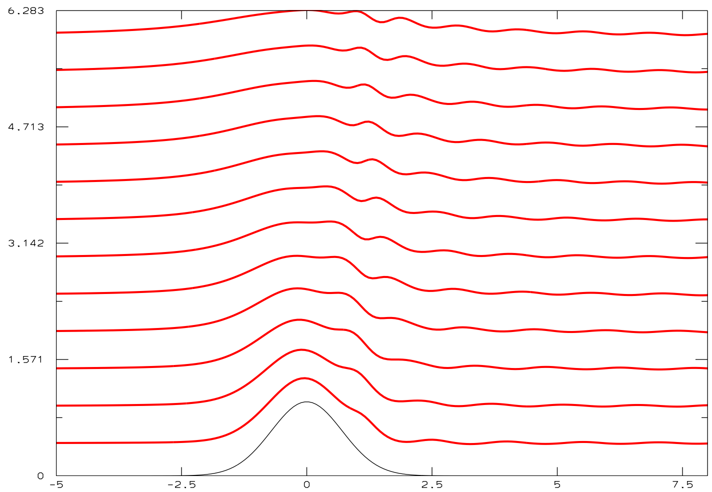
A Few Surprises Yet in Steady 2D Topographic Wave Flows

- ▷ nonlinearity & rotational influences on wave generation
- ▷ a rotating version of Long's theory



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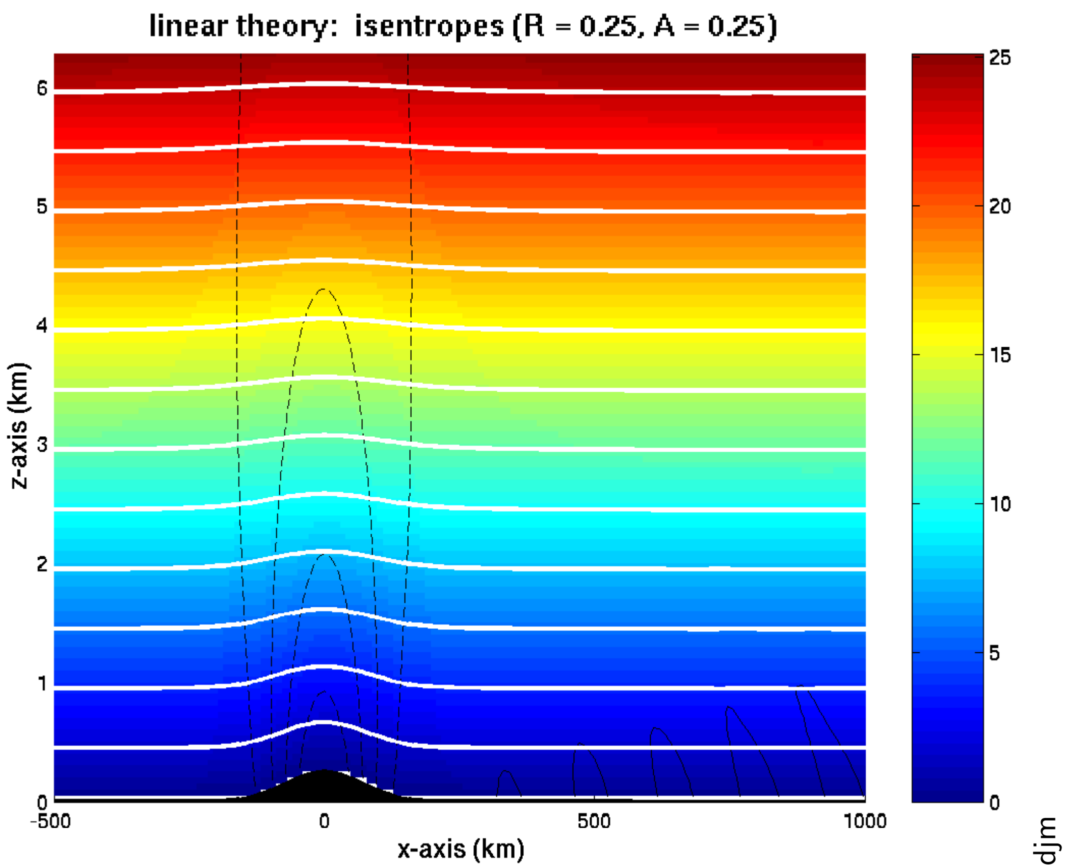
Linear Theory: Tiny Rossby Number

