Quantitative estimation of turbulence intensity in mountain flows from airborne Doppler radar measurements

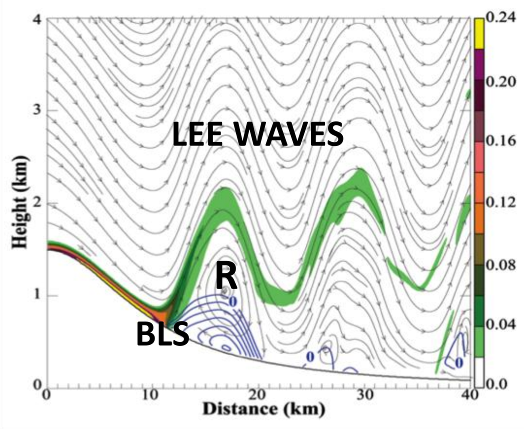
Lukas Strauss[1], Stefano Serafin[1], and Vanda Grubišić[1,2]

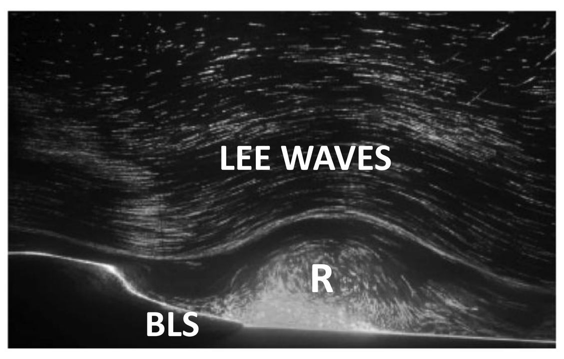
[1] Department of Meteorology and Geophysics, University of Vienna, Vienna (Austria)

[2] Earth Observing Laboratory, National Center for Atmospheric Research, Boulder (Colorado)

Introduction: Mountain-induced turbulent processes

- **Various turbulence-generating processes in the presence of mountainous terrain** are known, ranging from convection over orography to gravity-wave breaking and boundary-layer separation.
- The **focus of this work** is on **wave-induced boundary-layer separation (BLS)**. BLS has received significant attention in numerical as well as laboratory studies due to its **key role in the formation of atmospheric rotors (R)**.
- **Direct observational evidence** of the phenomenon, however, **was lacking** until recently.

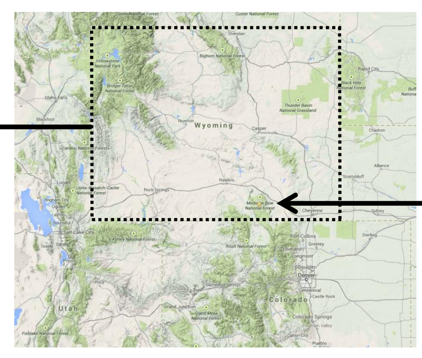




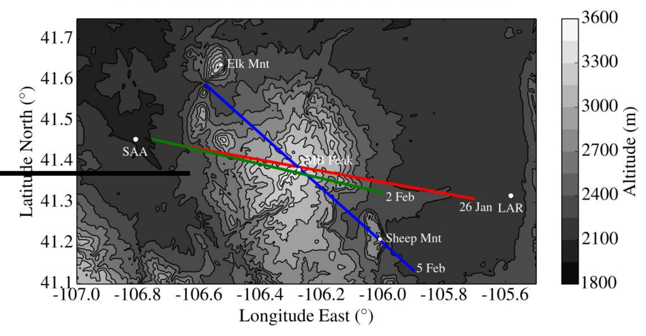
Left: Numerical experiments of boundary-layer separation by Doyle and Durran (2002). **Right: Laboratory experiments** in a water tank by Knigge et al. (2010).

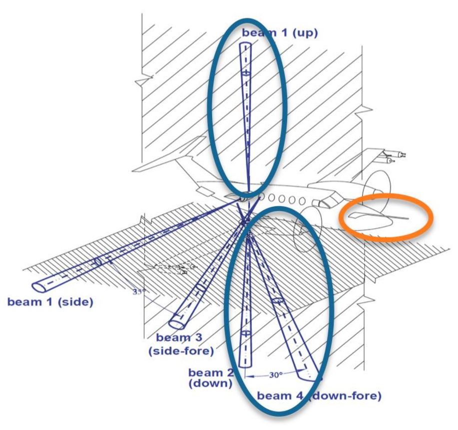
Observations: Airborne Doppler radar measurements

- In winter 2006, the **NASA Orographic Clouds Experiment (NASA06)** was conducted over the **Medicine Bow Mountains in SE Wyoming**. Measurements were collected by the **University of Wyoming King Air (UWKA) aircraft** and the **Wyoming Cloud Radar (WCR).**
- On 26 January and 5 February 2006, multiple straight-and-level legs were flown across the ridge along the mean wind direction. **High-resolution radar data reveal wave-induced boundary-layer separation** in the lee of the mountain and ensuing **rotor formation** (French et al., 2014).



