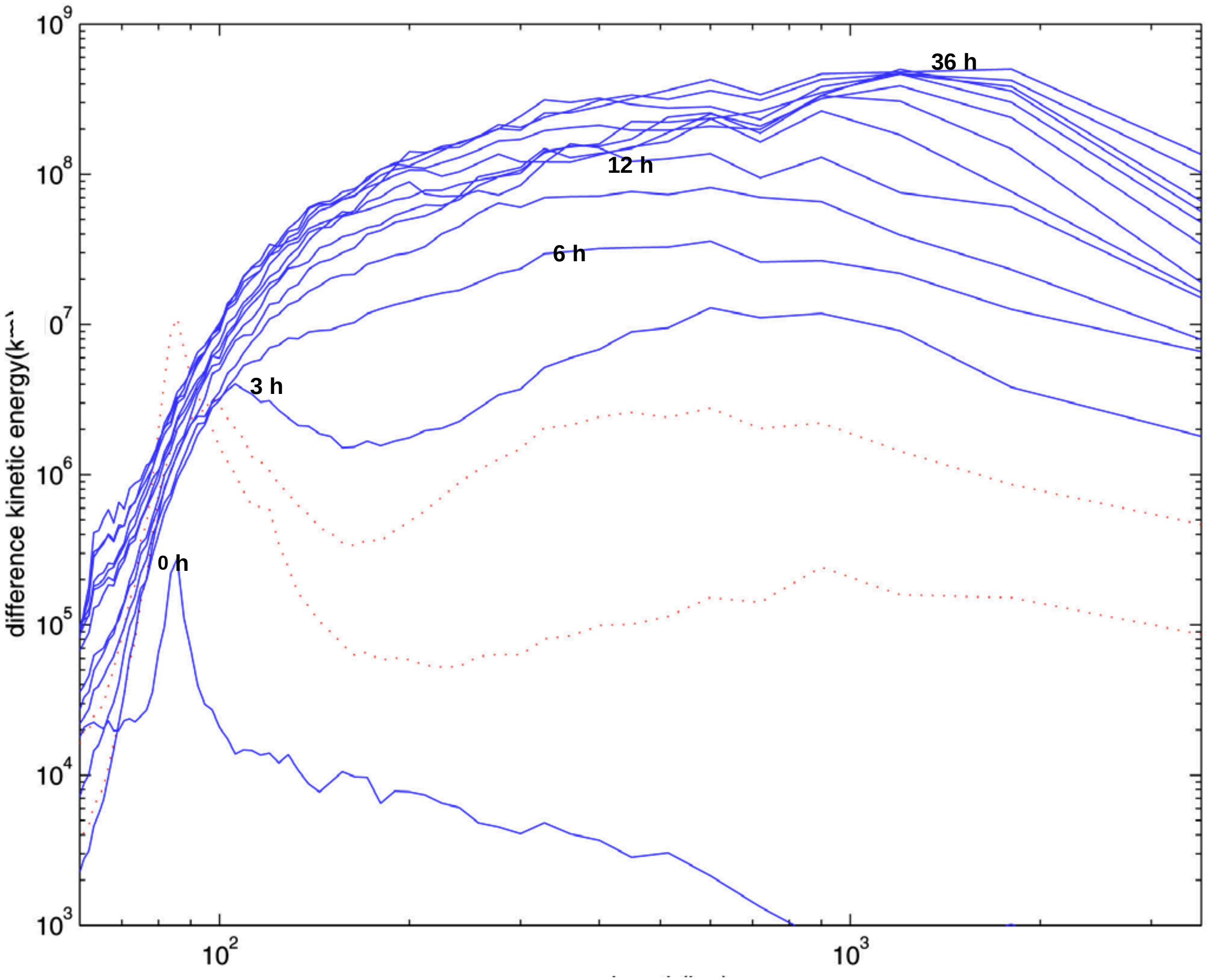


6h 12h 30h (06Z 25 Jan)

Even with near perfect ICs, mesoscale predictability limited (Zhang et al. 2003 JAS)

Intrinsic Predictability of the *Surprise* Snowstorm

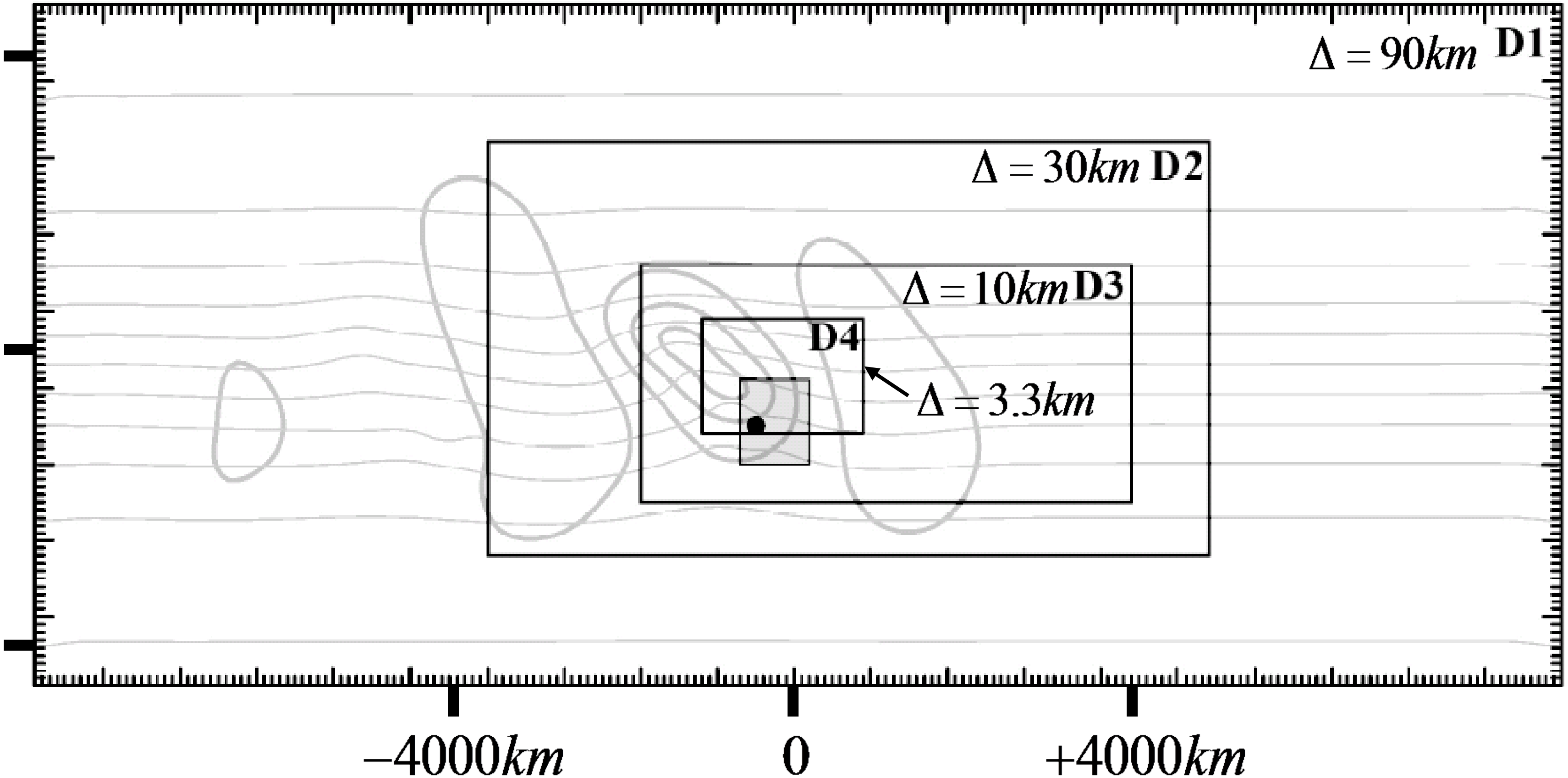
Difference or Error Energy Spectra at Various Times for the 3.3-km Simulations



Uncontrollable small-scale IC error grows to >1000km in 36h (Zhang et al. 2003 JAS)

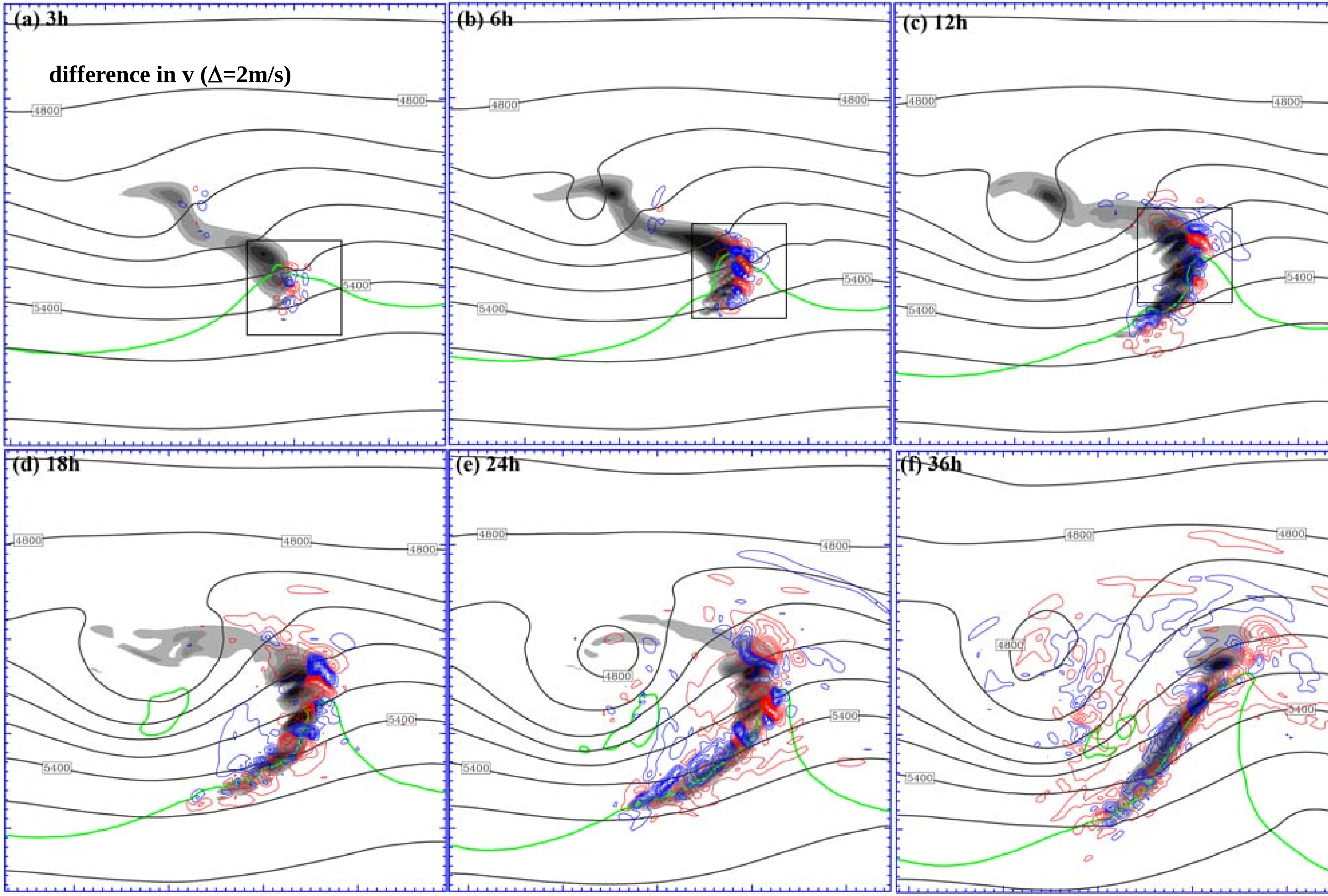
Mesoscale Predictability of Moist Baroclinic Waves

(Zhang, Bei, Rotunno, Snyder and Epifanio 2007, JAS)



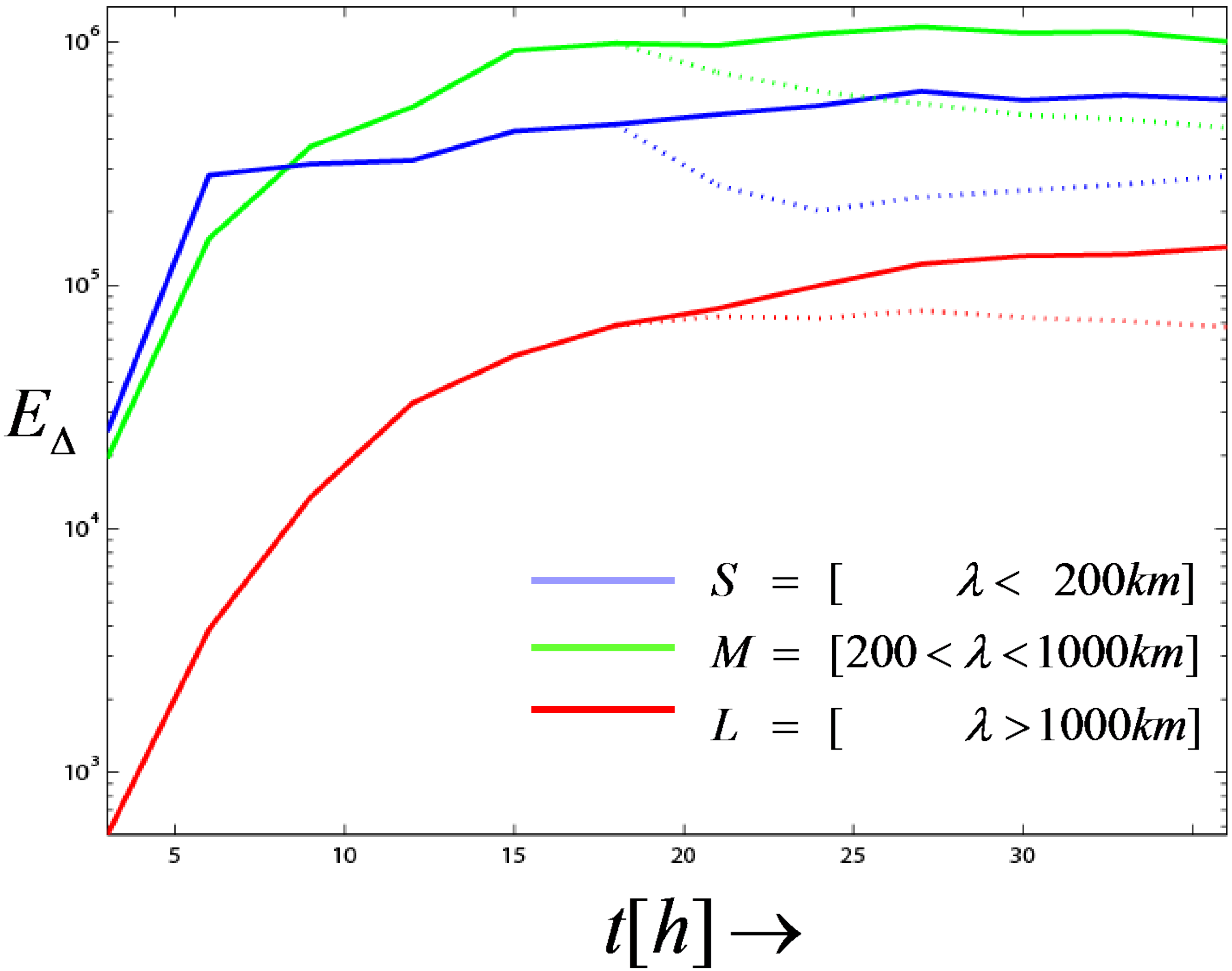
white noise $T_{\max}' = \pm 0.2^{\circ}C$ added to D2 at t = 36h
the same ICs as in 30-km study *Tan, Zhang, Rotunno and Snyder (2004, JAS)*
except for the addition of D3 and D4 convection permitting domains

