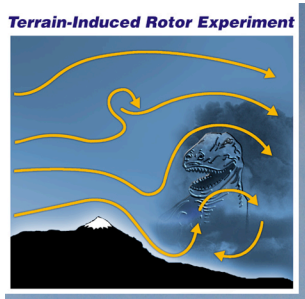


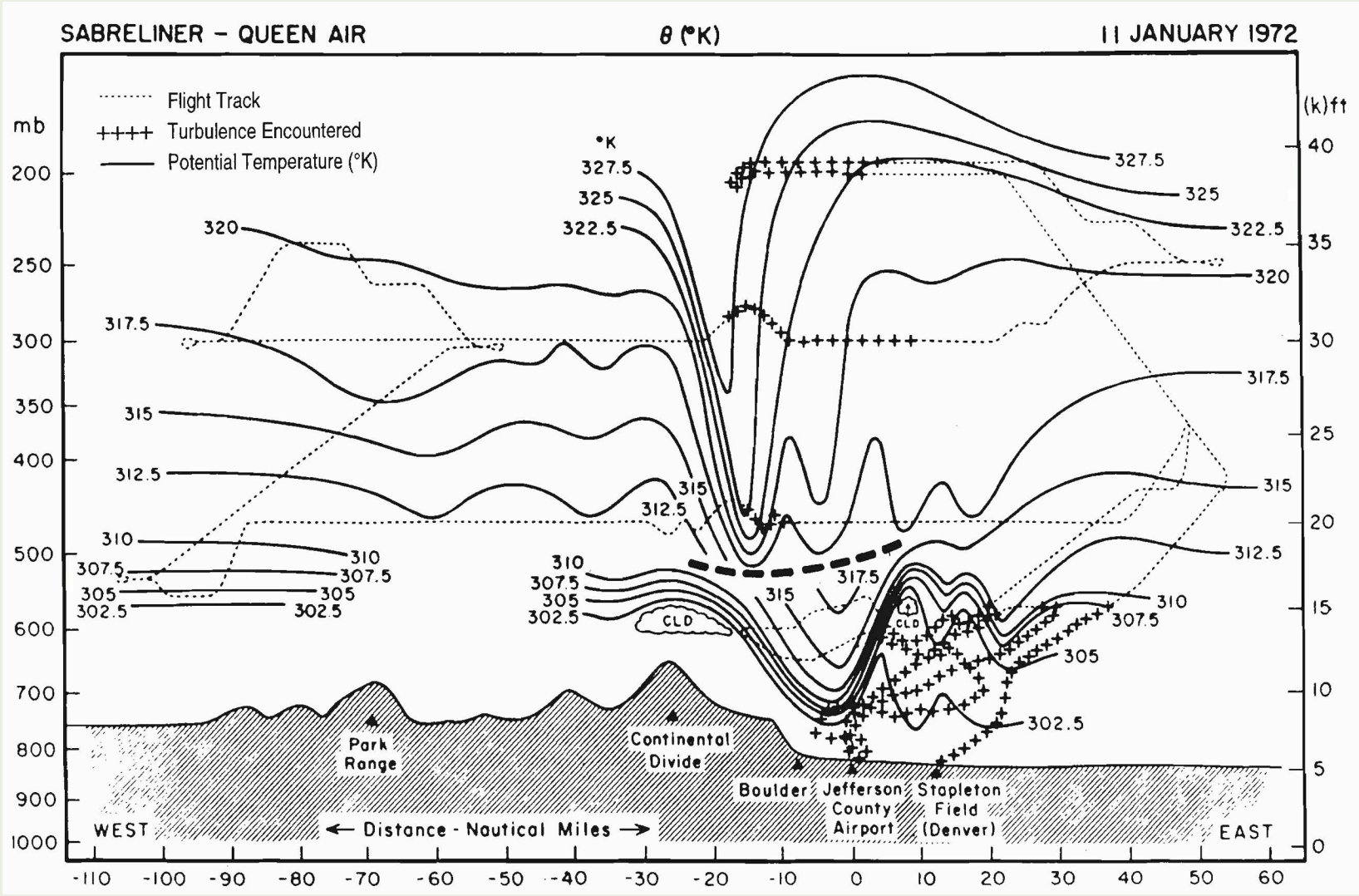
Wave-induced Turbulence in the Lower Troposphere: A T-REX Perspective

Vanda Grubišić

Division of Atmospheric Sciences

Desert Research Institute

Acknowledgements: June Wang (NCAR), Lakshmi Kantha (CU Boulder), James Doyle (NRL Monterey), Qinfang Jiang (NRL Monterey), Al Rodi (U Wyoming)


SABRELINER – QUEEN AIR
θ (°K)
11 JANUARY 1972
Flight Track
Turbulence Encountered
Potential Temperature (°K)
mb
(k)ft
°K
327.5
325
322.5
320
317.5
315
312.5
310
307.5
305
302.5
CLD
Park Range
Continental Divide
Boulder
Jefferson County Airport
Stapleton Field (Denver)
WEST
← Distance - Nautical Miles →
EAST

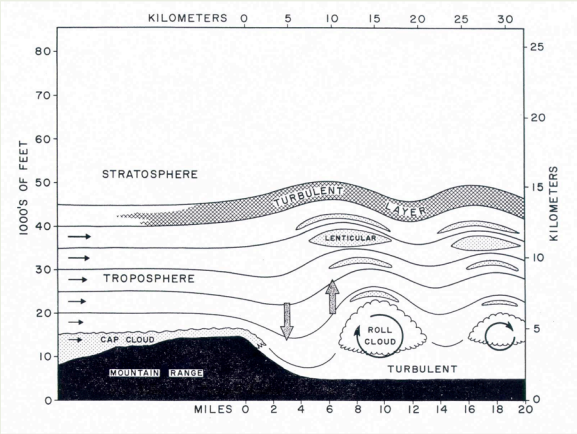
Lilly (1978)

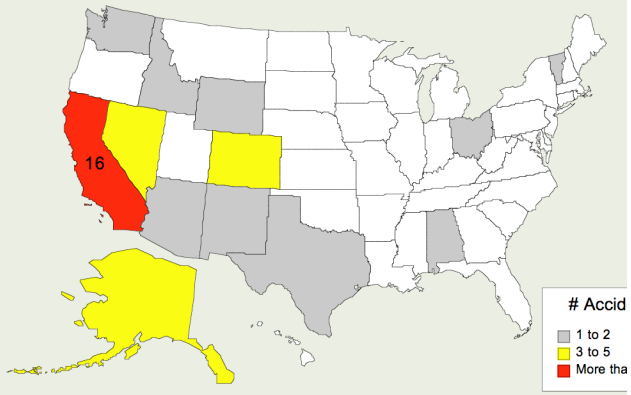
Outline

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

Atmospheric Rotors

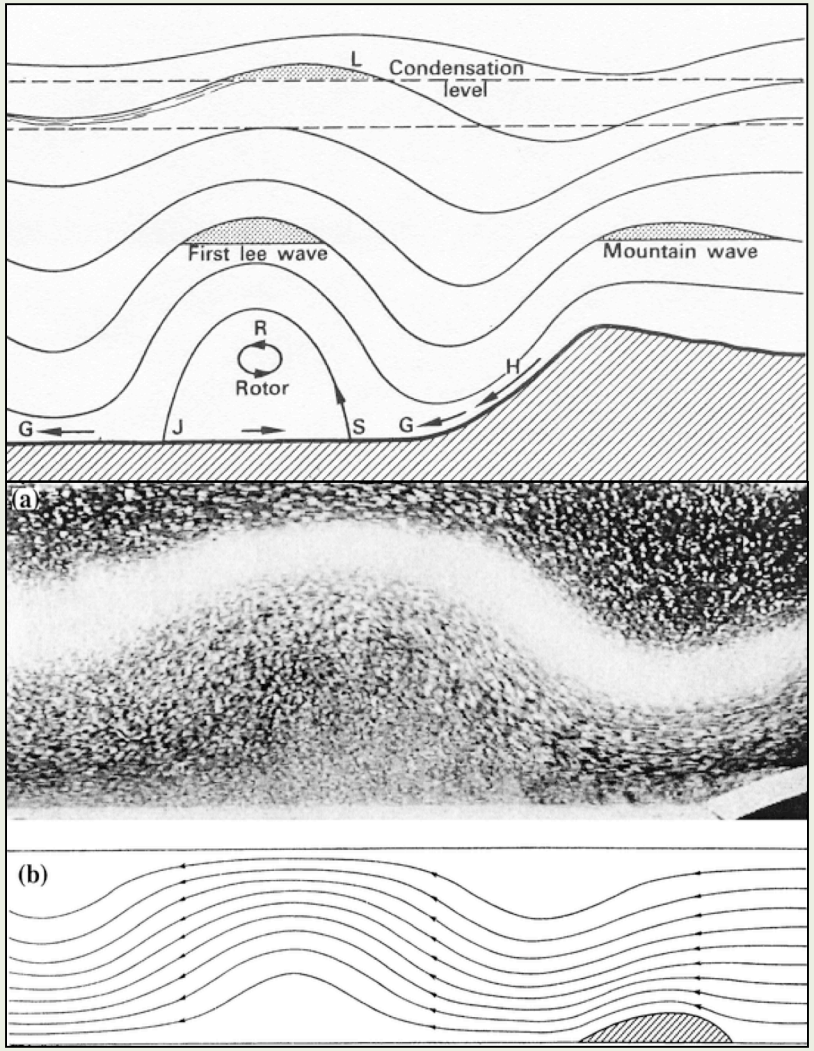
Mountain Wave Induced Turbulence at Lower Tropospheric Levels



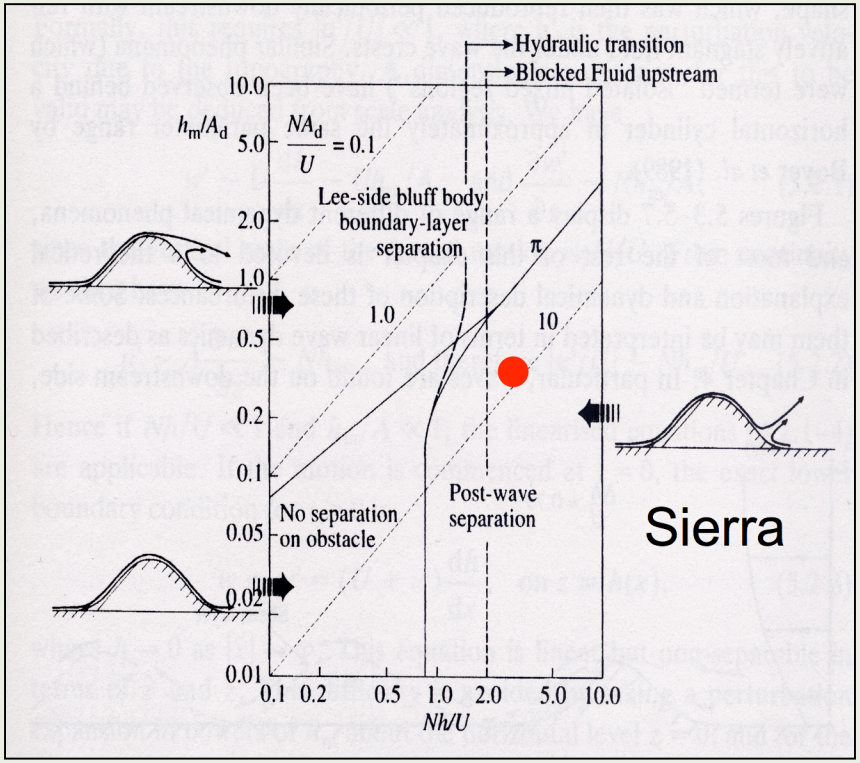


- Forming a strongly coupled system with overlying mountain waves and underlying boundary layer
- Improved understanding and prediction important for aviation safety in complex terrain

Rotor Origin: Wave-induced BL Separation



Long (1955)



Baines (1995); Baines & Hoinka (1985)

Recent idealized numerical studies:

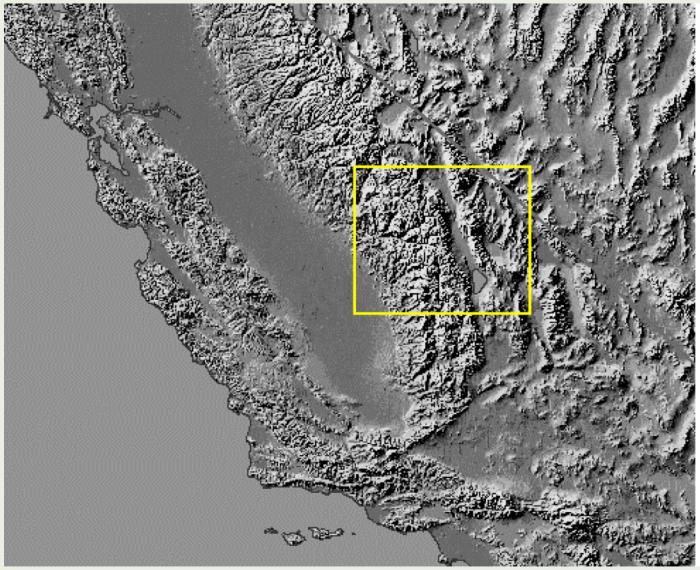
Doyle and Durran (2002)	2D
Vosper et al. (2006)	2D
Jiang et al. (2007)	2D
Doyle and Durran (2007)	3D