Medicine Bow Mountains





Aircraft in situ data

- Three wind components at a frequency of 25 Hz

Wyoming Cloud Radar

- Dual-Doppler radar
- Operated in multi-beam mode
- Single-Doppler frequency of 30 Hz
- Vertical resolution of 30 m
- Sensitivity to cloud ice

Objective: Quantitative estimation of turbulence intensity

--- Objectives of this study ---

Detect locations of strong turbulence across the mountain ridge using aircraft in situ and radar data.

Quantify turbulence and shed light on the origin of turbulent processes in complex terrain.

Gain insight into levels of turbulence within regions of boundary-layer separation and **atmospheric rotors**.

Methods: Measures of turbulence intensity

TKE and σ_w^2

Wind variances along 1.5 km long flight segments

- **Aircraft measurements:**

$$\mathrm{TKE} = \frac{1}{2}\left(\sigma_u^2 + \sigma_v^2 + \sigma_w^2\right)$$

- **Doppler radar measurements:**

$$\sigma_w^2 = \sigma_{\dot{r},\mathrm{meas}}^2 - \sigma_{\mathrm{noise}}^2 + \sigma_{\mathrm{PVA}}^2$$

$$+\begin{cases} +\sigma^2_{\mathrm{PVA,err}} & \qquad\qquad +\sigma^2_{\mathrm{HC,B}} \\ -\sigma^2_{\mathrm{PVA,err}} & -\sigma^2_{\mathrm{HC,A}} \quad -\sigma^2_{\mathrm{HC,B}} - \sigma^2_{\mathrm{ac}} - \sigma^2_{\mathrm{ba}} - \sigma^2_{v_t} \end{cases}$$

measurement uncertainty upper & lower bounds

"EDR"

Eddy-dissipation rate using **"Kolmogorov's law"**

$$S_{u_i}(k) = \alpha_i\, \varepsilon_{u_i}^{2/3}\, k^{-5/3}$$

- **Aircraft and radar measurements:**

$$\mathrm{EDR}_w \equiv \varepsilon_w^{1/3} = \left[\frac{2\pi}{\mathrm{TAS}}\left(\frac{\overline{S_{\dot{r}}(f)\, f^{5/3}}}{\alpha_w}\right)^{3/2}\right]^{1/3}$$

EDR is proportional to the **"subjective feel of turbulence"** of pilots and passengers on aircraft. It is thus **linked to aviation turbulence categories** "light" , "moderate", and "severe".

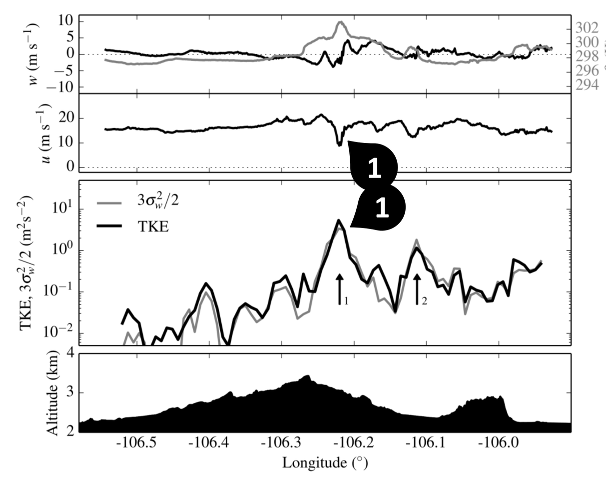
Please don't hesitate to ask for details!

