Gravity Waves in Shear and Implications for Organized Convection

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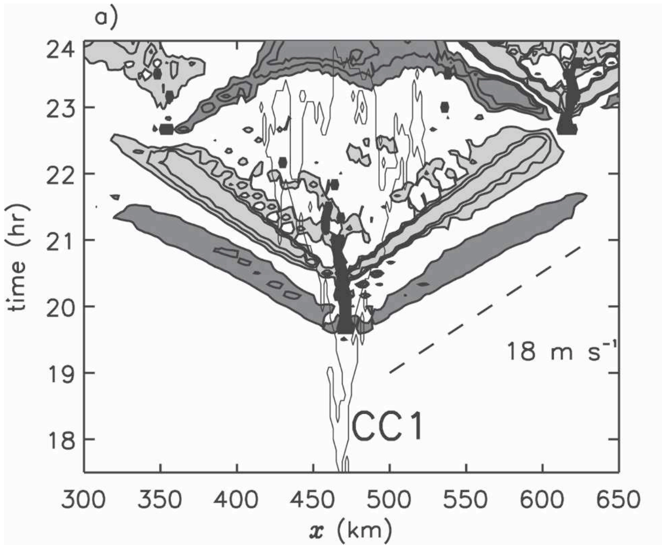
INTRODUCTION

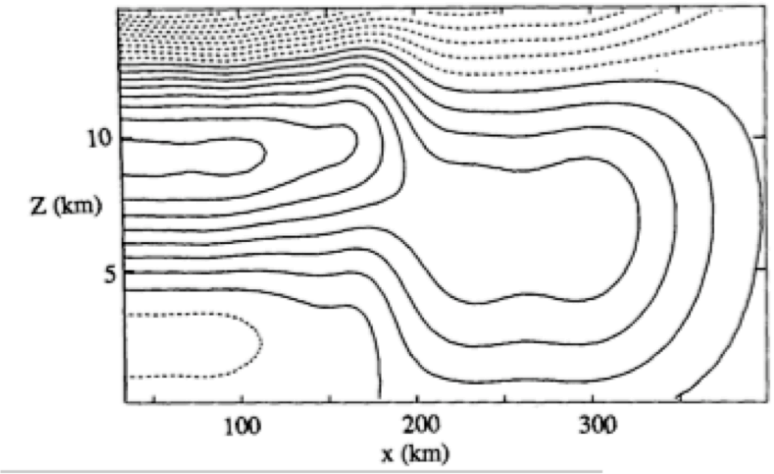
Abstract

- Gravity waves can trigger/favor the formation of new convection
- If new convection forms repeatedly on a preferred side of preexisting convection, then a *convectively coupled wave* is formed
- What creates a preferred side? Hypothesis: wind shear
- Design a simple model for interactions of gravity waves and wind shear
- Results:
  - Wind shear can create a preferred side
  - Jet shears create the greatest difference in favorability between two sides
  - *Predictions of preferred propagation direction of convectively coupled waves in a given background wind shear*
- Other application:
  - Formation of new cells within an individual mesoscale convective system
  - *Resonance* renders upstream more favorable than downstream

Gravity waves and organized convection



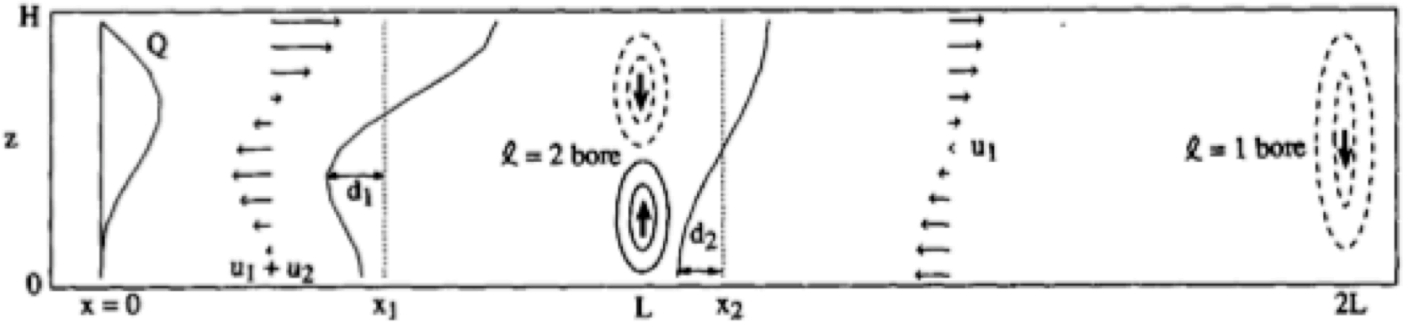
Buoyancy anomalies excited by top-heavy heating