Mesoscale Predictability of Moist Baroclinic Waves



(Zhang et al. 2007, JAS)

Error Growth and Saturation at Different Wavebands



Difference Energy of Band-Pass Filtered Fields

Derivation of DKE Budget for Incompressible and Inviscid Flow

$$Momentum\ \ eqn: \ \frac{\partial u_i}{\partial t} + u_j \frac{\partial u_i}{\partial x_j} - f\varepsilon_{ij3} u_j = -\frac{\partial \phi}{\partial x_i} + b\delta_{3i}$$

$$Assume: \qquad u = u^0 + \delta u \qquad (u,\ u^0,\ \delta u\ \ solution\ 1,\ 2\ \ and\ \ difference)$$

$$Difference\ eqn: \ \frac{\partial \delta u_i}{\partial t} + u_j^0 \frac{\partial \delta u_i}{\partial x_j} + \delta u_j \frac{\partial u_i^0}{\partial x_j} + \delta u_j \frac{\partial \delta u_i}{\partial x_j} - f\varepsilon_{ij3} \delta u_j = -\frac{\partial \delta \phi}{\partial x_i} + \delta b \delta_{3i}$$

$$DKE\ \ eqn: \qquad \frac{\partial}{\partial t}\left\langle \frac{\delta u_i^{\,2}}{2} \right\rangle = -\left\langle \delta u_i \delta u_j \frac{\partial u_i^0}{\partial x_j} \right\rangle + \left\langle \delta u_3 \delta b \right\rangle$$

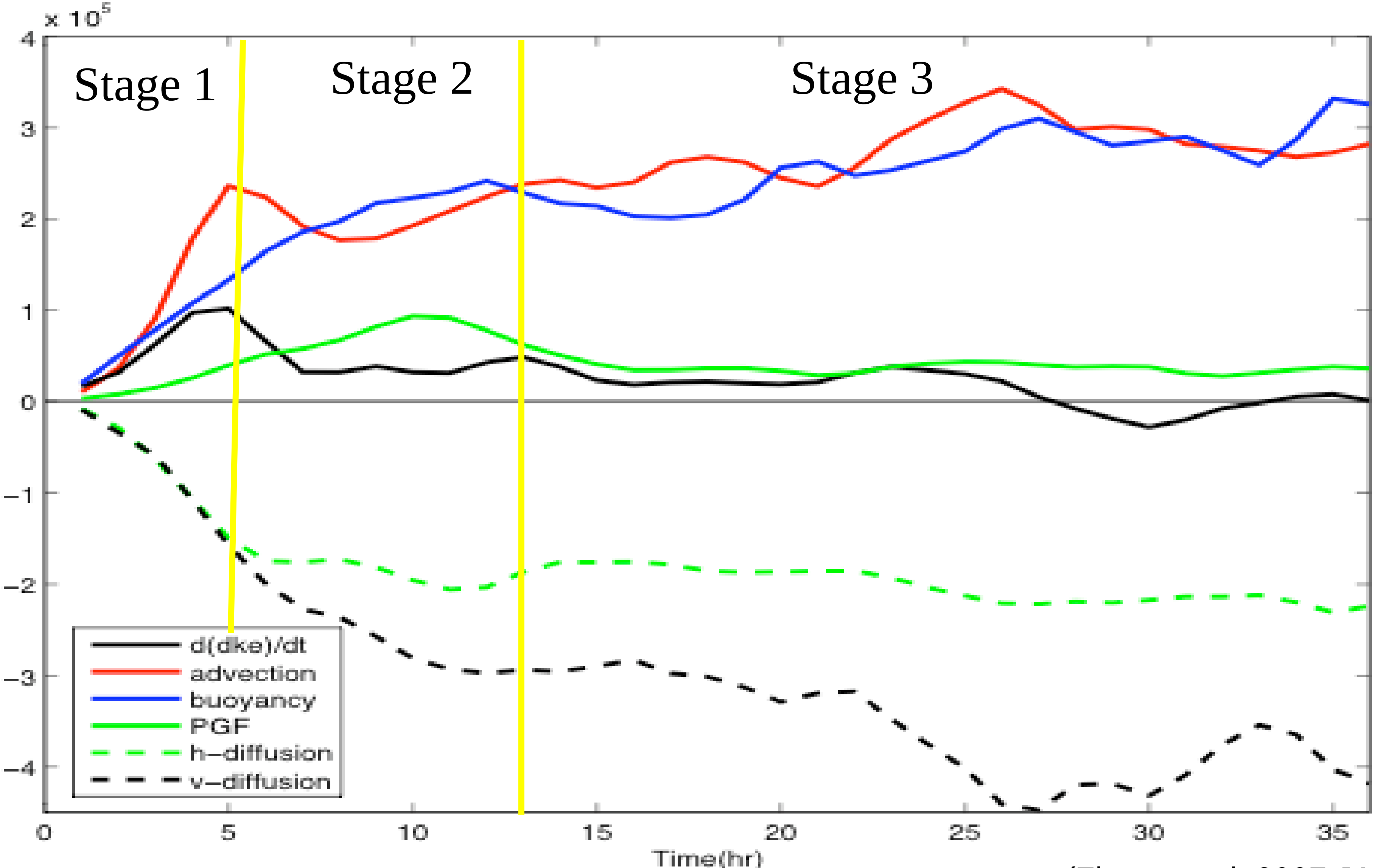
Difference Kinetic Energy (DKE) Budget Analysis for the MM5 system (VERY similar to TKE budget eqn)

$$\frac{\mathrm{d}}{\mathrm{dt}}\langle \mathrm{DKE} \rangle = \langle \mathrm{advection} \rangle + \langle \mathrm{buoyancy} \rangle + \langle \mathrm{PGF} \rangle - \langle \mathrm{diffusion\_h} \rangle - \langle \mathrm{diffusion\_v} \rangle$$

(Zhang et al. 2007 JAS)

Difference Kinetic Energy (DKE) Budget Analysis

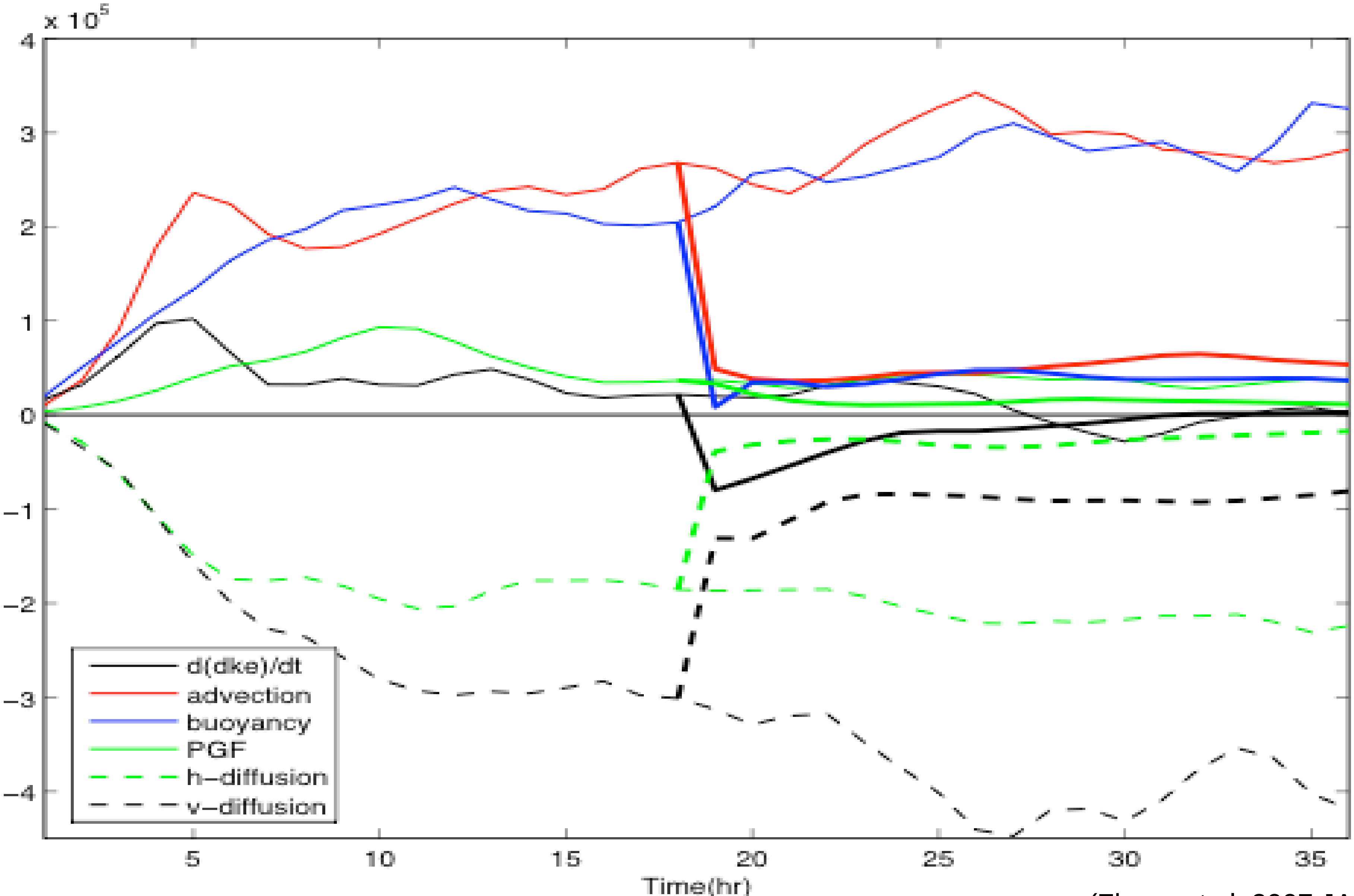
Time evolution of the DKE tendency and each of the source/sink terms



(Zhang et al. 2007 JAS)

Budget of Error Energy: w/ and w/o moist convection

Heating turned off after 18h for both perturbed and unperturbed runs



(Zhang et al. 2007 JAS)

A Multistage Error Growth Model for Mesoscale Predictability

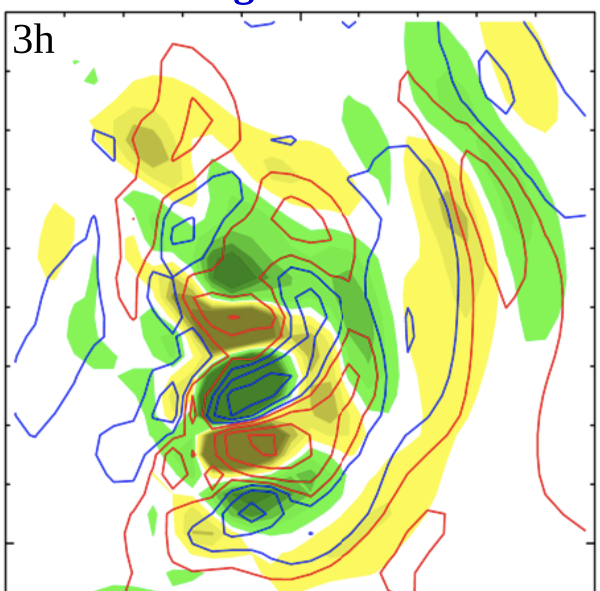
(Zhang et al. 2007, JAS)

Stage 1, 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 2, transient growth: Saturated errors transform from convective-scale unbalanced to larger-scale balanced motions through balance adjustment and GWs at the time scale *O(1/f)*.

***Stage 3, baroclinic growth**:* Balanced components of the saturated error project onto the larger-scale flow and grow with background dynamics and instability at the time scale of *O(1day)*.

