Shear-Parallel Mesoscale Convective Systems in a Moist Low-Inhibition Mei-Yu Front Environment

Liu and Moncrieff (2017 JAS)

Introduction

- Balance of lower-tropospheric wind shear and strength of evaporation-generated cold pool is highly important in governing TS squall line organization (Rotunno et al. 1988; RKW theory)
- For other types of convective systems (eg. TL-AS MCS), the mechanism regulating their organization (eg. back-building) is highly dependent on near-surface cold outflow (Parker 2007a)
- *Role of cold pool much more uncertain in Mei-yu front environment!*
- Crucial characteristic of mei-yu front environment is the nearly-saturated low troposphere -> Limited evaporative cooling and weakened density current

Past results on MCSs in near-saturated environments

i. *Lack of cold pool forcing increases the importance of other processes (eg. mesoscale forcing. gravity wave) [Crook and Moncrieff 1988]*

ii. *Studies for quasi-stationary heavily raining MCS suggests that convectively-generated gravity wave forcing is influential for flow organization [Schumacher and Johnson 2008; Schumacher 2009, 2015]*

iii. *Fovell et al. (2006) has established the relationship between gravity wave forcing and the observed "convective initialization prior to squall line gust front" phenomenon*

Experiment Design

- WRF model [2401x1801x101 grid points, (0.5km horizontal, 0.2km vertical)
- Sounding used previously by Yamasaki (2009) used to simulate a 2004 mei-yu rainband, under strong westerly shear
- Mei-yu environment is approximated by the following perturbation equations:

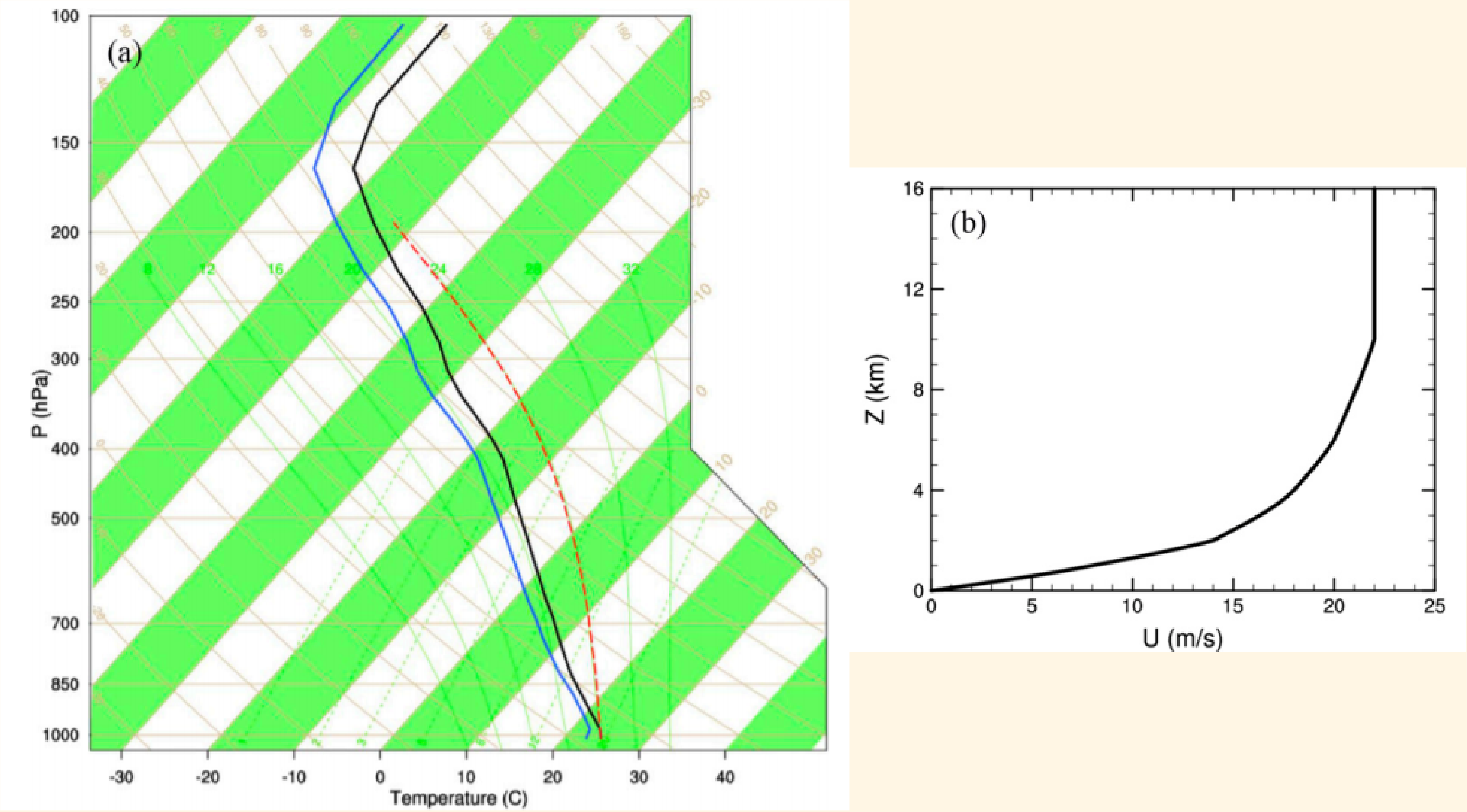
$$\theta(x, y, z) = \Delta\theta \cos^2[(\pi/2) \times \mathrm{RAD}], \quad \mathrm{RAD} \le 1, \qquad (1)$$

$$\mathrm{RAD} = \{[(x - x_c)/100]^2 + [(y - y_c)/100]^2 + (z - z_c)^2\}^{1/2}$$

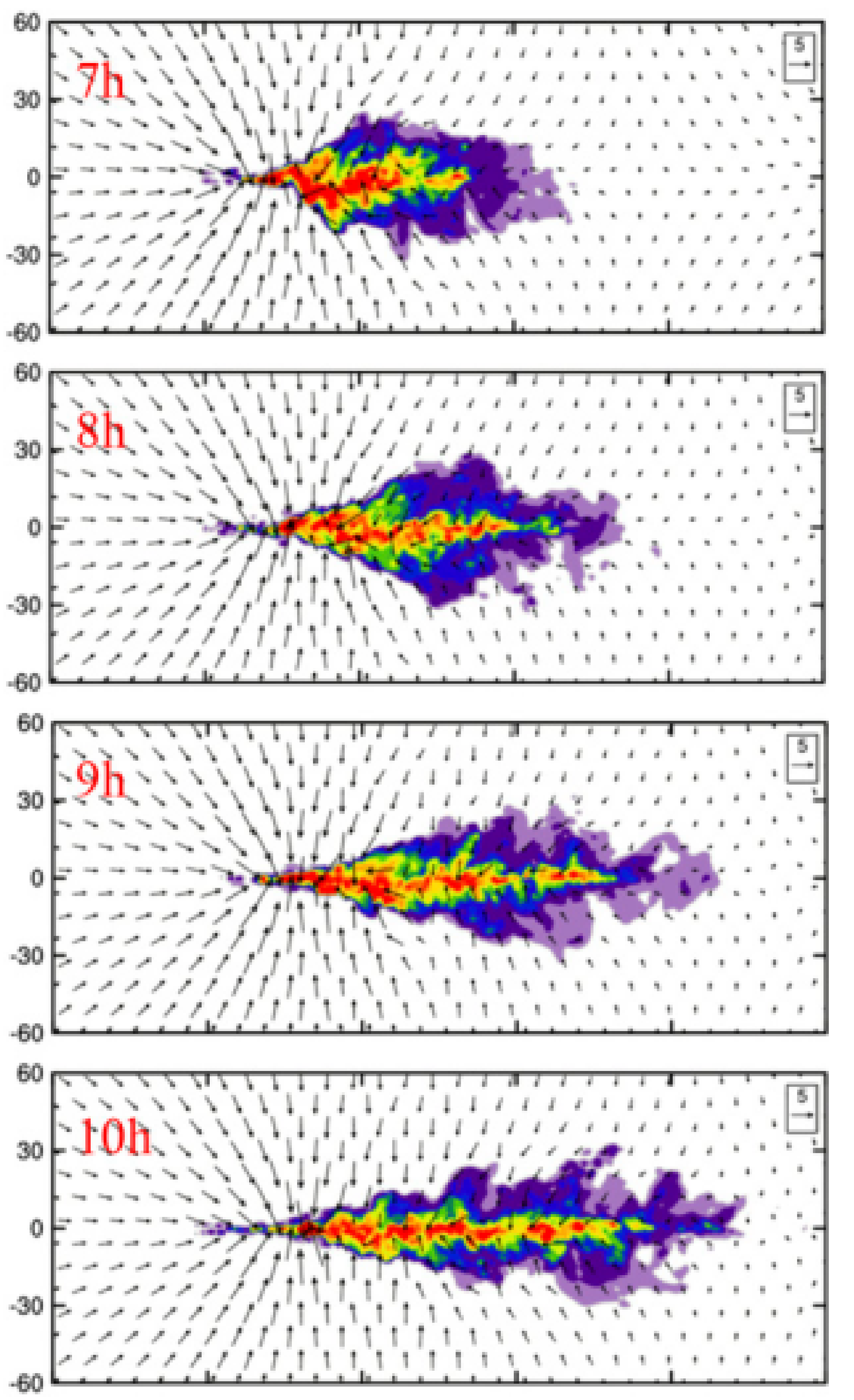
$$q_v(x, y, z) = Q_v(z)\left\{0.85 + 0.15 \exp\left[-(y/100)^2\right]\right\}, \qquad (2)$$

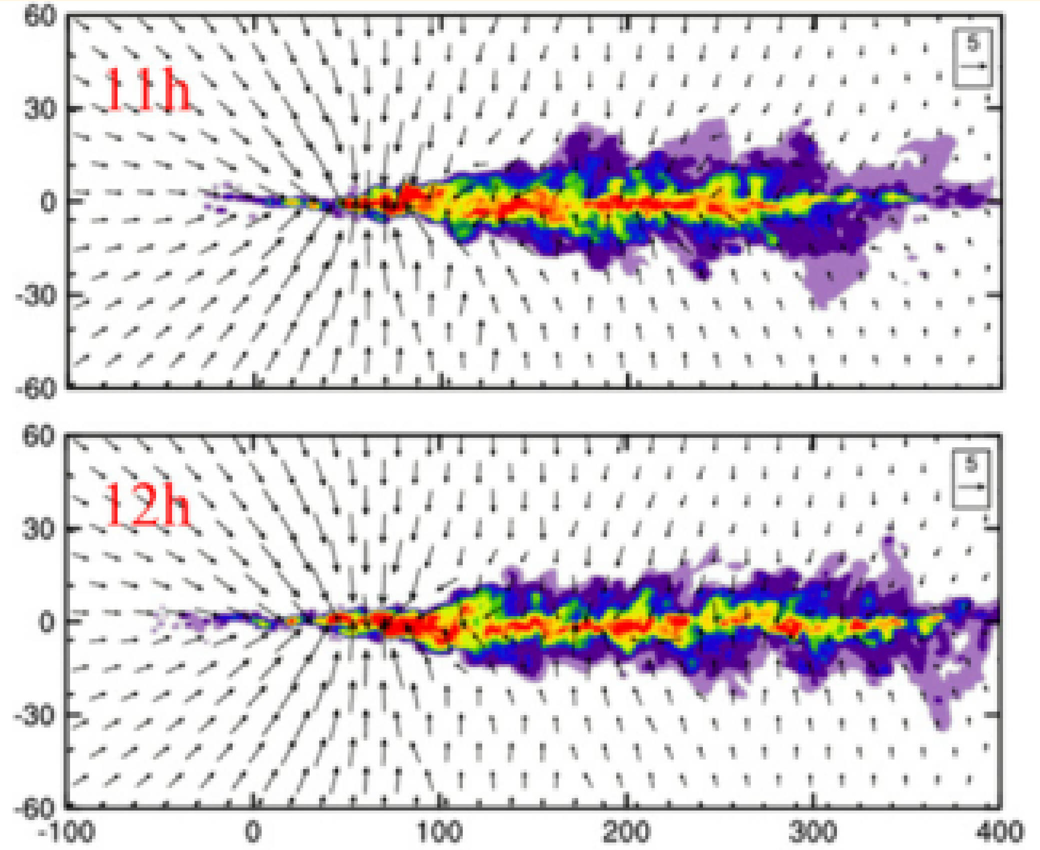
  - These equations define a 200-km-wide moisture front, corresponding to a Tv gradient of ~0.3K/100km
  - 1 sensitivity test (No rainwater evaporative cooling)

Initialized sounding



Does weak cold pool play a role?