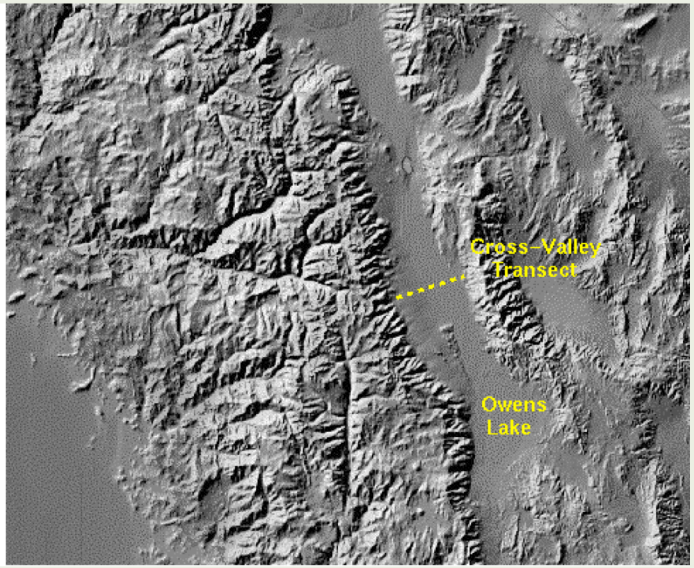
Field Campaign

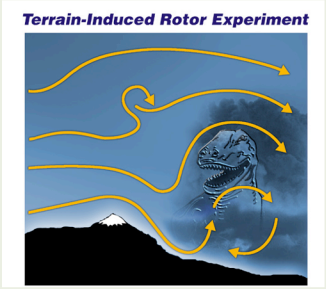
Phase I **Sierra Rotors**
Mar-Apr 2004

Phase II **T-REX**
Mar-Apr 2006

Field site of both phases
Southern Sierra Nevada Eastern California

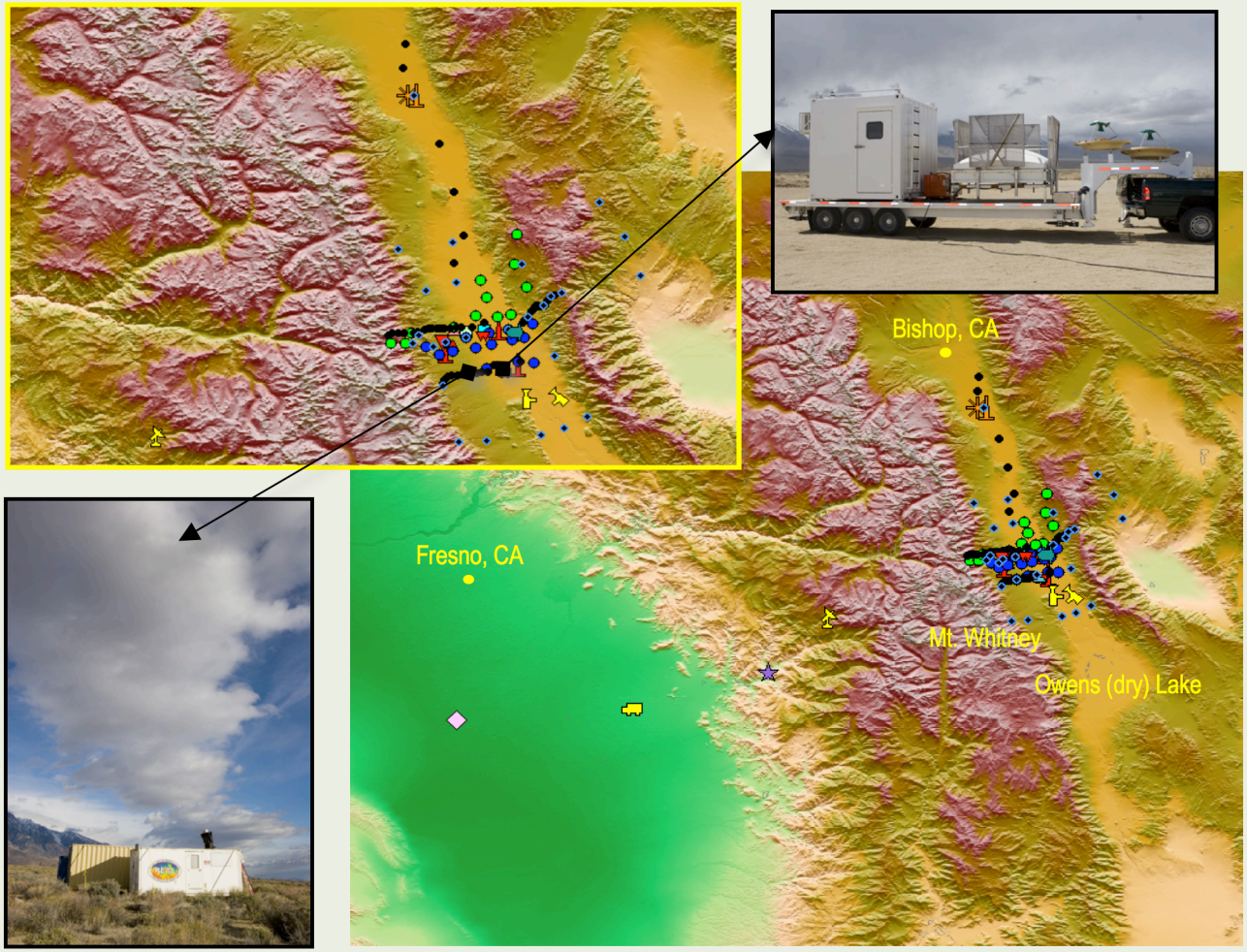


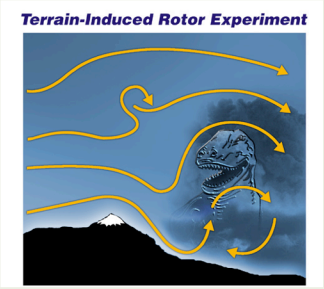




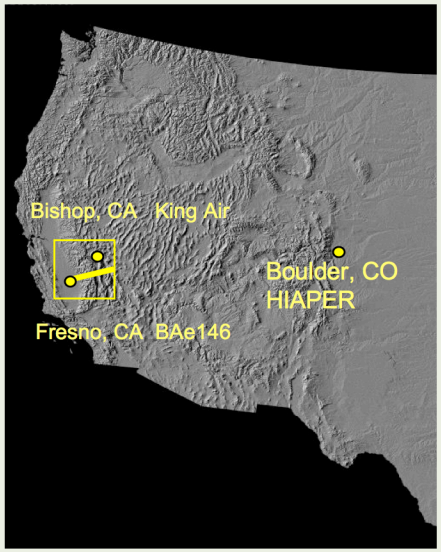
T-REX Experiment Design
Ground-based Instrumentation

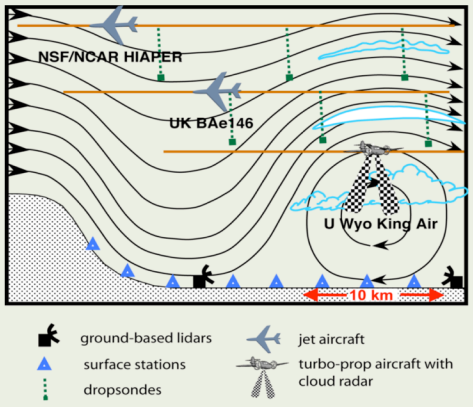
- Yale video cameras
- CU Tethered Lifting System
- Yale K-band Radar
- NCAR Soil M&T
- U. Innsbruck instrumented car
- NCAR MISS
- NCAR ISS DBS
- NCAR ISS MAPR
- AFRL Thermosonde
- GPS sounding site
- MGLASS
- U. Utah HOBOs
- DRI AWS
- U. Leeds AWS
- U. Houston flux tower
- U. Houston sodar
- NRL Aerosol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



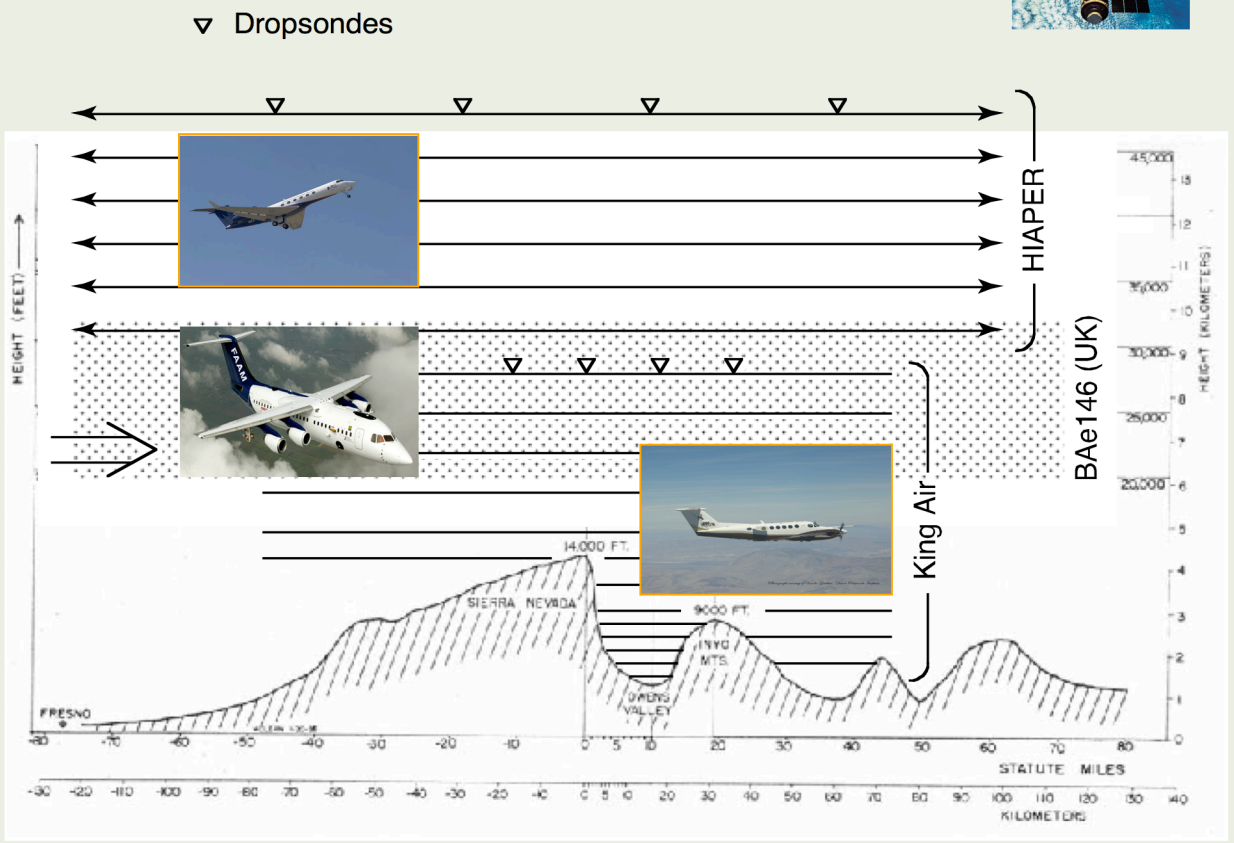


T-REX Experiment Design
Airborne Platforms

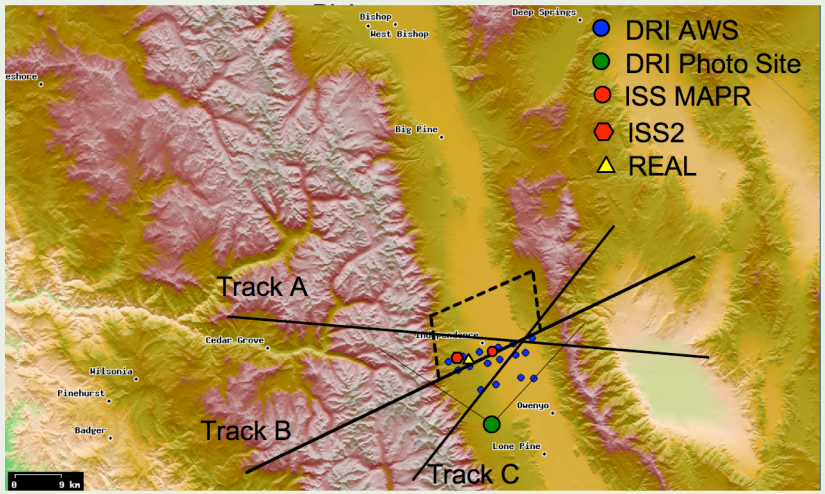


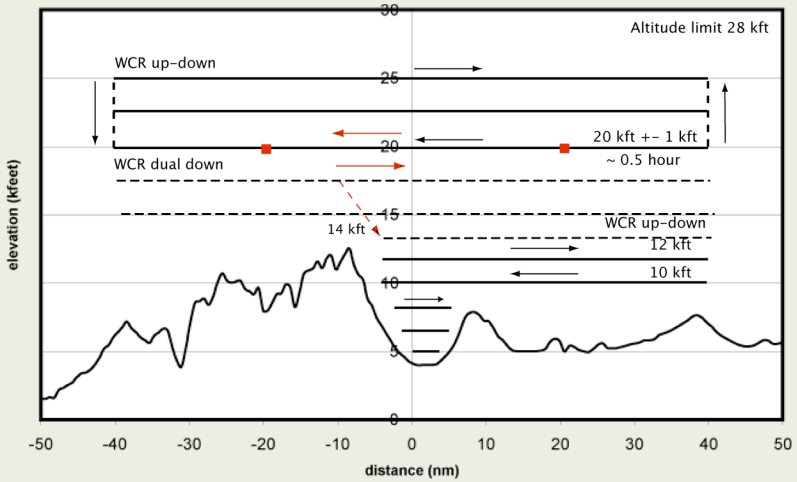


ground-based lidars
surface stations
dropsondes
jet aircraft
turbo-prop aircraft with cloud radar



