Mean Flow Steepening in Internal Gravity Wave Breaking

Group Meeting Presentation

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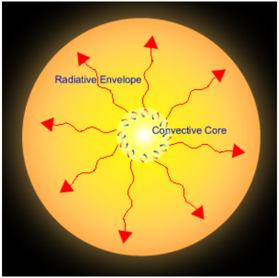
Background

Goldreich & Nicholson 1989

- *Tidal Friction in Early-Type Stars*.
- Tidal torques excite outgoing internal gravity waves (IGW) at boundary between convective core and radiative envelope.
- IGW amplify as they propagate due to density rarefaction, break and deposit angular momentum.
- Transfers energy from the orbit to the star and synchronizing the spin to the orbit outside-in.



- 2D incompressible, isothermal, stratified plane parallel atmosphere.
- For a barotropic $P(\rho, S) = P(\rho)$, incompressibility $c_s^2 \to \infty$ produces

$$\vec{\nabla} \cdot \vec{u} = 0, \tag{1a}$$
$$\frac{\partial \rho}{\partial t} + \vec{u} \cdot \vec{\nabla} \rho = 0, \tag{1b}$$
$$\frac{\partial \vec{u}}{\partial t} + \left(\vec{u} \cdot \vec{\nabla}\right)\vec{u} + \frac{\vec{\nabla} P}{\rho} + g\hat{z} = 0. \tag{1c}$$

- Numerics: instead of $\frac{P}{\rho}$, $\rho T = P$ and $\rho = \rho_0 e^{\Upsilon}$ for stratification $\rho(z) \propto e^{-z/H}$.

$$\vec{\nabla} \cdot \vec{u} = 0, \tag{2a}$$
$$\frac{\partial \Upsilon}{\partial t} - \frac{u_z}{H} = 0, \tag{2b}$$
$$\frac{\partial \vec{u}}{\partial t} + \left(\vec{u} \cdot \vec{\nabla}\right)\vec{u} + \vec{\nabla} T + gH\vec{\nabla}\Upsilon + T_1\vec{\nabla}\Upsilon - \frac{T_1 \hat{z}}{H} = 0. \tag{2c}$$

- In linear regime $\left(\vec{u}\cdot\vec{\nabla}\right) \ll \partial_t$, $\vec{u} \propto e^{z/2H}$.
- Perturbation $(\vec{u}, \rho_1, P_1)$ carries average horizontal momentum flux $\left\langle F_{p,x}\right\rangle_x = \left\langle \rho u_x u_z \right\rangle_x$.
- Induces mean flow

$$\langle u_x \rangle_x \equiv \bar{U}_x(z) \neq 0 = \frac{\langle u_x u_z \rangle_x}{c_{g,z}}. \tag{3}$$

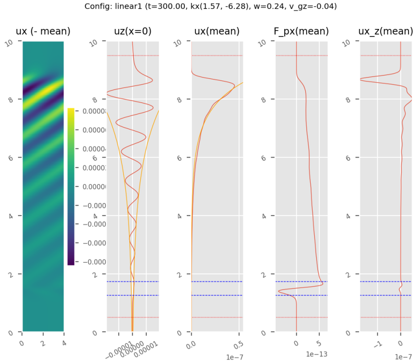
- Critical layer (equivalent to corotation resonance in other systems): where Doppler-shifted frequency (in fluid rest frame) $\omega \Rightarrow \omega - k_x \bar{U}_x = 0$.
- Note $\bar{U}_x \propto e^{z/H}$ so there is eventually $z_c : \omega - k_x \bar{U}_x(z_c) = 0$.

Background

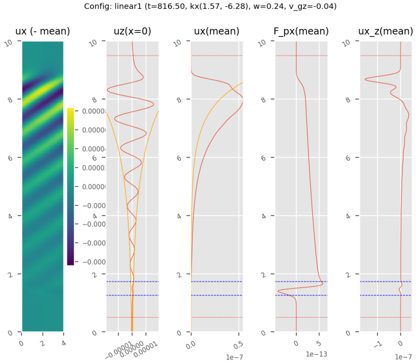
Hypothesis

- Since critical layers almost always induce full absorption (recall, $\propto \exp\left[-\pi\sqrt{\mathrm{Ri}^2 - \frac{1}{4}}\right], \mathrm{Ri} = \frac{N}{\bar{U}_x'}$), hypothesis:
  - $\vec{u}_1$ is excited, induces $\bar{U}_x$ mean flow.
  - Where $\bar{U}_x$ satisfies critical layer criterion, $\boldsymbol{F}_{p,x}$ is fully absorbed.
  - Horizontal momentum goes into spinning up more fluid up to $\bar{U}_{x,crit} = \frac{\omega}{k_x}$.
  - Thus, critical layer should propagate down.
- Exactly the *spin up outside in* tidal synchronization picture..

- Permit $z \in [0H, 10H]$, full $\rho_0 \propto e^{-z/H}$, allow $\vec{u} \propto e^{z/2H}$ to source growing mean flow.
- Low-Amplitude ($k_z \xi_z \ll 1$ everywhere). Orange = analytical solution.



