Mountain Waves and Rotors – Revisiting the Concept of the "Lower Turbulent Zone" (LTZ)

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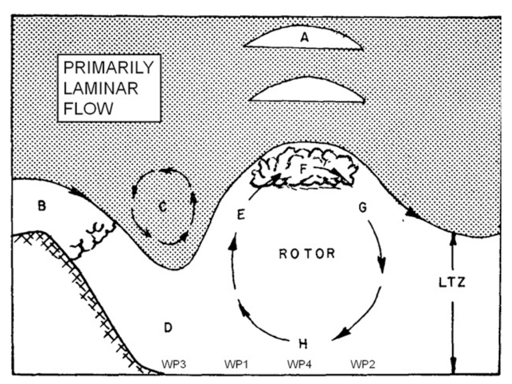
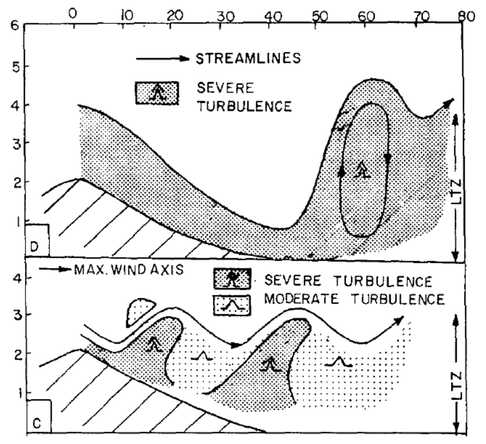
Previous studies of the Lower Turbulent Zone (LTZ)

- In their seminal 1974 paper on "Lower Turbulent Zones Associated with Mountain Lee Waves" Lester and Fingerhut characterised **regions of strong low-level turbulence in the lee of mountain ranges** that are commonly associated with **large-amplitude mountain waves aloft**.
- In later observational and numerical studies, the **"lower turbulent zone" (LTZ)** was found to be a **direct consequence of wave-induced boundary-layer separation** lee-side of mountains and of the ensuing **formation of atmospheric rotors**.





Left: Conceptual model of the LTZ after Kuettner (1959) and Holmboe and Klieforth (1957).

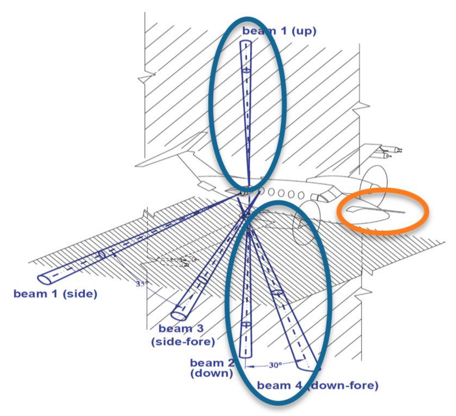
Right: Locations of severe turbulence in the LTZ for "jump-type" and "wave-type" rotors (Lester and Fingerhut 1974).

The Terrain-Induced Rotor Experiment (T-REX)

- The Terrain-Induced Rotor Experiment (**T-REX**, Sierra Nevada, CA, 2006) is the most recent, major effort organized to **investigate the characteristics of LTZs by studying the coupled mountain-wave, rotor, and boundary-layer system** (Grubišić et al. 2008).
- During the T-REX IOPs, the **Wyoming King Air (WKA) research aircraft** and the **Wyoming Cloud Radar (WCR)** captured the variation of the mountain flow across the Sierra Nevada.
- **High-rate in situ and cloud radar measurements** allow to document the **structure of the LTZ** and the turbulence within it **at unprecedented spatial resolution**.

Sierra Nevada, Owens Valley, and Inyo Mnts

Wyoming King Air research aircraft



Aircraft in situ data
- Wind components (u, v, w) and temperature (T) at up to 25 Hz
- Eddy-dissipation rate (EDR) from the MacCready Turbulence Meter

Wyoming Cloud Radar
- Sensitive to cloud ice
- Single-Doppler frequency of 30 Hz
- Vertical resolution of 30 m
- Operated in multi-beam mode

Revisiting the conceptual model of the LTZ

Objectives of this study

Revisit and, if possible, extend the LTZ concept using aircraft data from those T-REX IOPs with the strongest gravity wave forcing.

Characterize the **spatial distribution and intensity of turbulence in the LTZ**.

