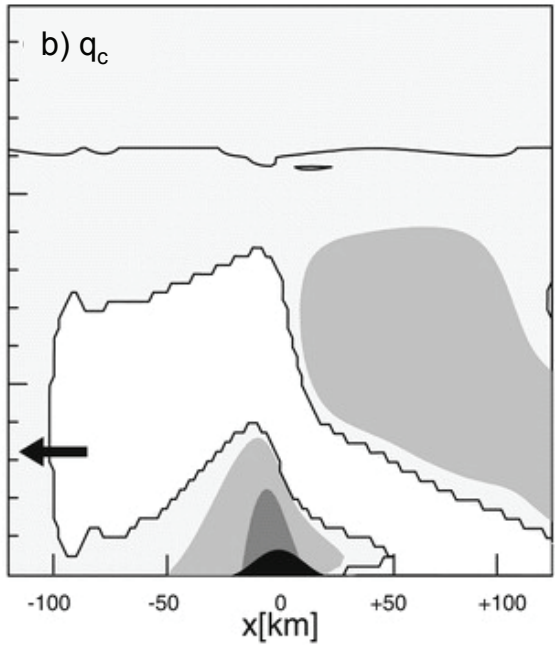
Internal gravity waves in a saturated, moist-neutral atmosphere

- upstream wave of subsidence in start-up for moist topographic flow
- asymmetric buoyancy response of cloud-free air to up/down displacements
- cloud-edge motion by a gravity-wave shock



- David J Muraki (Simon Fraser Univ) & Rich Rotunno (NCAR)

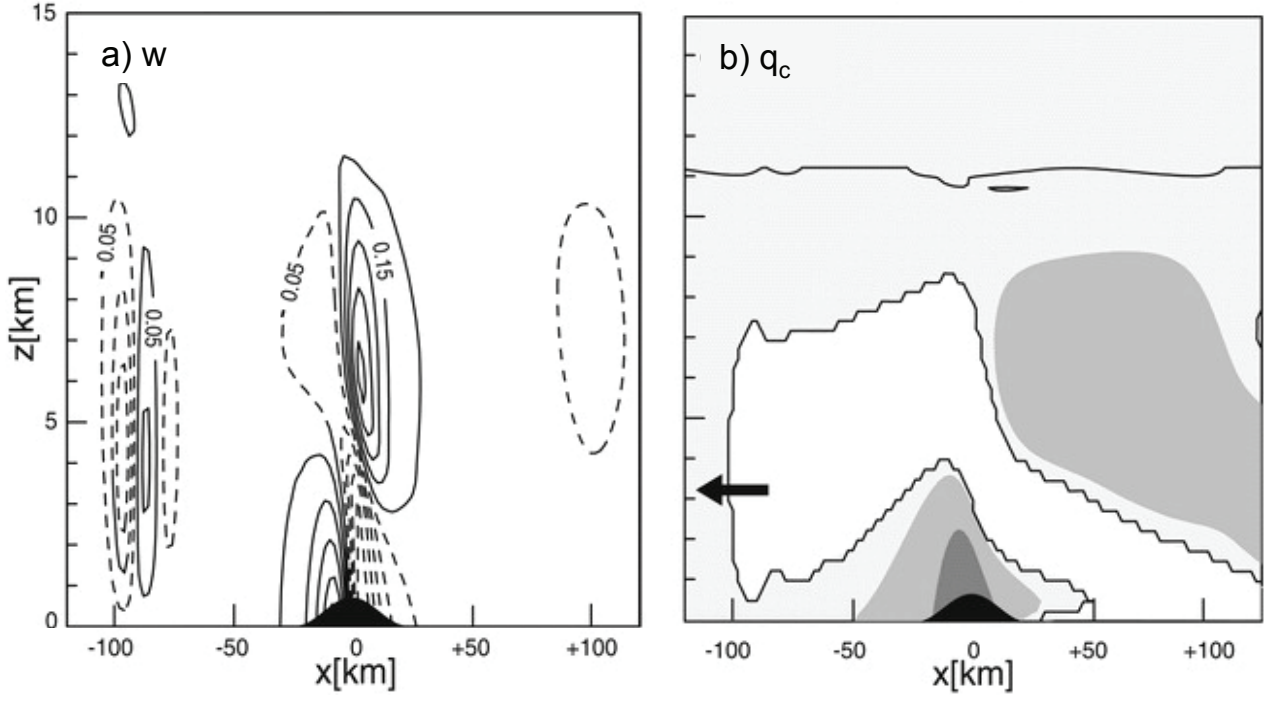
NSERC CRSNG

Start-Up for Moist 2D Flow Over Topography

Saturated, Moist-Neutral Atmosphere

- ▷ WRF: full-physics, topographic lower boundary (Miglietta/Rotunno, 2005)
  - ▷ waves trapped by tropopause boundary (Keller, et al., 2012)

vertical motion, w cloud water, q_c



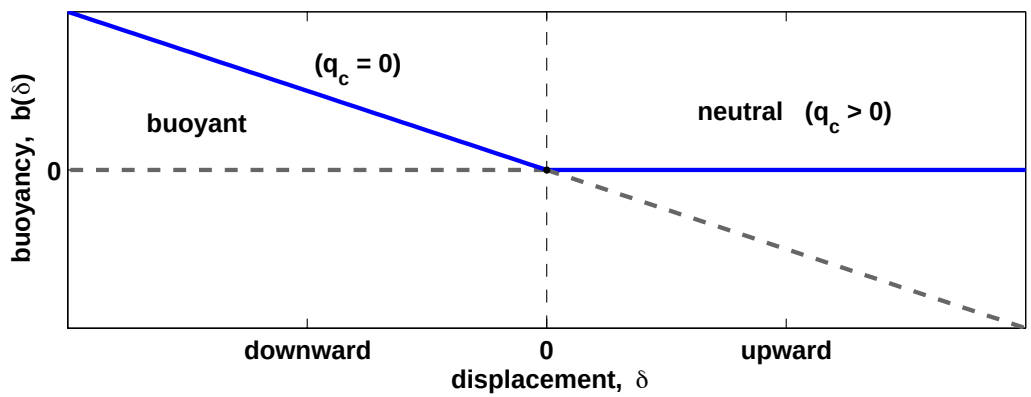
- ▷ why is there an upstream propagating wave of subsidence $\rightarrow$ de-saturated, cloud-free air?