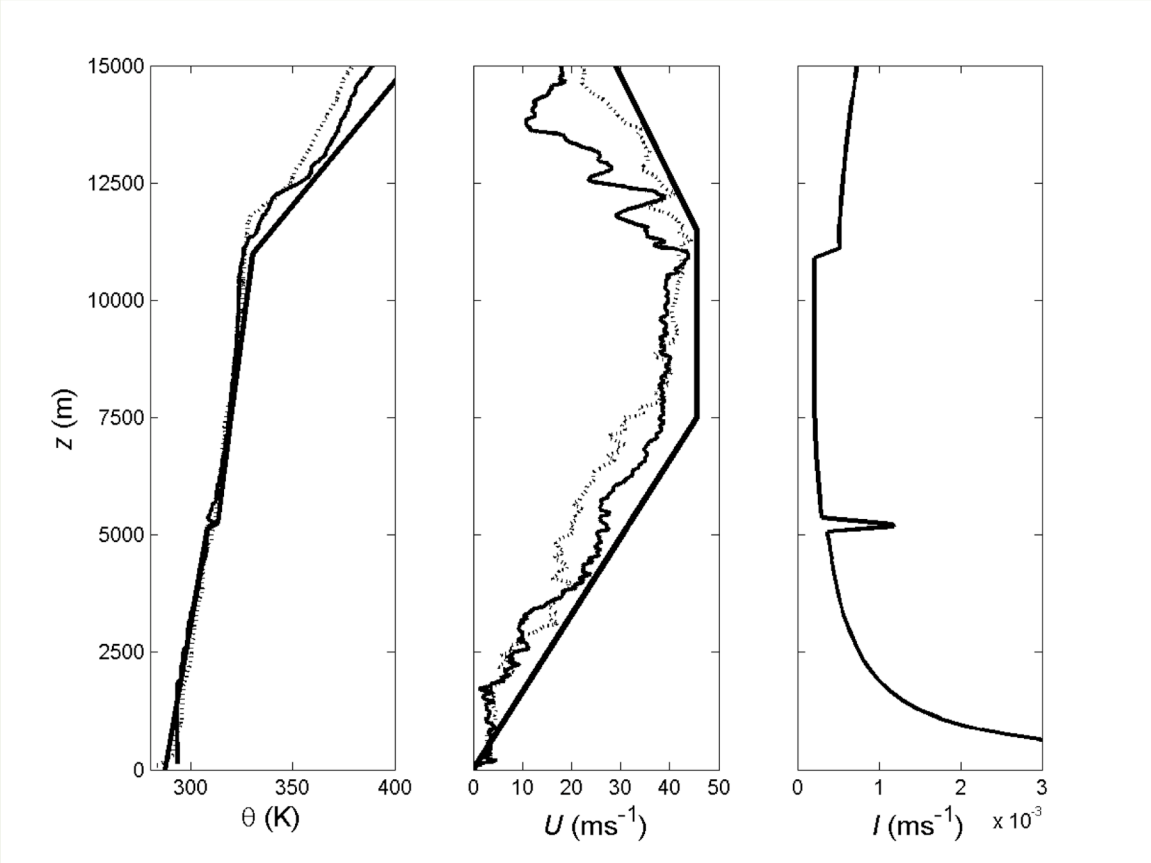
King Air Missions in T-REX





- 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 (275º), B(245º), C(215º)
- Vertical stack and box