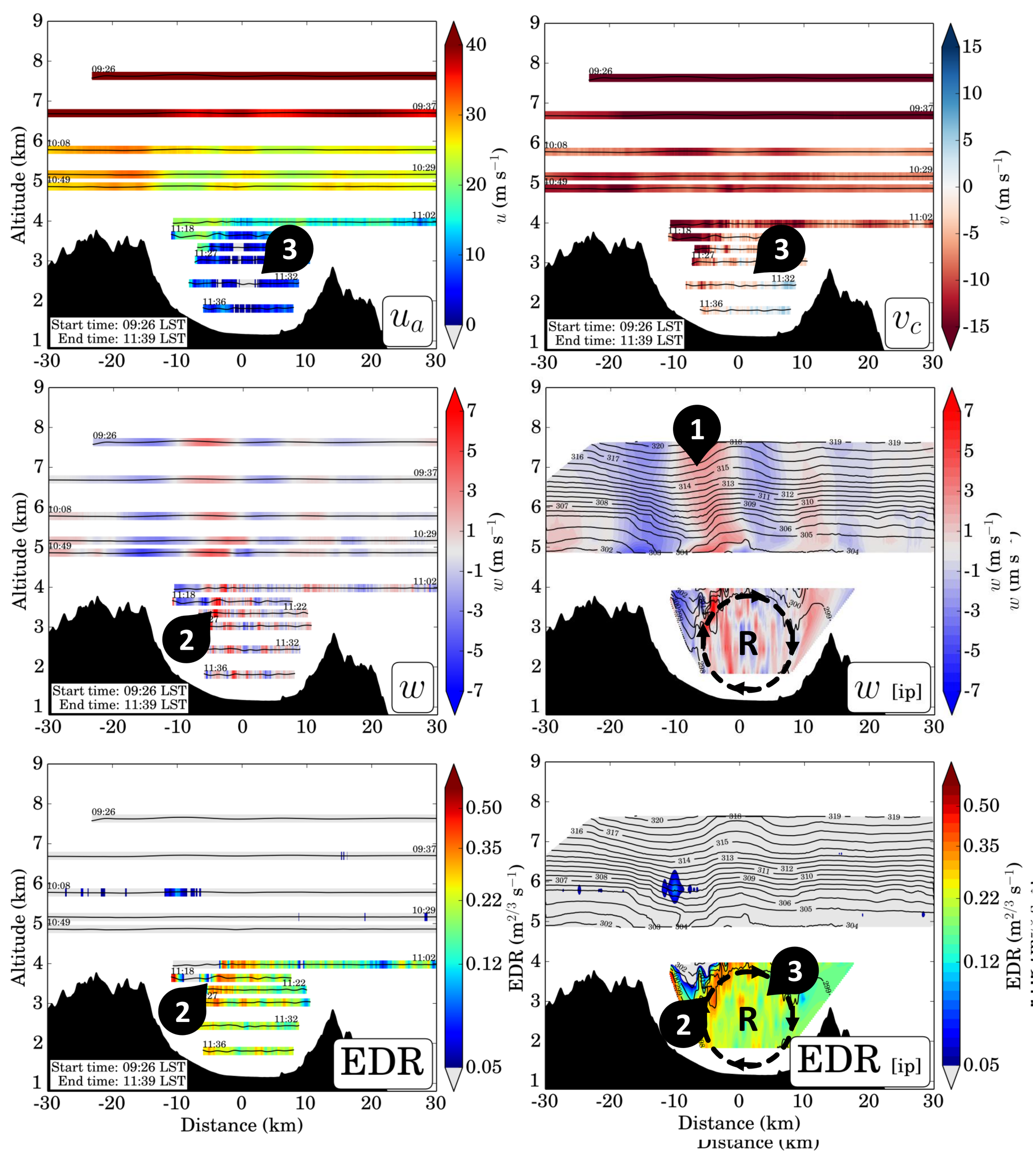
Data analysis approach

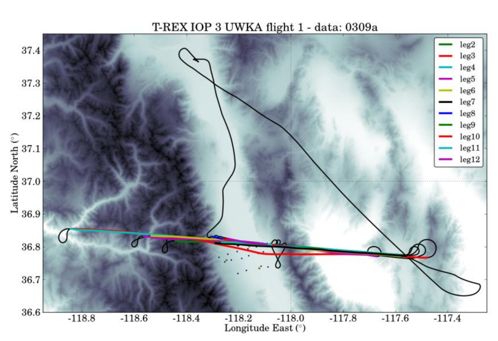
Aircraft data from stacked, straight-and-level flight legs are interpolated in order to study the spatial structure of the LTZ. **Radar data complement** the in situ data in cloudy regions.