Desaturation of Cloud-Free, Moist-Neutral Air

Primary Cause: Asymmetry to Up/Down Displacements

- saturated & cloud-free ($q_c = 0$) at zero displacement ($\delta = 0$)
- UPward displacement ($\delta > 0$):
  - release of latent heat by condensation $\rightarrow$ neutral buoyancy (reversible)
  - $\approx$ constant θ_e, Clausius-Clapeyron thermodynamics
- DOWNward displacement ($\delta < 0$):
  - unsaturated (no available cloud water) $\rightarrow$ stratified buoyancy
  - constant N^2

Buoyancy as a Function of Displacement, $b(\delta)$

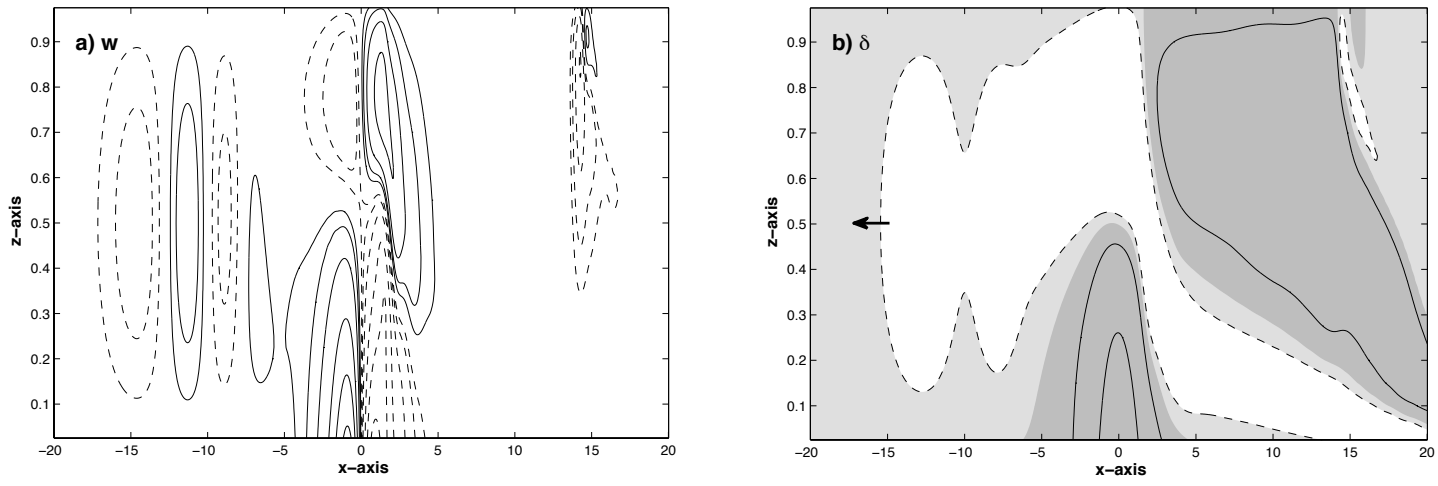


- critical sensitivity of wave propagation to downward displacement

A Hierarchy of Models, Part I

Dynamics of Asymmetric Buoyancy

- ▷ 2D "linear" Boussinesq primitive equations & linearized topographic boundary
  - ▷ vertical motion, w displacement, δ



- ▷ 2D vorticity/streamfunction: $u = \psi_z \ , \ w = -\psi_x$

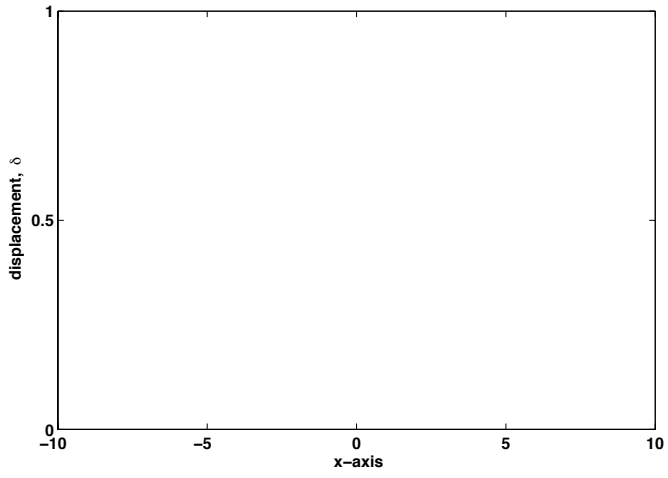
$$
\begin{aligned}
(\eta_t + U\eta_x) \quad + \quad (b(\delta))_x \quad &= \quad 0 \\
(\ \delta_t + U\delta_x) \quad + \quad \psi_x \quad &= \quad 0 \\
\psi_{xx} + \psi_{zz} \quad &= \quad \eta
\end{aligned}
$$

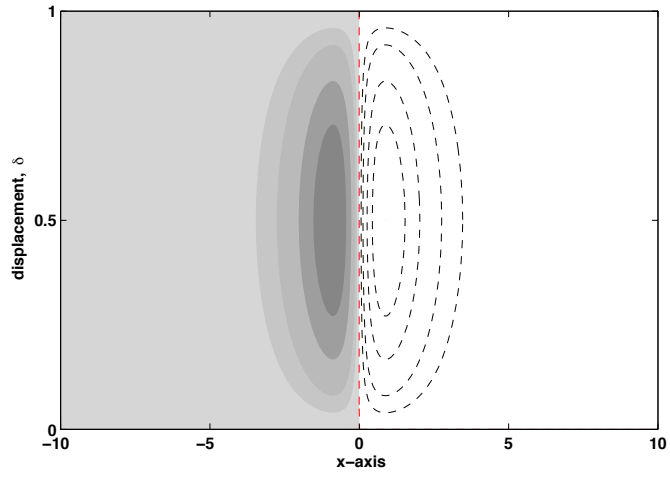
- ▷ the upstream propagating wave of subsidence persists . . .

