Gravity waves near convection:
causes and consequences

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Outline

- Basics
- Mechanically generated stratospheric gravity waves
- Thermally induced low frequency tropospheric gravity waves
- Thermally/mechanically excited high frequency tropospheric gravity waves
- Mechanically forced obstacle effect gravity waves

Terms

- Frequency ω and period P

$$P = \frac{2\pi}{\omega}$$

- Wavelengths L_x, L_z; wavenumbers k, m

$$k = \frac{2\pi}{L_x};\ m = \frac{2\pi}{L_z}$$

- Intrinsic frequency (relative to mean flow)

$$\hat{\omega} = \omega - \bar{U}k$$

Terms (continued)

- Dispersion equation (*N* = B-V frequency)

$$\hat{\omega} = \pm \frac{Nk}{\sqrt{k^2 + m^2}}$$

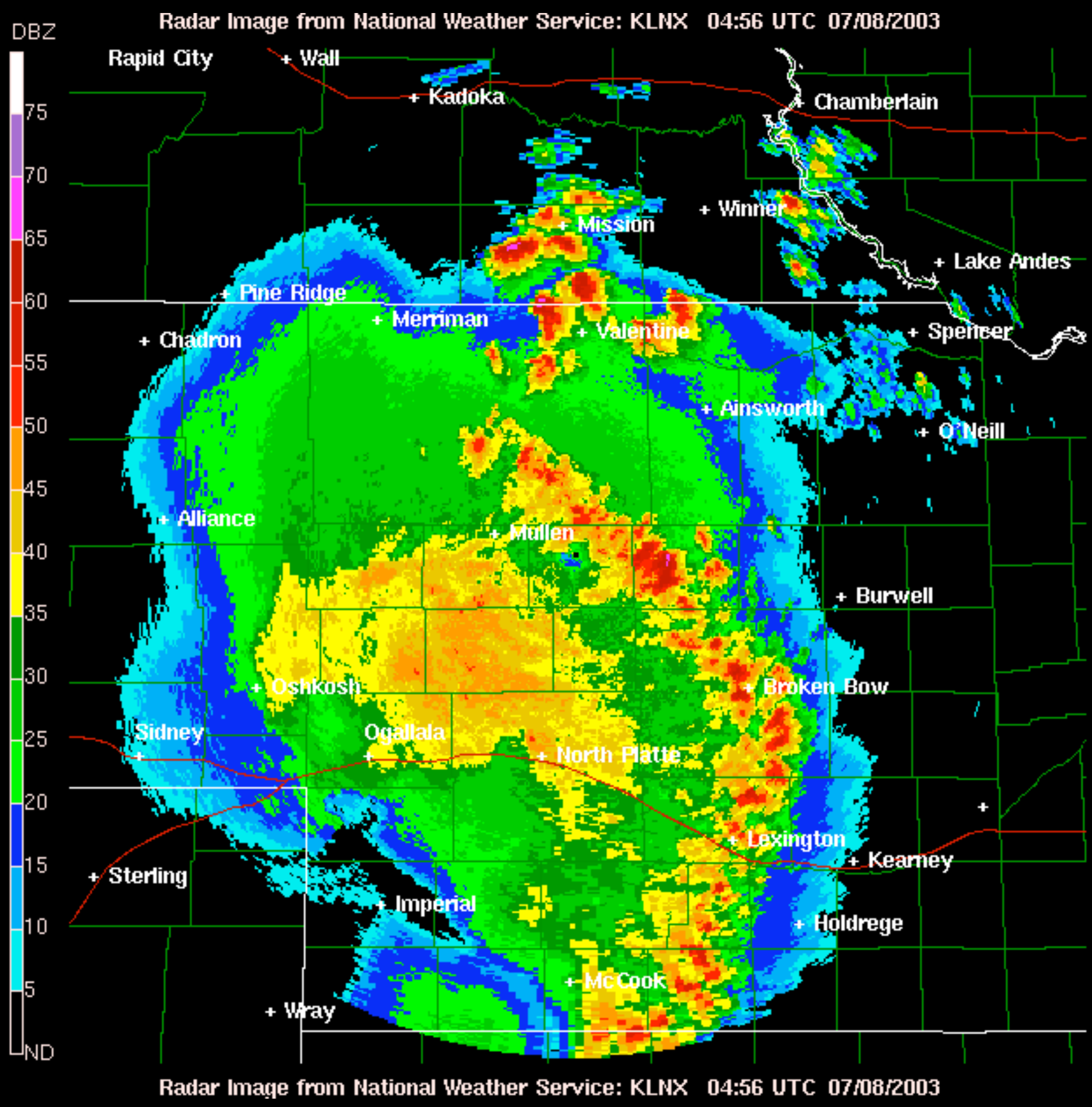
- Phase line tilt from vertical

$$\cos\alpha = \frac{L_z}{\sqrt{{L_x}^2 + {L_z}^2}} = \frac{\hat{\omega}}{N}$$

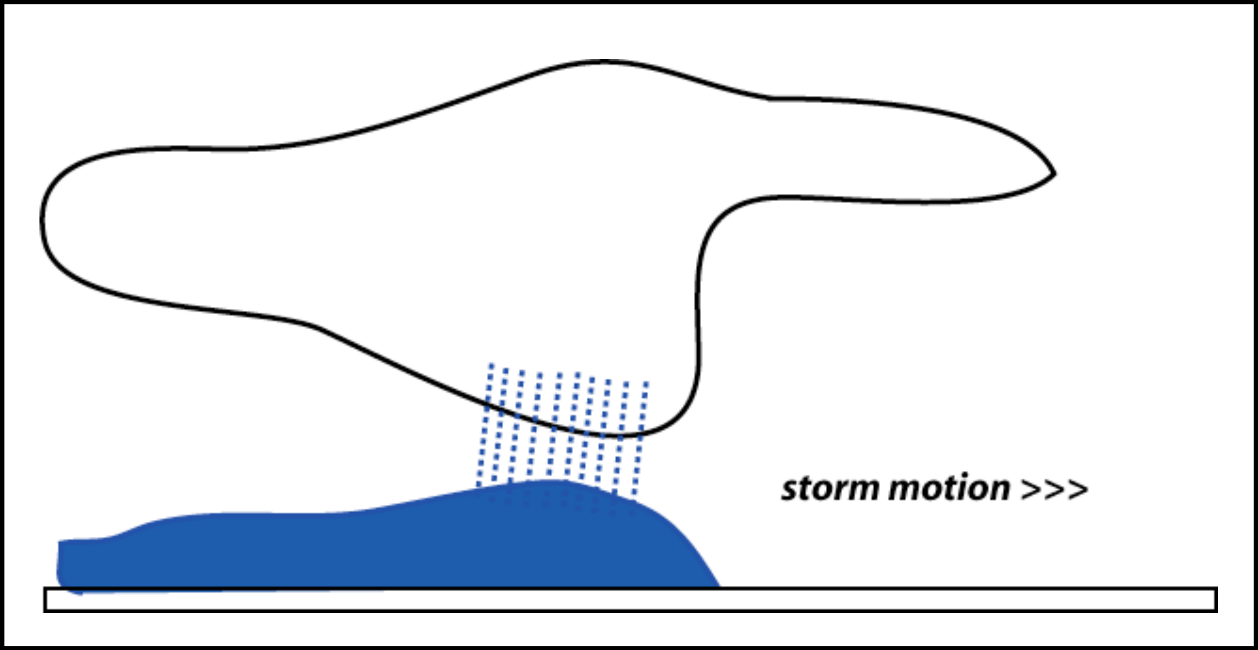
- Phase speed (flow relative)

$$\hat{c}_x = \frac{\hat{\omega}}{k}$$

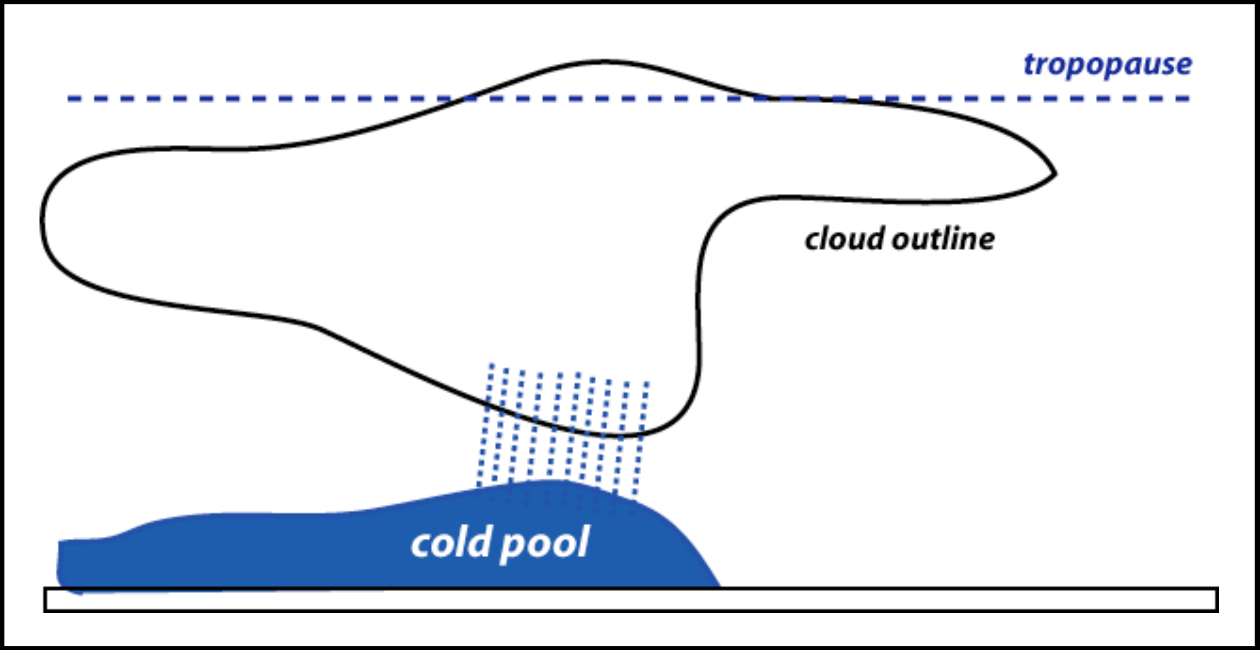
Multicellular squall line storm



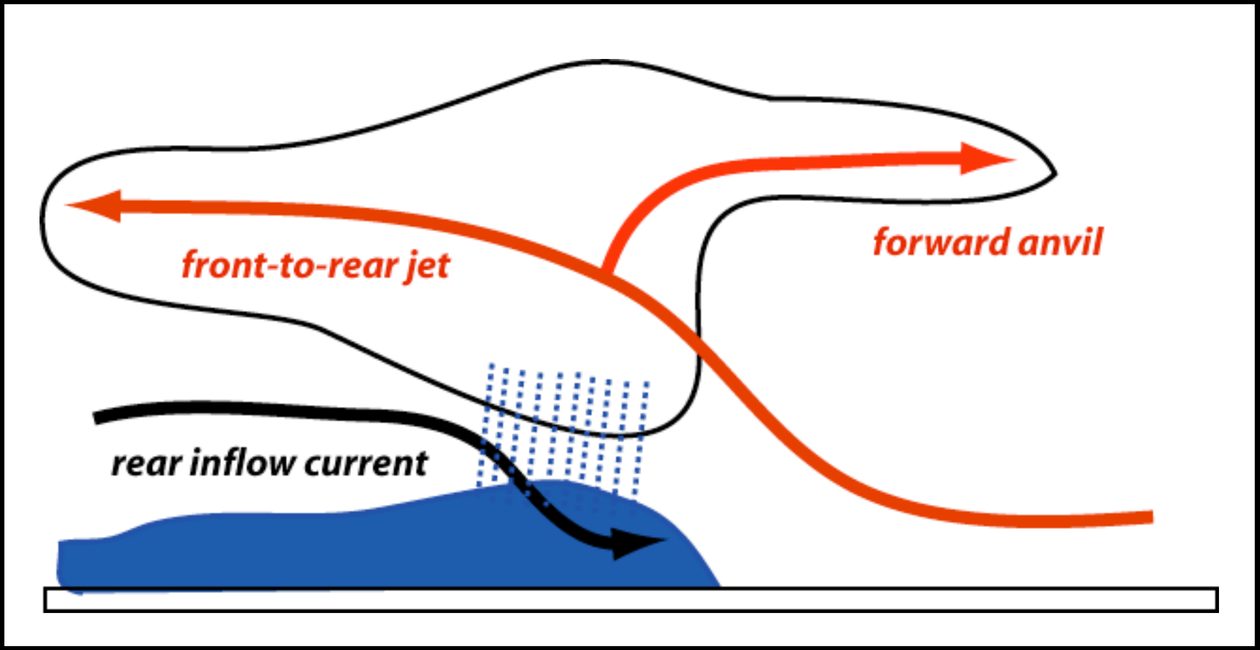
Vertical cross-section



Vertical cross-section

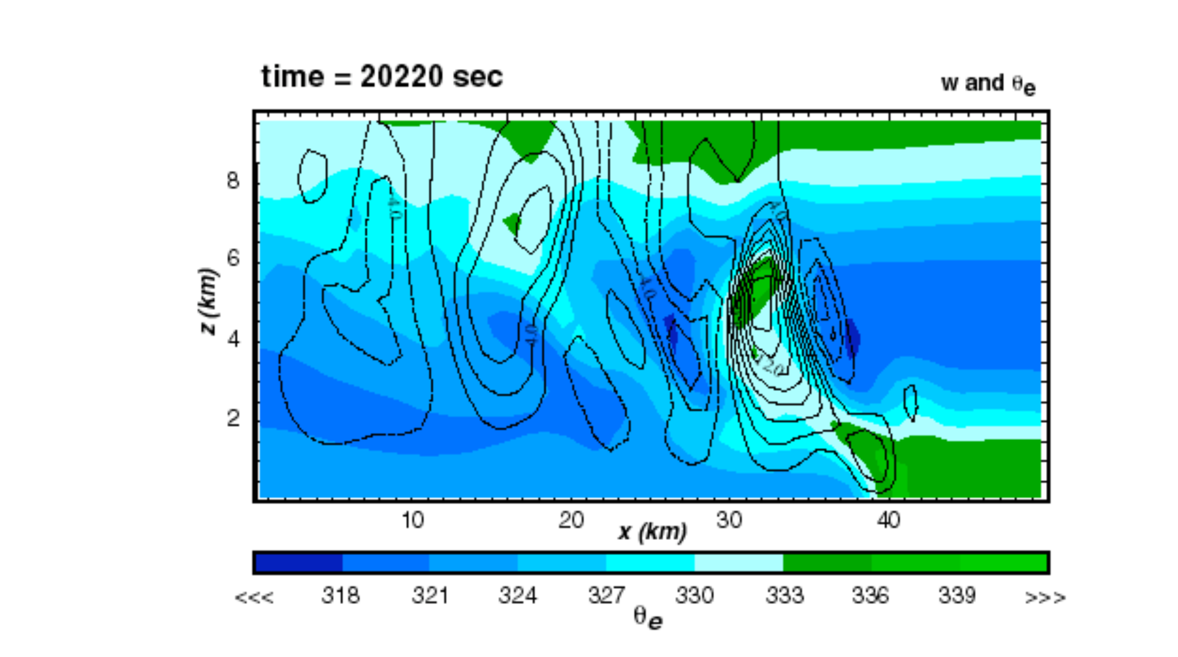


Vertical cross-section



Storm-relative airflow

Animation



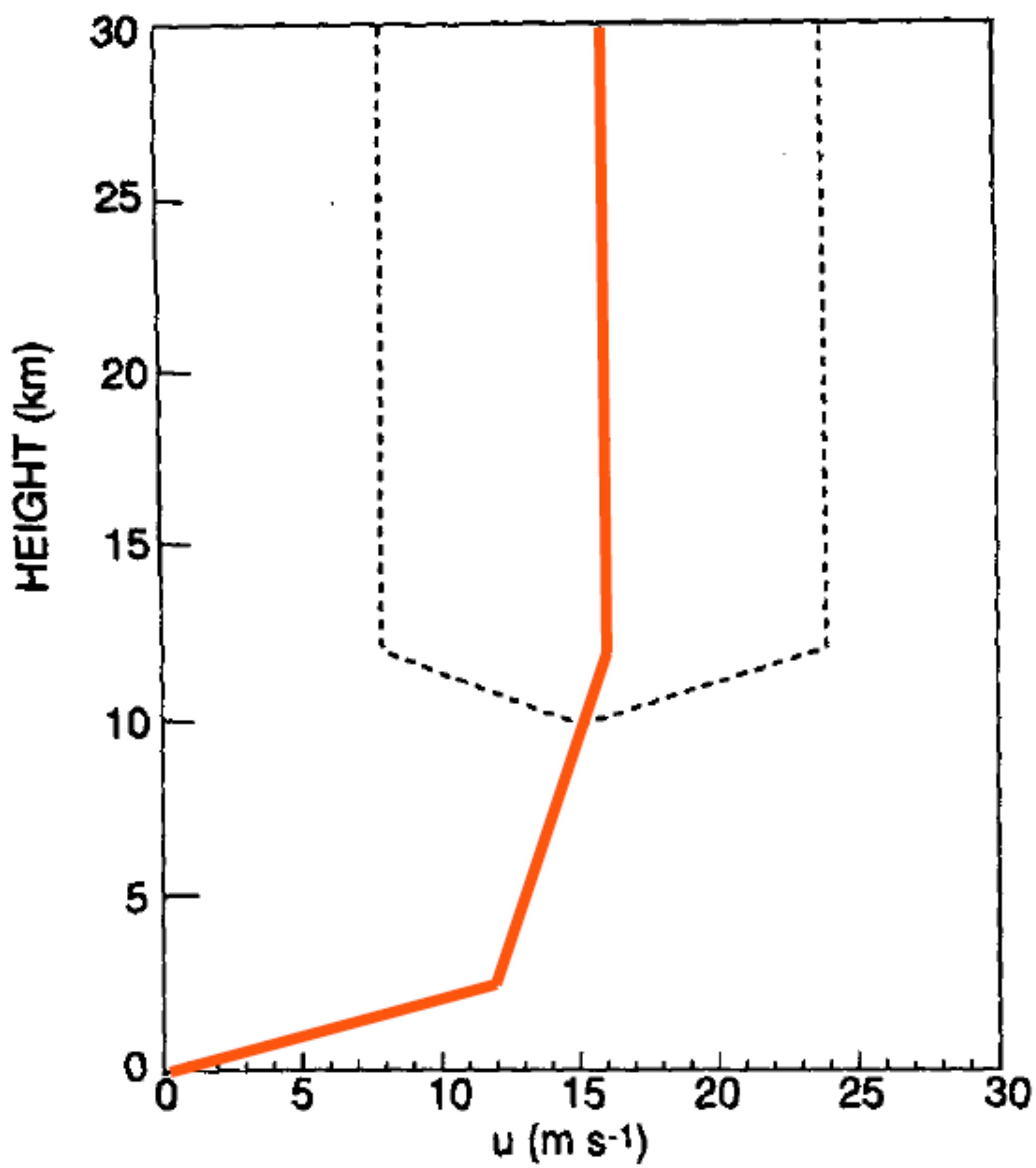
Storm is heat and momentum source;
high frequency and low frequency components

Fovell and Tan (1998)

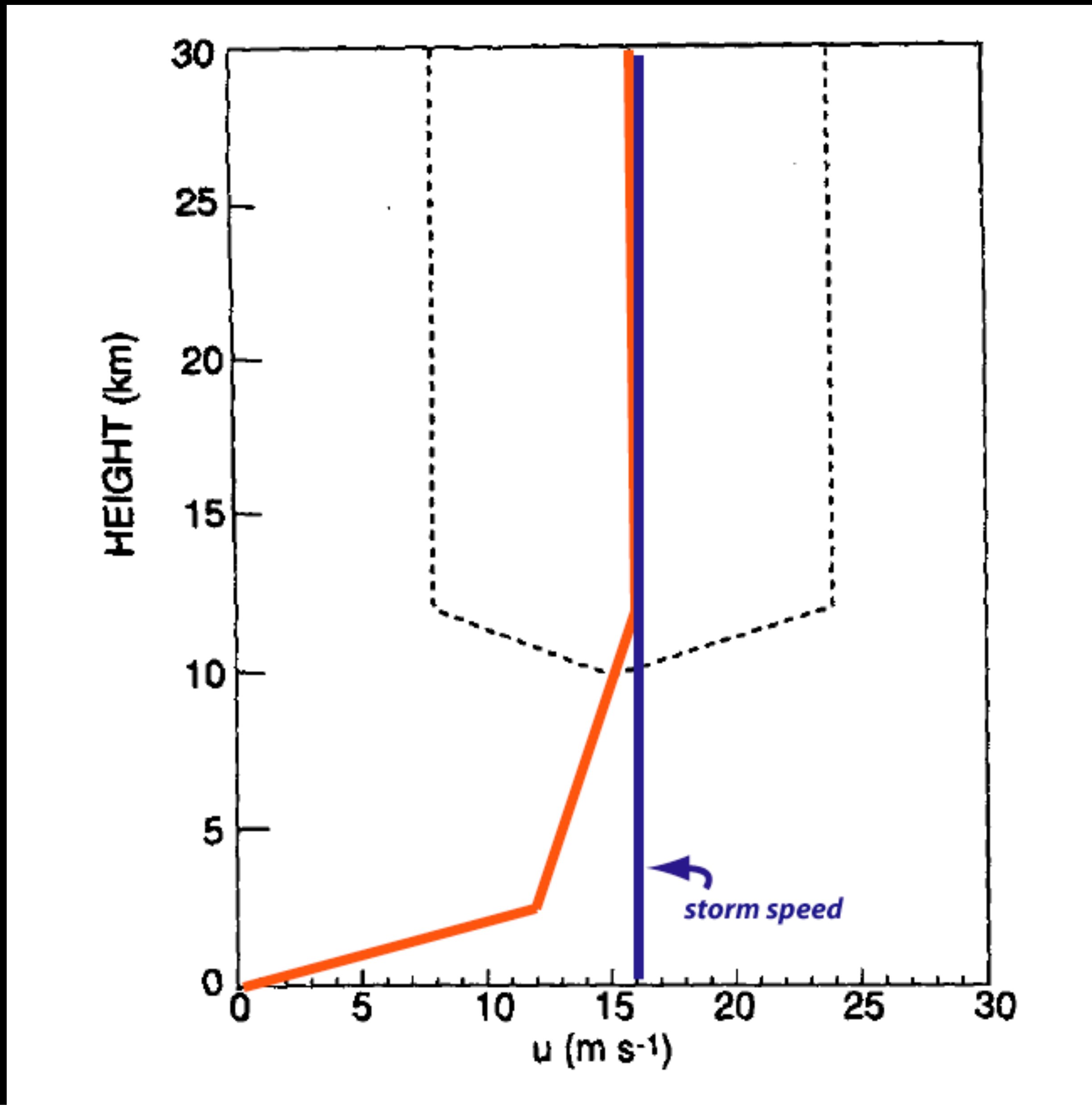
Theme

- Convective storms are an excellent source of gravity waves
- Some of these waves significantly impact the surrounding environment
- Some of those impacts feed back onto the convection
- GCM import: subgrid phenomena that do not remain subgrid

Gravity waves above convection

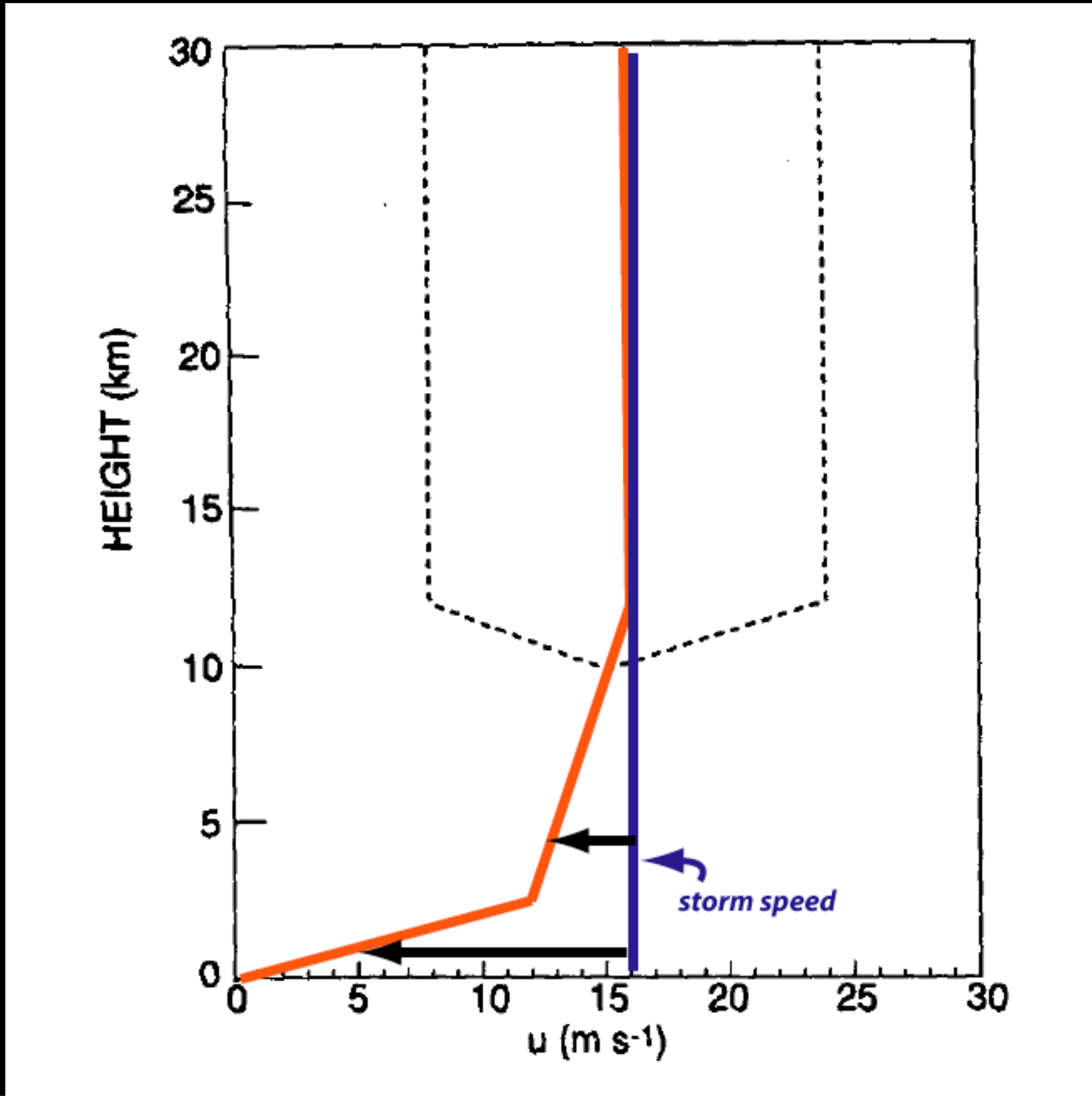


Fovell, Durran and Holton (1992)



