BOUNDARY LAYER INFLUENCE ON TRAPPED LEE WAVES

Ivana Stiperski

DHMZ

ivana.stiperski@cirus.dhz.hr

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1.5-day Mini-Workshop on ABL, Zagreb,
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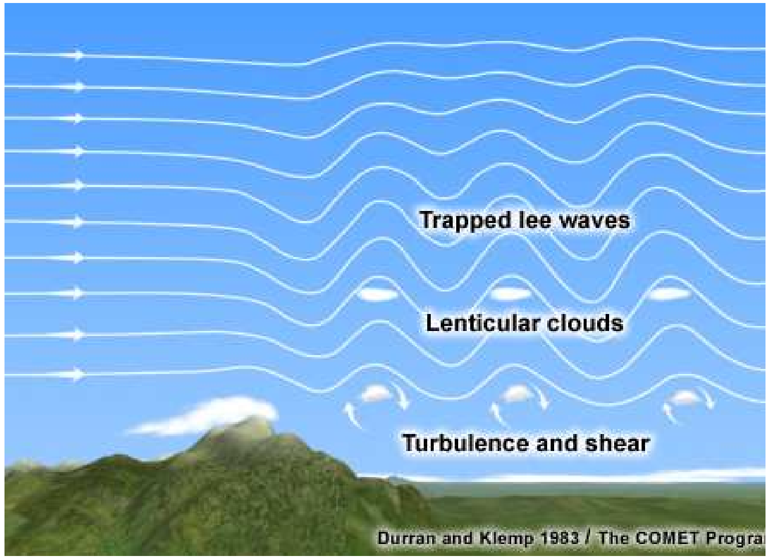
TRAPPED LEE WAVES



Scorer (49') was the first to set the theory

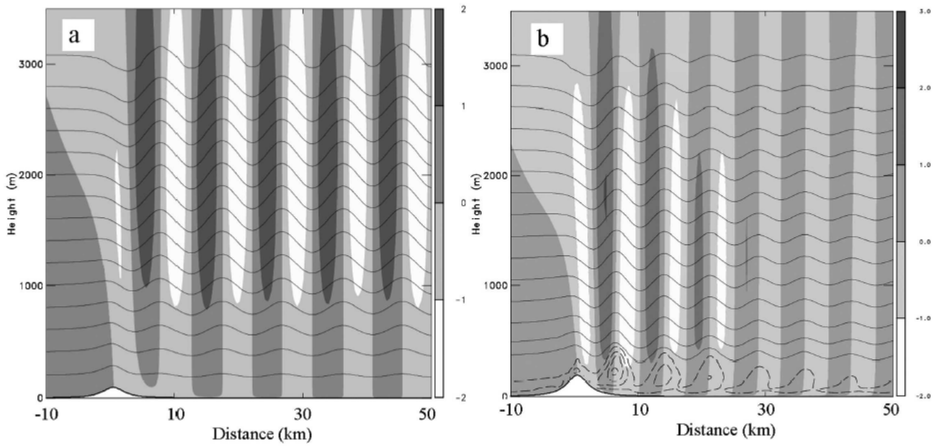
When Scorer parameter $l^2(z)$ decreases sharply with height

$$l^2 = \frac{N^2}{U^2} - \frac{1}{U}\frac{\partial^2 U}{\partial z^2}$$

→Increase of horizontal windspeed with height or/and
→Decrease of potential temperature with height

Non-hydrostatic standing waves
→ Superposition of vertically propagating and reflected wave
→ Vertical phase lines
→ Amplitude is evanescent
→ Energy propagates in the horizontal
→ Extend far downstream with no surface friction

ABL EFFECTS



Upstream phase shift of the wind in the BL compared to free atmos. :
→ Modulates flow divergence
→ Absorbs incident wave + advances phase of reflected wave
= **exponential decay**
(Smith et al. 06'; linear model)

Shortening the wavelength, decrease of wave amplitude (Smith et al. 06')