Results: Turbulence in a "classic" lee-wave rotor

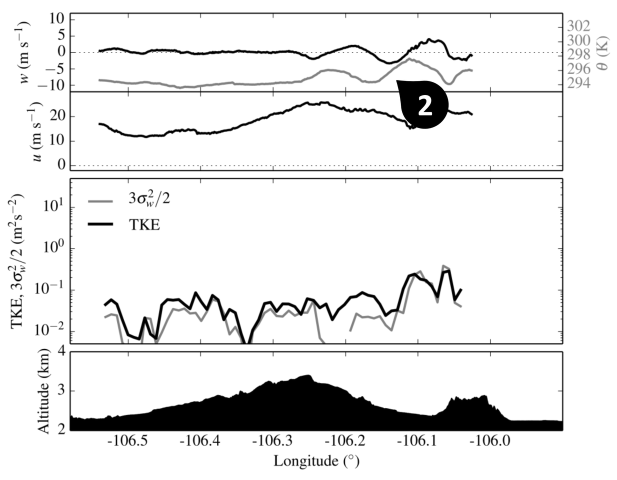
- On **5 February 2006**, a large-amplitude mountain wave broke over the Medicine Bow Mountains and **trapped lee waves formed over the lee slope**.
- The lee wave forcing gave rise to **wave-induced boundary-layer separation and a large atmospheric rotor**, characterised by "severe" levels of turbulence.
- **In situ and radar data** along flight legs 1 and 3, **document the evolution of the rotor event**.