A Hierarchy of Models, Part II

Dynamics of Asymmetric Buoyancy

- 1D "linear" single vertical-mode & ($U = 0$) initial displacement
  - vertical motion, $w \to w(x,0)\sin z$ displacement, $\delta \to \delta(x,0)\sin z$





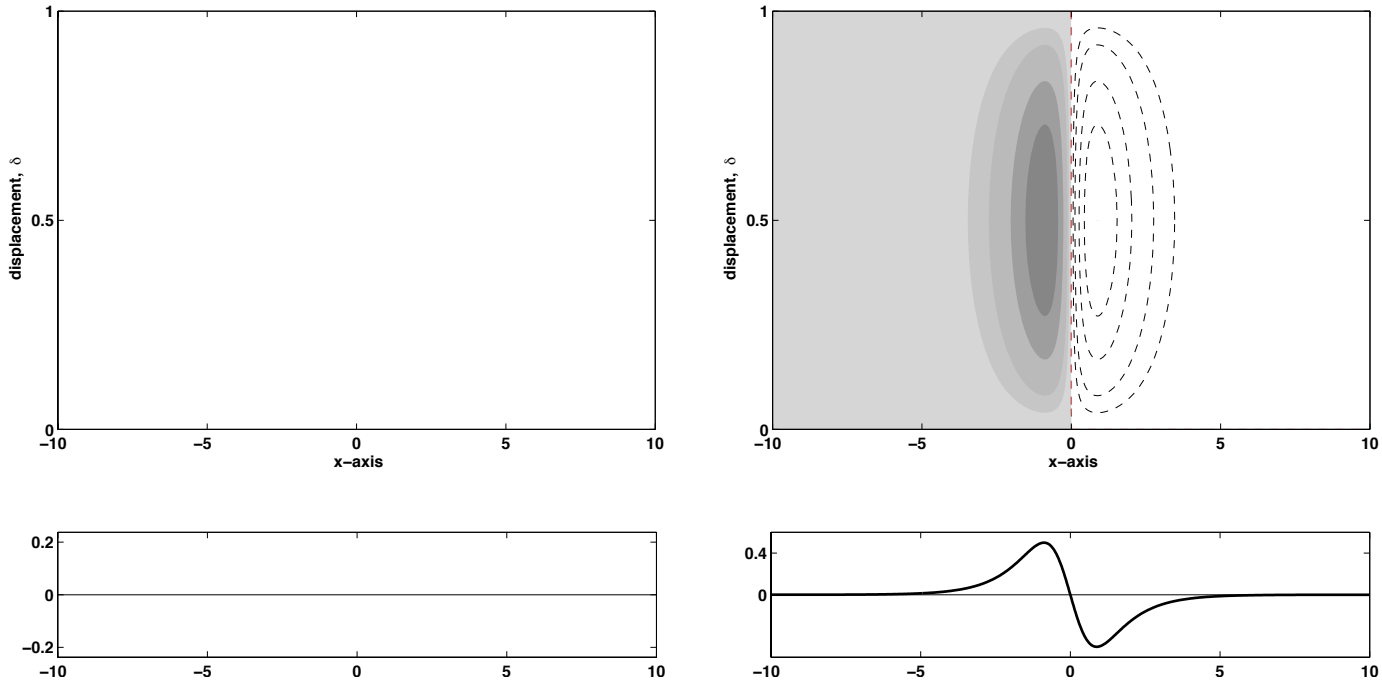
- 2D vorticity/streamfunction: $w = -\psi_x$

$$\begin{aligned} \eta_t &+ (b(\delta))_x &= 0 \\ \delta_t &+ \psi_x &= 0 \\ & \psi_{xx} - \psi &= \eta \end{aligned}$$

A Hierarchy of Models, Part II

Dynamics of Asymmetric Buoyancy

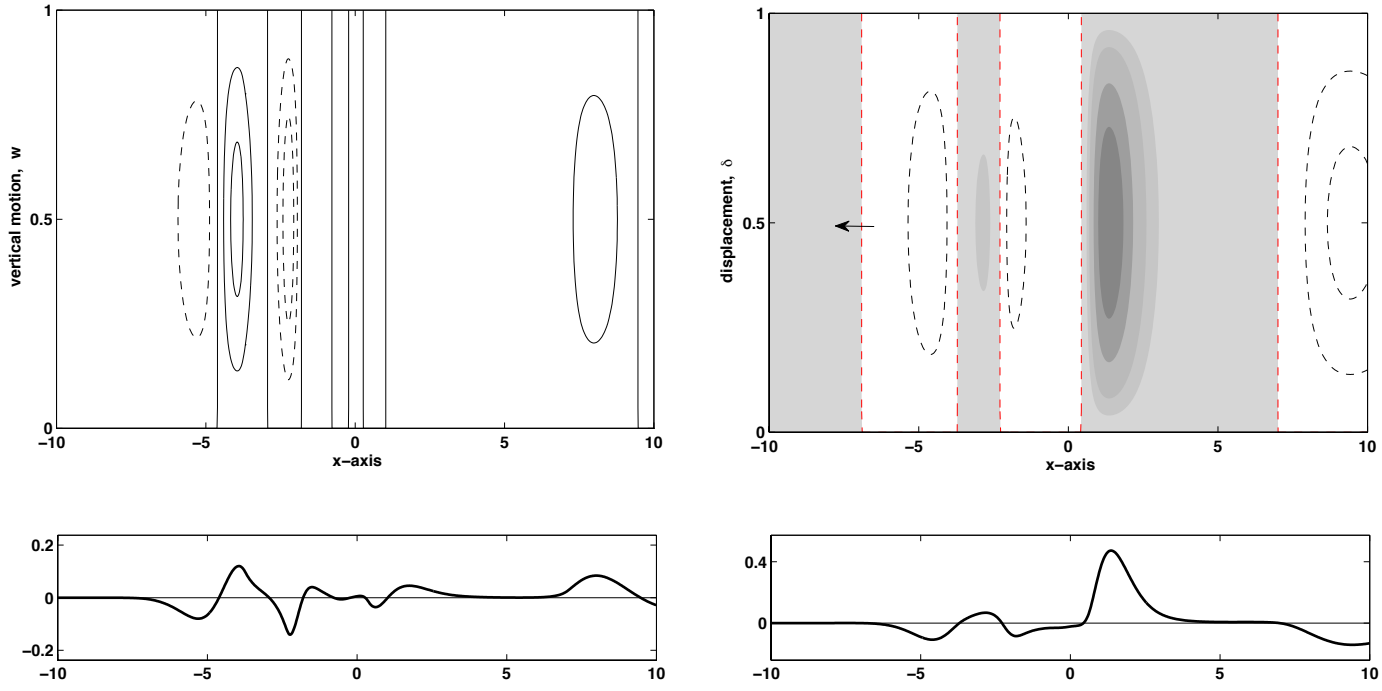
- 1D "linear" single vertical-mode & $(U = 0)$ initial displacement
  - vertical motion, $w \to w(x,0)\sin z$ displacement, $\delta \to \delta(x,0)\sin z$