Convection can excite gravity waves

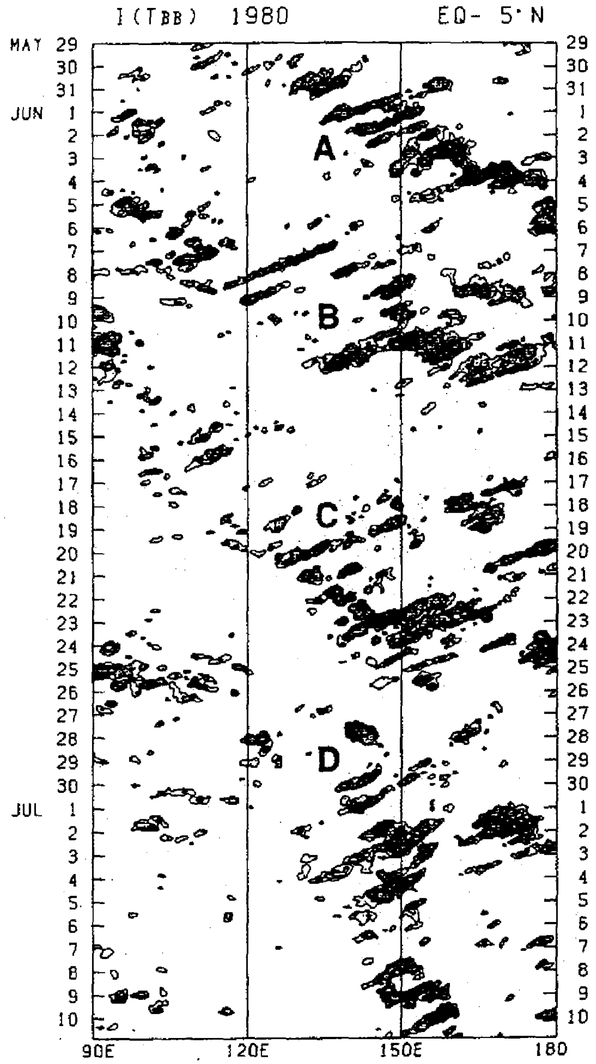
Gravity waves can excite new convection

Theory: the role of (1) deep convection and (2) stratiform heating



from Tulich and Mapes (2008) and Mapes (1993)

Convectively coupled waves: Envelopes of mesoscale convective systems



from Nakazawa (1988)

- Embedded cloud systems propagate in opposite direction of wave envelope
- New cloud systems tend to form on a preferred side of preexisting cloud systems

- What causes wave trains to form preferentially (rather than scattered convection)?
- What determines the preferred propagation direction of the convectively coupled wave?

- Hypothesis: interactions of gravity waves with wind shear

SIMPLIFIED MODEL

Starting point: Hydrostatic Boussinesq equations

$$\begin{aligned}
\frac{\partial U}{\partial t} + U\frac{\partial U}{\partial x} + W\frac{\partial U}{\partial z} + \frac{\partial P}{\partial x} &= 0 \\
\frac{\partial P}{\partial z} &= g\frac{\Theta}{\theta_{ref}} \\
\frac{\partial \Theta}{\partial t} + U\frac{\partial \Theta}{\partial x} + W\frac{\partial \Theta}{\partial z} + W\frac{d\theta_{bg}}{dz} &= 0 \\
\frac{\partial U}{\partial x} + \frac{\partial W}{\partial z} &= 0
\end{aligned}$$

