The dynamical connection between hydraulic control and wave radiation aloft in stratified airflow over mountain ridges

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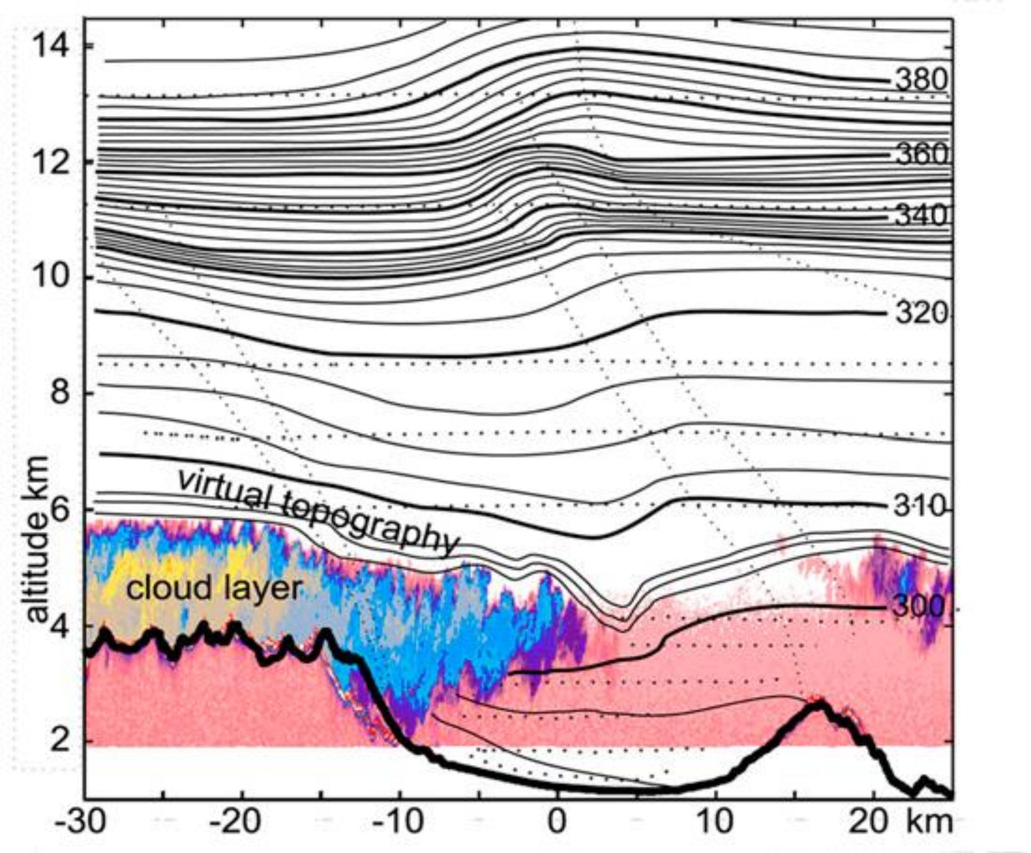
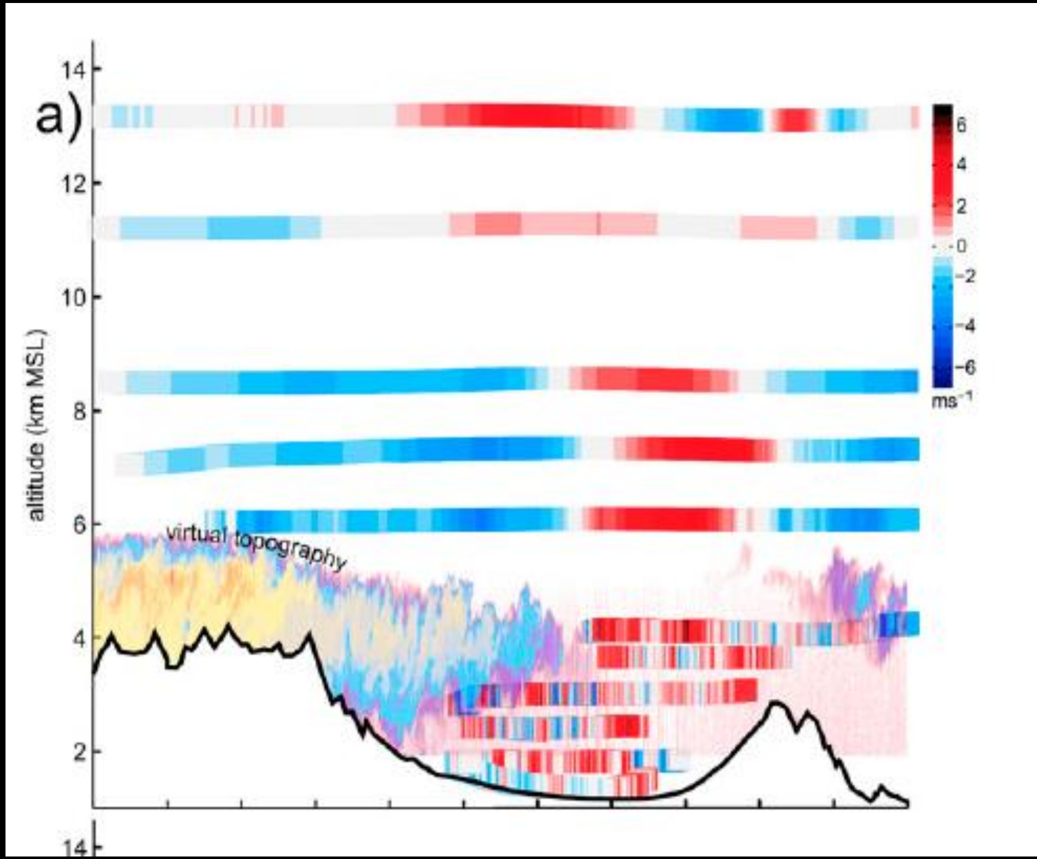
Armi and Mayr (JAMC, 2015) T-Rex March 2006

Vertical section of 14 March 2006 overflow across the Sierra Nevada



Potential temperature

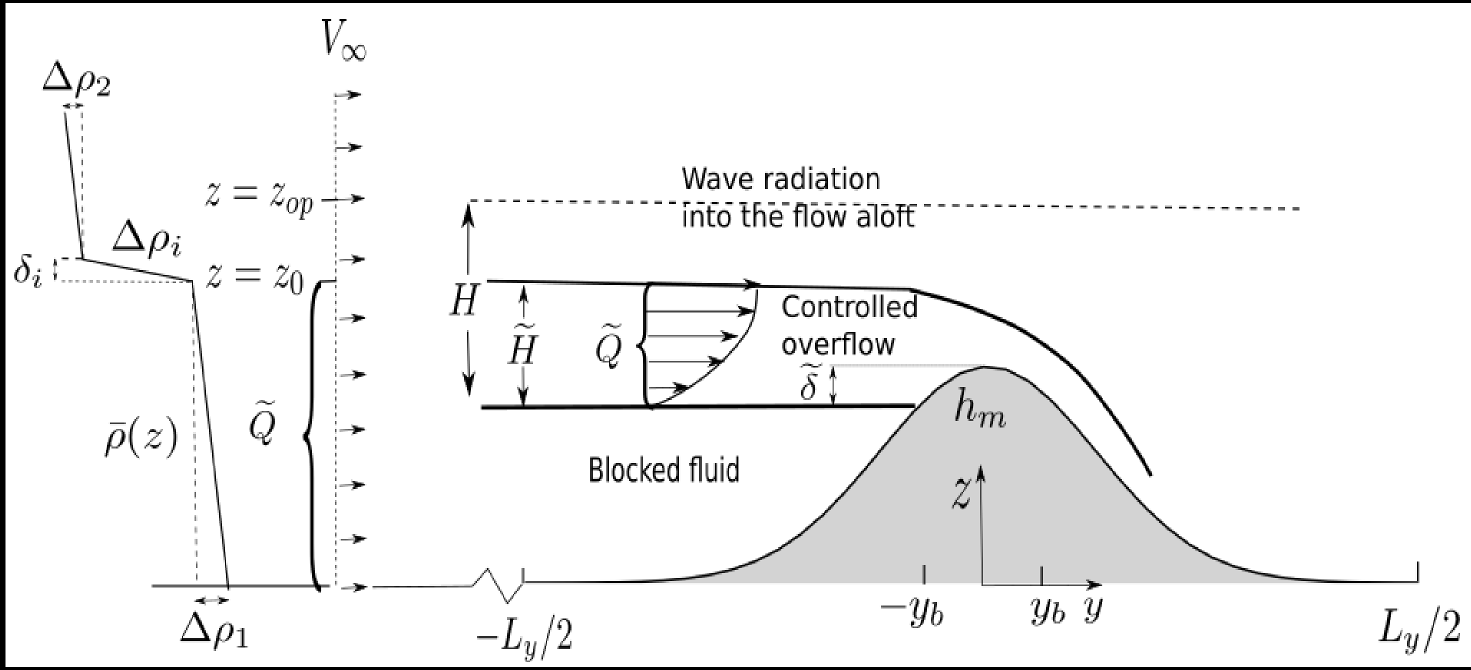


Vertical velocity

Motivation and goals

- Virtual topography effects in blocked flows capped by a density step (inversion layer) – sensitivity to vertical location of the density step.
- Explore dynamical connection between the hydraulic response of the overflow and wave excitation aloft.
- Practical consequences for form drag, wave energy density and fluxes aloft.