A Hierarchy of Models, Part II

Dynamics of Asymmetric Buoyancy

- 1D "linear" single vertical-mode & $(U = 0)$ initial displacement
  - vertical motion, $w \to w(x, t) \sin z$ displacement, $\delta \to \delta(x, t) \sin z$

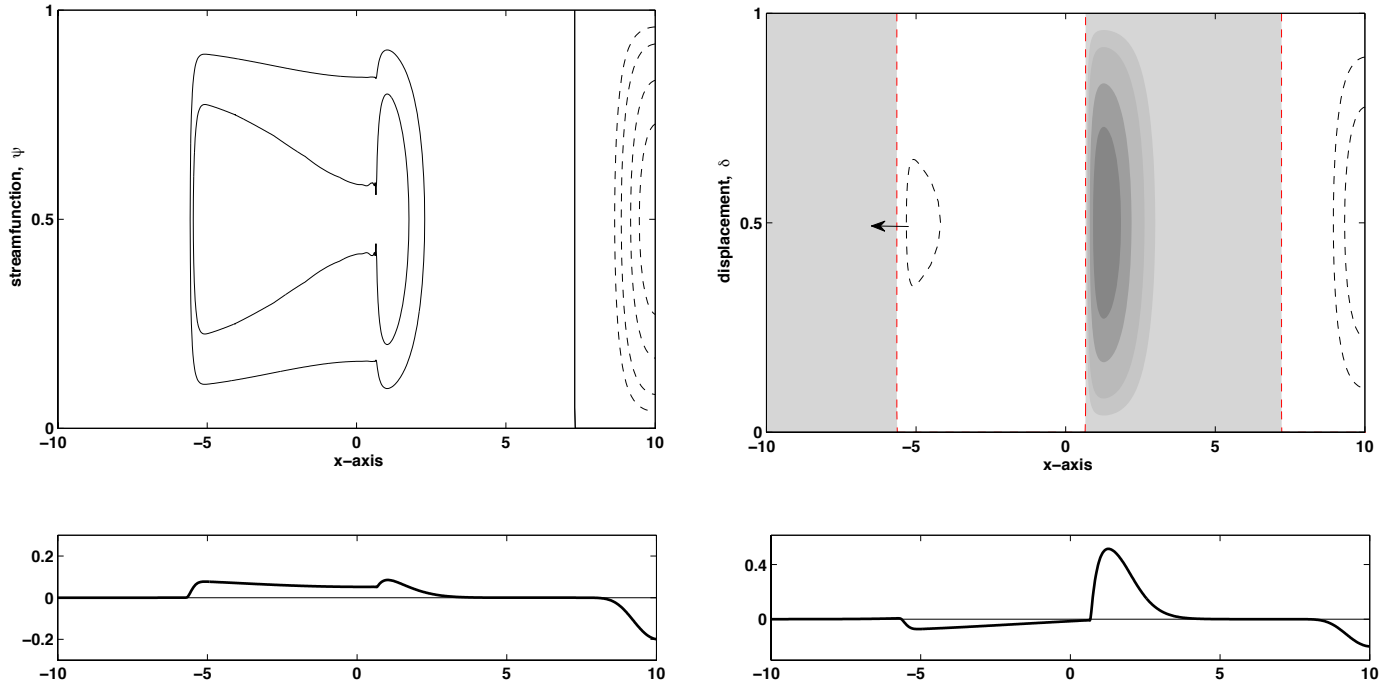


- the upstream propagating wave of subsidence yet persists . . .

A Hierarchy of Models, Part III

Dynamics of Asymmetric Buoyancy

- 1D "linear" single vertical-mode, hydrostatic & $(U = 0)$ initial displacement
  - streamfunction, $\psi \to \psi(x, t) \sin z$ displacement, $\delta \to \delta(x, t) \sin z$

