Wave-induced Turbulence in the Lower Troposphere: A T-REX Perspective

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Outline

• Background on atmospheric rotors
• Terrain-induced Rotor Experiment (T-REX)
• Turbulence structures from aircraft data
• Turbulence from radiosonde data
• Summary
Atmospheric Rotors

Mountain Wave Induced Turbulence at Lower Tropospheric Levels

- Forming a strongly coupled system with overlying mountain waves and underlying boundary layer
- Improved understanding and prediction important for aviation safety in complex terrain

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Rotor Origin: Wave-induced BL Separation

Baines (1995); Baines & Hoinka (1985)

Recent idealized numerical studies:
Doyle and Durrant (2002) 2D
Vosper et al. (2006) 2D
Jiang et al. (2007) 2D
Doyle and Durrant (2007) 3D
Field Campaign

Phase I  Sierra Rotors  Phase II  T-REX
Mar-Apr 2004          Mar-Apr 2006

Field site of both phases
Southern Sierra Nevada Eastern California
T-REX Experiment Design
Ground-based Instrumentation

- Yale video cameras
- CU Tethered Lifting System
- Yale K-band Radar
- NCAR Soil H&T
- U. Innsbruck instrumented car
- NCAR MISS
- NCAR ISS DBS
- NCAR ISS MAPR
- AFRL Themosonde
- GPS sounding site
- MGLASS
- U. Utah MOBOS
- DRI AWS
- U. Leeds AWS
- U. Houston flux tower
- U. Houston sodar
- NRL Aerosol Lidar
- NCAR REAL
- ASU Doppler Lidar
- DLR Doppler Lidar
- NCAR ISFF

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T-REX Experiment Design
Airborne Platforms

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King Air Missions in T-REX

- 25 research flights
- Average duration 3.5 hrs
- Only 3 single UWKA research flights (IOP 5, IOP 11, IOP 12)
- Only 2 research flights flown outside the target area (IOP 15)
- Basic cross-mountain tracks: A (275°), B(245°), C(215°)
- Vertical stack and box

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Typical Upstream Profile

N ~ 0.01 s\(^{-1}\)
U ~ 15-20 ms\(^{-1}\)
H ~ 3 \times 10^3 m

Fr = \frac{U}{NH} \sim 0.5-0.7
Observed Lower-Tropospheric Wave Structures
Moderate $\rightarrow$ Large Amplitude

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All Flights 1Hz Data

![Graph showing data points for Abs(Wmax - Wmin) above and below 4km.](image)

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All Flights 1Hz Data

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All Flights 1Hz Data

Lee-waves

Downslope windstorms
Turbulence Spatial Structures

Streamlines
Turbulence Dissipation Rate from 25 Hz data
$\varepsilon^{1/3} \, [m^{2/3}s^{-1}]$

Lester and Fingerhut (1974)

<table>
<thead>
<tr>
<th></th>
<th>$0.088 - 0.188$</th>
<th>$m^{2/3}s^{-1}$</th>
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<tbody>
<tr>
<td>Light</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Moderate</td>
<td>$0.229 - 0.314$</td>
<td>$m^{2/3}s^{-1}$</td>
</tr>
<tr>
<td>Severe</td>
<td>$0.351 - 0.459$</td>
<td>$m^{2/3}s^{-1}$</td>
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</tbody>
</table>
“Downslope Windstorms”

IOP 3b

IOP 6c
IOP 3a

\( \varepsilon^{1/3} \text{ [m}^{2/3}\text{s}^{-1}] \)
IOP 3a Aircraft Data

16:57 - 19:00 UTC
4.8 - 8.6 km ASL  Track A
Waves

19:03 - 19:26 UTC
3.5 - 4.0 km ASL  Track A
Rotor

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T-REX IOP 6 Coordinated Three-Aircraft Mission

HIAPER 1 RF (RF05) Mar 25

BAe146-3 RF (B179-181) Mar 24 & 25

17:43-22:34

17:20-19:50

16:23-18:53

South 43 kft

w (m s⁻¹)

Terrain (m)

North 43 kft

w (m s⁻¹)

Terrain (m)

UWKA 3 RF Mar 24 & 25

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T-REX IOP 6 Coordinated Three-Aircraft Mission