Wave absorption (Jiang et al. 06')**:**

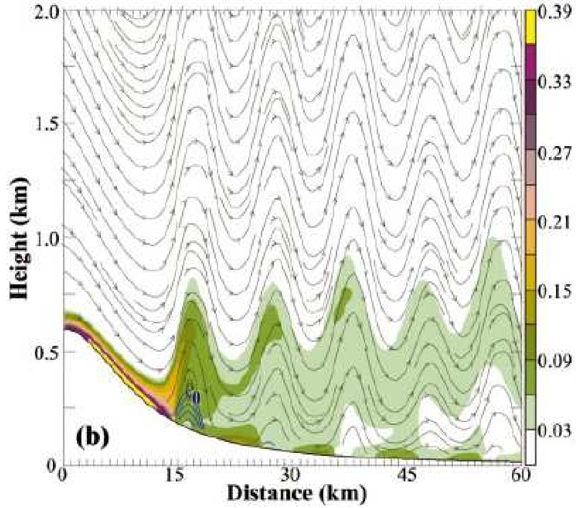
Decay depends on surface roughness and heat flux

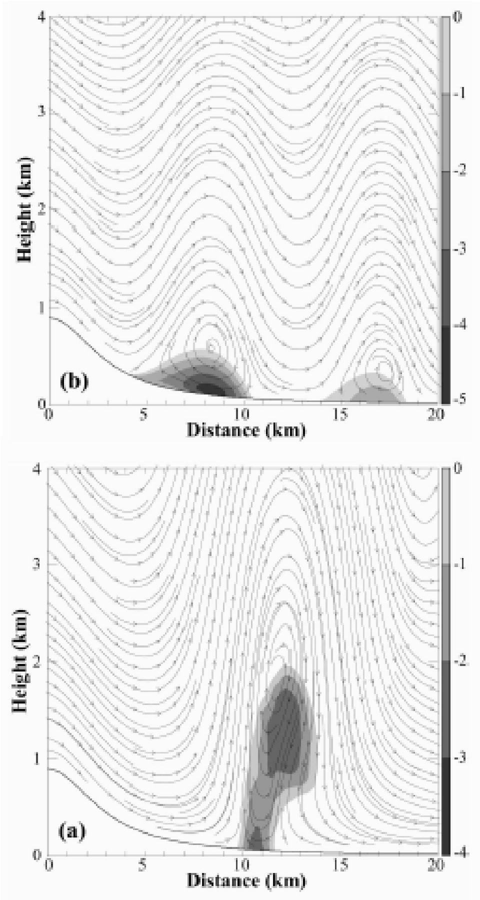
→ stronger for rougher surfaces and surface cooling = nocturnal stable BL more effective in absorbing waves

→ stagnant layer shows strongest attenuation (especially in mountain valleys)

BOUNDARY LAYER SEPARATION

ABL thickens and lifts of the surface
Highly turbulent recirculating regions
→ **rotors** underneath the wave crests

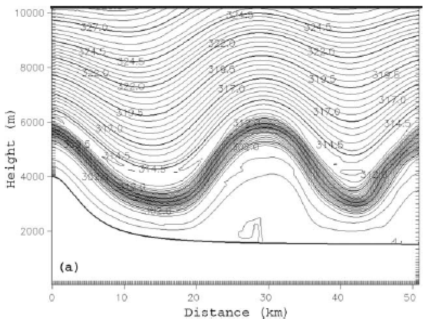


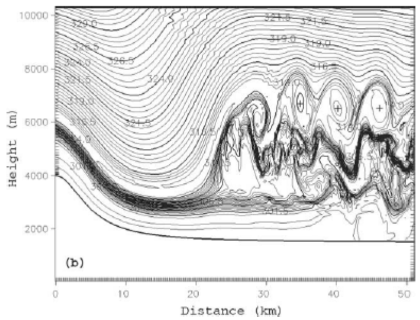


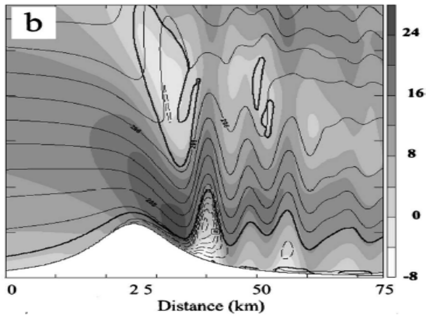
Adverse wave induced pressure gradients + **ABL** surface drag produce realistic rotors (Doyle & Durran 02’; Vosper et al. 06’)
→ positive horiz. vorticity the same sign as in ABL

Transient rotors can develop also in **free slip**
→ negative horiz. vorticity produced by waves

ROTORS







Two types rotors (Hertenstein & Kuettner 05’): trapped waves & hydraulic jump.