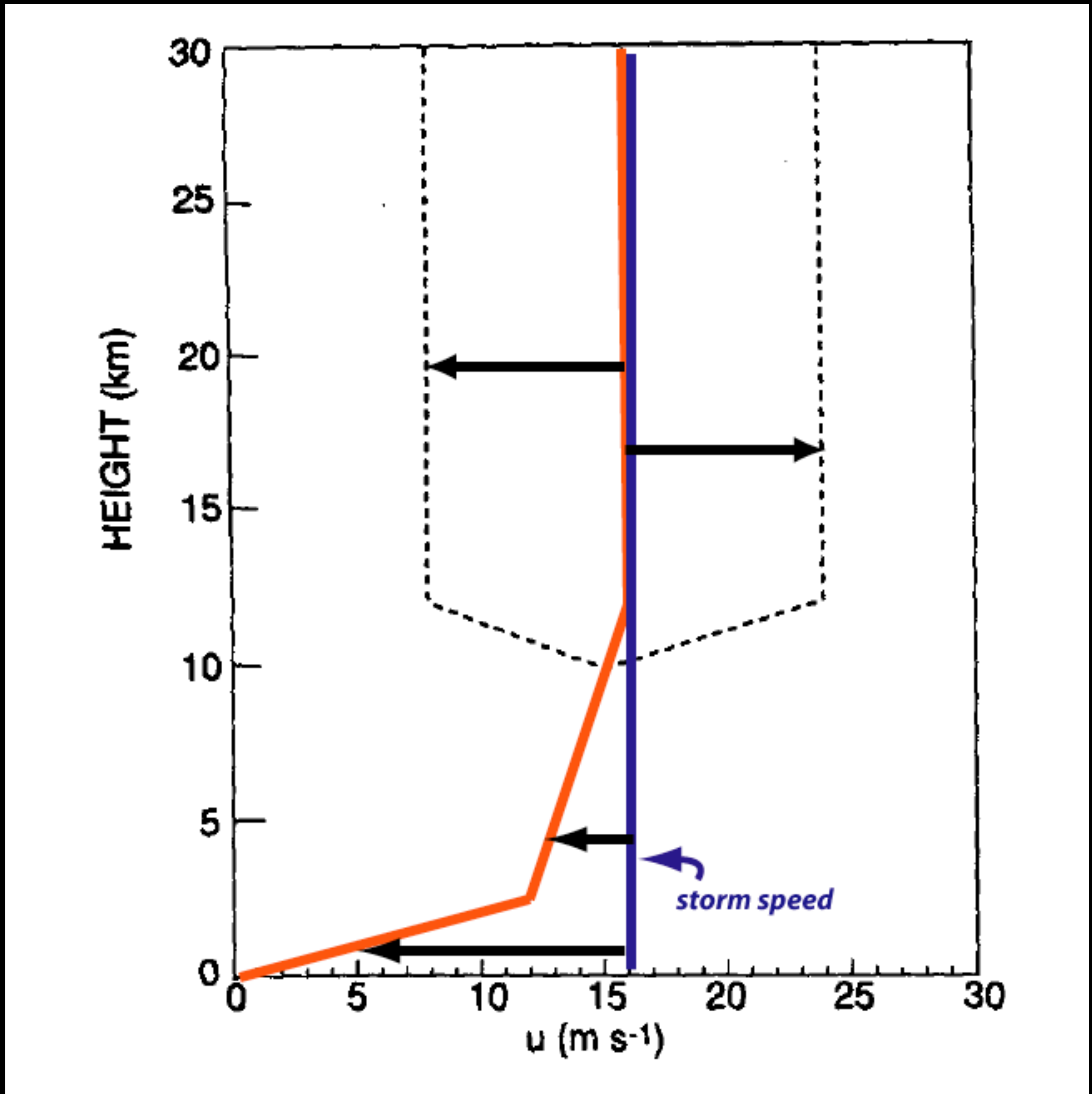
Fovell, Durran and Holton (1992)

S(0) case



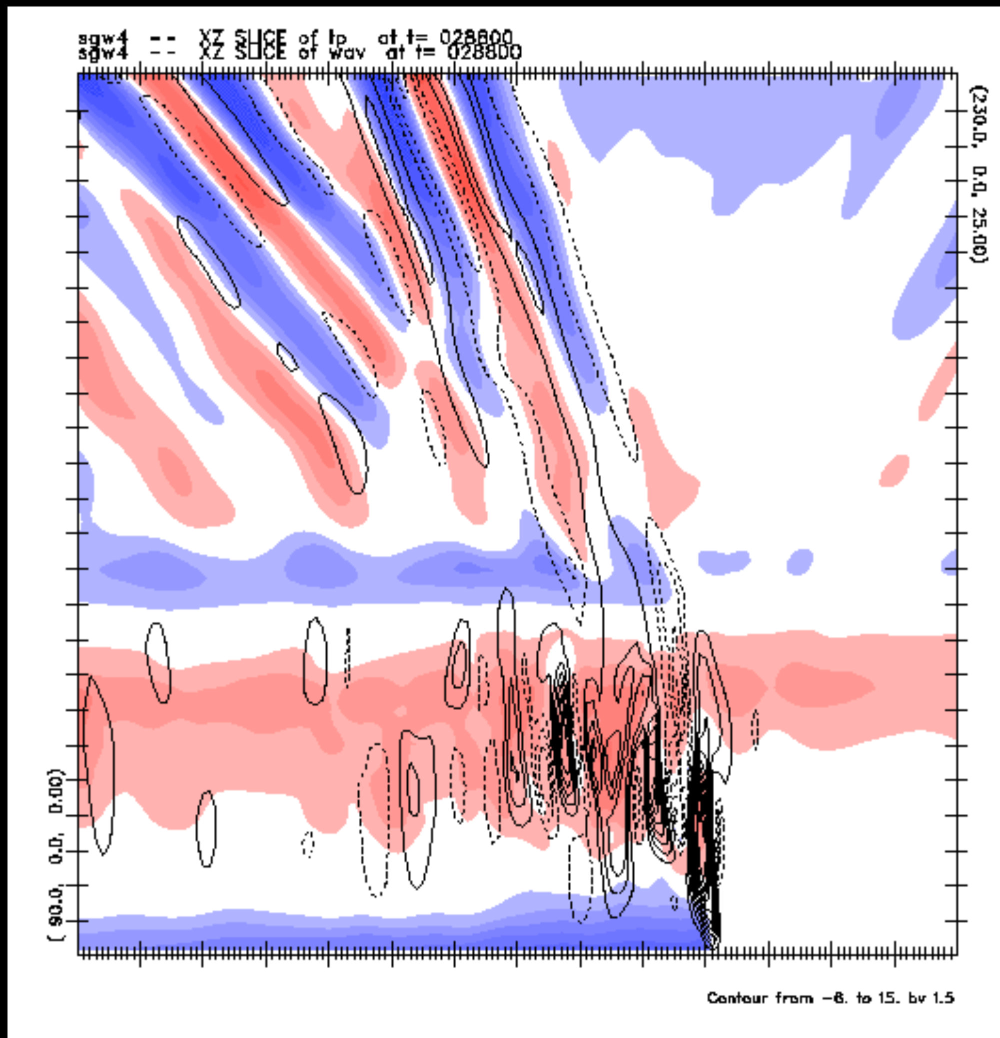
Fovell, Durran and Holton (1992)

S(-8) and S(8) cases

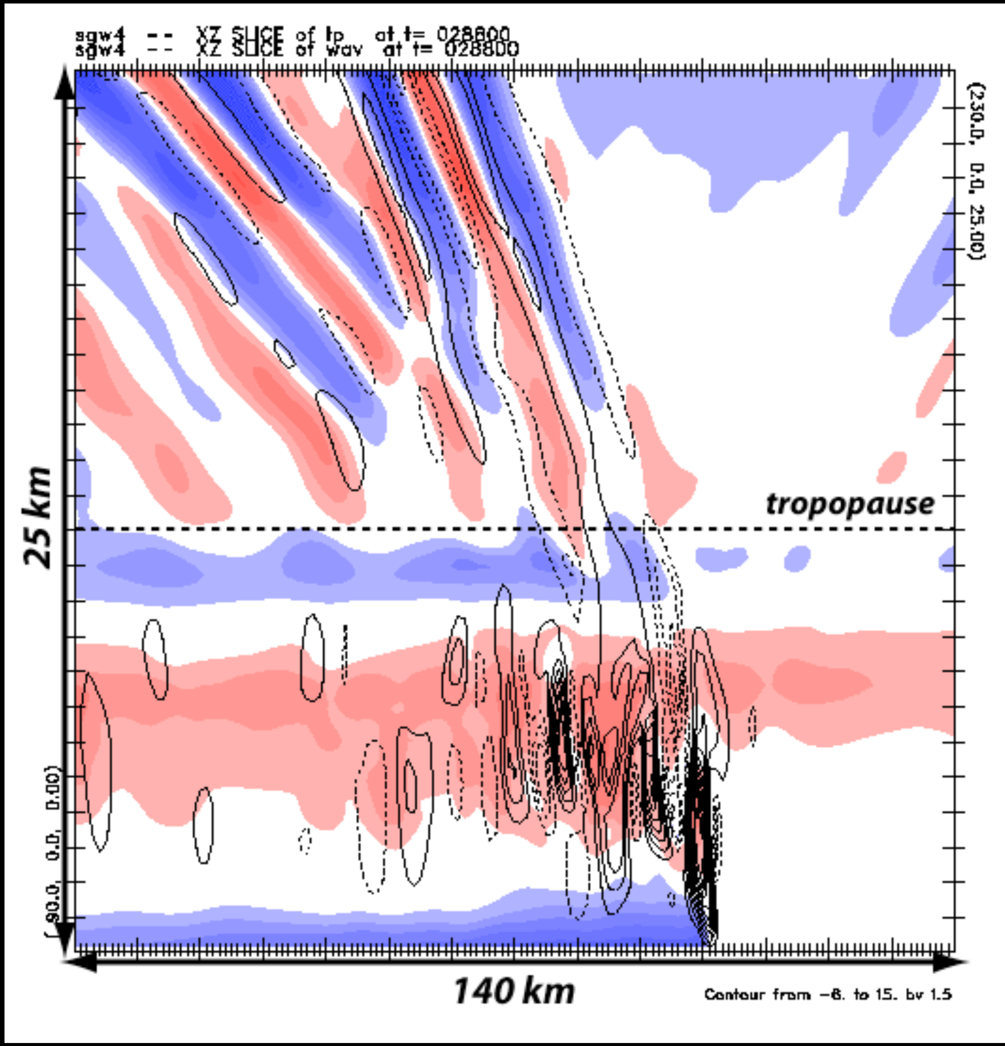


Fovell, Durran and Holton (1992)

An S(0) case

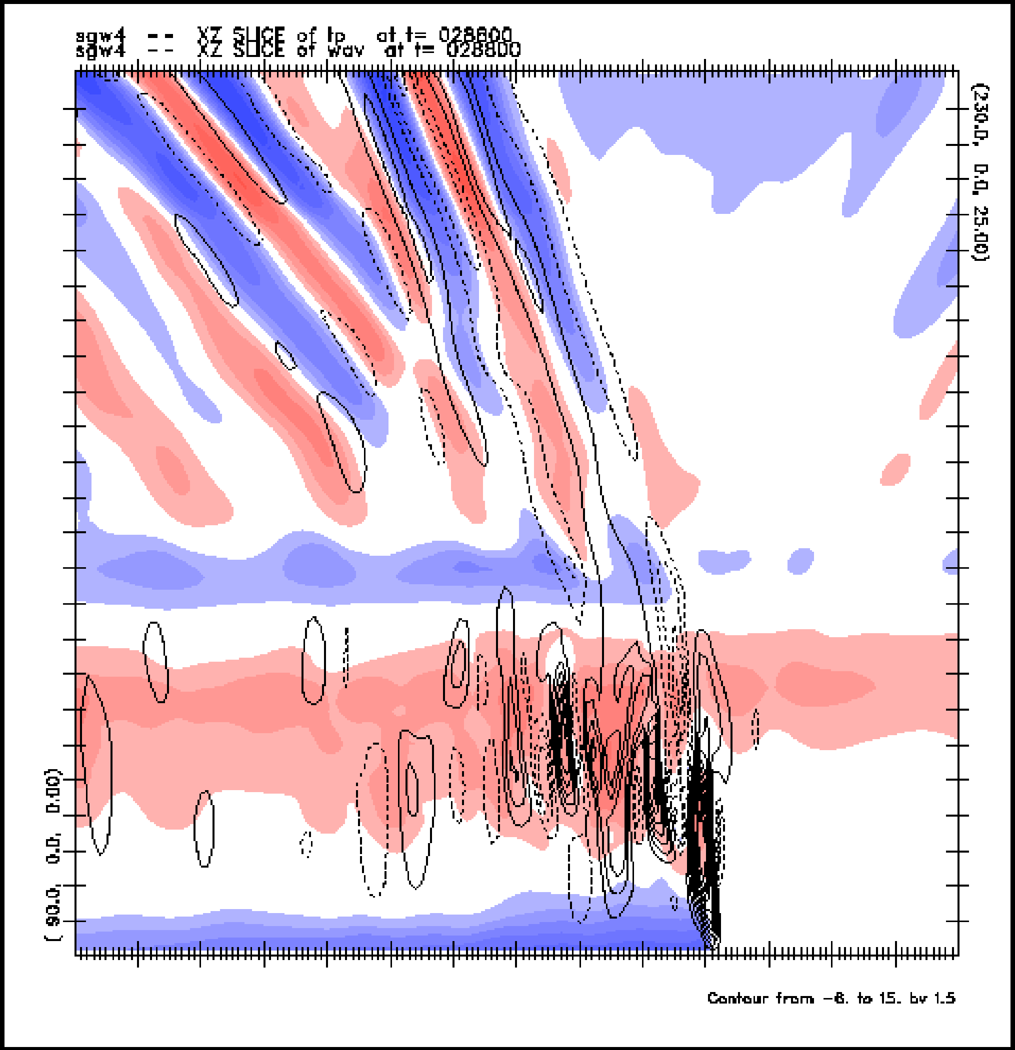

sgw4 -- XZ SLICE of tp at t= 028800
sgw4 -- XZ SLICE of wav at t= 028800
(230.0, 0.0, 25.00)
(90.0, 0.0, 0.00)
Contour from -6. to 15. by 1.5

An S(0) case



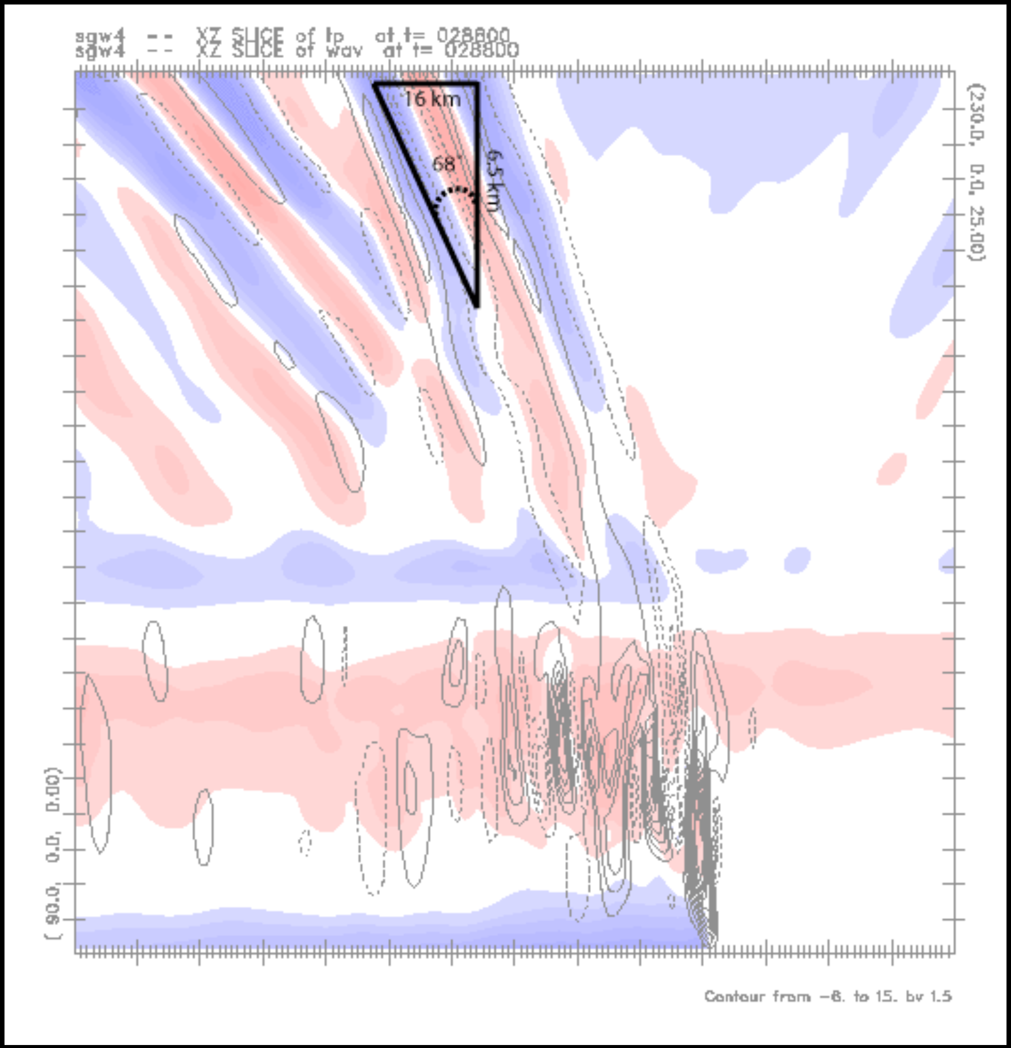
sgw4 -- XZ SLICE of tp at t= 028800
sgw4 -- XZ SLICE of wav at t= 028800
(230.0, 0.0, 25.00)
(90.0, 0.0, 0.00)
25 km
tropopause
140 km
Contour from -6. to 15. by 1.5

An S(0) case



sgw4 -- XZ SLICE of tp at t= 028800
sgw4 -- XZ SLICE of wav at t= 028800
(230.0, 0.0, 25.00)
(90.0, 0.0, 0.00)
Contour from -6. to 15. by 1.5

$$\alpha = \arctan\left[\frac{16}{6.5}\right] = 68^\circ$$



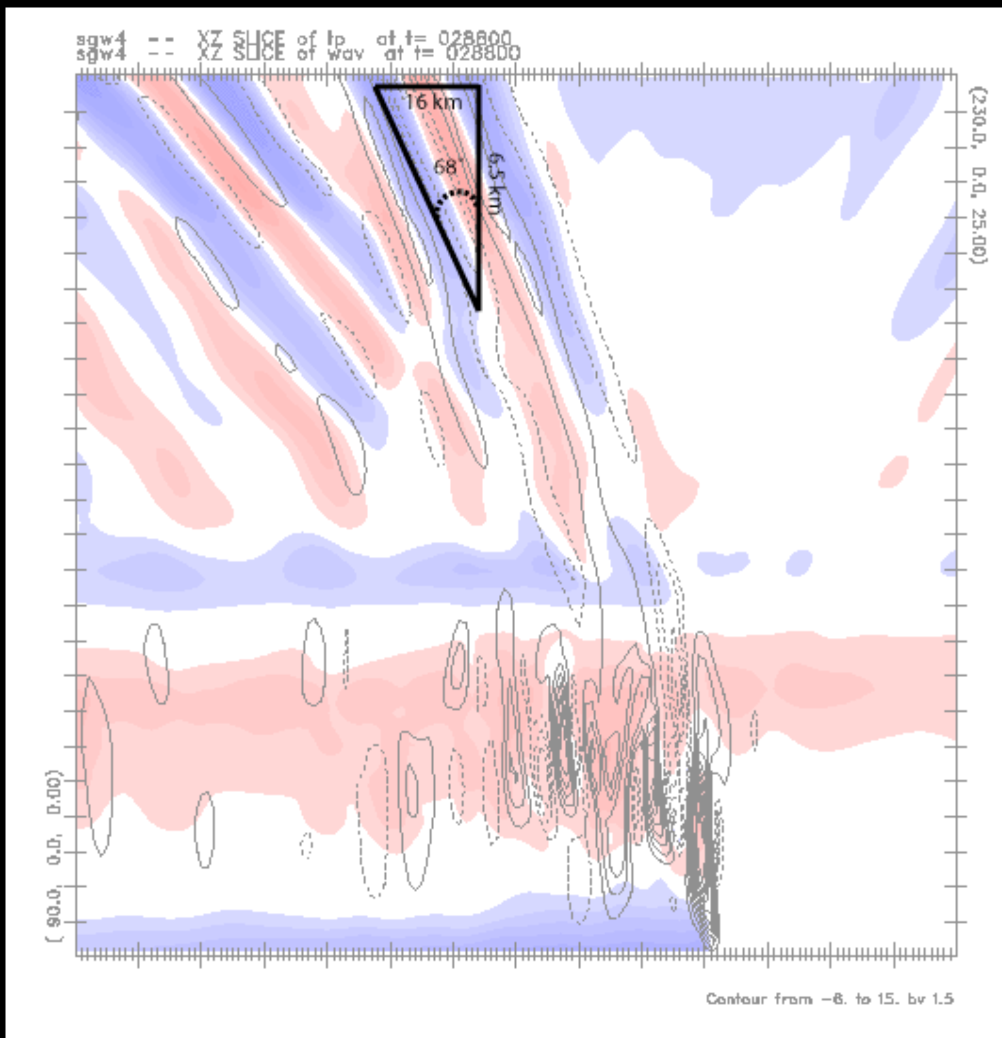
Aspect ratio
not 1:1

$$\alpha = \arctan\left[\frac{16}{6.5}\right] = 68^\circ$$

$$\cos\alpha = \frac{\omega}{N} \therefore \omega = 0.0075\ \mathrm{s}^{-1}$$

$$P = \frac{2\pi}{\omega} = 14\ \mathrm{min}$$

(principal cell period)