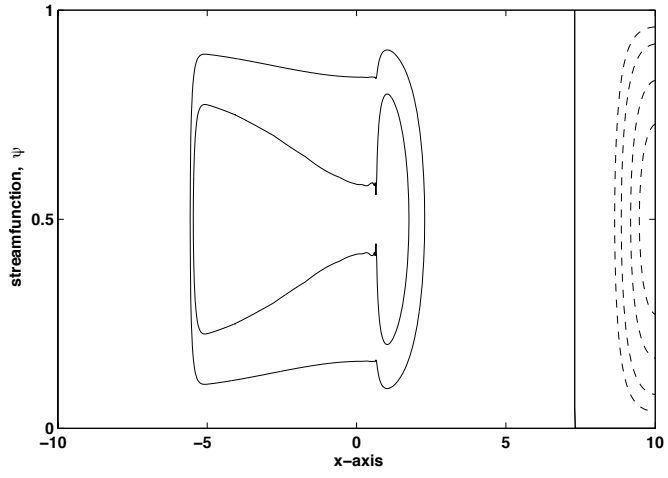


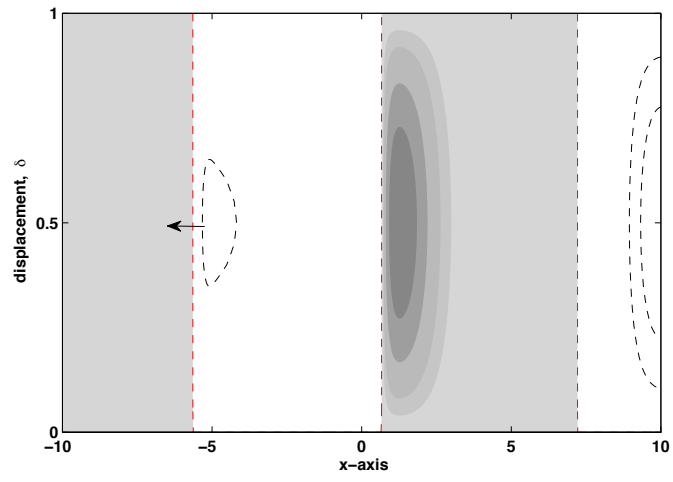
- . . . & the upstream propagating wave of subsidence stubbornly remains

A Hierarchy of Models, Part III

Dynamics of Asymmetric Buoyancy

- 1D "linear" single vertical-mode, $U = 0$, hydrostatic & initial displacement
  - streamfunction, $\psi \to \psi(x, t) \sin z$ displacement, $\delta \to \delta(x, t) \sin z$





- PDE conservation laws for ψ and δ

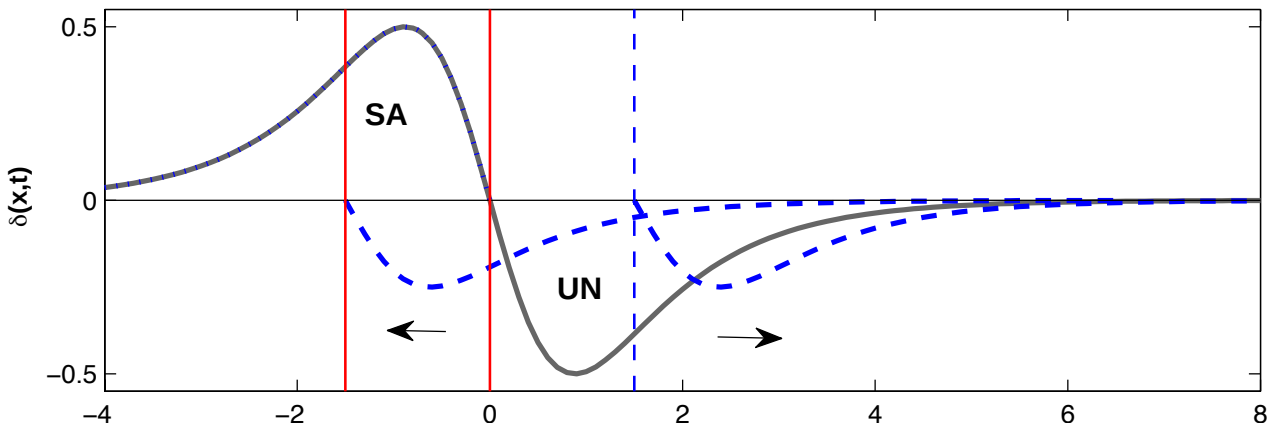
$$\begin{aligned} -\psi_t &+ (b(\delta))_x &= 0 \\ \delta_t &+ \psi_x &= 0 \end{aligned}$$

- so now . . . why is there an upstream propagating wave of subsidence?

Two Buoyancy Regimes

Saturated, No Propagation vs Unsaturated Gravity Waves

- hydrostatic waves have a characteristic speed
- saturated (SA): upward displacement, $\delta > 0$
  - wavespeed $= 0 \rightarrow$ no buoyancy waves
- unsaturated (UN): downward displacement, $\delta < 0$
  - wavespeed $= \pm c \rightarrow$ wave equation $(\delta_{tt} - c^2 \delta_{xx} = 0)$



- what happens at the upstream "collision" of SAturated & UNsaturated air . . . ?