HIAPER 1

17:43-22:34

17:20-19:50

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South 43 kft

North 43 kft

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IOP 6  Aircraft Data

16:23 - 17:26 UTC
5.3 - 7.2 km ASL  Track B
Above Rotor and Cap Clouds

17:41 - 17:59 UTC
3.9 km ASL  Track B & Box
Below Rotor Cloud Base
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Turbulence Characteristics Observed Over Owens Valley (IOP 1)

Objective Analysis of W and U of IOP 1a

Wavelet Analysis: IOP 1a

w (m s\(^{-1}\)) at 4900 m

w (m s\(^{-1}\)) at 3600 m

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Internal Rotor Structure: Subrotors

Doyle et al. (2008)
Radiosonde: Rise rate calculation

Buoyancy force = Drag force

\[ [BV \rho_s - (m_s + m_b + m_h)] \times g = C_D \times A \times \rho \times \frac{V_{rr}^2}{2} \]

\[ m_h = BV \times \rho \times 4.0026/28.9644 \]

\[ V_{rr} = \left( \frac{2 \times BF}{C_D \times A \times \rho} \right)^{1/2} \]

BV0: ~20-40 ft³  
m_s = 330g  \hspace{1cm} m_b = 200g  
C_D \sim 0.2-0.5  
\[ A = 4 \times \pi \times \left[3 \times \frac{BV}{(4 \times \pi)}\right]^{2/3} \]
\[ \rho: \text{density (kg m}^{-3}\text{)} \]

Vertical Wind = \( V_{\text{measured}} - V_{\text{rr}} \)
Factors affecting $C_d$ (Lalas and Einaudi, 1980)

1. The radiosonde balloon is not super-pressurized, so does not retain the spherical shape. For $Re=10^5$, $C_d \approx 0.5$ for a sphere, $C_d = 1.2$ for a semi-sphere.

2. The weight of the instrument package results in some stretching of the bottom part, which leads to a shape with a conical afterbody and then reduce $C_d$.

3. The balloon motion in the atmosphere lies in a flow regime with $Re$ close to the critical value of $2.5 \times 10^5$, near which $C_d$ experiences drastic changes.

4. The free stream turbulence and unsteadiness affects $C_d$.

5. The dependence of $C_d$ on the effective radius of the balloon, which is almost impossible to estimate.
T-REX Valley Soundings 1Hz Data

GAUS-ISS (March 2006; Soundings 1-30)

- Stratospheric Gravity Waves
- Waves/Rotors
- Larger Rise Rate and Larger Variability Turbulence

May 29, 2008  IMAGE TOY 2008 Geophysical Turbulence Phenomena
Figure 6.2. The sorting algorithm. This is used to create a stable profile of density with $d\rho/dz \leq 0$ shown in (b) from the observed profile, (a), in which there is a statically unstable region where $d\rho/dz > 0$. The points, A–O, represent the discrete measured values of density at their respective levels, $z$. Those between C and N are statically unstable in the sense that, because of the density inversion, there is denser fluid above or less dense below them even though the density only decreases with depth between G and J. The vertical lines and arrows show the displacements in $z$ required to re-sort the observed density profile into the statically stable order shown.

Ozmidov Scale (indicative of maximum overturning scale in a stably stratified fluid):

$$L_O = \epsilon^{1/2} N^{-3/2}$$

Thorpe scale $L_T \sim L_O$

Therefore TKE dissipation rate

$$\epsilon = c_K L_T^2 N^3$$

Also Eddy Diffusivity

$$K = \gamma \epsilon N^{-2}$$
IOP 13
(April 16, 2006)
Upstream Sonde
Comparison with Aircraft Data along the Sonde Track

IOP 03 (March 09)  IOP 13 (April 16)  IOP 15 (April 26)

Black points - x component, Red points - average of 3 components
Summary

- Low-level terrain-induced perturbations consist predominantly of (partially) trapped lee waves – long wavelength waves (>30 km) have largest amplitudes
- Lower-tropospheric turbulence zones: Behind the leading edge of the wave updrafts and underneath wave crests, Turbulence levels encountered light to severe
- Internal rotor structure: KH instability of the separated BL vortex sheet leads to preponderance of small scale eddies within the rotor
- Estimates of turbulence dissipation rate (TDR) from dropsonde data utilizing stably stratified turbulence arguments agrees well with TDR derived from aircraft observations