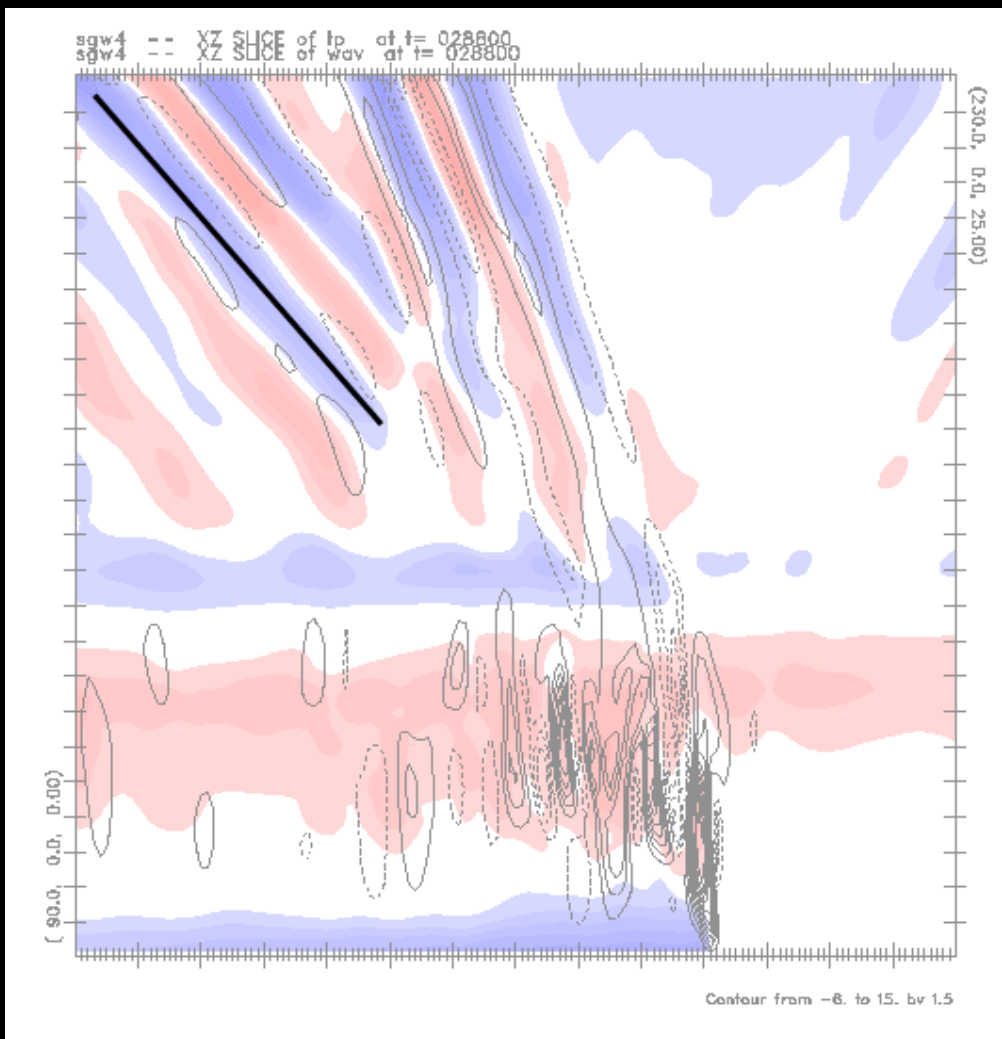
Horizontal phase speed

$$c_x = \frac{\omega}{k}$$

$$\therefore \ c_x = \frac{\omega L_x}{2\pi}$$

$$\approx 19 \text{ m s}^{-1}$$

(to west)



larger α

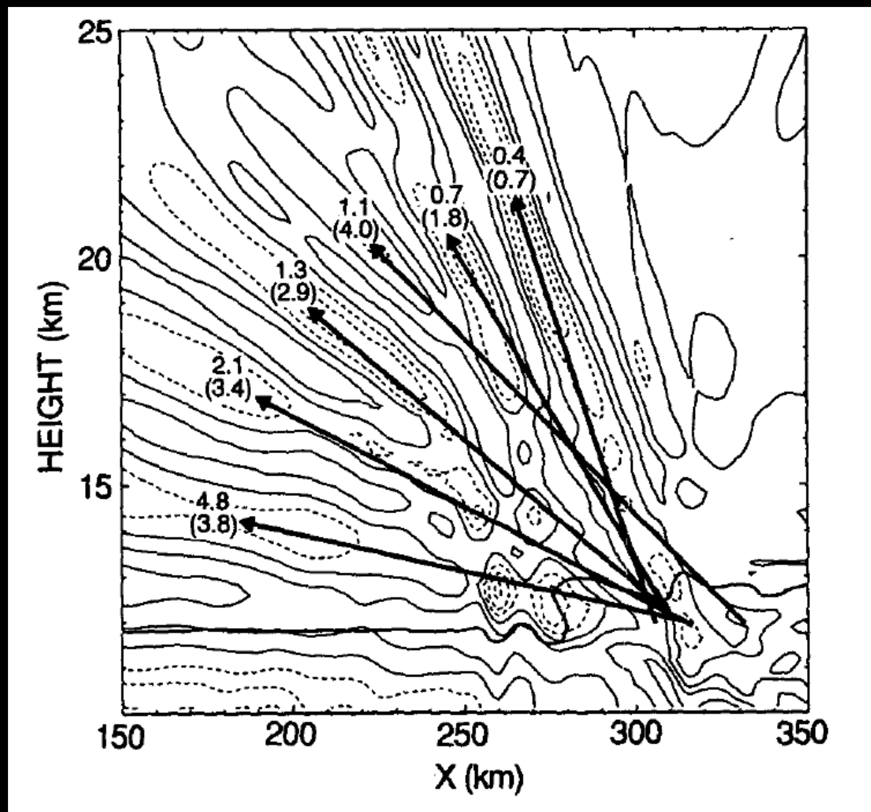
smaller $\cos\alpha$

$\therefore$ smaller ω

$\therefore$ longer P

≈ 23 min

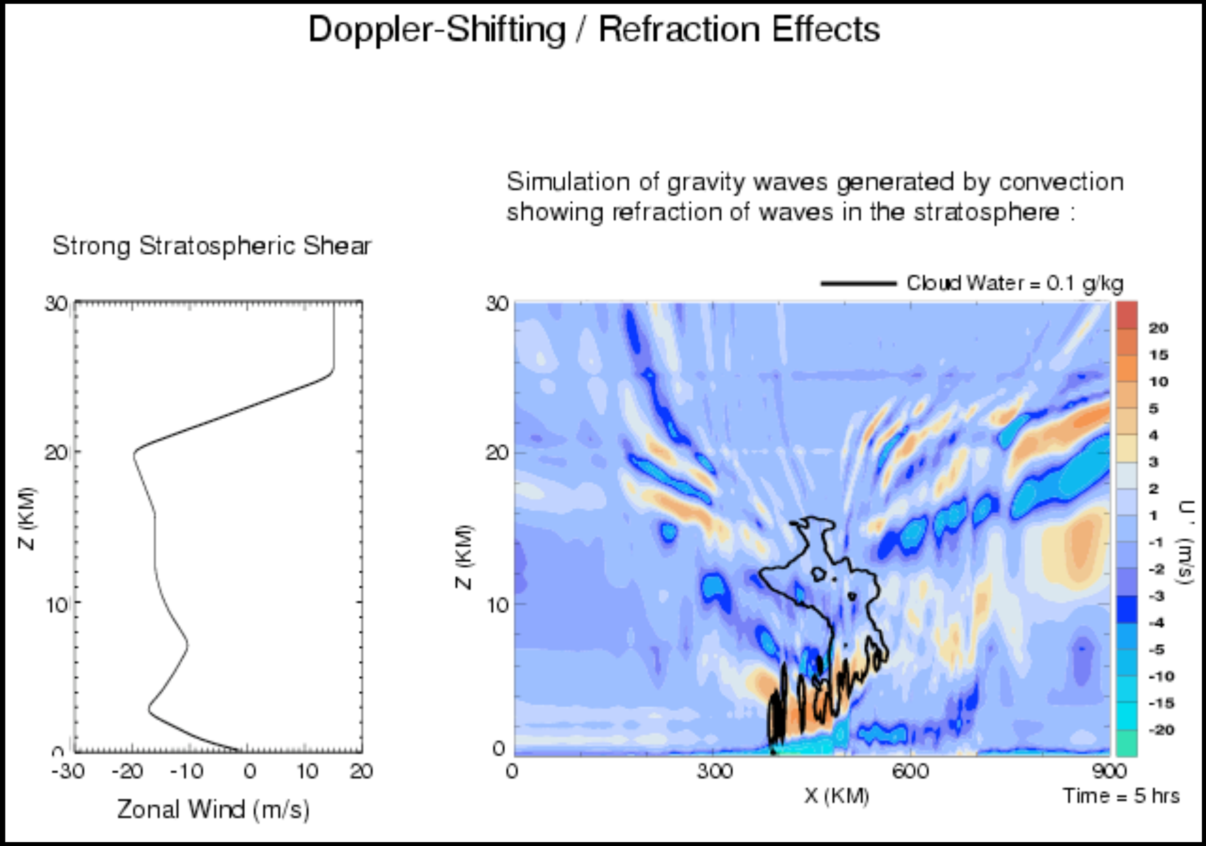
FDH's S(0) gravity wave "fan"



Fovell, Durran and Holton (1992)

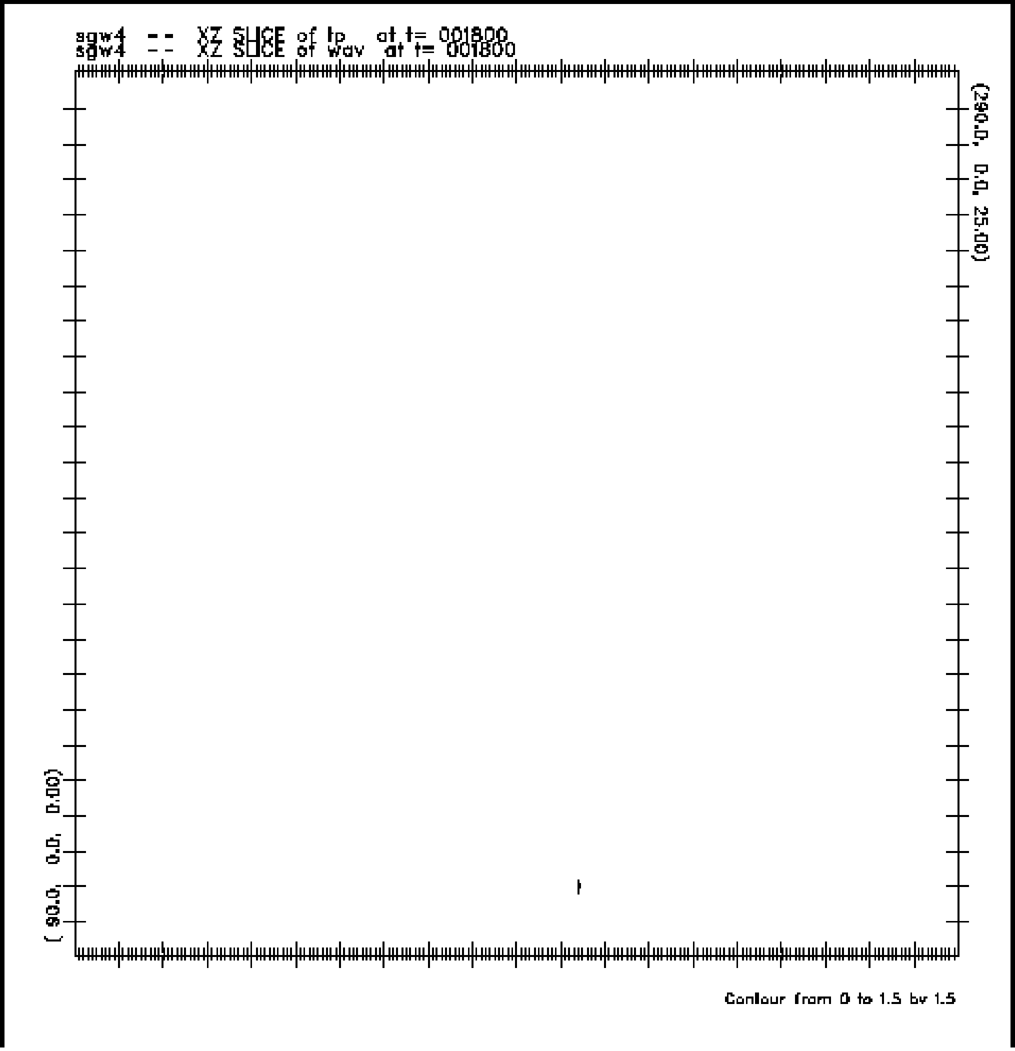
Wave period given in hours

Impact of stratospheric GWs



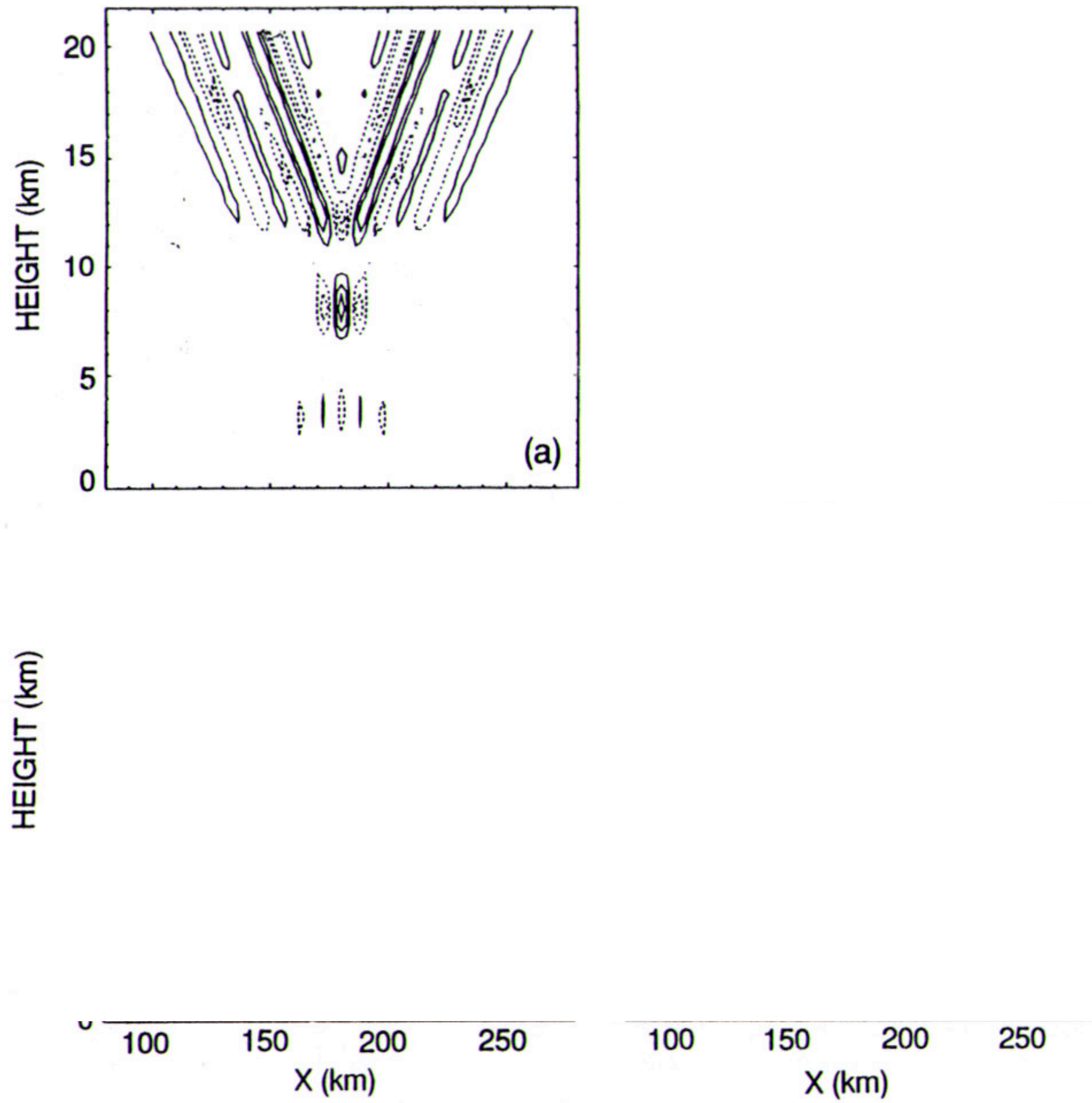
Alexander and Holton (1997)

Evolution of stratospheric waves

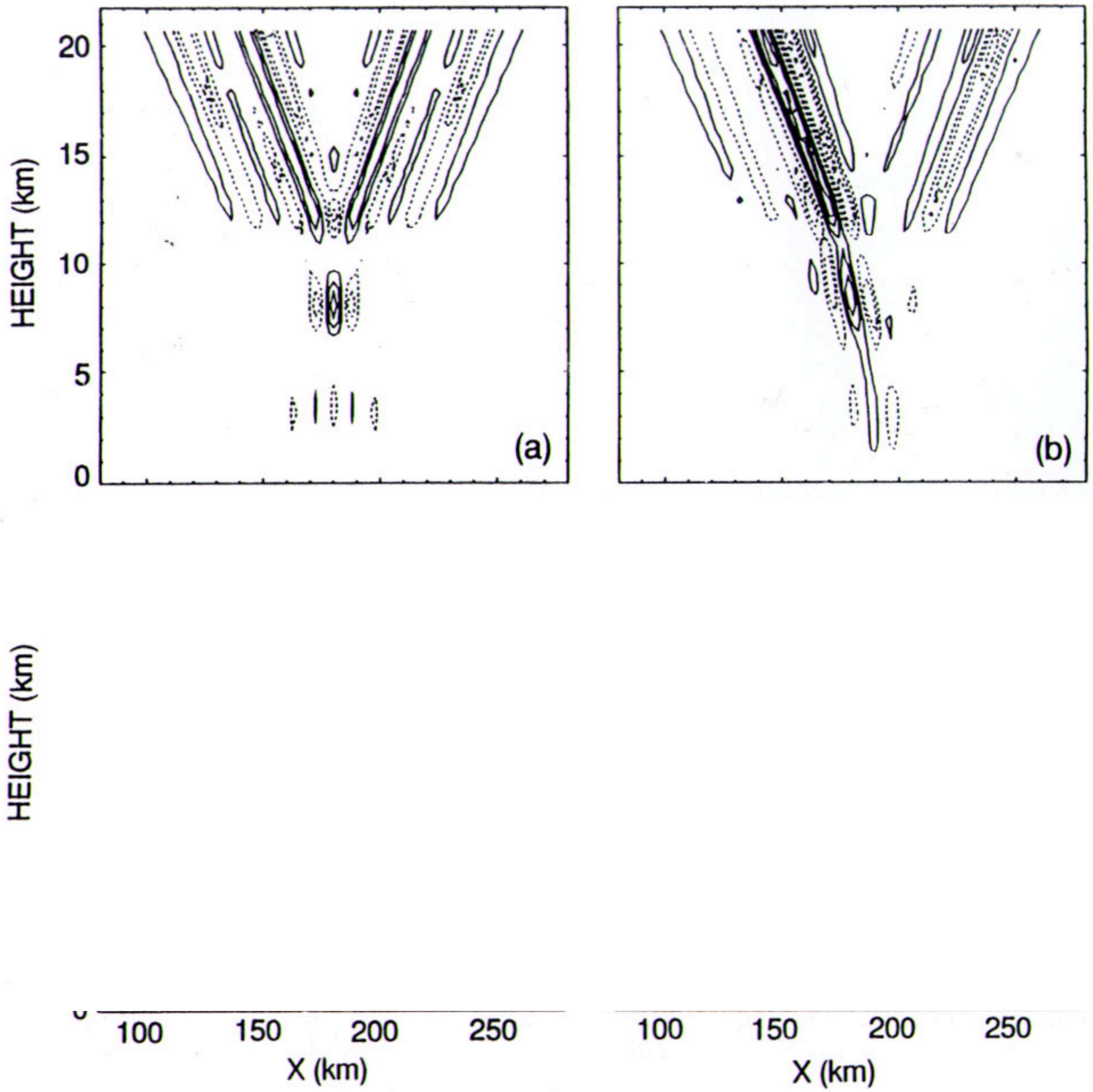


Simple oscillator model

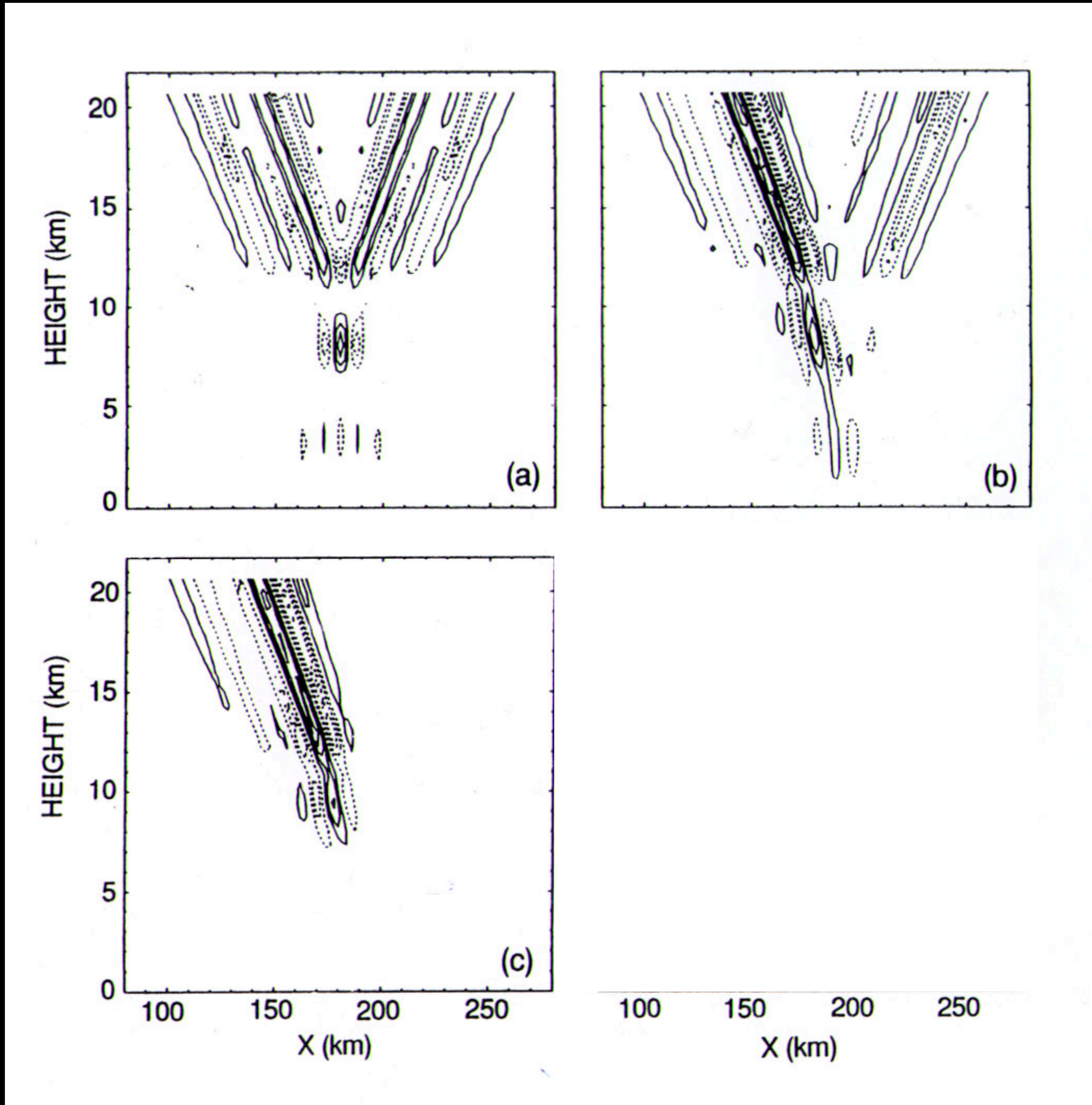
- Tropospheric momentum source mimicking a convective cell updraft
- Oscillate at set period *P*
- Source may be tilted
- Source may be “moved” horizontally



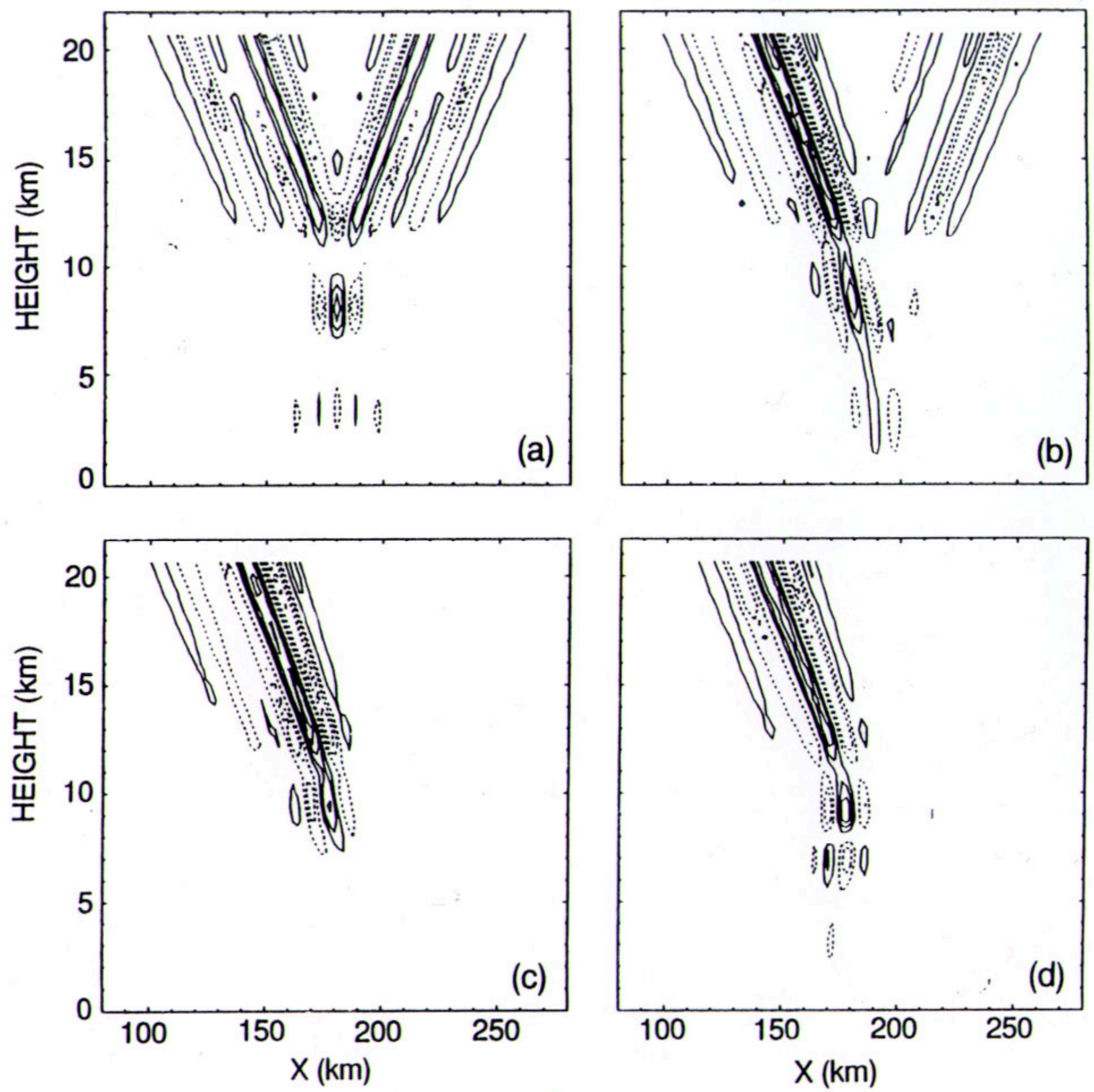
Fovell, Durran and Holton (1992)



