Towards a climatology of orographic induced wave drag in the stable boundary layer over real terrain

Michal Adam Kleczek, G. J. Steeneveld, C. J. Nappo and A. A. M. Holtslag

Research questions

- How does orographically induced **gravity-wave drag affect the Stable Boundary Layer**(SBL) development for a range of realistic meteorological and orographical conditions?
- Can we improve **numerical weather prediction models** for the Stable Boundary Layer by accounting for **wavedrag**?

Hypothesis

Waves which are propagated, generated by gravity force in a stable stratification are called gravity waves. Gravity waves are triggered by i.e. wind blowing over some obstacles, i.e. hills or roughness changes (Fig. 1).

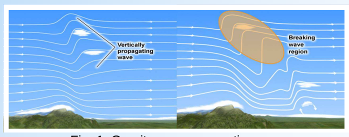


Fig. 1: Gravity wave generation.

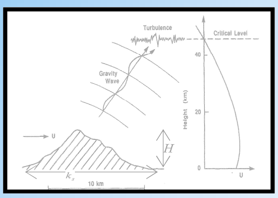


Fig. 2: Illustration of propagating gravity.

This research focuses on the importance of gravity wave drag on the SBL. According to linear theory, if the flow is sufficiently stratified, gravity waves will propagate upward and will form tilted wave fronts above the hills. This will provide surface drag on the flow.

In principle wave drag is constant with height. However when wind speed vanishes or turns strongly with height, non-linear effects occurs (i.e. wave breaking (Fig.1) or critical levels (Fig. 2)) and wave drag will diverge with height. That will cause deceleration of the synoptic flow.

Gravity waves may have an important impact, can redistribute energy and momentum. One can observe in equation of motion the impact of wave drag (red squares in Fig. 3), which depends on hill height H, surface wind, stratification N and ks (Fig. 4).

$$\frac{\partial U}{\partial t} = -f\left(V - V_g\right) - \frac{\partial \overline{u'w'}}{\partial z} - \frac{1}{\rho}\frac{\partial \tau_{wave,u}}{\partial z},$$
$$\frac{\partial V}{\partial t} = f\left(U - U_g\right) - \frac{\partial \overline{v'w'}}{\partial z} - \frac{1}{\rho}\frac{\partial \tau_{wave,v}}{\partial z}.$$

Fig. 3: Equations of motion.

$$\tau_{wave} = \tfrac{1}{2}\rho_0 k_s H^2 N U_0$$

Fig. 4: Simplified τ_{wave} for week winds.

Unfortunately gravity-wave drag factor is currently not fully understood in Stable Boundary Layers schemes.

Methodology

To determine the influence of gravity waves we will use a sophisticated atmospheric modelling system (WRF) at a high vertical resolution. To compare the difference between the Planetary Boundary Layer schemes we have chosen Mellor-Yamada-Janjic (MYJ), Quasi Normal Scale Elimination (QNSE) and Yonsei University (YSU) schemes.

For our study we used observations collected during CASES99 campaign. It is clear that the CASES99 terrain (Fig. 6) cannot be captured by a single H and k_s. Therefore, in this study, the Taylor Goldstein Equation is solved for 36 wind sectors φ of 10º, each with different H and k_s, and wave drag is added up to estimate an area-averaged wave drag.

$$\frac{d^2}{dz^2}\hat{w}_\phi(k_s,z) + \left[\frac{N^2}{U_\phi^2} - \frac{U_\phi^2}{U_\phi} - k_s^2\right]\cdot \hat{w}_\phi(k_s,z) = 0$$

with boundary conditions for u and w for each sector (in Fourier space):

$$\hat{w}_\phi(0) = -ik_{s,\phi}\hat{u}_\phi(0)\hat{h}_\phi(k_{s,\phi}) \qquad \hat{u}_\phi = i/k_s \nabla_z \hat{w}_\phi$$

For each night of the CASES99 campaign, the WRF single column model is initialized with a local radio sounding, and it consequently forecasts the wind and temperature profiles. These fields are forwarded to the wave drag module, which estimates near surface wave drag (see scheme on Fig. 5).