Experimental configuration



Topographic Froude number:

$$Fr = \frac{V_\infty}{N_0 h_m} \ll 1$$

$N_0 \equiv$ Stratification away from the step

$$N_{\delta_i}/N_0 \approx 8.6$$

- Hydraulic control, asymmetric across crest (e.g. Winters and Armi, JFM 2014)
- What about the density step?

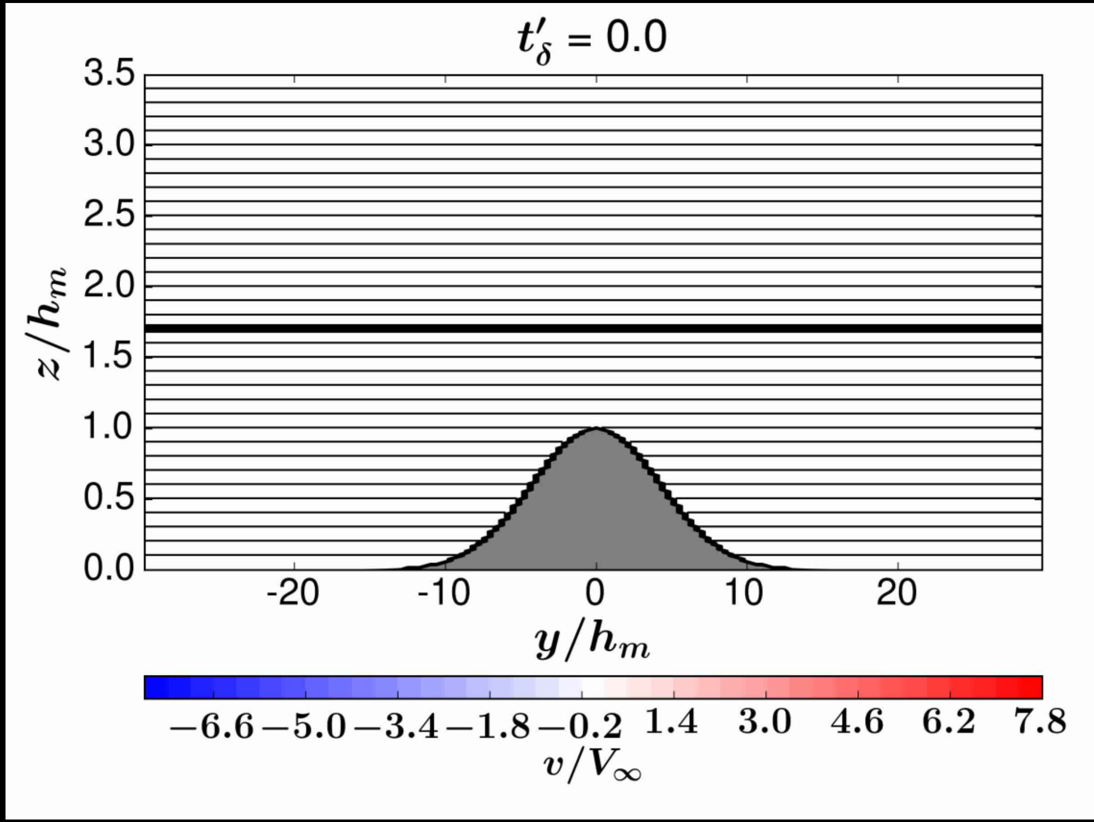
Numerical approach

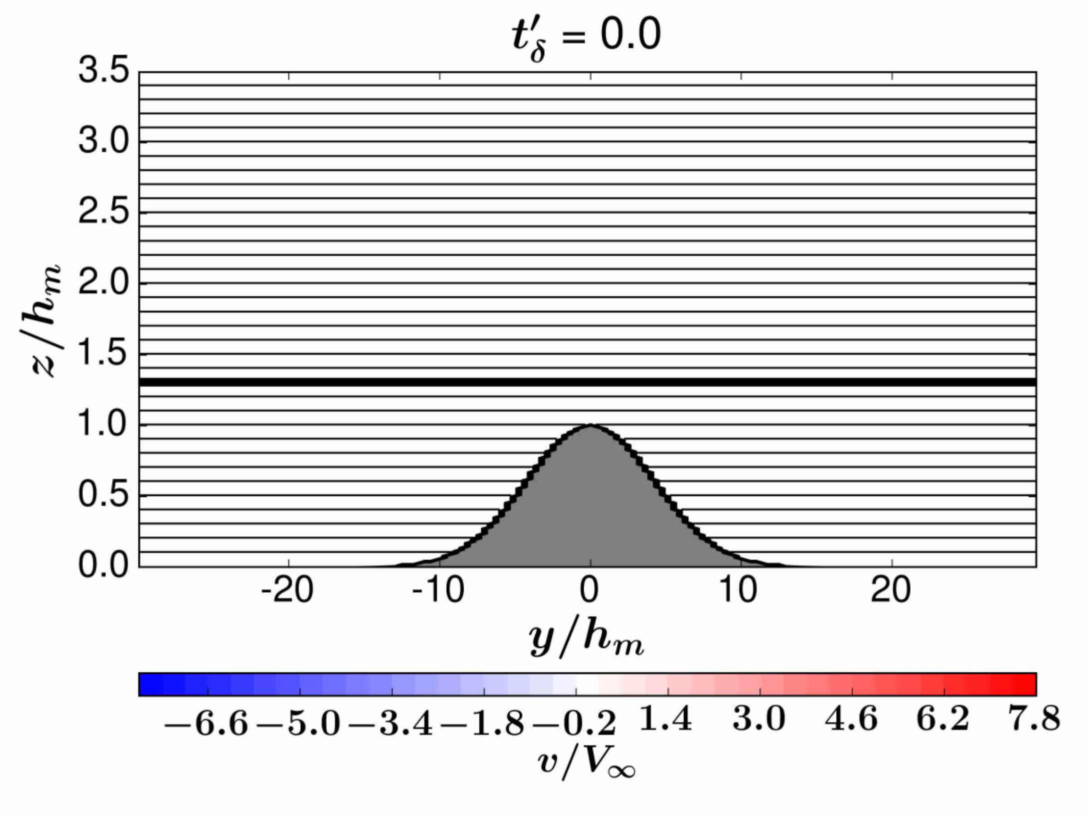
- Spectral Navier Stokes solver with Boussinesq approx., (Winters and De La Fuente, 2012)
- Immersed boundary formulation.
- Free slip at solid boundaries, sponge layers at top and sides.
- 6th order $(\partial^6/\partial x_i^6)$ hyperdiffusivity to dissipate sub-grid scale motions
- Nudging to minimize reflections of upstream propagating columnar modes:

The vertical location of the density interface has a dramatic effect on the wave dynamics aloft