(a) Early Low-A



(b) Later Low-A

Simulations

Large Domain, Low-Amplitude

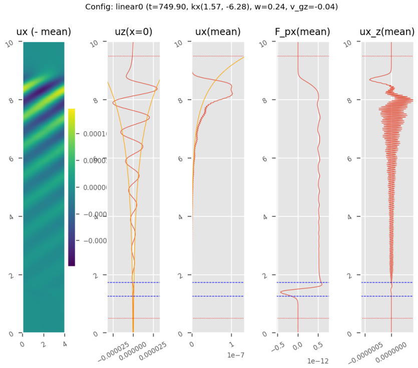
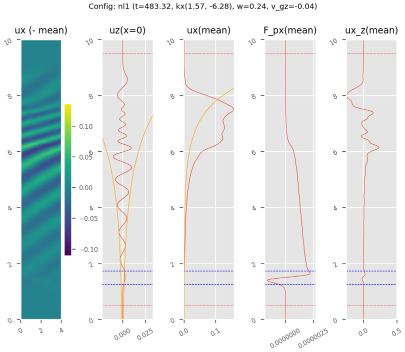


Figure: Low-Amplitude, nearly zero viscosity.

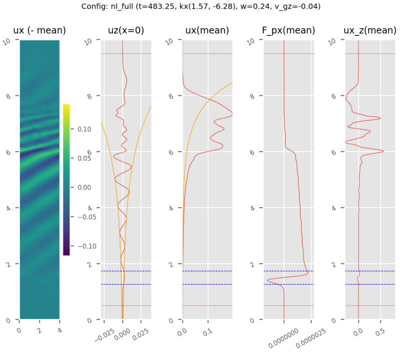
Simulations

Large Domain, High-Amplitude

- Note steepening region ($N = 1$, so $\frac{\partial \bar{U}_x}{\partial z} = \frac{N}{\mathrm{Ri}} = \mathrm{Ri}^{-1}$).



(a) Lower-res.

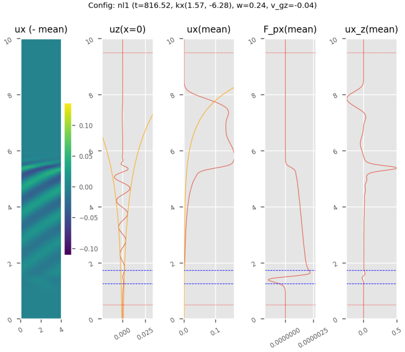


(b) Double N_z.

Simulations

Large Domain, High-Amplitude

- Later



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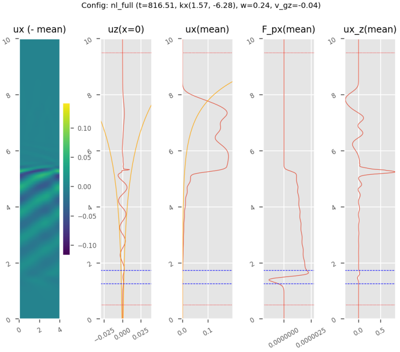


(b) Double N_z.

Simulations

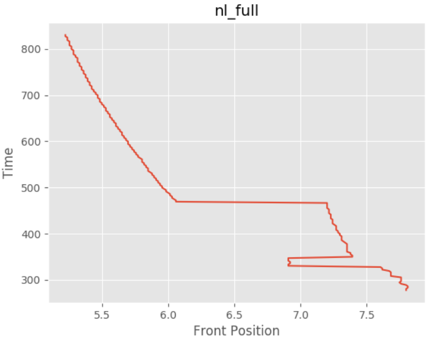
Large Domain, Comments

- While damping layers pump up $\bar{U}_x$, ran on higher amplitude, damping layer is not chief cause of $\bar{U}_x$ critical layer behavior.
- Would expect reflections due to $\mathrm{Ri} \gtrsim 1/2$, different from hypothesis!
  - No reflections seen, could be *viscously limited*?
  - Indeed, $\mathrm{Ri}^{-1} \sim \left|\vec{k}\right| d$ where d is the width of the spinup layer, then $\nu\rho_0 \frac{\bar{U}_{x,c}}{d^2} \sim \frac{F_{p,x}}{d}$.
- Separately, matching $F_{p,x} = \langle \rho_0 u_x u_z \rangle$ with spinning up mass $F_{p,x} = u_{front}\rho_0 \bar{U}_{x,crit}$ lets us predict u_{front}, next page.