$U =$ horizontal velocity

$W =$ vertical velocity

$P =$ pressure

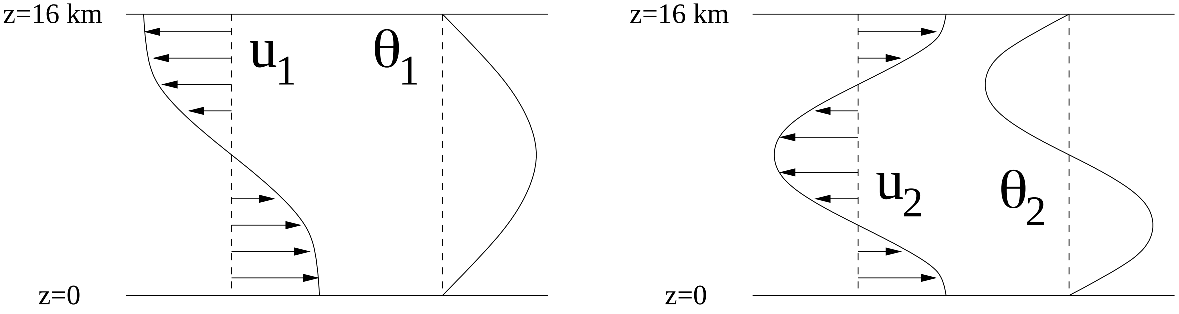
$\Theta =$ temperature

Gravity waves in the tropical atmosphere

Linear waves:

- Independent vertical modes: $U(x,z,t) = \sum_j u_j(x,t) \cos jz$, etc.
- Shallow water system for each vertical mode j:

$$\frac{\partial u_j}{\partial t} - \frac{\partial \theta_j}{\partial x} = 0$$
$$\frac{\partial \theta_j}{\partial t} - \frac{1}{j^2}\frac{\partial u_j}{\partial x} = 0$$



Nonlinear waves:

- Project nonlinear equations

$$\partial_t U + U\partial_x U + W\partial_z U + \partial_x P = 0$$

onto vertical modes

$$U(x,z,t) = u_1(x,t)\cos z + u_2(x,t)\cos 2z$$

- The result is ...

2-Mode Shallow Water Equations

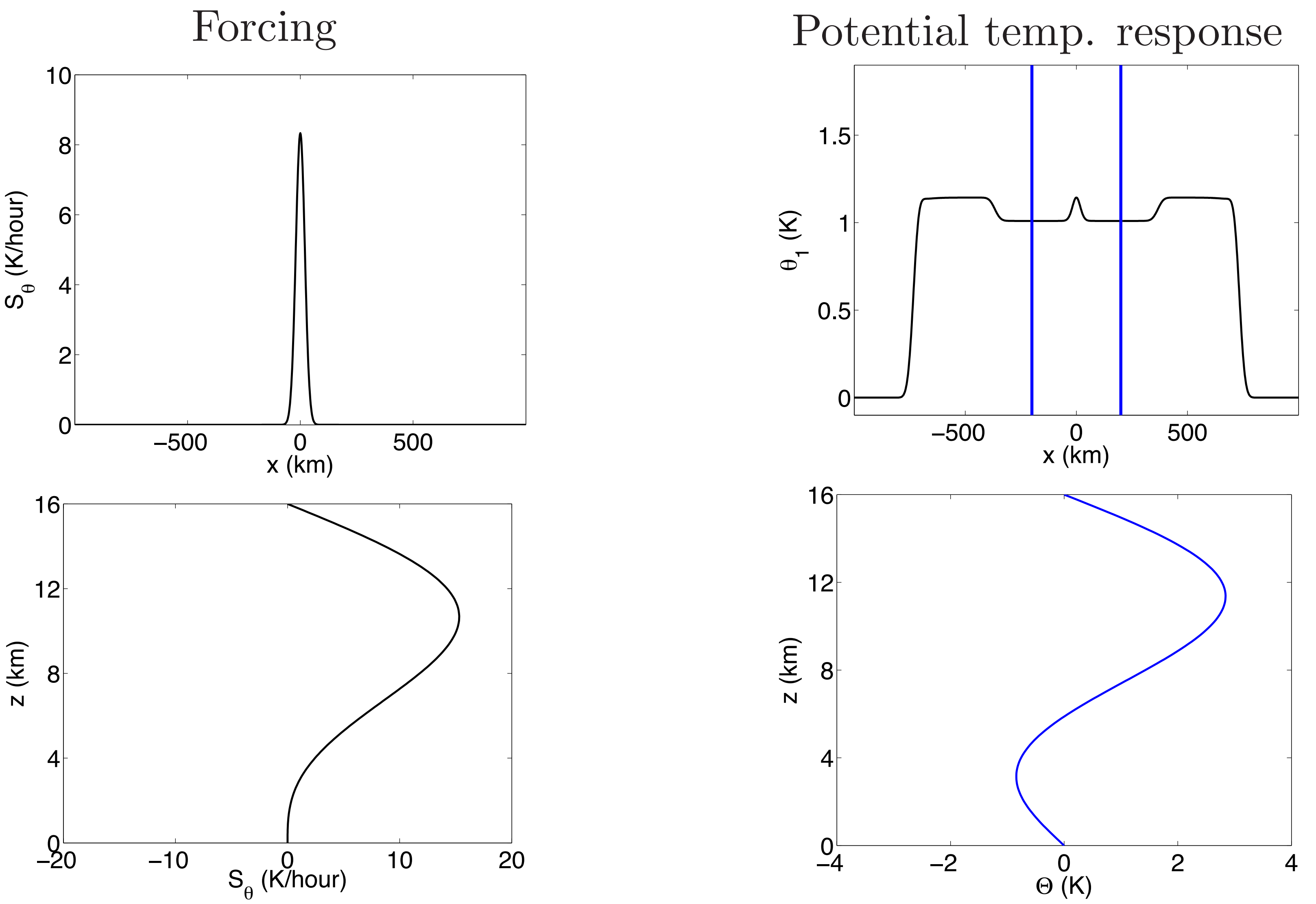
$$\left\{\begin{array}{rcl} \dfrac{\partial u_1}{\partial t} - \dfrac{\partial \theta_1}{\partial x} & = & -\dfrac{3}{\sqrt{2}}\left[u_2\dfrac{\partial u_1}{\partial x} + \dfrac{1}{2}u_1\dfrac{\partial u_2}{\partial x}\right] \\[2em] \dfrac{\partial \theta_1}{\partial t} - \dfrac{\partial u_1}{\partial x} & = & -\dfrac{1}{\sqrt{2}}\left[2u_1\dfrac{\partial \theta_2}{\partial x} + 4\theta_2\dfrac{\partial u_1}{\partial x} - u_2\dfrac{\partial \theta_1}{\partial x} - \dfrac{1}{2}\theta_1\dfrac{\partial u_2}{\partial x}\right] \end{array}\right.$$