Quasigeostrophic Flow Over A Ridge

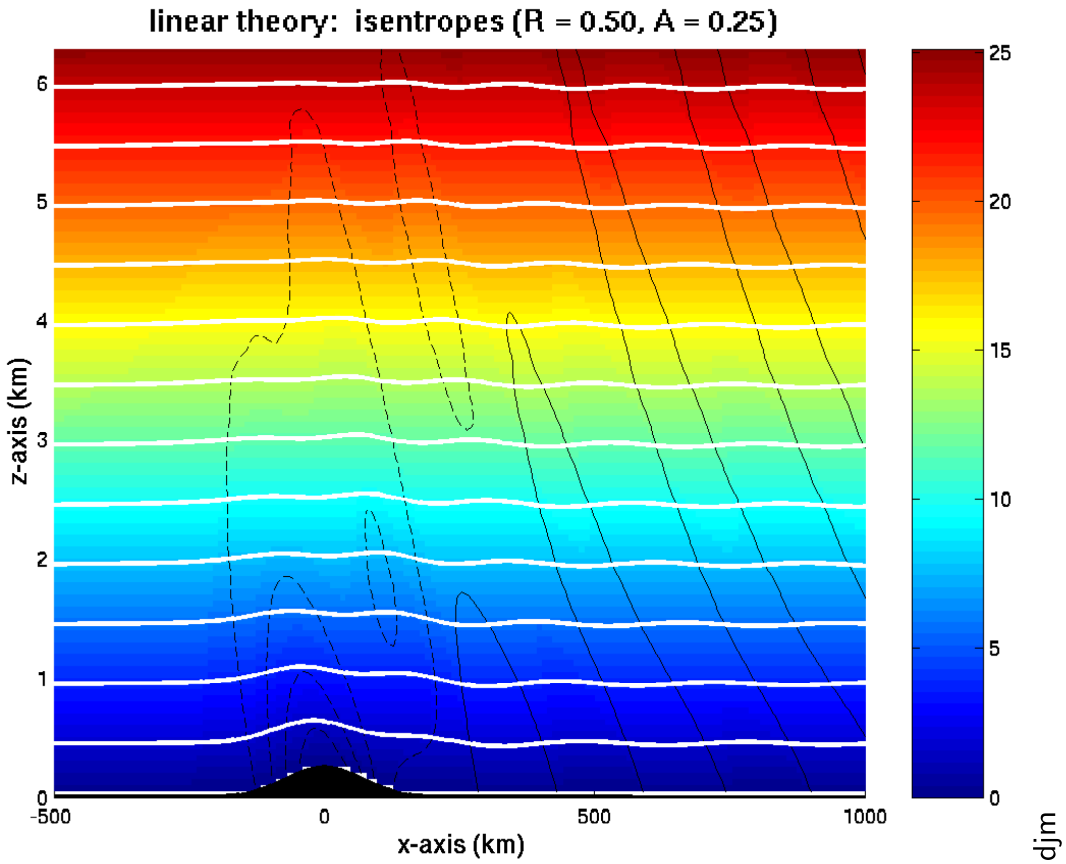
- ▷ small height gaussian ridge ($\mathcal{A} = NH/U = 0.25$)
- ▷ predominantly balanced QG flow ($\mathcal{R} = U/fL = 0.25$)
- ▷ very weak wave anomalies near leeward surface (Pierrehumbert, 1984)