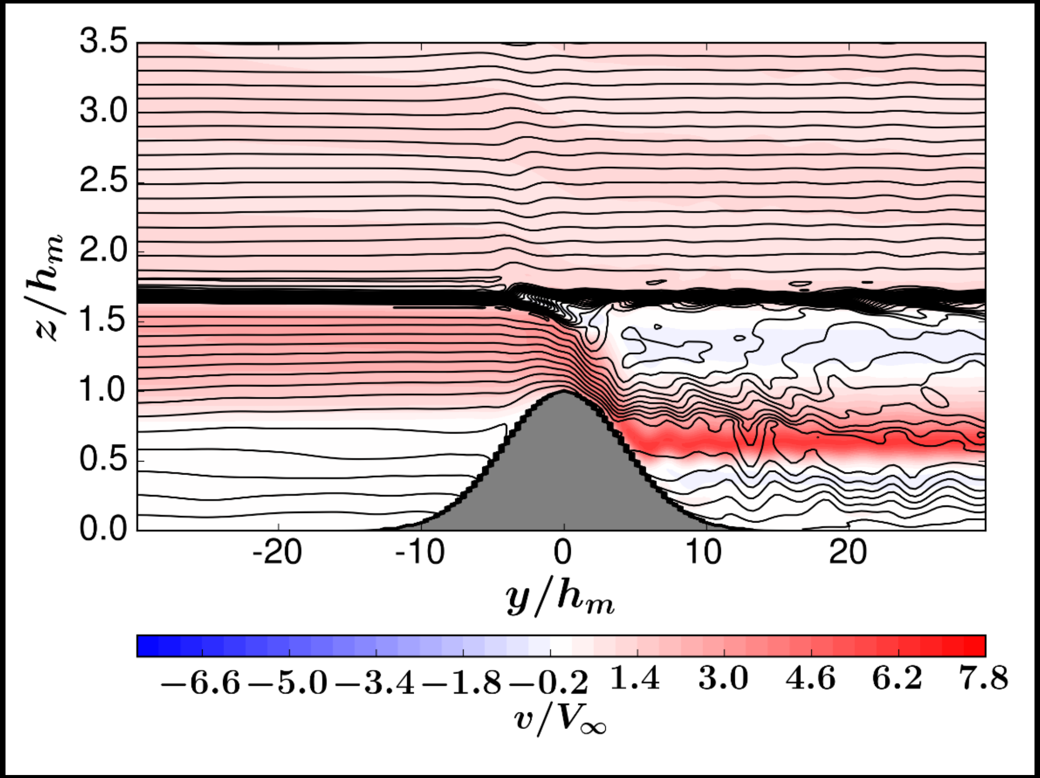
Flat interface $z_0 \approx 1.73h_m$

Plunging interface $z_0 \approx 1.33h_m$





Flat interface – weak perturbations aloft



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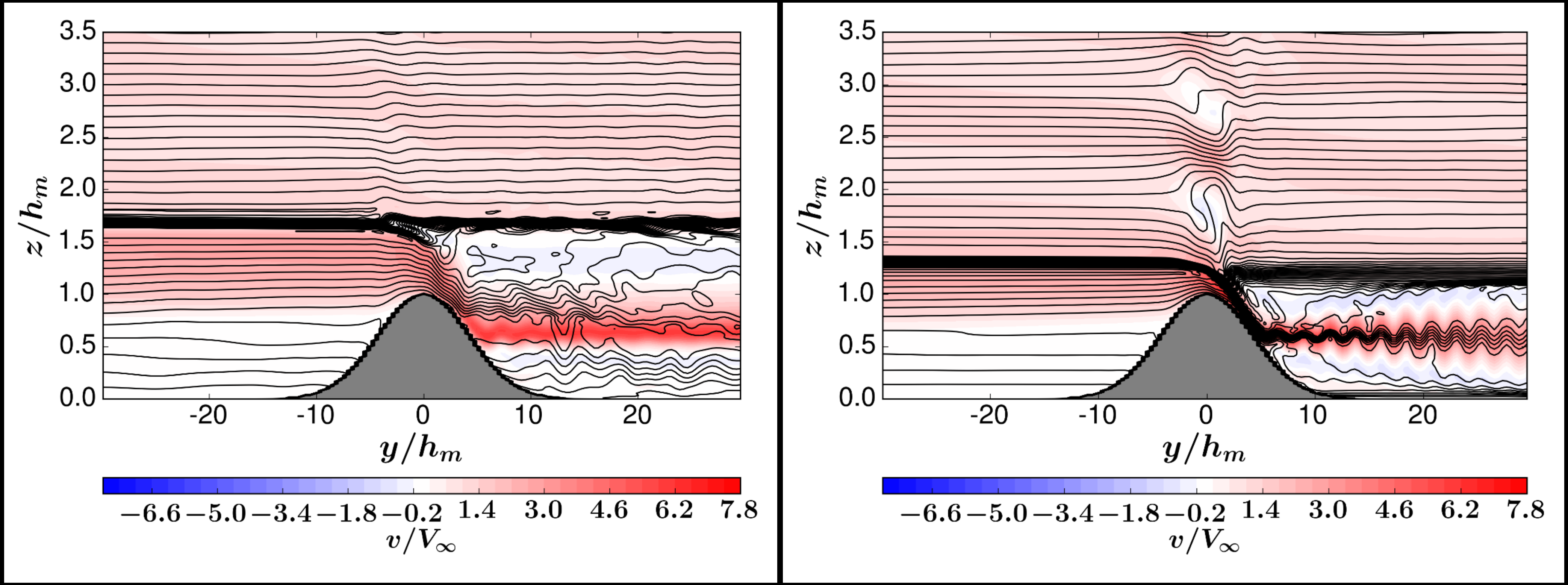
Plunging interface –energetic wave response aloft



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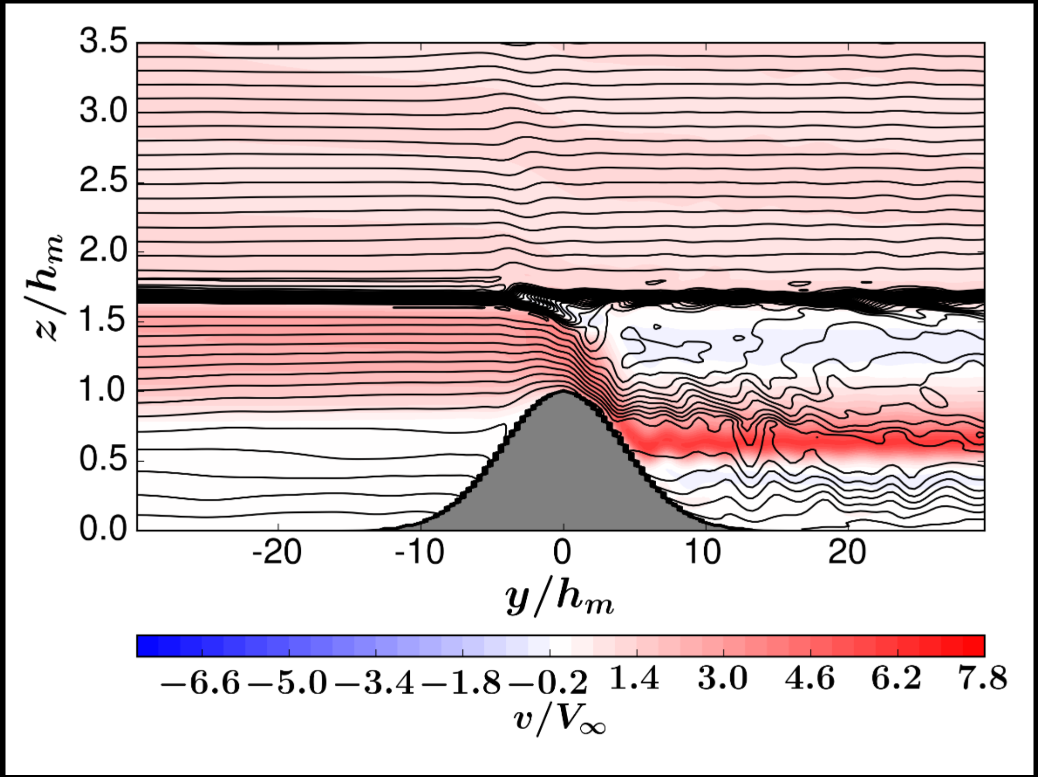

