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Boundary Layer Separation in Different Mountain Flow Regimes: Investigations on Rotor Characteristics

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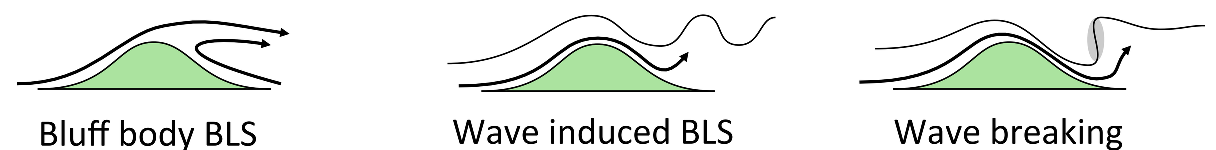
Introduction

Boundary layer separation (BLS)

If a sufficiently large reversed pressure gradient force at the surface is imposed against a boundary layer flow, the boundary layer may detach from the ground and regions of strong turbulence known as rotors may form downstream of the separation point.

BLS Regimes



The location and the regime of BLS depend on:

N ... stratification
U ... flow speed
H ... mountain height
L ... mountain half width

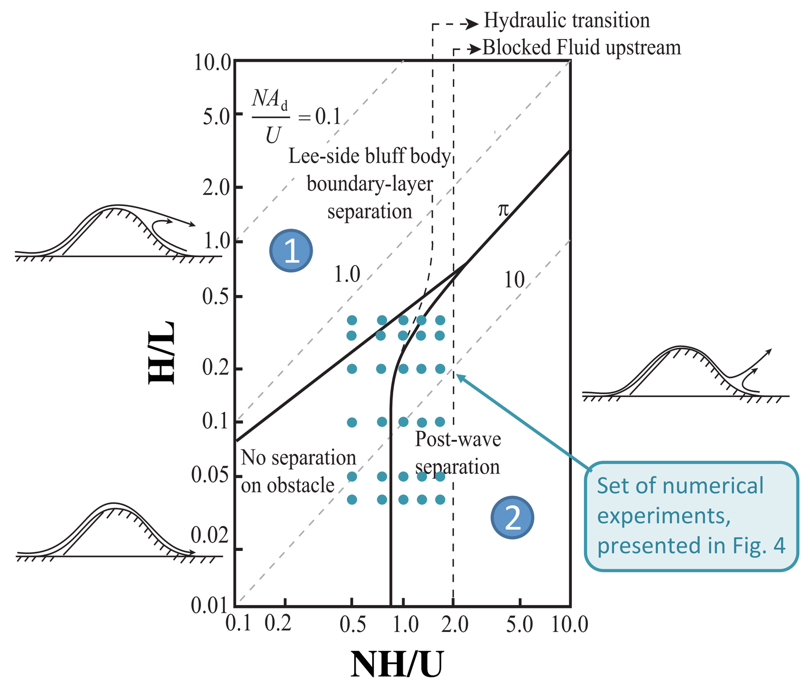
combined to

NH/U ... degree of non-linearity of the flow
NL/U ... degree of hydrostatic effect
H/L ... vertical mountain aspect ratio

Laboratory experiments

Laboratory experiments confirm that these quantities are key governing parameters and characterize the flow regime.

Fig 1 (right): The occurrence of bluff body-, wave induced- and no BLS is shown in dependence of NH/U, NH/L (dashed grey lines) and H/L. This plot is based on water tank experiments. [adapted from *Baines 1995*]