Additionally: undular hydraulic jumps (Jiang et al. 07’)

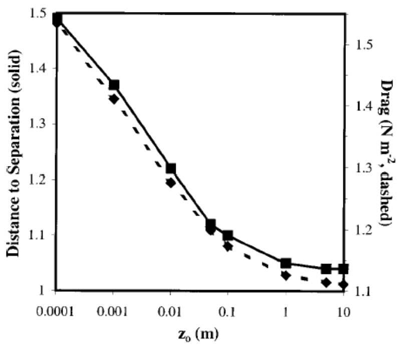
Strong **coupling** between overlying trapped waves and underlying ABL (Doyle & Durran 02’):

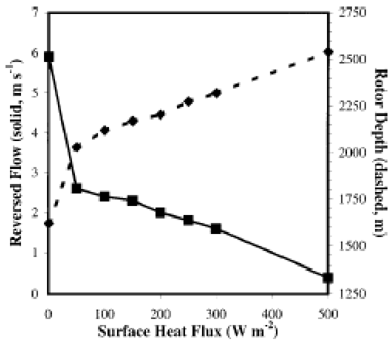
Sensitivity to **surface friction**

→ increase: decrease in rotor strength

Sensitivity to **surface heat flux**

→ positive: increase in depth and turbulence but decrease in strength

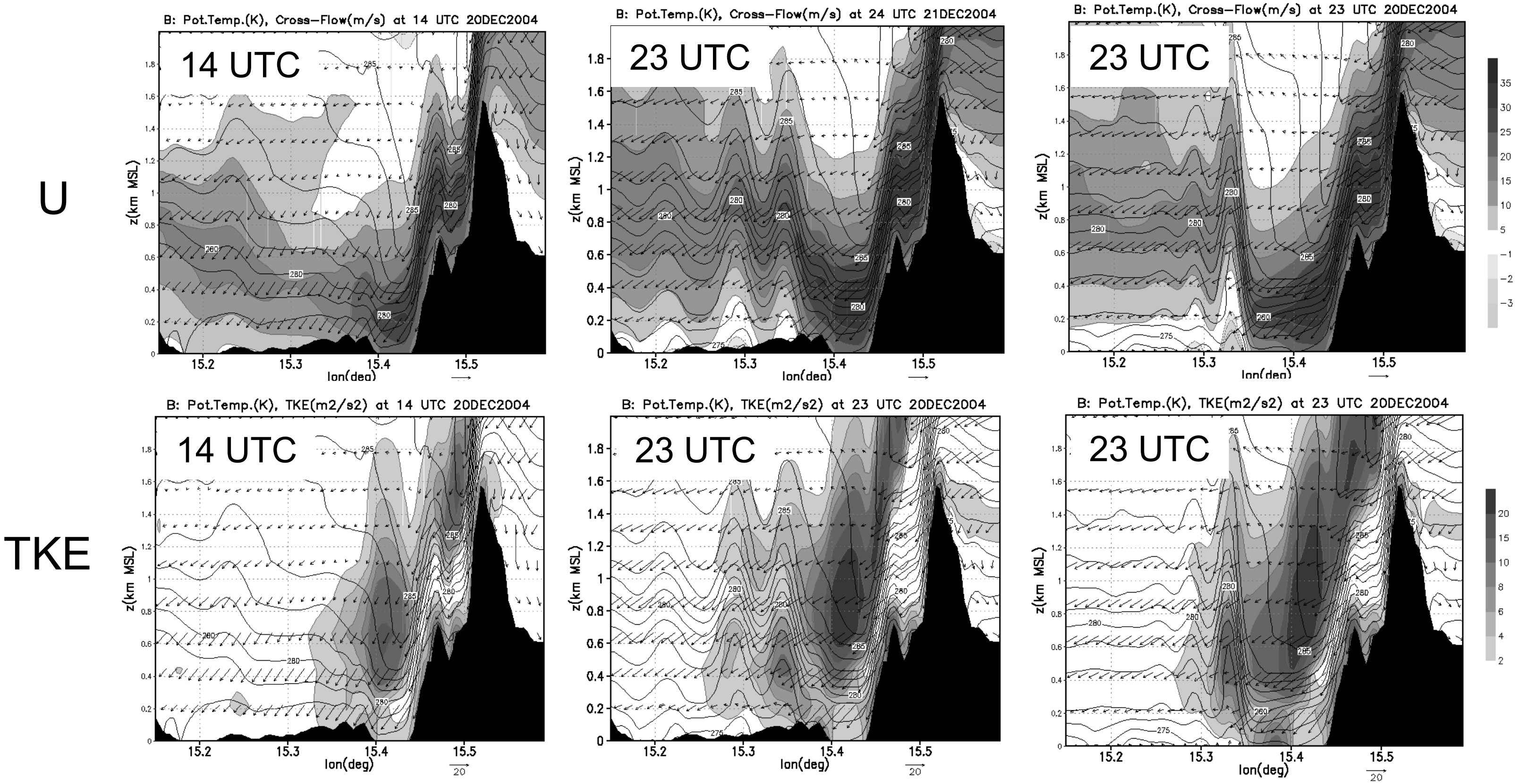




BORA ROTORS

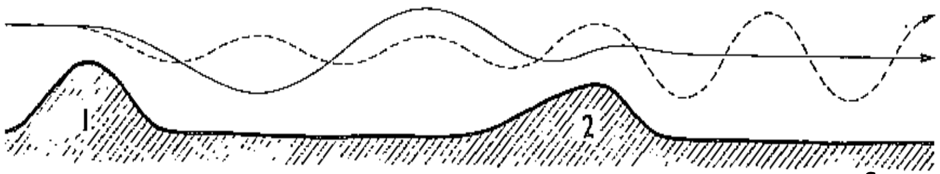
Mostly associated with trapped waves

Belušić et al.(07’);Grubišić & Orlić (07’);Gohm & Mayr (08’);Prtenjak &Belušić (09’)