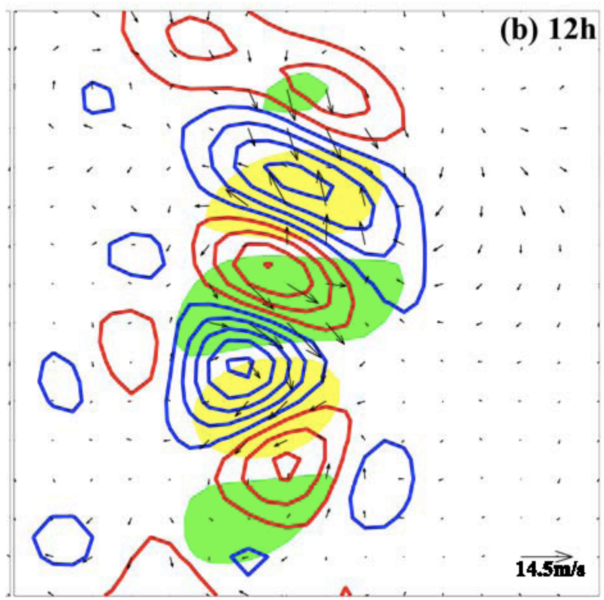
Stage 1



300km

T and w differences

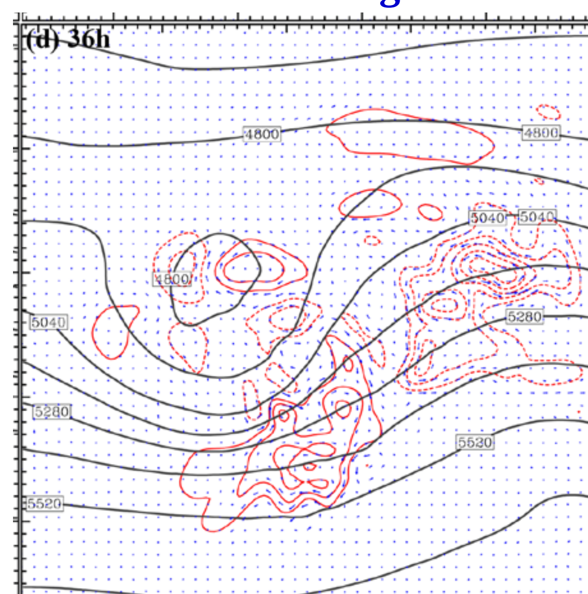
Stage 2



1200km

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

Stage 3

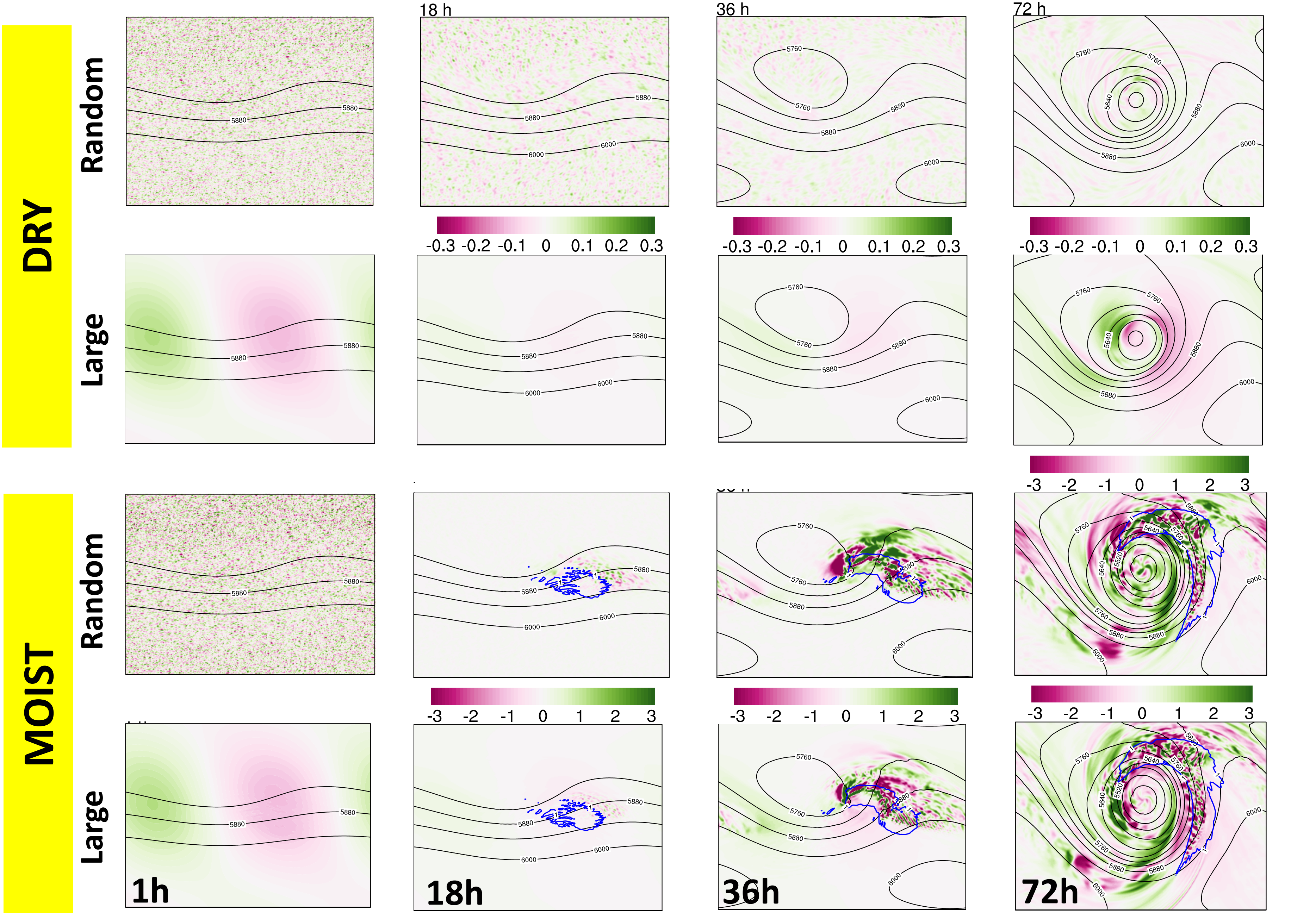


4200km

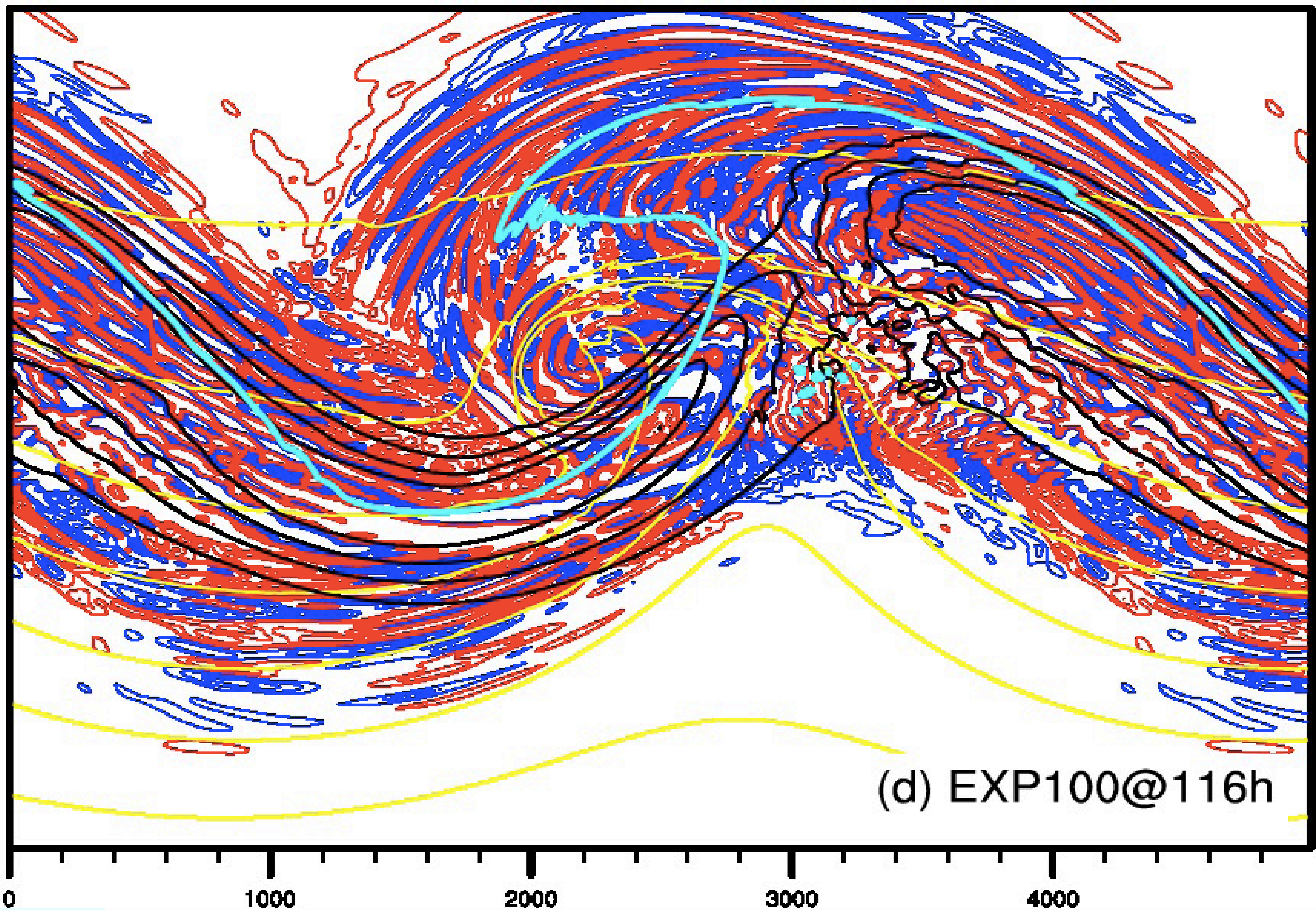
Pressure and **V** differences

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

Ongoing research by Y. Qiang Sun

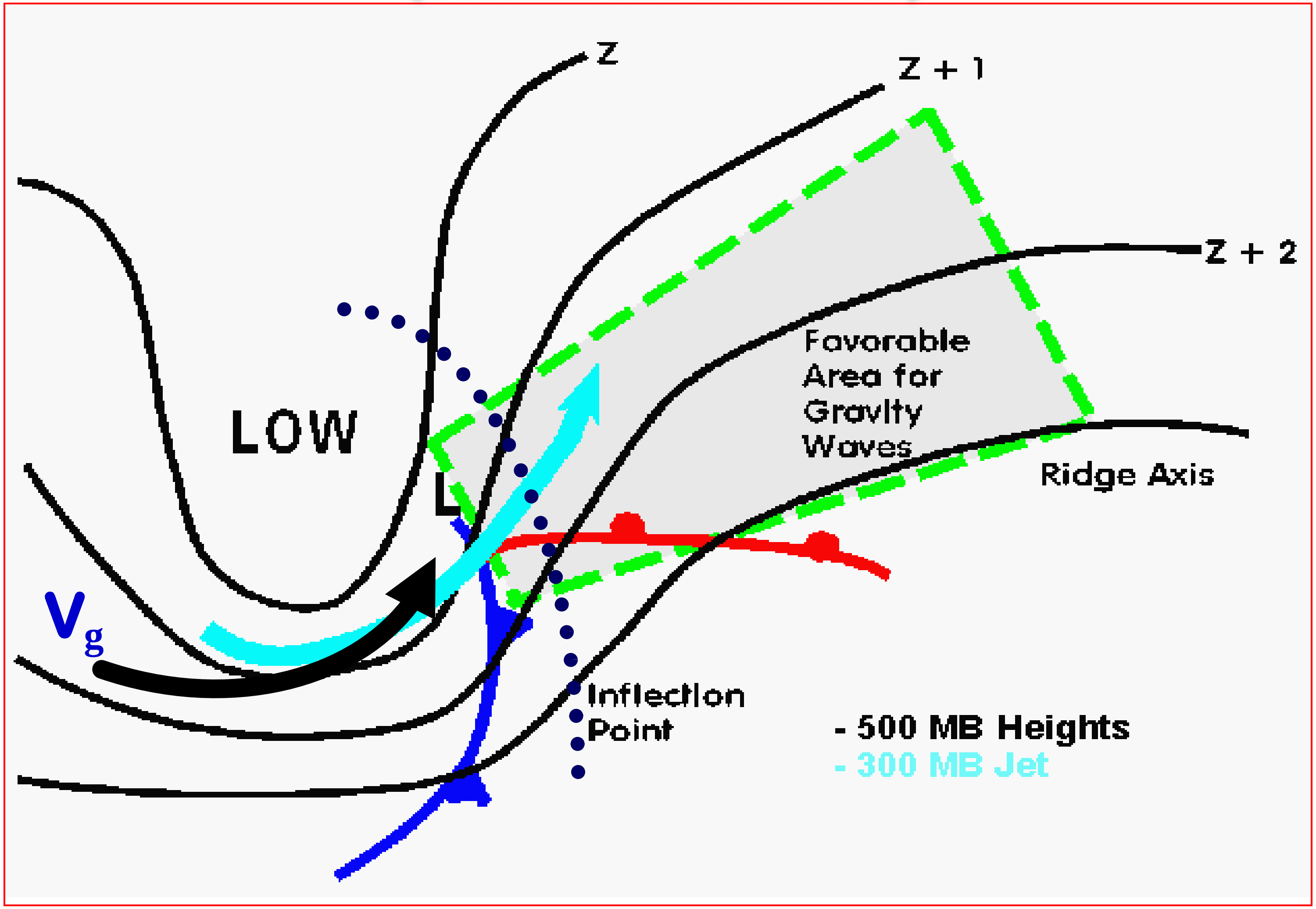


Gravity Waves from Moist Jets: *Devil in the details*



Jet/front Gravity Wave: Synoptic Environment

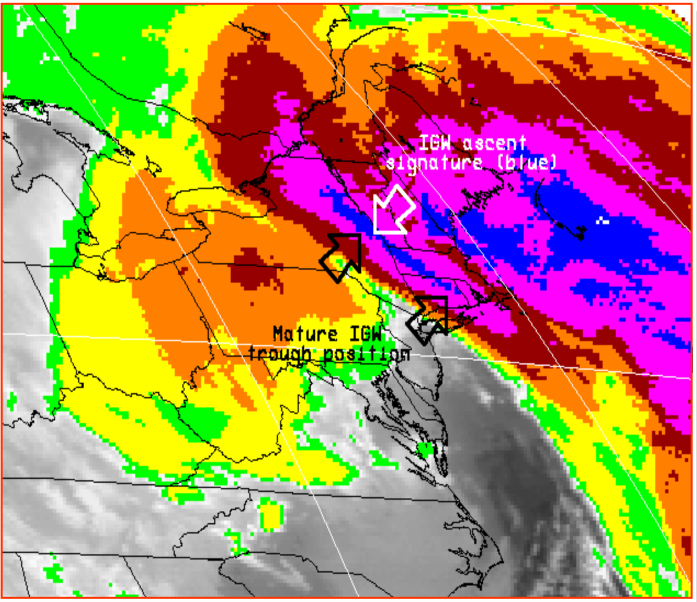
(Uccellini and Koch 1987)