Motivation for this work

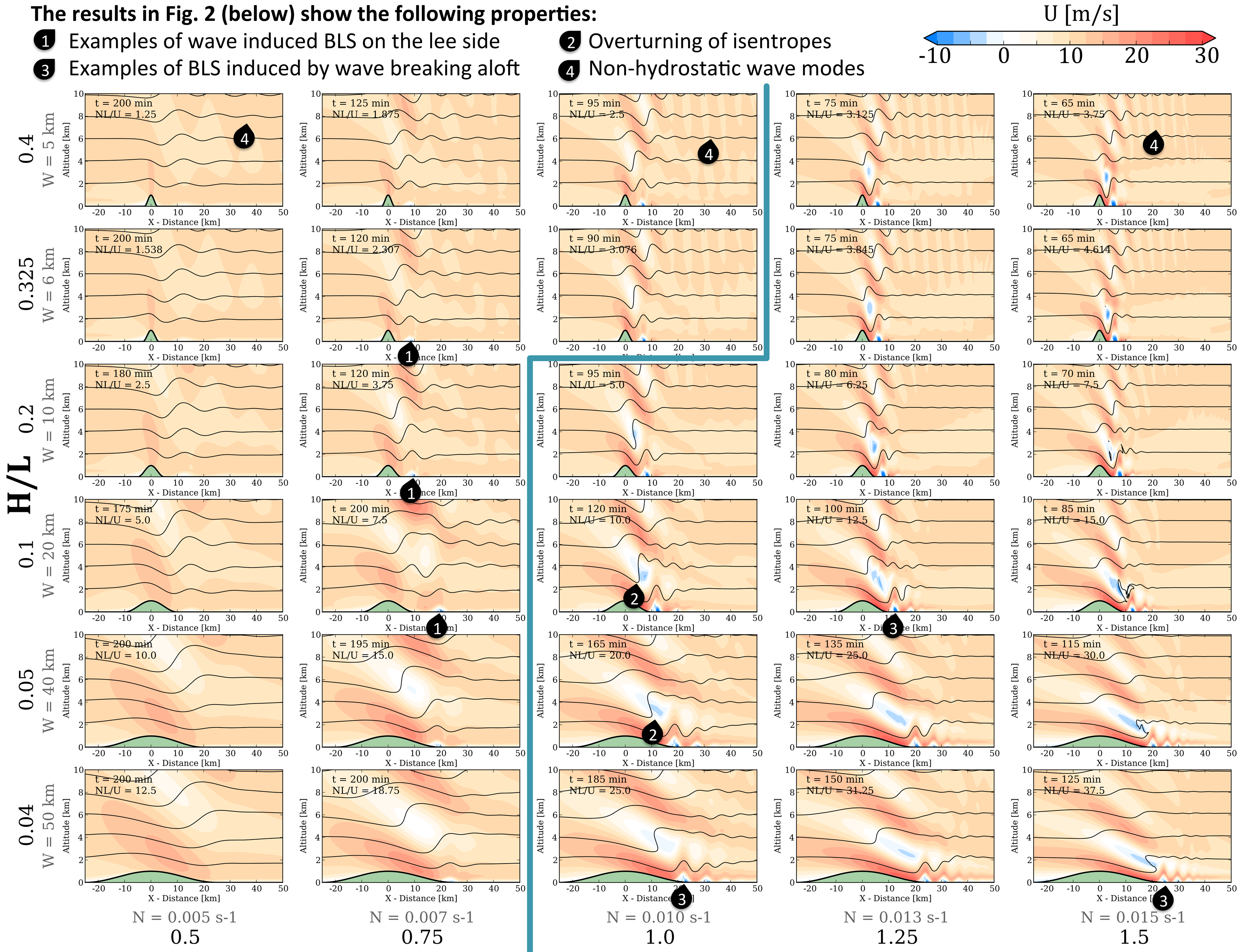
Although the mechanisms behind BLS were extensively investigated in the recent years, little is known about the onset, the location and the type of boundary layer separation in dependence of the atmospheric flow regime.
Therefore numerical experiments are carried out, to investigate the response of BLS to NH/U, NL/U, H/L and surface friction.

Simulation results

The surface roughness length in the simulations of Fig. 2 is z_0 = 10 cm . Thus, flow at the surface is decelerated due to friction and the boundary layer separates from the surface in case of a sufficiently strong reversed pressure gradient.

The results in Fig. 2 (below) show the following properties:

1. Examples of wave induced BLS on the lee side
2. Overturning of isentropes
3. Examples of BLS induced by wave breaking aloft
4. Non-hydrostatic wave modes



Transition line between no separation and post wave induced separation in the regime diagram of Baines 1995 in Fig.1

Note: The output times in Fig. 2 correspond to the strongest rotor state (maximum of the reversed flow).