In the lee of Southern Velebit: undular hydraulic jump rotor (Stiperski et al. 10’)
Dependent on the evolution of the underlying ABL (night time) and roughness

TRAPPED LEE WAVES OVER DOUBLE MOUNTAINS

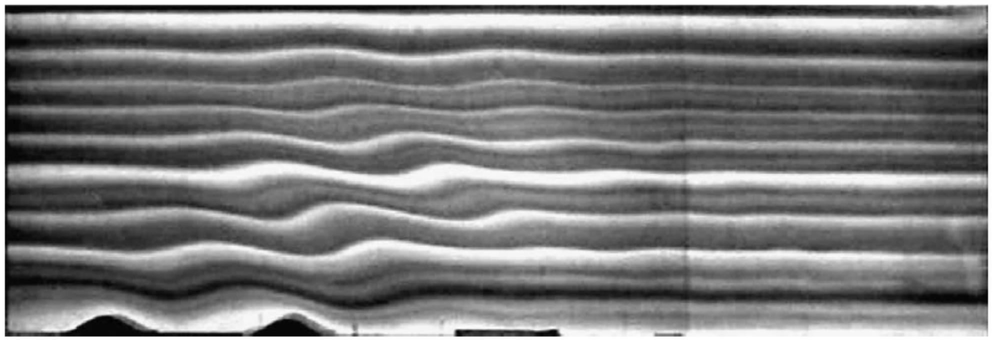


Scorer 97’

LINEAR **INTERFERENCE** THEORY (e.g. Scorer 97’)

Constructive (A2=2*A1) & destructive (A2=0) interference

determined by the ratio of valley width V to intrinsic lee wave wavelength λs



NONLINEARITY & T-REX
(Gyüre & Jànosi 03’; Grubišić & Stiperski 09’)
→ No doubling or cancellation
→ Wavelength change