$$\left\{\begin{array}{rcl} \dfrac{\partial u_2}{\partial t} - \dfrac{\partial \theta_2}{\partial x} & = & 0 \\[2em] \dfrac{\partial \theta_2}{\partial t} - \dfrac{1}{4}\dfrac{\partial u_2}{\partial x} & = & -\dfrac{1}{2\sqrt{2}}\left[u_1\dfrac{\partial \theta_1}{\partial x} - \theta_1\dfrac{\partial u_1}{\partial x}\right] \end{array}\right.$$

- Nonlinear, hydrostatic internal gravity waves with effect of background shear

CONVECTIVELY COUPLED WAVES

Numerical experiment WITHOUT wind shear

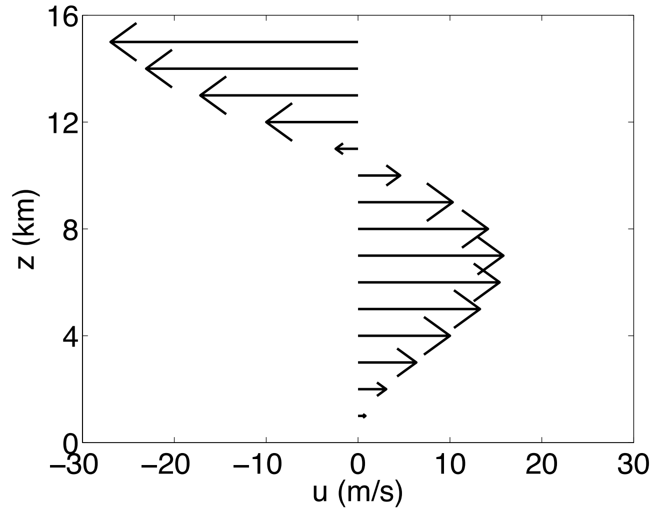


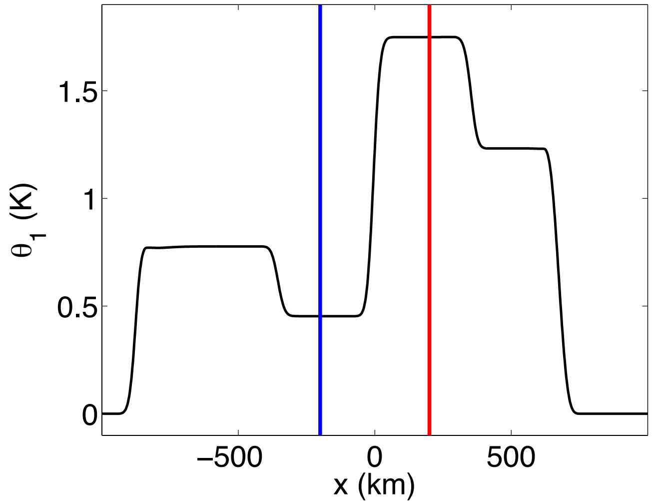
Forcing

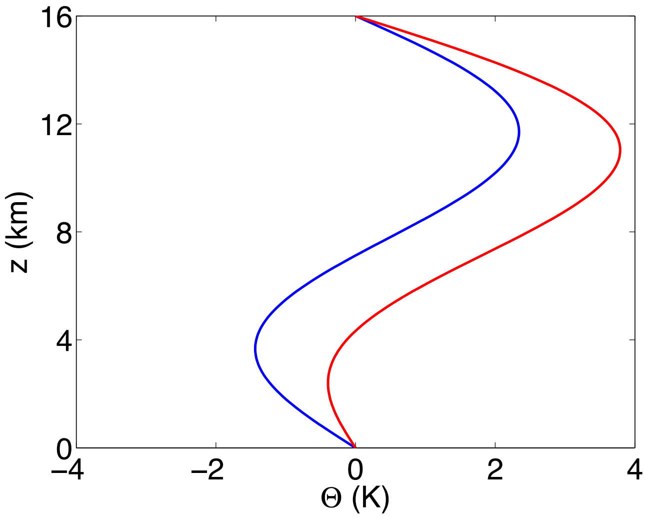
Potential temp. response

Results symmetric to east and west of forcing

Numerical experiment WITH wind shear







- West of forcing is more favorable for new convection than east