Fovell, Durran and Holton (1992)

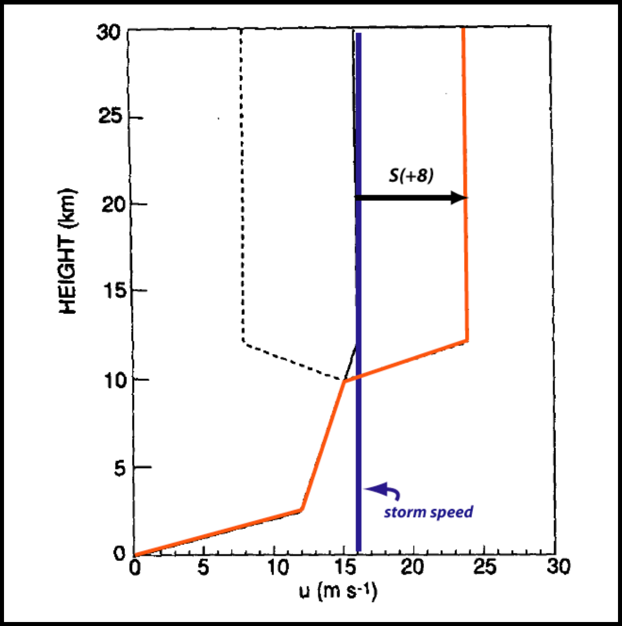


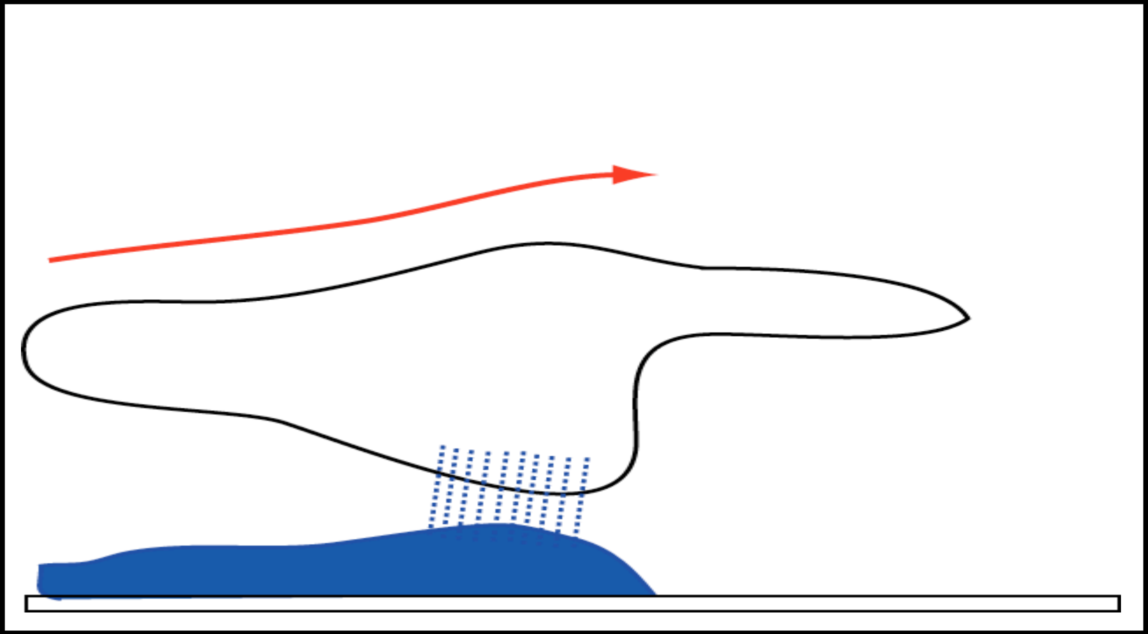
Fovell, Durran and Holton (1992)



Fovell, Durran and Holton (1992)

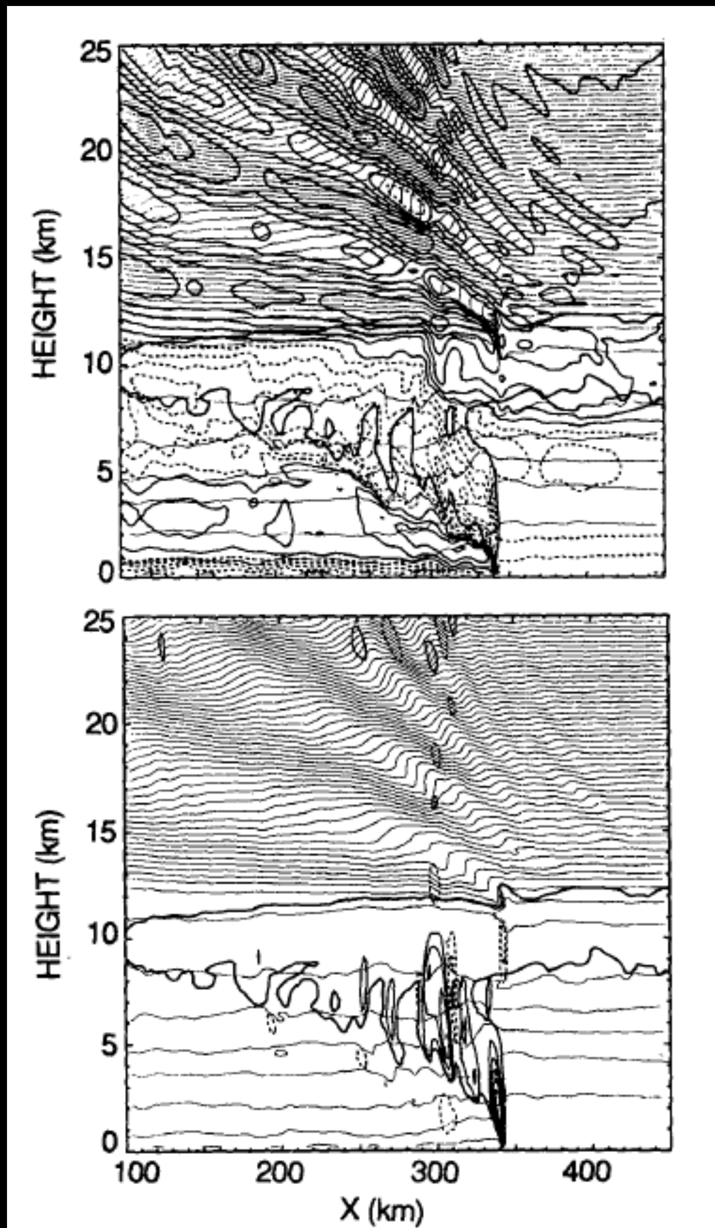
S(+8) case



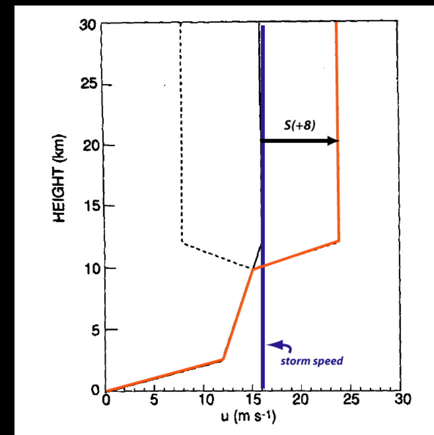


Storm's convective region acts as equivalent obstacle

S(+8) case



Fovell, Durran and Holton (1992)



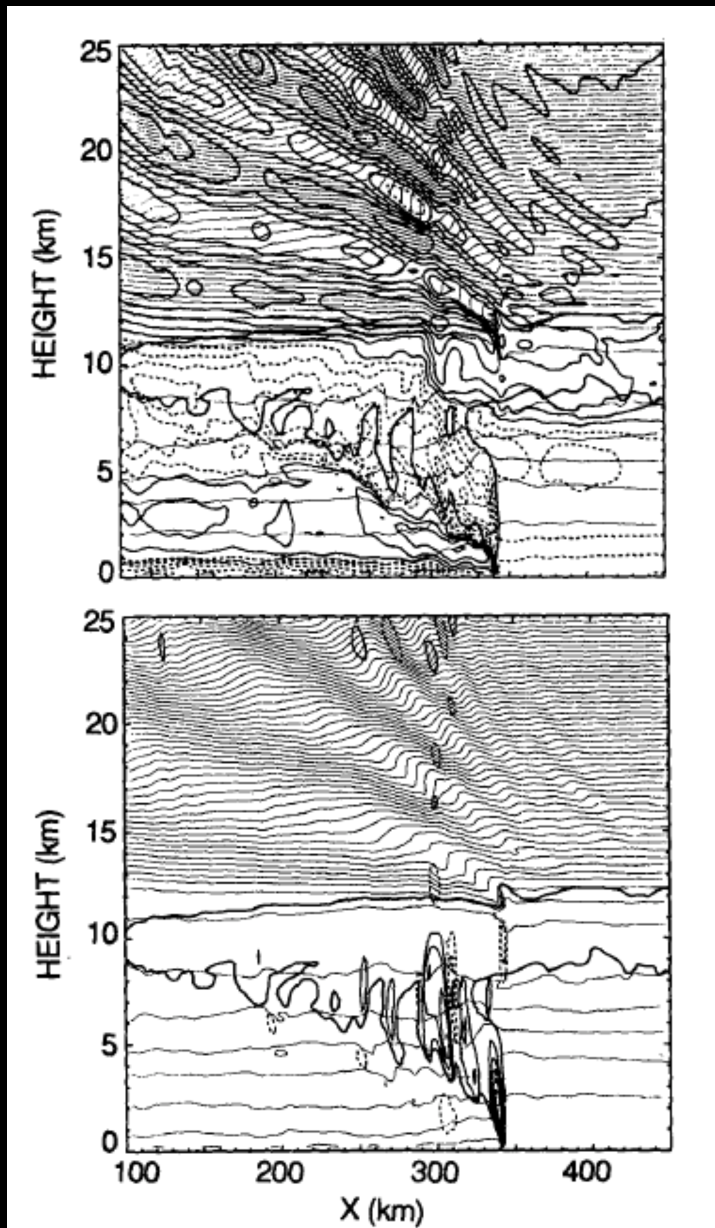
$$\omega = 0$$

$$\hat{\omega} = \omega - \bar{U}k = -\bar{U}k$$

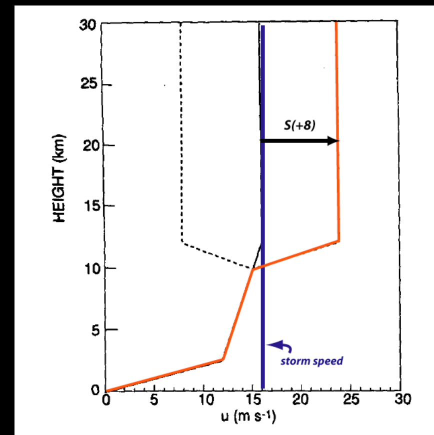
$$\hat{\omega} = \pm \frac{Nk}{\sqrt{k^2 + m^2}}$$

$$\therefore \; m^2 = \frac{N^2}{\bar{U}^2} - k^2$$

S(+8) case



Fovell, Durran and Holton (1992)



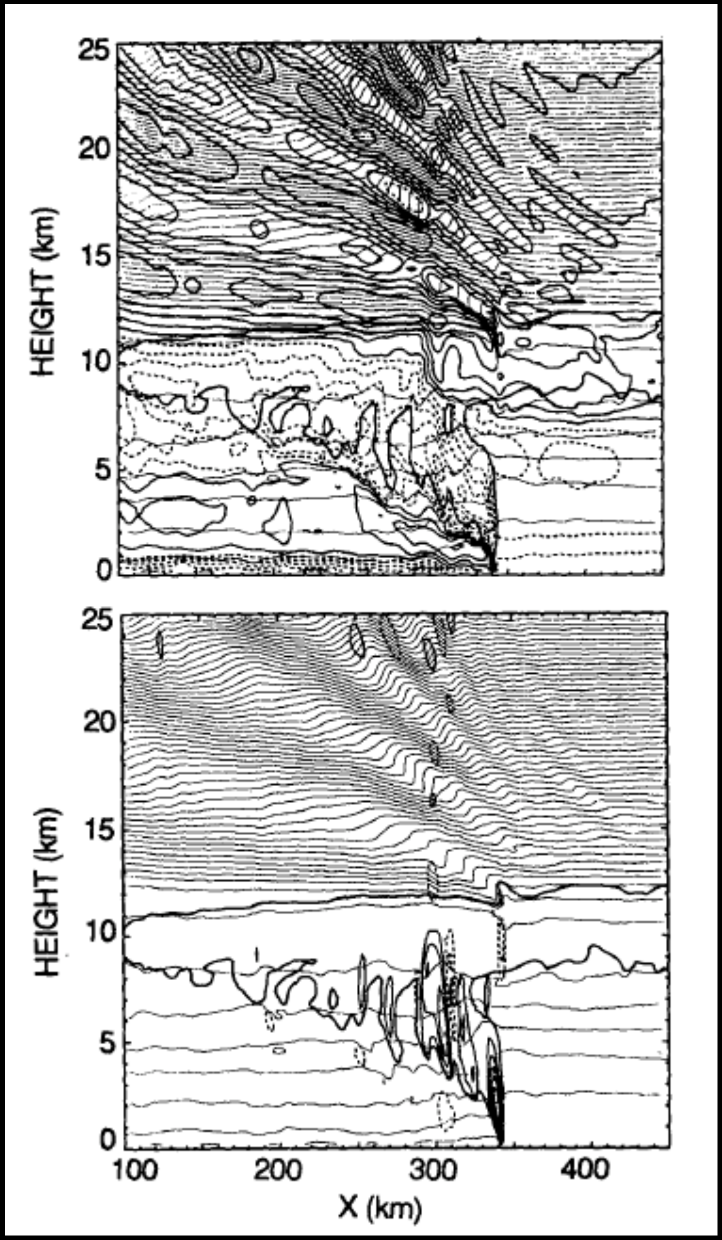
$$k \rightarrow \infty$$

$$\therefore \; L_z = \frac{2\pi \bar{U}}{N}$$

$$L_z \approx 2.4 \text{ km}$$

S(+8) case

What happened to the high frequency waves?



Fovell, Durran and Holton (1992)

$$\hat{\omega} = \omega - \bar{U}k$$

$$\bar{U} > 0; \ k < 0$$

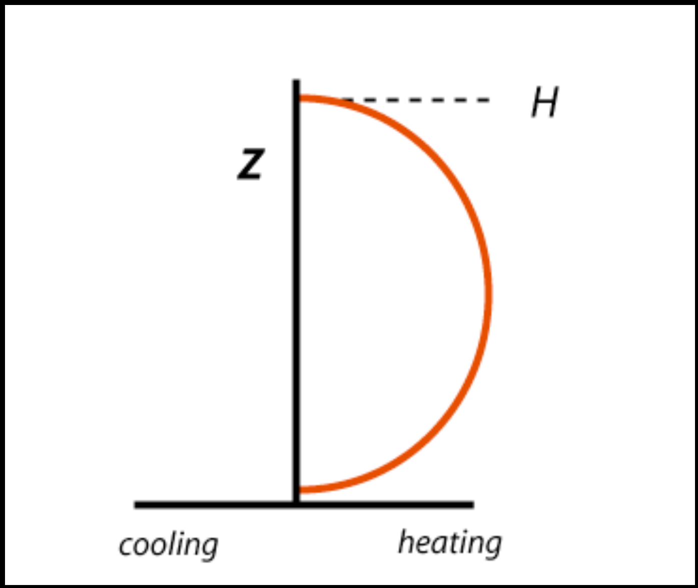
$$\therefore \ \hat{\omega} > \omega$$

$$\text{As } \hat{\omega} \to N, \ \cos\alpha \approx 1$$

$$\therefore \ \alpha \approx 0$$

Low frequency tropospheric gravity waves

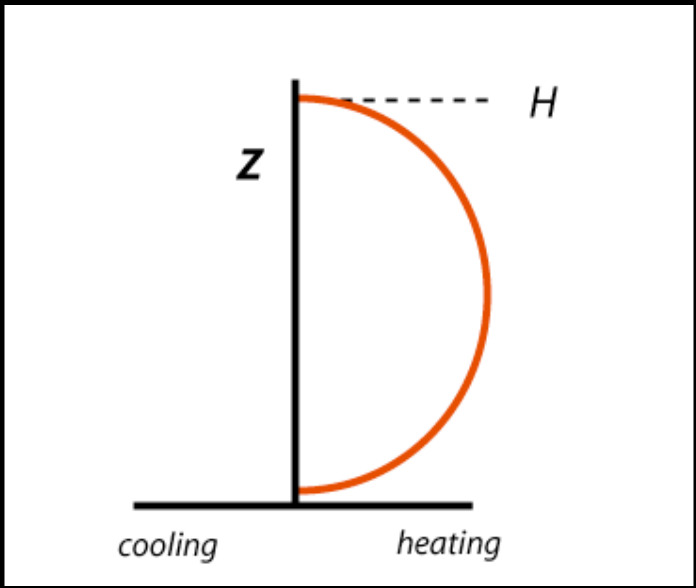
Vertical half-sine heating profile

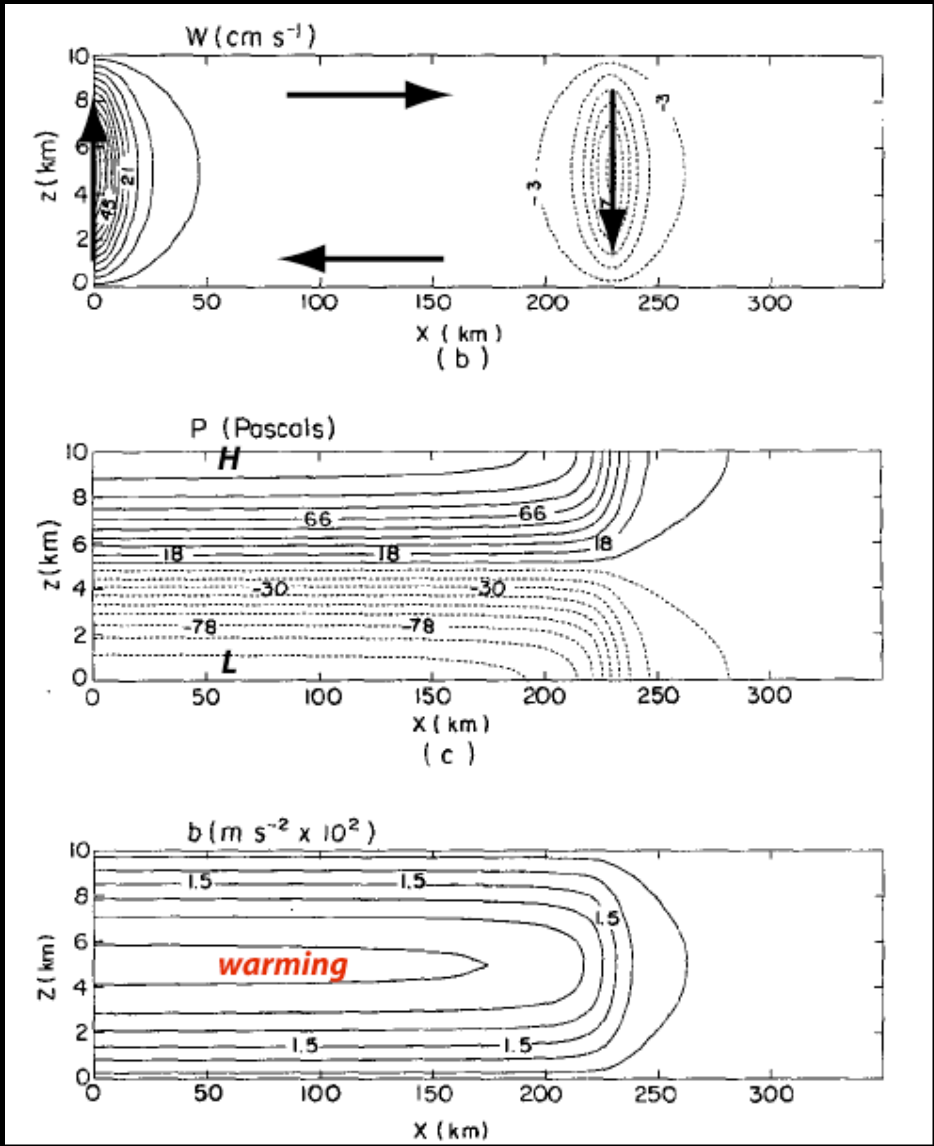


$$Q = \sin\left[\frac{\pi z}{H}\right]$$

For $z \leq H$

$$L_z = 2H$$



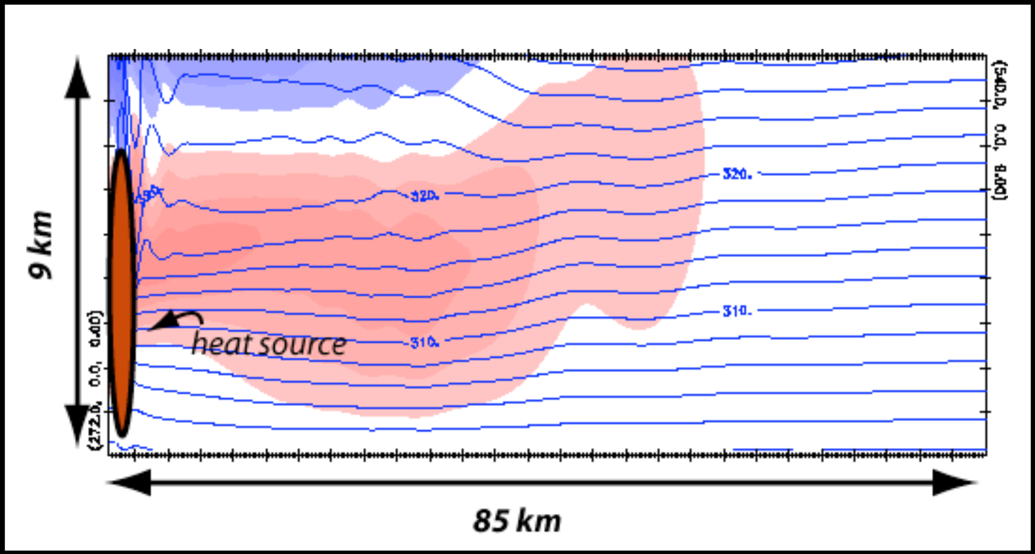


Nicholls et al. (1991)

Dry heat source model

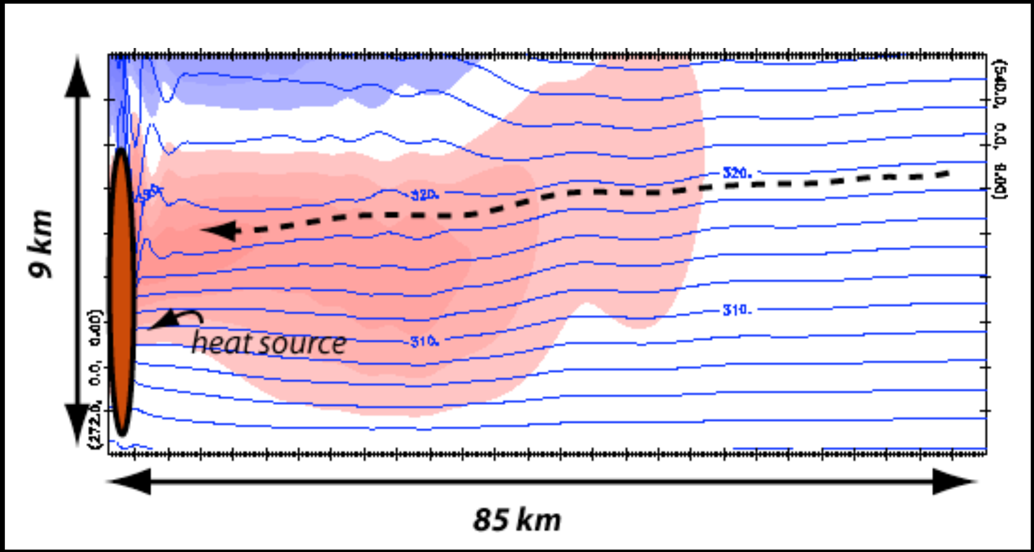
- Compressible, nonlinear with stratosphere
- No mean flow
- Maintained, vertically oriented heat source