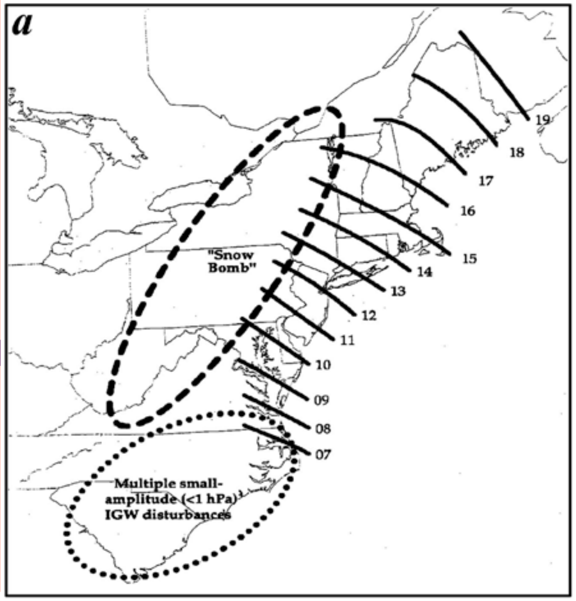


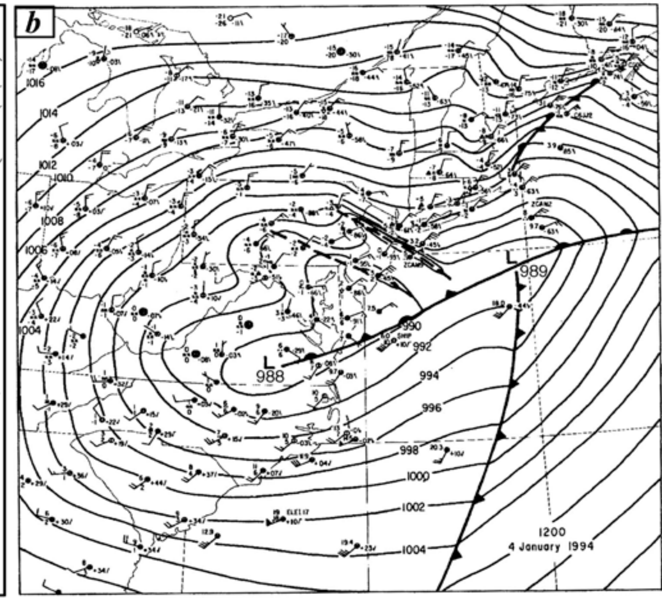
- Observations: 13 documented cases of mesoscale gravity waves; L~50-500km
- Preferred region: exit region of upper jet streak; cold side of surface front
- Leading hypothesis of wave generation: geostrophic adjustment

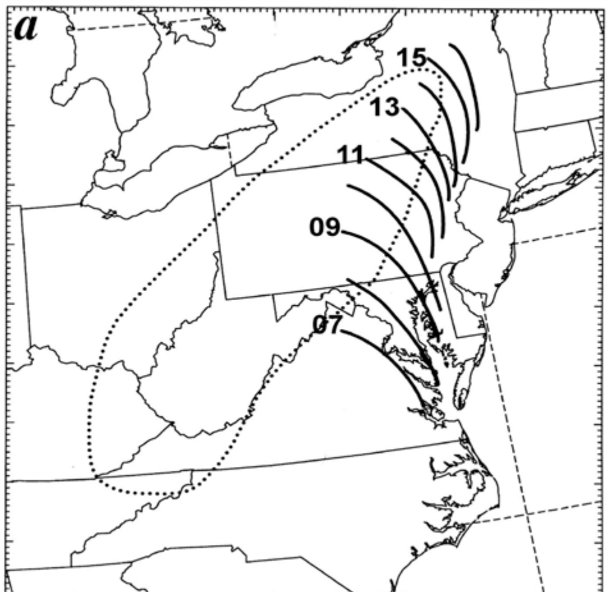
Large-Amplitude MGW Event of 4 Jan 1994

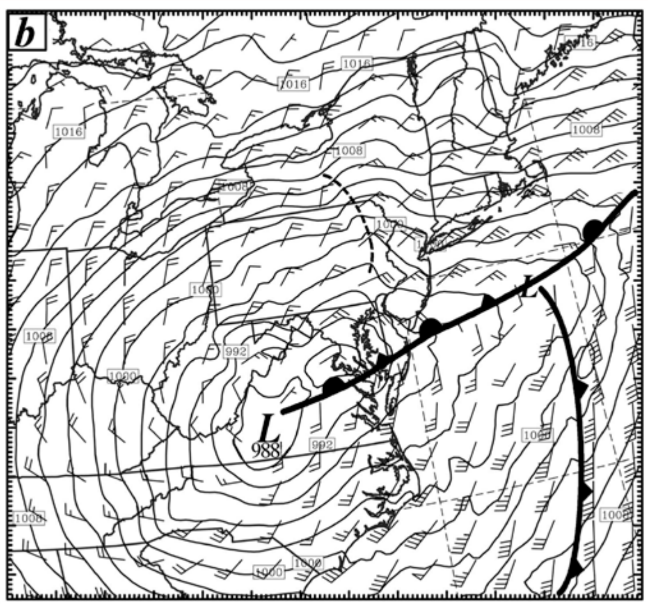
Bosart et al. (1998 MWR), Zhang et al. (2001QJ)











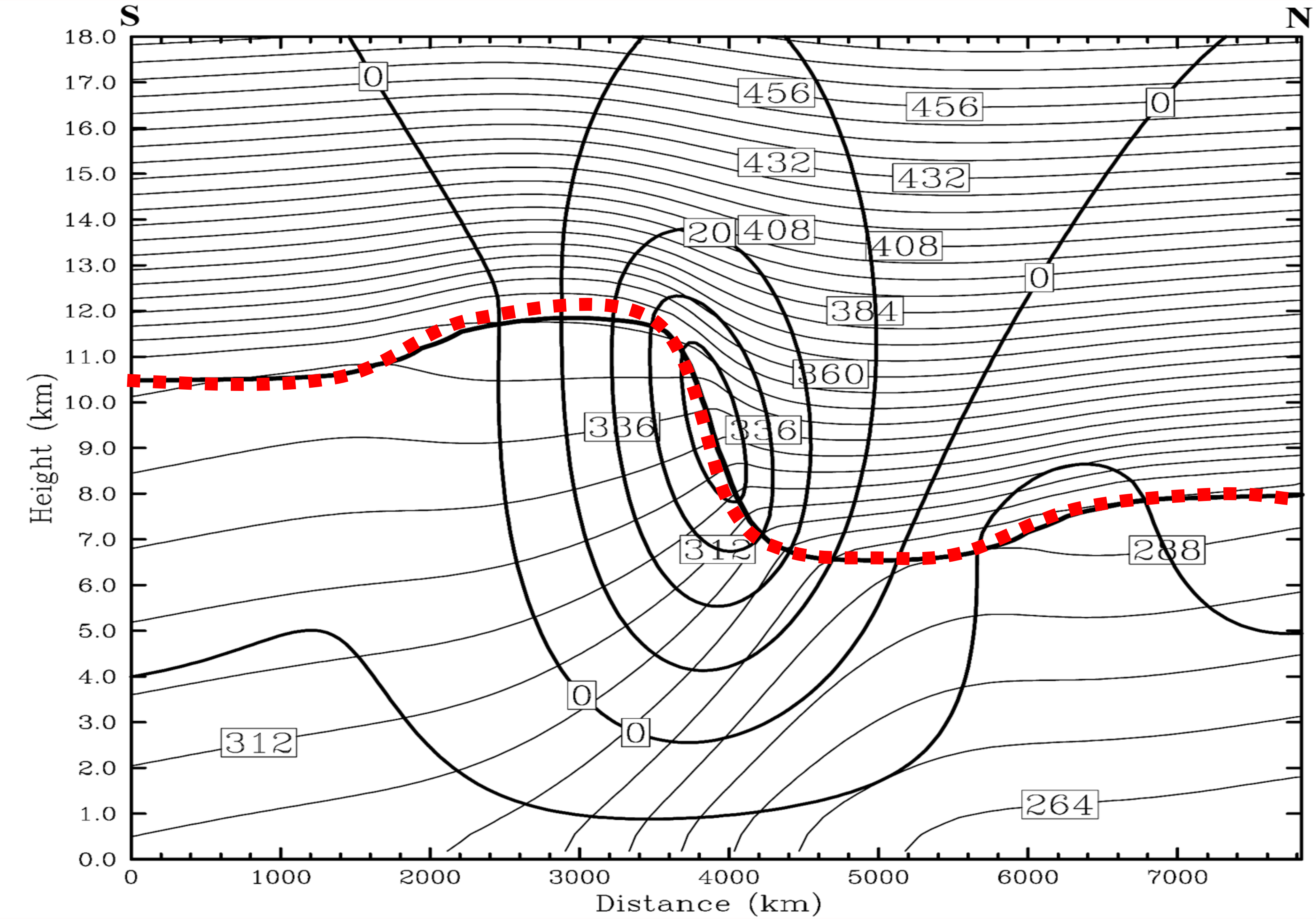
Observations vs. Simulations

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

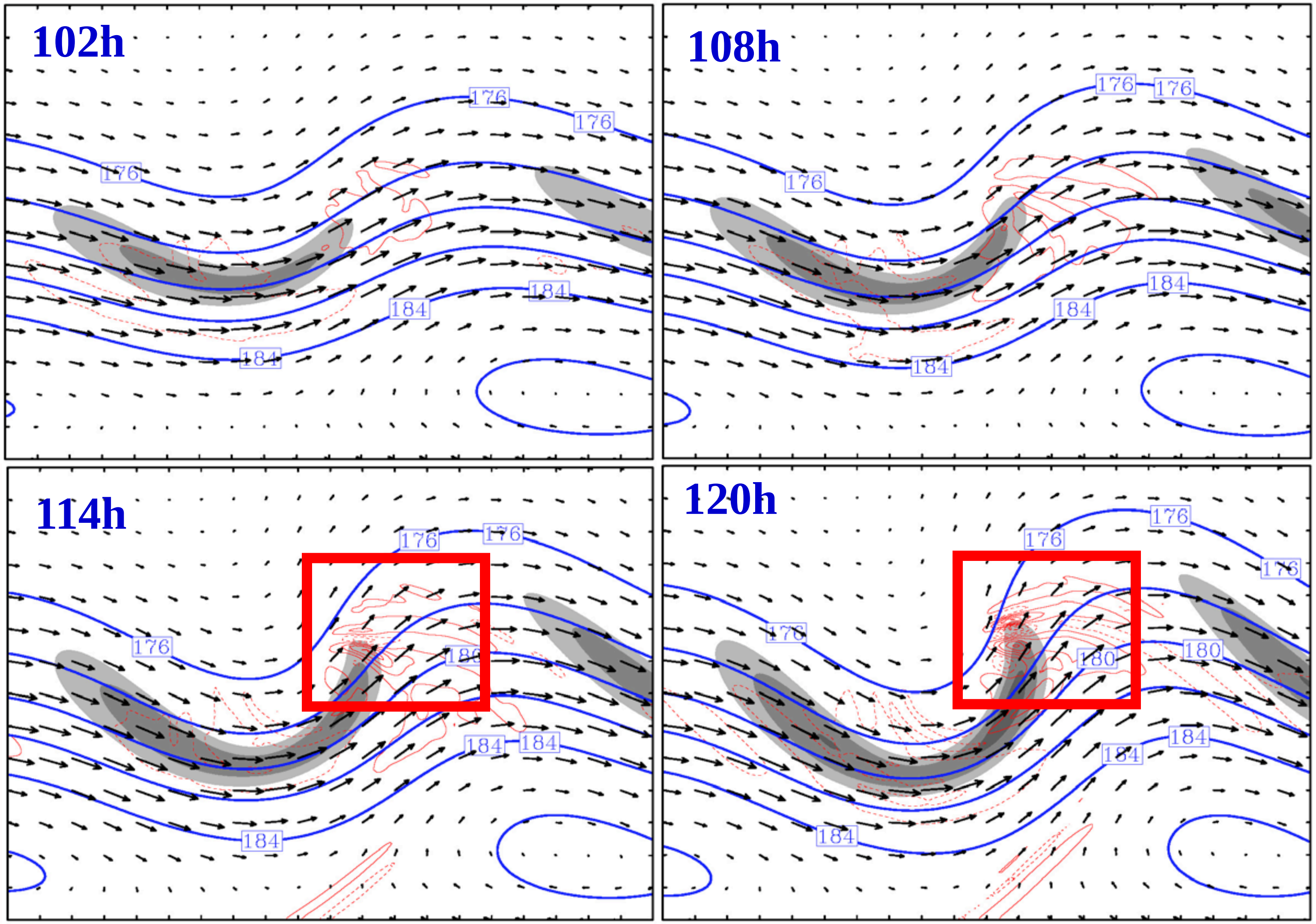
Initial 2-D Baroclinic Jet



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

(Zhang 2004 JAS)

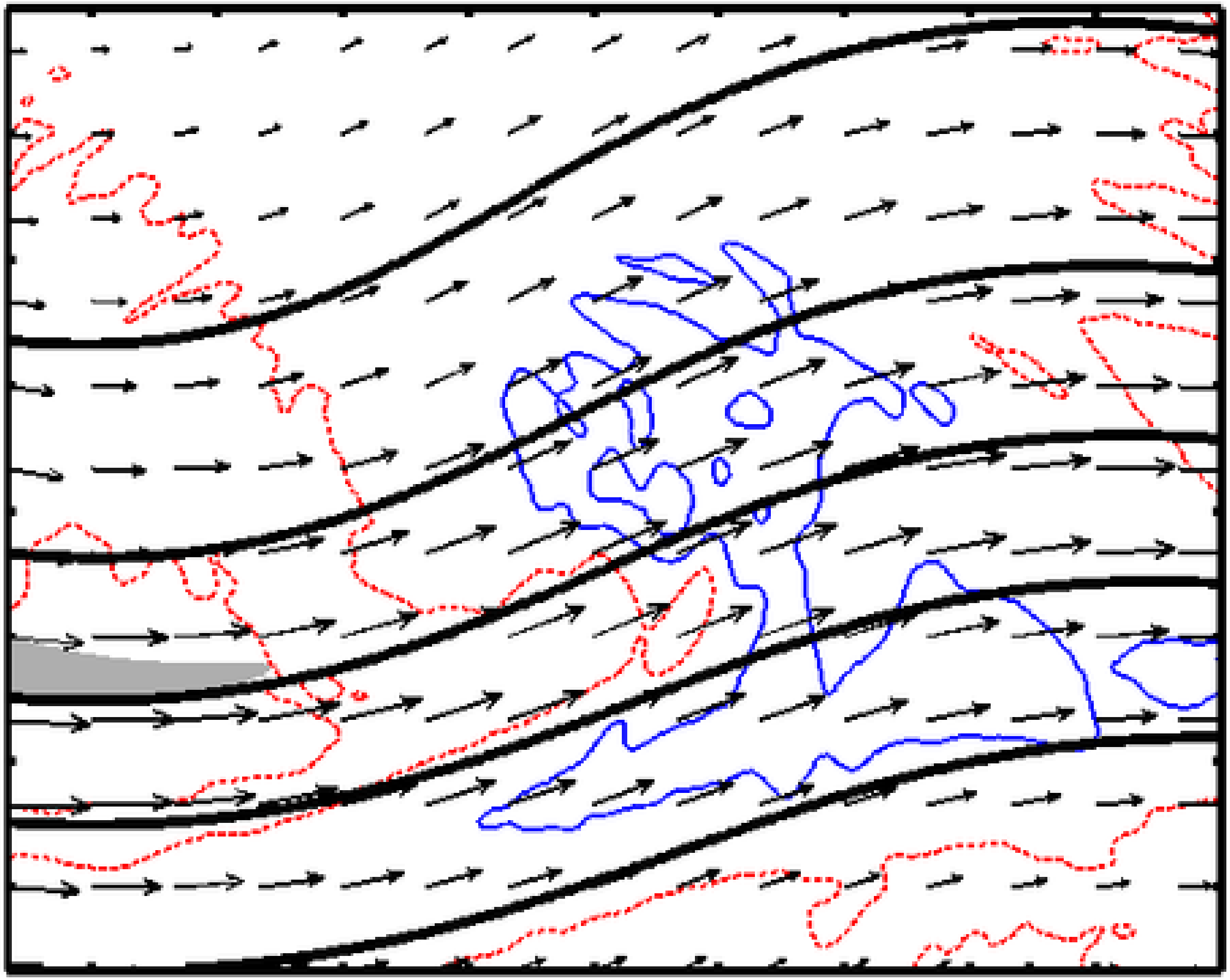
Upper-tropospheric Jet and Lower-Stratospheric Gravity Waves