Typical Upstream Profile

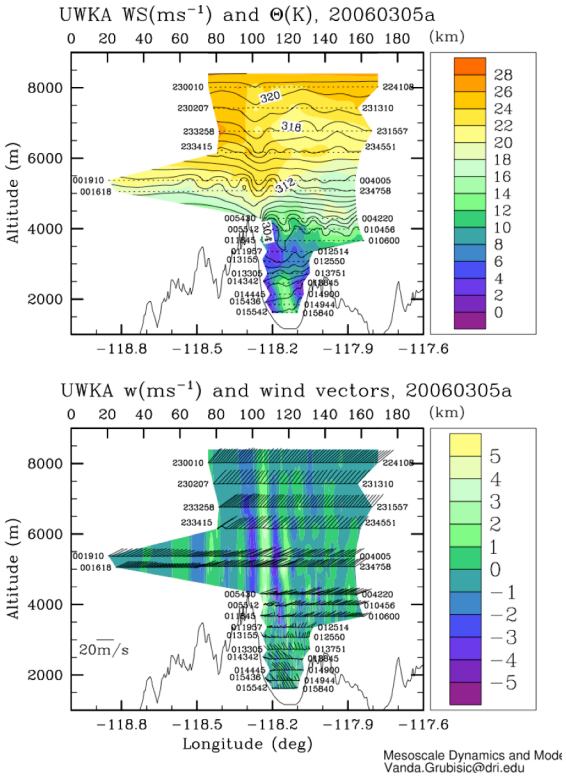


N~0.01 s^{-1}
U~15-20 ms^{-1}
H~3x10^3 m

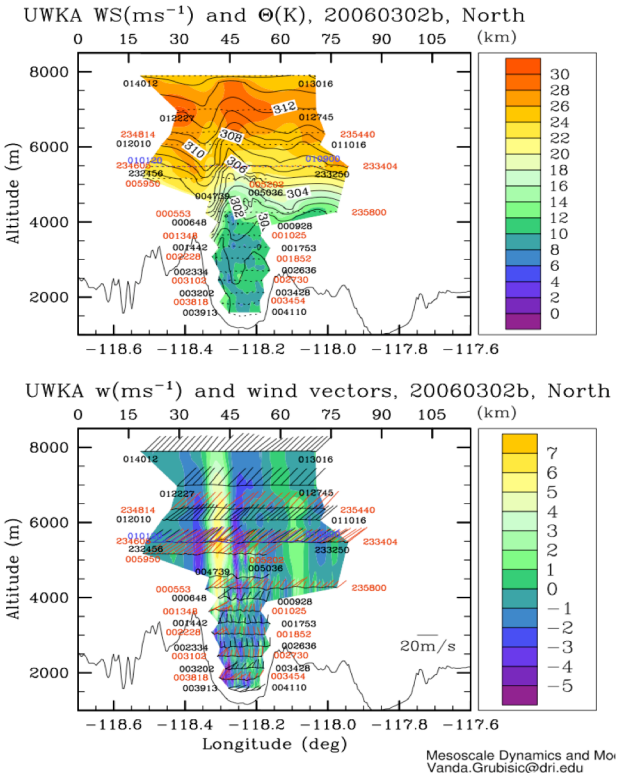
Fr=U/NH~0.5-0.7

Observed Lower-Troposheric Wave Structures
Moderate → Large Amplitude

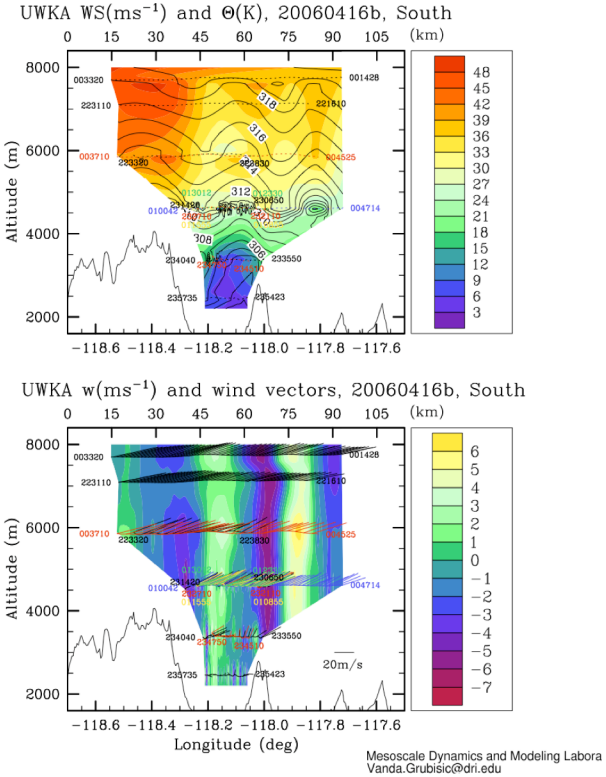
IOP 2



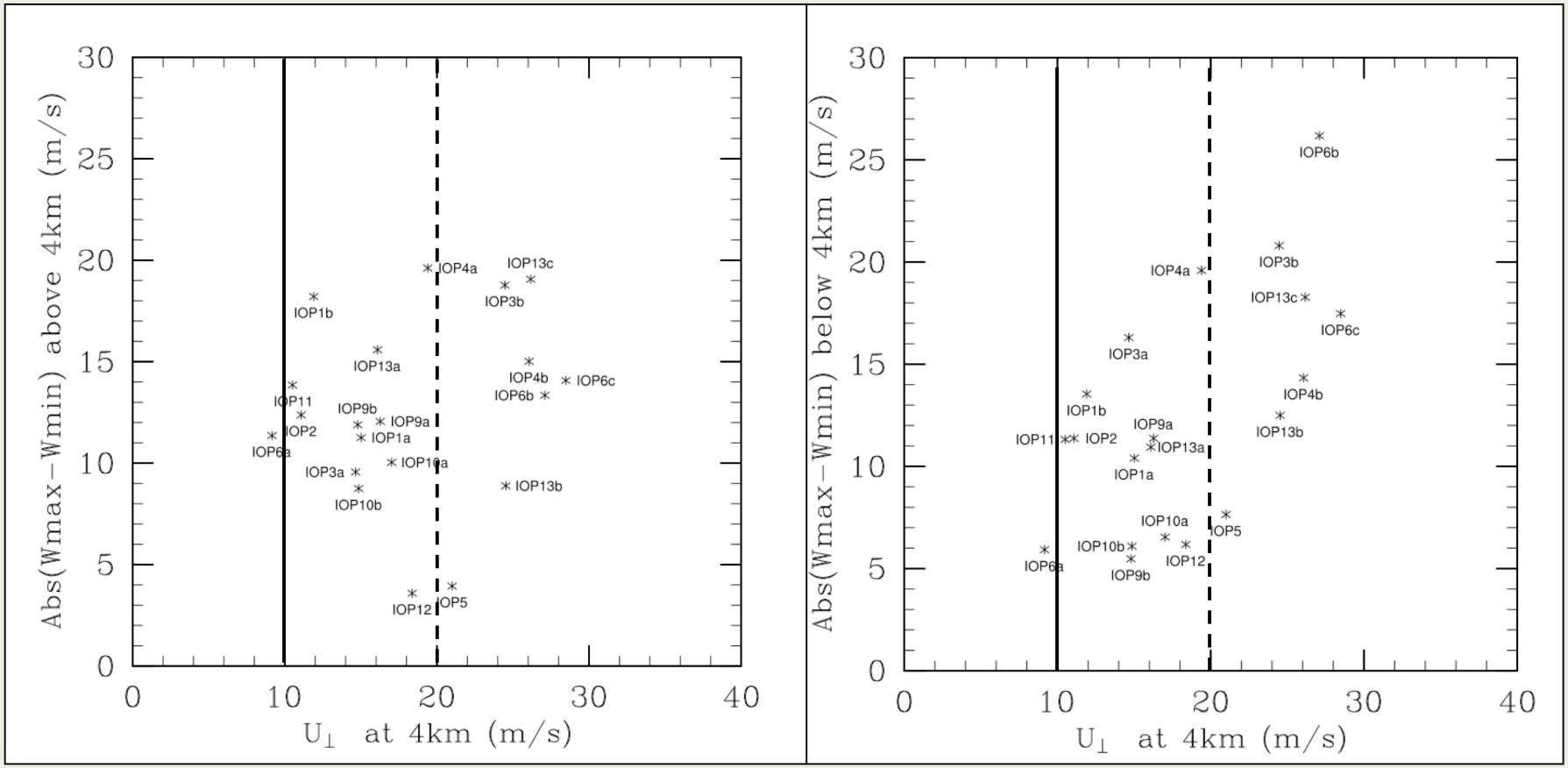
IOP 1b



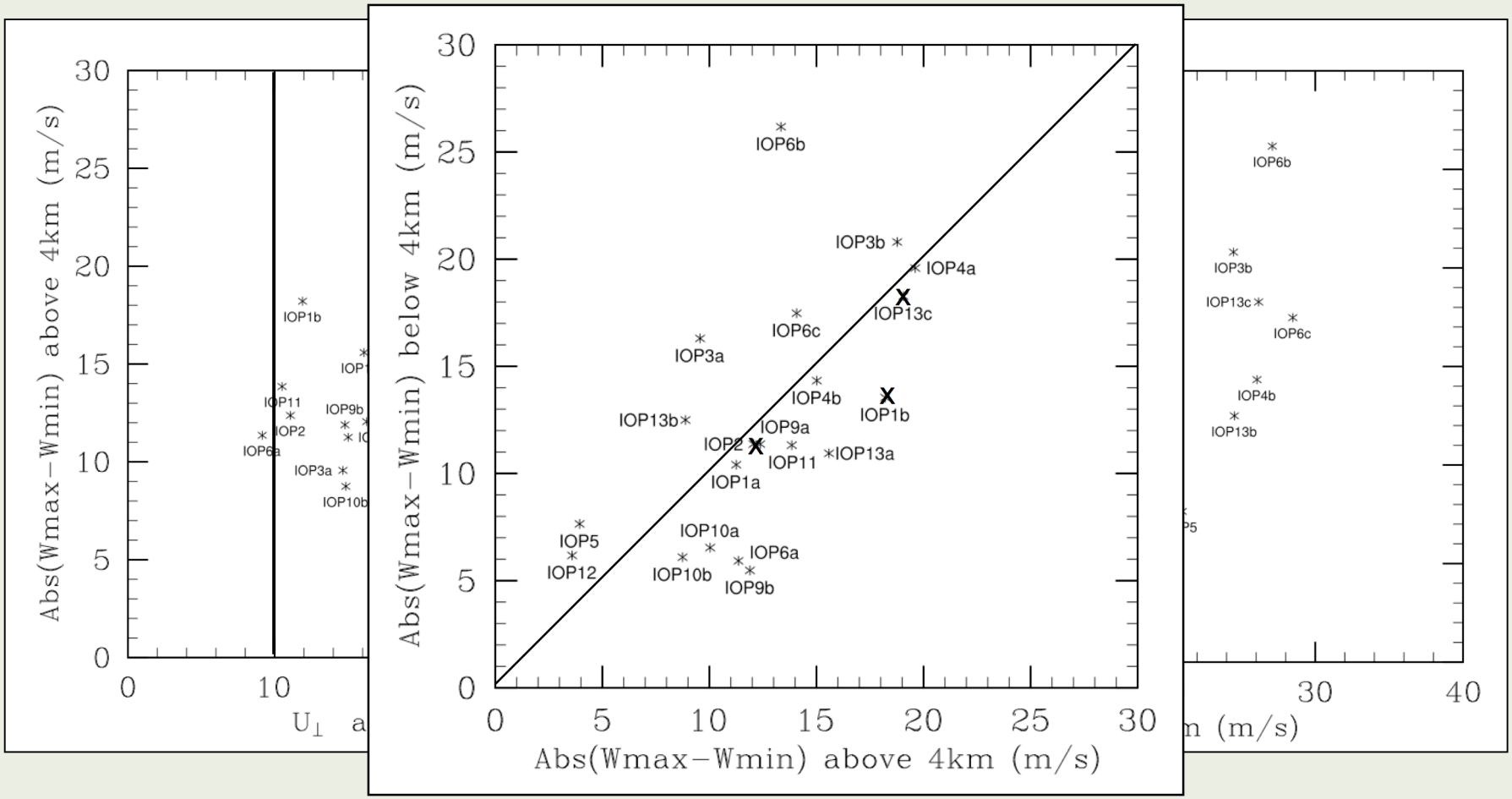
IOP 13c



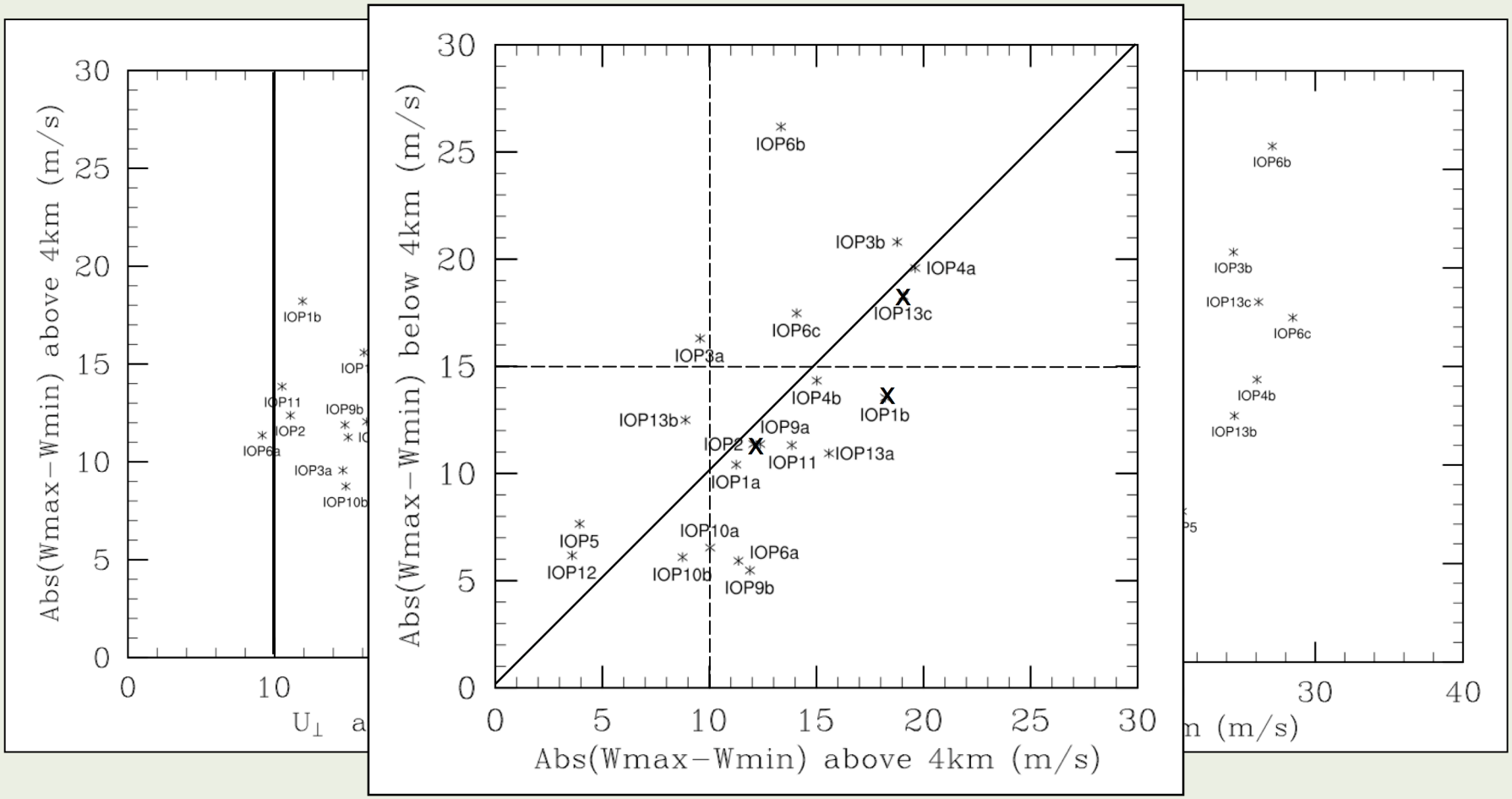
All Flights 1Hz Data



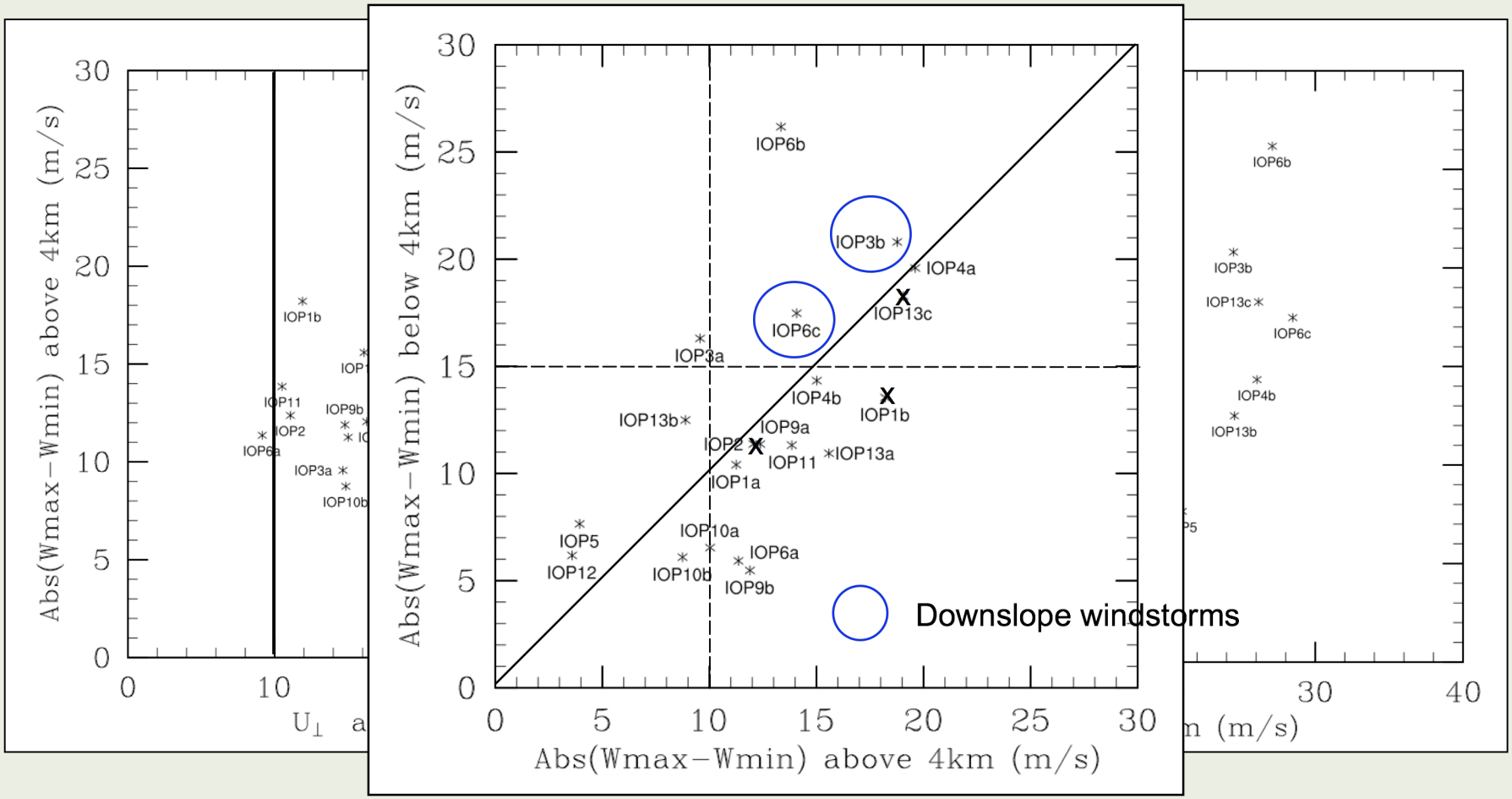