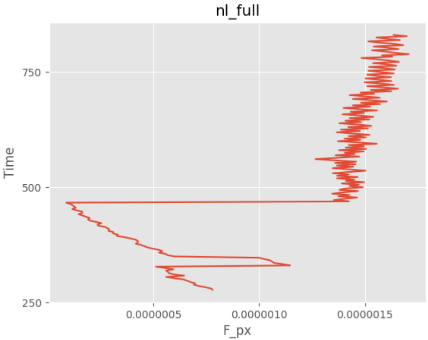
Simulations

Large Domain, Predicting u_{front}

- Front position is $z_f = \text{argmax}_z \frac{\mathrm{d}\bar{U}_x}{\mathrm{d}z}$, while $F_{p,x} = 2F_{p,x}(z_f)$ ($\sim$ halfway in front).
- Predicts $u_{front} = \frac{F_{p,x}}{\rho_0(z)\bar{U}_{x,c}} \approx 2.2 \times 10^{-3} NH$ (using $z \approx 5.5H$), or $2H/3$ in $300N$. Pretty close, seems to imply perfect absorption.



(a) Front Position. Slight exponential.

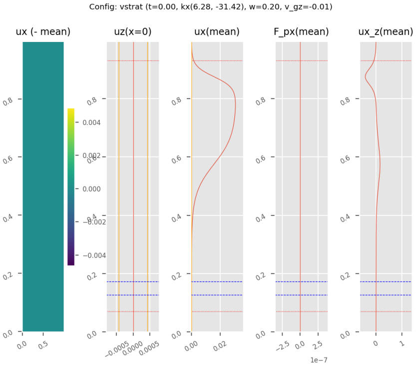


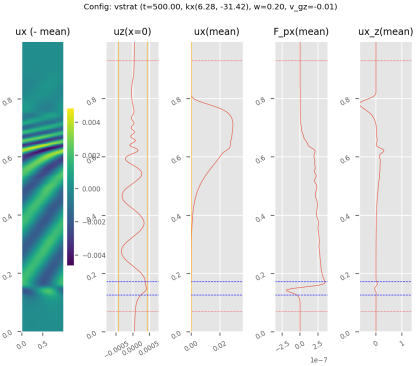
(b) $F_{p,x} = \langle \rho u_x u_z \rangle_x$.

Simulations

Local Boussinesq

- Go to Boussinesq, "zoom in." Use $\mathfrak{D} = \nabla^6$ regularization. Set up initial mean flow $\bar{U}_x(z)$ such that $\max_z \bar{U}_x(z) = \bar{U}_{x,c}$.
- Reflection indeed develops!

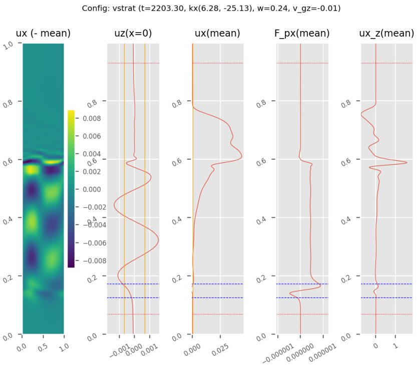


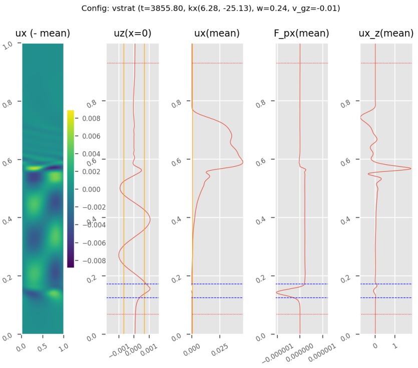


Simulations

Local Boussinesq

- Expect Kelvin-Helmholtz instability to develop; resolution-limit?
- Not viscosity-limited: $\nu^{(6)}\rho_0 \frac{\bar{U}_{x,c}}{d^6} \ll \frac{F_{p,x}}{d}$!

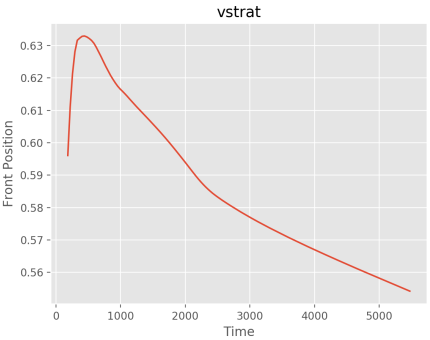




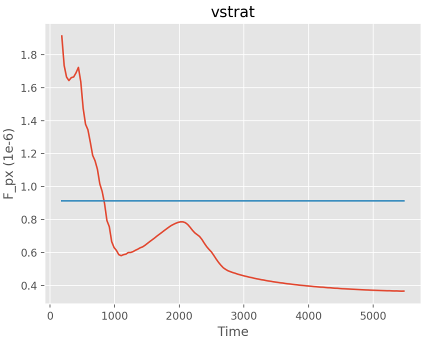
Simulations

Comparing u_{front}

- Same as for anelastic, but predicts $u_{front} \approx \frac{4.5\times 10^{-7}}{\rho_0 \bar{U}_{x,c}} \approx 1.4 \times 10^{-5} HN$ or $0.014H$ in $1000N$. $t \in [1000, 2000]$ accurate, $t \in [2000, 3000]$ less so.
- No front slowdown is expected since ρ_0 is constant in space, but is observed; could be explained by increasing reflectivity.



(a) Front Position. Slowing down.



(b) $F_{p,x}$.