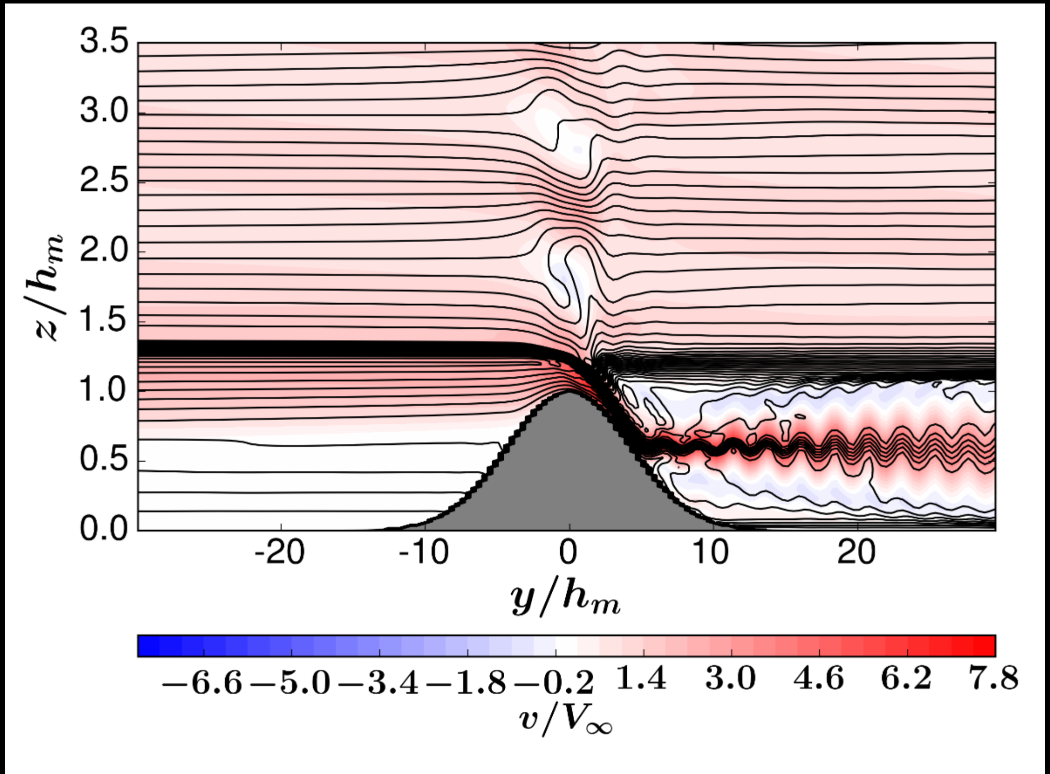

Density interface acts as ‘Virtual topography` for flow aloft

Case: $z_0 = 1.33h_m$ – why does the interface plunge

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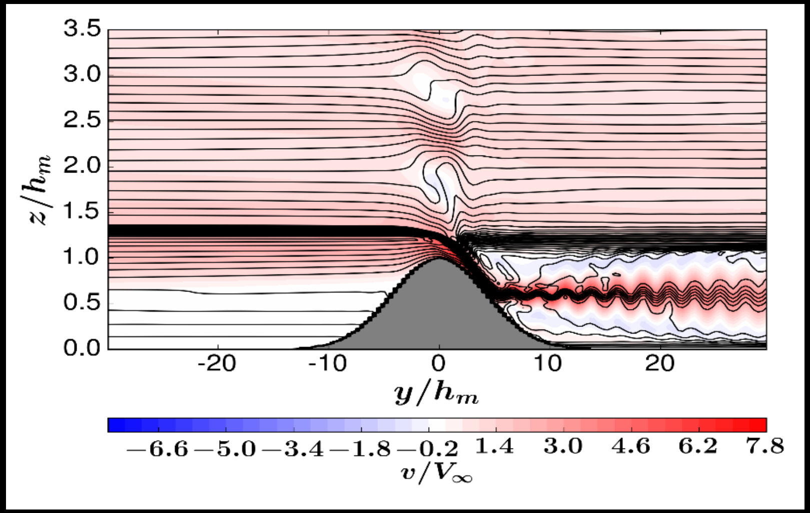

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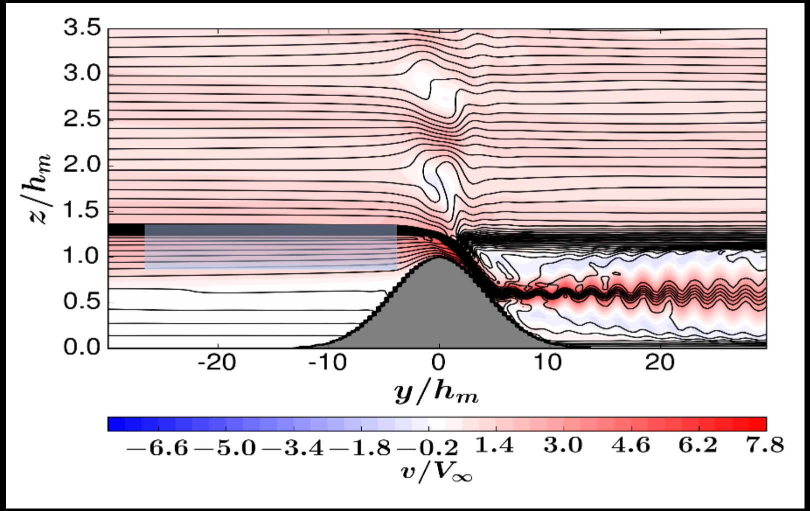
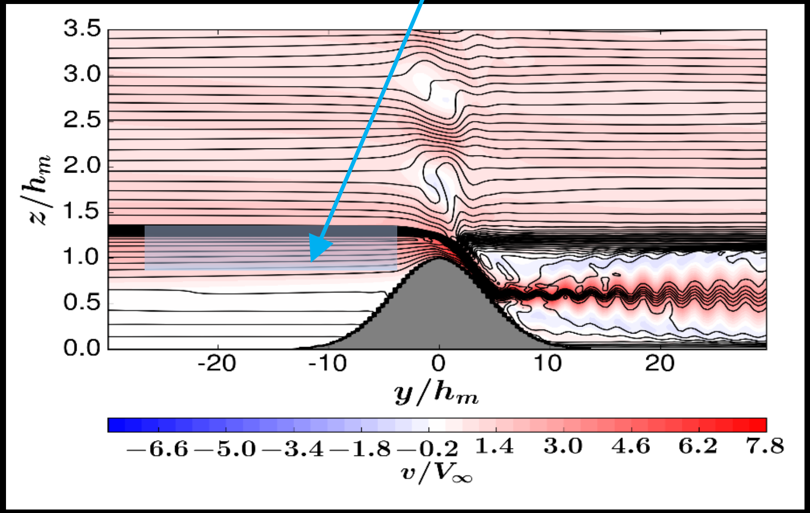


Case: $z_0 = 1.33h_m$ – why does the interface plunge

Across-crest asymmetry implies flow within upstream ‘wave-guide` must be subcritical and there is a transition to super-criticality across the crest



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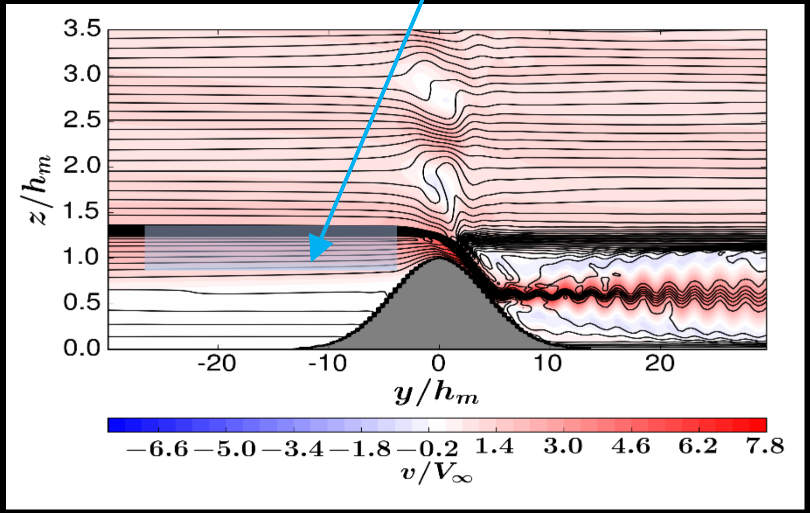