Friction sensitivity test

While the governing flow regime mainly influences the size of rotors, friction changes the rotor's interior structure. For weak surface friction, the interior structure is a large single horizontal vortex with a strong reversed flow. If surface roughness increases, the single confined vortex breaks up. Another sensitivity test (not shown) suggests that surface roughness underneath the rotor plays an important role in the break-up process rather than the strength of the upstream vorticity sheet. Hence it is likely that the break-up is a result of sub-separation inside the rotor.

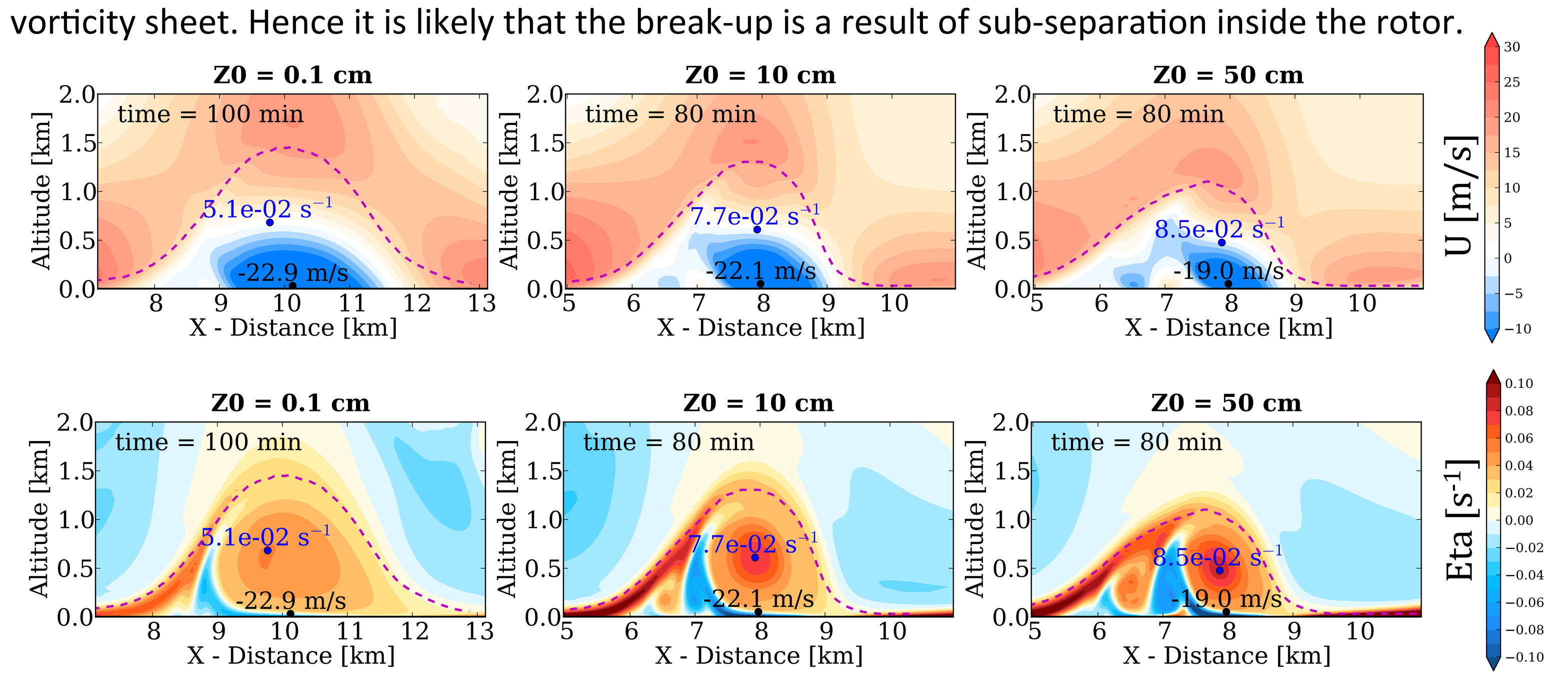


Fig. 5: Values of horizontal wind speed (top) and spanwise vorticity (bottom) of three identical simulations (NH/U = 1.25 and H/L = 0.2) with the exception of the surface roughness length z_0. The time frames correspond to the strongest rotor state. Dashed lines are the rotor shapes detected by the algorithm. Indicated values are local maxima (eta) or minima (U).

