Observations and numerical simulations of downslope flow separation at a valley inversion

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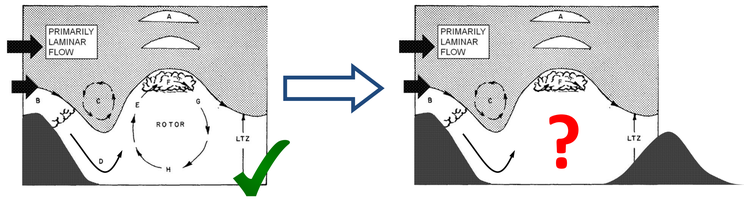
Lee-side flow separation and low-level turbulence

- **Severe low-level turbulence in the lee of a mountain** is frequently associated with large-amplitude lee waves causing **lee-side flow separation and the formation of turbulent atmospheric rotors**.
- An **early conceptual model of rotors emerged from field experiments** over the Sierra Nevada and the Colorado Rockies in the 1950s and 1970s (Holmboe & Klieforth 1957, Lester & Fingerhut 1974).
- However, the **concept proves to be too simplistic** for the description of rotors **in more complex terrain**, for example, two parallel ridges separated by a deep valley.



Early conceptual model of a rotor for a single mountain ridge after Kuettner (1959) and Holmboe and Klieforth (1957).

A valley and a second ridge ...
- thermal stratification
- slope and valley flows
- flow channelling

The Terrain-Induced Rotor Experiment (T-REX)

- The **Terrain-Induced Rotor Experiment** (**T-REX**, Sierra Nevada, CA, 2006) was the most recent field experiment **studying the coupled system of mountain waves, rotors, and the boundary layer** (Grubišić et al. 2008).
- Comprehensive measurements by **ground-based and airborne in situ and remote sensors** were made **in and over Owens Valley** during 15 T-REX intensive observing periods (IOPs).

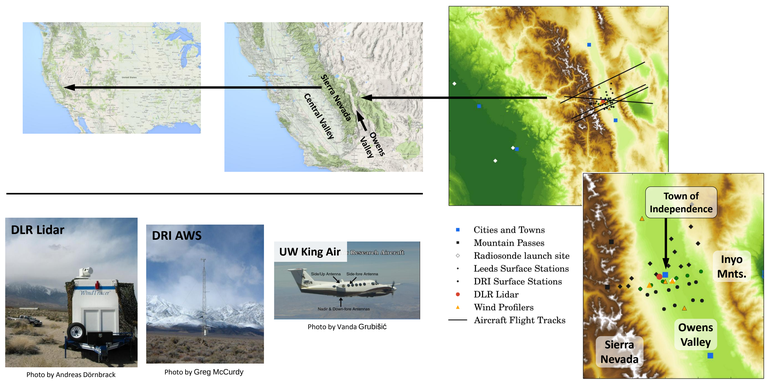


Photo by Andreas Dörnbrack
Photo by Greg McCurdy
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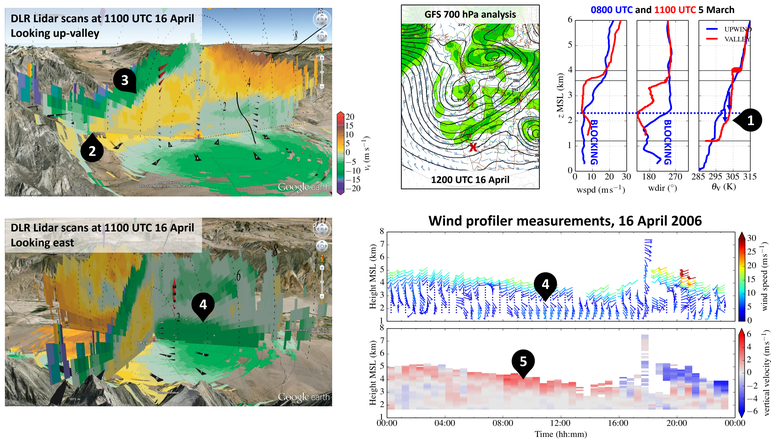
Objectives of this study

- Understand better the **mechanisms behind flow separation** in Owens Valley
- Elucidate the **relative importance of dynamically and thermally driven processes** in the valley determining the location of flow separation and severe turbulence

Downslope flow separation at a valley inversion

- During the nighttime hours of T-REX IOP 13, **cold air accumulated in the lowest valley layers**.
- The **downslope flow separated from the lee slope** as it reached its level of neutral buoyancy and **a rotor-like turbulent structure formed** (Strauss et al. 2016).