- Agrees with observations for this wind shear (Wu and LeMone, 1999)
- Consistent with features of CCW envelope and embedded cloud systems
  - Individual cloud systems propagate *eastward*
  - Convectively coupled wave propagates *westward*

Optimal shears for east–west asymmetry

A measure of the east–west asymmetry due to wind shear:

- the jump in θ across the source, $[\theta] = \theta^+ - \theta^-$

Which shear profiles $\bar{U}(z)$ *maximize* $[\theta_1]$*?*

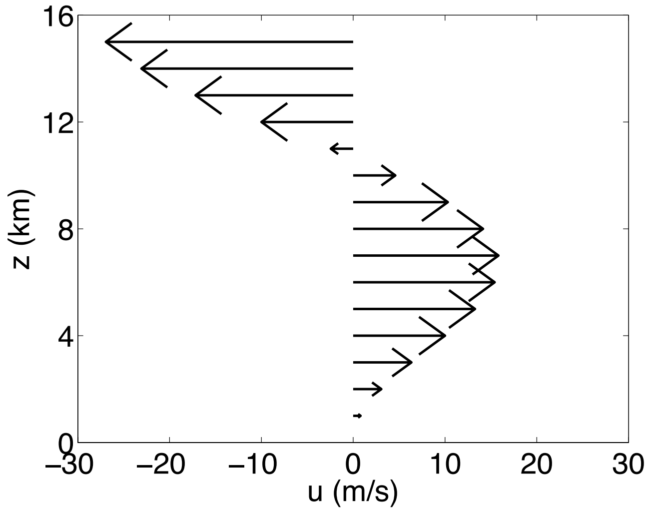
Which shear profiles $\bar{U}(z)$ *lead to* $[\theta_1] = 0$

Use linear theory with singular source term:

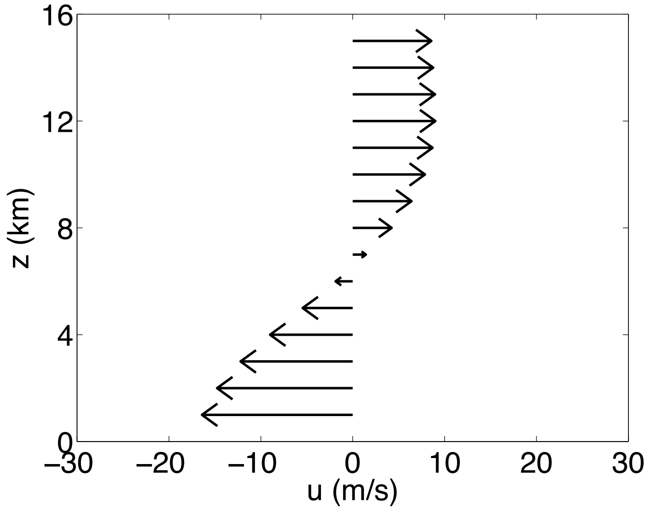
$$\partial_t \mathbf{u} + A(\bar{\mathbf{u}})\partial_x \mathbf{u} = \mathbf{S}^* \delta(x)$$