Dry heat source model

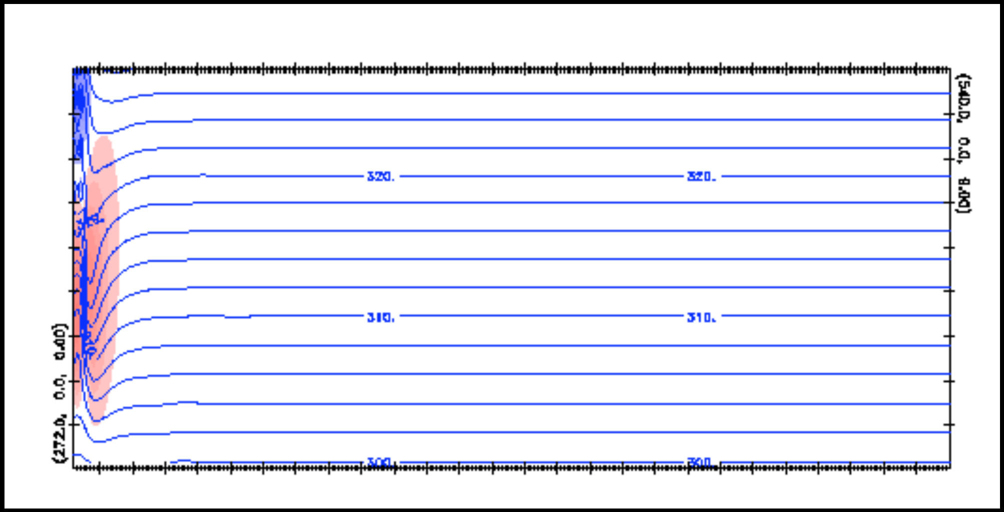


Temperature perurbation (colored);
potential temperature (contoured)

Dry heat source model



Animation



Note displaced air does not return to original elevation

Phase speed…

$$\omega = \pm \frac{Nk}{\sqrt{(k^2 + m^2)}}$$

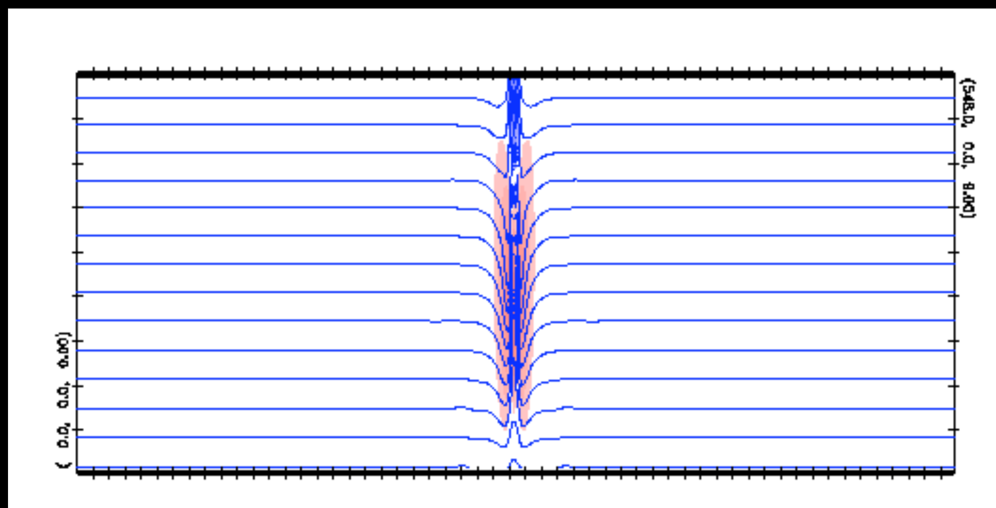
$$\text{As } k \rightarrow 0, \text{since } m = \frac{\pi}{H}$$

$$c_x = \pm \frac{NH}{\pi}$$

$$\text{If } N = 0.01 \text{ s}^{-1}, H = 10 \text{ km}$$

$$c_x \approx 32 \text{ m s}^{-1}$$

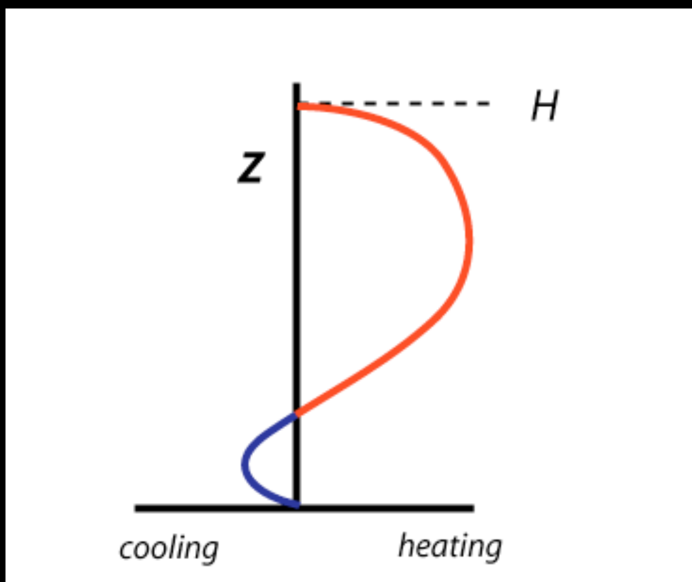
Dry heat source model



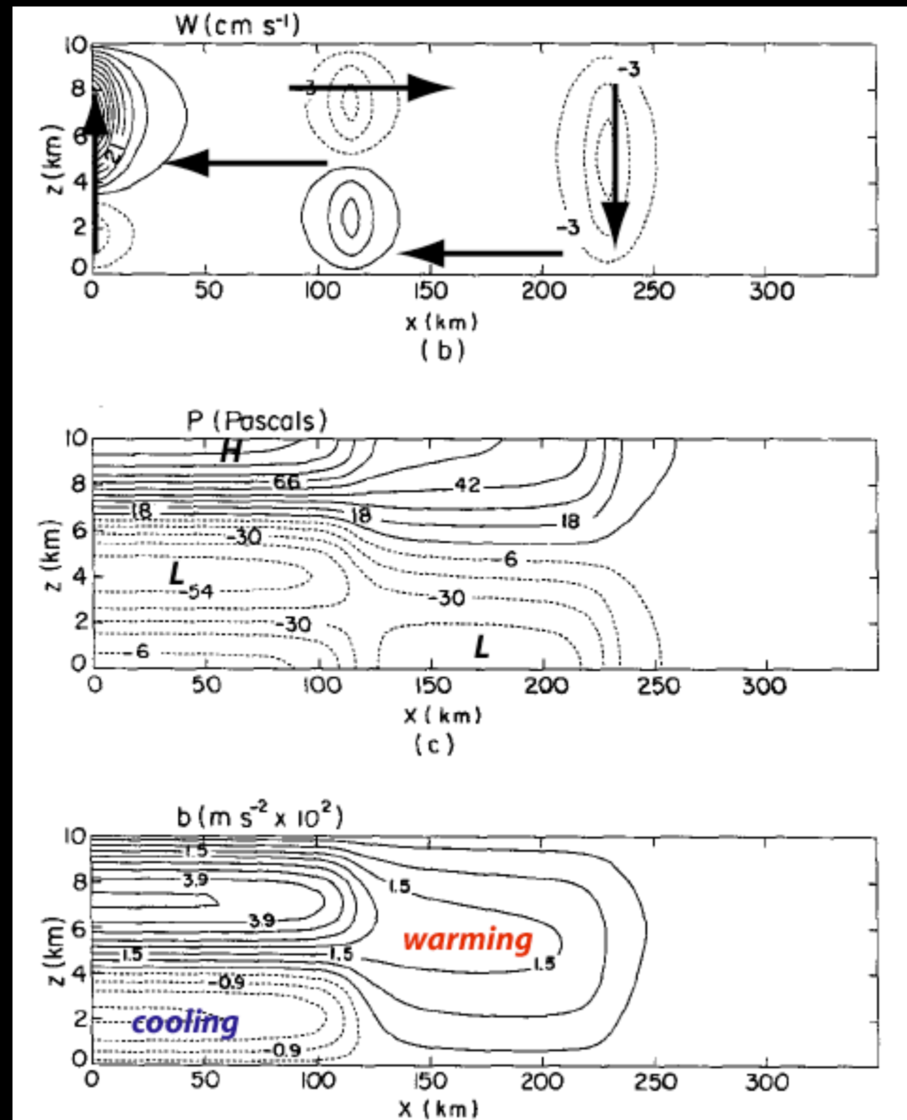
Heat source deactivated halfway through animation

Two vertical modes

$$L_z \downarrow \therefore c_x \downarrow$$

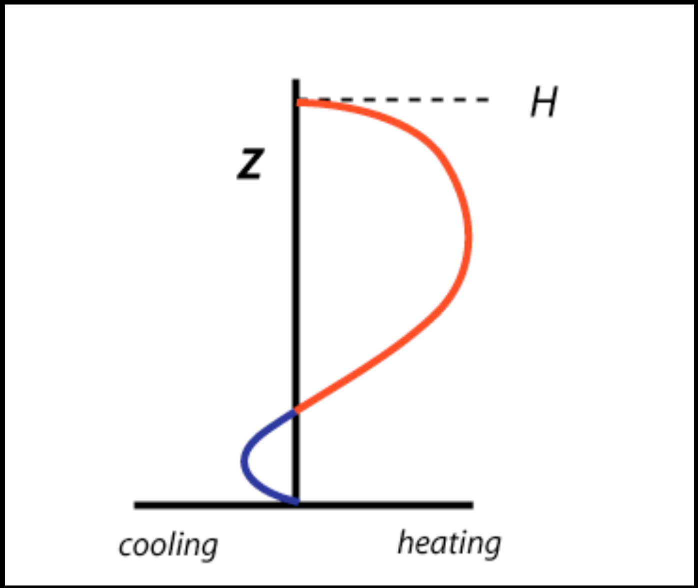


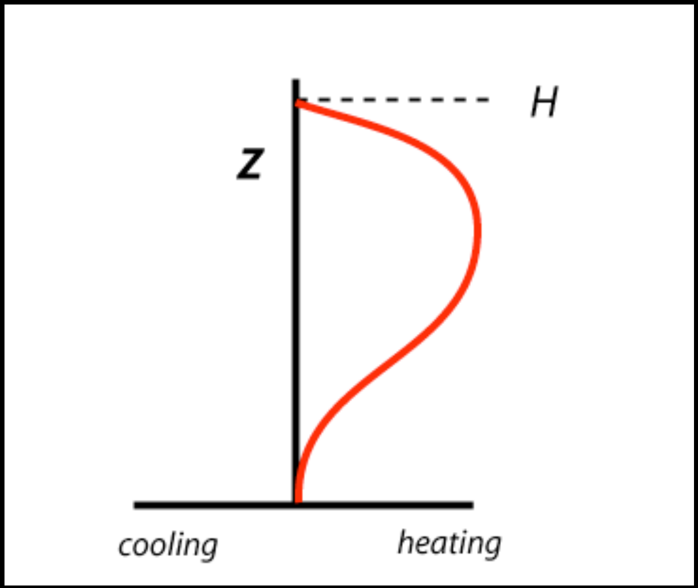
$$Q = \sin\left[\frac{\pi z}{H}\right] - \sin\left[\frac{2\pi z}{H}\right]$$



Nicholls et al. (1991)

No applied cooling needed…

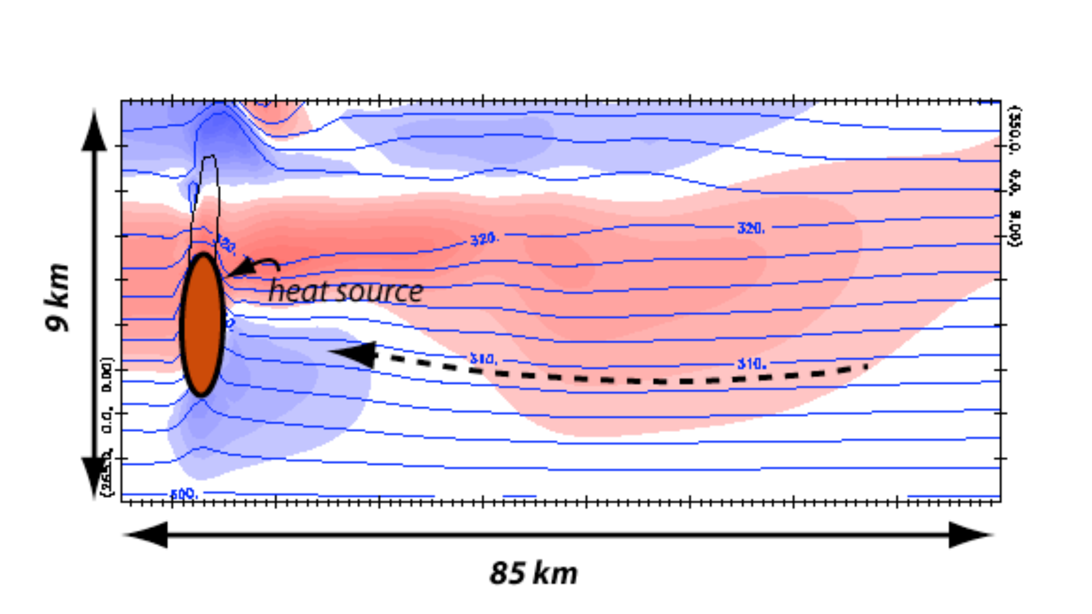




"top heavy" profile

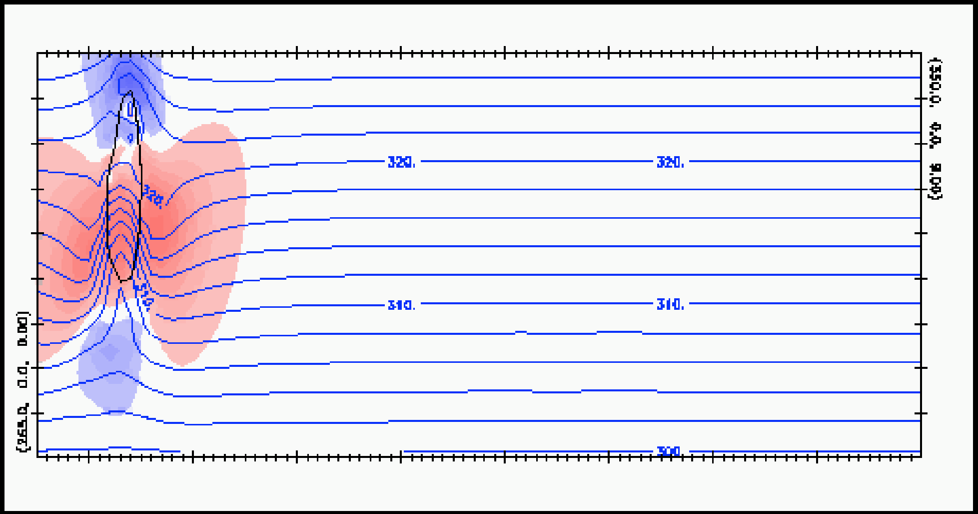
Mapes (1993)

Dry heat source model



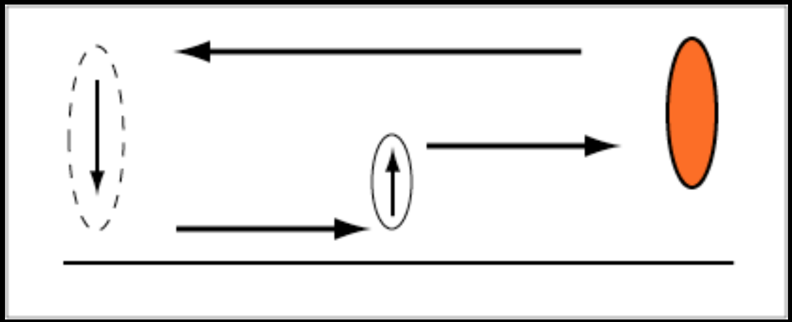
"Top heavy" heating profile in
vertically sheared atmosphere

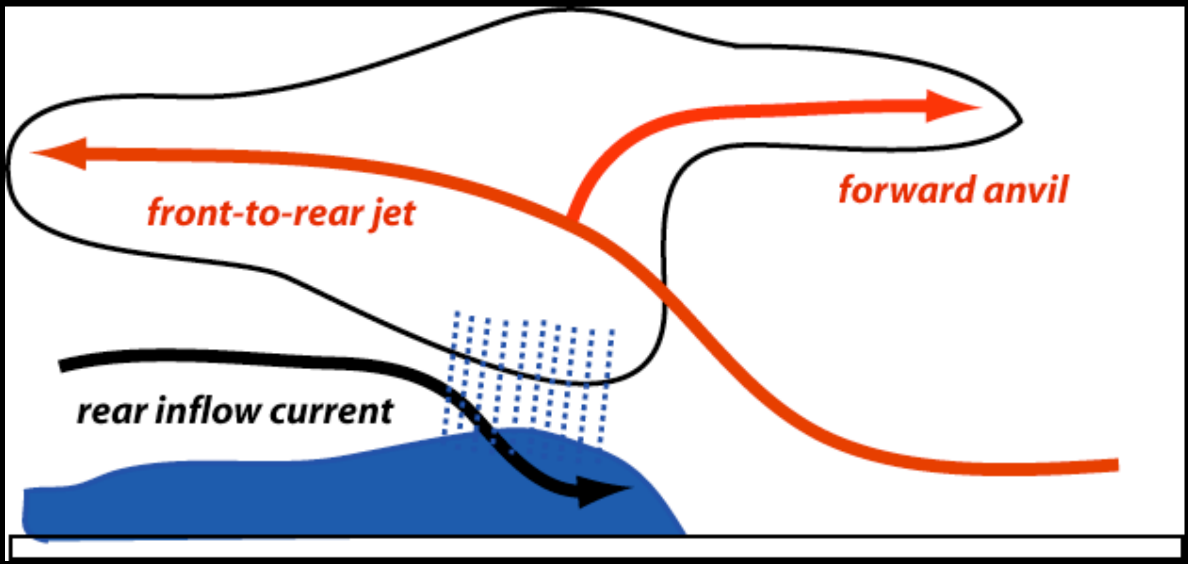
Animation



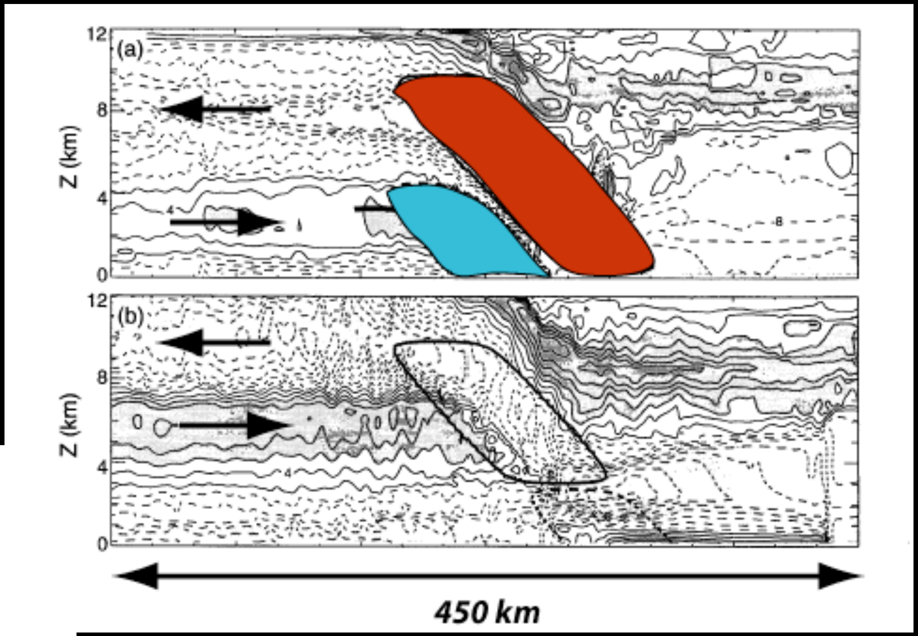
Result of the two modes:
Net ascent in lower troposphere
in vicinity of source

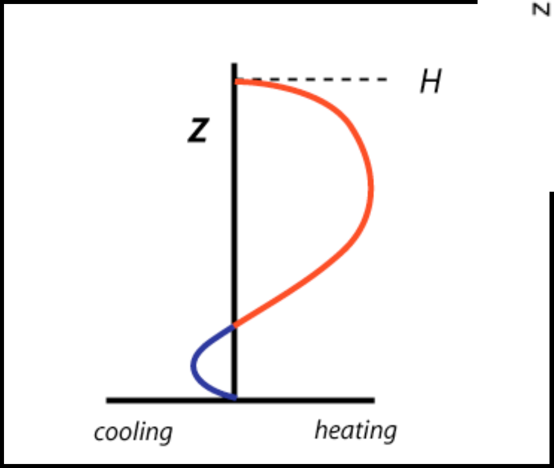
Rear side of storm…





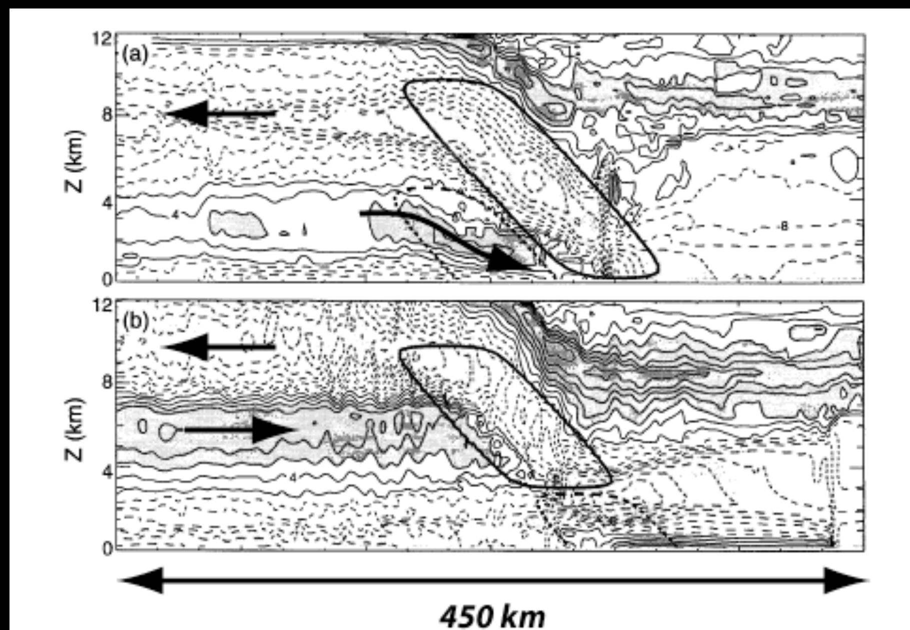
Rear inflow current





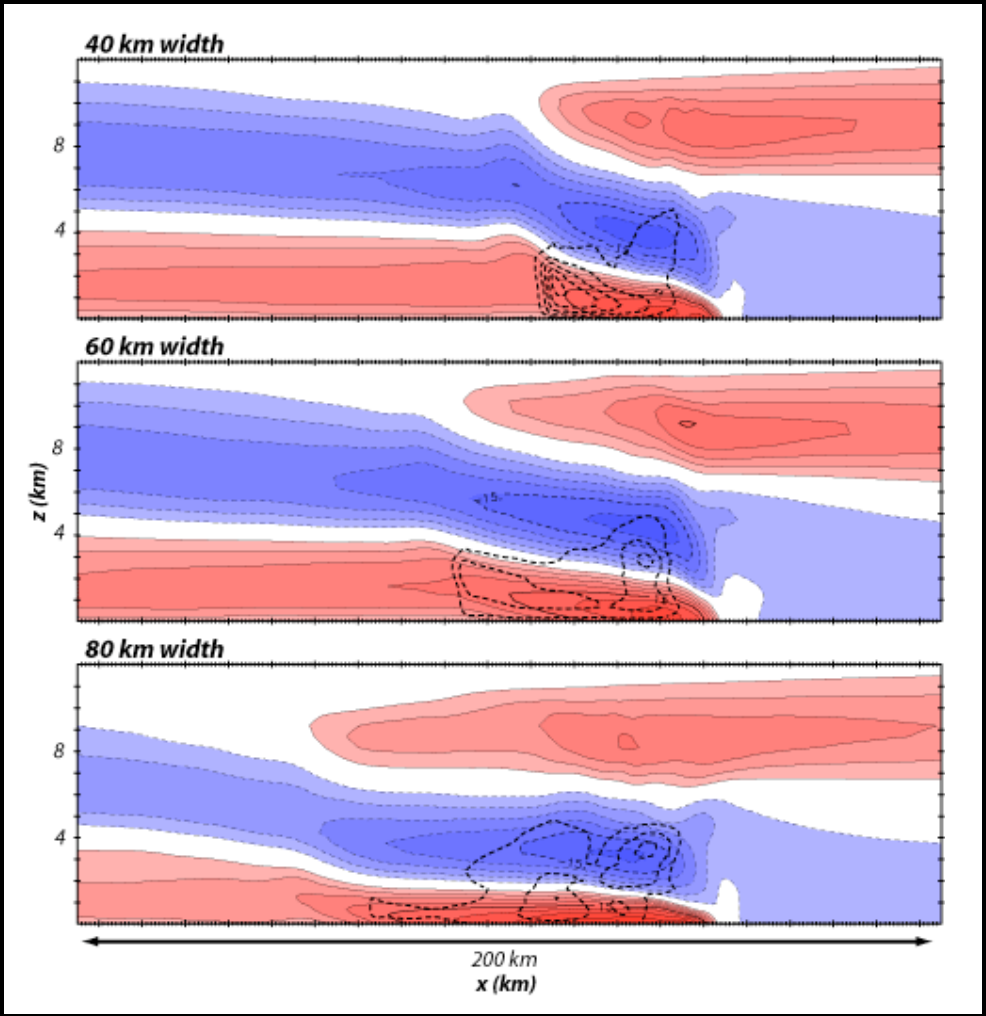
Pandya and Durran (1996)