All Flights 1Hz Data



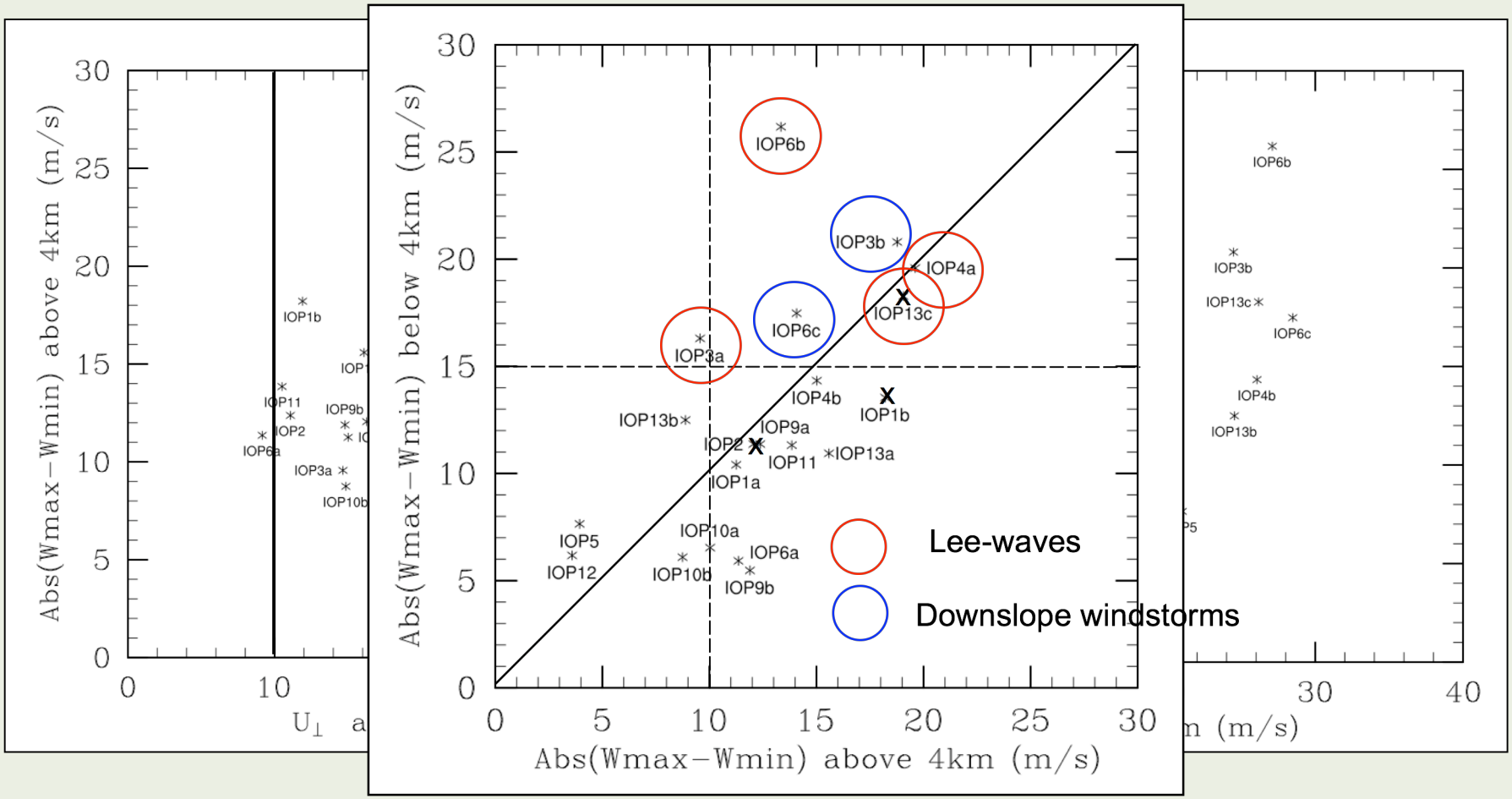
All Flights 1Hz Data



All Flights 1Hz Data



All Flights 1Hz Data



Turbulence Spatial Structures

Streamlines

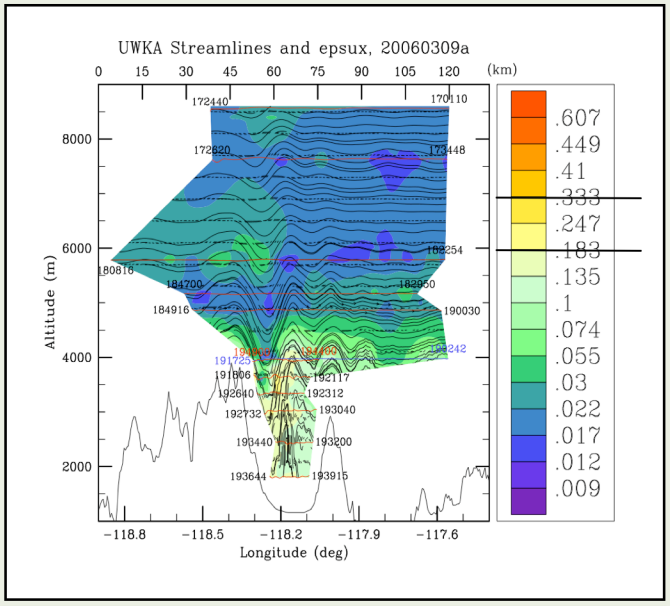
Turbulence Dissipation Rate from 25 Hz data
$\varepsilon^{1/3}$ [$m^{2/3}s^{-1}$]

Lester and Fingerhut (1974)

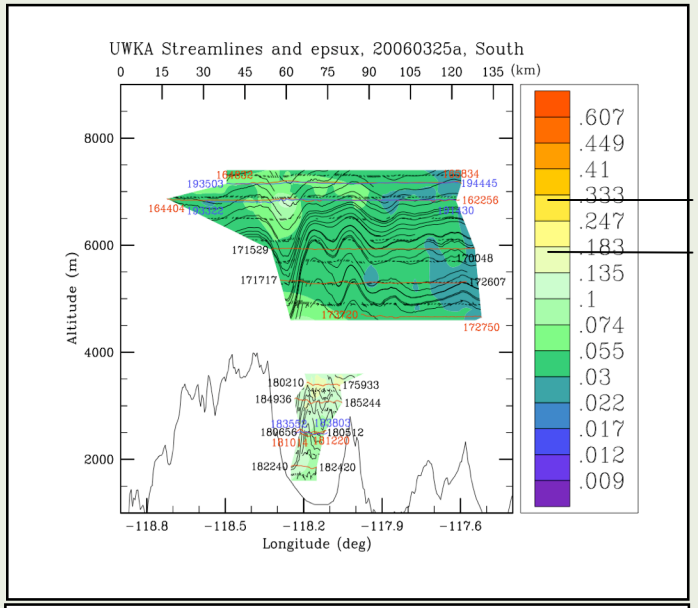
Light	0.088 – 0.188	$m^{2/3}s^{-1}$
Moderate	0.229 – 0.314	$m^{2/3}s^{-1}$
Severe	0.351 – 0.459	$m^{2/3}s^{-1}$