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

(Zhang 2004 JAS)

A 24-h Animation of the Gravity Waves at 13 km

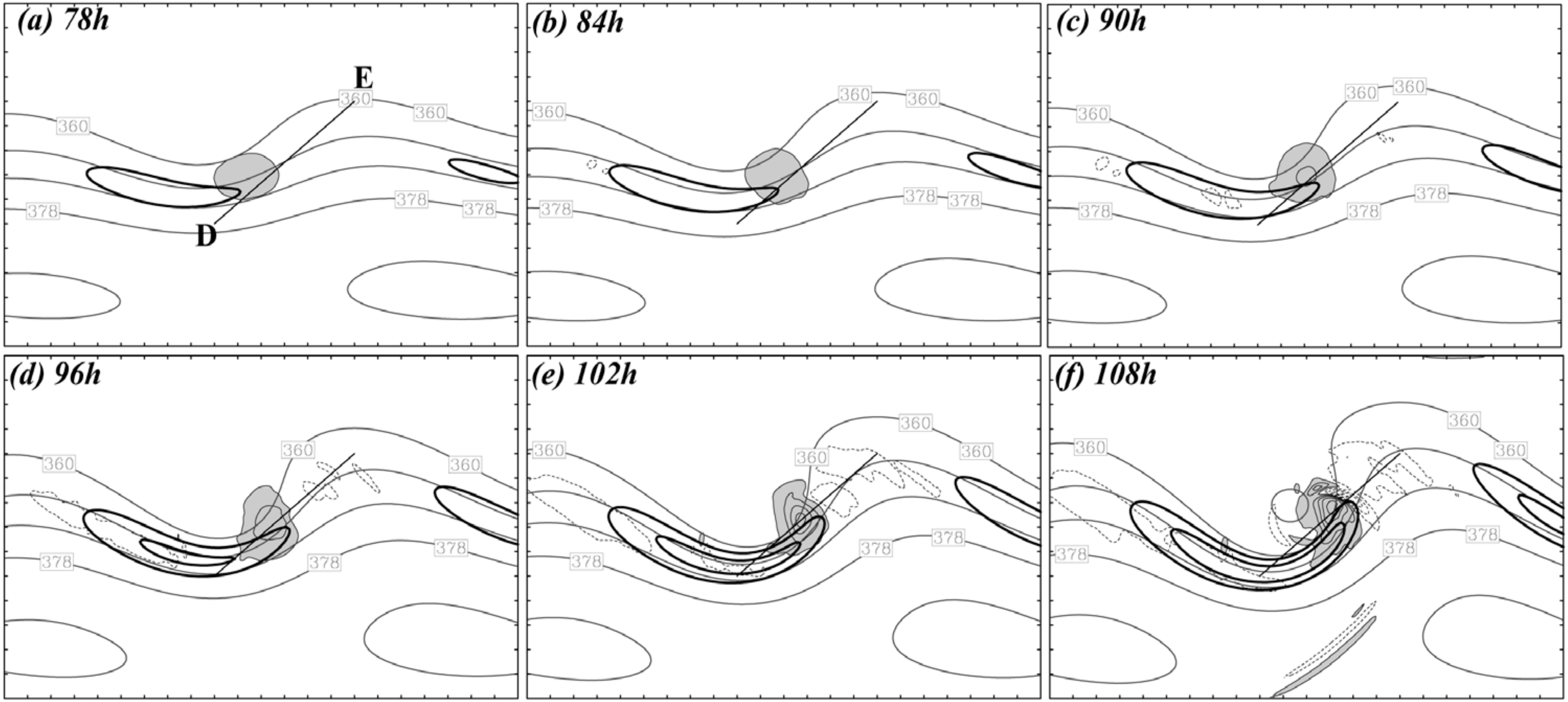


Thick lines: 13-km pressure, D=2hPa; thin lines: divergence, negative, dashed; shaded: 8-km jet>55m/s

Flow imbalance diagnosed with nonlinear balance equation

(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)

Hypothesis: Spontaneous Balance Adjustment

(Zhang 2004 JAS; Plougonven&Zhang 2007 JAS; Wang&Zhang 2010 JAS)

- ***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

Spontaneous Balance adjustment: Linear wave response to forcing

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

$$L(w') = \left[(D_\gamma^2 + f^2)\partial_{zz} + N^2 \Delta_H \right] w' = D_\gamma \partial_z (\Delta NBE) - f \partial_z F_\varsigma - \frac{g}{\Theta} \Delta_H F_\theta$$

F_δ , F_θ and F_ζ are forcings diagnosed from balanced flow in the full nonlinear model (the divergence forcing, vorticity forcing and thermodynamic forcing).

$$F_\delta = -(\partial_t + \overrightarrow{U_B} \nabla)\overline{\delta} + \overline{\Delta NBE} + \cdots$$

$$F_\varsigma = -(\partial_t + \overrightarrow{U_B} \nabla)\overline{\varsigma} - f\,\overline{\delta} + \cdots$$

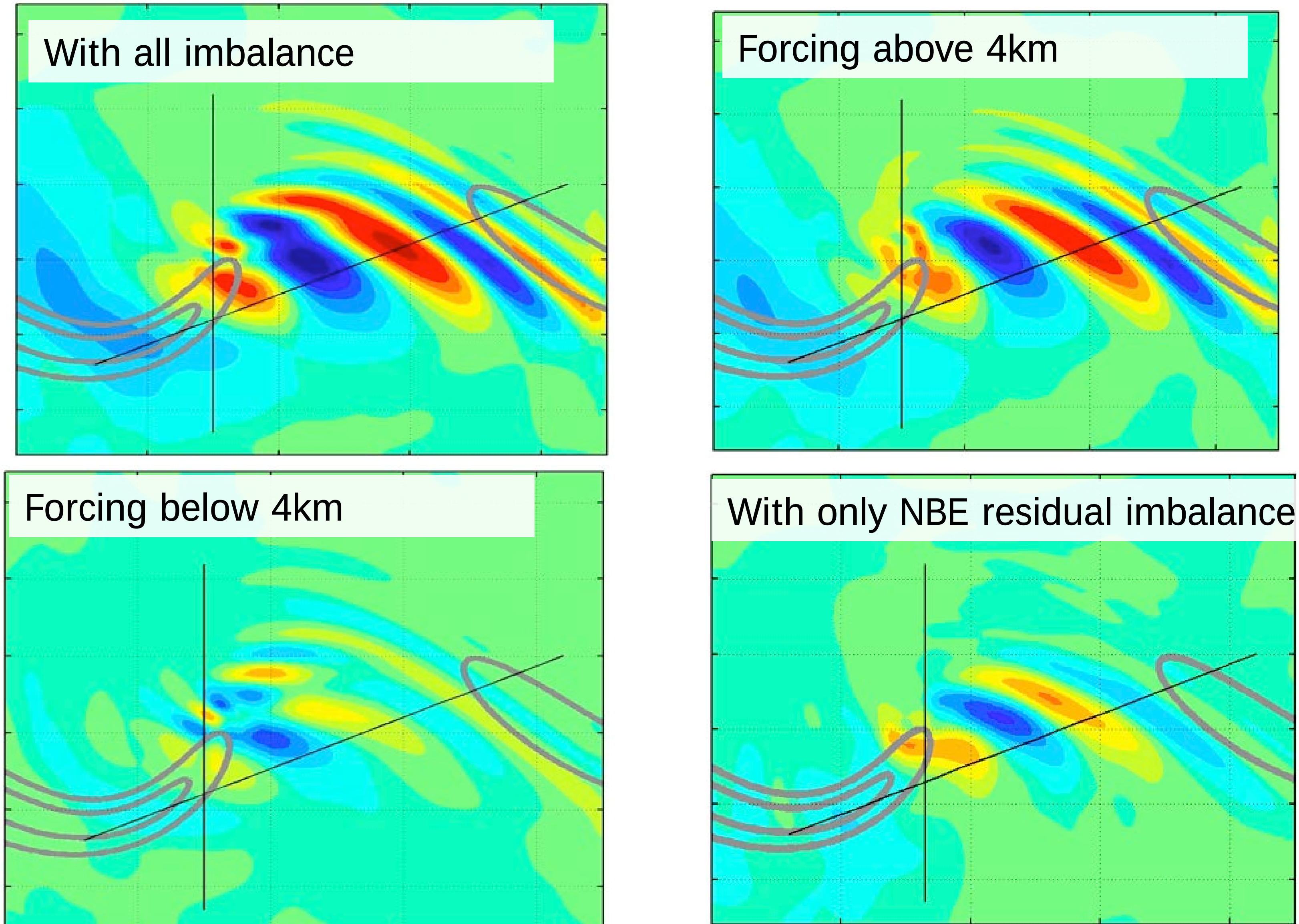
$$F_\theta = -(\partial_t + \overrightarrow{U_B} \nabla)\overline{\theta} + \cdots$$

See alternative hypotheses and theories in Plougonven and Zhang 2014, review of geophysics

Gravity wave response to imbalance forcing in the dry jet

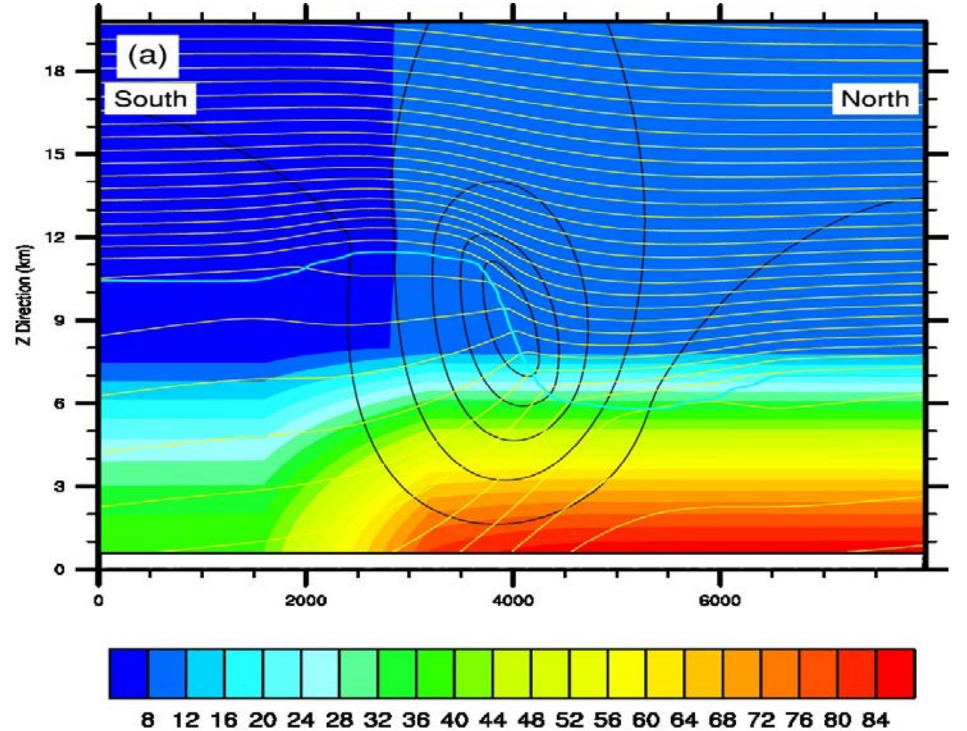
Linear numerical model solution verification

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

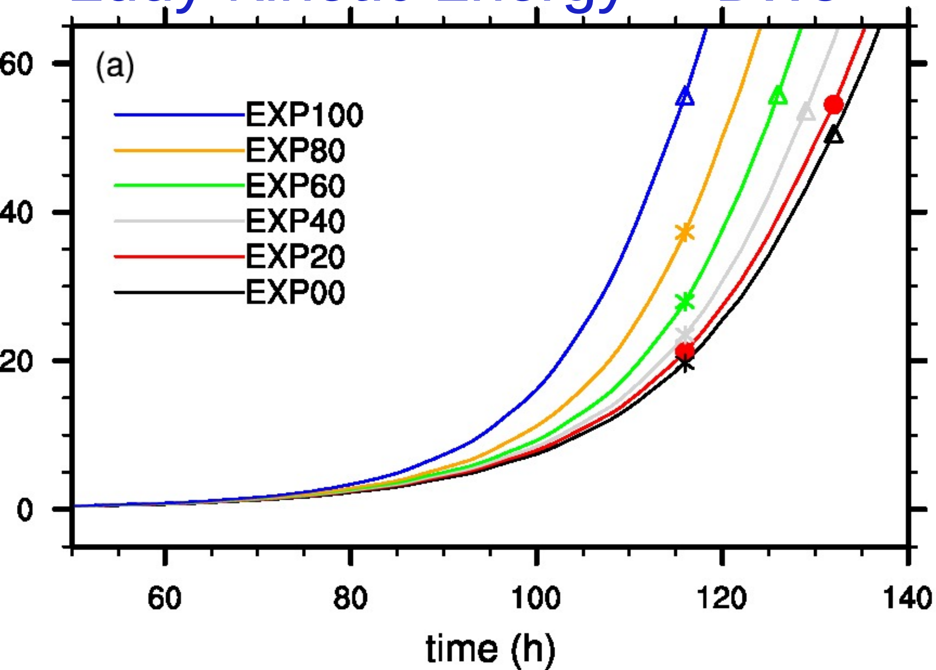


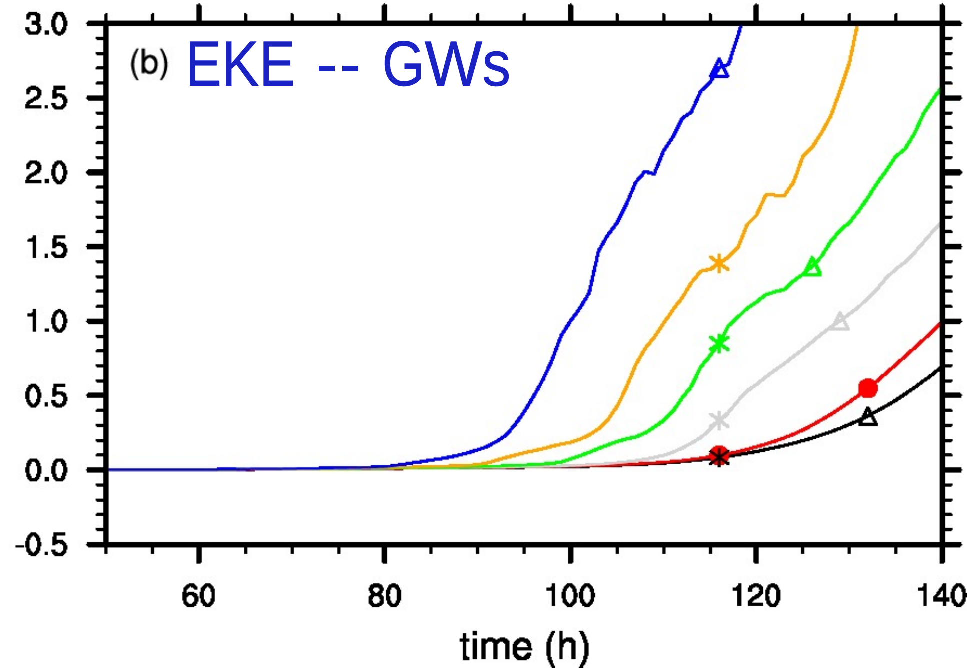
Gravity Waves from Moist Baroclinic Jets