Results:

Jet shears maximize $[\theta_1]$

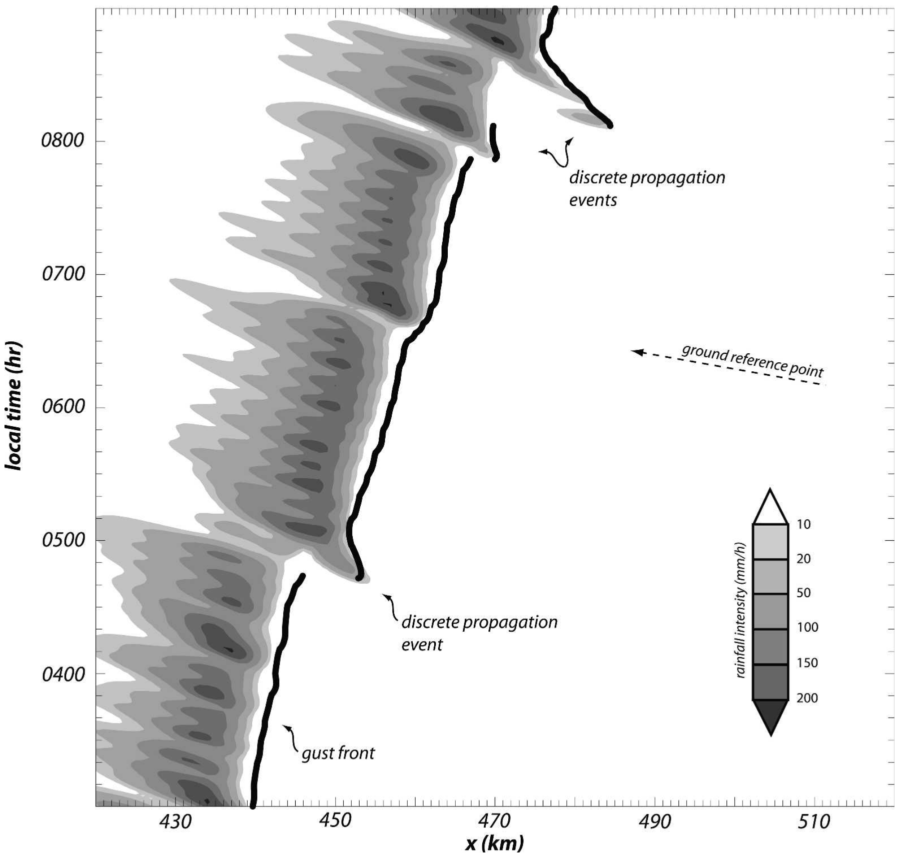


Profiles with zero shear
at upper levels lead to $[\theta_1] = 0$

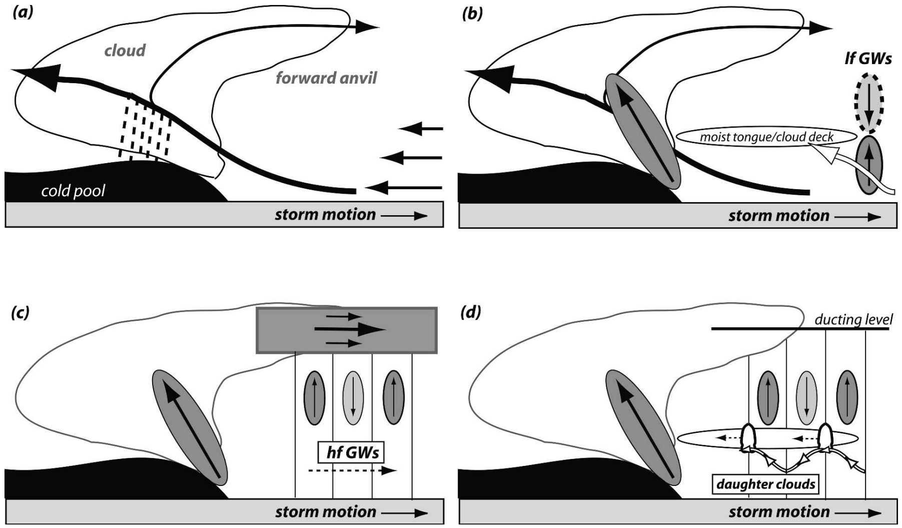


MESOSCALE CONVECTIVE SYSTEMS

Gravity waves can excite new convective cells