NUMERICAL SIMULATIONS

→ **MODEL**: NRL COAMPS

Compressible, non-hydrostatic, 2D, irrotational

→ **RESOLUTION**

ABL: dz= 30 -100m, dx=400m

→ **LOWER BC**:

1. FREE SLIP (fS)

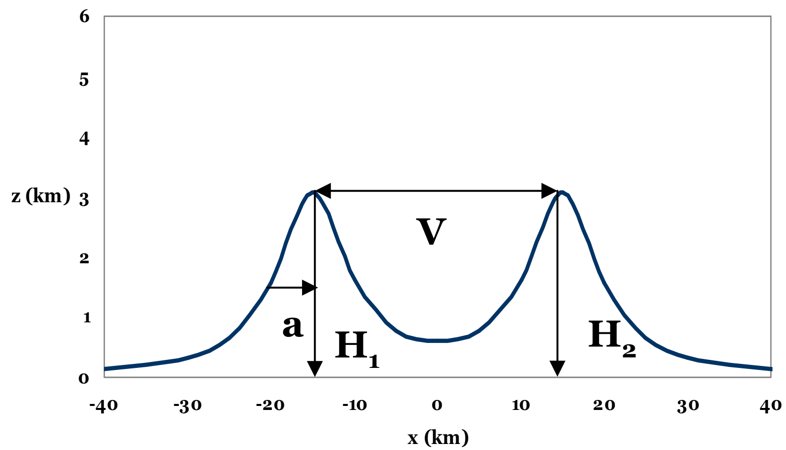
2. NO SLIP (nS)

Surface roughness zo = 0.1 m

TKE 1.5: Mellor Yamada (82')

Vertical fluxes of horizontal momentum (Louis 79'; Louis et al. 82')

Heat & moisture fluxes = 0



→ **OROGRAPHY**

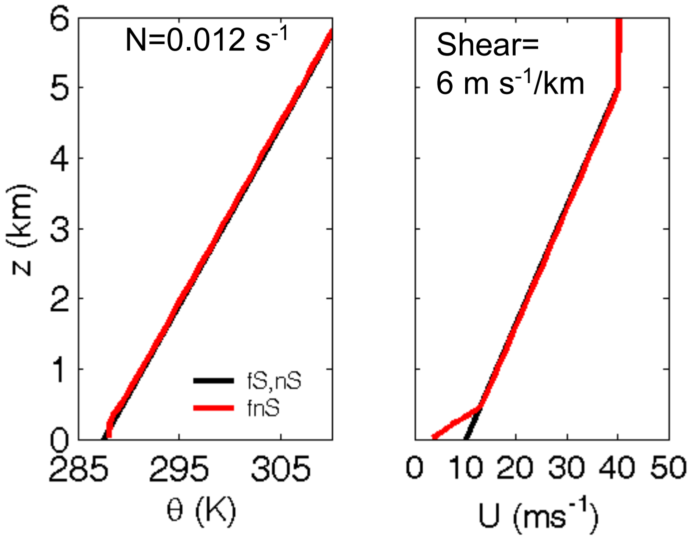
$$h(x) = \frac{H_1 \cdot a^2}{(x+V/2)^2 + a^2} + \frac{H_2 \cdot a^2}{(x-V/2)^2 + a^2}$$

H1= H2 =300-1500 m

V = 30 – 65 km

a = 5 km

NUMERICAL SIMULATIONS



3 SETS OF SIMULATIONS

fS – free slip BC

fnS – free slip BC but profile modified by ABL

nS – no slip BC but profile like in fS

Intrinsic horizontal wavelength (λs)

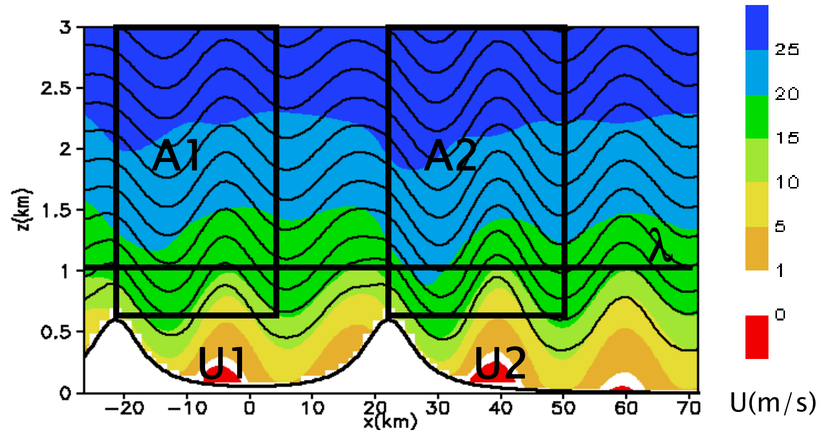
=in the lee of a single mountain

Wave drag (D)