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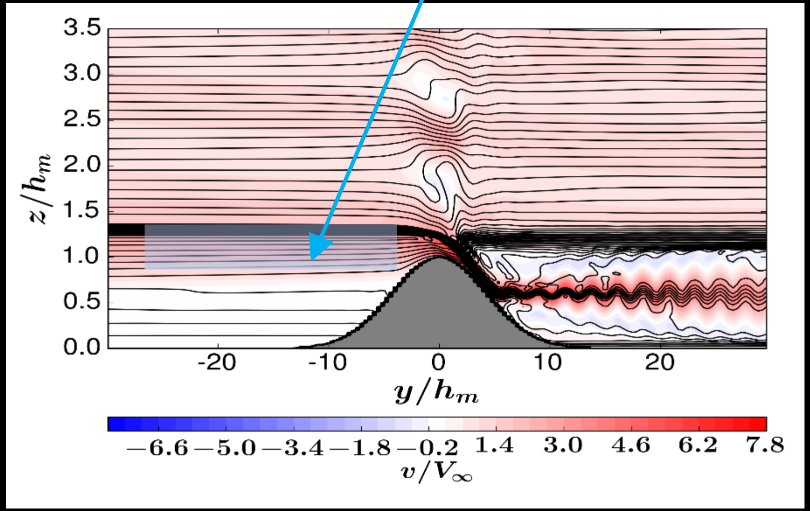

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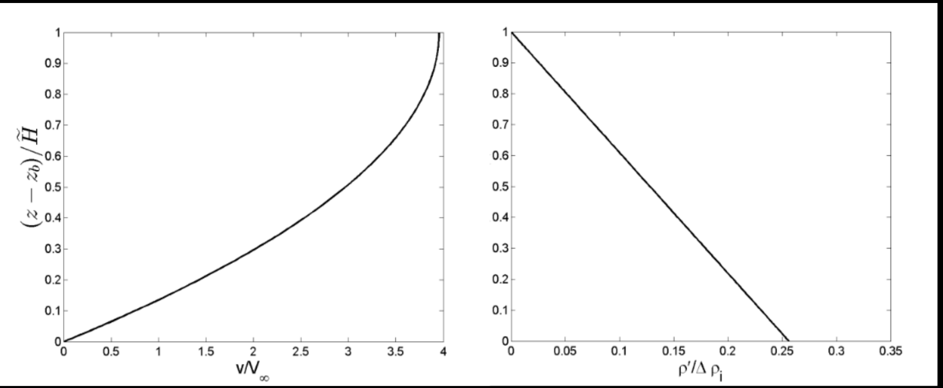
Exclude density interface



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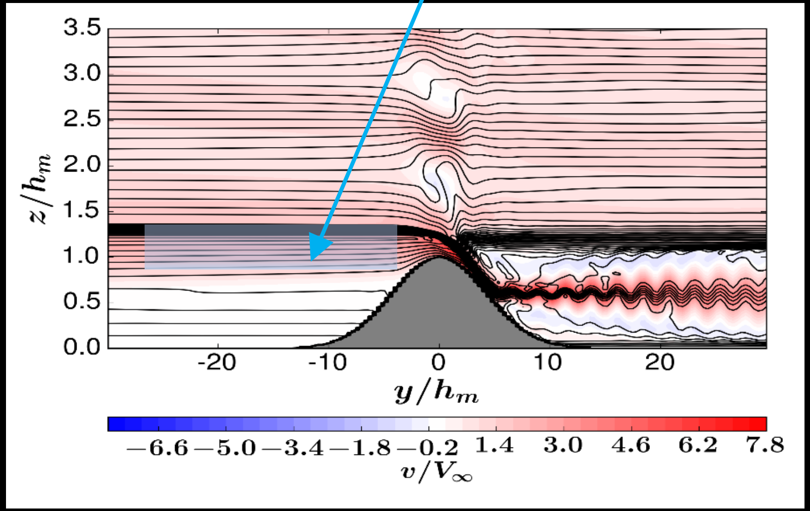

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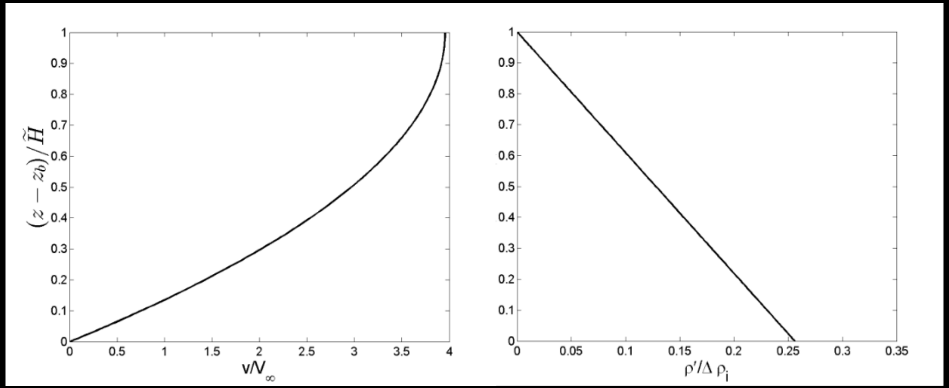

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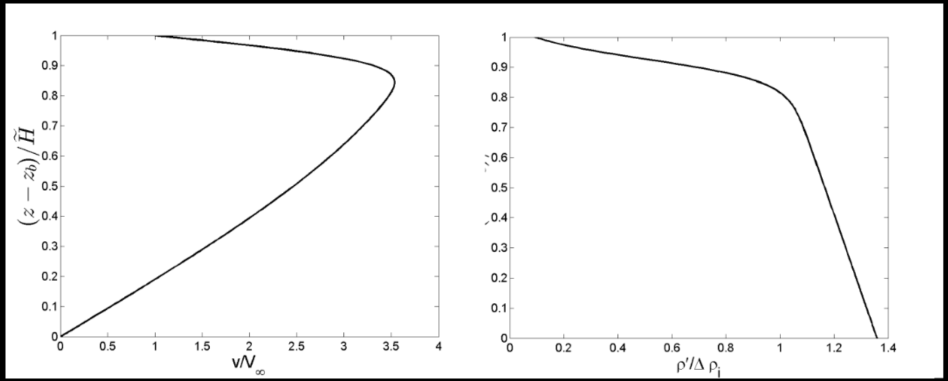
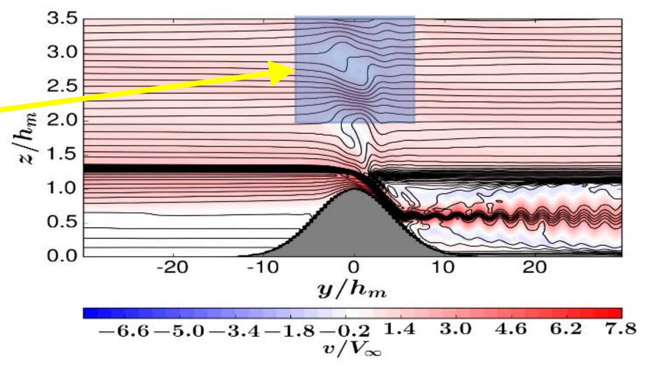
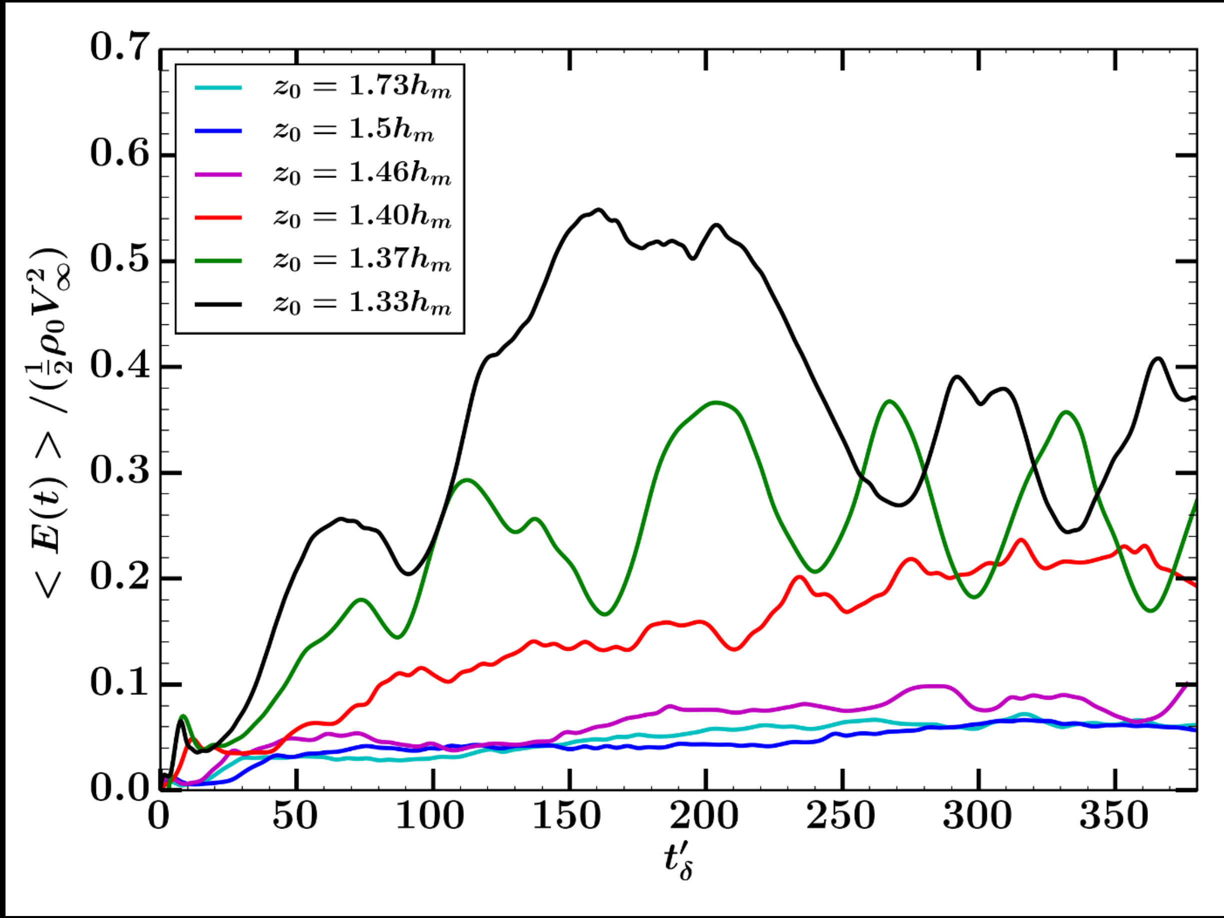