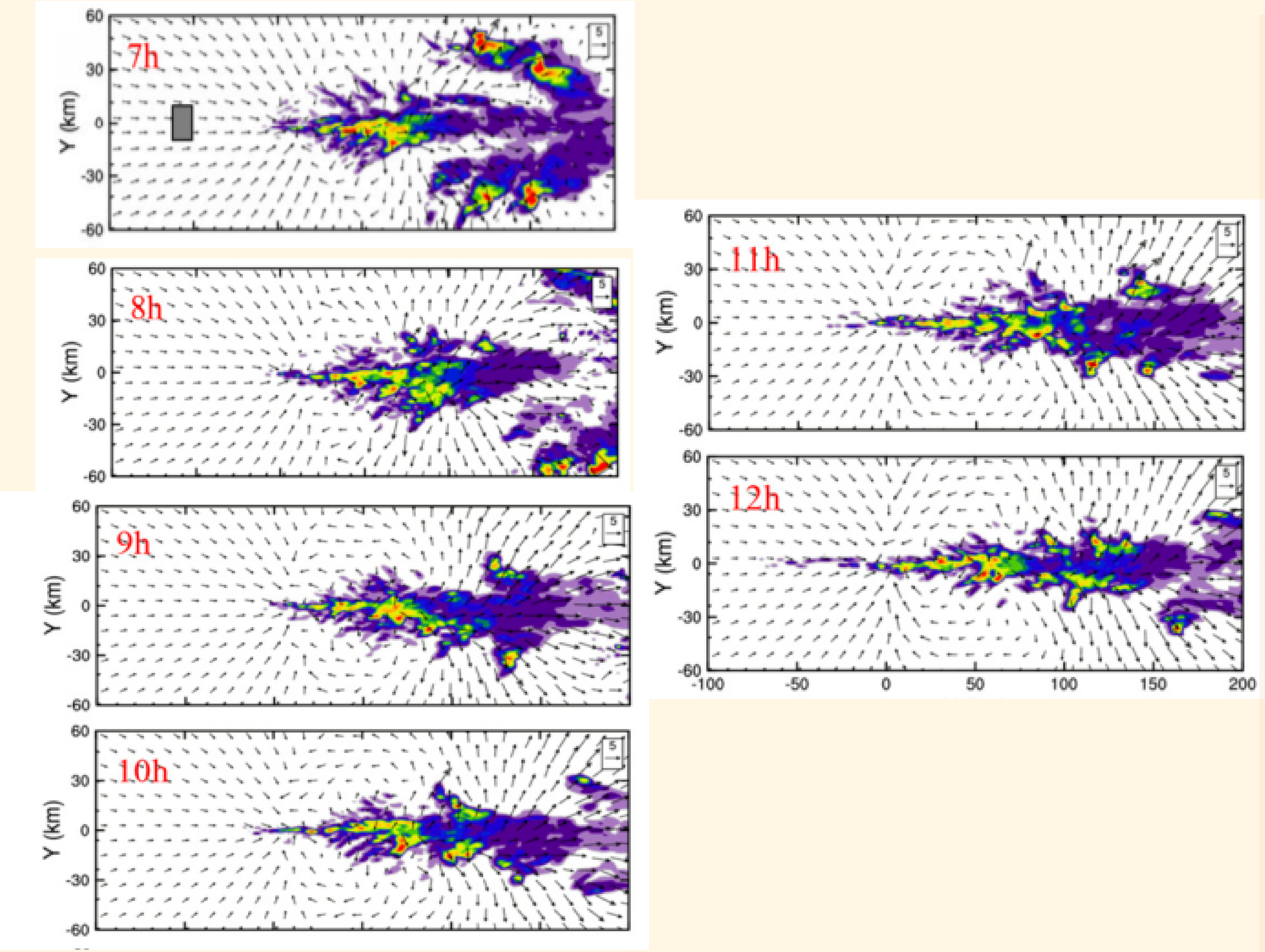


Hypothesis

Turning off rainwater evaporation ->
Less diabatic cooling to neutralize latent heat release->
Stronger MCS

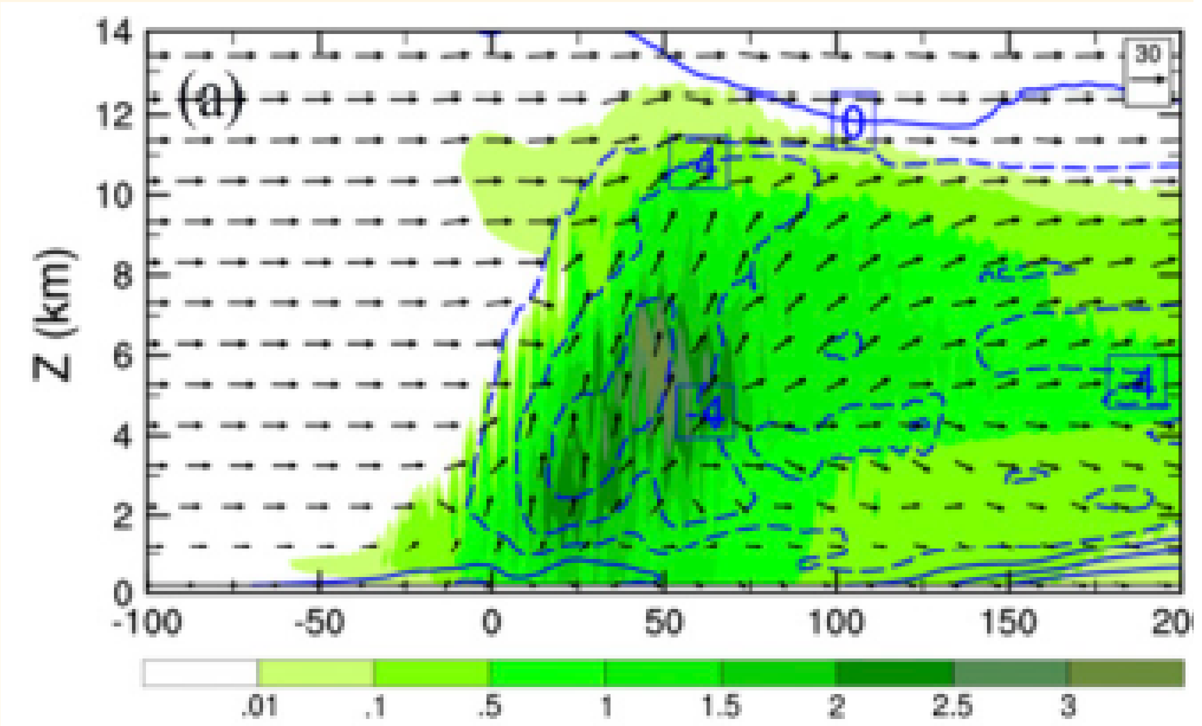
- System evolution similar to CTRL (initial downstream propagation due to ambient wind advection -> quasi-stationary -> slow upstream propagation)
- MCS is narrower than CTRL and extends further upstream
- Much heavier precipitation and precipitation seems to be "locked" along moisture front
- Shear-parallel, quasi-stationary, elongated rainband is produced is both simulations

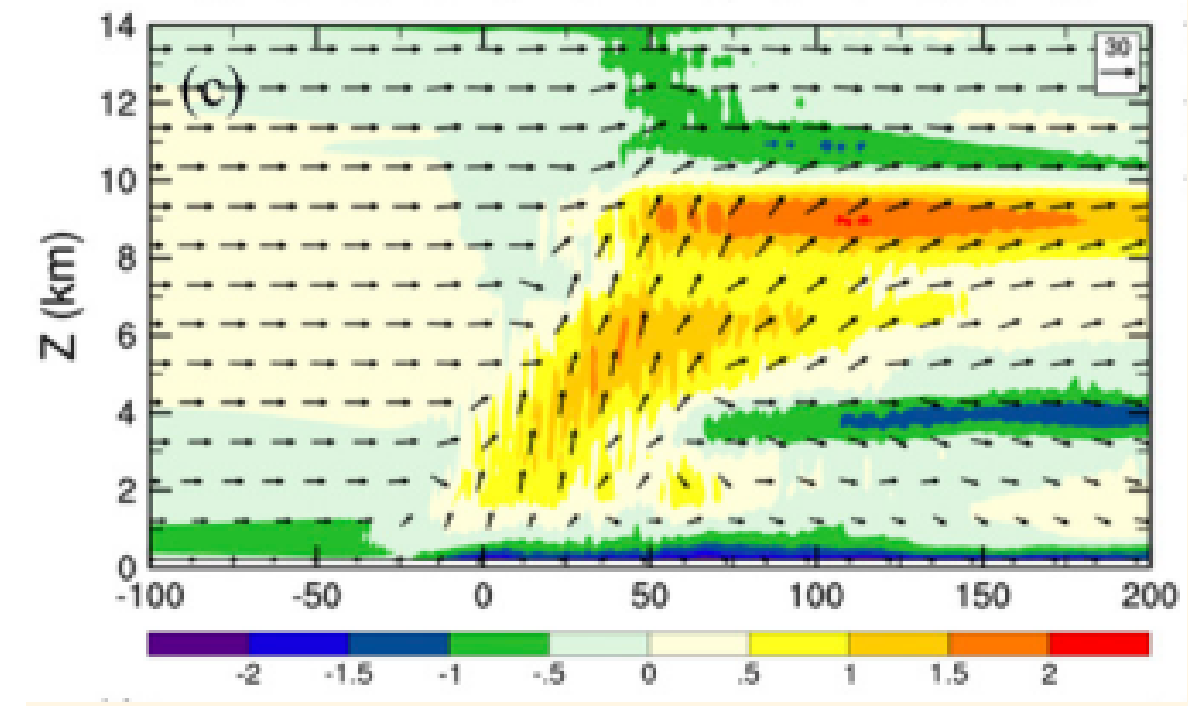
Surface precipitation

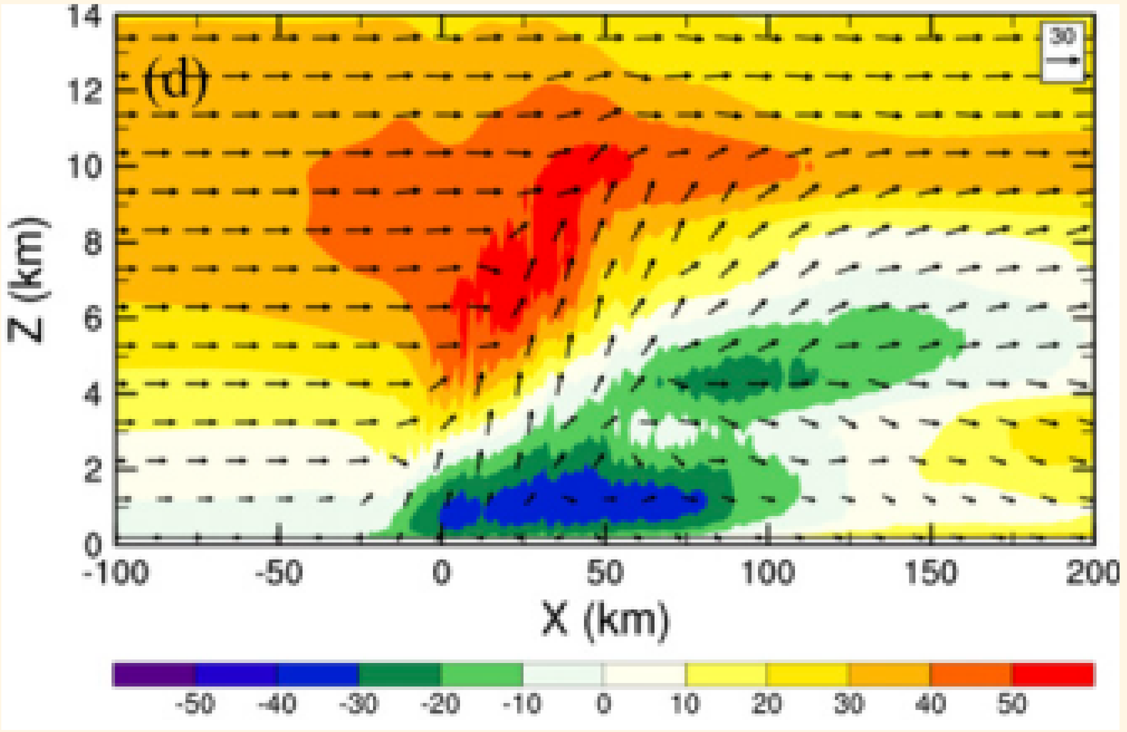


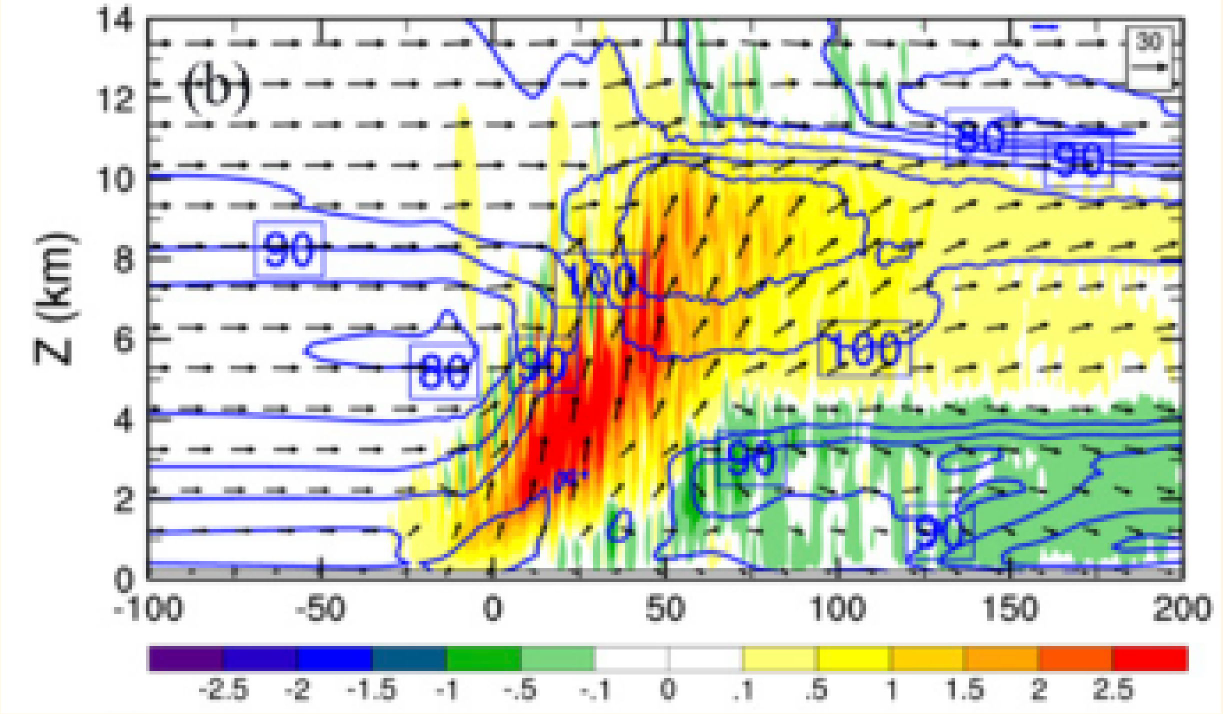
- Strong convective precip centered on moisture front, weak stratiform precip downstream
- Quasi-stationary MCS moves upstream slowly due to repeated convective initiation
- The overall structure similar to back-building/parallel-stratiform MCS (Parker 2007a,b; Wang et al. 2014)
- The MCS is characterized by "upstream building" as cells regenerate to the east of MCS system