(Wei and Zhang 2014 JAS)

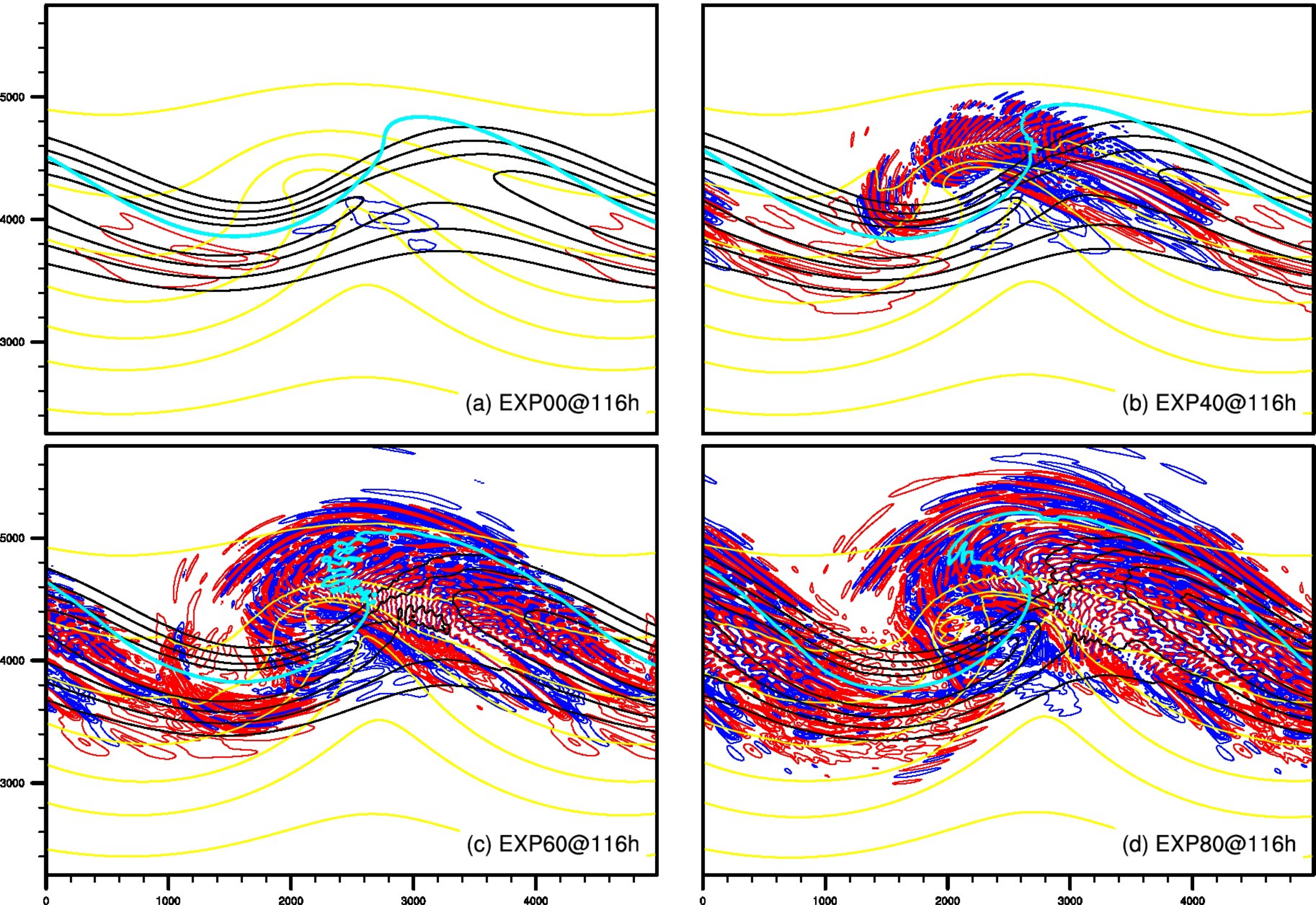


Eddy Kinetic Energy -- BWs

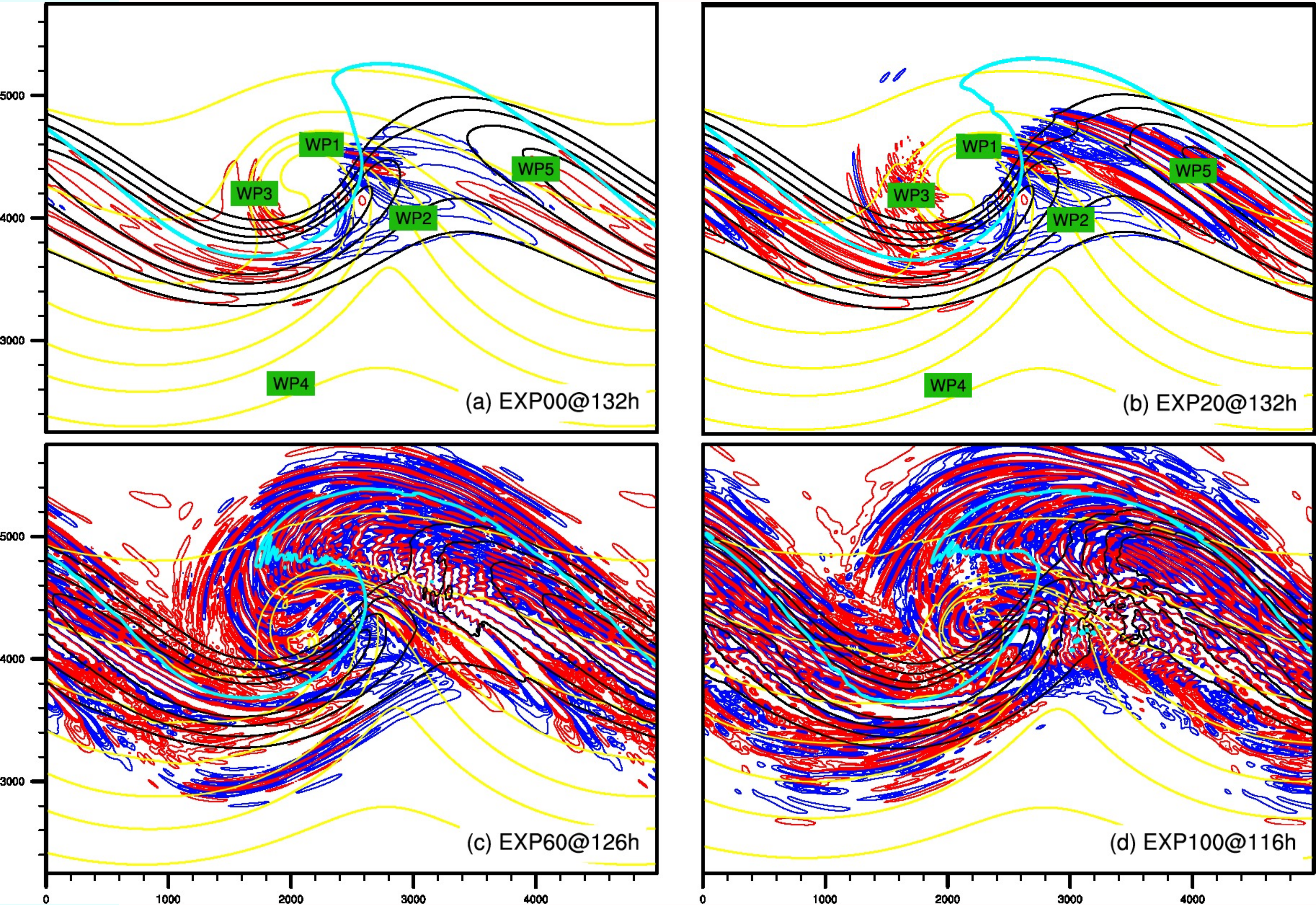




Gravity Waves in Moist Jets: same model time

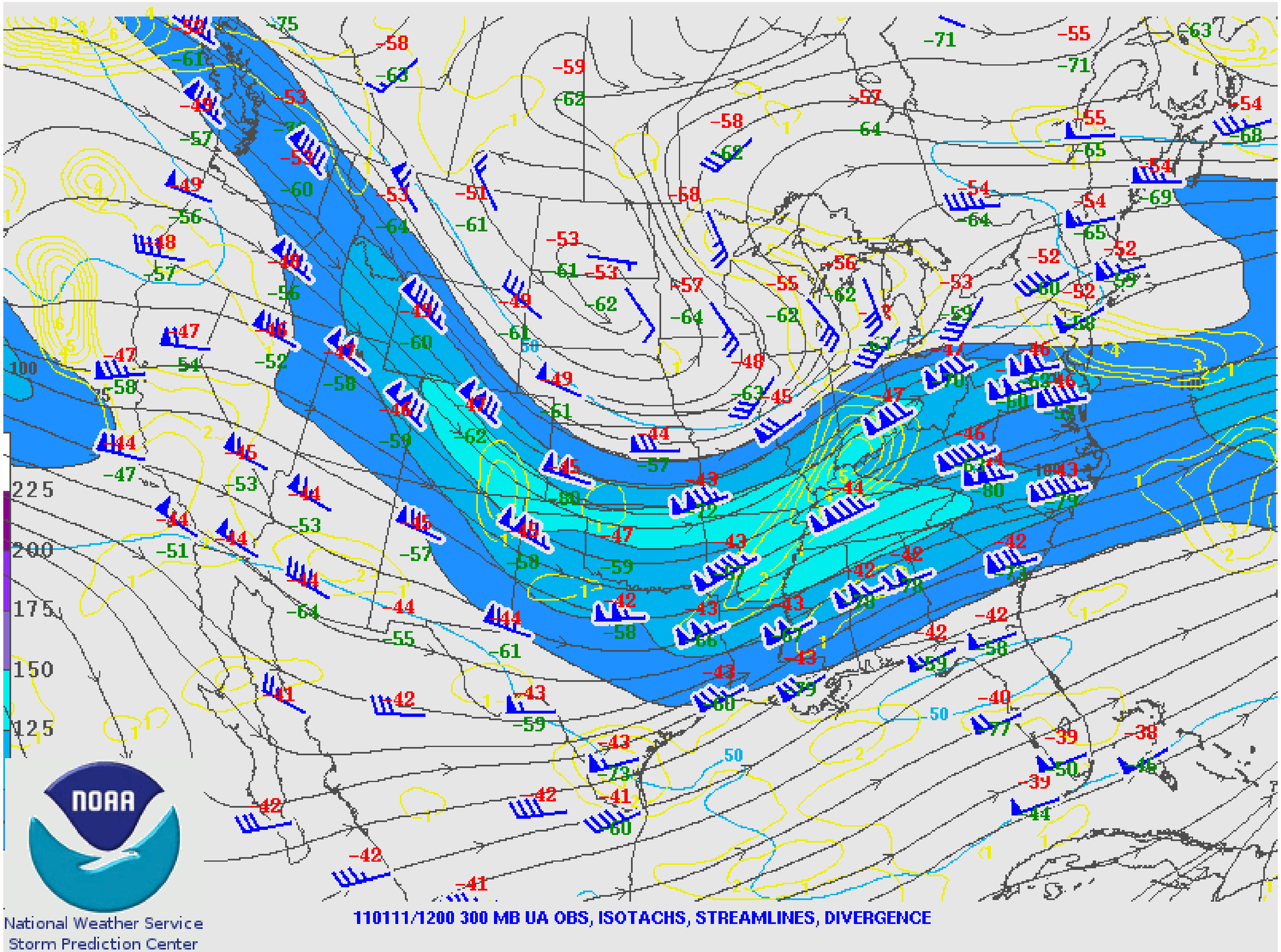


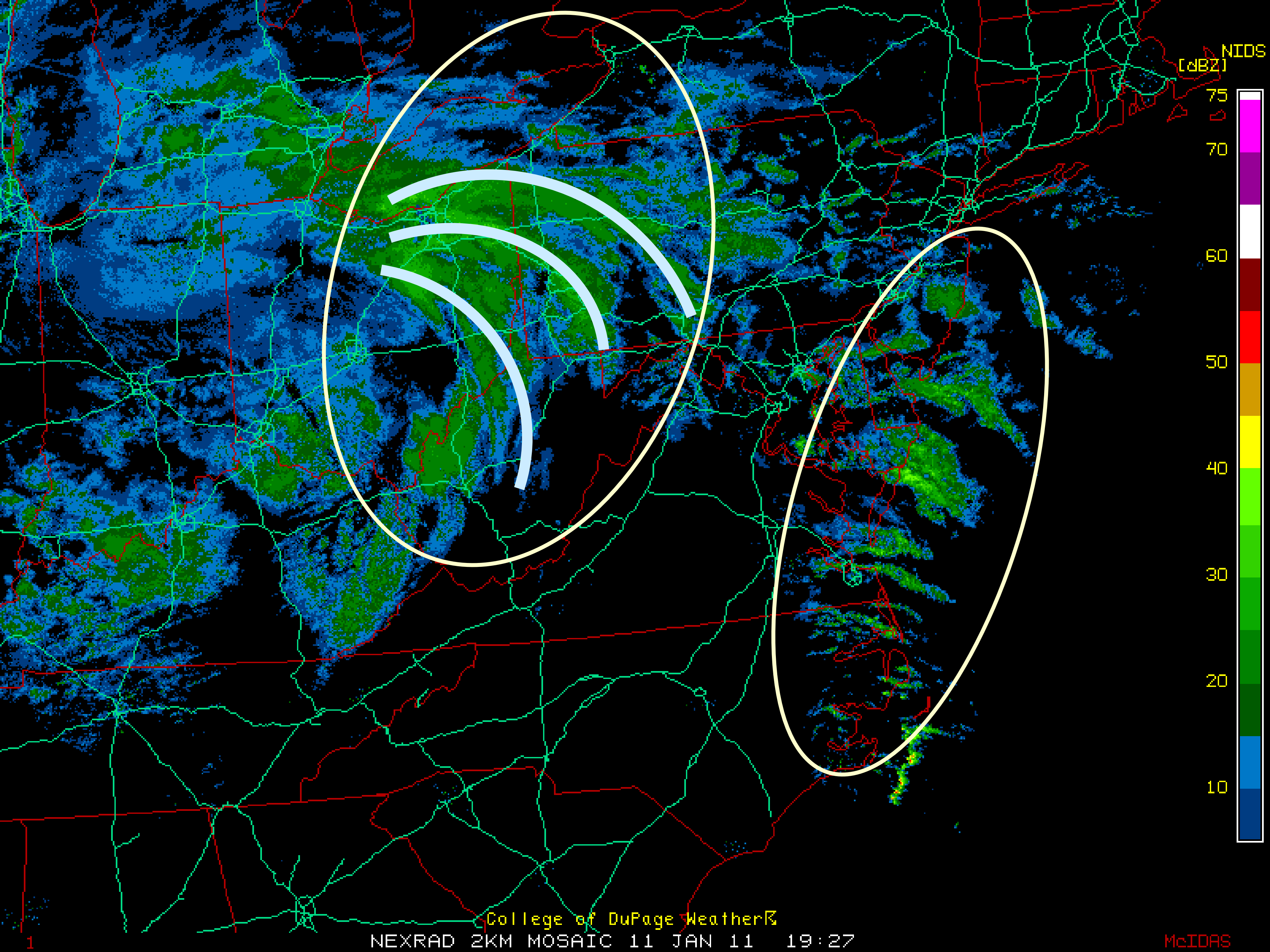
Gravity Waves in Moist Jets: similar stage of BWs



Gravity Waves in Moist Baroclinic Jets/fronts

Real world examples: Jan 11, 2011

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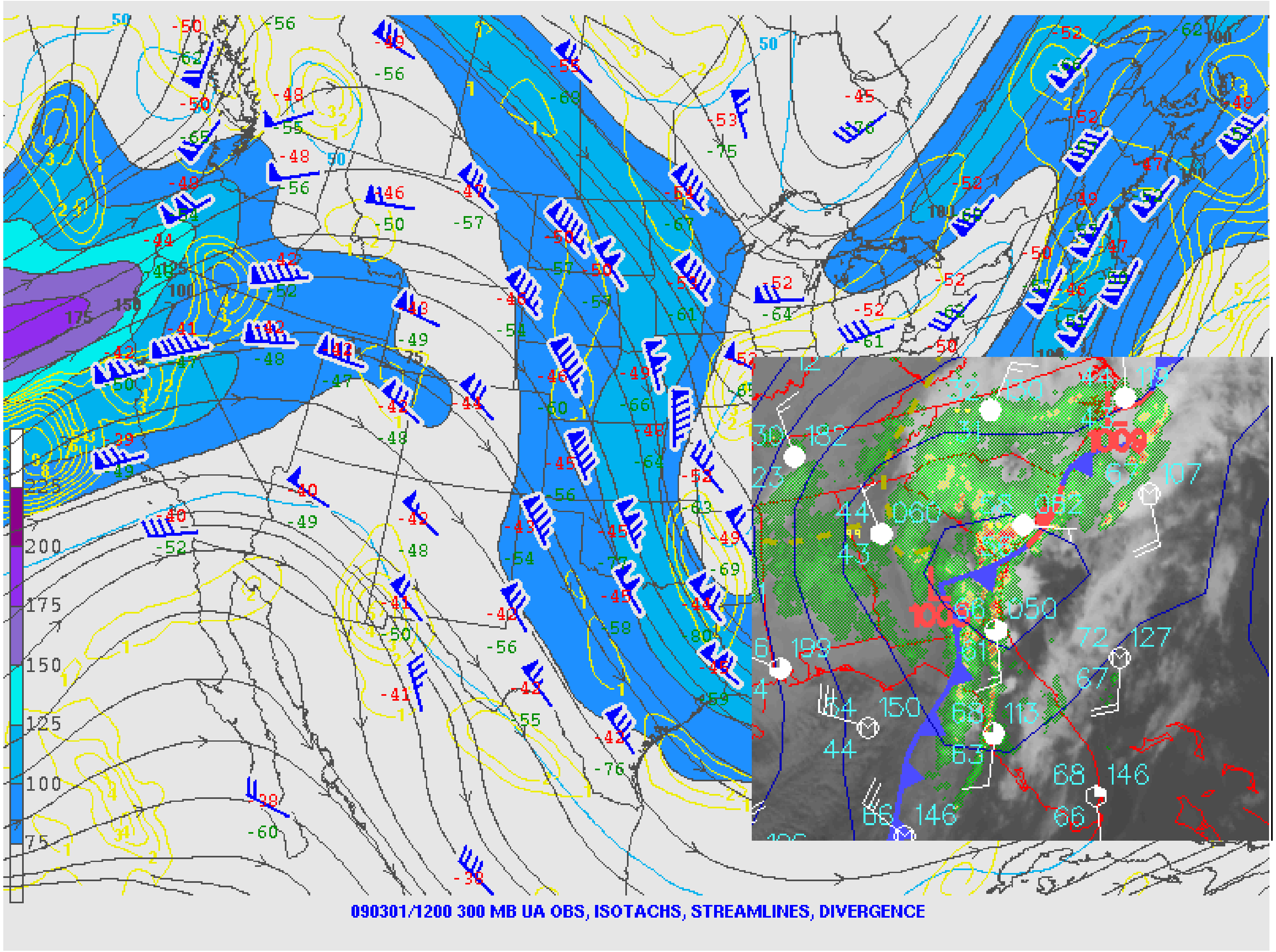
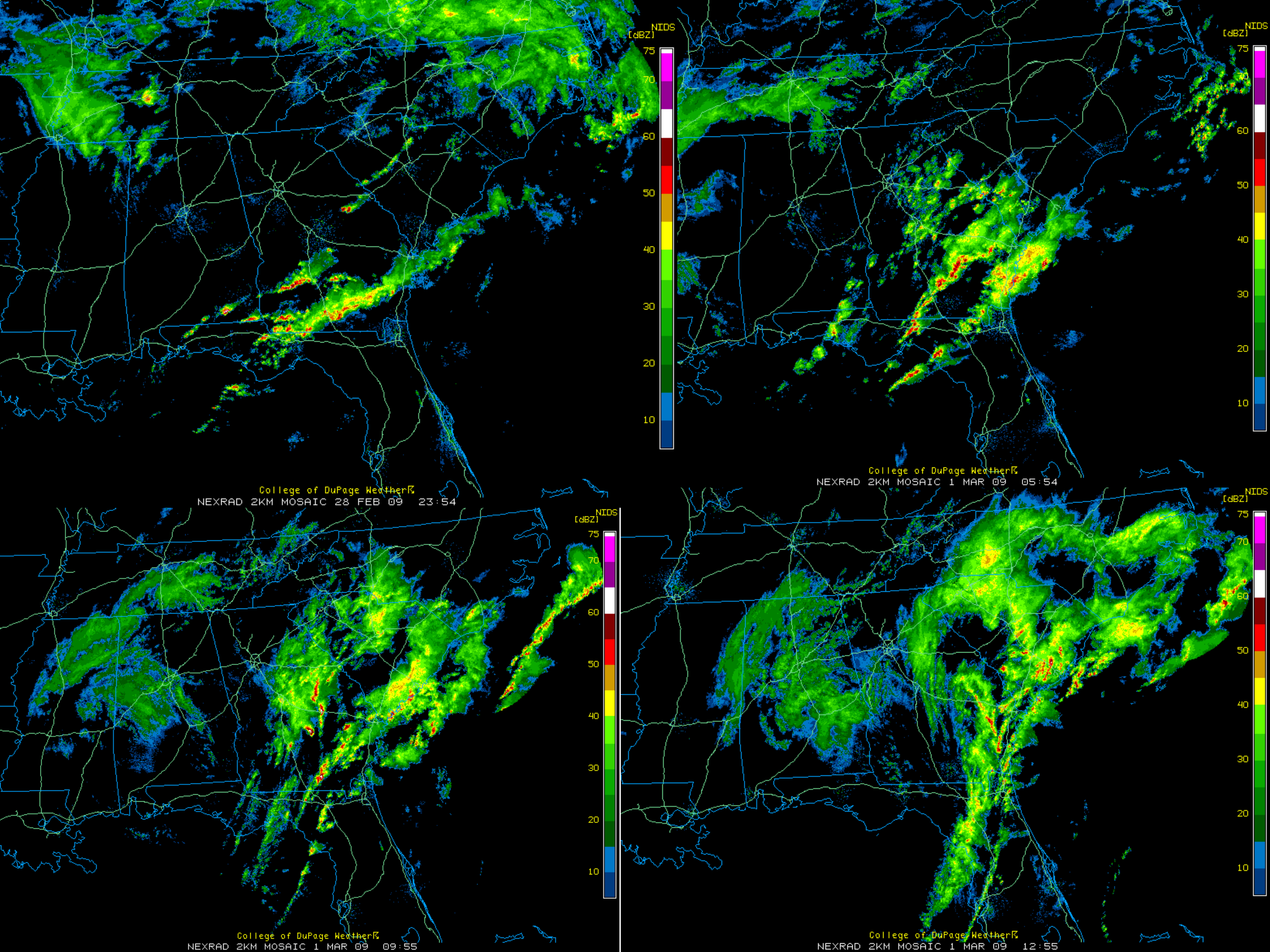
Gravity Waves in Moist Baroclinic Jets/fronts

Real world examples: March 1, 2009

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60
50
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20
10
College of DuPage Weather
NEXRAD 2KM MOSAIC 28 FEB 09 23:54
NEXRAD 2KM MOSAIC 1 MAR 09 05:54
NEXRAD 2KM MOSAIC 1 MAR 09 09:55
NEXRAD 2KM MOSAIC 1 MAR 09 12:55

Concluding Remarks

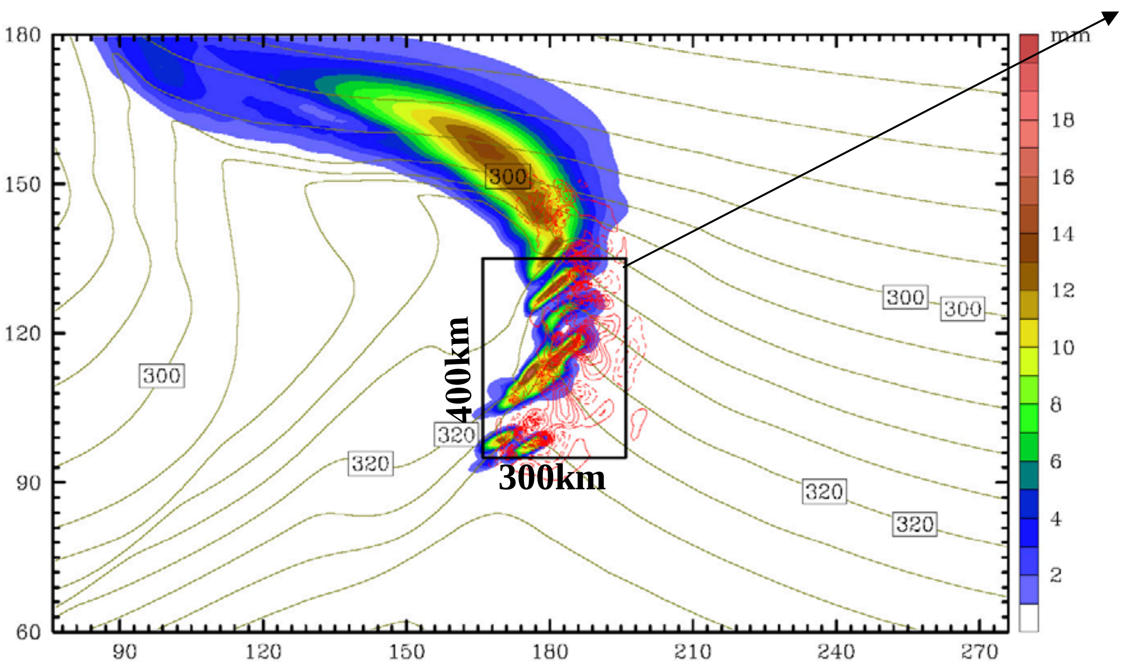