Linear Theory: Small Rossby Number

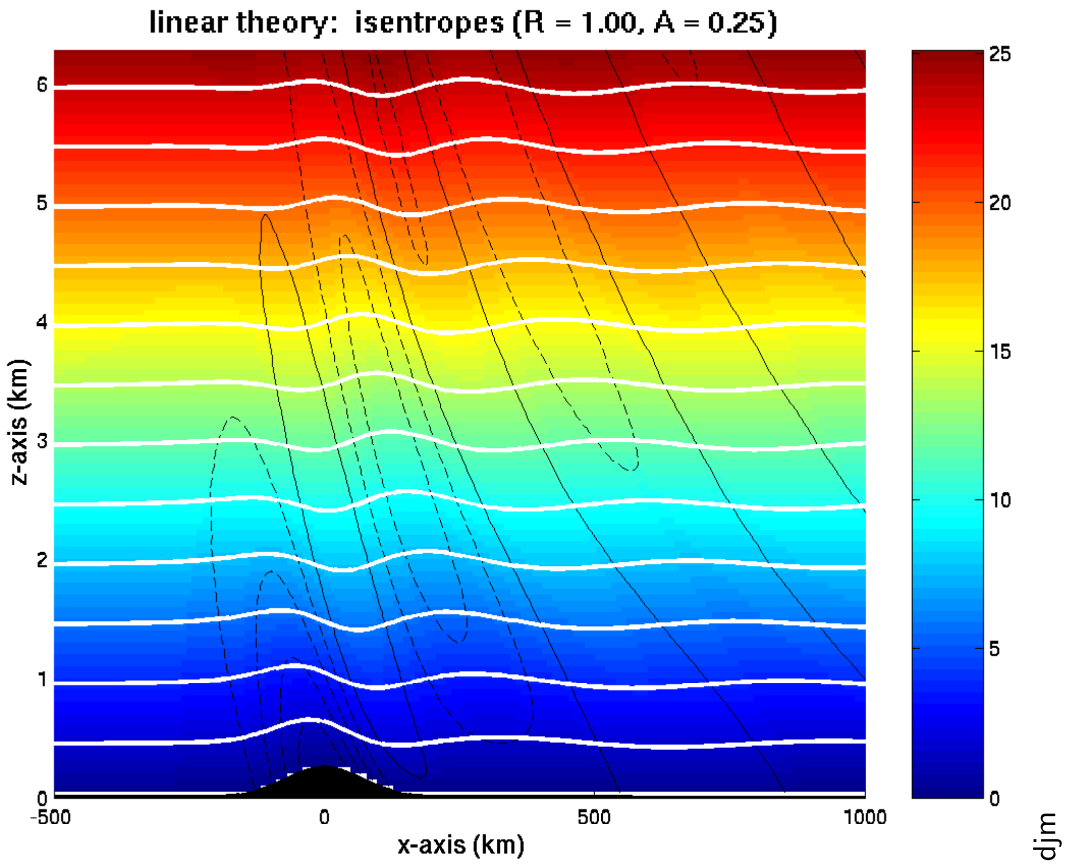
Appearance of Waves

- ▷ steady uniform flow, constant stratification
- ▷ intermediate case: QG summit flow with short waves ($\mathcal{R} = 0.50$)
- ▷ development of downstream (dispersive) wavetrain



Fully Developed Wave Field

- strong waves with similar scale to QG summit flow ($\mathcal{R} = 1.0$)
- significant wave radiation aloft



- as $\mathcal{R} \nearrow$, waves grow in amplitude (exponentially) & wavelength (linearly)

Linear Theory: A Singular Numerical Problem

Fourier Integral Solution (Queney, 1947)

$$b(x,z) = -\frac{N^2}{\pi}\,\text{Real}\left\{\int_0^\infty \hat{h}(k)\; e^{ik\,x}\; e^{m(k)\,z}\; dk\right\}$$

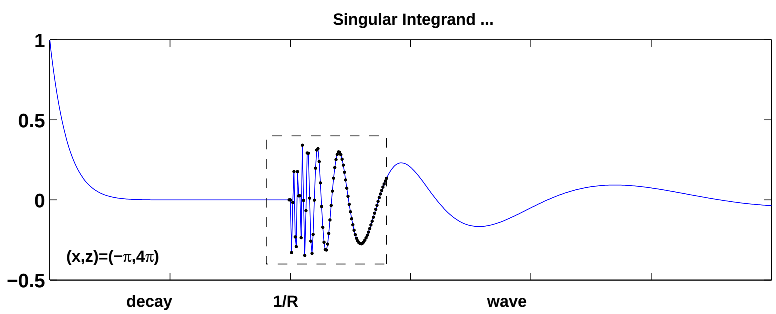
Buoyancy Anomaly

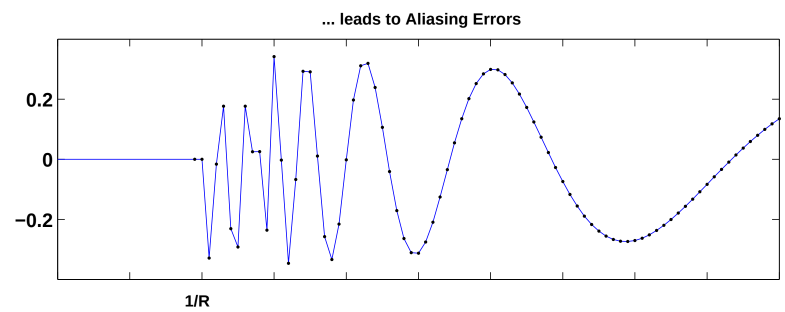
- linear waves with rotation, stratification & topography $h(x)$

$$\mathcal{A}^2\, b_{xx} + \mathcal{R}^{-2}\, b_{zz} + b_{xxzz} = 0 \quad ; \quad b(x,0) = -h(x)$$

- 2D linear dispersion relation gives a singular exponent at $k = \mathcal{R}^{-1}$

$$m(k) = \begin{cases} -\dfrac{\mathcal{A}\,k}{\sqrt{\mathcal{R}^{-2} - k^2}} & \text{for} \quad 0 \le k < \mathcal{R}^{-1} \quad \text{(vertical decay)} \\[2ex] i\,\dfrac{\mathcal{A}\,k}{\sqrt{\mathcal{R}^{-2} - k^2}} & \text{for} \quad \mathcal{R}^{-1} < k < \infty \quad \text{(outgoing waves)} \end{cases}$$





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- rotating wave case prone to severe numerical Fourier errors

Three Questions

a: Is There an Analog to Long's Theory that includes Coriolis Rotation?