Rear inflow current

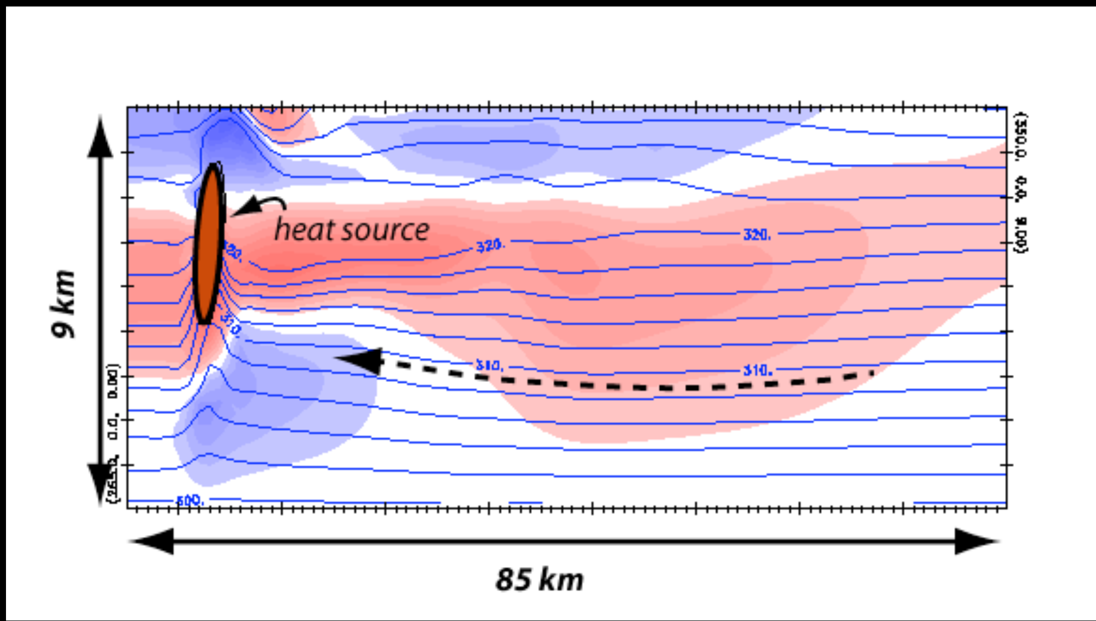


Pandya and Durran (1996)

Microphysical impact

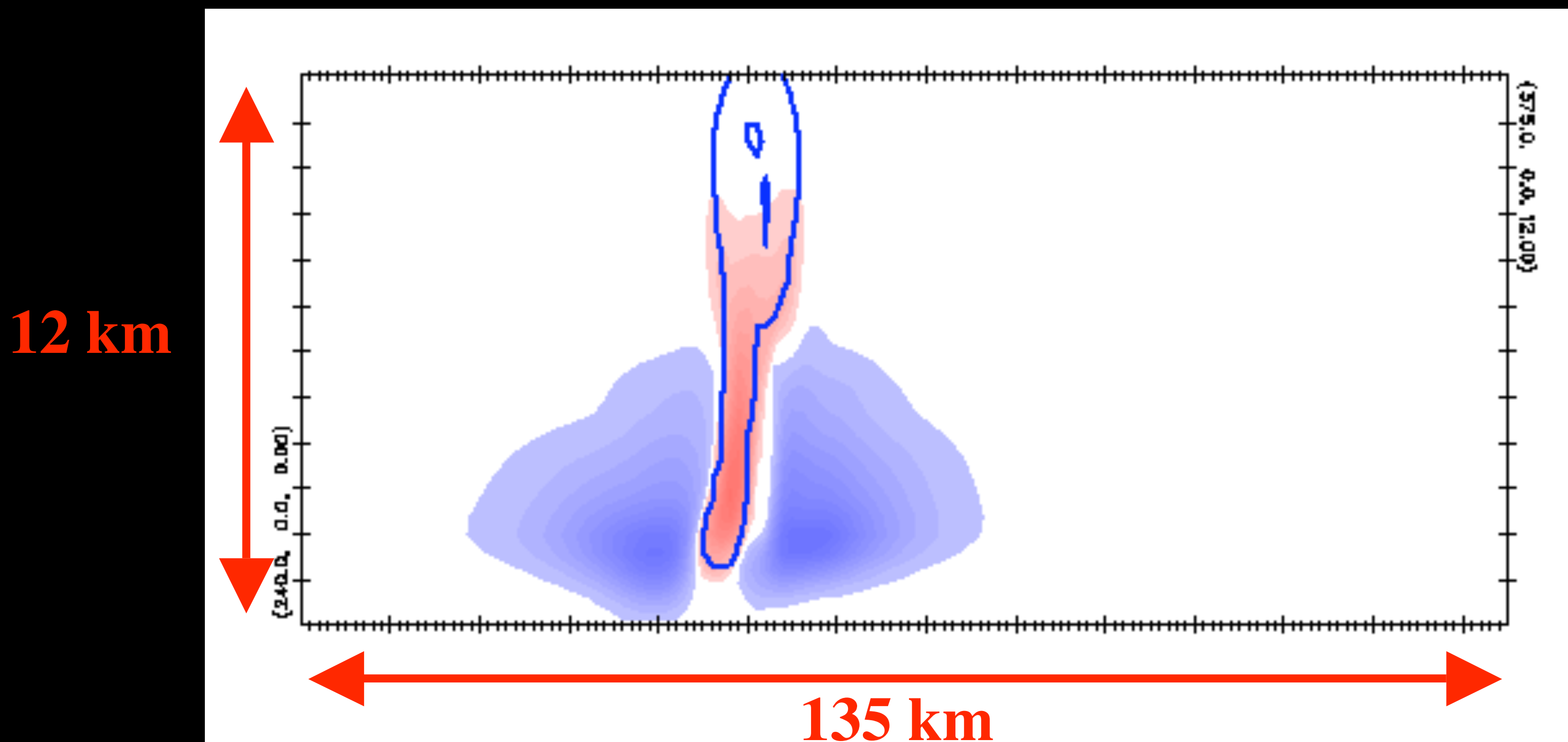


Squall line forward environment

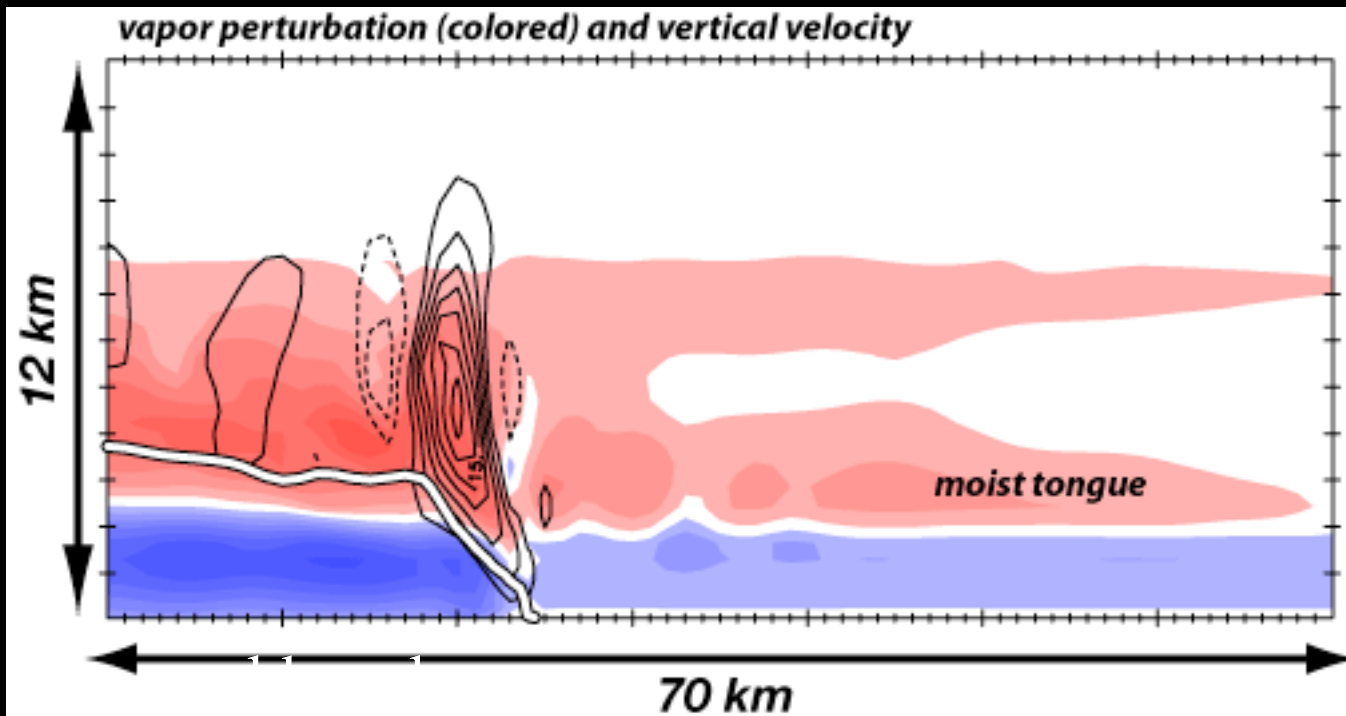


Gentle, sustained lower tropospheric lifting generates "cool and moist tongue" ahead of storm

Water vapor perturbations



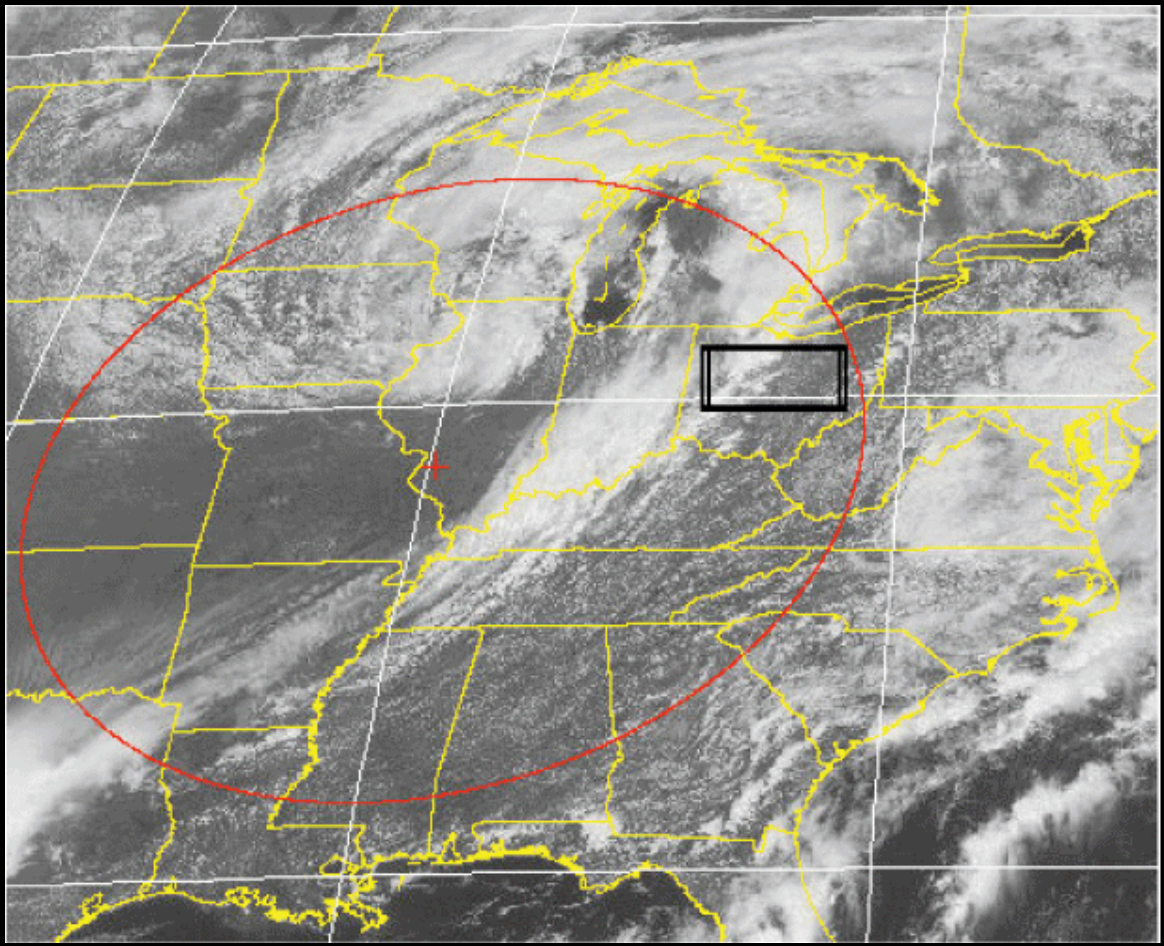
Mature phase moist tongue



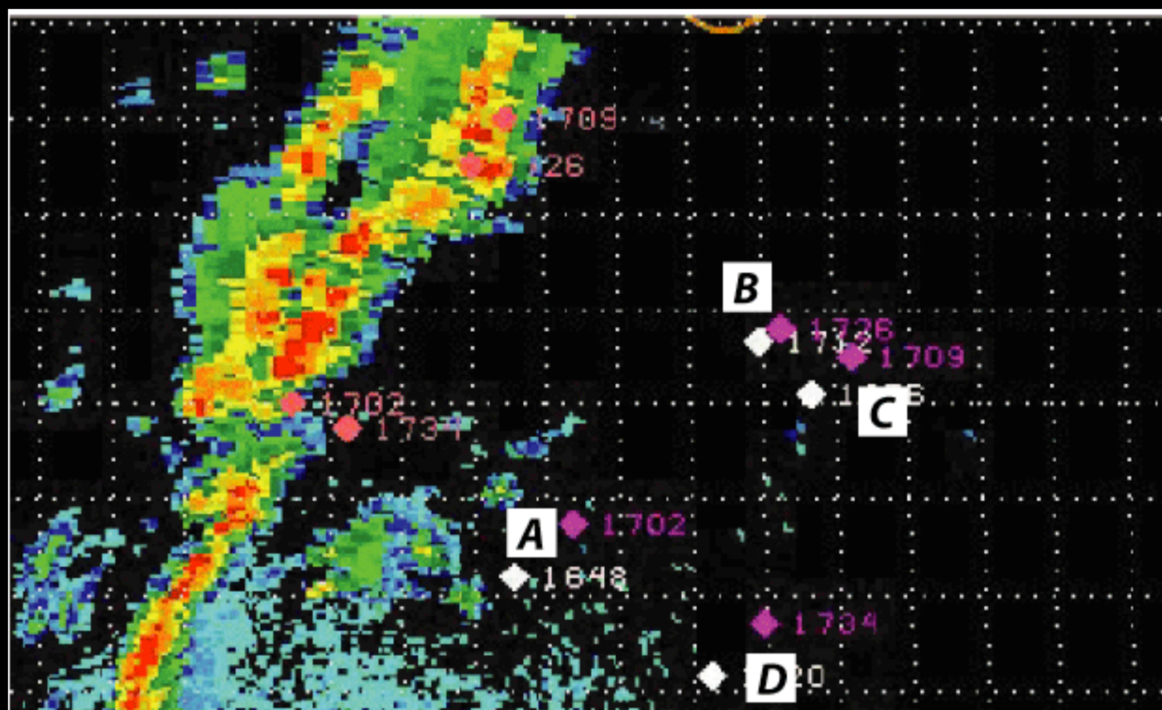
Import of this low frequency GW response:
lower troposphere is **more moist, less stable**
(especially in near-field)

“In theory, there is no difference between theory and practice.
But, in practice, there is.”
-- Jan LA van de Snepscheut
(Caltech professor)

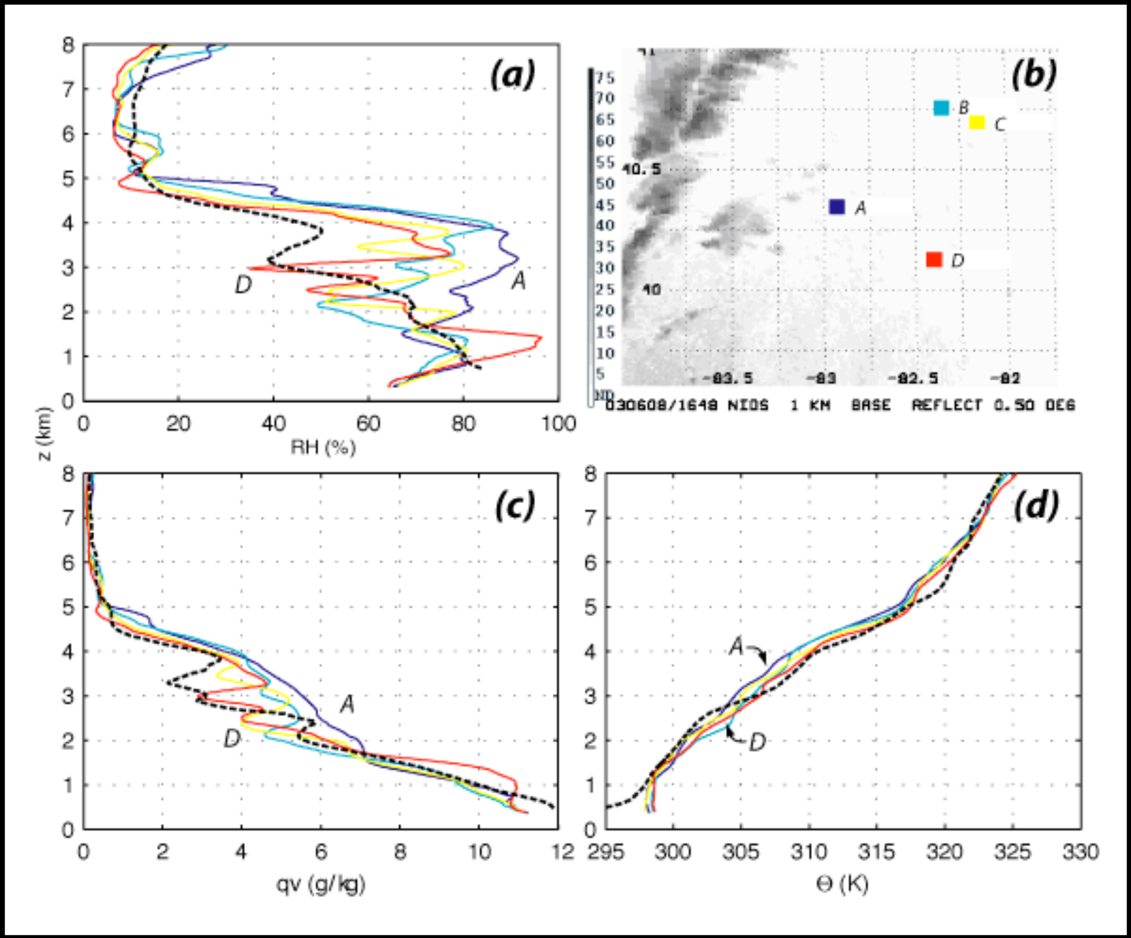
BAMEX IOP6



BAMEX IOP6 radar and dropsonde locations

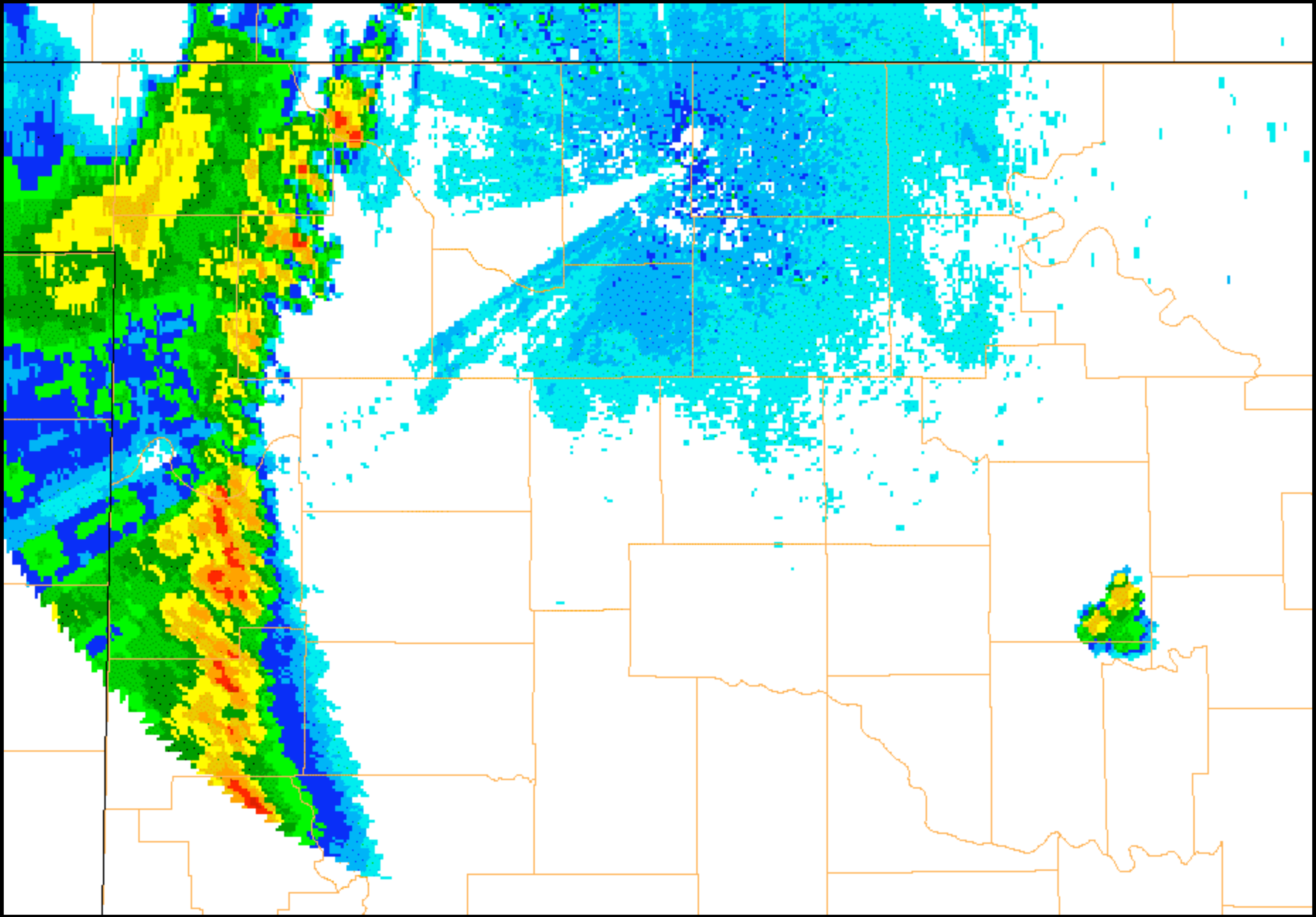


BAMEX IOP6 dropsondes



Mullendore and Fovell (in progress)