Two Buoyancy Regimes

Saturated, No Propagation vs Unsaturated Gravity Waves

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  - wavespeed $= 0 \rightarrow$ no buoyancy waves
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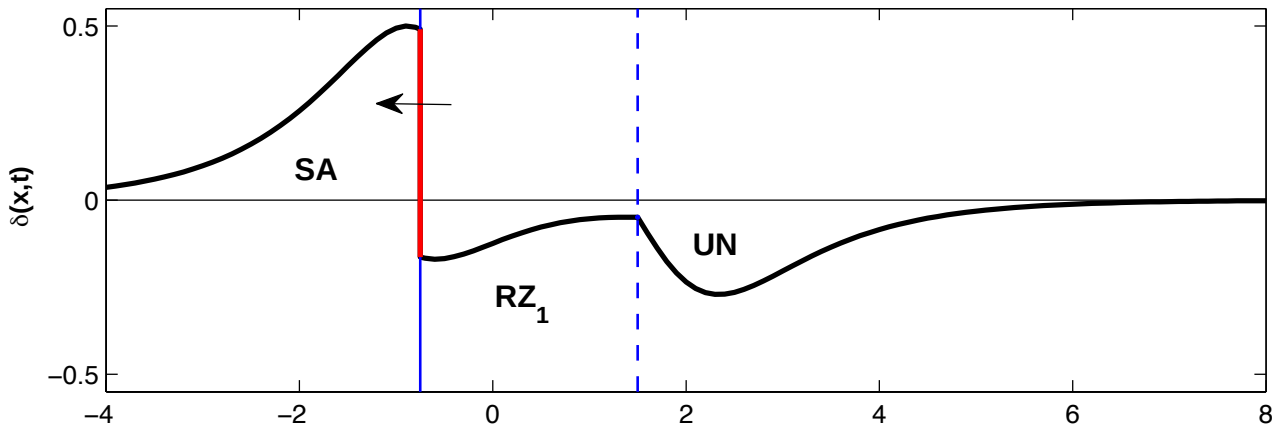
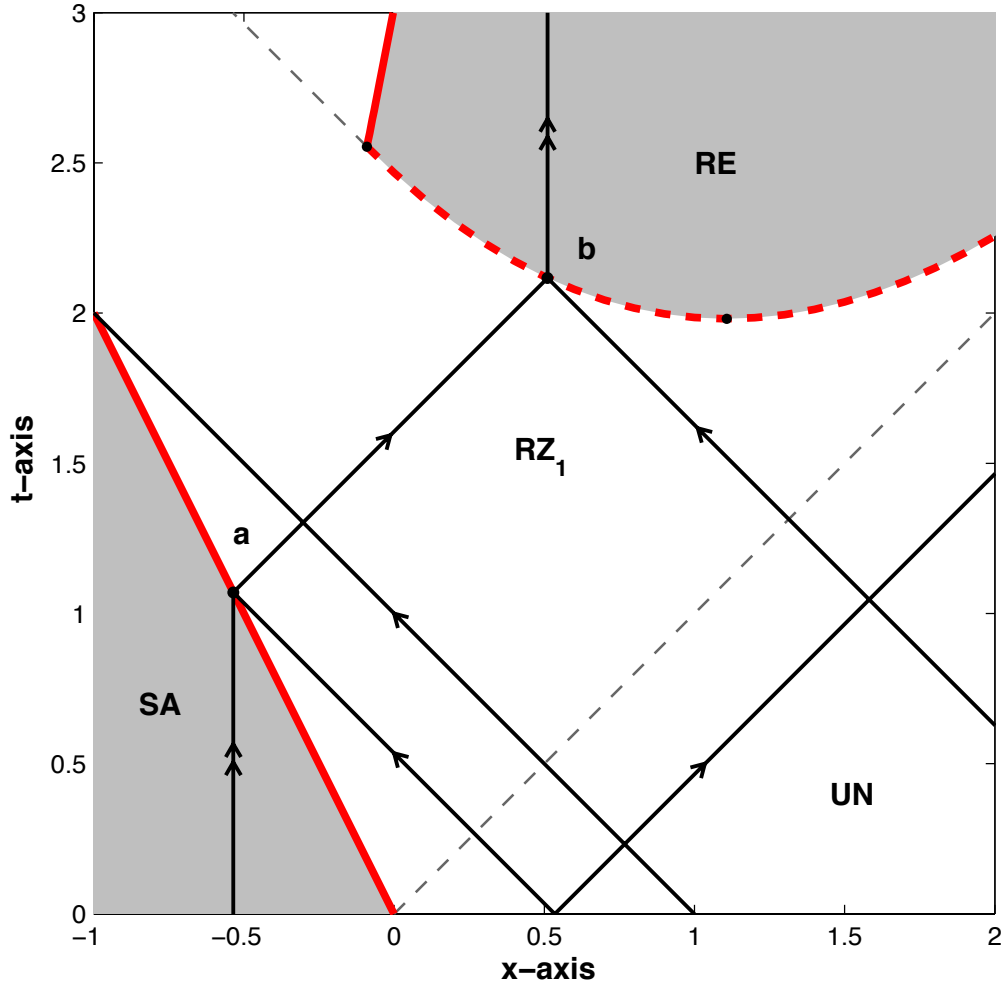


- . . . an upstream propagating shock $\rightarrow$ wave of subsidence
  - speed $\approx -c/2$ by Rankine-Hugoniot (consistent with MR, 2005)

Hydrostatic Solution by Method of Characteristics

Characteristics, Shocks & $\delta = 0$ Discontinuities

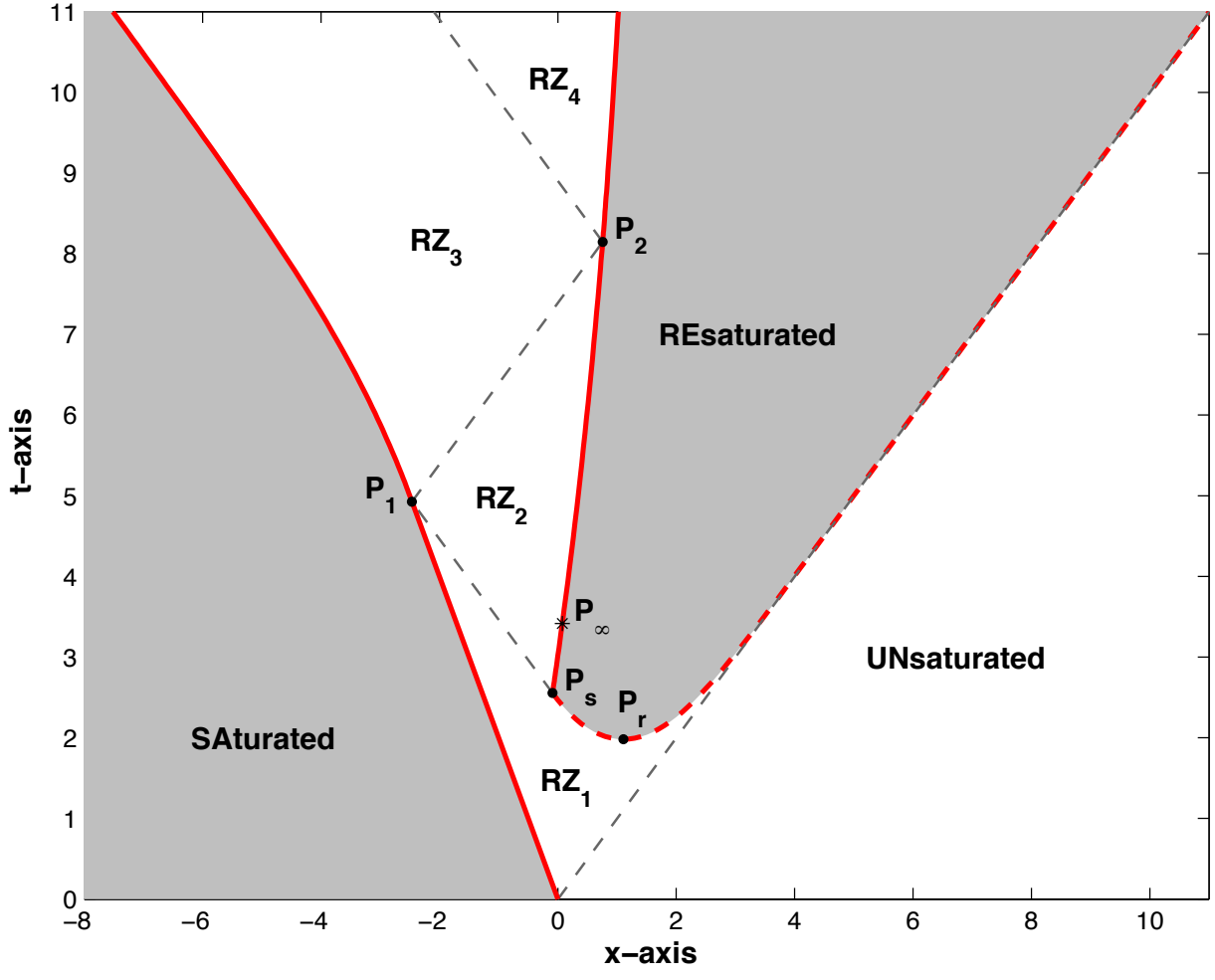
- space-time (Hovmüller) map of SAturated & UNsaturated regions