Eddy-dissipation rate (EDR) and turbulent kinetic energy (TKE) are used as turbulence indicators.
TKE is computed from the along-track, cross-track, and vertical wind component (**u_a, v_c,** and **w**) along 1.5 km long flight segments.

The "classical" LTZ (T-REX IOP 3)

- The development of a **downslope windstorm event exhibiting trapped lee waves and a large rotor** was observed during the morning hours of **T-REX IOP 3**.
- Observations are in **good agreement with the "classical" notion of the LTZ**.

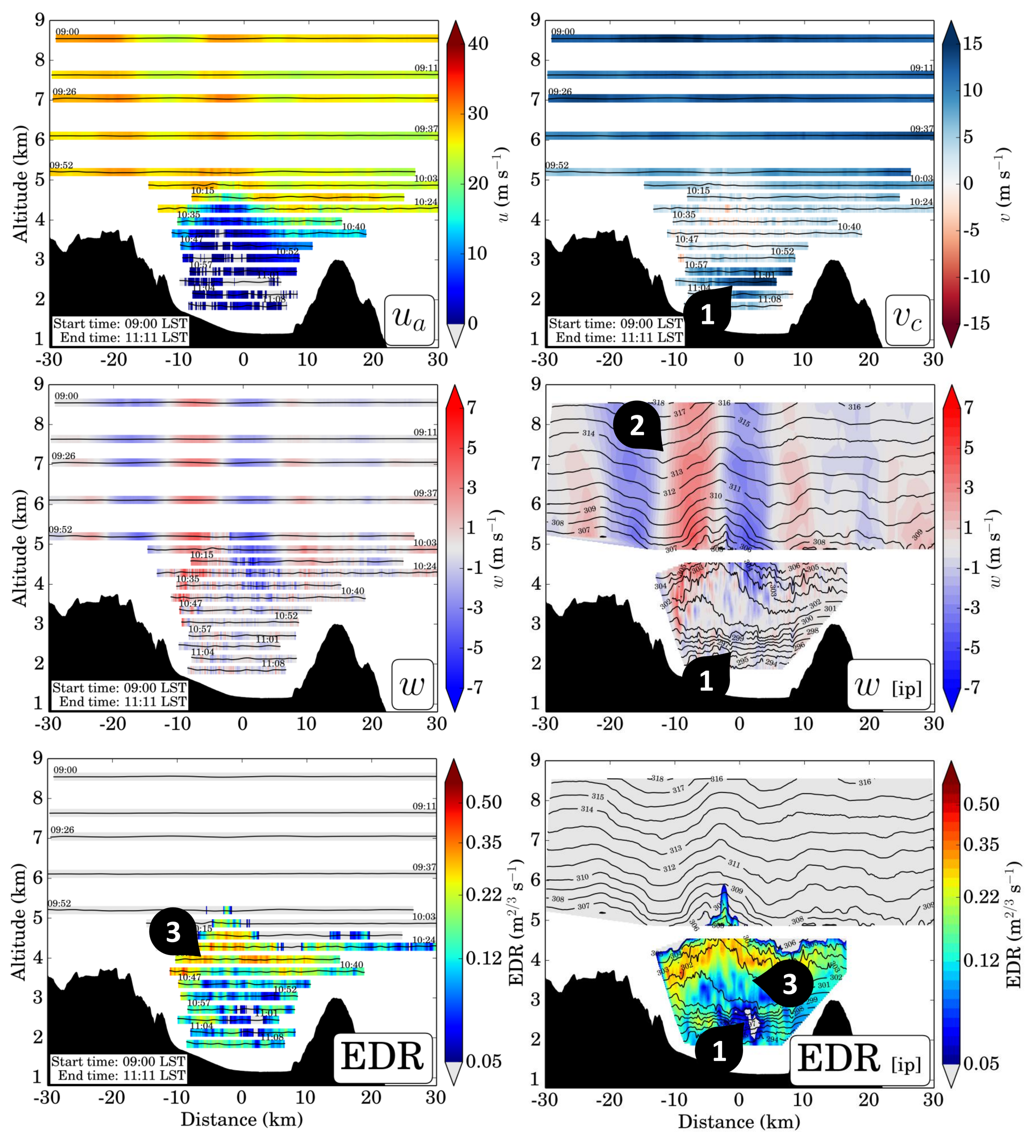


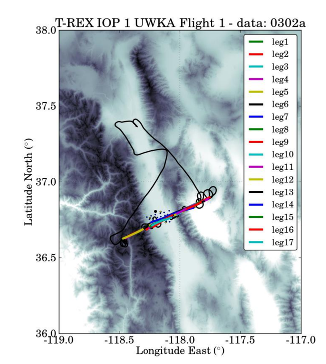


1. Strong stratification in the mid-troposphere. Trapped lee waves with vertical velocities of +/- 5 m s^{-1}.
2. Moderate to severe turbulence at the leading edge of the rotor.
3. Stagnant and well mixed air in the **interior of a rotor (R)**. Moderate turbulence with some patches of more strongly turbulent air.