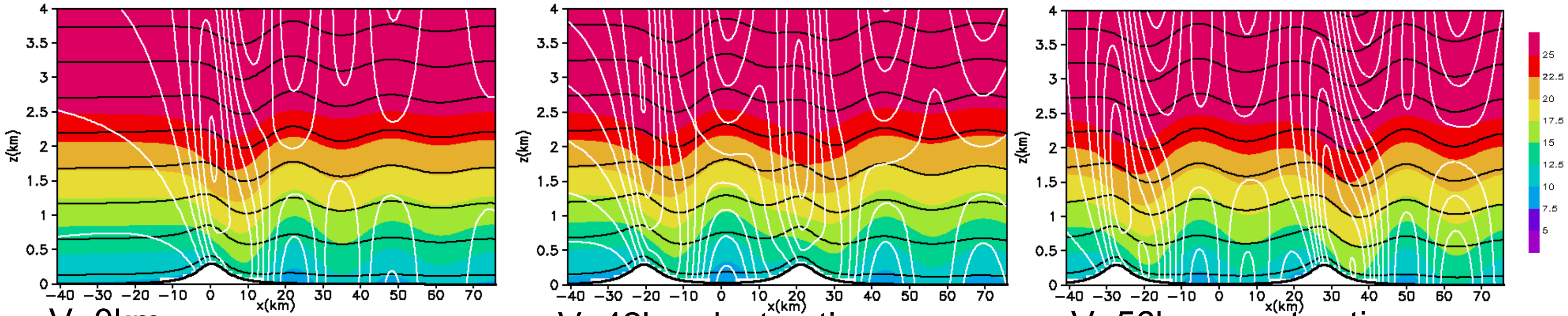
Amplitude (**A1** & **A2**)

Minimal horizontal wind speed (Umin)

→Averaged over stationary period



TRAPPED LEE WAVE INTERFERENCE

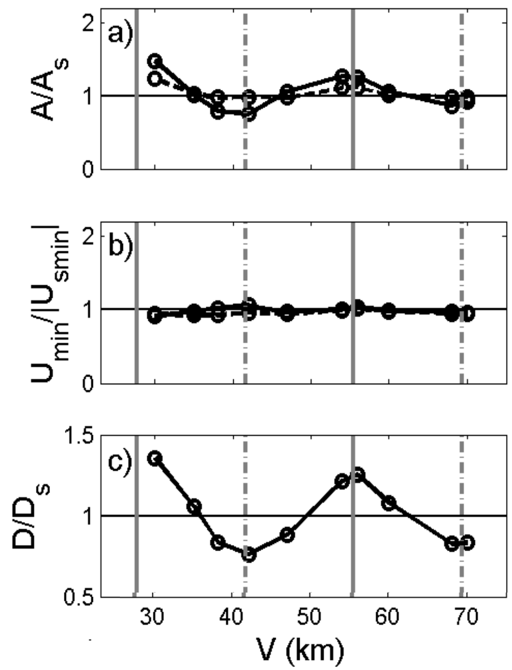


V=0km V=42km-destructive V=56km-constructive

Flow in the valley doesn't feel 2nd mountain (Lee et al. 87')

Free slip (fS) interference evident in A2 and D
No interference in U2min

Linear theory
→ correct for wavelength:
Constructive n*λs λs=28 km
Destructive (2n-1)/2 *λs
→ incorrect for amplitude: A2≠0; 2*As



SURFACE FRICTION & INTERFERENCE

In fS, fnS & nS simulations:

→ Linear prediction for interference holds

→ Amplitude oscillations: std(A2/As) the same

In fnS and nS simulations:

→ Change in intrinsic wavelength λs (A2)

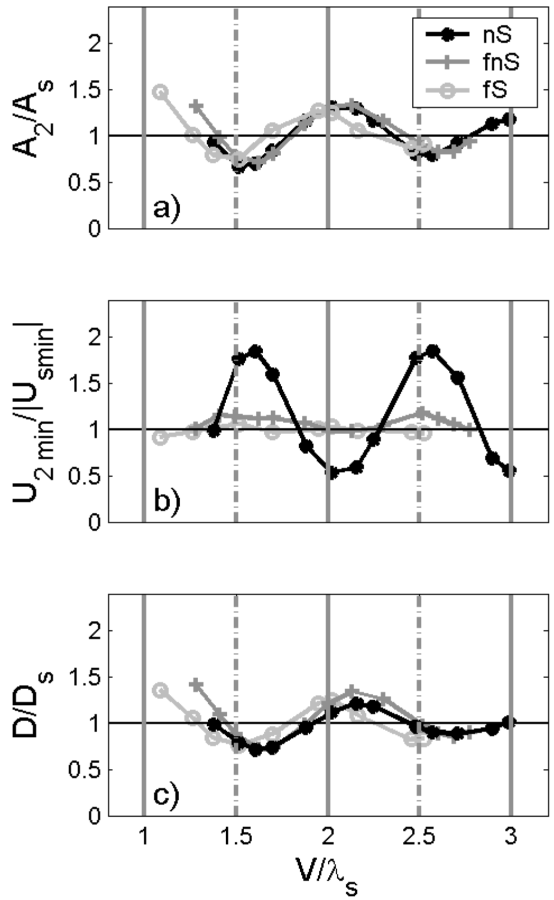
→ Alternative intrinsic wavelength for surface pressure (D)

= Decoupling of interference evident in A2 and D

In nS simulations:

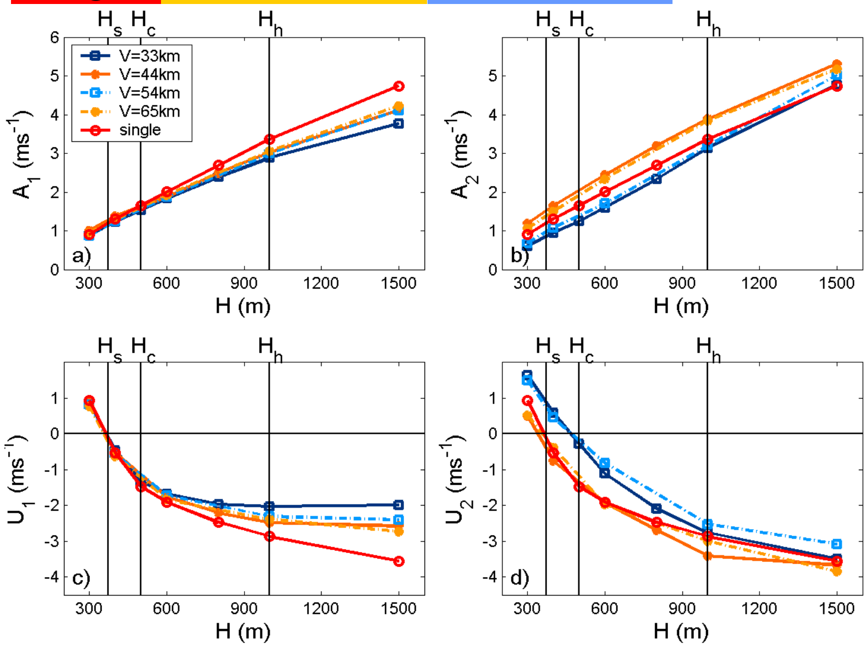
→ The interference in the BL evident in U2min develops

→ Coupling between A2 and U2min



NONLINEARITY

single constructive destructive



1. WEAKLY NONLINEAR (370m<H<500m)

→Rotors in the valley and for constructive interference

→For destructive interference flow is linear (no rotors)

→Critical mountain for rotors under constructive int. same as for single

2. MODERATELY NONLINEAR (500m<H<1000m)

→Flow in the valley weaker than for single mountain

→Rotors form under destructive int.