- ▷ Long's theory (1953) for buoyancy anomaly
- ▷ steady, nonlinear & non-rotating flows are obtained exactly via linear Helmholtz solutions

  ⟶ no obvious extension to include rotation

b: What is the Nature of Pierrehumbert's Finite $\mathcal{R}$ Singularity?

- ▷ semi-geostrophic approximation: Pierrehumbert (1985)
- ▷ SG solutions have singular breakdown at finite Rossby number

  ⟶ a true finite amplitude flow transition, or merely a manifestation of SG approximation?

c: How can Waves be Generated at Small Rossby Number?

- ▷ Pierrehumbert/Wyman (1985) & Trüb/Davies (1995)
- ▷ wave generation by finite amplitude ridges at small $\mathcal{R}$
- ▷ relaxation of time-dependent flow computations

  ⟶ how does nonlinearity circumvent quasigeostrophic balance?

a: Long's Theory for Non-Rotating Topographic Waves

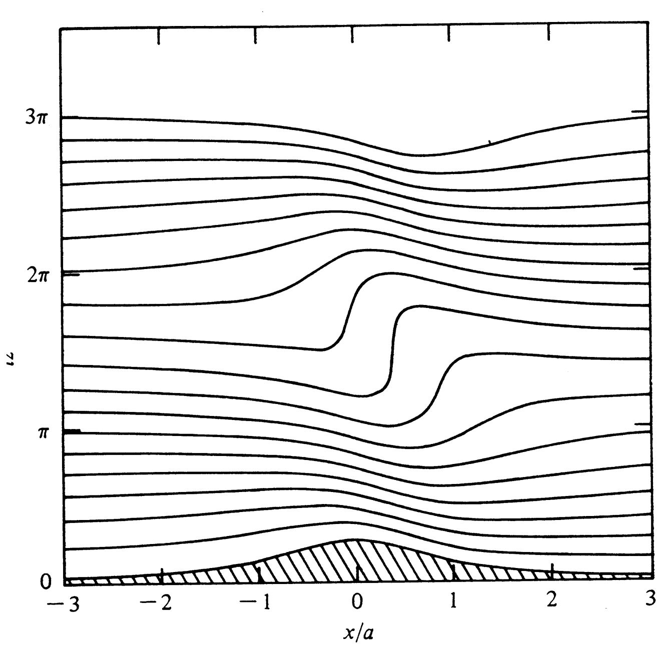
An Exact Nonlinear Theory for Buoyancy

- ▷ steady, non-rotating & hydrostatic/nonhydrostatic (Long, 1953)
- ▷ 2D helmholtz equation: stratified ($\mathcal{A} = NH/U$) & nonhydrostatic (δ^2)

$$\mathcal{A}^2\, b + b_{zz} + \delta^2 \mathcal{A}^2\, b_{xx} = 0 \quad ; \quad b(x, h(x)) = 0$$

- ▷ downstream waves derive from radiation boundary conditions

  $\longrightarrow$ except hydrostatic waves (δ^2=0) are nondispersive



Klemp & Lilly, 1979

- ▷ nonlinear fluid system reduces to a single equation for buoyancy

Isentropic Coordinates

2D Primitive Equations

- nondimensional: steady, rotating & nonhydrostatic
- potential temperature θ as vertical coordinate ($\theta_z = 1/z_\theta$)

$$
\begin{aligned}
\mathcal{D}u \quad - \mathcal{R}^{-1}\, v \quad &= \quad - M_x \quad - \delta^2\, z_x\, \mathcal{D}w \\
\mathcal{D}v \quad + \mathcal{R}^{-1}\, u \quad &= \quad 0 \\
\delta^2\, z_\theta\, \mathcal{D}w \quad + \quad z \quad &= \quad - M_\theta \\
\mathcal{D}z \quad - \quad \mathcal{A}\, w \quad &= \quad 0
\end{aligned}
$$

- Montgomery potential: $M = \phi - z\theta$
- steady 2D advection: $\mathcal{D} = (1 + \mathcal{A}\, u)\, \partial_x$
- 2D divergence: $z_\theta\, u_x - z_x\, u_\theta + w_\theta = 0$

Steady Streamline Property

- divergence + thermodynamic $\longrightarrow \{(1 + \mathcal{A}\, u)\, z_\theta\}_x = 0$

  $\longrightarrow$ squeezing isentropes (streamlines) accelerates flow
- velocity relations: $1 + \mathcal{A}\, u = \mathcal{A}/z_\theta \quad ; \quad w = z_x/z_\theta$
- across-ridge flow: $\mathcal{A}^2\, v_x = \mathcal{R}^{-1}\, (z_\theta - \mathcal{A})$
- eliminating M through vorticity gives . . .