AIRCRAFT

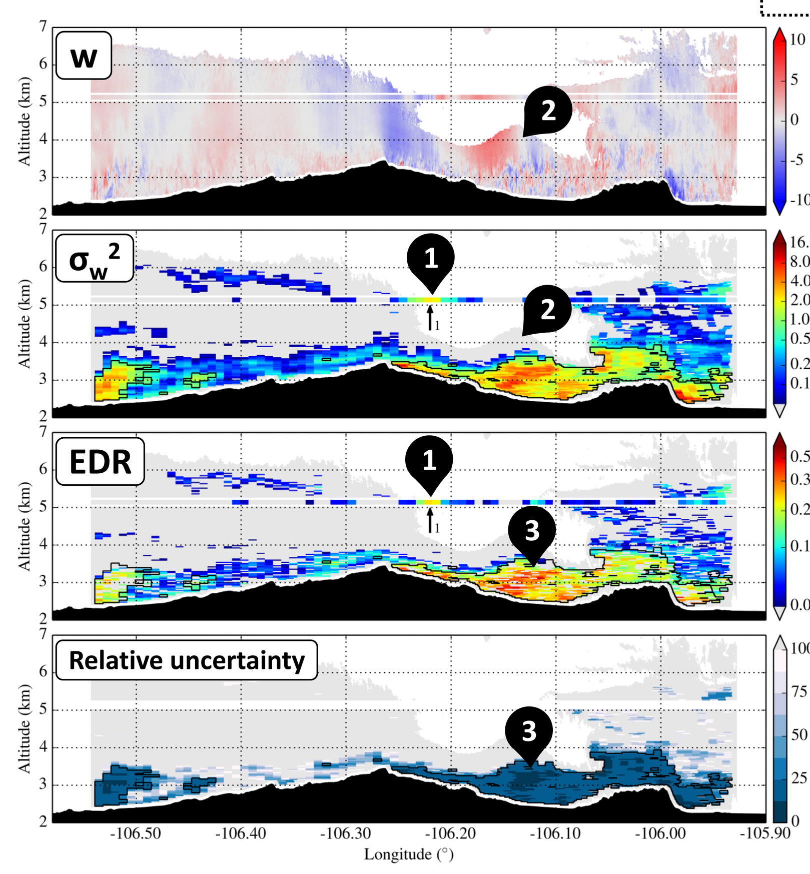
Leg 1 on 5 February

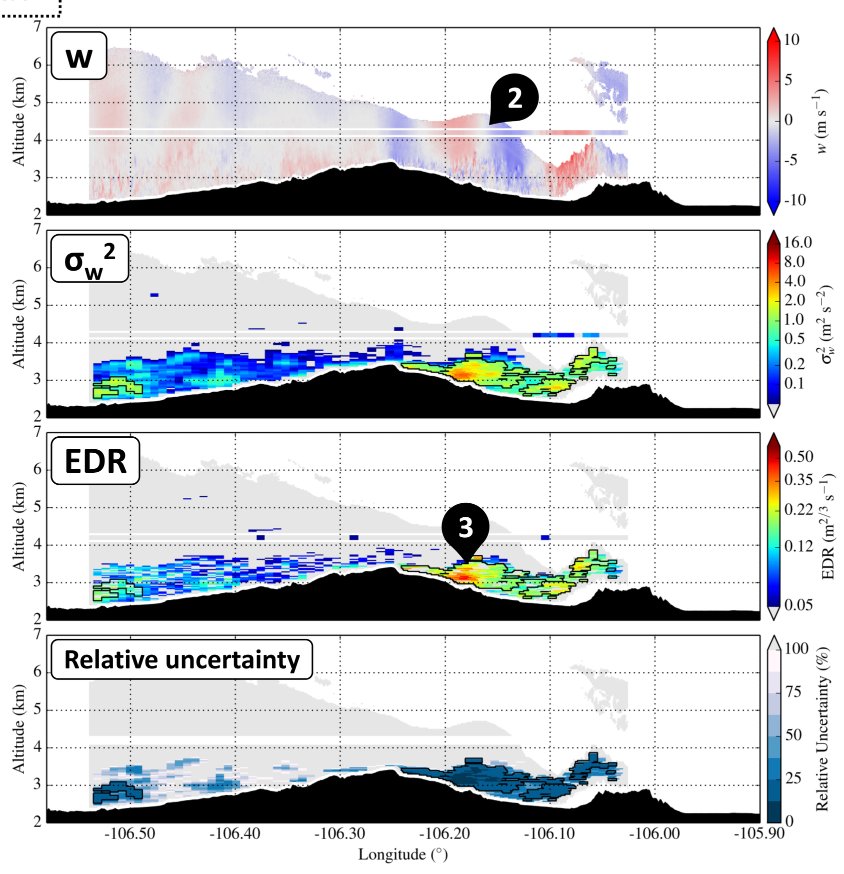


Leg 3 on 5 February



RADAR

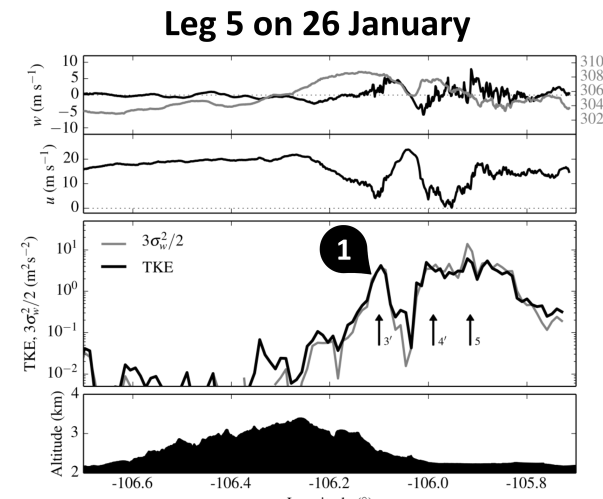


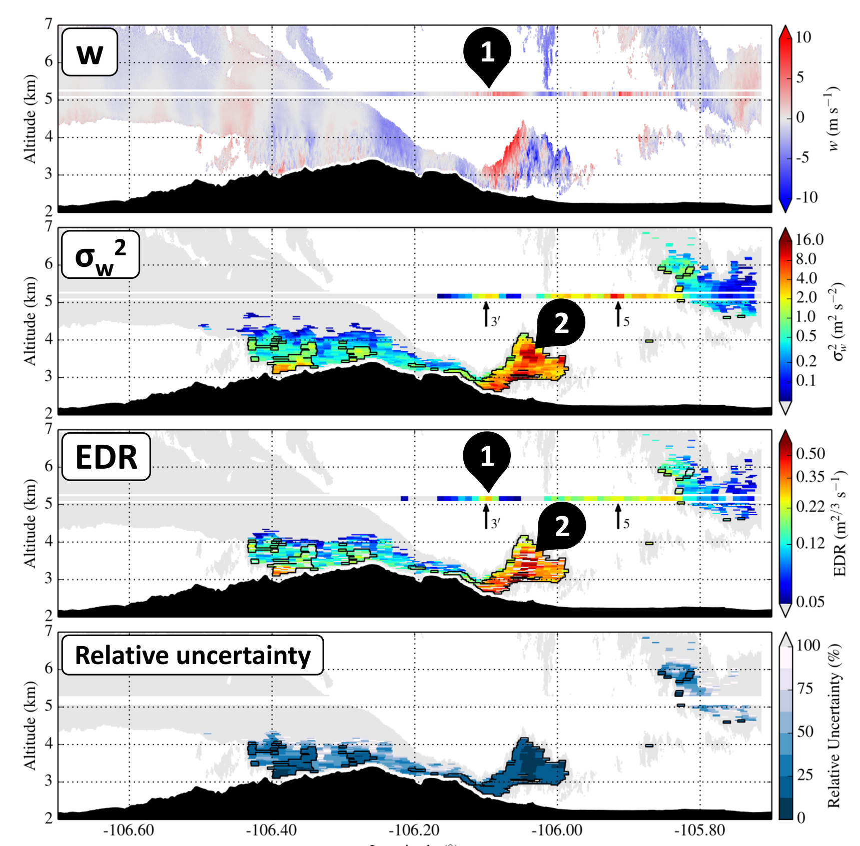


1. Mid-tropospheric **gravity wave breaking**. "Moderate" levels of turbulence.
2. Smooth **trapped lee waves**. No detectable level of turbulence.
3. "Severe" turbulence in the **interior of the rotor**. 25% accuracy and better on turbulence estimates.

Results: Turbulence in a hydraulic jump-type rotor

Leg 5 on 26 January





1. "Moderate-severe" turbulence encountered at flight level in a hydraulic jump-like feature.
2. "Severe" turbulence in the interior of a huge atmospheric rotor.

Summary of results

Terrain-induced process	Event	$\mathrm{TKE}_{\mathrm{max}}$ ($\mathrm{m^2\,s^{-2}}$)	$\sigma^2_{w,\mathrm{max}}$ ($\mathrm{m^2\,s^{-2}}$)	$\mathrm{EDR}_{\mathrm{max}}$ ($\mathrm{m^{2/3}s^{-1}}$)	Turbulence category
mid-tropospheric wave breaking	26 Jan	$4.6^{+0.0\%}_{-0.3\%}$	$4.8^{+0\%}_{-0.2\%}$	$0.25^{+16\%}_{-16\%}$	moderate
	5 Feb	$5.4^{+0\%}_{-0.3\%}$	$2.3^{+0\%}_{-0.2\%}$	$0.25^{+16\%}_{-16\%}$	moderate
hydraulic jump	26 Jan	$12.1^{+0\%}_{-0.3\%}$	$12.7^{+0\%}_{-0.2\%}$	$0.38^{+16\%}_{-16\%}$	moderate-severe
rotor (hydraulic jump-type)	26 Jan	–	$16.4^{+8.2\%}_{-9.2\%}$	$0.77^{+41\%}_{-23\%}$	severe
rotor (lee-wave type)	5 Feb	–	$7.8^{+7.9\%}_{-9.8\%}$	$0.50^{+41\%}_{-23\%}$	severe