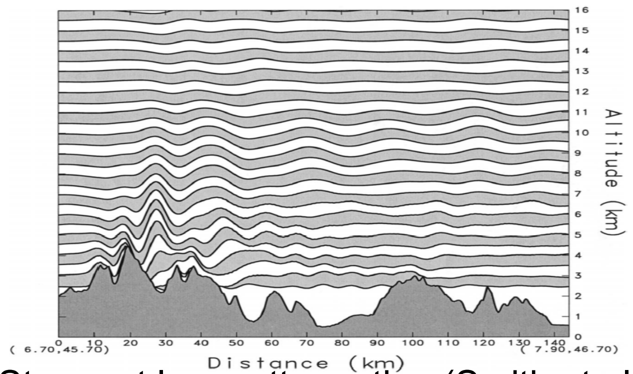
→Rotors under constructive int. only as strong as for single mountain

3. HIGHLY NONLINEAR (H>1000m)

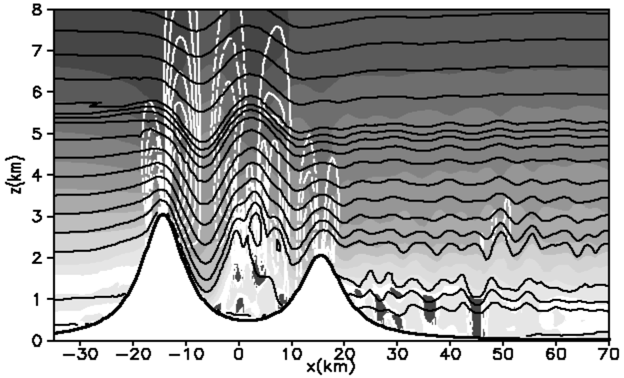
→ Rotors within the valley have constant strength

→ In the lee of second peak stronger than for single mountain

ABL ATTENUATION vs. COMPLETE DESTRUCTIVE INTERFERENCE



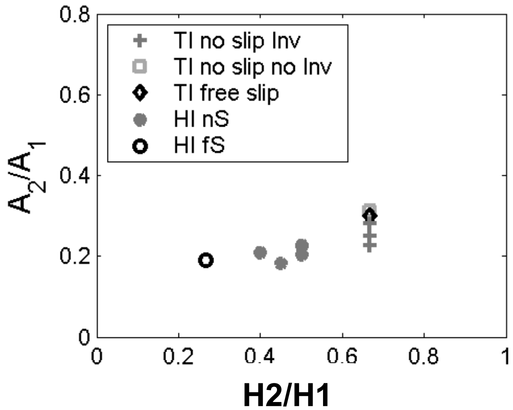
Stagnant layer attenuation (Smith et al. 02')



"Complete" destructive interference

Waves **almost completely** cancel out in the lee of second peak for specific critical H2<H1
This occurs **irrespective** of surface friction

The amount of amplitude reduction is the **same** (~80%)
Rotors are more attenuated for lower mountains



CONCLUSIONS

INFLUENCE OF ABL ON TRAPPED WAVES:

→upstream phase shift of the BL wind
→exponential decay of trapped waves downstream
→reduction in wavelength and wave amplitude
Stronger friction: more wave attenuation, weaker rotors
Positive heat flux: less wave attenuation, weaker rotors extending higher

INFLUENCE OF ABL ON WAVE INTERFERENCE:

→ resonant wavelengths agree with linear theory

$2n*\lambda s$ n=2,3,4,… constructive
$(2n-1)/2 *\lambda s$ n=2,3,4,… destructive

amplitudes do not but

→ decoupling of interference in D and A2 due to ABL change in profile
→ development of interference in Umin

CONCLUSIONS

IN THE VALLEY:

→ weaker rotors in the nonlinear regimes
→ for highly nonlinear regime: rotor strength is constant with H

IN THE LEE OF THE SECOND MOUNTAIN:

→ Constructive interference does not enhance rotors and rotors do not form for lower mountains than for single mountain
→ Destructive interference strongly diminishes rotor strength
→ Complete destructive interference also causes strong attenuation of waves downstream

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