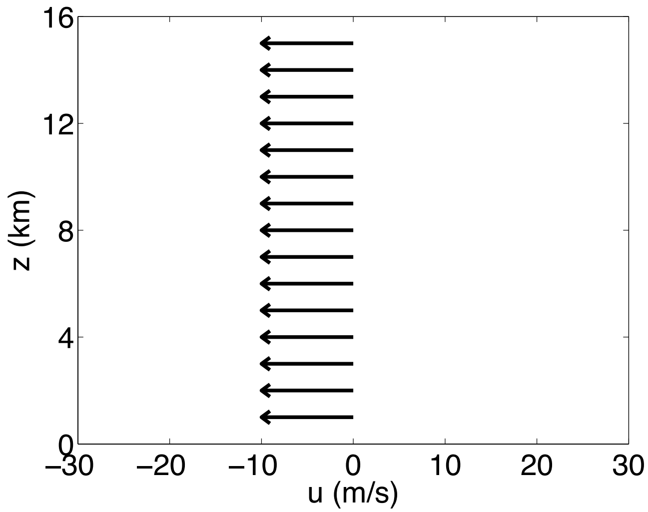


from Fovell et al. (2006)

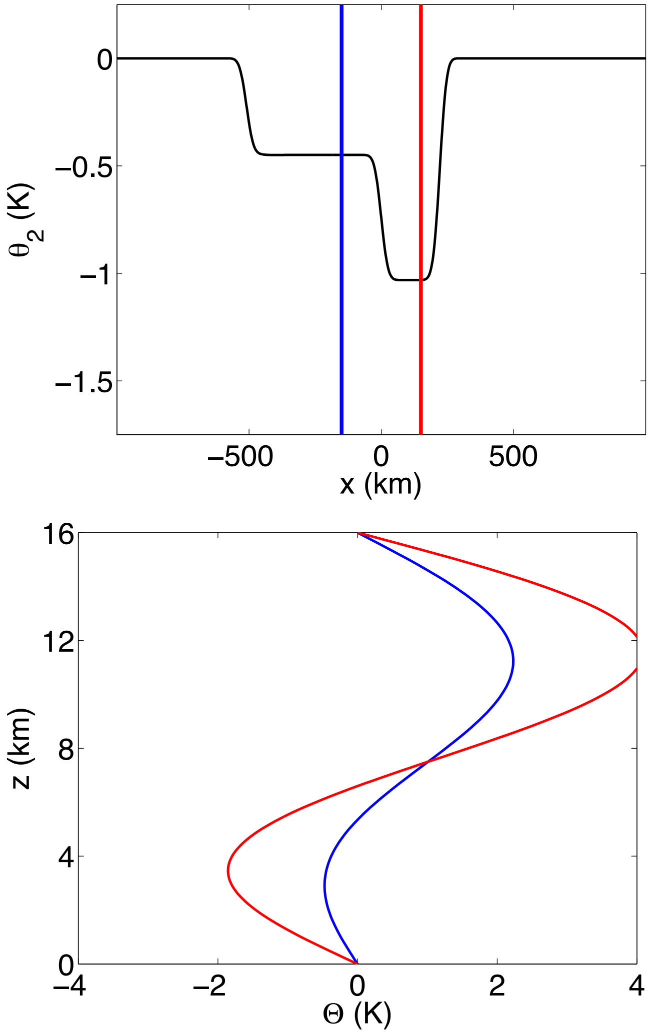


- New cells initiated *ahead of* existing squall line due to gravity waves
- New cells merge with existing squall line
- *What are the physical mechanisms involved?*