21 June 2003 (midnight-5AM), Oklahoma

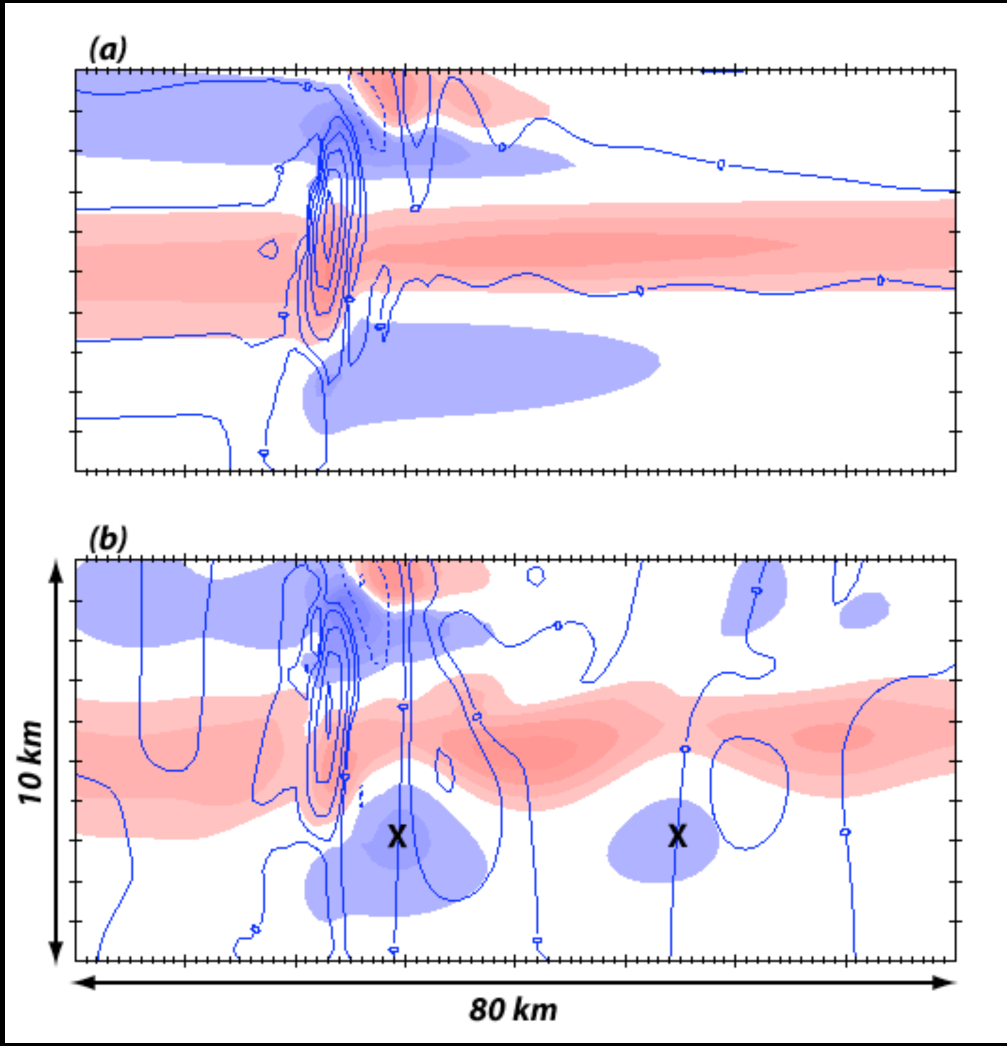


High frequency tropospheric gravity waves

Dry heat source model

Steady heat source

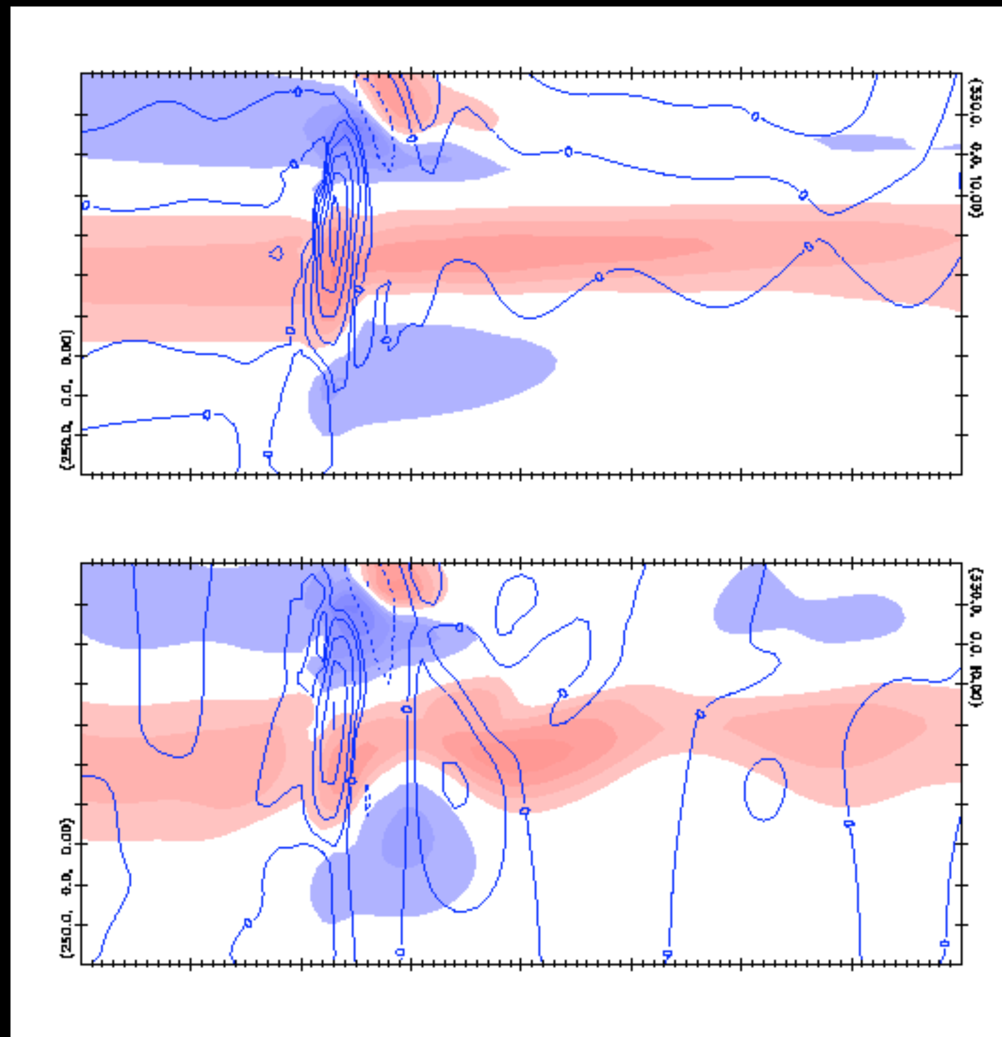
Unsteady heat source



Dry heat source model

Steady
heat source

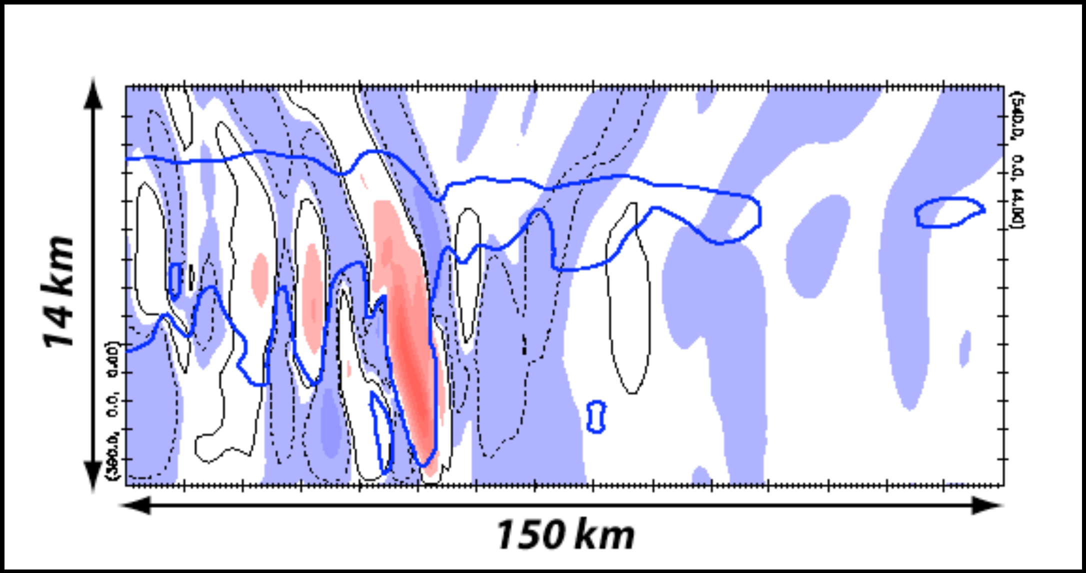
Unsteady
heat source



Idealized nocturnal simulation

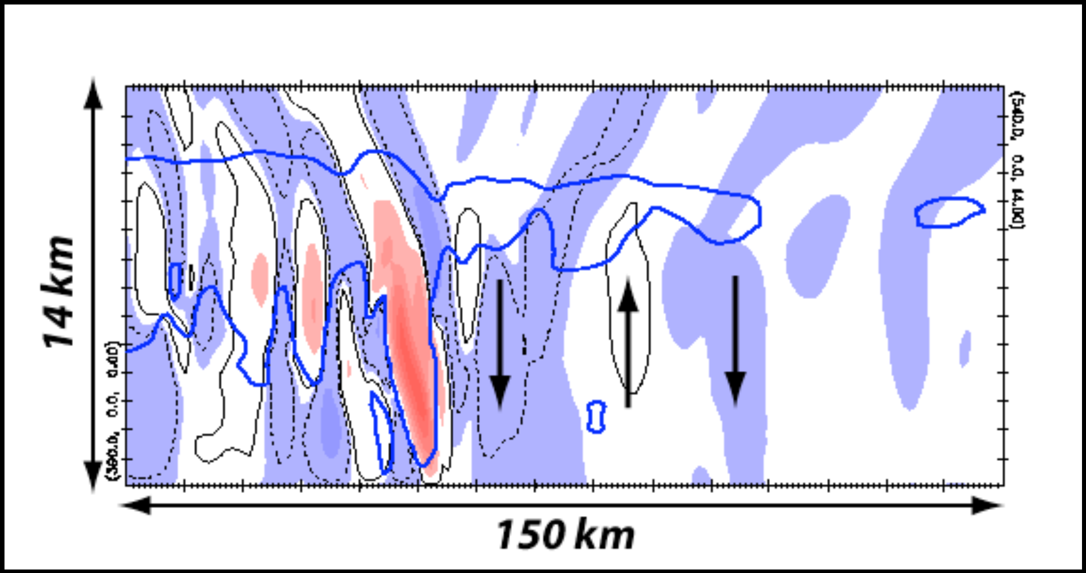
- OU ARPS “cloud model” - 2D and 3D
- Idealized setup
- Integrated 6 PM ‘till past sunrise
- Model physics:
  - surface physics
  - atmospheric radiation (clear sky & cloud)
  - ice microphysics

Idealized nocturnal simulation



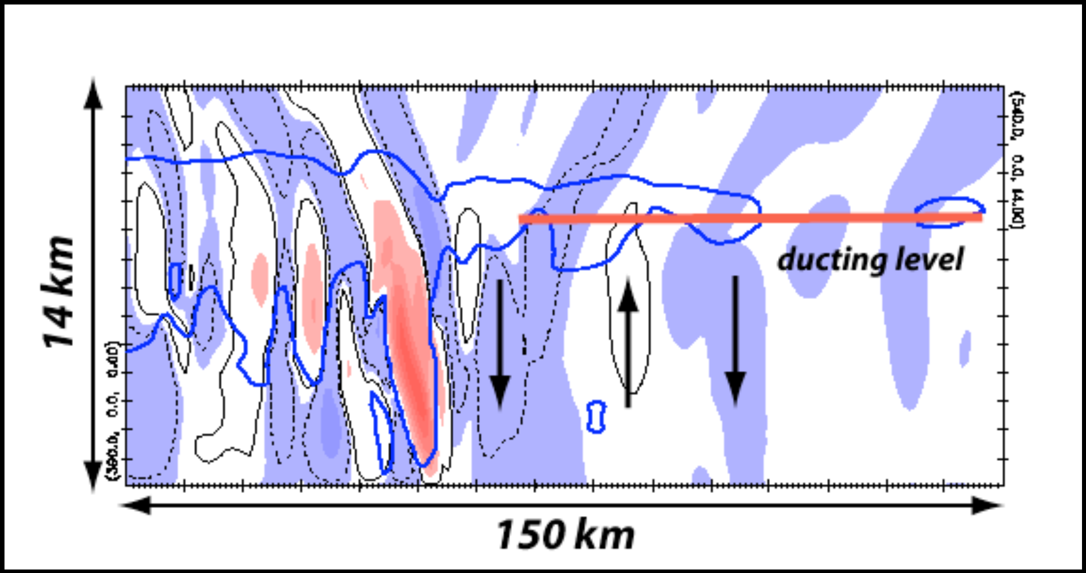
Fovell, Mullendore and Kim (2006)

Idealized nocturnal simulation



Fovell, Mullendore and Kim (2006)

Idealized nocturnal simulation



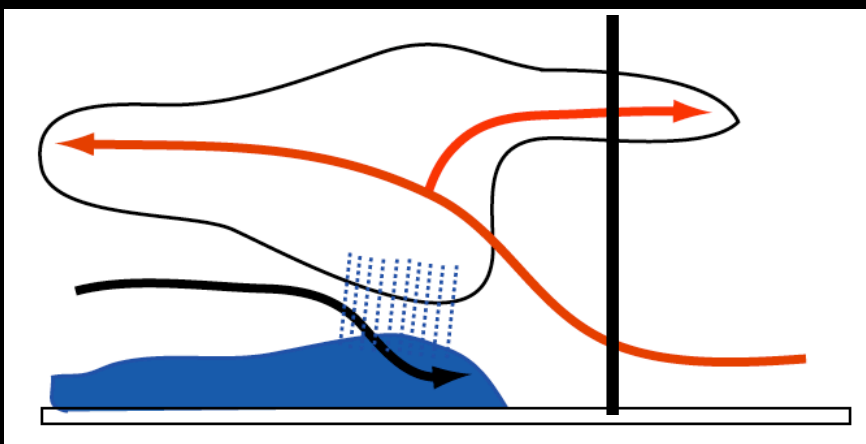
Fovell, Mullendore and Kim (2006)

Trapping of gravity waves

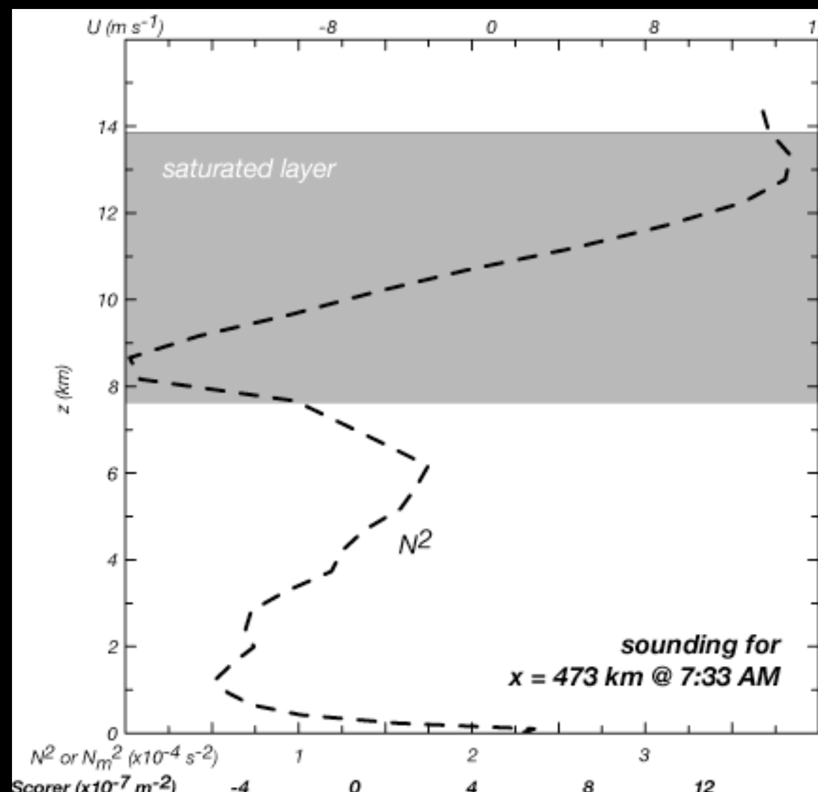
$$l^2 = \frac{N_*^2}{(U-c)^2} - \frac{U_{zz}}{(U-c)}$$

- Associated with sharp decrease of Scorer parameter l^2 with height
- Forward anvil serves as wave duct
  - Decreased stability
  - Jet-like wind profile

$$l^2 = \frac{N_*^2}{(U-c)^2} - \frac{U_{zz}}{(U-c)}$$

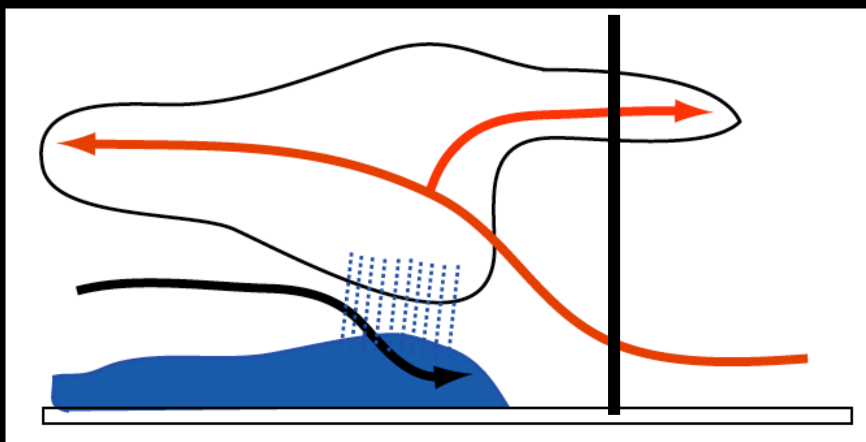


upstream sounding

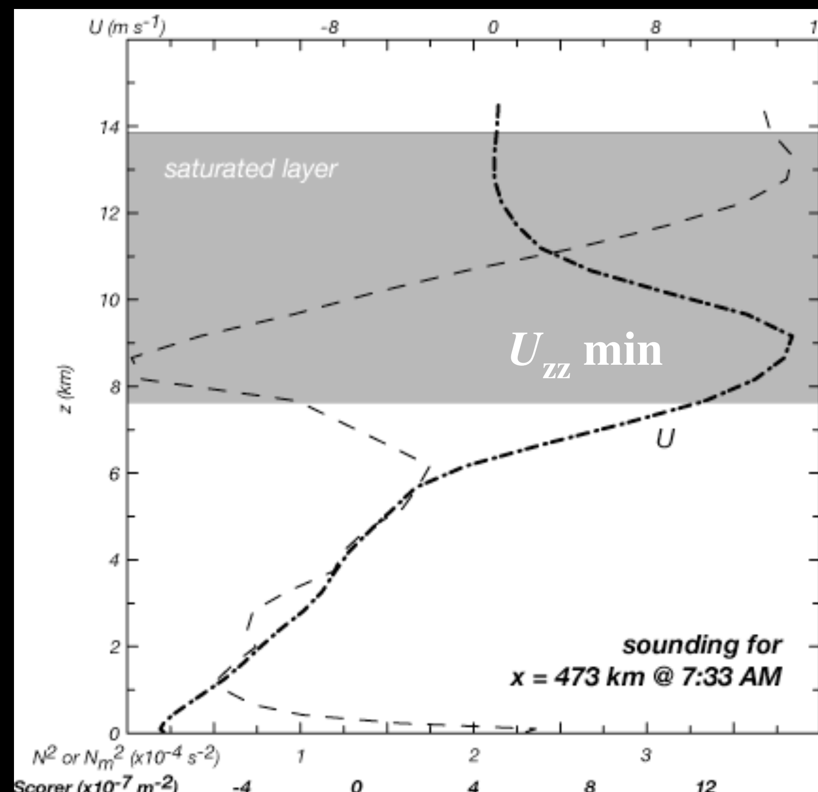


Fovell, Mullendore and Kim (2006)

$$l^2 = \frac{N_*^2}{(U-c)^2} - \frac{U_{zz}}{(U-c)}$$

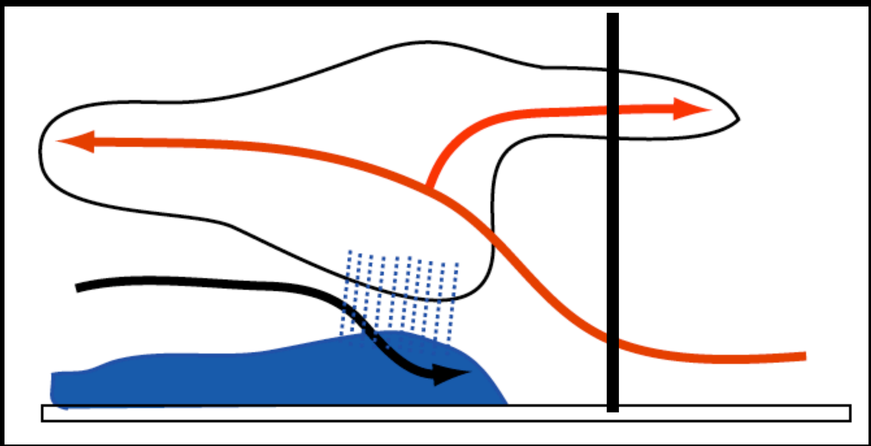


upstream sounding

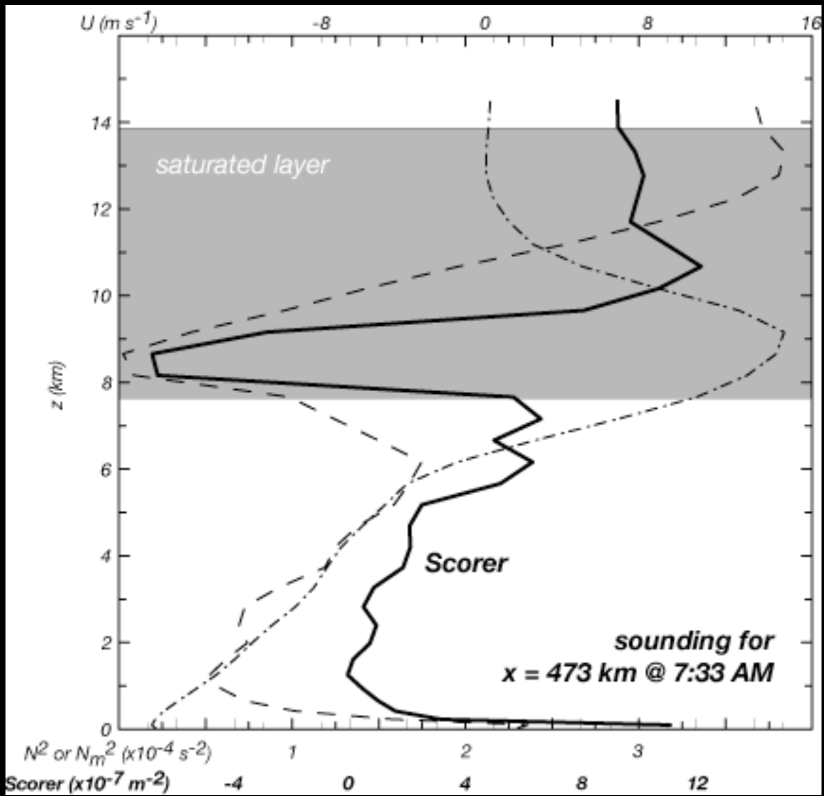


Fovell, Mullendore and Kim (2006)

$$l^2 = \frac{N_*^2}{(U-c)^2} - \frac{U_{zz}}{(U-c)}$$

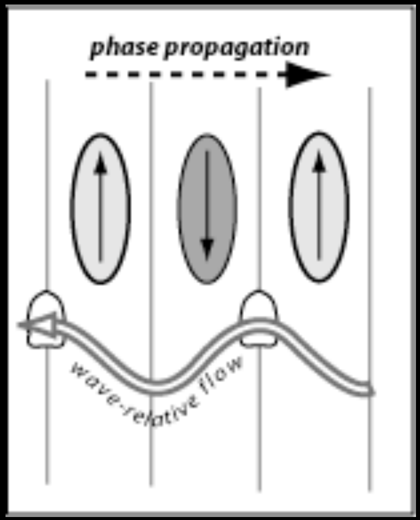


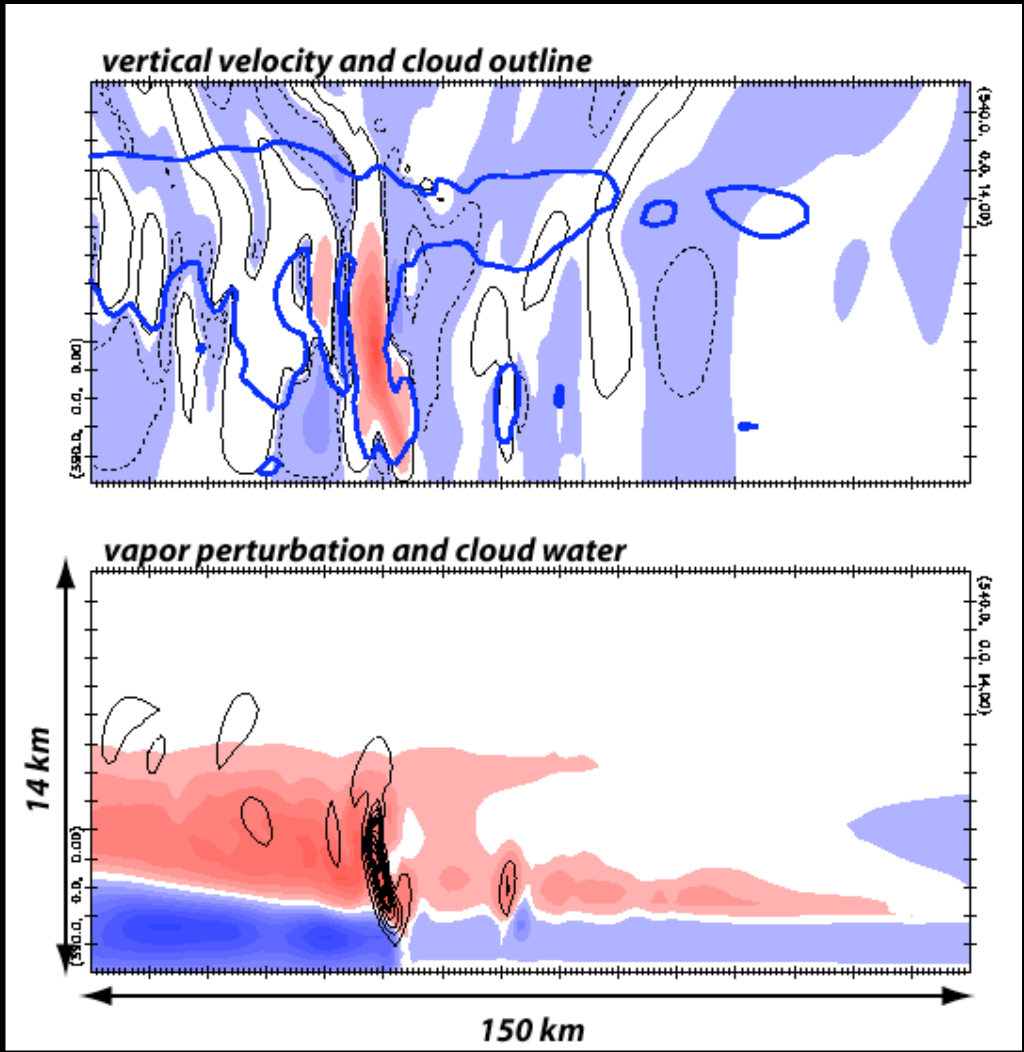
upstream sounding



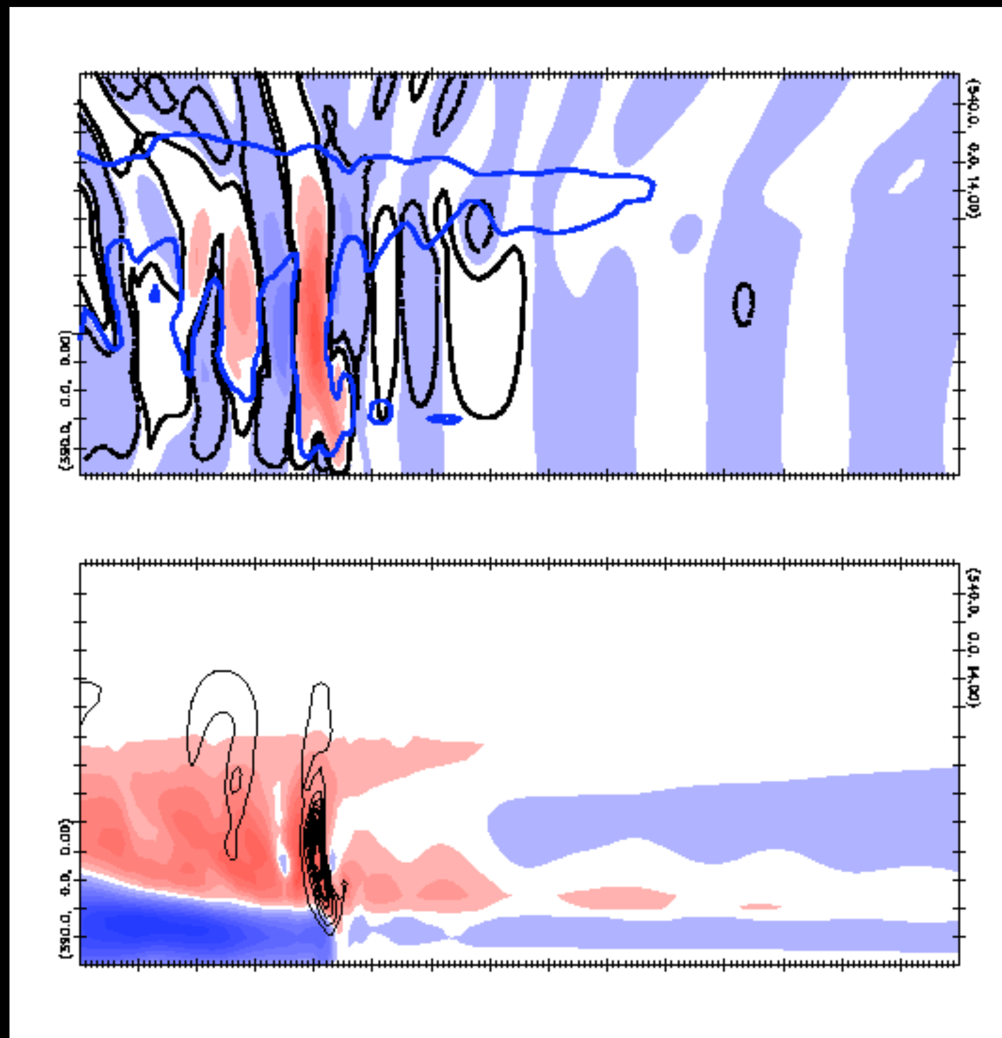
Fovell, Mullendore and Kim (2006)