- **Predictability of extratropical cyclones can be intrinsically limited at the mesoscales due to the chaotic nature of moist convection**
- **Baroclinic jet-front systems are prolific sources of mesoscale gravity waves, especially in the exit region of the jet streak**
- **These gravity waves are hypothesized to be generated through *spontaneous balance adjustment* (as a generalization of geostrophic adjustment) in which imbalance continuously produced by large-scale baroclinic 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**
- **Stronger baroclicity in moist BWs and thus stronger flow imbalance, diabatic heating can force and enhance gravity waves in the moist jet-front systems**
- **Balance adjustment and gravity waves may play important role in limiting the predictability of mesoscale weather and the parent synoptic cyclones**

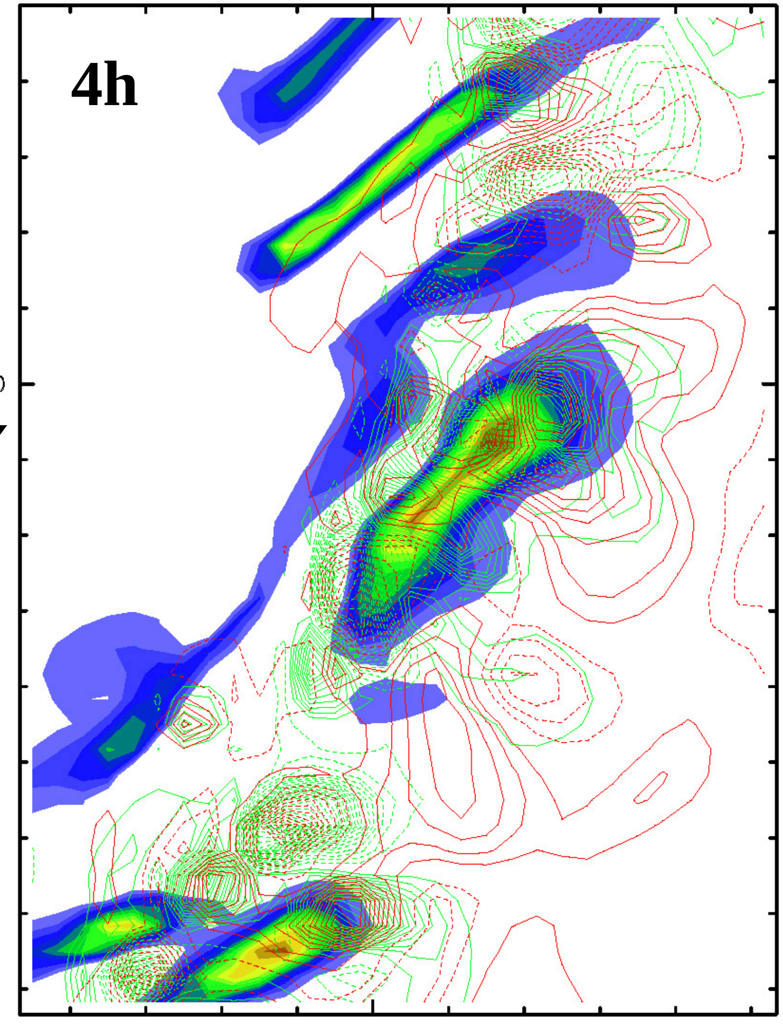
A Multistage Error Growth Conceptual Model

Stage 1, convective growth (0-6h): 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.