Mesoscale kinematic and thermodynamic characteristics

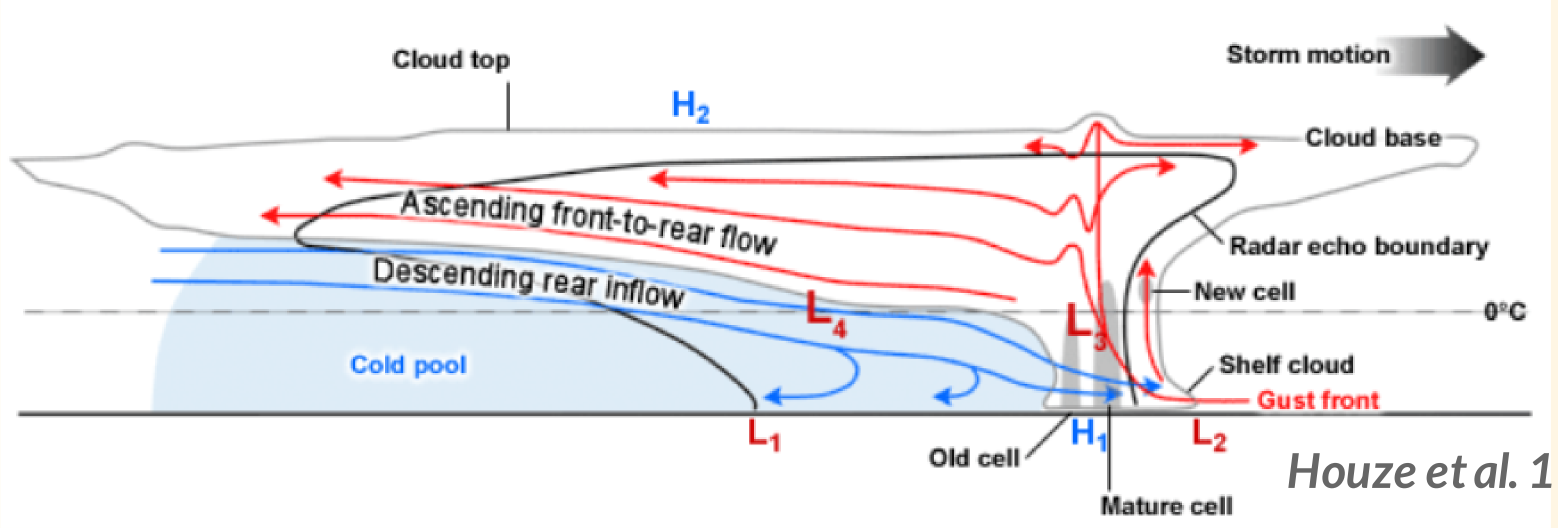




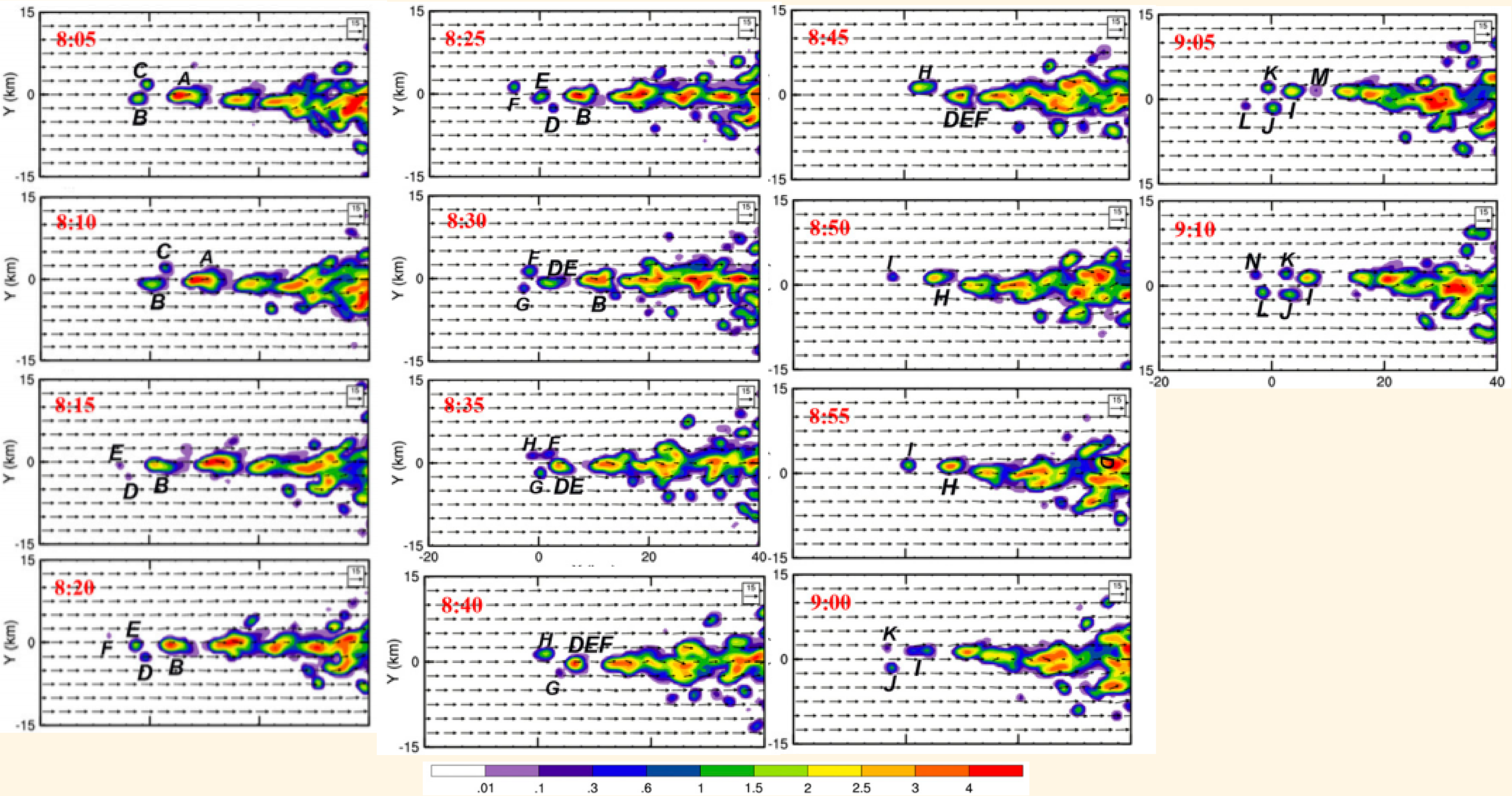




(a) Condensate (shading, g/kg) and u-wind perturbation (contours)
(b) Vertical Velocity (shading, m/s) and RH (contours)
(c) Potential temperature perturbation (shading, oC)
(d) Pressure perturbations (shading, Pa)



Houze et al. 1989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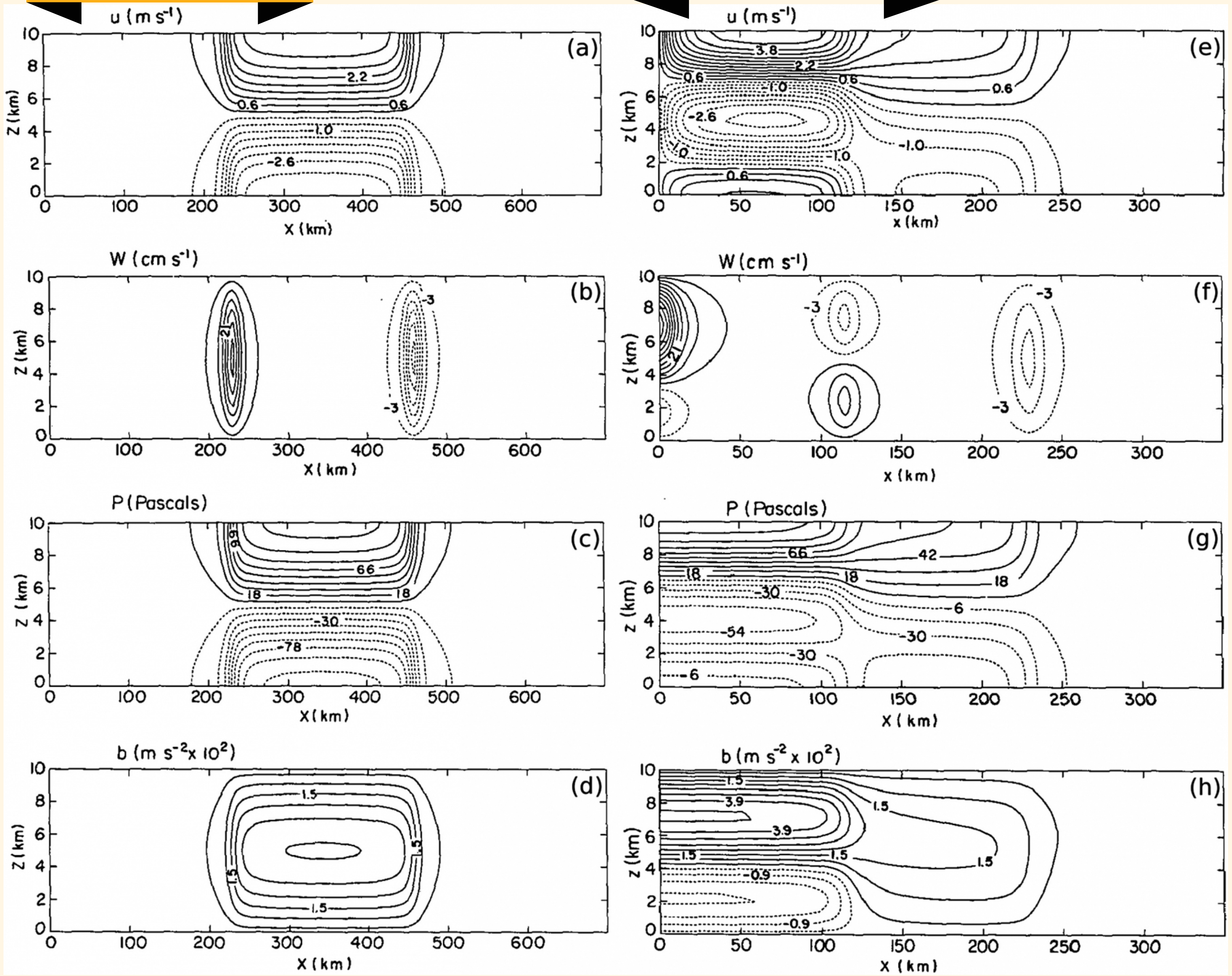
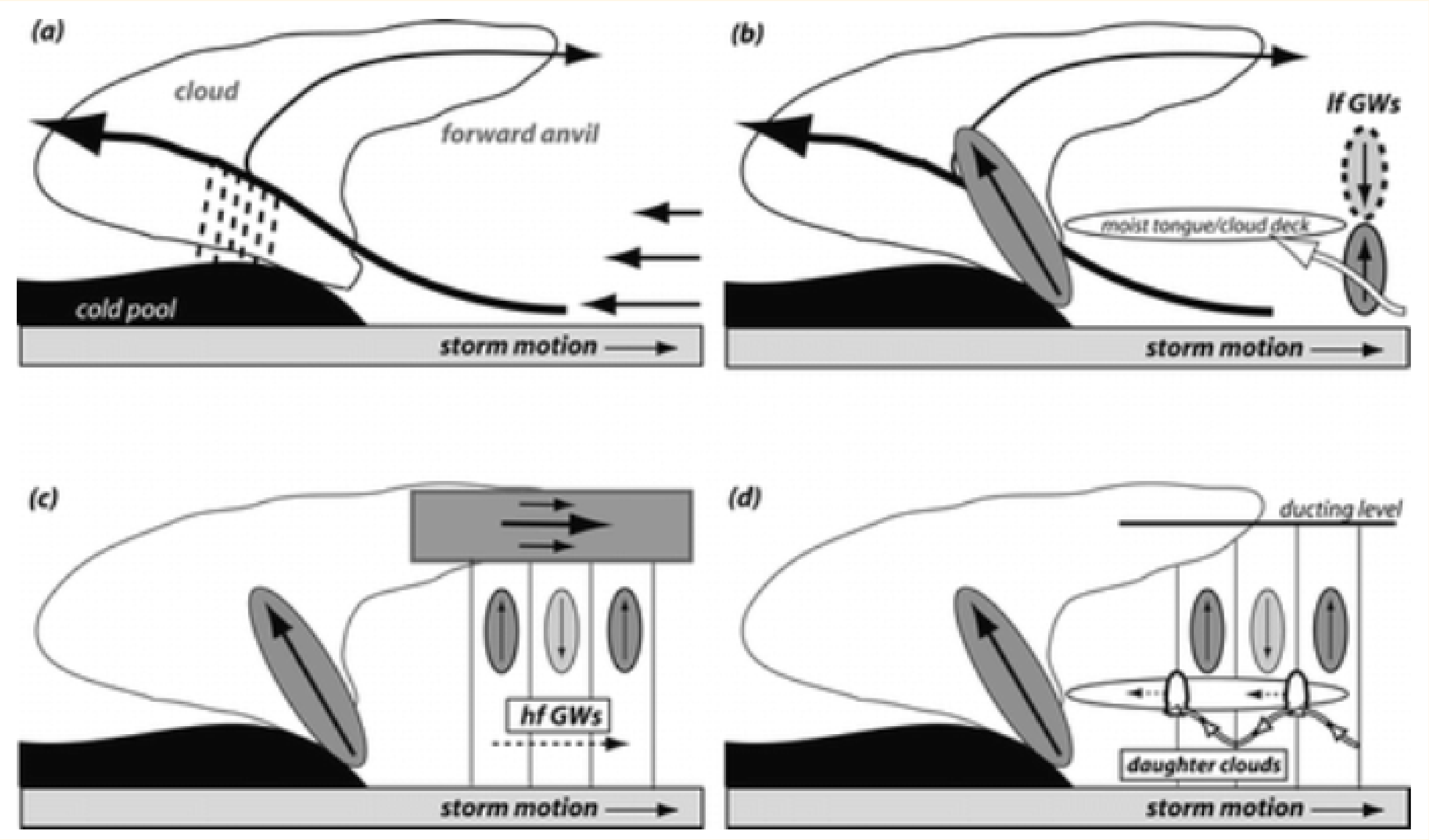
Gravity-waves-generated lifting