Supports upstream propagating long wave with $c \approx -0.2\ V_\infty$!

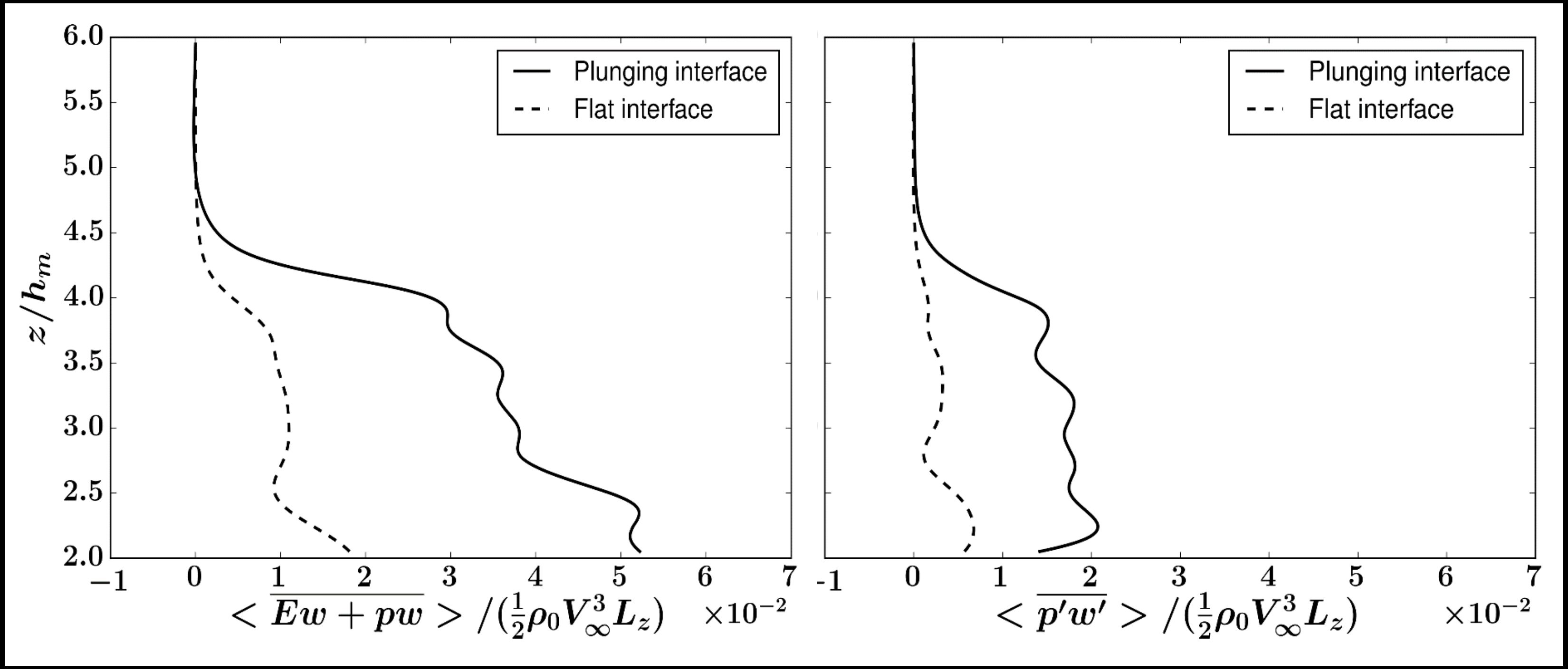
Wave energy density aloft





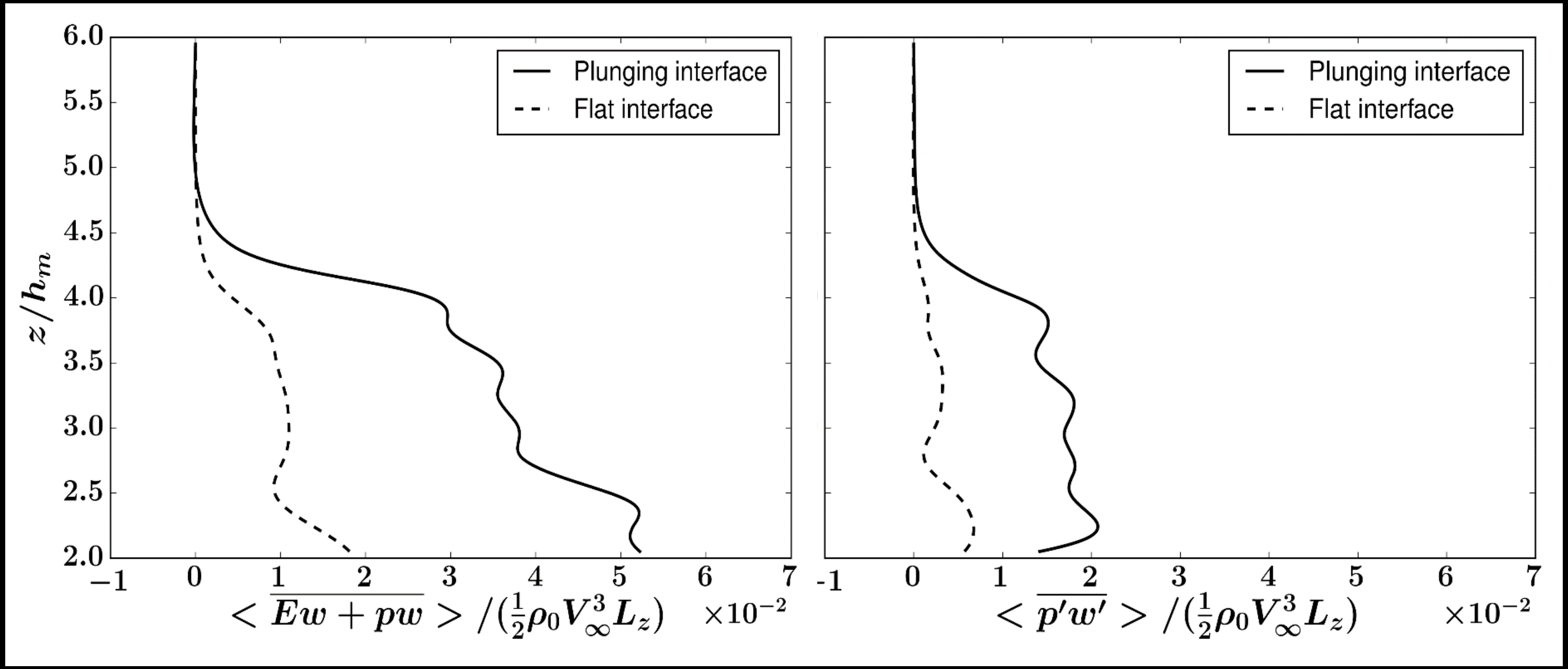
About 6 times larger WED when the interface plunges!