Left: MSLP (blue), surface theta-e (gray) 1h precipitation (colored), and difference T (red, every 0.5K)

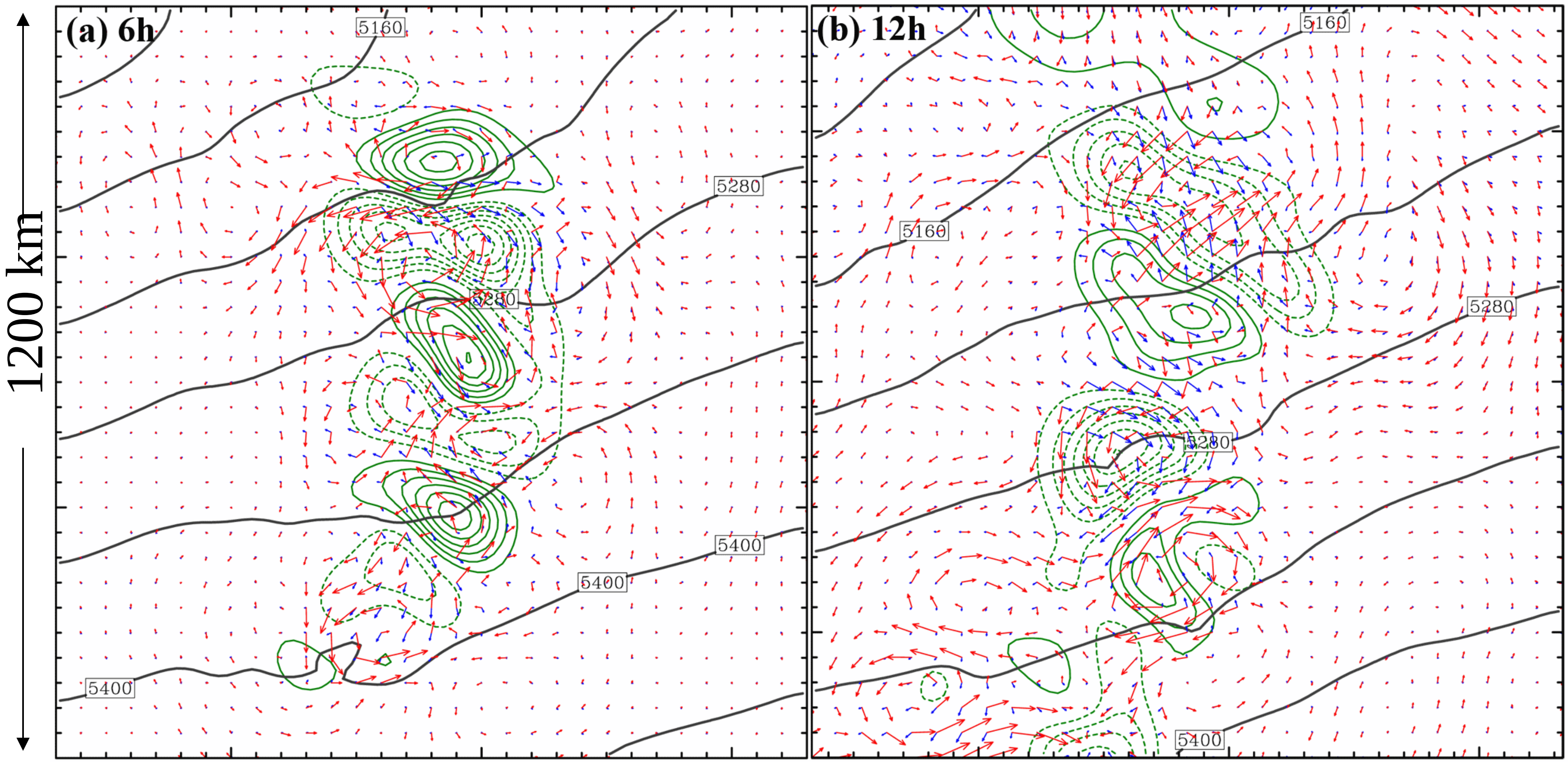
Right: difference 1h precipitation (only >0 colored), T (red) and w (green, every 0.5m/s)





(Zhang, et al. 2007 JAS)

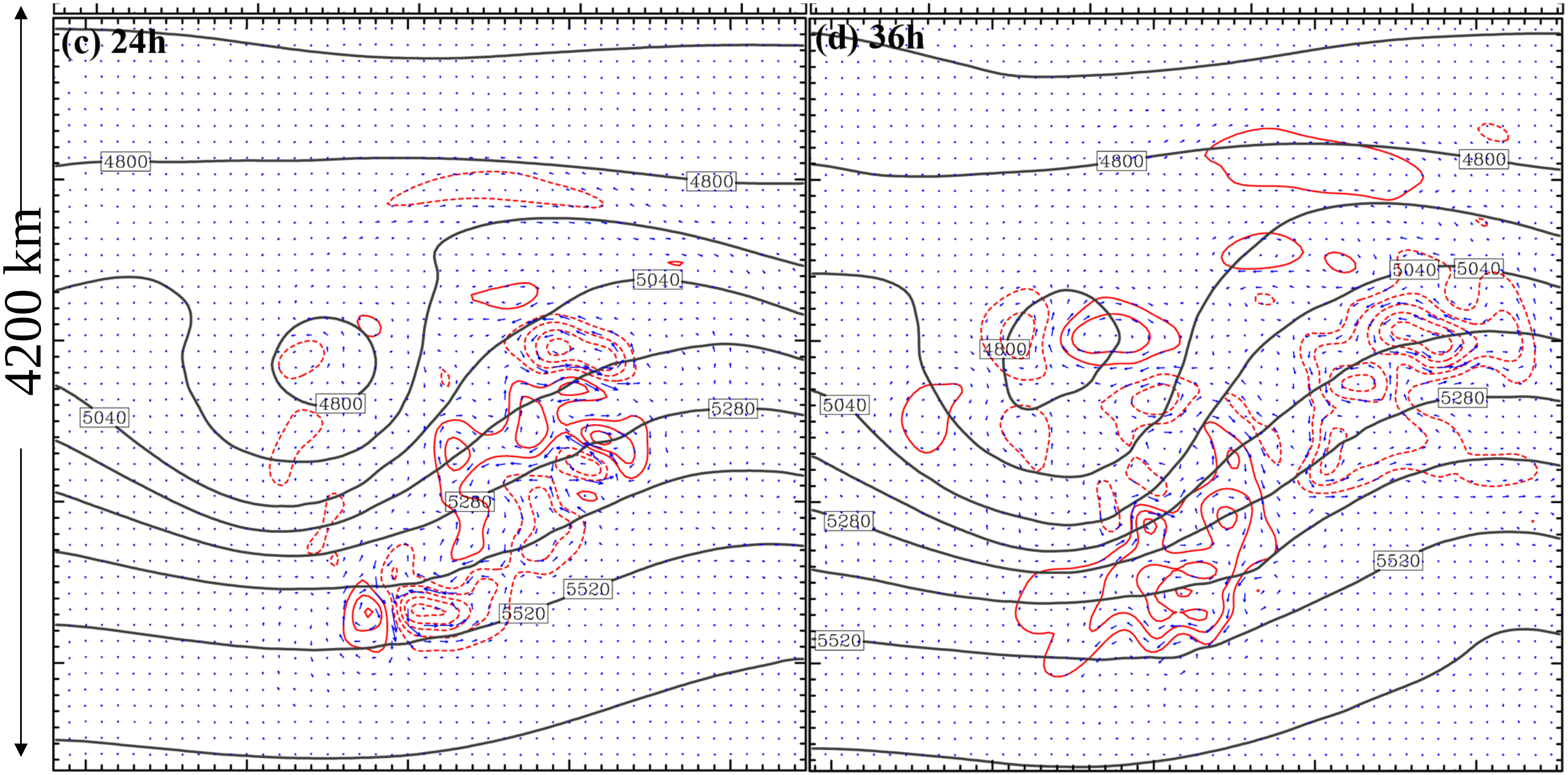
Stage 2, transient growth (6-18h): Saturated errors transform from convective-scale unbalanced to larger-scale balanced motions through geostrophic adjustment and/or cold pool dynamics at time scale *O(2π/f)*



500hPa geopotential heights (black), highly-smoothed difference PV (green, every 0.2PVU), difference winds (blue arrows) and difference ageostropic winds (red arrows)

(Zhang, et al. 2007 JAS)

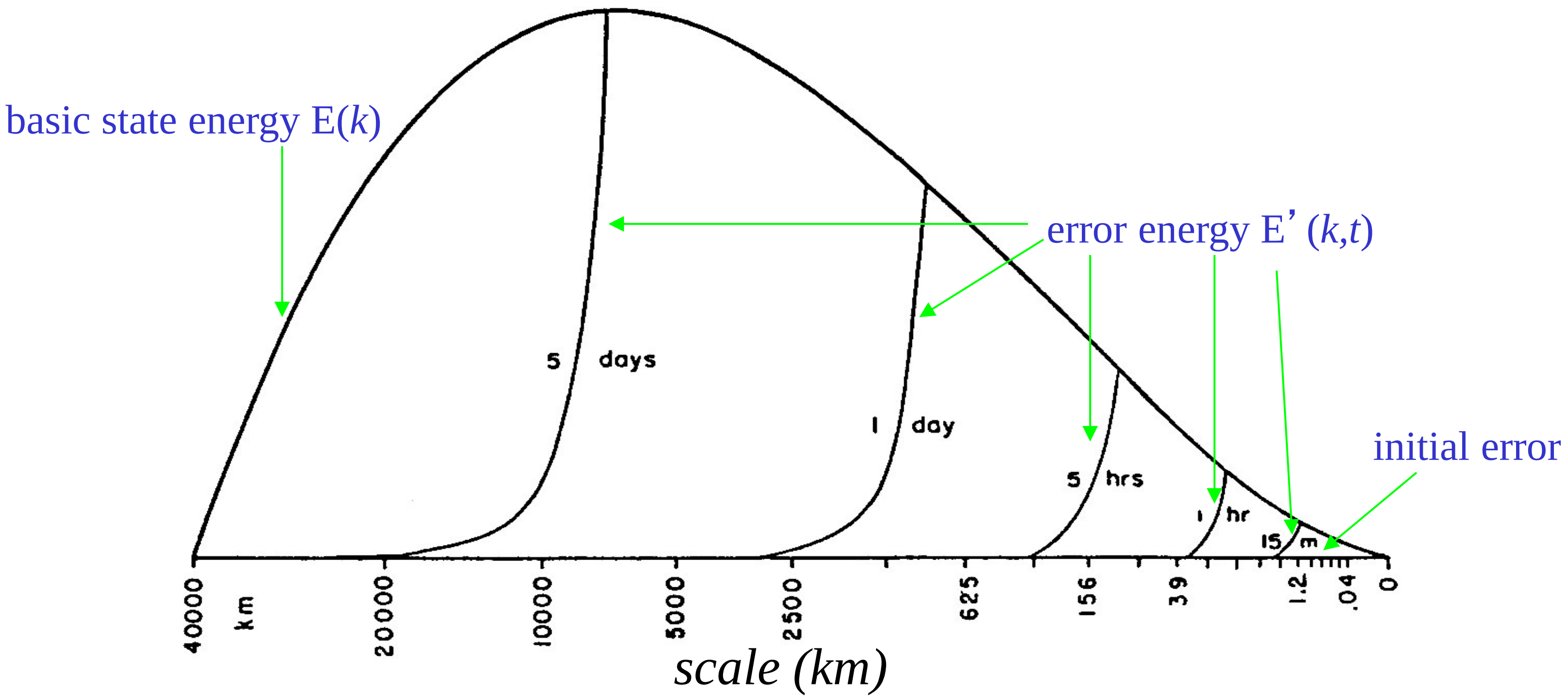
Stage 3, baroclinic growth: Balanced components of the saturated error project onto the larger-scale flow and grow with background dynamics and instability at the time scale of *O(1day)*.



500hPa geopotential heights (black), highly-smoothed difference pressure perturbations (red, every 0.2mb), difference winds (blue arrows)

(Zhang, et al. 2007 JAS)

Multi-Scale Predictability Foreseen by Lorenz (1969)



"An error in observing a thunderstorm, after doubling perhaps every fifteen minutes until it becomes large, may subsequently lead to an error in a larger scale of motion, which may then proceed to double every five days. If this is the case, cutting the original error in half would increase the range of predictability of the larger scale not by five days but by only fifteen minutes."

Practical Predictability vs. Intrinsic Predictability

(Lorenz 1996; Zhang et al. 2006; Melhauser and Zhang 2012)

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.

Implication: setting up expectations and priorities for advancing deterministic mesoscale forecasting (through better model, observing network and/or data assimilation); guidance on the design of mesoscale ensemble prediction systems (through understanding of the mesoscale error growth mechanisms)