Lee-Waves

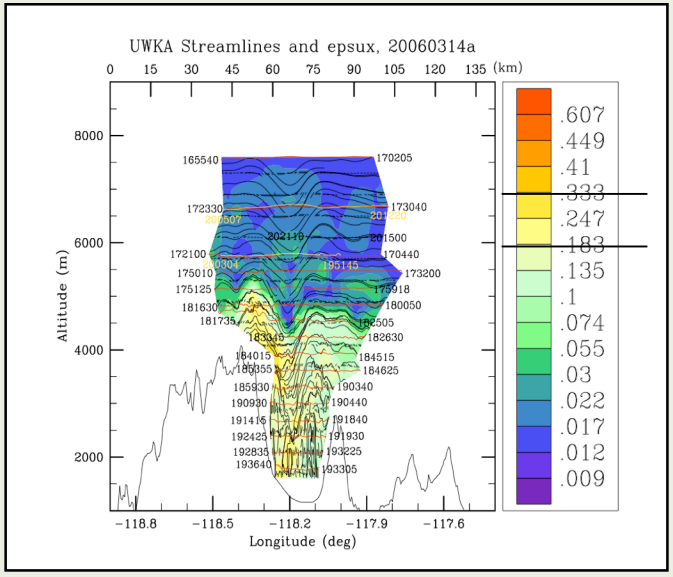
IOP 3a



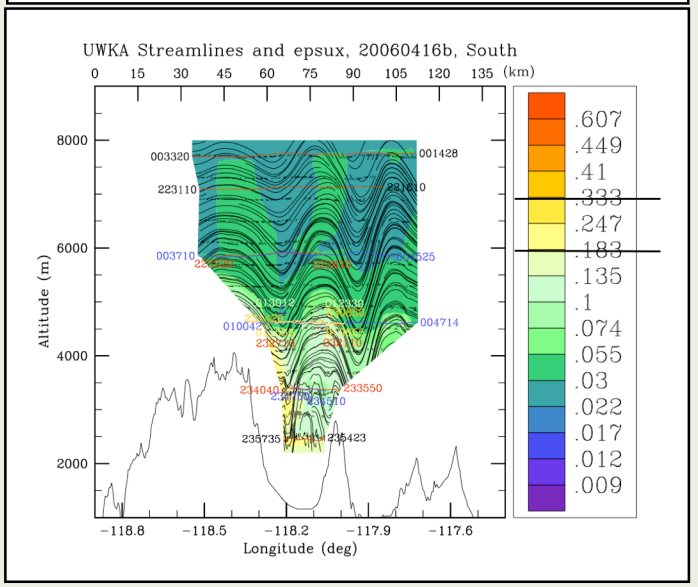
IOP 6



IOP 4a

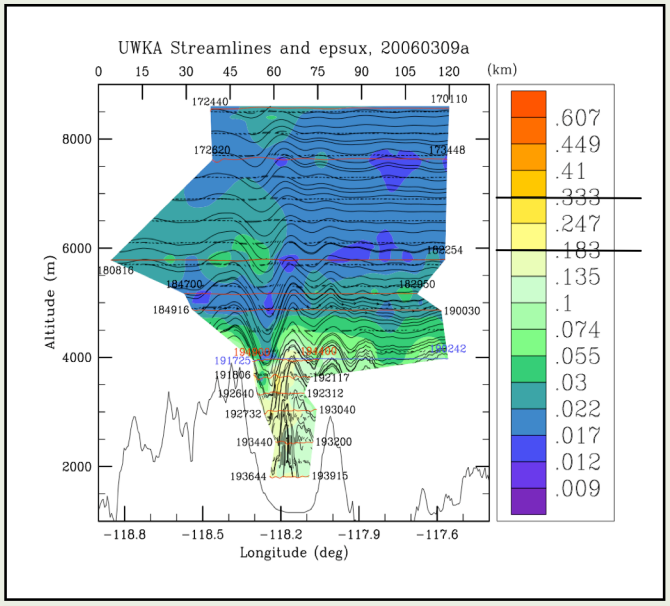


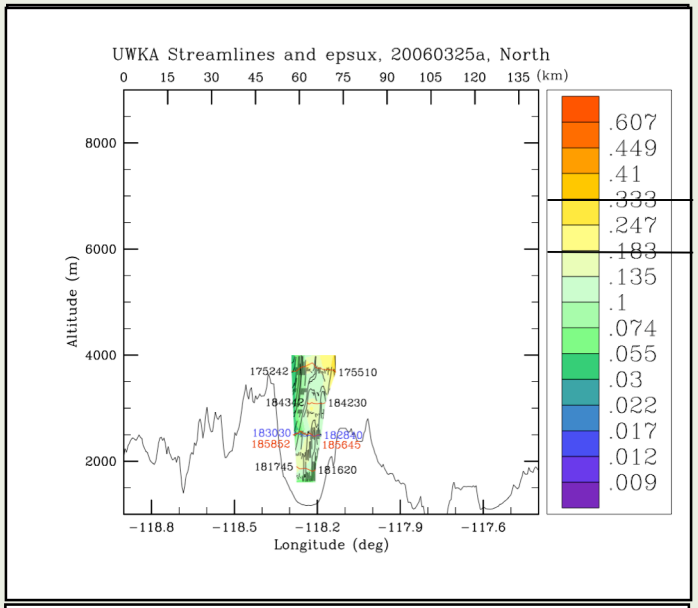
IOP 13



Lee-Waves

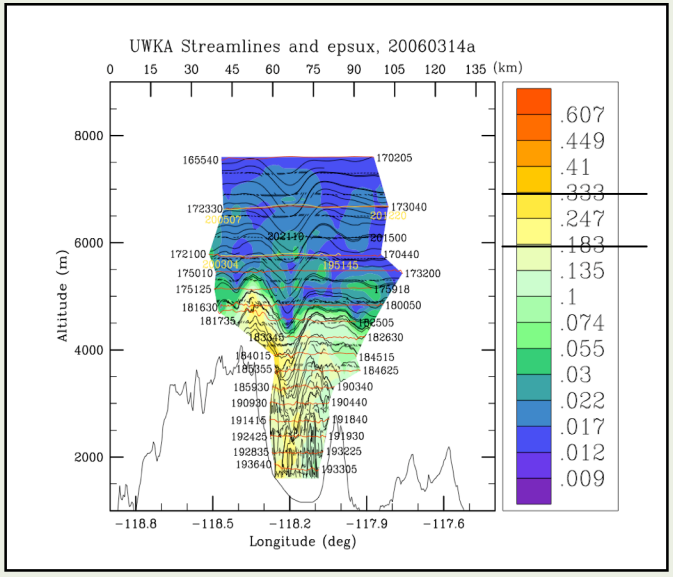
IOP 3a

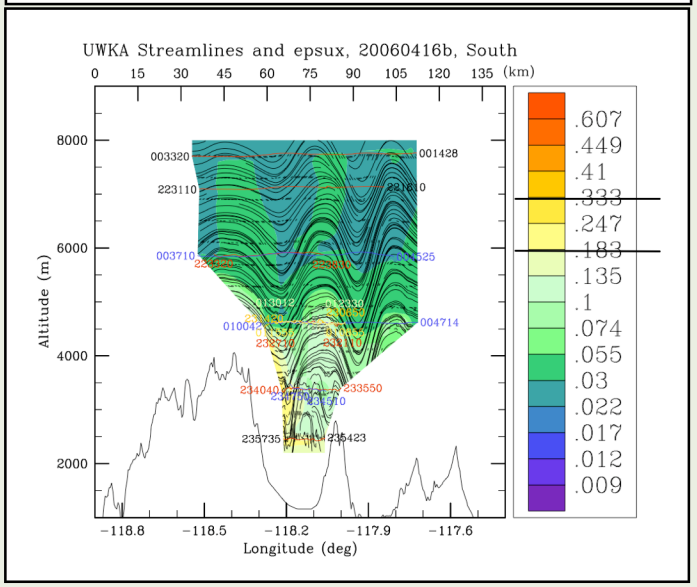




IOP 6

IOP 4a

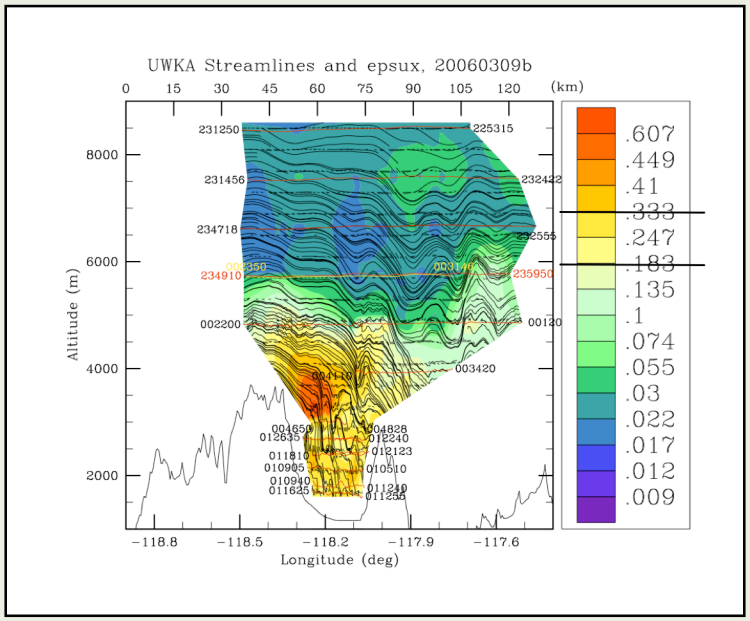




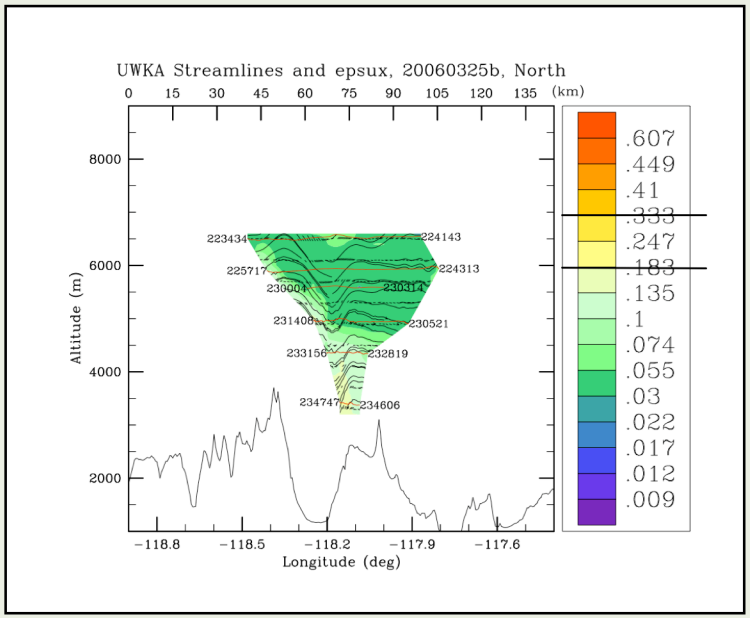
IOP 13

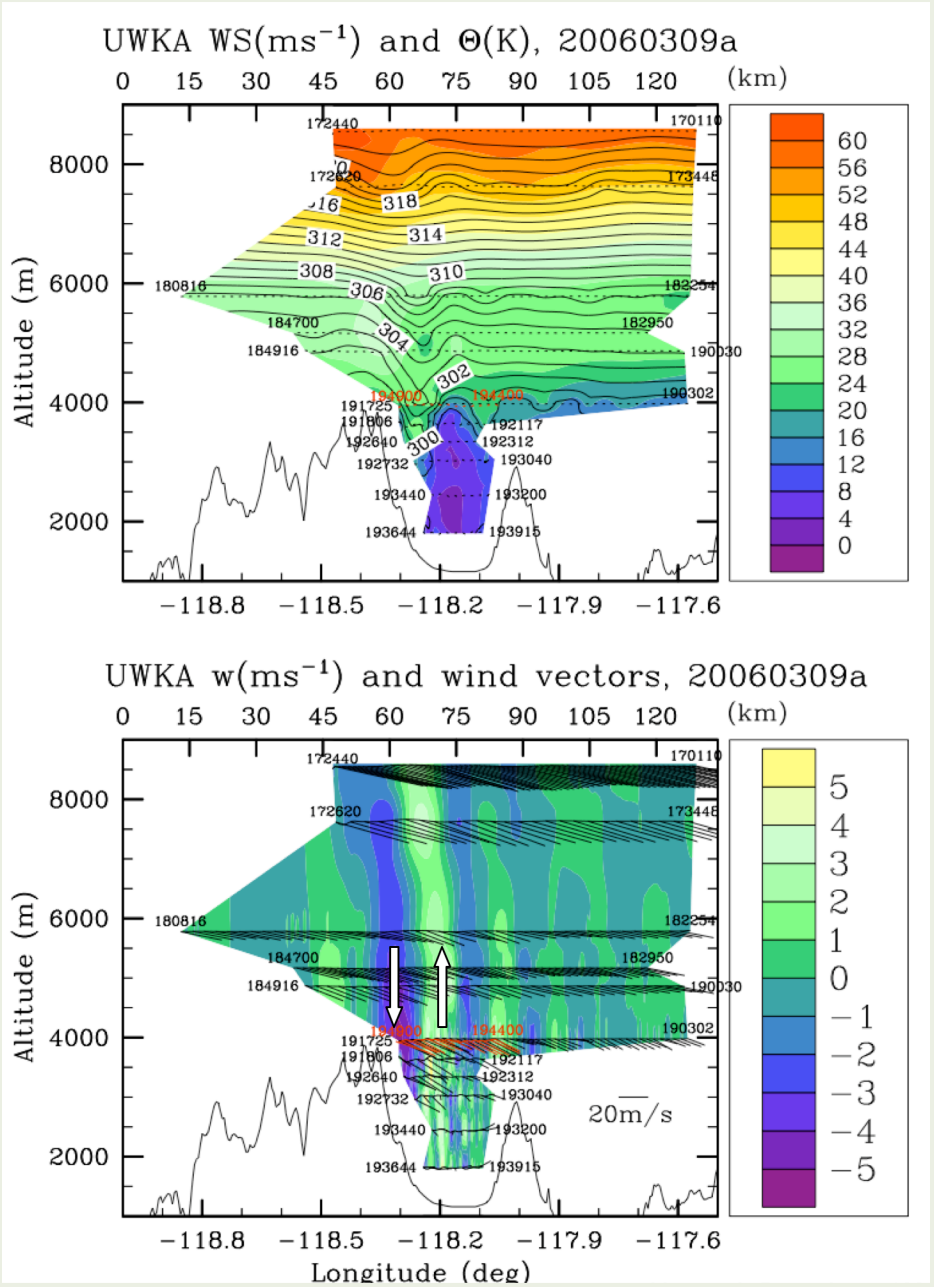
“Downslope Windstorms”

IOP 3b



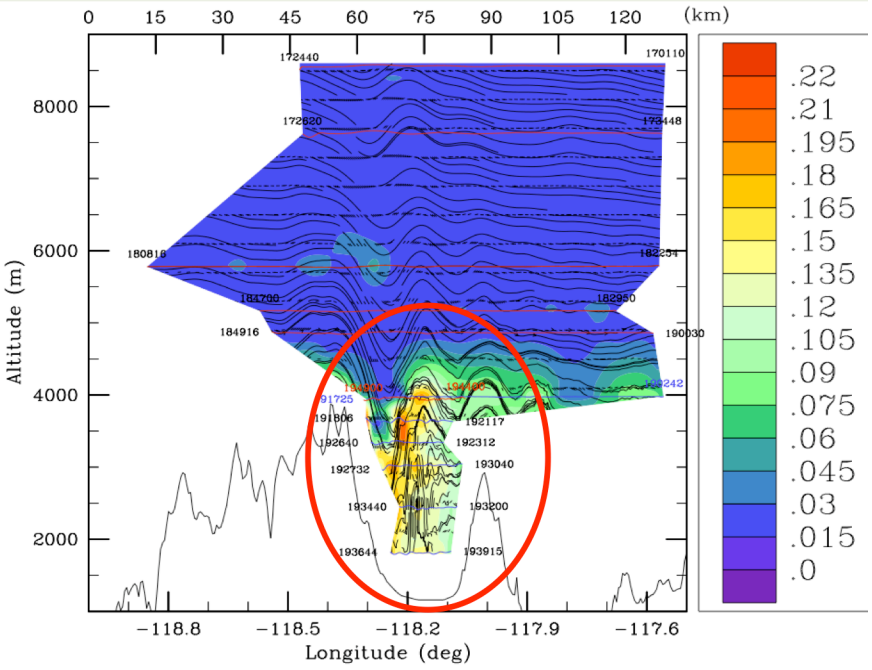
IOP 6c





IOP 3a

$\varepsilon^{1/3}$ [$m^{2/3}s^{-1}$]