A Master Equation for Buoyancy

Vertical Displacement Equation

- includes both f-plane and non-hydrostatic effects

$$\mathcal{A}^2 z_{xx} + \mathcal{R}^{-2} z_{\theta\theta} - \frac{\mathcal{A}^3}{2}\left(\frac{1+\delta^2 z_x^2}{z_\theta^2}\right)_{xx\theta} + \mathcal{A}^3\delta^2\left(\frac{z_x}{z_\theta}\right)_{xxx} = 0$$

- surface condition: $z(x,0) = -\mathcal{A}\, h(x)$ & radiation BCs
- equivalent to Long's equation without rotation ($\mathcal{R}^{-2} \to 0$)

Hydrostatic Buoyancy Equation ($\delta^2 = 0$)

- constant stratification: $z = \mathcal{A}\,(\theta - b(x,\theta))$

$$\boxed{\mathcal{A}^2 b_{xx} + \mathcal{R}^{-2} b_{\theta\theta} + b_{xx\theta\theta} = -\frac{1}{2}\left(\frac{3-2b_\theta}{(1-b_\theta)^2}\, b_\theta^2\right)_{xx\theta}}$$

- surface condition: $b(x,0) = -h(x)$ & radiation BCs
- linear Queney operator in isentropic coordinates = nonlinearity

Isentropic Coordinate Singularities

- breakdowns in coordinate inversion of $z = \mathcal{A}\,(\theta - b(x,\theta))$

$$\theta_z = \frac{1}{z_\theta} = \frac{1}{\mathcal{A}(1 - b_\theta)} \rightarrow \begin{cases} \infty & \text{isentrope collapsing, } u \rightarrow \infty \\ 0 & \text{isentrope overturning, } u \rightarrow 0 \end{cases}$$

Semigeostrophic Approximation

- small $\mathcal{R}$ extension of quasigeostrophy: Robinson (1960), Pierrehumbert (1985)
- SG truncation of *hydrostatic master equation*

$$\mathcal{A}^2\, b_{xx} + \mathcal{R}^{-2}\, b_{\theta\theta} = 0 \qquad ; \qquad b(x,0) = -h(x)$$

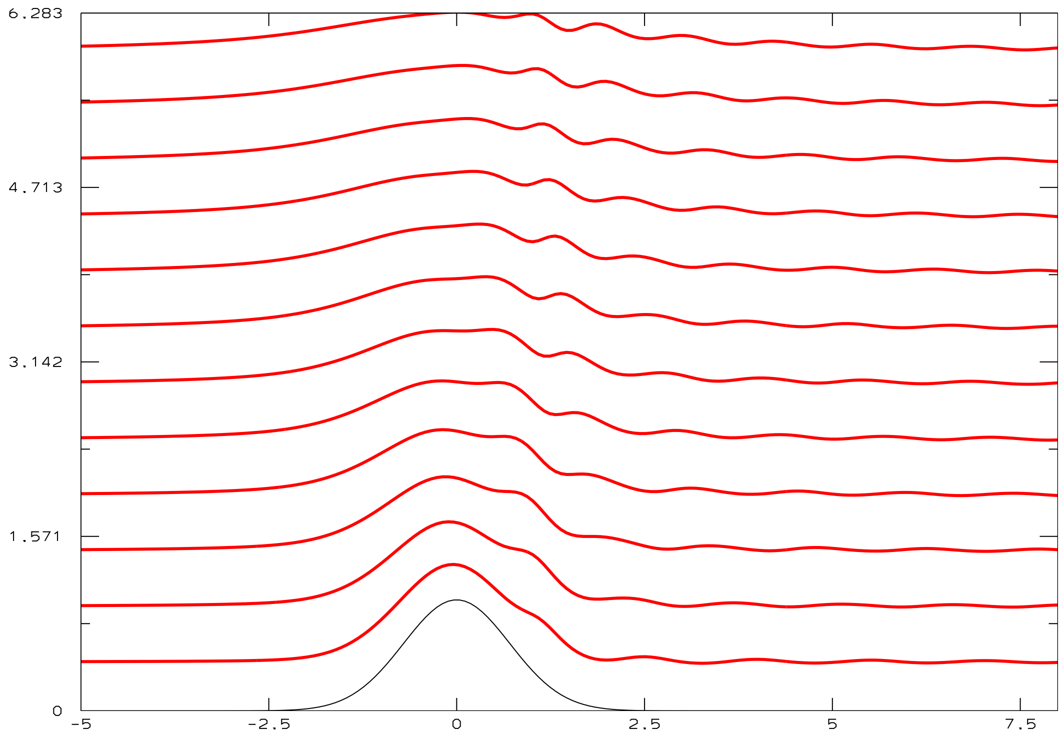
- isentrope collapse <u>must</u> occur above $h(x)$-dependent critical value of $\mathcal{R}\mathcal{A}$

Enhanced Wave Generation & Singularity Suppression?