Hydrostatic Solution by Method of Characteristics

Characteristics, Shocks & $\delta = 0$ Discontinuities

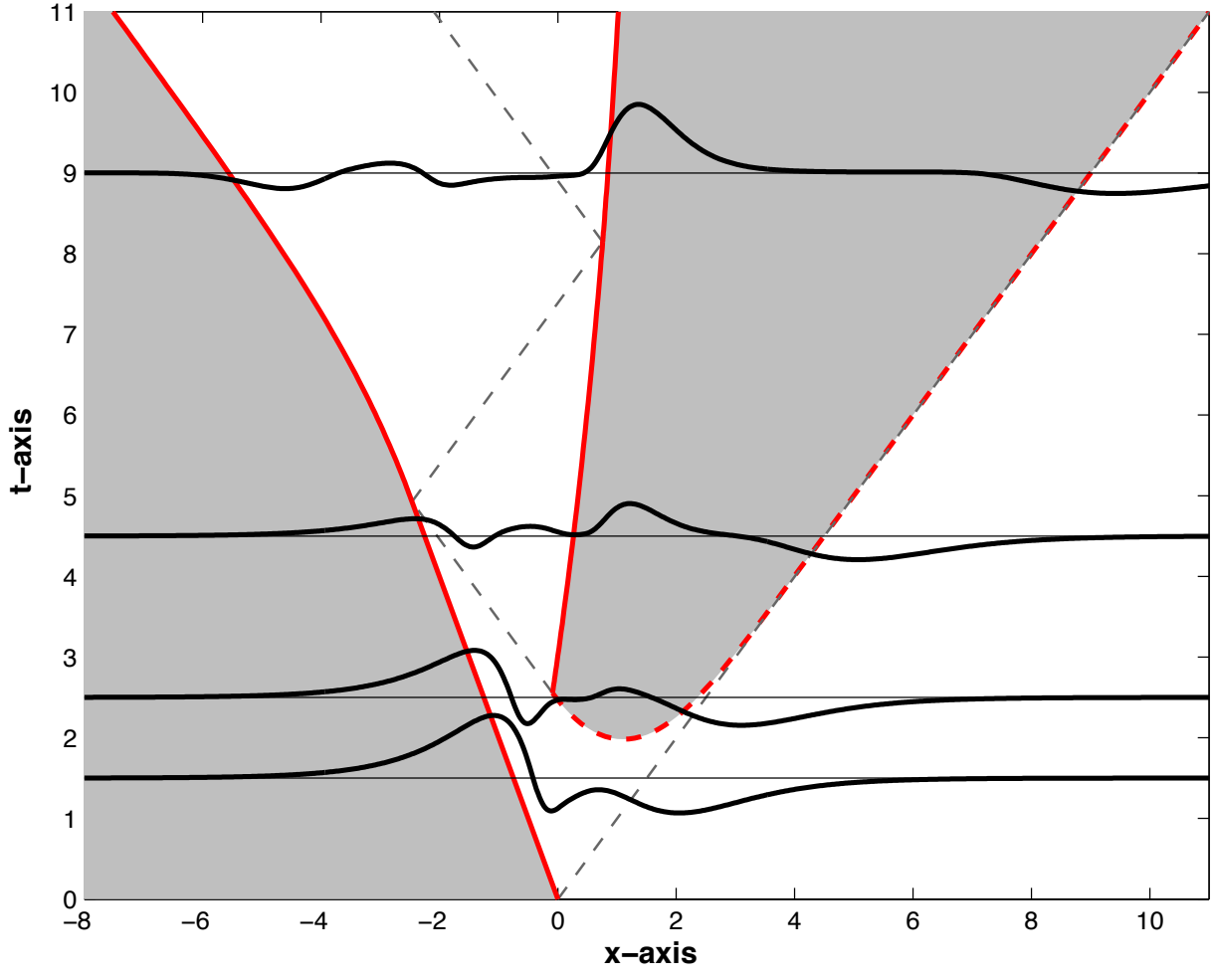
- ▷ space-time (Hovmüller) map of SAturated & UNsaturated regions



Nonhydrostatic Waves vs Hydrostatic Regions

Upstream Wave of Subsidence

- ▷ 1D nonhydrostatic displacement, $\delta(x, t)$: wave regions & shock-like transitions