1. Stable valley air during nighttime. Crest-level upstream air can only penetrate to top of **low-level inversion**.
2. **Downslope flow separates** from lee slope.
3. A rotor-like structure forms.
4. Channelled up-valley flow at low levels in the valley.
5. During the flow-separation event, **moderate-amplitude waves** (~3-4 m s^{-1}) are present at crest level above the valley.

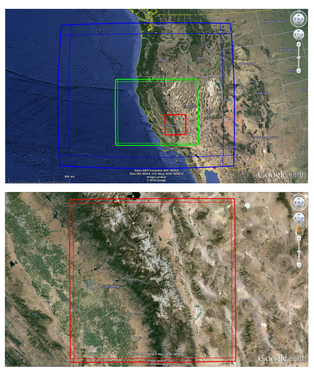
Numerical modelling of flow separation with WRF

- The Weather Research and Forecasting (**ARW-WRF**) Model (Skamarock & Klemp 2008) has been run in a **nested configuration** to simulate the observed flow-separation event.
- The aim is **to better understand the interplay between dynamically driven and thermally driven processes** in Owens Valley determining this case.
- The nested configuration has been chosen so as to allow the **large-scale weather system, mesoscale surface pressure pattern, and small-scale in-valley processes** to be represented faithfully in the model.

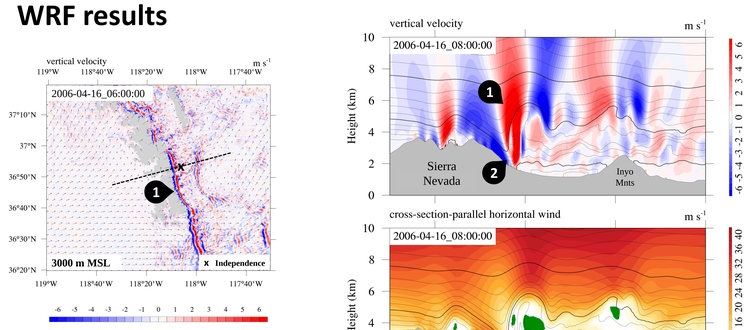
Model setup

- Three nested domains
  - **10 km, 2 km, 400 m horizontal grid spacings**
  - **~25 m vertical spacing at the ground**, vertical stretching towards the domain top (10 hPa, or ~28 km)
- Initial and boundary conditions
  - **ECMWF analyses**, 6-hourly intervals
  - Simulation start: 1200 UTC 15 April 2006
- **Rayleigh damping** for vertical velocity in the top 12 km of the model domain
- PBL vertical sub-grid-scale fluxes: **Mellor-Yamada-Janjić scheme**
- Microphysics: **Thompson scheme**

Nested domains

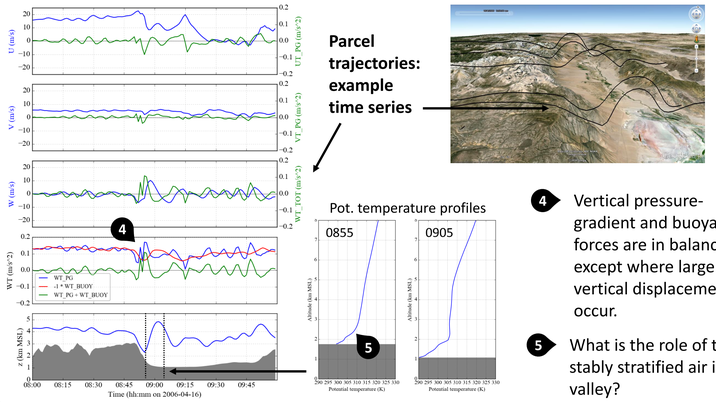


WRF results



1. Short, moderate-amplitude (~5 m s^{-1}) mountain waves form along the Sierra early in the night.
2. Flow separation in the valley is relatively well reproduced.
3. The air in the valley is stably stratfied, however, an inversion is missing.

Pressure-gradient vs buoyancy forces along trajectories



4. Vertical pressure-gradient and buoyancy forces are in balance except where large vertical displacements occur.
5. What is the role of the stably stratified air in the valley?

Summary and outlook

- Flow separation over the lee slope of the Sierra Nevada in the night of 16 April 2006 has been successfully reproduced in numerical simulations with WRF.
- An evaluation of forcings along parcel trajectories reveals the magnitudes of the vertical pressure-gradient and buoyancy forces equalling those of the horizontal pressure-gradient forces.
- The hypothesized importance of the stratification of the lowest layers in the valley should be further consolidated with model sensitivity runs (e.g., heat-flux vs. no-heat-flux runs).

References

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