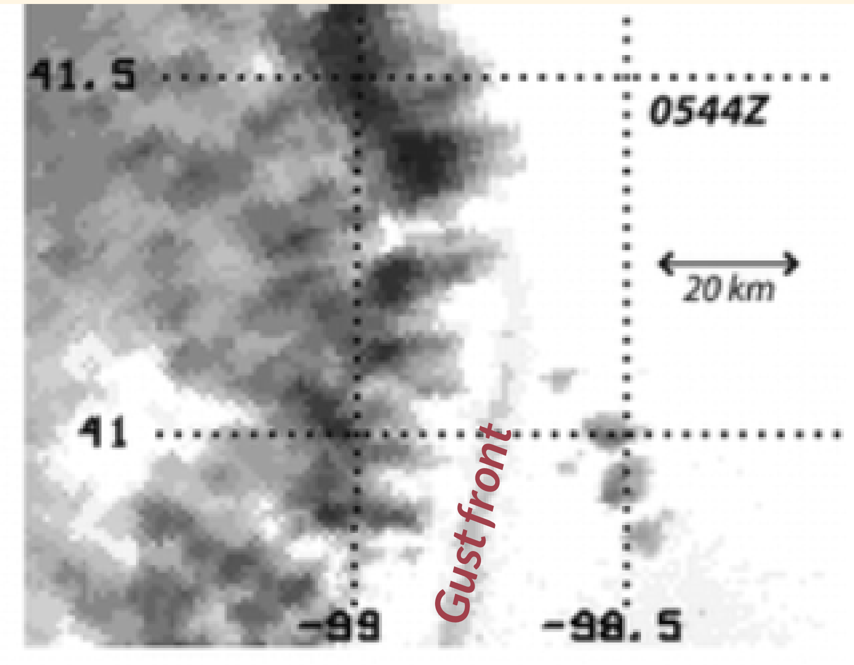
n=1 heating

n=1+2 heating



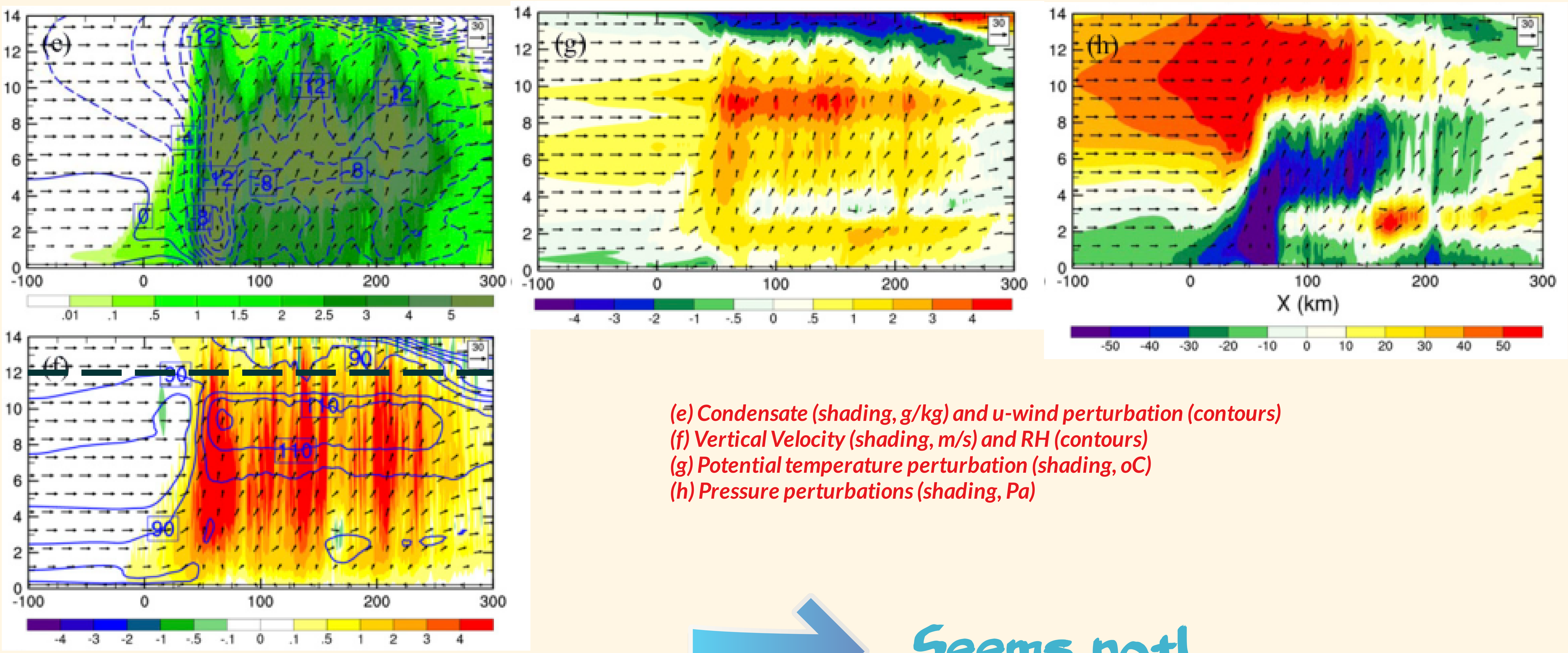
Nicholls et al. (1991)





Fovell et al. (2006)

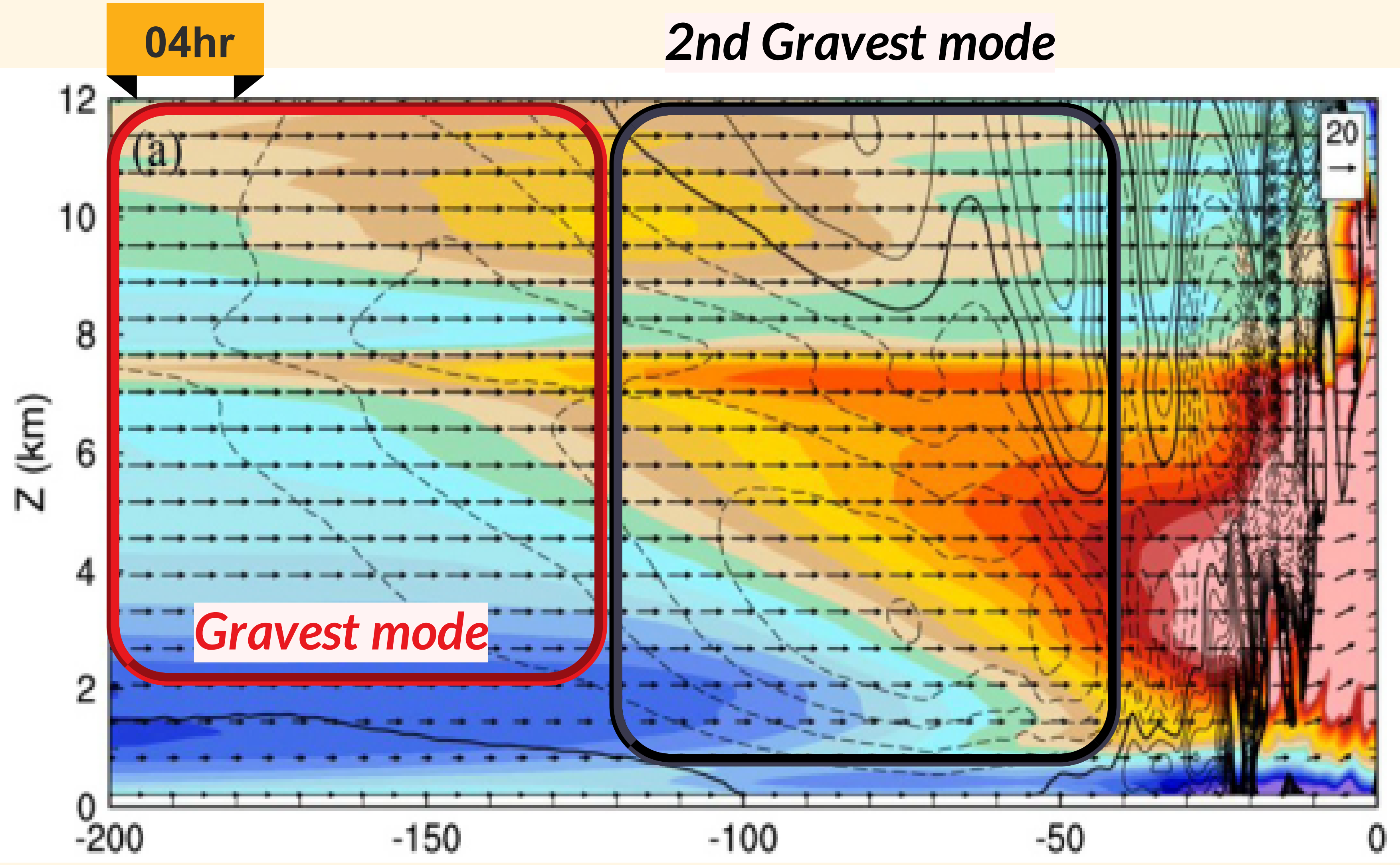
Does weak cold pool play a role?

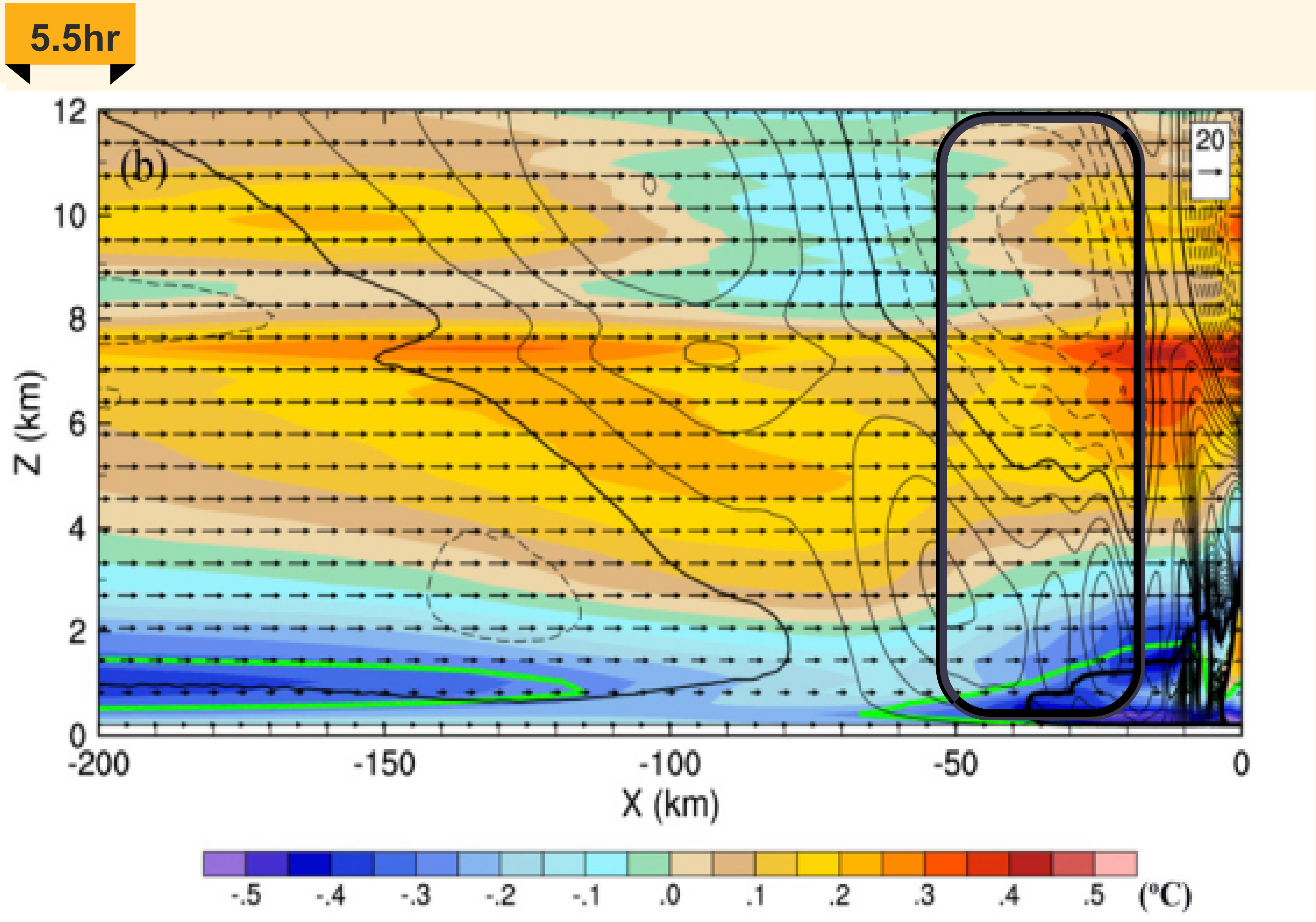


(e) Condensate (shading, g/kg) and u-wind perturbation (contours)
(f) Vertical Velocity (shading, m/s) and RH (contours)
(g) Potential temperature perturbation (shading, oC)
(h) Pressure perturbations (shading, Pa)

Seems not!