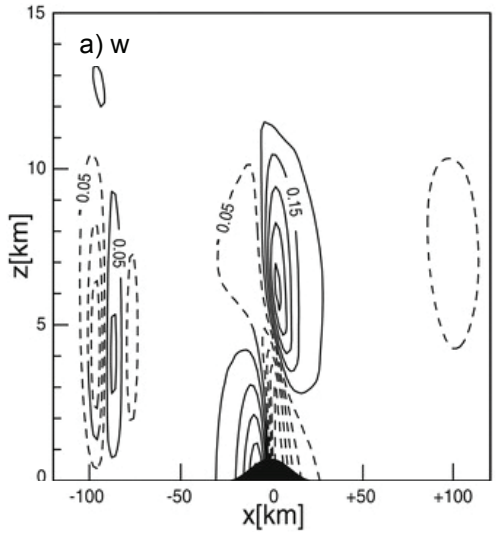


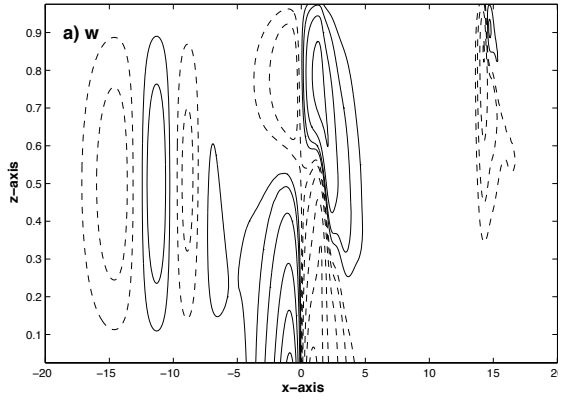
In Closing

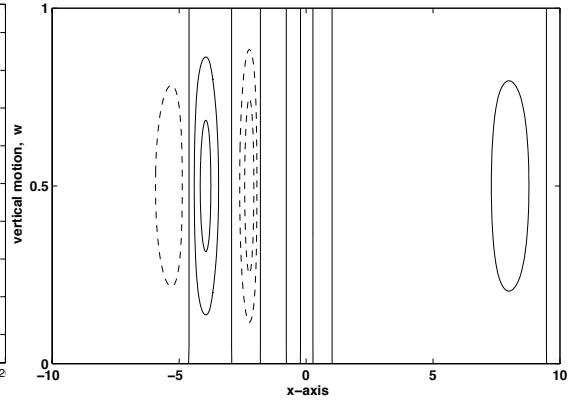
Dynamics of Saturated, Moist-Neutral Air

- asymmetric vertical motions about cloud-free state
- topographic start-up: upstream wave of subsidence as a (hydrostatic) propagating shock
- gravity-wave shock: a new mechanism for the motion of cloud-edges (in moist-neutral air)

- upstream wave of downward vertical motion
  - WRF 2D 1D nonhydrostatic



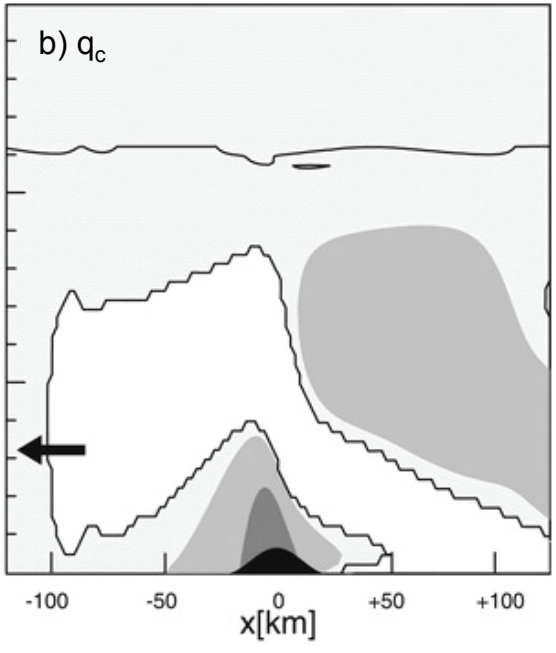




In Closing

Dynamics of Saturated, Moist-Neutral Air

- ▷ asymmetric vertical motions about cloud-free state
- ▷ topographic start-up: upstream wave of subsidence as a (hydrostatic) propagating shock
- ▷ gravity-wave shock: a new mechanism for the motion of cloud-edges

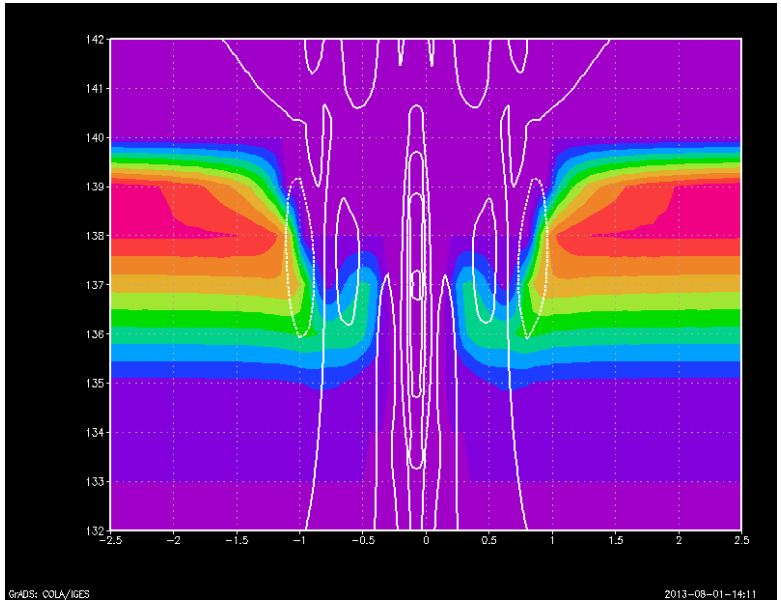


In Closing

Dynamics of Saturated, Moist-Neutral Air

- asymmetric vertical motions about cloud-free state
- topographic start-up: upstream wave of subsidence as a (hydrostatic) propagating shock
- gravity-wave shock: a new mechanism for the motion of cloud-edges

- hole-punch clouds (Heymsfield, et al, 2010/11)



- WRF simulations: Morrison & Thompson (NCAR)