- approach to collapse invalidates SG approximation, as nonlinearity <u>must</u> become large
- <u>does nonlinearity ultimately suppress collapse singularity through enhanced wave generation?</u>

Nonlinear Wave Generation

- moderate height gaussian ridge ($\mathcal{A} = NH/U = 1.00$)
- tiny Rossby number flow ($\mathcal{R} = U/fL = 0.25$)
- time-transient computation to steady state



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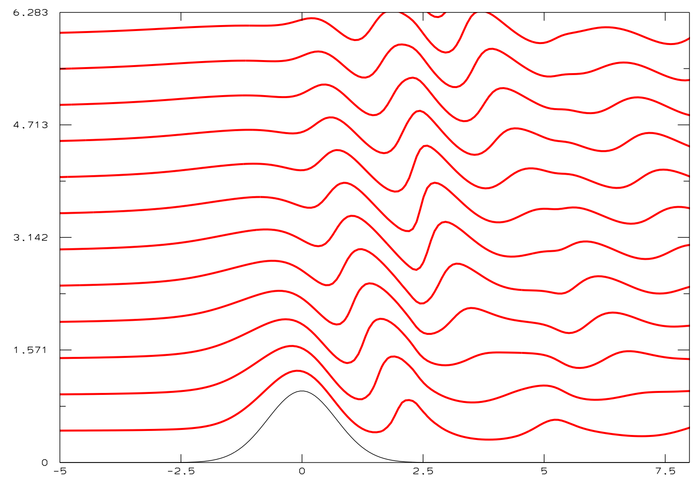
- how are these waves generated?

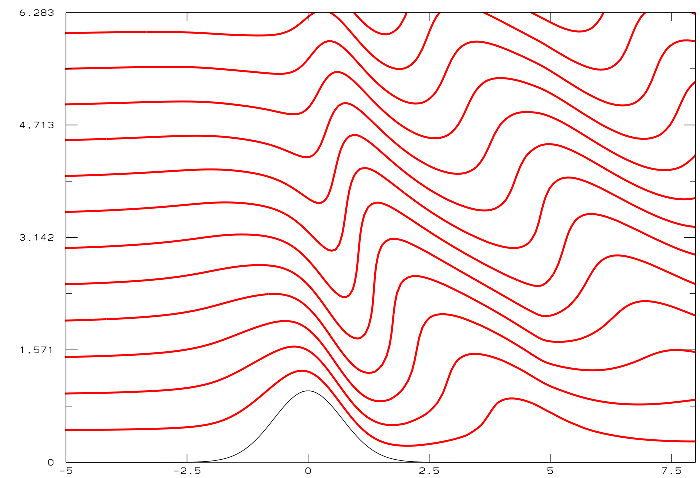
Nonlinear Wave Enhancement

- moderate height gaussian ridge ($\mathcal{A} = 1.00$)
- Rossby number flows ($\mathcal{R} = 0.50, 1.00$)
- time-transient computation to steady state

$\mathcal{R} = 0.50$



$\mathcal{R} = 1.00$



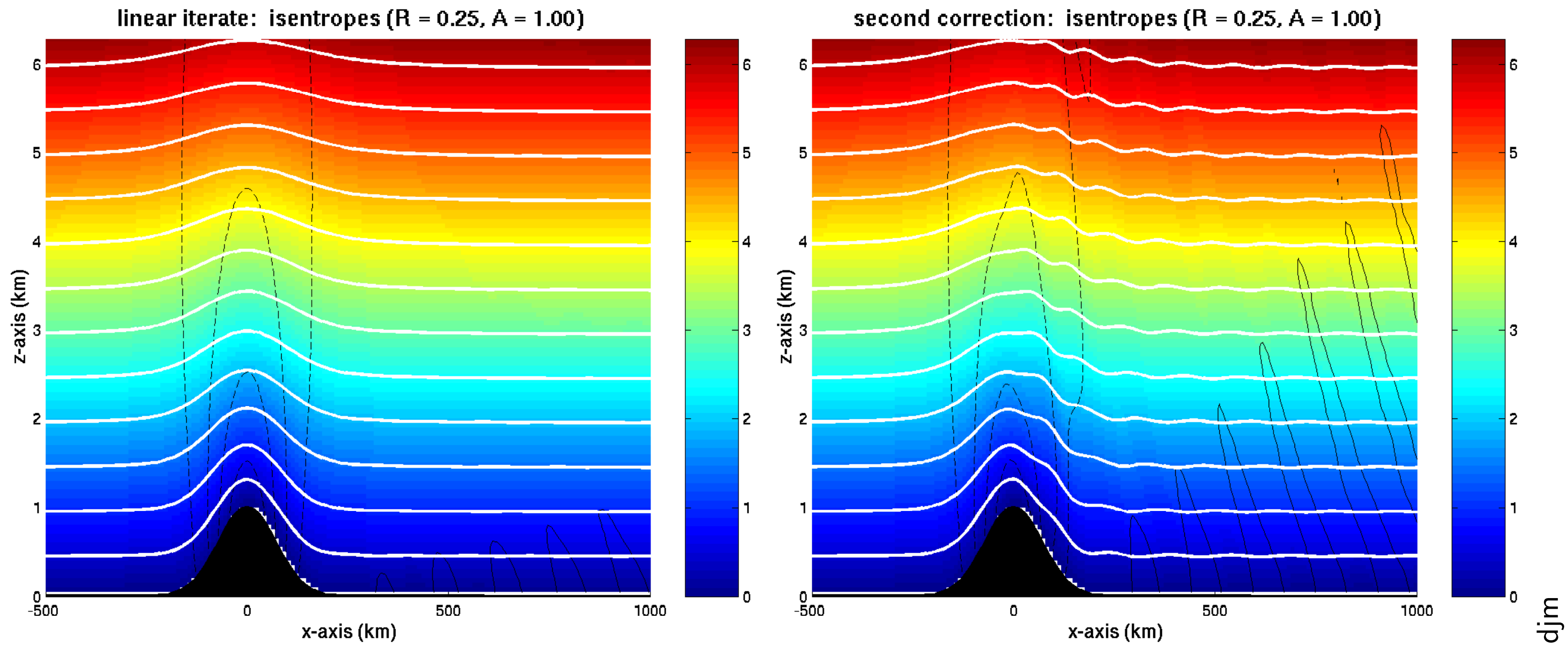
- wave amplitudes approach overturning as $\mathcal{R} \nearrow$