Gravity wave-induced clouds



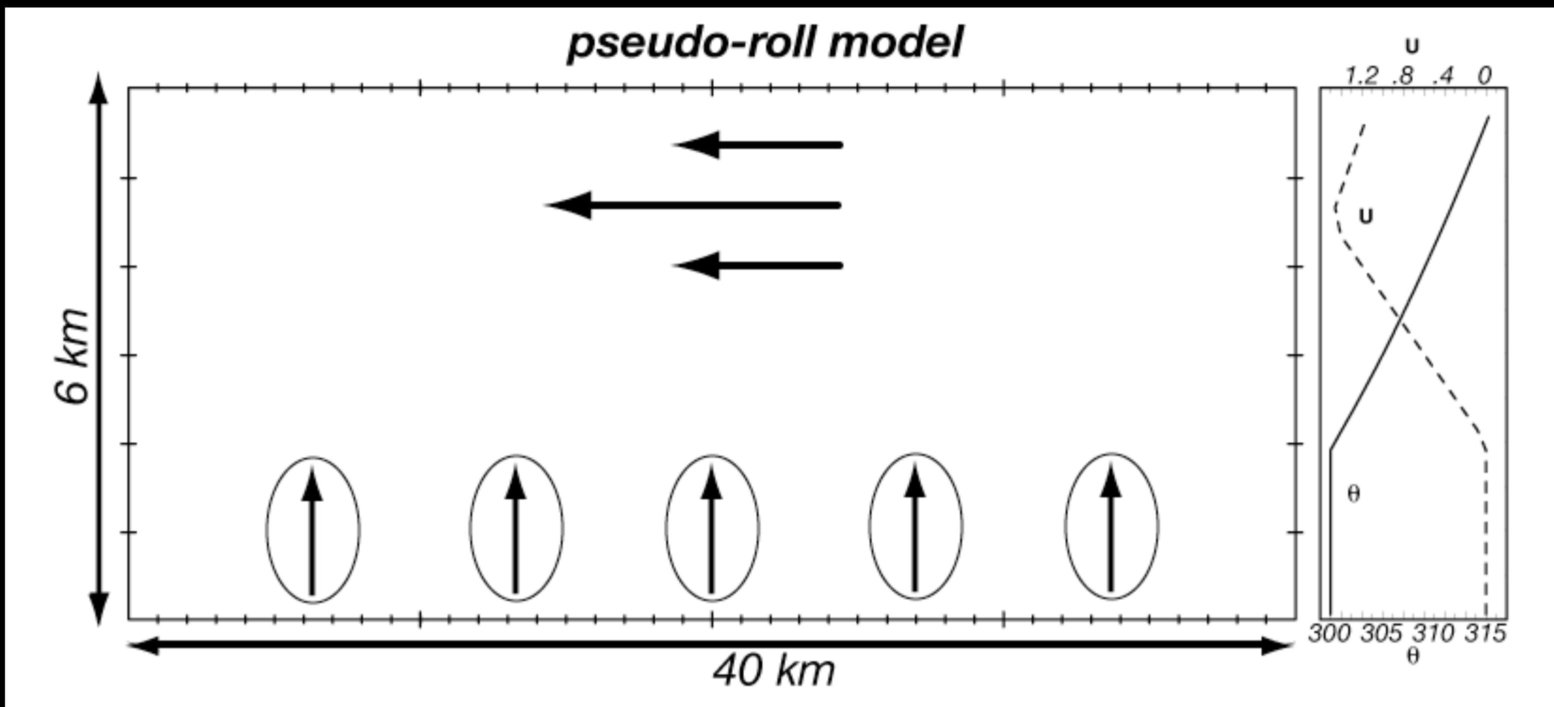


Fovell, Mullendore and Kim (2006)

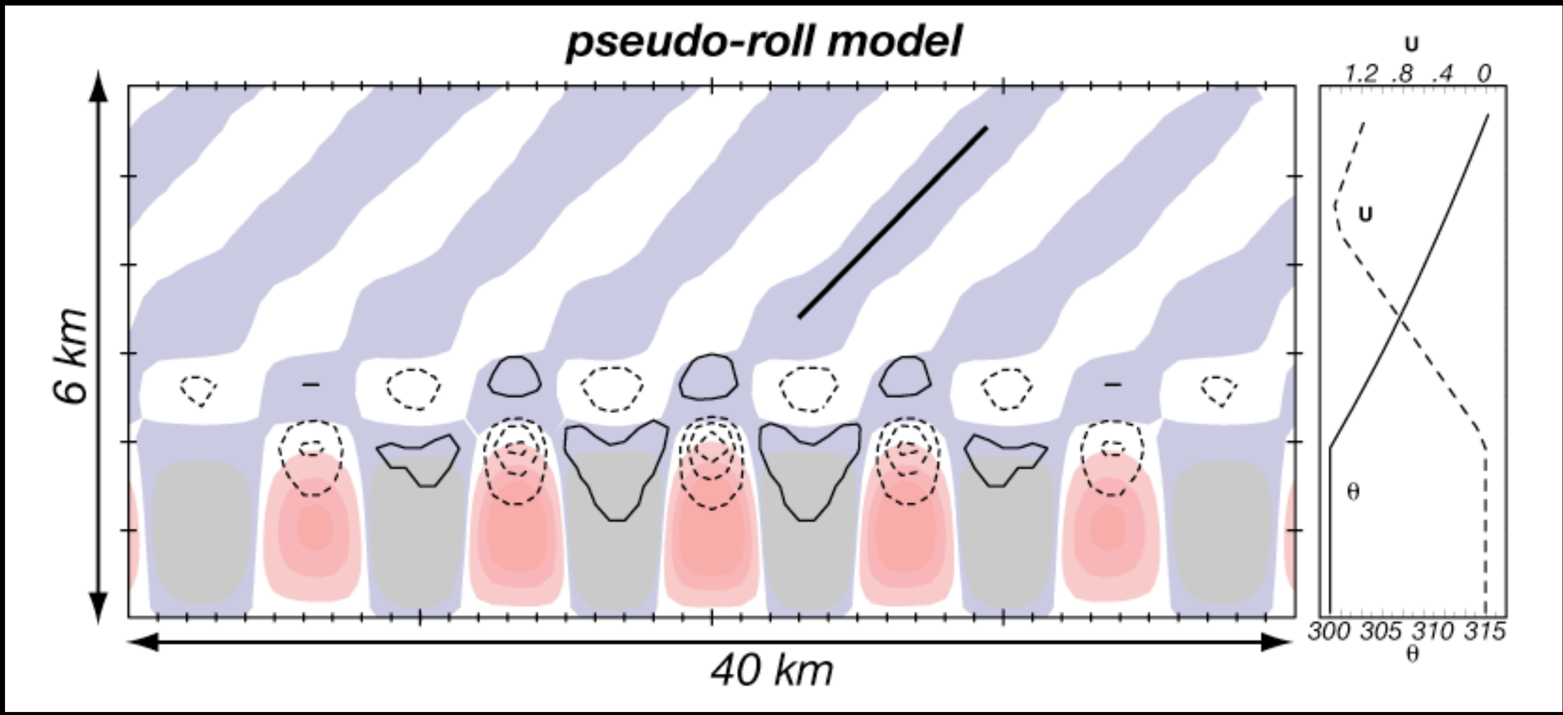


Fovell, Mullendore and Kim (2006)

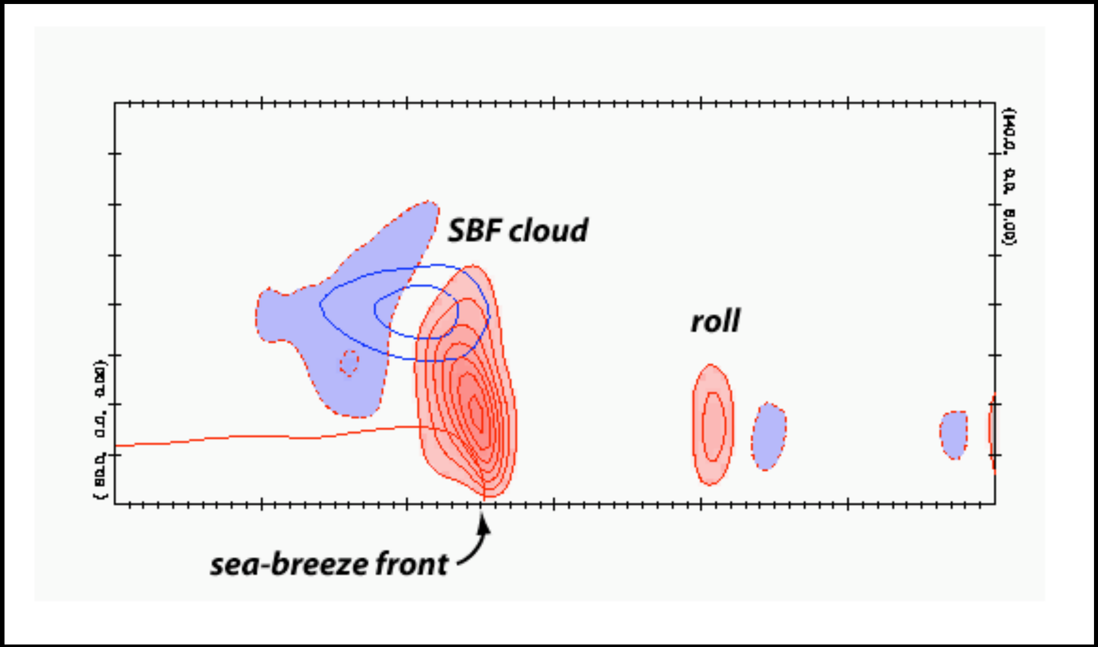
Obstacle effect gravity waves above convective rolls



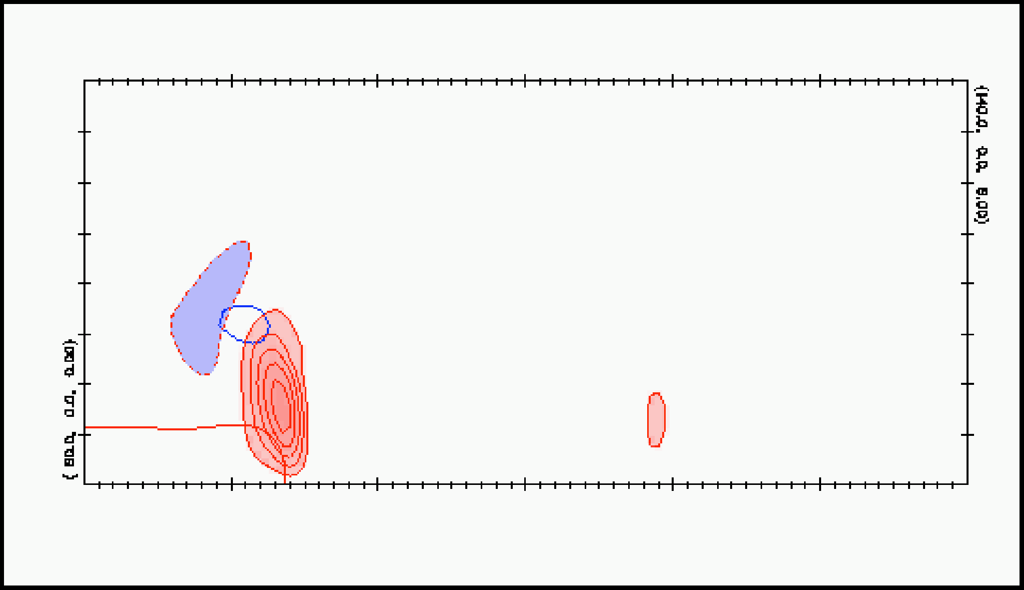
Fovell (2004)



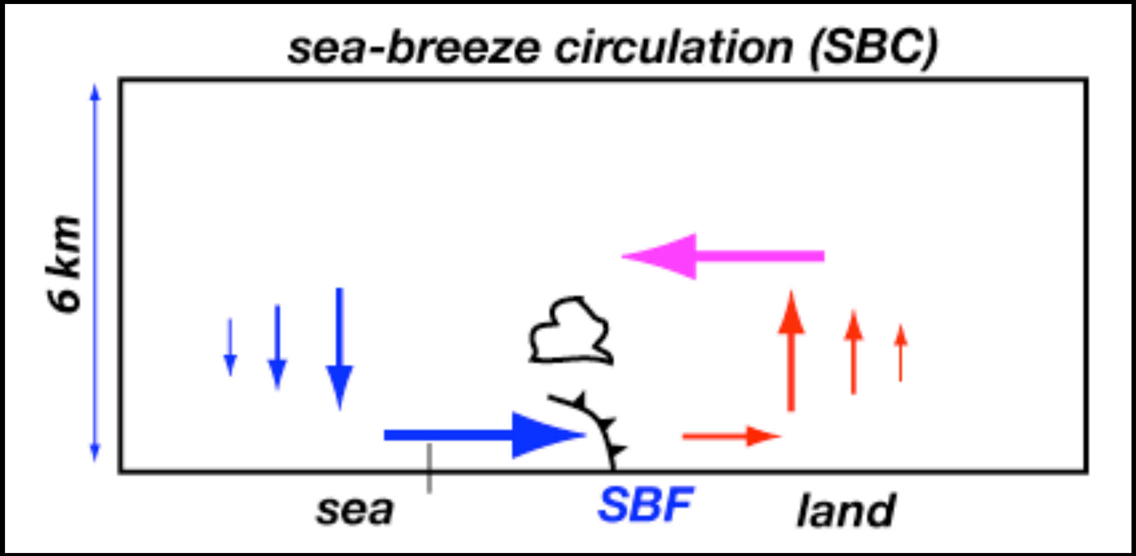
Fovell (2004)

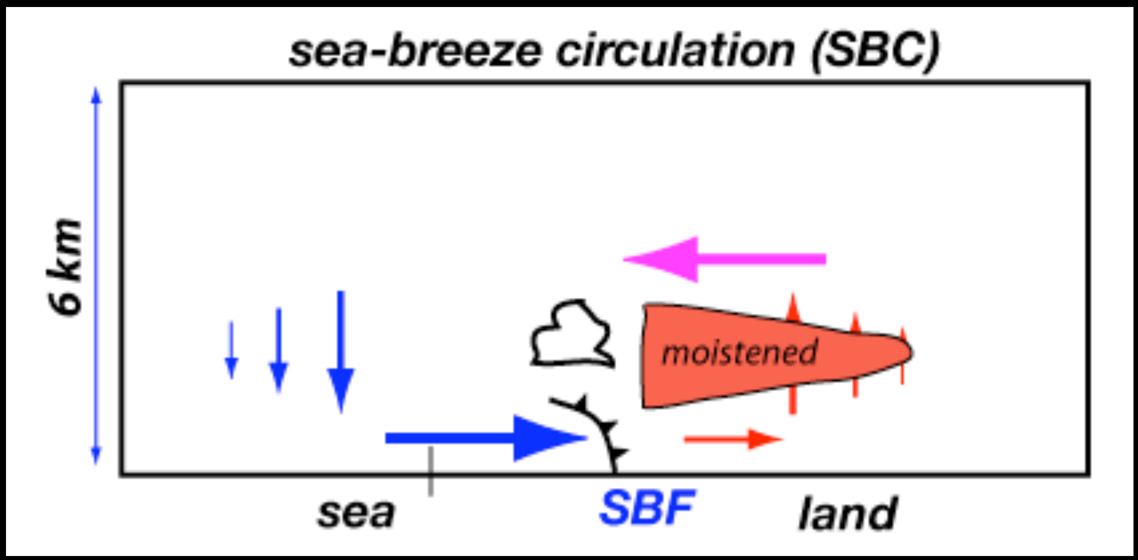


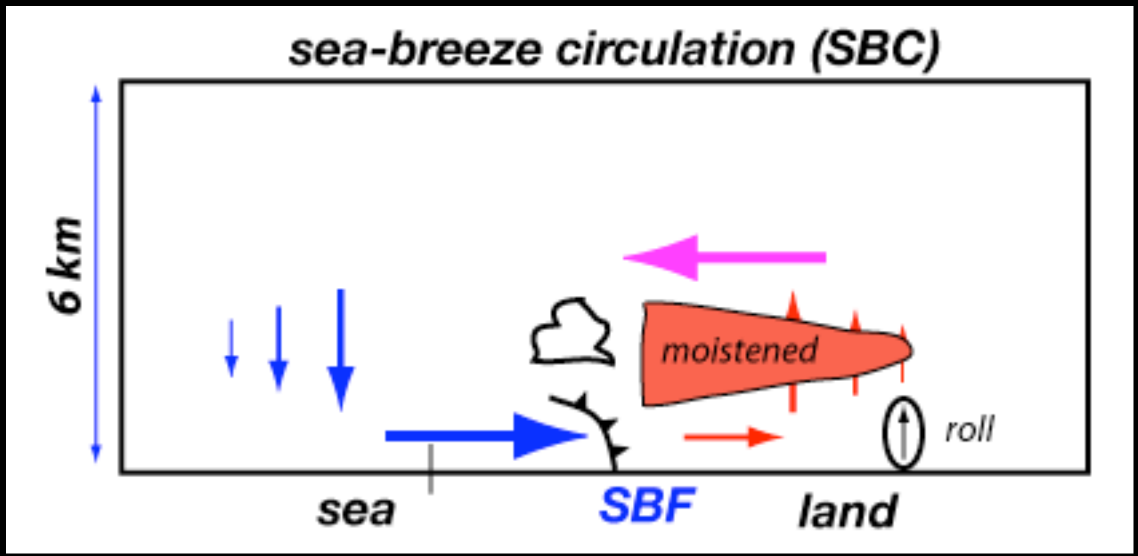
Fovell (2004)



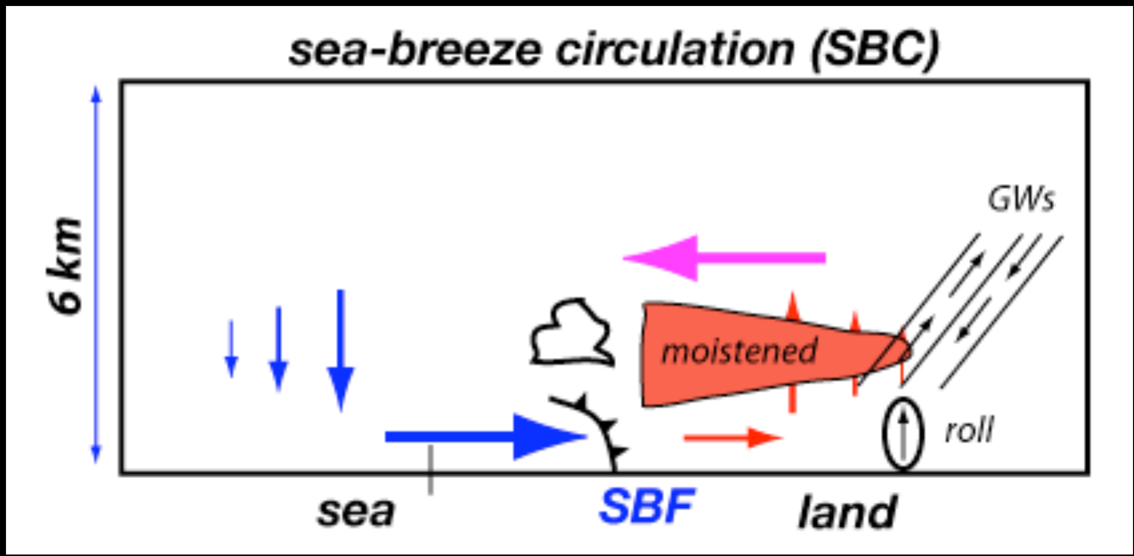
Fovell (2004)

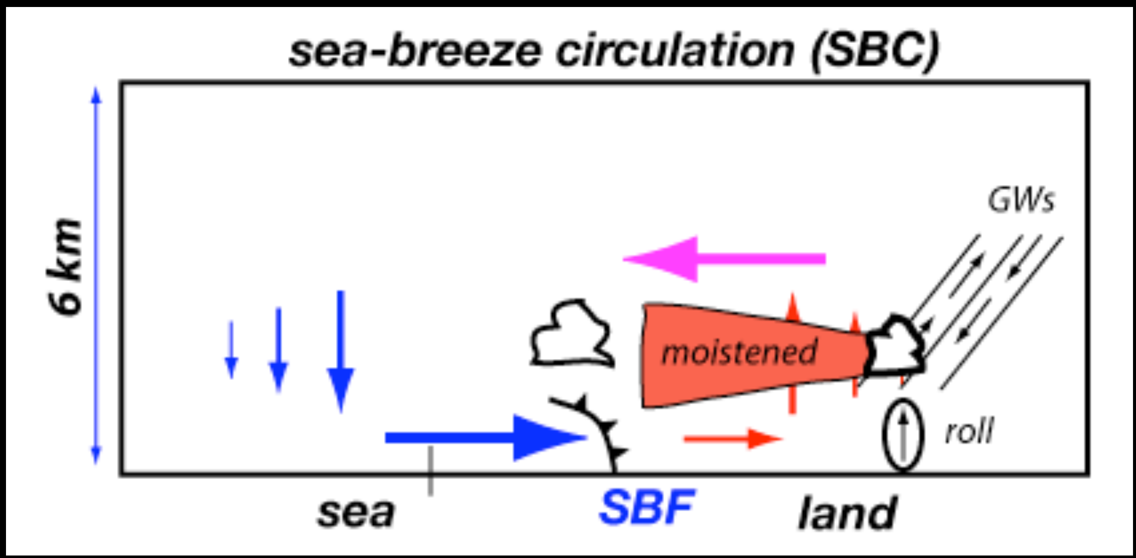

sea-breeze circulation (SBC)
6 km
sea
SBF
land


sea-breeze circulation (SBC)
6 km
moistened
sea
SBF
land



sea-breeze circulation (SBC)
6 km
moistened
roll
sea
SBF
land


sea-breeze circulation (SBC)
6 km
GWs
moistened
roll
sea
SBF
land


sea-breeze circulation (SBC)
6 km
GWs
moistened
roll
sea
SBF
land

Summary

- Convective phenomena (deep convection, rolls) superb source of gravity waves
- High frequency gravity waves
  - Vertically propagating above deep convection
  - Trapped waves ahead of convection
- Low frequency gravity waves
  - Responding to maintained heating/cooling
  - Owing to flow over obstacles
- How gravity waves impact convective environment
- Feedback of impact on convective source
- Subgrid in GCMs… for some time to come