Rotors as virtual obstacles

It appears, that rotors can act as a virtual obstacle for the incoming flow. In the example below, there is an obvious difference in the downstream upper atmosphere between the FS and the NS simulation. A test with rotors replaced by topography suggests that rotors can act like topography.

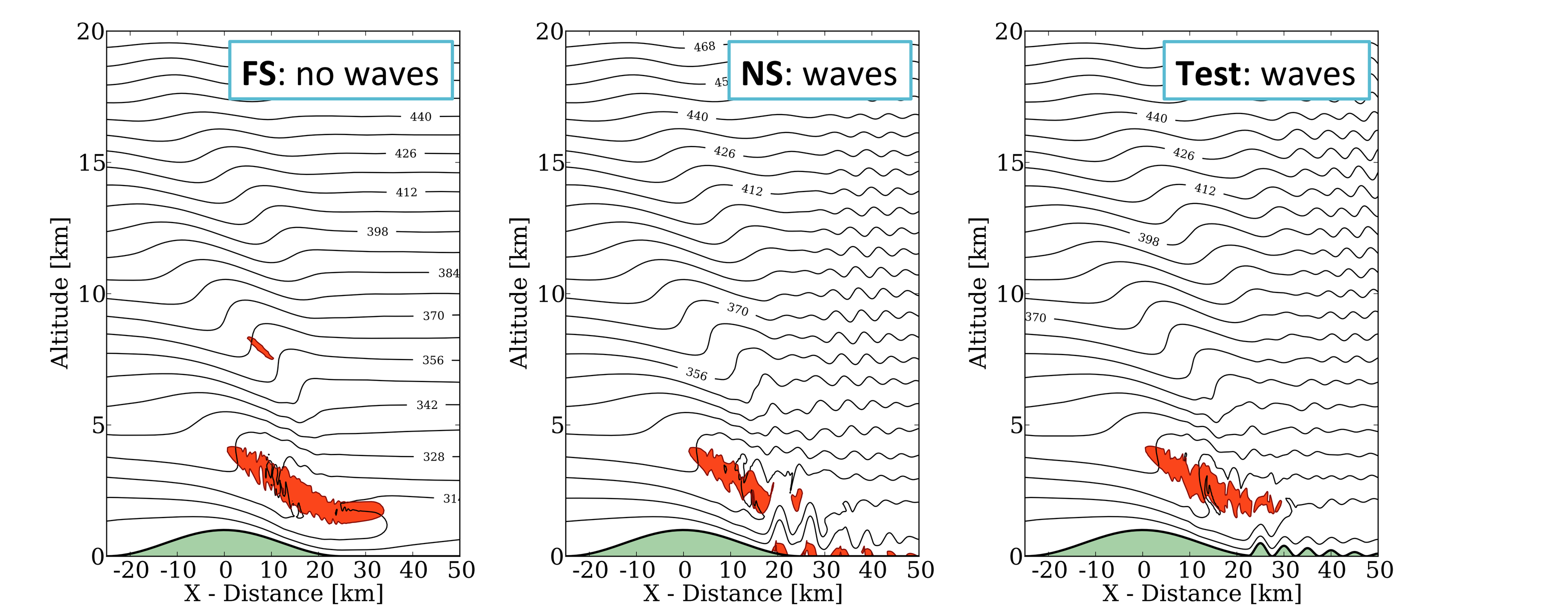
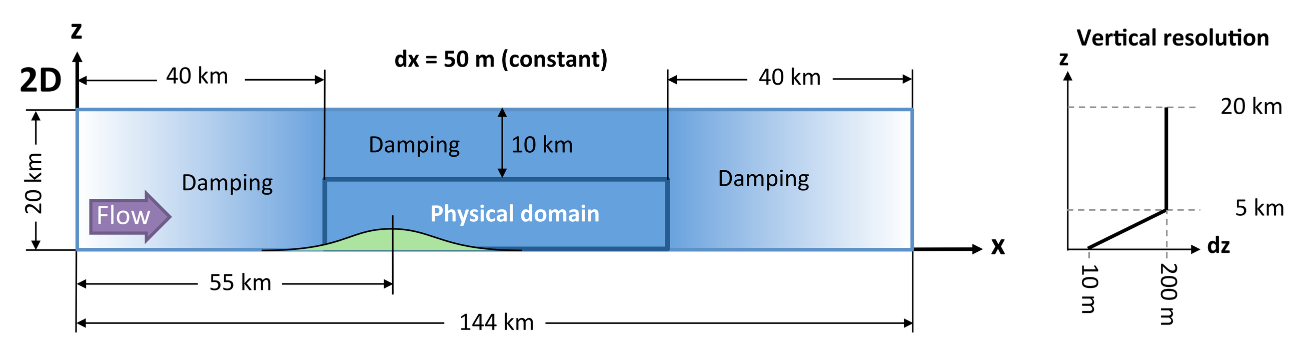