Generation at $\mathcal{R} = 0.25$

▷ iterate on nonlinearity in *hydrostatic master equation*: $b^{old}(x,\theta) \rightarrow b^{new}(x,\theta)$

$$\mathcal{A}^2\, b^n_{xx} + \mathcal{R}^{-2}\, b^n_{\theta\theta} + b^n_{xx\theta\theta} = -\frac{1}{2}\left(\frac{3-2b^o_\theta}{(1-b^o_\theta)^2}\,(b^o_\theta)^2\right)_{xx\theta}$$

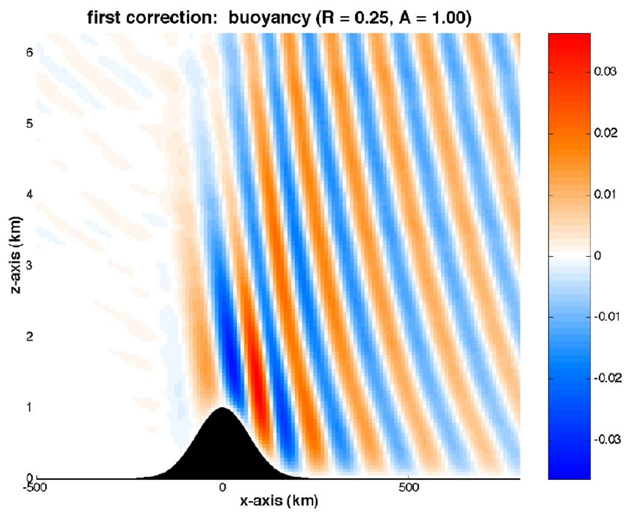
linear solution: $b^0(x,\theta)$ waves after two nonlinear iterations: $b^2(x,\theta)$