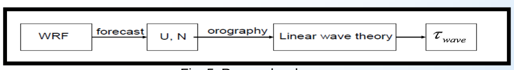


Fig. 5: Research scheme.

CASES-99 field experiment

The terrain over the CASES99 SBL experiment (October 1999) is on average relatively flat, but substantial small scale orography is present (Fig 6).

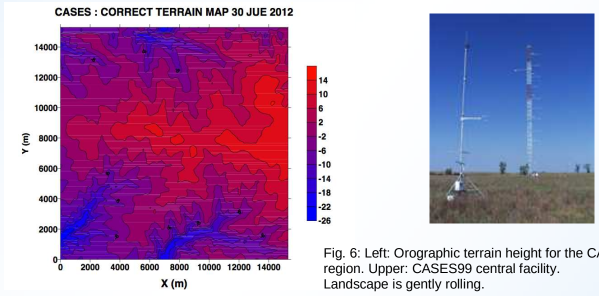
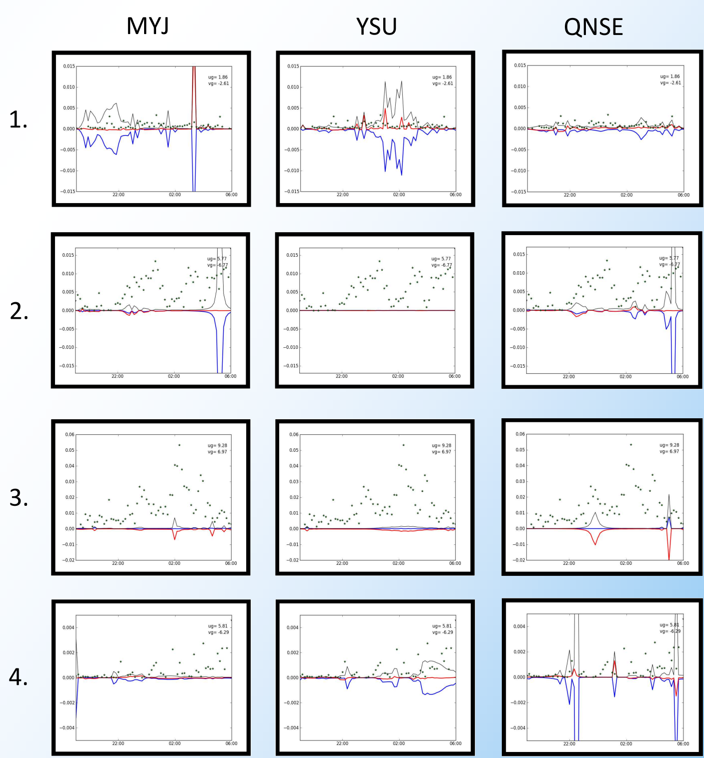


Fig. 6: Left: Orographic terrain height for the CASES99 region. Upper: CASES99 central facility. Landscape is gently rolling.

Time series



On above figures we can observe night-time drag for following dates:
1.) 09 - 10.10.1999
2.) 19 - 20.10.1999
3.) 20 - 21.10.1999
4.) 25 - 26.10.1999

For certain cases we can observe that the order of magnitude of the wavedrag (solid lines where the black line is total drag, **blue** and **red** indicate wavedrag in **x** and **y** direction respectively) is comparable to the turbulent drag (green stars). Orographically induced gravity wave drag is an often overlooked but non-negligible player as we can observe on above results in the stable boundary layer momentum budget during low winds.

Conclusions

The major conclusions of this work are:

- The importance of wave drag for certain cases has been confirmed;
- Estimated wavedrag depends on WRF PBL scheme;
- Further comparison with observations from complex terrain is needed.

Contact: michal.kleczek@wur.nl, Meteorology and Air Quality Section ,
Wageningen University, P.O. Box 47, 6700 AA Wageningen, The Netherlands.

References:
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2. Steeneveld, G.J., Nappo, C.J. and Holtslag, A.A.M., 2009. Estimation of orographically induced wave drag in the stable boundary layer during the CASES-99 experimental campaign. Acta Geophysica, Vol.57(4), pp.857-881

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