Gravity wave activity
I. Upstream-propagating deep mode



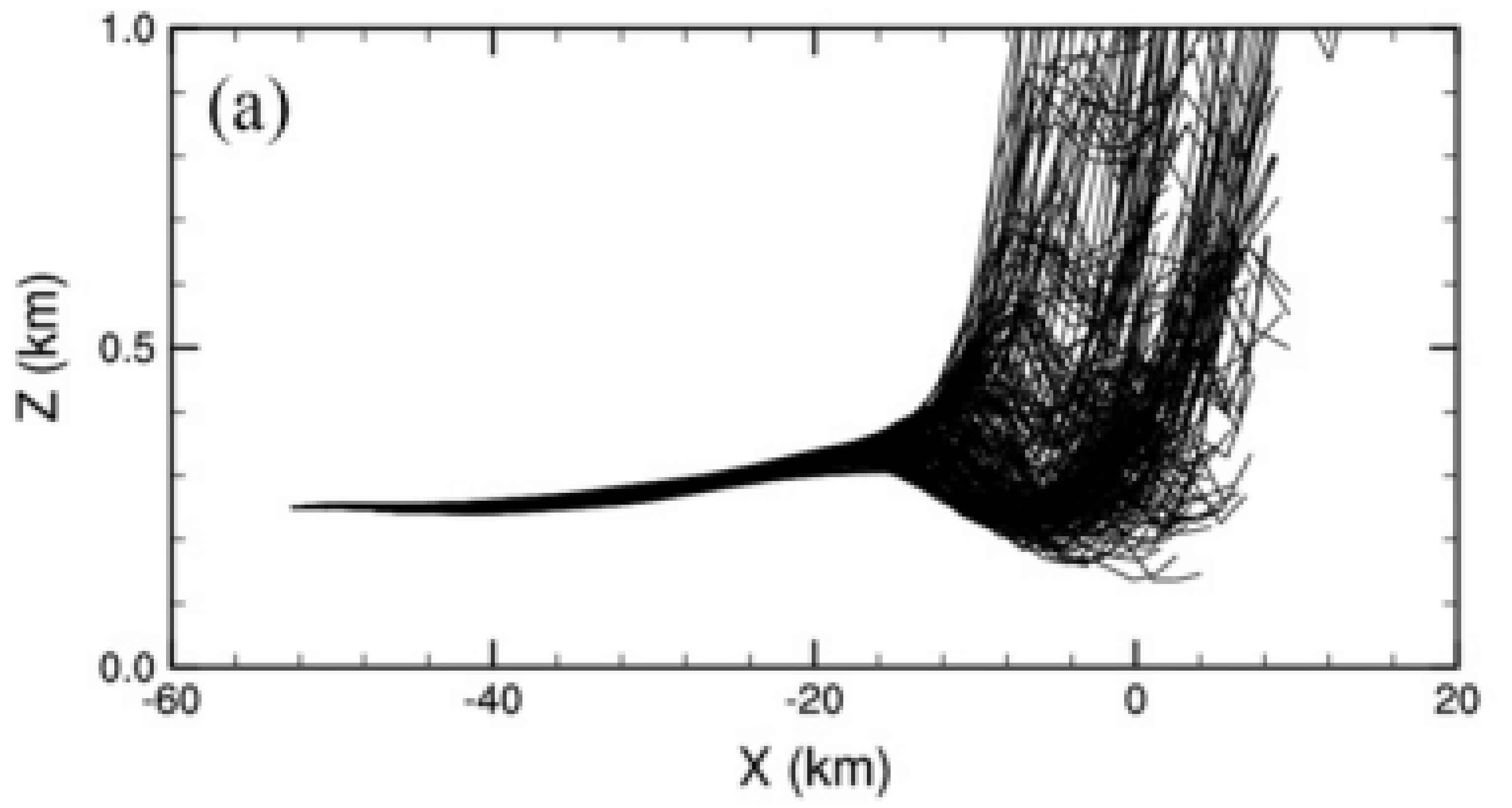


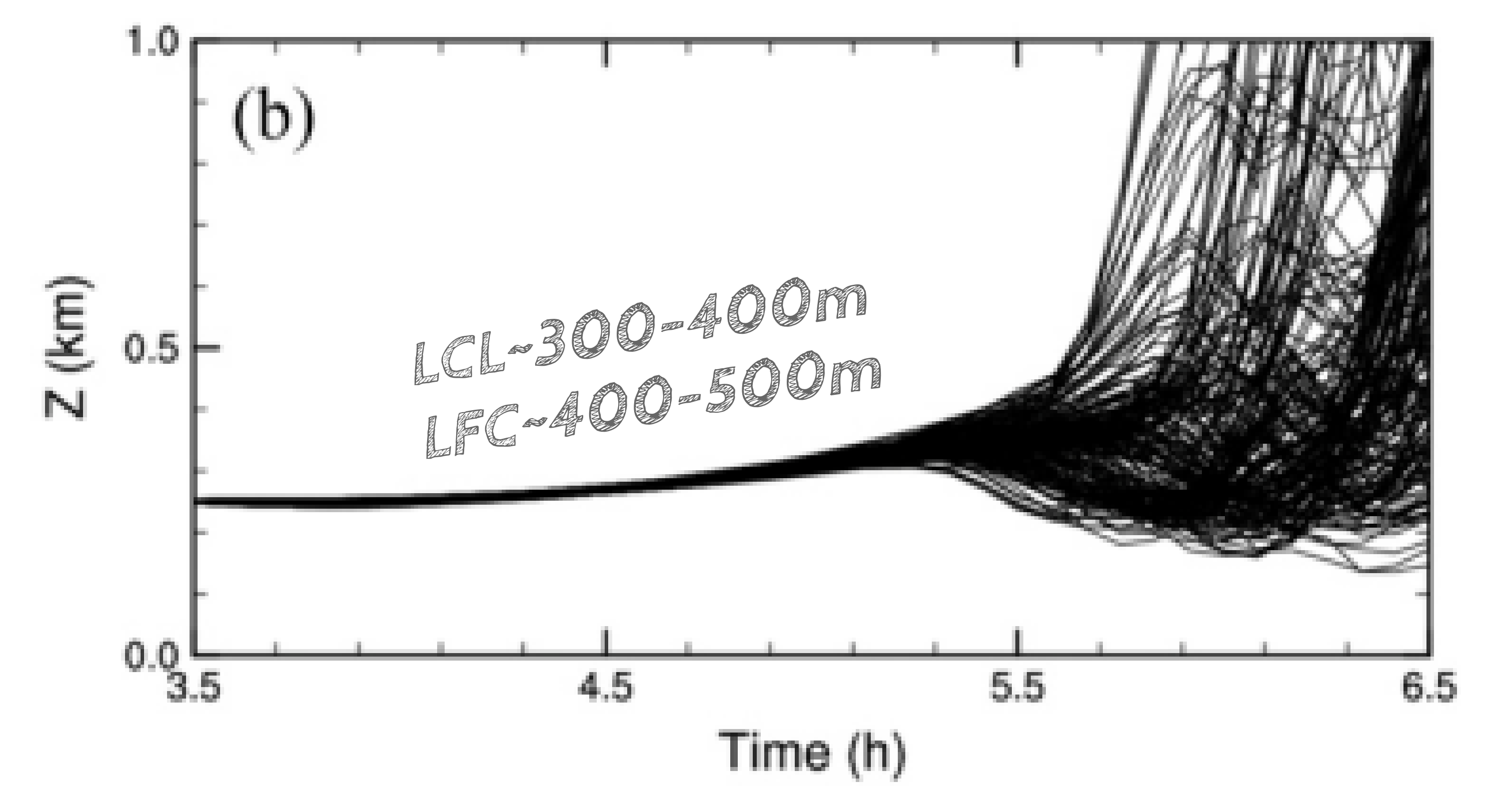
Vertical Velocity [Contours - Updraft (solid), downdraft (dashed)]
Potential Temperature Perturbation (Shading)

Relative Humidity >98% (Green Contours at 5.5hr)
Cloud Boundary (Black Contours at 5.5hr)

Gravity wave activity

I. Upstream-propagating deep mode

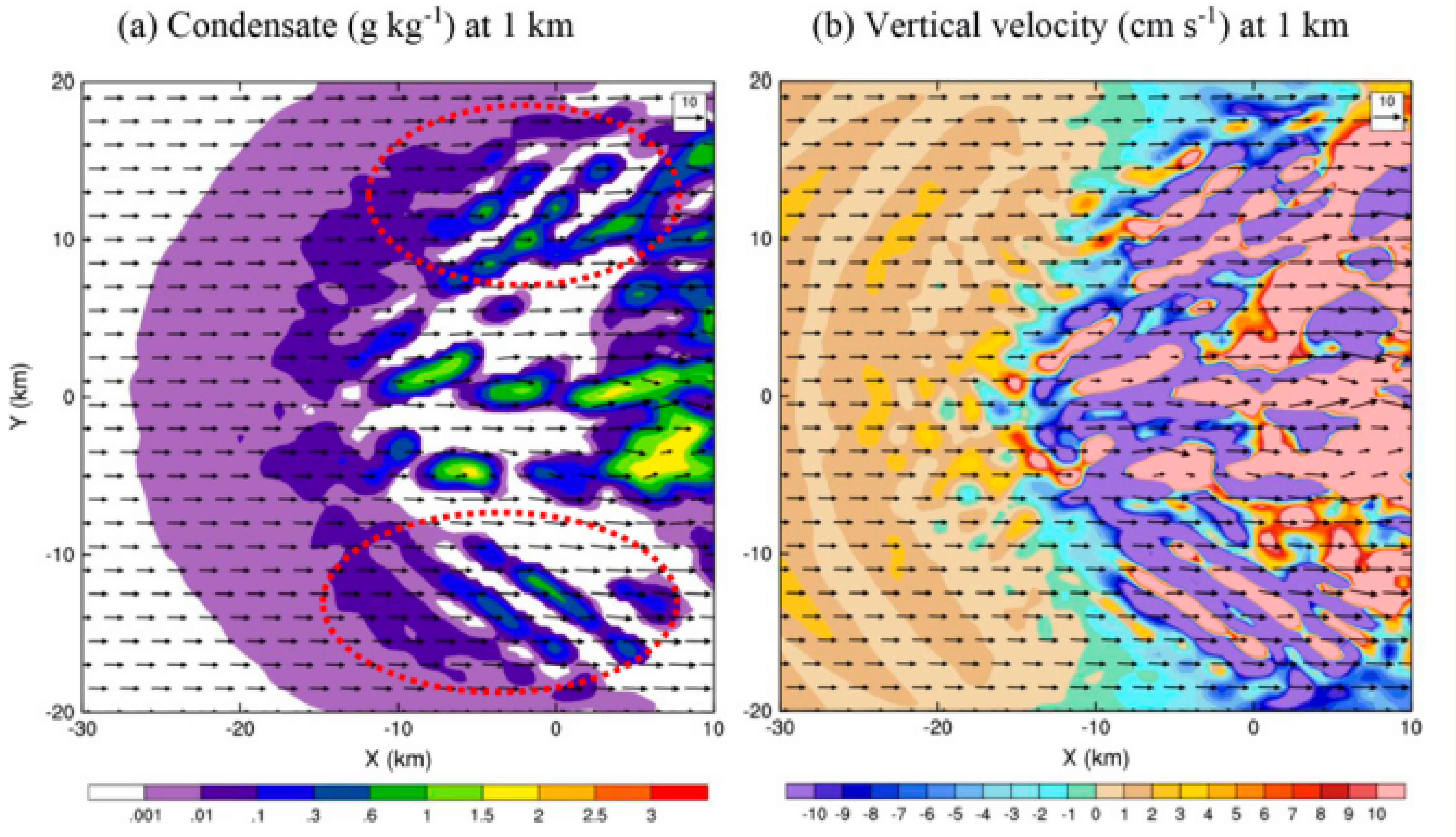




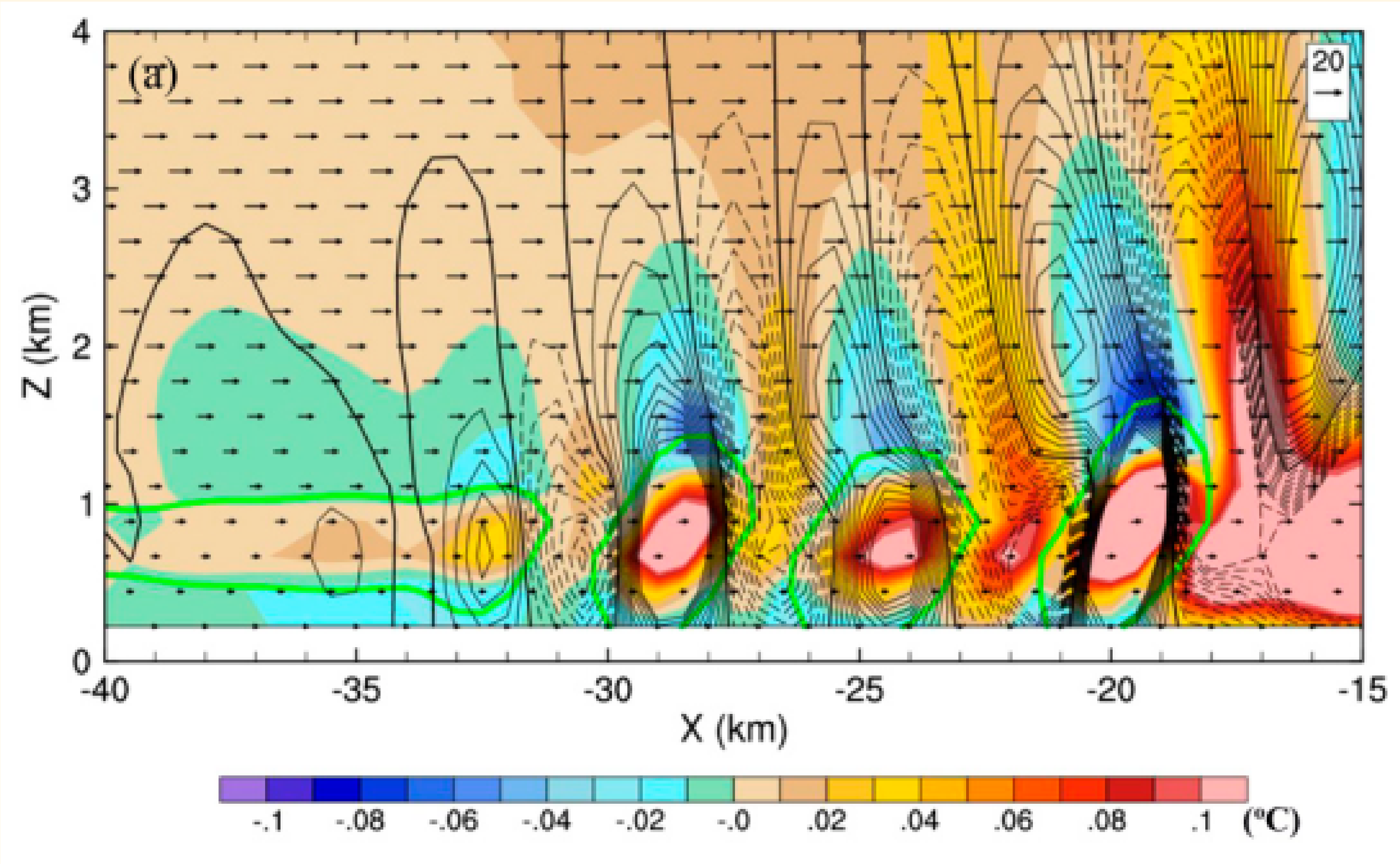
- *Trajectories of 200 parcels released upstream of MCS*
- *(a) Altitude time in W-E direction*
- *(b) Altitude changes with time*