Vertical energy flux



Total non-linear flux (time mean) Eddying pressure work component

Vertical energy flux



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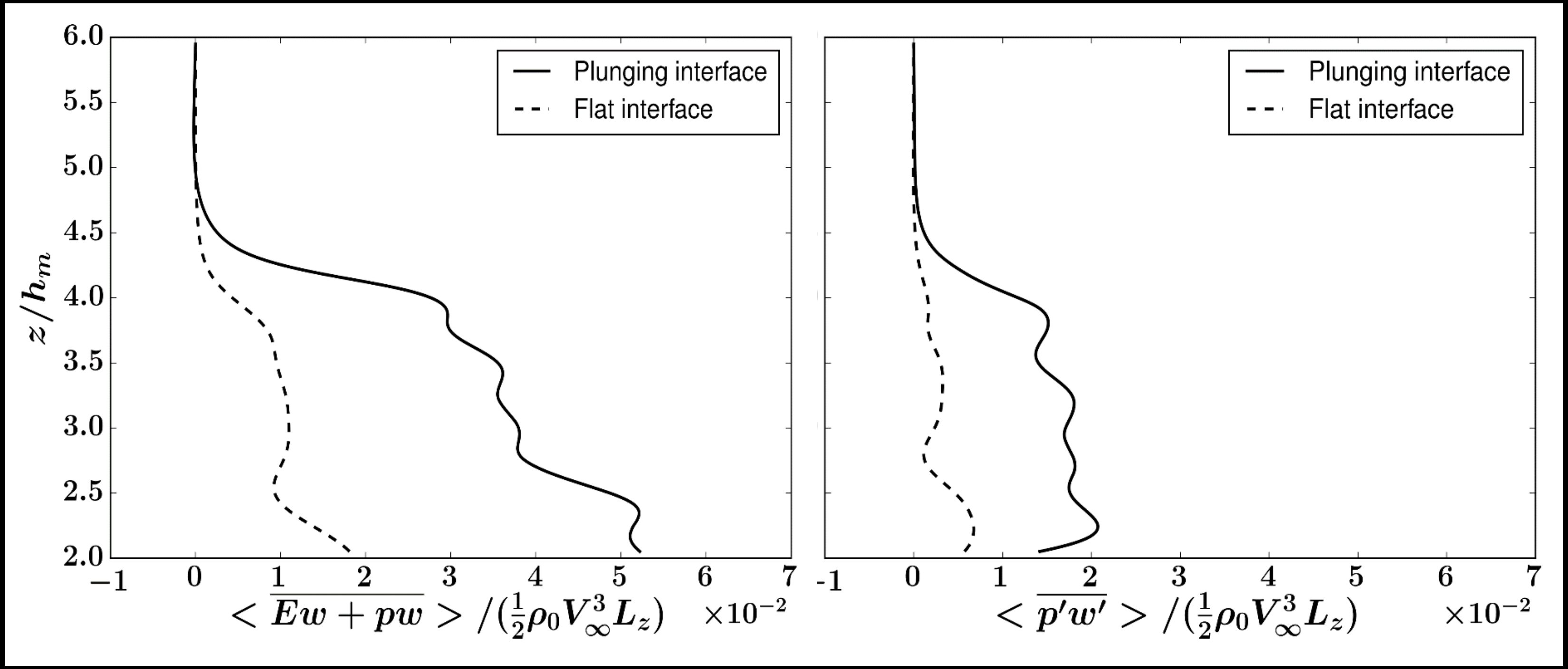

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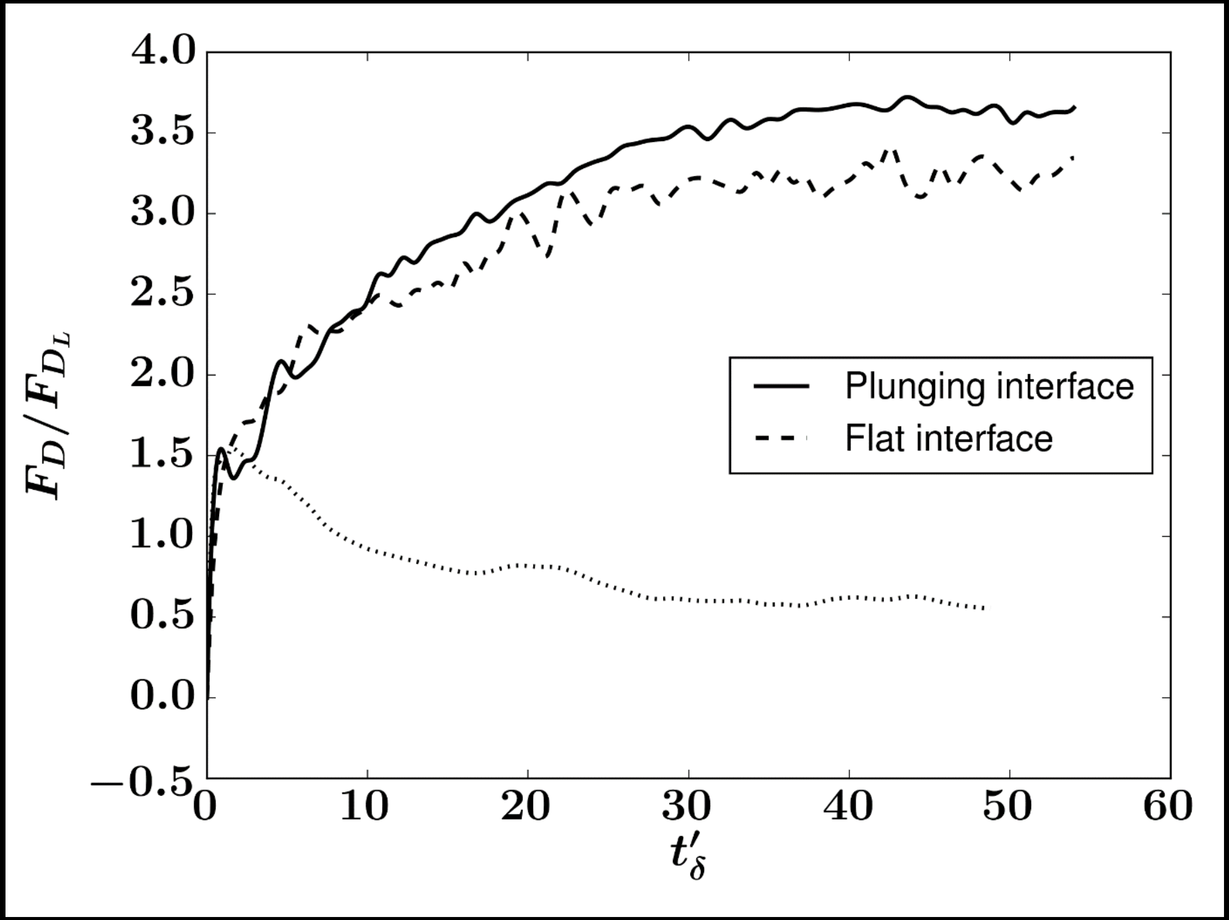
In general, the relative amplification of the wave response will depend on the stratification ratio N_{δ_i}/N_0 ($\approx$ 8.6 in our experiments)