Fig. 6: Potential temperature contours of three identical simulations with the exception of the lower boundary conditions. Red contours show regions of reversed flow.
Left: free-slip (FS); Center: no-slip (NS); Right: rotors replaced by topography, but free-slip (no BLS!)

Numerical Experiments

Model

The numerical experiments are carried out using the Bryan Cloud Model **CM1** (*Bryan and Fritsch 2002*). Beside its capabilities as a cloud resolving LES model, CM1 can be used for LES simulations of flow over complex topography as well.



Design of experiments

For each of the five surface roughness lengths (z_0 = 0.001, 0.05, 0.1, 0.2, 0.5 m) a set of 30 simulations with different combinations of NH/U and H/L (see blue dots in Fig. 1) is carried out.

NH/U	H/L
0.5	0.04
0.75	0.05
1.0	0.1
1.25	0.2
1.5	0.325
	0.4

With:
U = 10 m/s
H = 1000 m

N [s-1]	L [km]
0.005	25
0.0075	20
0.01	10
0.0125	5
0.015	3
	2.5

The input sounding and the topography (cosine shape) are adjusted for each simulation with the corresponding values in the red boxes below.

U(z) = 10 m/s and **H = 1000 m** are constant for all simulations

Rotor height and strength

Detection algorithm

An algorithm detects the first rotor on the leeside based on the potential temperature field (rotors are neutrally stratified) and records its height and strength. Using these values, the strongest and the highest rotor state can be detected.

Linear model

Solution of the Taylor Goldstein Equation:

$$w(x,z) = \frac{1}{n}\sum_{k=-2\pi/L}^{k=2\pi/L} -ikU_0\hat{h}_k \cdot e^{-i(kx+mz)} \qquad m = -\sqrt{\frac{N^2}{U_0^2} - k^2}$$