Impact of a stable valley atmosphere (T-REX IOP 1)

- In the morning hours of **T-REX IOP 1, lee waves** of similar strength as those of IOP 3 developed **but the valley atmosphere remained decoupled** from the flow aloft, leading to an **"elevated LTZ"**.
- Lee waves over the Sierra Nevada and a rotor within Owens Valley were observed only in the afternoon hours.

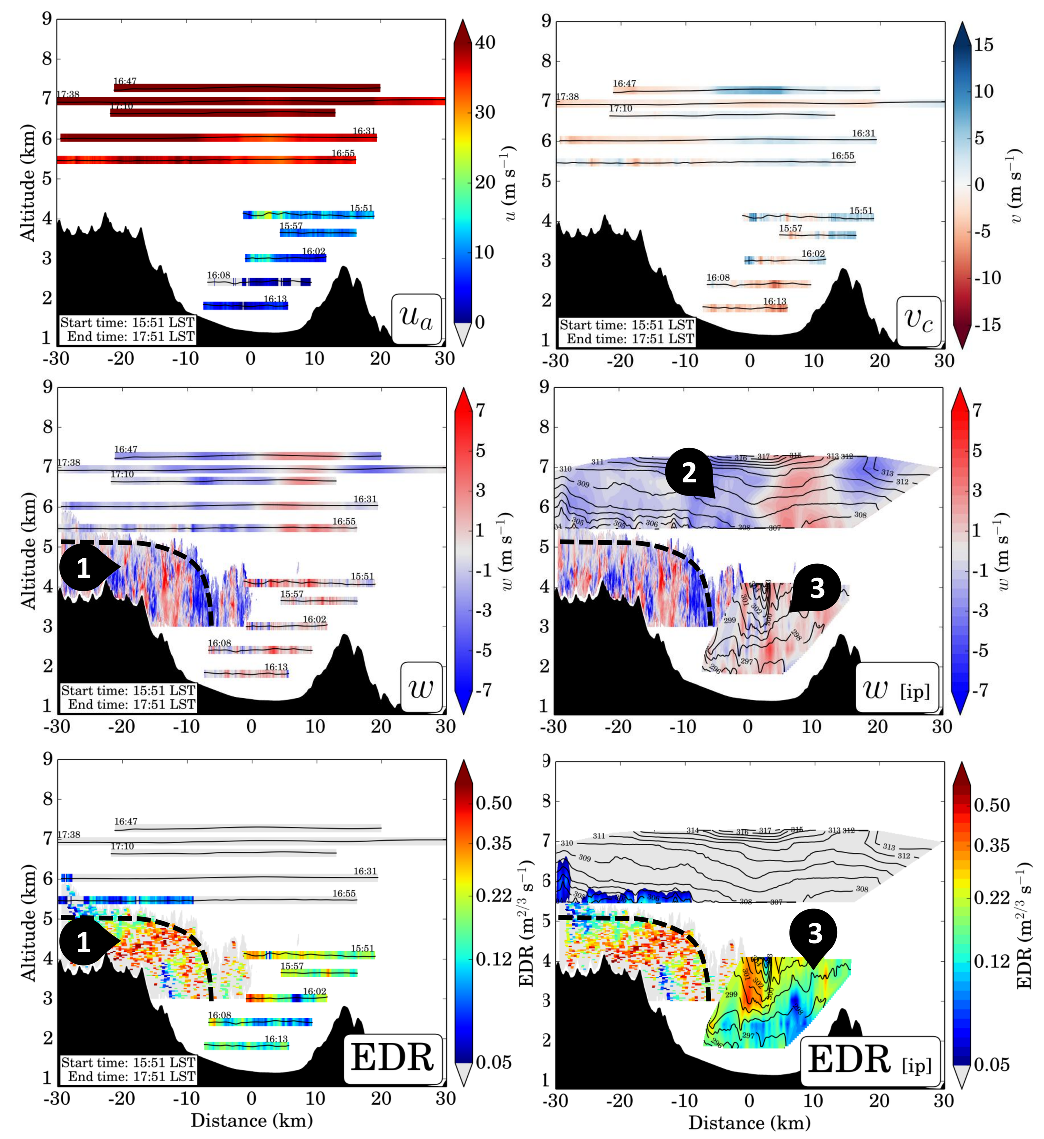


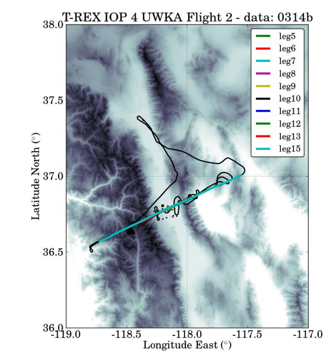


1. Strongly stratified, non-turbulent valley atmosphere. Up-valley flow due to pressure-driven channelling.
2. Lee wave pattern similar to that of T-REX IOP 3. Vertical velocities of +/- 5 m s^{-1}.
3. Elevated layer of moderate to severe turbulence around crest level. Weak stratification underneath it. **An "elevated rotor"??**

Influence of convection on LTZ formation (T-REX IOP 4)

- **Strong convection over the Sierra Nevada** was present during the afternoon hours of **T-REX IOP 4**.
- Strong gravity **waves aloft were shifted downstream**, indicative of the flow responding to an effectively heightened and widened obstacle (**"virtual topography"**).





1. Radar data reveal strong convection in the cap cloud over the Sierra. Up- and downdrafts up to +/- 10 m s^{-1}. Severe turbulence.