Normalized form drag



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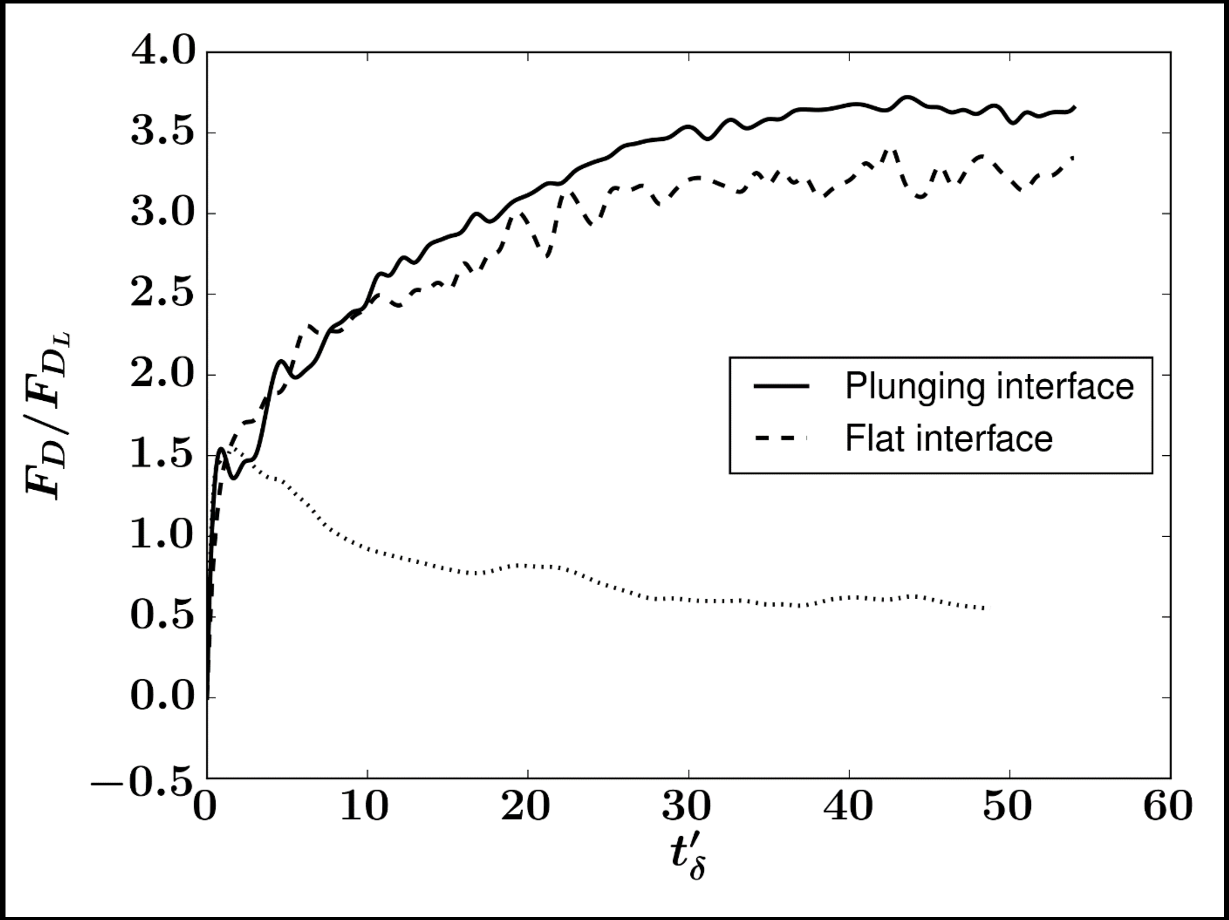

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- 20% higher form drag

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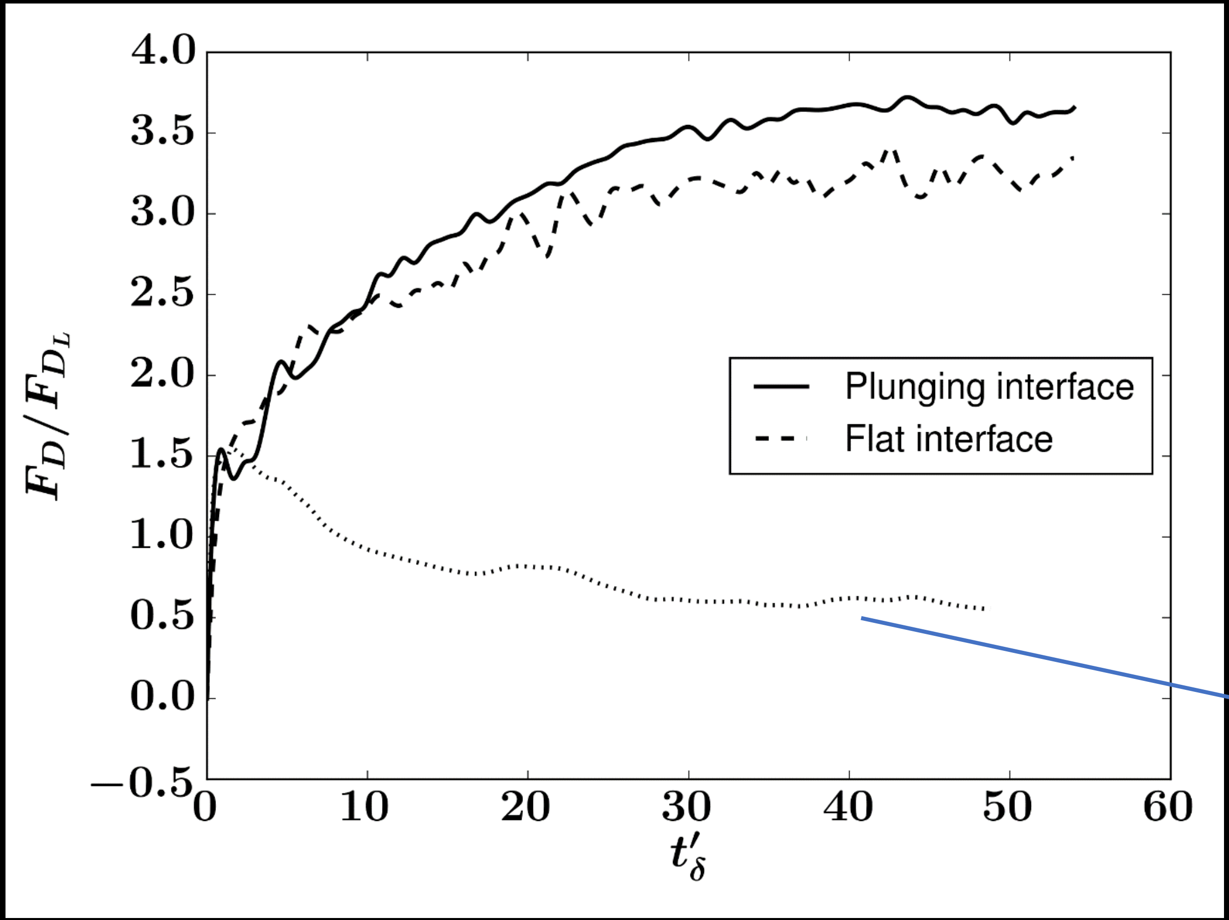

- Plunging interface produces a further drop in hydrostatic pressure in the lee.
- 20% higher form drag

- Long 3D ridge – The drag force initially rises as the hydraulically controlled overflow develops, but falls off as the flow starts splitting ‘around’ (JAS, 2019)

Summary

- The wave response aloft depends sensitively on the vertical location of the density step.
- The question of whether or not the density step plunges across the crest is fundamentally connected to the hydraulic dynamics.
- A plunging density interface increases the form drag and produces a significantly more energetic wave field aloft.

References

- Jagannathan, Arjun, Kraig Winters, and Laurence Armi. "The effect of a strong density step on blocked stratified flow over topography." *Journal of Fluid Mechanics* 889 (2020).
- Jagannathan, Arjun, Kraig Winters, and Laurence Armi. "Stratified flows over and around long dynamically tall mountain ridges." *Journal of the Atmospheric Sciences* 76.5 (2019): 1265-1287.

Thank you!

QA time: 11 AM MT, Tuesday, July 14,

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