▷ numerical process overwhelmed by noise beyond two iterations

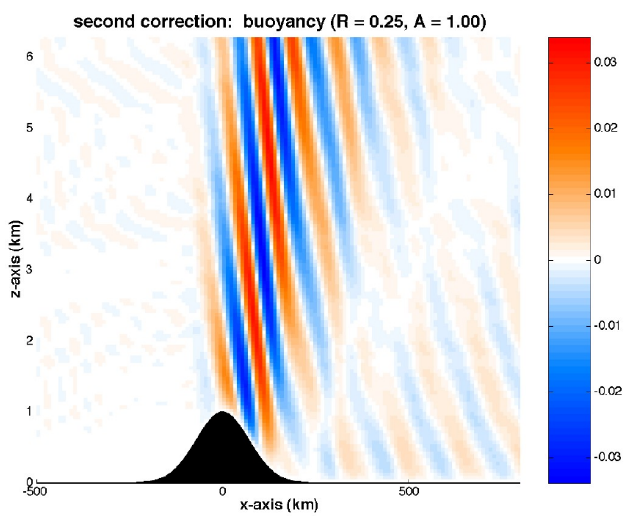
Generation & Enhancement

Nonlinear Corrections



- 1^{st} correction: generation

  $\longrightarrow$ wavetrain downstream & aloft



- 2^{nd} correction: enhancement

  $\longrightarrow$ waves intensified aloft

- preliminary computations

  $\longrightarrow$ fourier noise upstream

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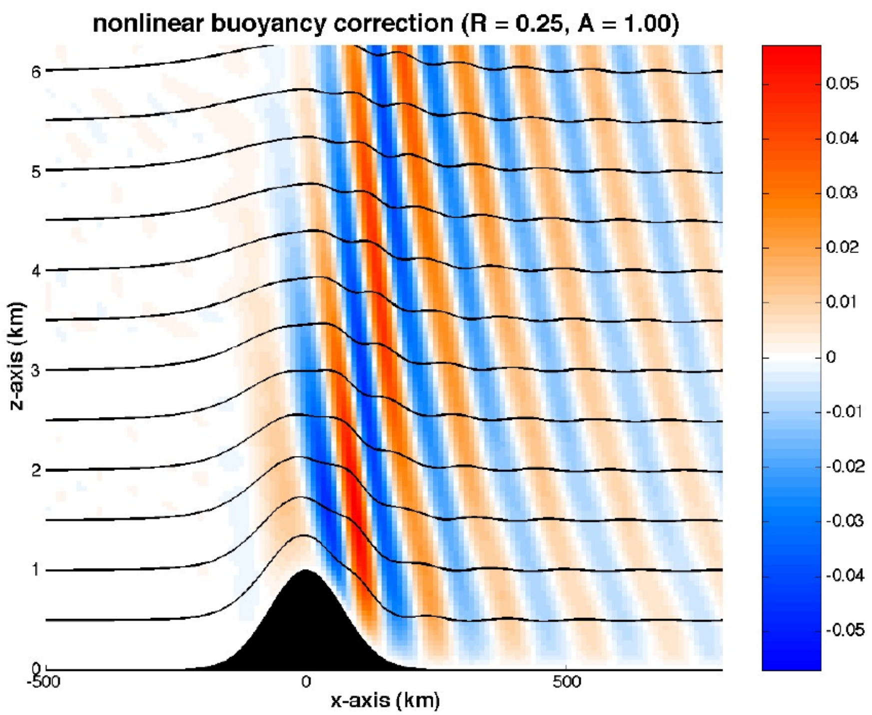
Nonlinear Waves

Possible Nonlinear Mechanisms

- ▷ nonlinear modification of local Rossby number
  - $\longrightarrow$ enhanced topographic wave generation at ridge summit
  - $\longrightarrow$ modification of wave propagation (rays) in interior
- ▷ nonlinear wave generation in interior?
- ▷ total nonlinear corrections (two iterations)



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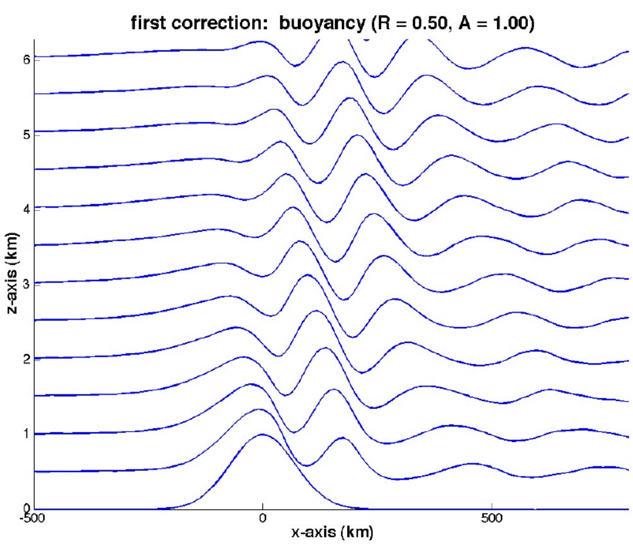
Summary

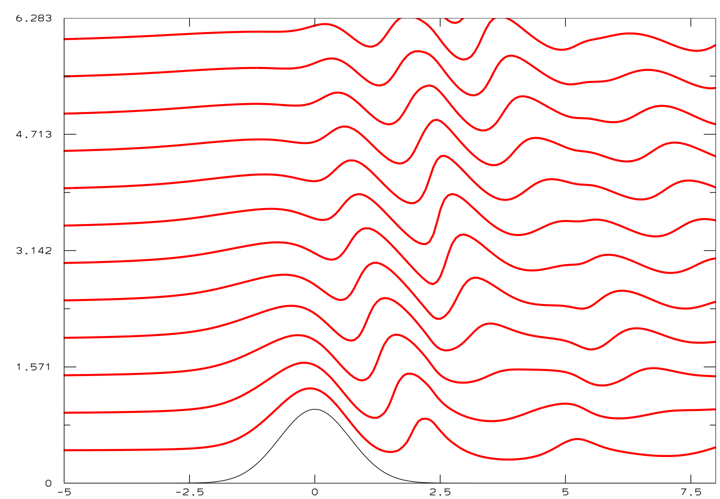
Master Equation for Buoyancy

- single equation for 2D topographic wave flow spanning non-hydrostatic to QG regimes
- quantitative tool for understanding nonlinear wave processes
- key issue: stability & accuracy of numerical solves

one iteration at $\mathcal{R} = 0.50$



time-dependent computation



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