2. Gravity waves are shifted downstream in reaction to the increased "virtual topography".
3. The **secondary obstacle** constrains the full development of the LTZ.

Conclusions

- The complete analysis of all relevant T-REX IOPs (1, 2, 3, 4, 6, 11, and 13) calls for **augmenting the classical picture of the LTZ by several additional elements**.
- These include the **effective dimensions of the primary wave-generating obstacle, properties of the valley atmosphere** (stable vs. convective), and the **influence of the secondary ridge**.

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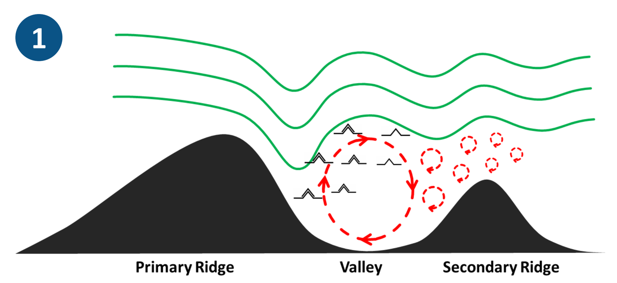

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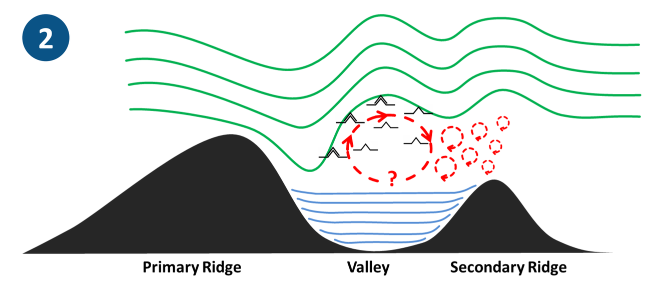

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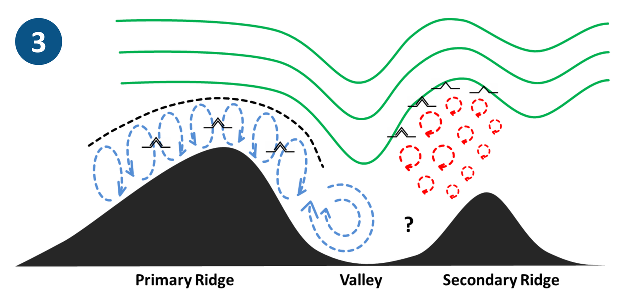

FLOW SCENARIOS for double-ridge orography

1. The "classical" LTZ, lee waves leading to a fully developed rotor circulation and turbulence in the valley.
2. A decoupled, stable valley atmosphere, lee waves aloft, and an elevated turbulence zone at crest level.
3. Strong convection over the primary ridge, delayed wave response to the virtual topography, diffuse turbulence zone.

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