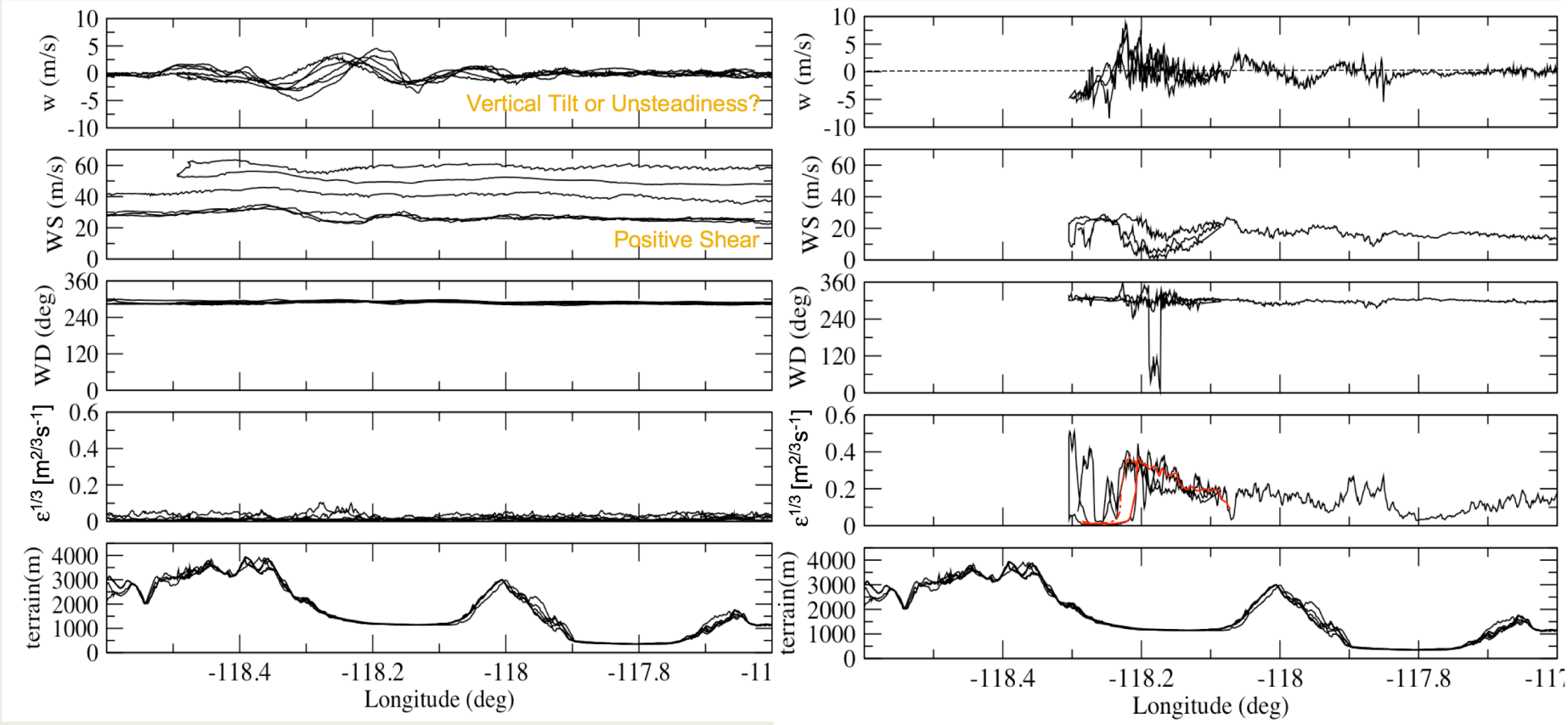


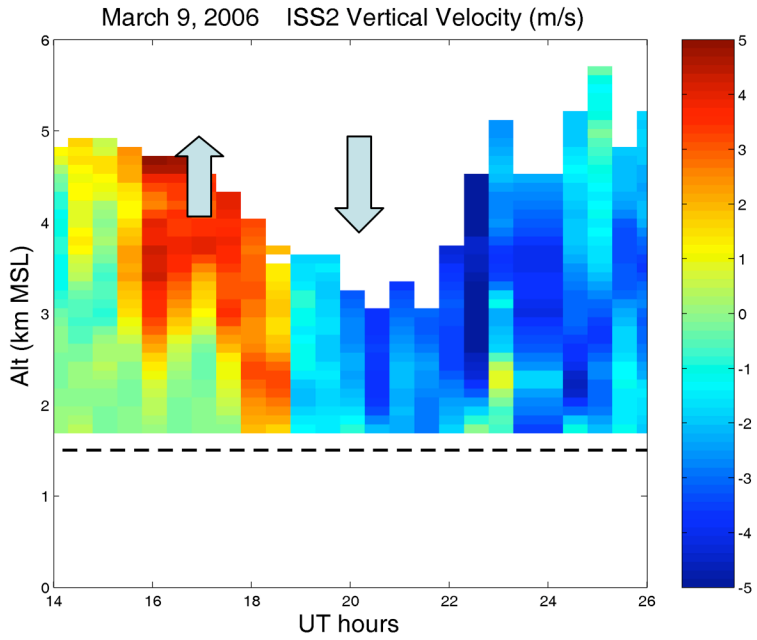
Mesoscale Dynamics and Modeling Laboratory
Vanda.Grubisic@dri.edu

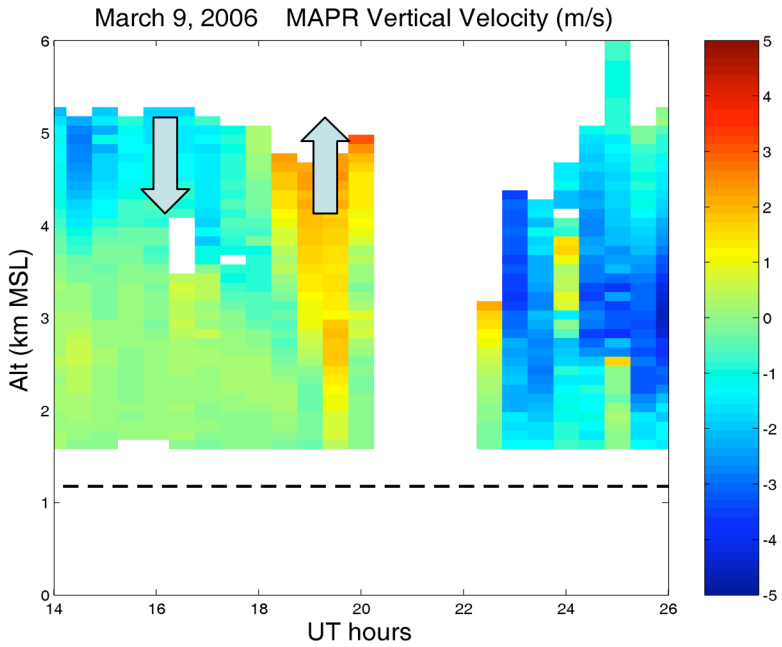
IOP 3a Aircraft Data

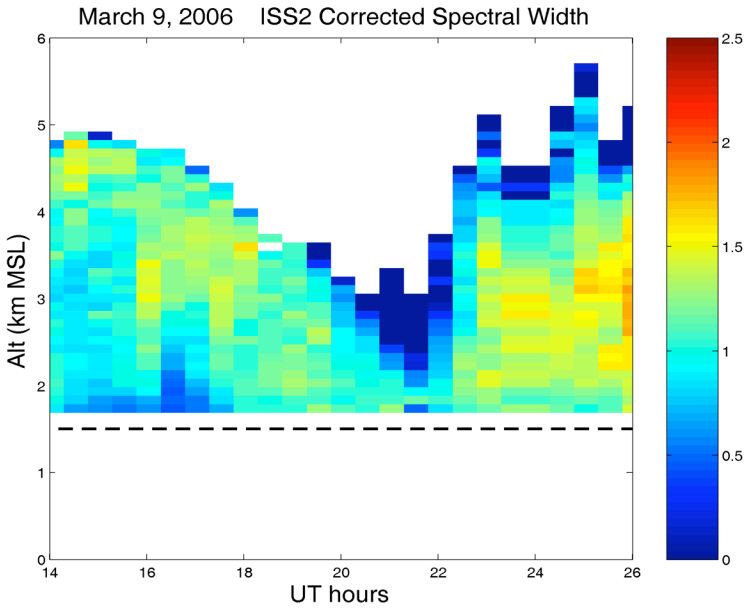
16:57 - 19:00 UTC
4.8 - 8.6 km ASL **Track A**
Waves

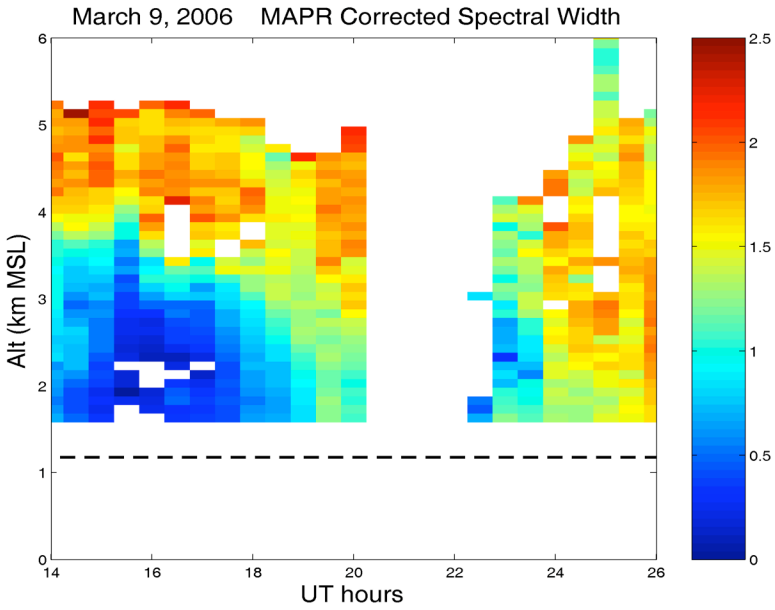
19:03 - 19:26 UTC
3.5 - 4.0 km ASL **Track A**
Rotor

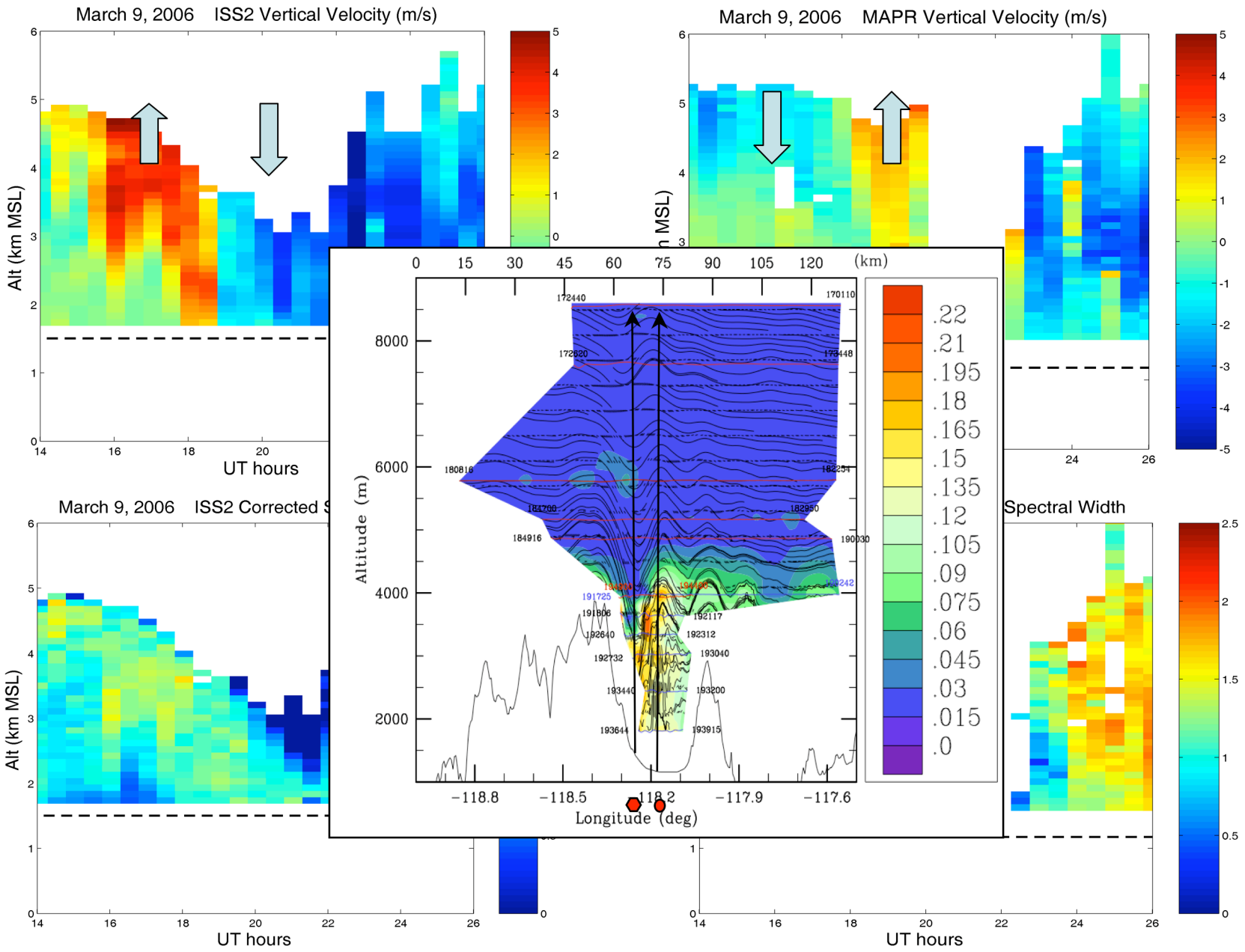



March 9, 2006 ISS2 Vertical Velocity (m/s)
Alt (km MSL)
UT hours


March 9, 2006 MAPR Vertical Velocity (m/s)
Alt (km MSL)
UT hours

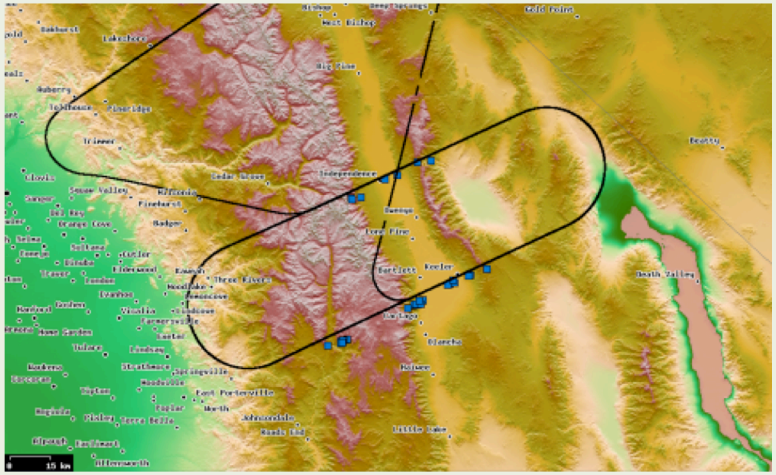

March 9, 2006 ISS2 Corrected Spectral Width
Alt (km MSL)
UT hours


March 9, 2006 MAPR Corrected Spectral Width
Alt (km MSL)
UT hours

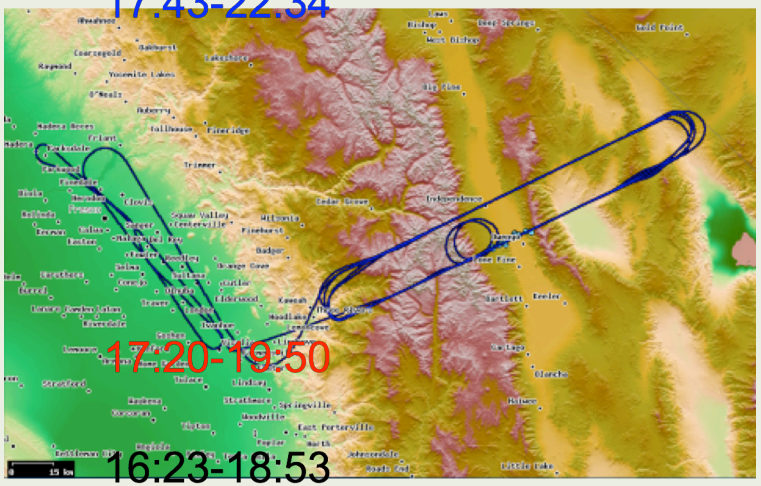

March 9, 2006 ISS2 Vertical Velocity (m/s)
Alt (km MSL)
UT hours
March 9, 2006 MAPR Vertical Velocity (m/s)
March 9, 2006 ISS2 Corrected
Spectral Width
Altitude (m)
Longitude (deg)
(km)
.22
.21
.195
.18
.165
.15
.135
.12
.105
.09
.075
.06
.045
.03
.015
.0