bluff-body BL separation	5 Feb	–	$10.3^{+8.5\%}_{-10.4\%}$	$0.41^{+41\%}_{-23\%}$	moderate-severe

Conclusions

- Data from airborne Doppler radar can be used to obtain **quantitative estimates of terrain-induced turbulence**.
- Better than 25% accuracy on the variance of vertical wind σ_w^2 is achieved in regions of moderate to severe turbulence in the lee of the mountain.
- A **unique result of this work** is the quasi-instantaneous, two-dimensional display of the **spatial distribution of turbulence in the interior of atmospheric rotors**.

References

- Doyle, J.D., and D.R. Durran, 2002: **The dynamics of mountain-wave-induced rotors**. J. Atmos. Sci., 59, 186-201.
- French, J., S. Haimov, and Coauthors, 2014: **Wave-induced boundary-layer separation in the lee of the Medicine Bow Mountains. Part I: Observations**. To be submitted to J. Atmos. Sci..
- Grubišić, V., and Coauthors, 2008: **The Terrain-Induced Rotor Experiment: A field campaign overview including observational highlights**. BAMS, 89, 1513-1533.
- Knigge, C., D. Etling, A. Paci, and O. Eiff, 2010: **Laboratory experiments on mountain-induced rotors**. Q. J. R. Meteorol. Soc., 136, 442–450.

Research partially supported by the Austrian Science Fund, FWF, through the project P24726–N27 **STABLEST – Stable Boundary Layer Separation and Turbulence**.

Contact:
Lukas Strauss [lukas.strauss@univie.ac.at]
University of Vienna
Department of Meteorology and Geophysics
http://img.univie.ac.at/en/research/tm