$\hat{h}_k$ ... Fourier transform of terrain, k... horizontal wave number

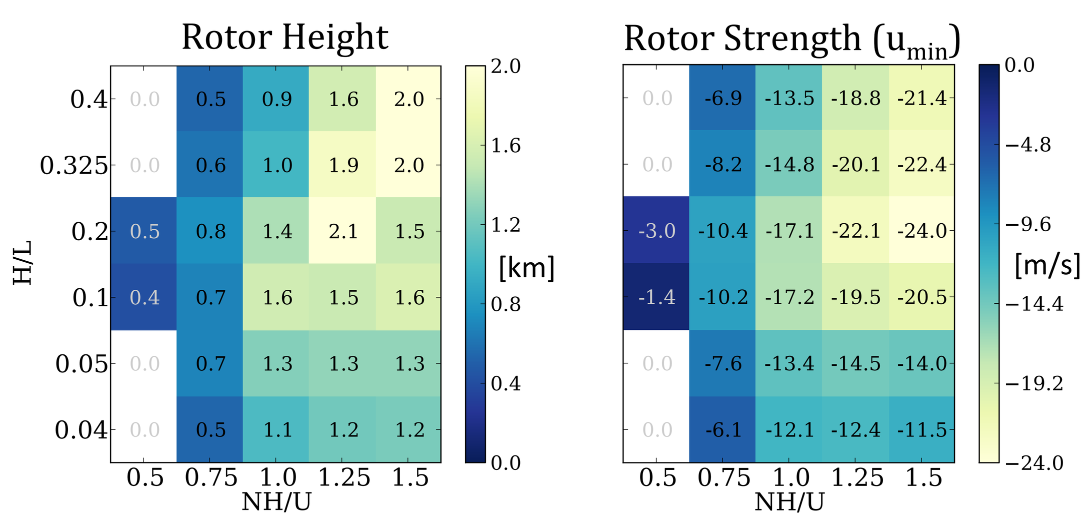


Fig. 3: Height (left) and strength (strength of reversed flow, right) of the highest and strongest rotor state in each simulation of the parameter space spanned by NH/U and H/L with z_0 = 10 cm.

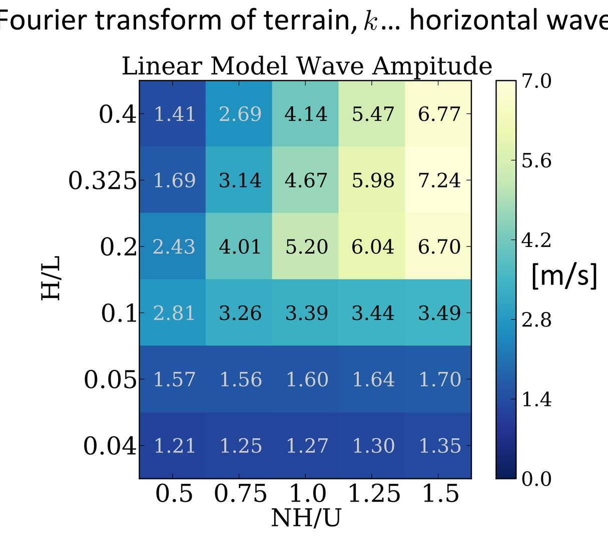


Fig. 4: Linear prediction of the maximum wave amplitudes $|w(x,z)|$ of a mountain wave (sinusoidal ridge) at a height of 10 km.

It is striking that there is an optimal H/L (depending on NH/U) for which the the highest and strongest rotors occur (see Fig. 3). It appears that this behavior is well in line with the linear model predictions of the wave amplitude in Fig. 4. It can be shown that maximum wave amplitudes occur, if the topographic forcing (depends on $\hat{h}_k$) is in optimal resonance with the atmospheric response (function of N, U and k). This suggests that the rotor characteristics are mainly determined by the mountain wave. However, this argument is not valid for wide mountains (lower two rows) because rotor formation occurs then underneath a self induced critical level and the simple linear model can not be applied anymore.

Summary & Outlook

- The regime diagram by *Baines 1995 (Fig. 1)* can be confirmed to a large part with numerical simulations
- Governing flow regime: mainly impacts the size
  Surface friction: impacts the interior structure of rotors
- Linear theory suggests that rotor characteristics like height and strength of the reversed flow ... are mainly influenced by the mountain wave in case of narrow topography
- Rotors can acts as a virtual obstacle and trigger "mountain" waves

- Move from 2D simulations to 3D (more realistic)
- Use different mountain shapes and aspect ratios
- Compare the findings with real case studies and measurements (e.g. T-REX data)

References
- Baines, P. G., 1995: Topographic Effects in Stratified Flows. Cam- bridge University Press, 482 pp.
- Bryan, G. H., and J. M. Fritsch, 2002: A benchmark simulation for moist non-hydrostatic numerical models. Mon. Wea. Rev., 130, 2917-2928.

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