Numerical experiment with headwind

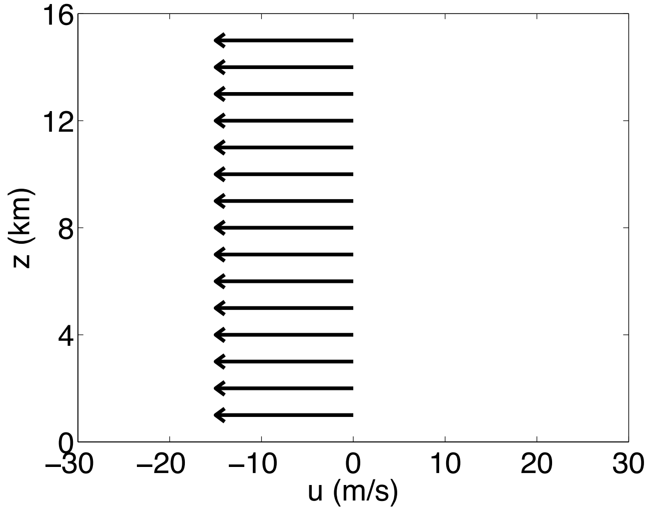


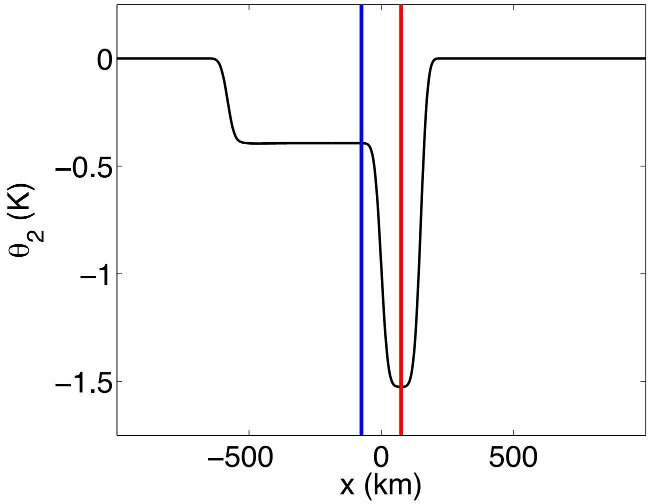
- Repeat earlier jet-shear experiment with headwind added

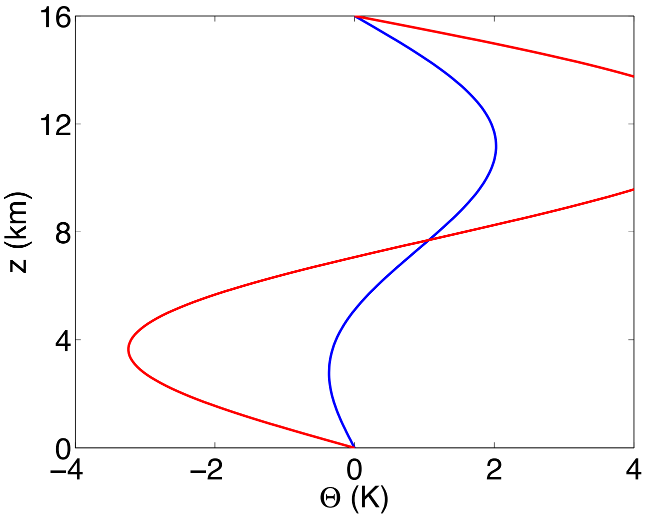


- Headwind is equivalent to propagating source (i.e., propagating squall line)
- Headwind confines upstream wave to vicinity of source
- East is more favorable for new convection than west *at low levels*

Numerical experiment with stronger headwind







Source propagation speed = 15 m/s

2nd baroclinic wave speed = 25 m/s

⇒ near resonant forcing

- Faster propagation leads to more favorable environment *at low levels*
- If squall line propagation speed ≈ gravity wave speed, then *wave amplitude is large due to near-resonance*

Conclusions

- 2-mode shallow water equations:
  - simplified nonlinear model for waves interacting with wind shear

- Predictions of preferred propagation direction of convectively coupled waves in a background wind shear
  - wind shear can lead to east–west asymmetries in favorability for new convection
  - jet shears lead to largest east–west asymmetries
  - linear theory is accurate to within 10 % (usually)

- Initiation of new convective cells ahead of individual convective system
  - Propagation of source leads to *near-resonant forcing and amplification* of upstream waves

Stechmann and Majda (2009), in *J. Atmos. Sci.*
Stechmann et al. (2008), in *Theoretical and Computational Fluid Dynamics*

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