Gravity wave activity
II. Downstream-moving slow mode

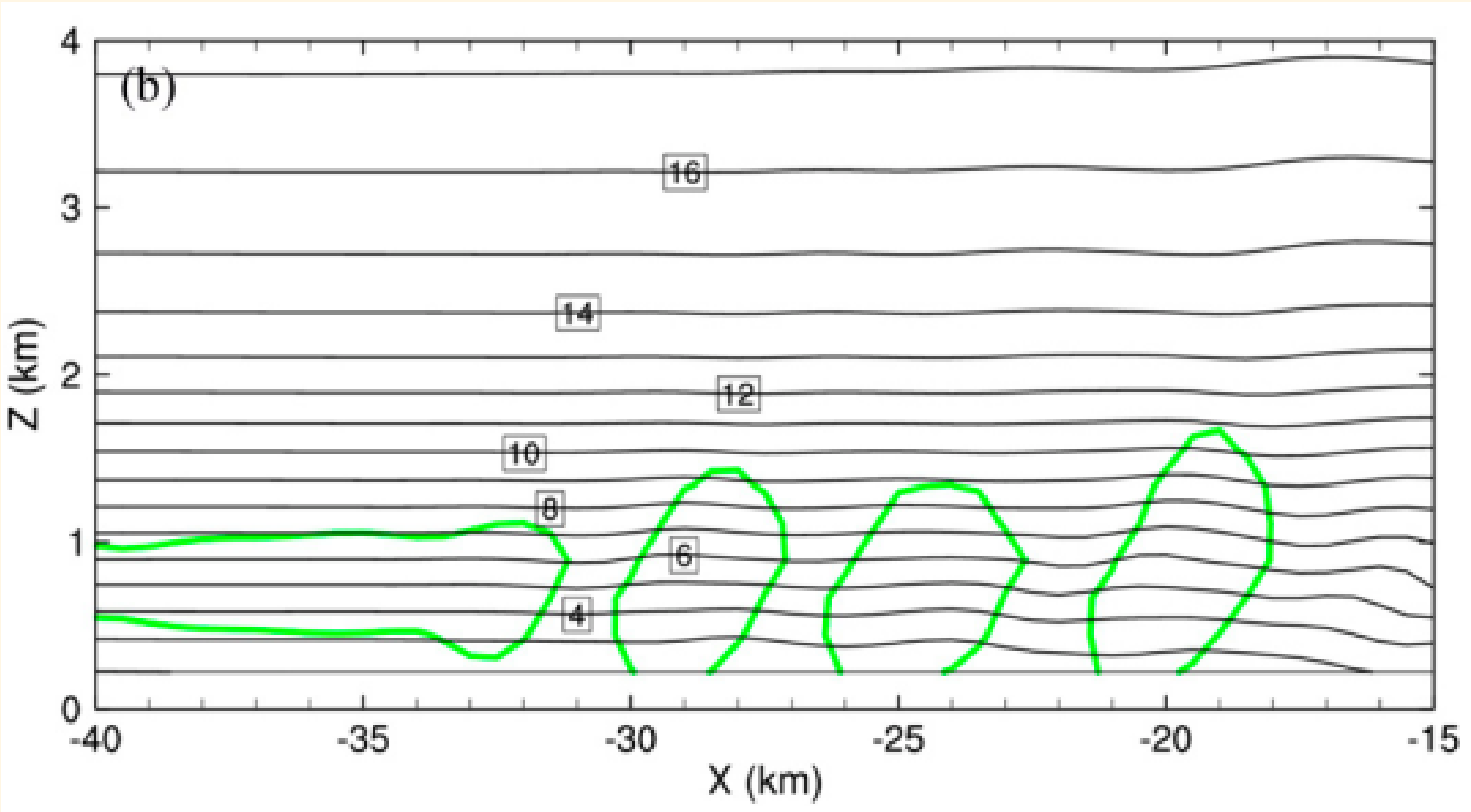
06hr



Gravity wave activity
II. Downstream-moving slow mode

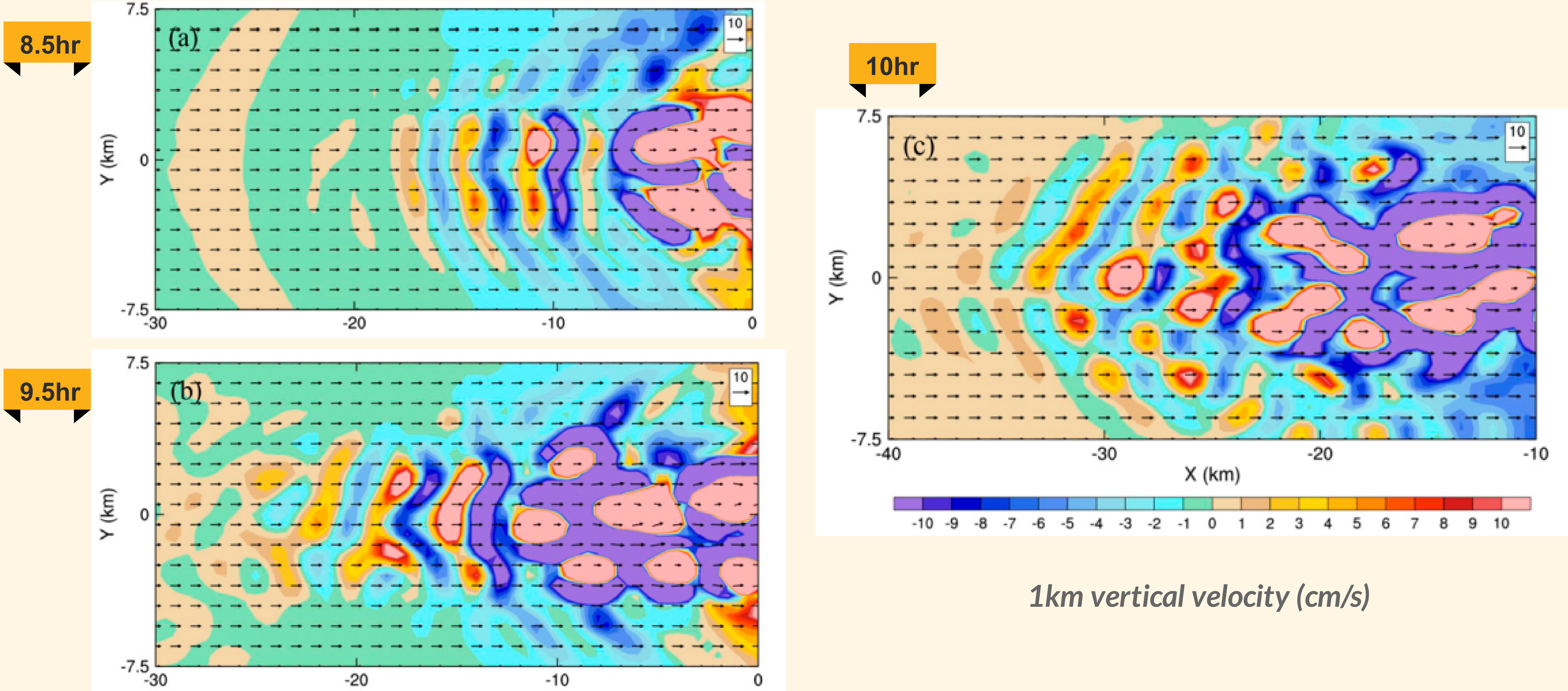


Vertical Velocity (Contours, cm/s)
Potential temperature perturbation (shading)



X-axis wind component (contours, m/s)
Cloud Boundaries (Green contours)

Gravity wave activity
II. Downstream-moving slow mode



1km vertical velocity (cm/s)

Gravity wave activity
II. Downstream-moving slow mode

$$\frac{\partial \theta'}{\partial t} + U\frac{\partial \theta'}{\partial x} + \frac{N^2\theta_0}{g}w' = \frac{\theta_0}{c_pT_0}q', \qquad (2)$$

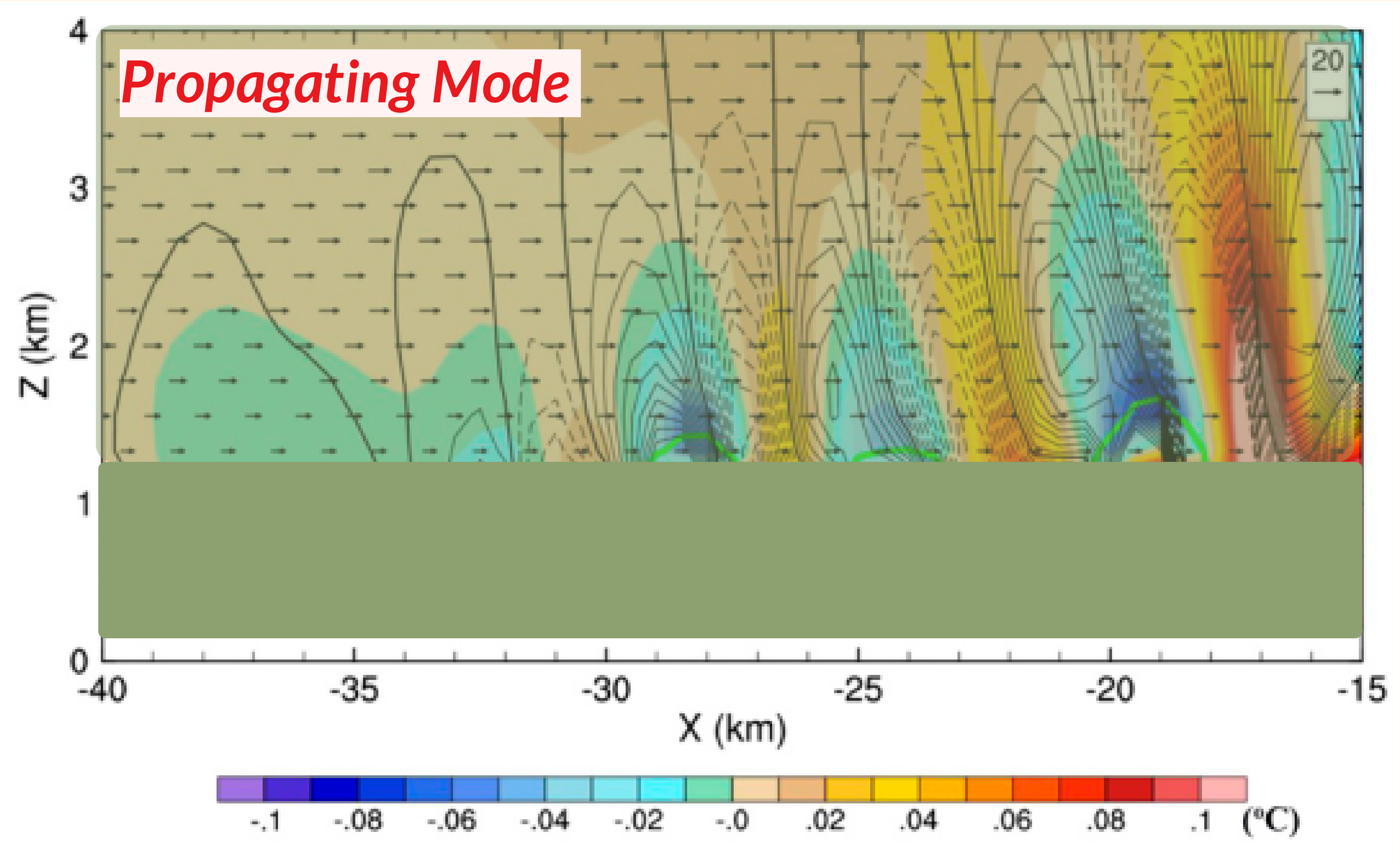
$$q' = \frac{c_pT_0N^2}{g}\varepsilon w'\alpha, \qquad (3)$$

$$\varepsilon = 1 - \frac{N_w^2}{N^2},$$

$$N^2 = \frac{g}{T}(\Gamma_d - \Gamma),$$

$$N_w^2 = \frac{g}{T}(\Gamma_s - \Gamma),$$

$$\alpha = \begin{cases} 1 & \text{if } w' > 0 \\ 0 & \text{if } w' < 0. \end{cases}$$


Propagating Mode

Temperature Advection

Diabatic heating

$$\frac{\partial \theta'}{\partial t} = -U\frac{\partial \theta'}{\partial x} - \frac{N^2\theta_0}{g}(1 - \varepsilon\alpha)w'.$$

Gravity wave activity
II. Downstream-moving slow mode

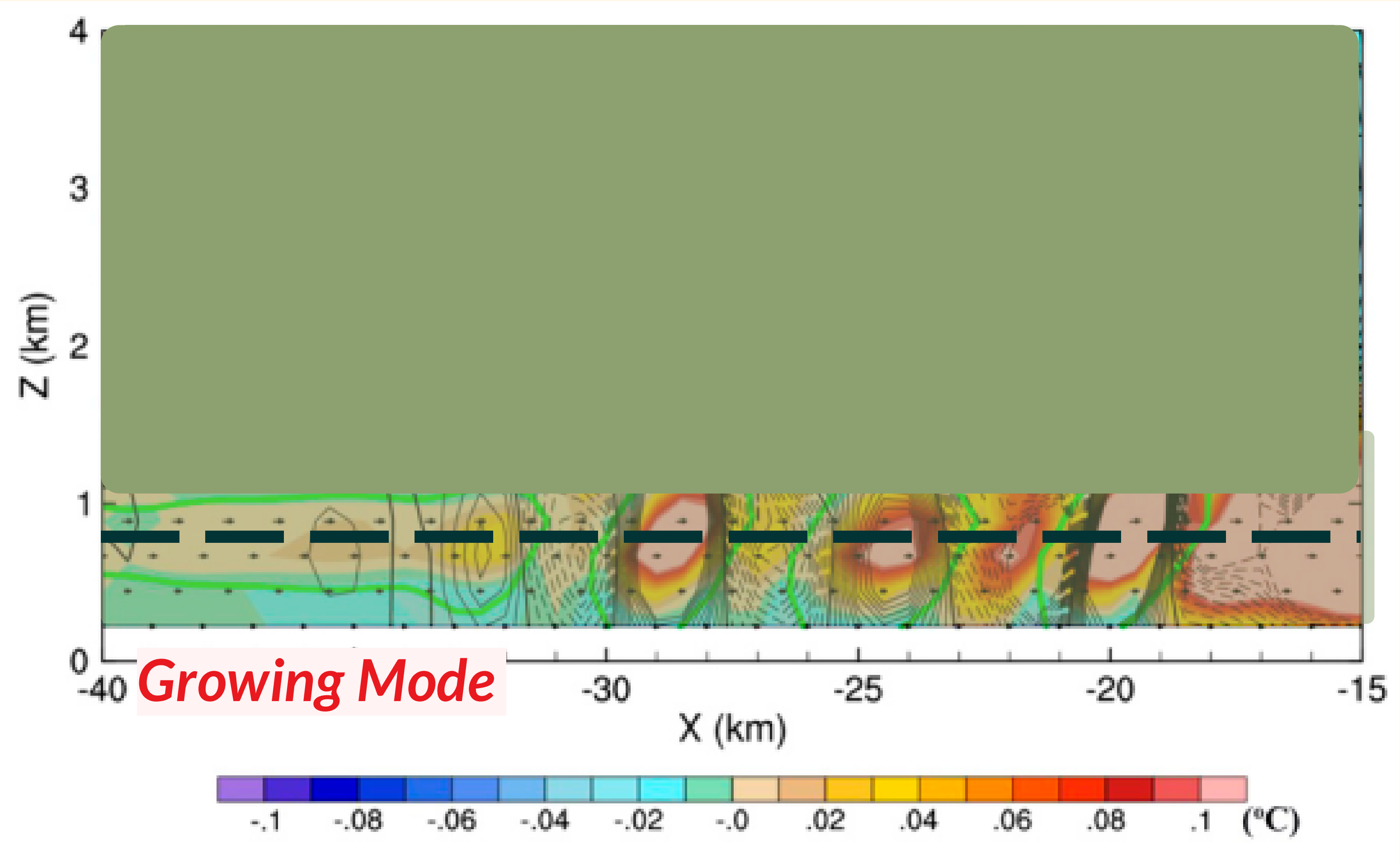
$$\frac{d^2\hat{w}}{dz^2} - \left(k^2 - \frac{N^2}{(U-c)^2} + \frac{U_{zz}}{U-c}\right)\hat{w} = \frac{g\hat{q}}{c_pT_0(U-c)^2}.$$

$$\hat{w} = \frac{D\eta}{Dt} \quad \text{or} \quad w = ik(U-c)\eta.$$

$$2\int_{z_1}^{z_2} c_i(U-c_r)\left(\left|\frac{d\eta}{dz}\right|^2 + k^2|\eta|^2\right)dz = \mathrm{Im}\int_{z_1}^{z_2}\frac{-iQ\eta^*}{k(U-c)}\,dz,$$

$$Q = Fe^{i\beta}w',$$

$$\int_{z_1}^{z_2} g|\eta|^2F\sin\beta\,dz.$$

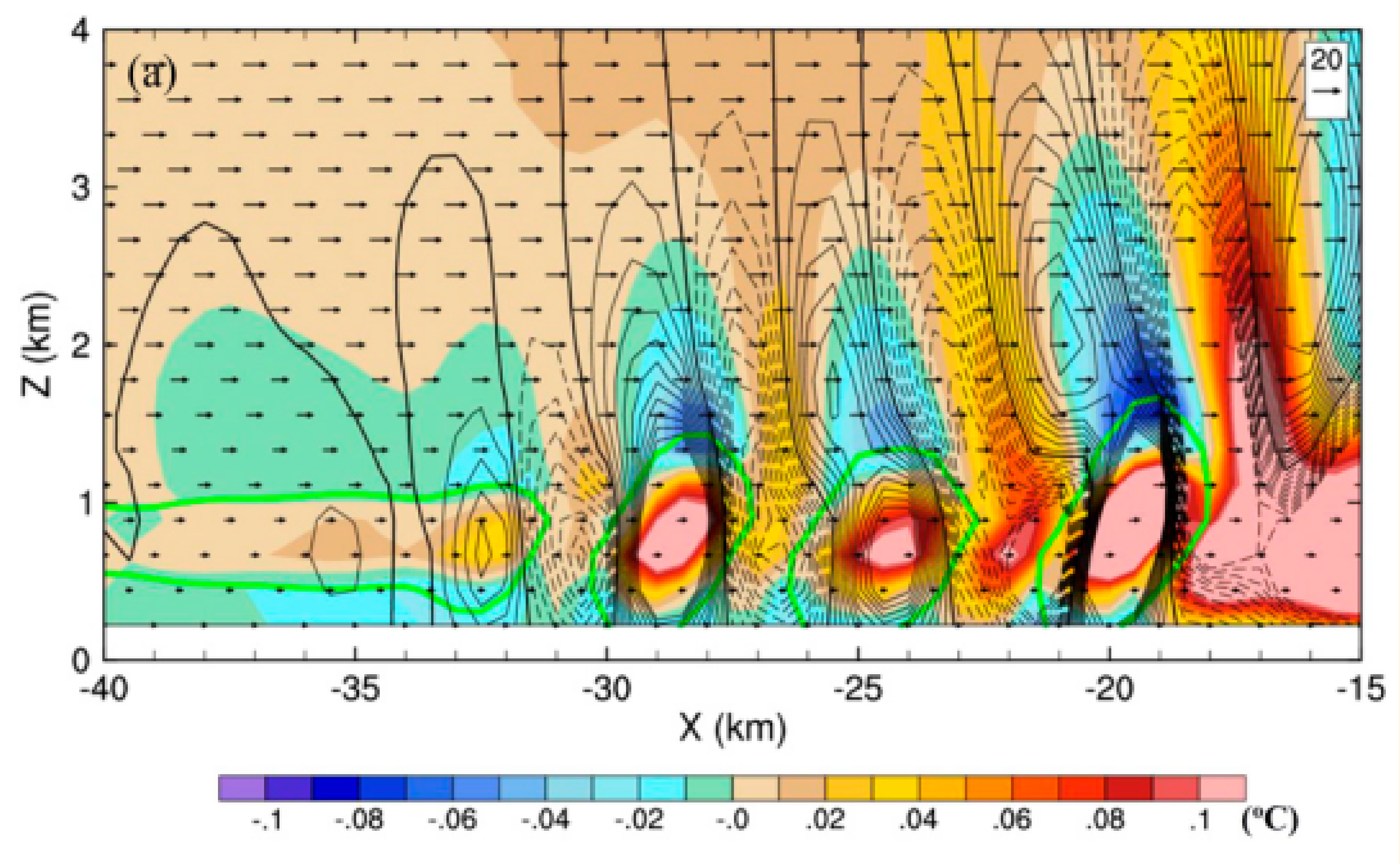


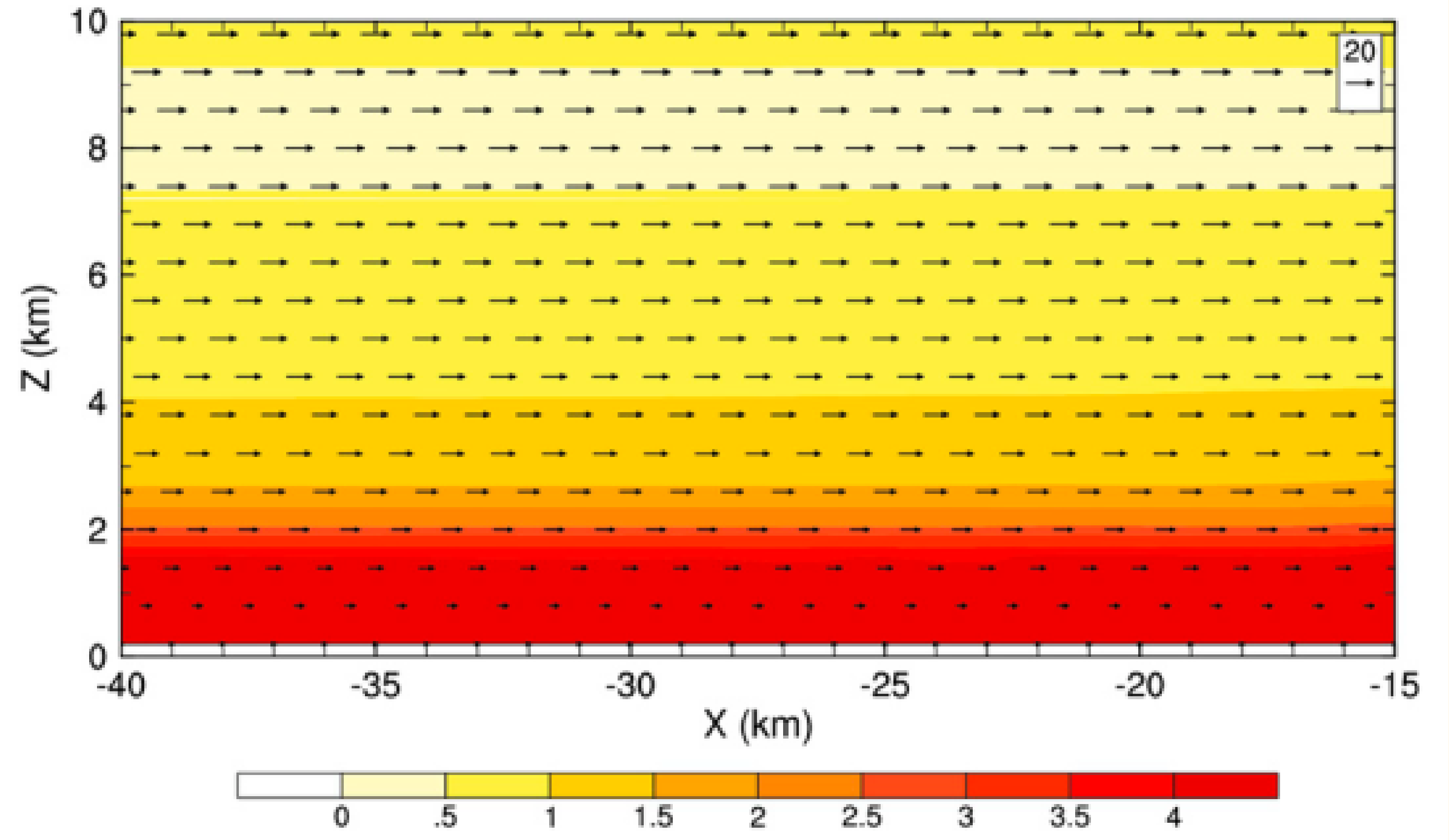
If there is no phase difference between Q, w' (beta=0)

Either: (1) ci=0 (disturbance cannot amplify)
(2) U-cr=0 (Existence of critical level)

Gravity wave activity
II. Downstream-moving slow mode

$$l^2 = N^2/(U-c)^2 - U_{zz}/(U-c).$$





Upstream scorer parameter across moisture front (10^-6 m^-2)

Summarizing gravity wave's role

H

High-frequency GW

Destabilizes environment (cooling tendency in moist low troposphere, creating shallow cloud deck upstream)

L

Low-frequency GW

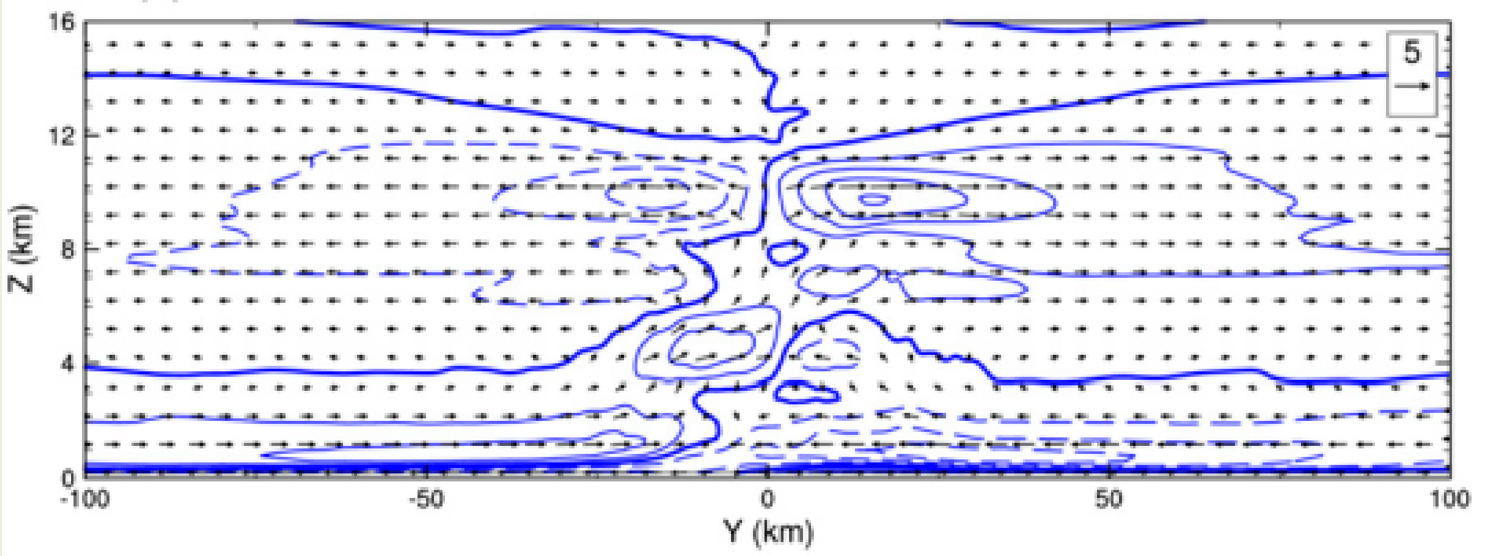
Triggering boundary layer cumulus cloud within the pre-conditioned saturated layer

Disparities between simulated system and Fovell et al. (2006)

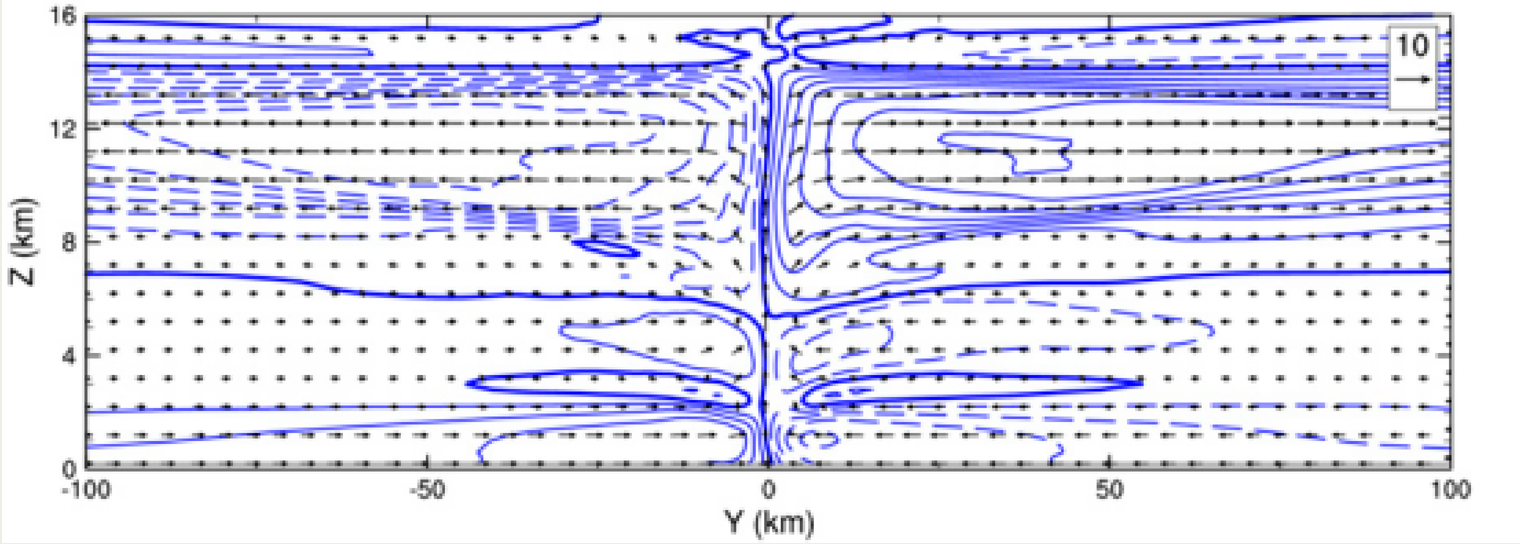
- New CI triggered ahead of gust front can be harmful to F06's system by undercutting unstable air inflow; GW cell triggering is vital in this study
- GWs in F06 originated from parent storm, move upstream, trigger new convection; High-frequency GWs in this study is excited upstream by boundary layer cumulus and moves downstream by ambient wind
- Wave-ducting mechanism in F06 is upper-tropospheric outflow from MCS; Background flow curvature in this study

Some remaining issues & MCS 3D structure

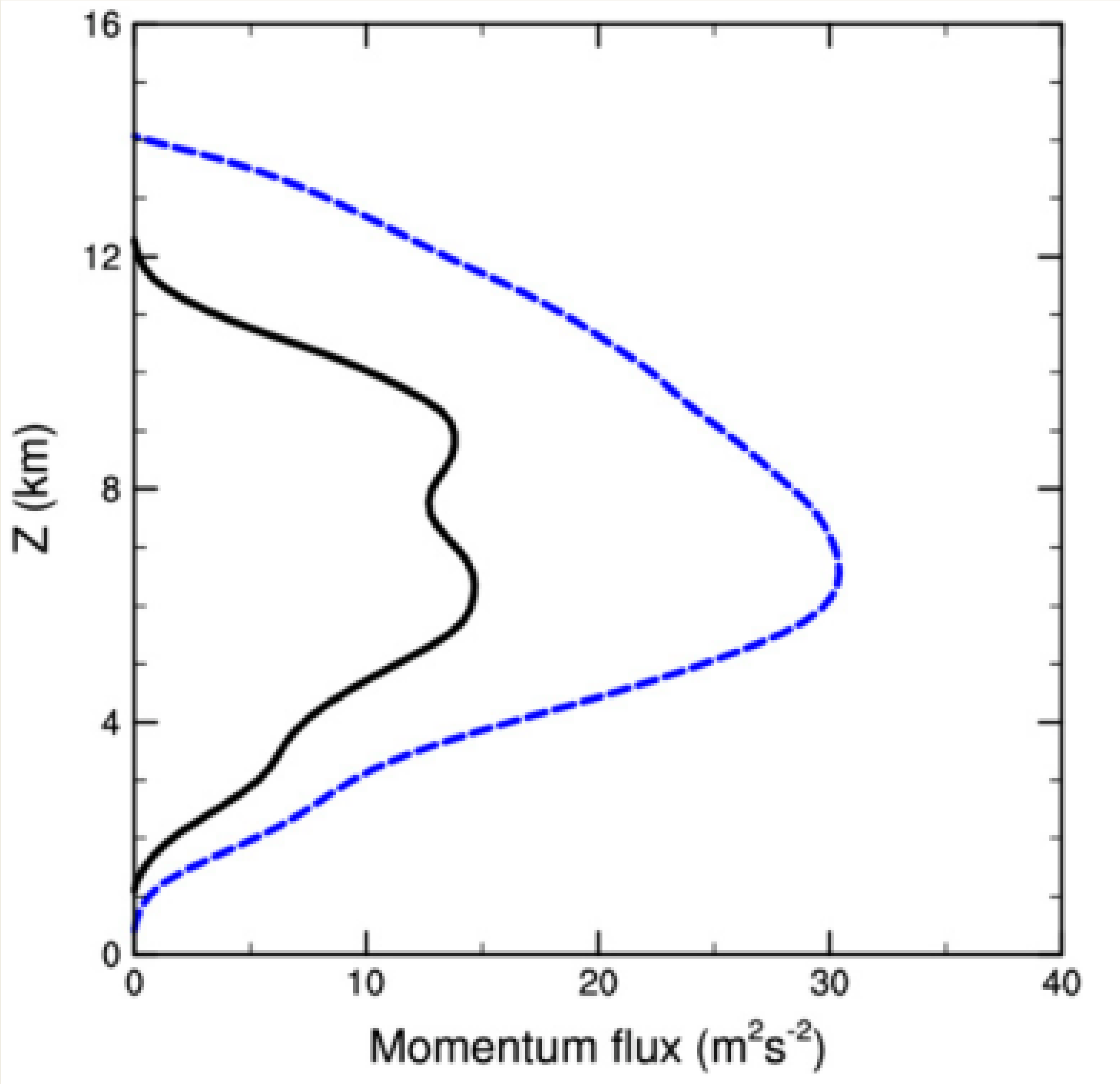
(a) CTRL



(b) no rainwater evaporation cooling

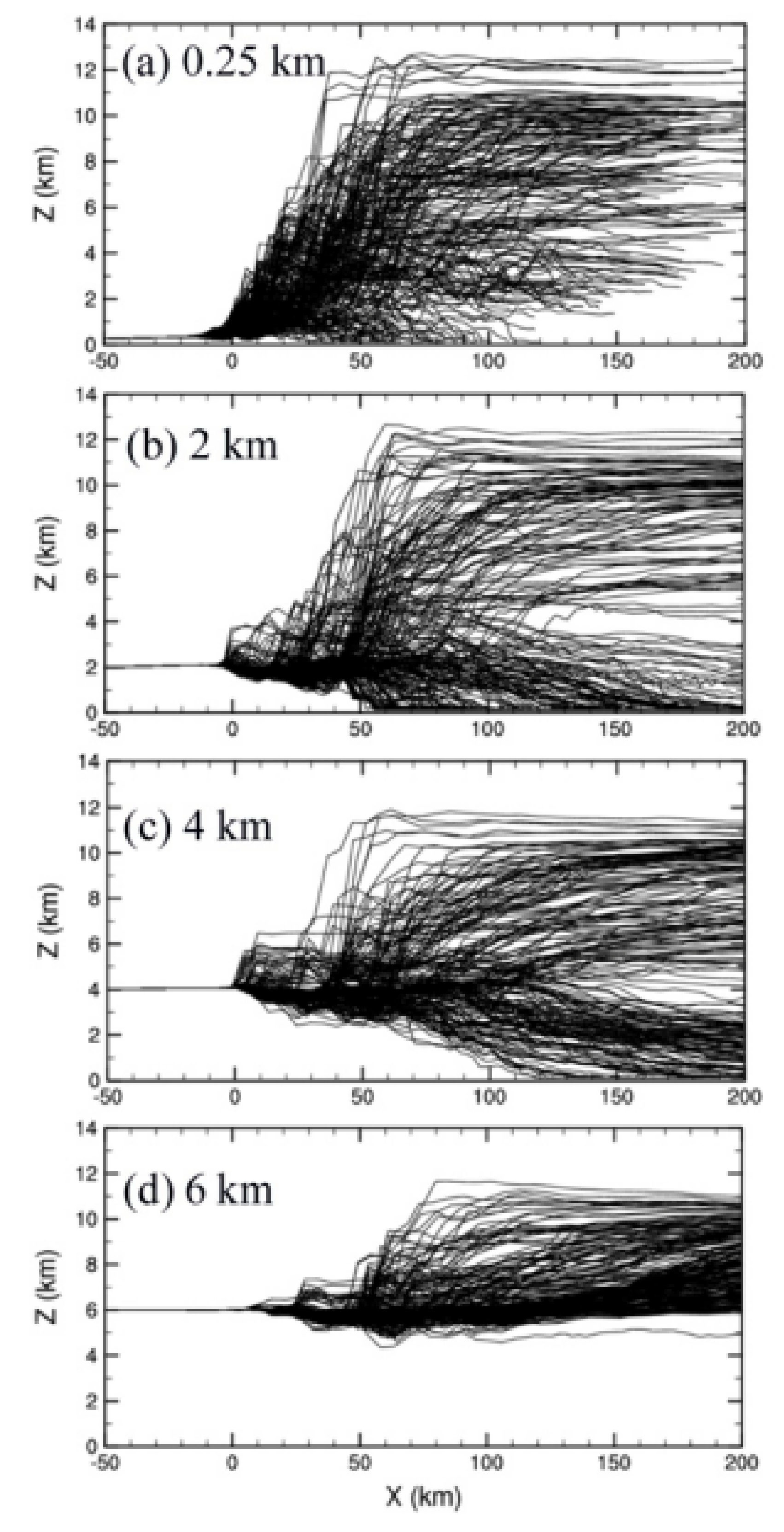


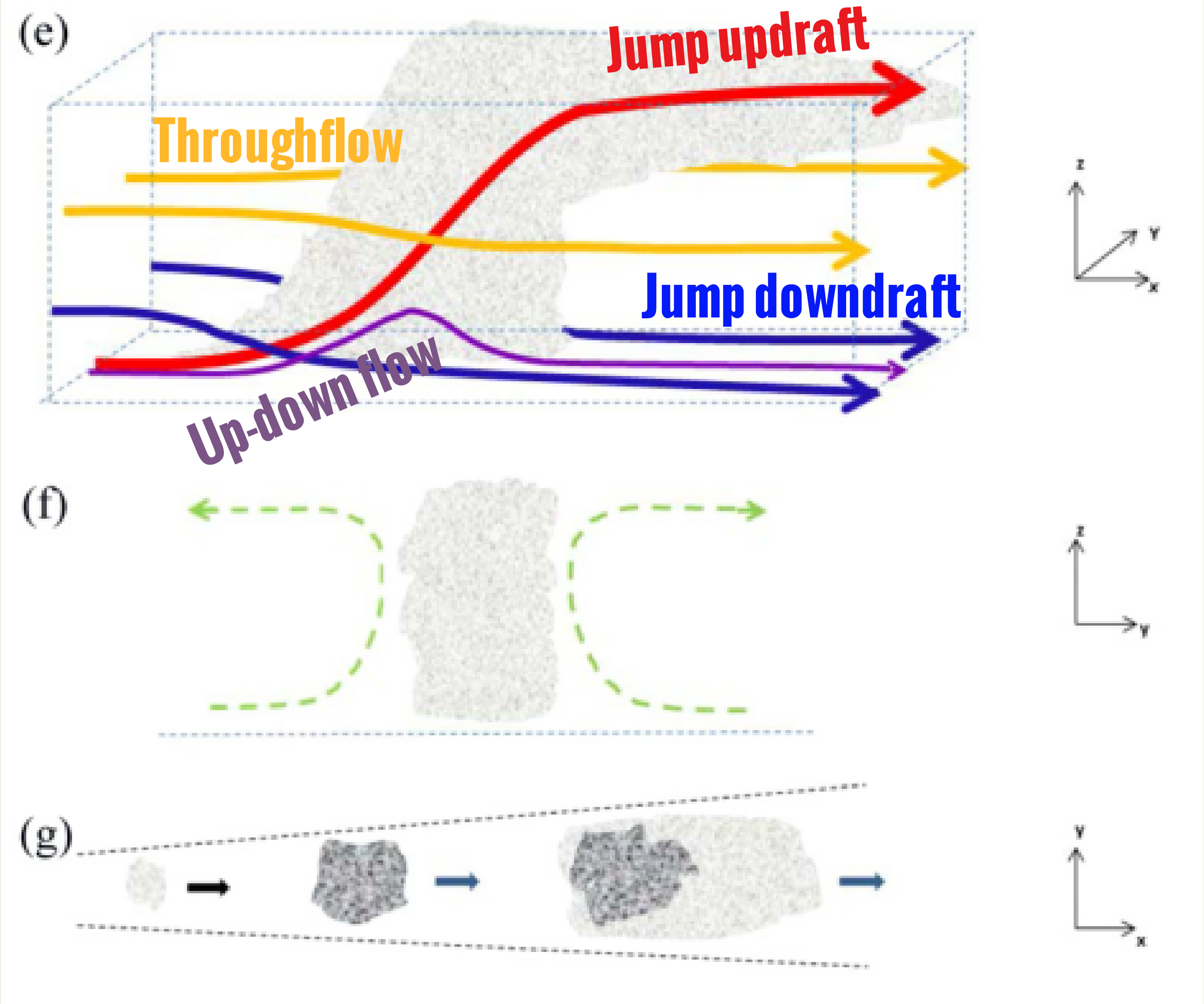
Line-normal wind (contour+vector) averaged between 9.5-10.5h



Line-parallel (u-wind) momentum transport vertical profile along moisture front

Some remaining issues & MCS 3D structure





- Rear-to-front downdraft completely absent in simulated MCS
- MCS propagates in wavelike manner
- Most boundary layer parcels are transported to 12-14km by jump updraft, a portion descends in up-down flow
- Most parcels above 6km traverse system in throughflow branch with small lifting
- 3D spatial & airflow structure, wavelike propagation similar to Moncrieff and Lane (2015)
- Upstream-building, shear-parallel evolution and strong transverse circulation resemble Dudhia and Moncrieff (1987), Khouider and Moncrieff (2015)

THE END

Thank you for listening