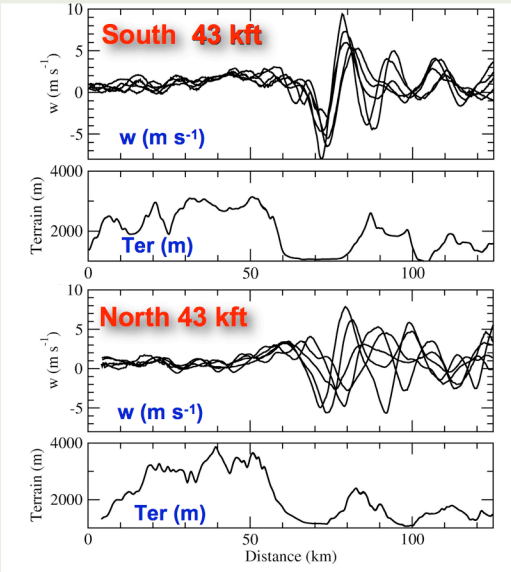
T-REX IOP 6 Coordinated Three-Aircraft Mission

HIAPER 1 RF (RF05) Mar 25

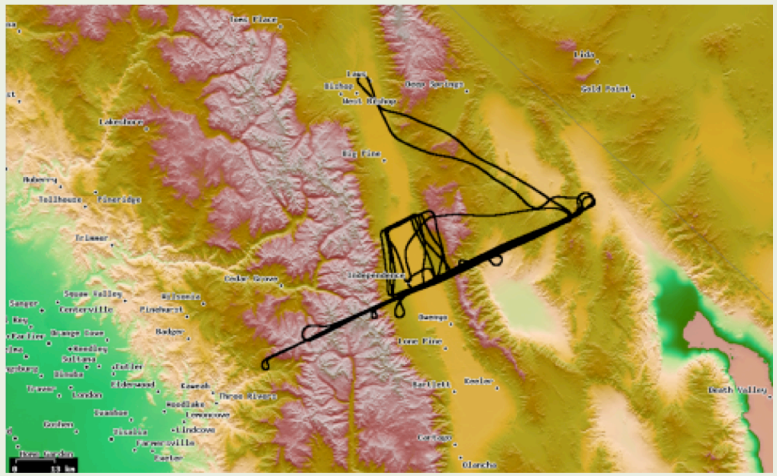


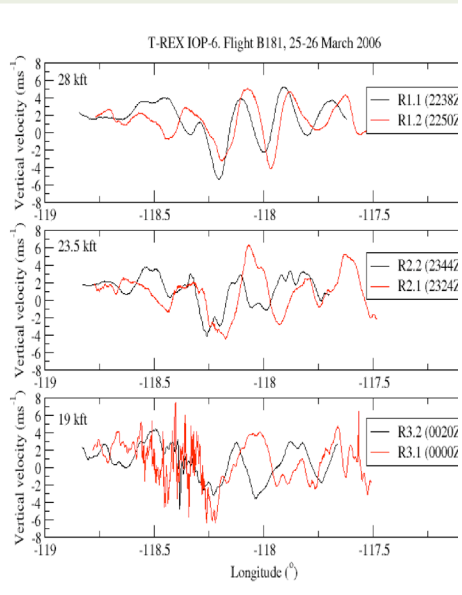
BAe146 3 RF (B179-181) Mar 24 & 25



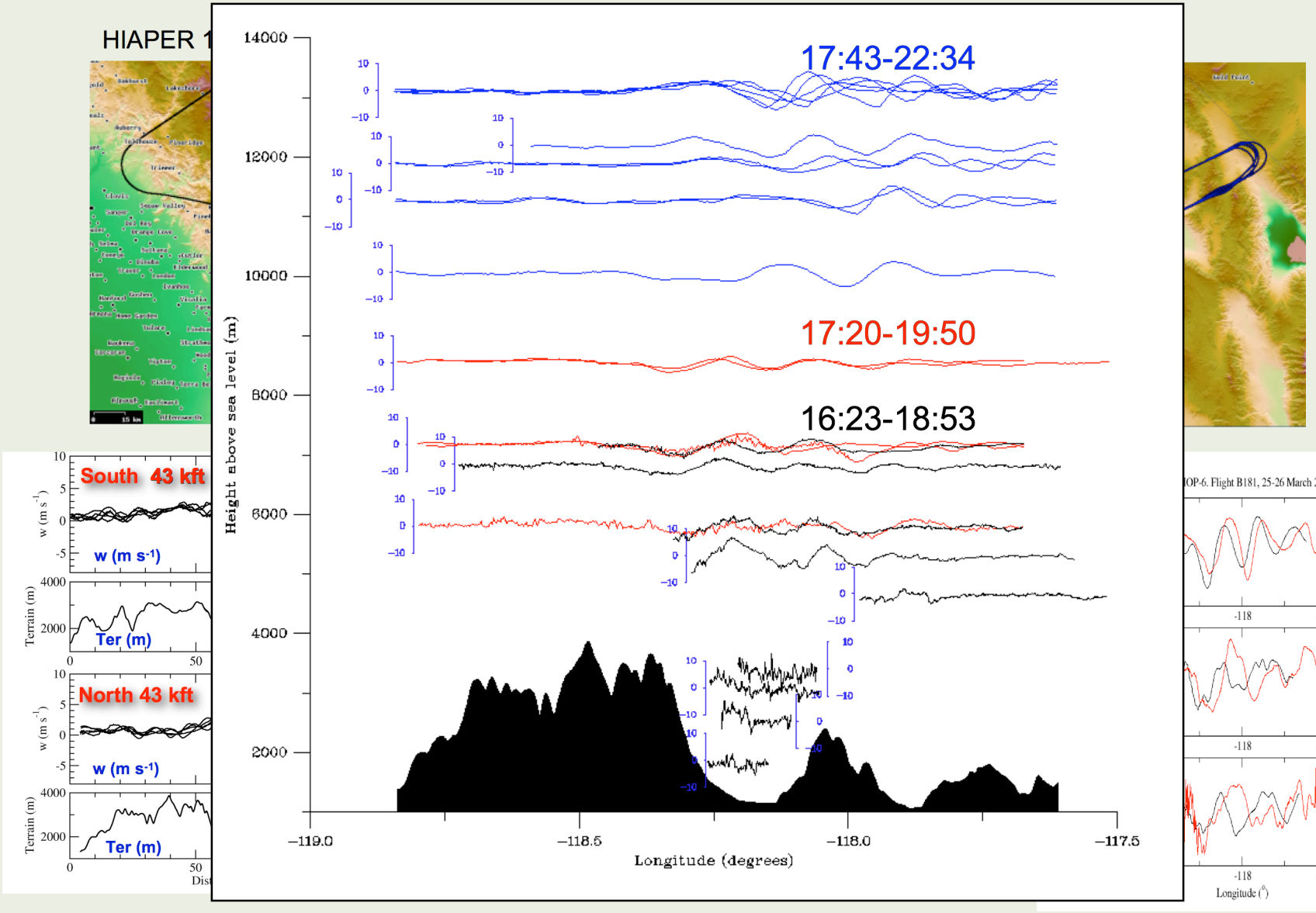


UWKA 3 RF Mar 24 & 25





T-REX IOP 6 Coordinated Three-Aircraft Mission

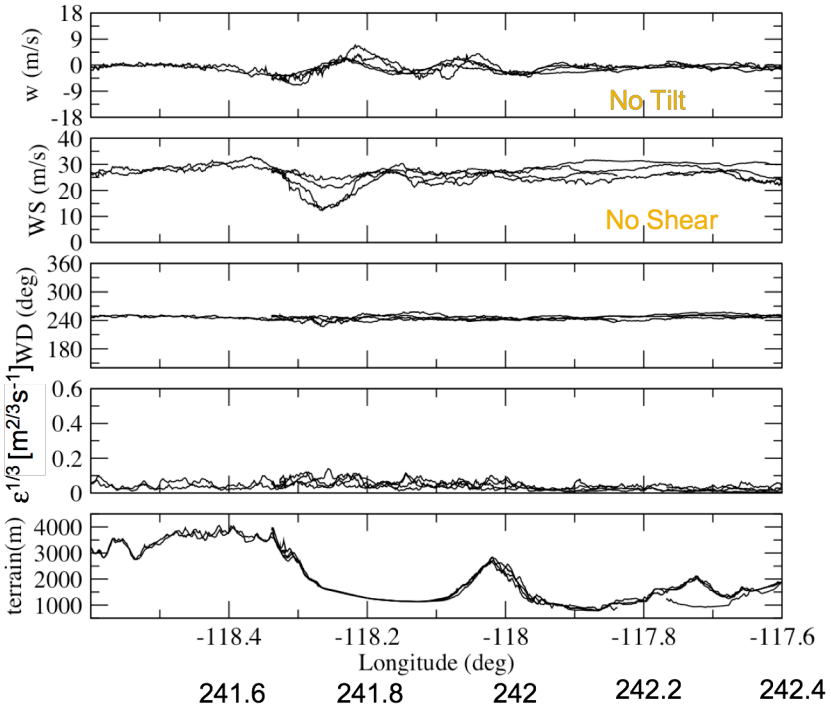


IOP 6 Aircraft Data

16:23 - 17:26 UTC

5.3 - 7.2 km ASL Track B

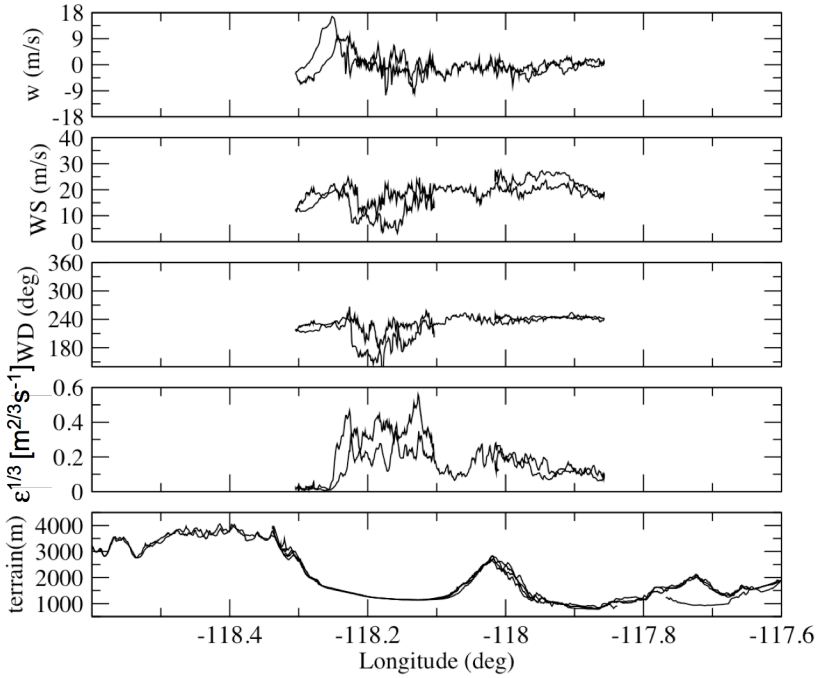
Above Rotor and Cap Clouds



17:41 - 17:59 UTC

3.9 km ASL Track B & Box

Below Rotor Cloud Base

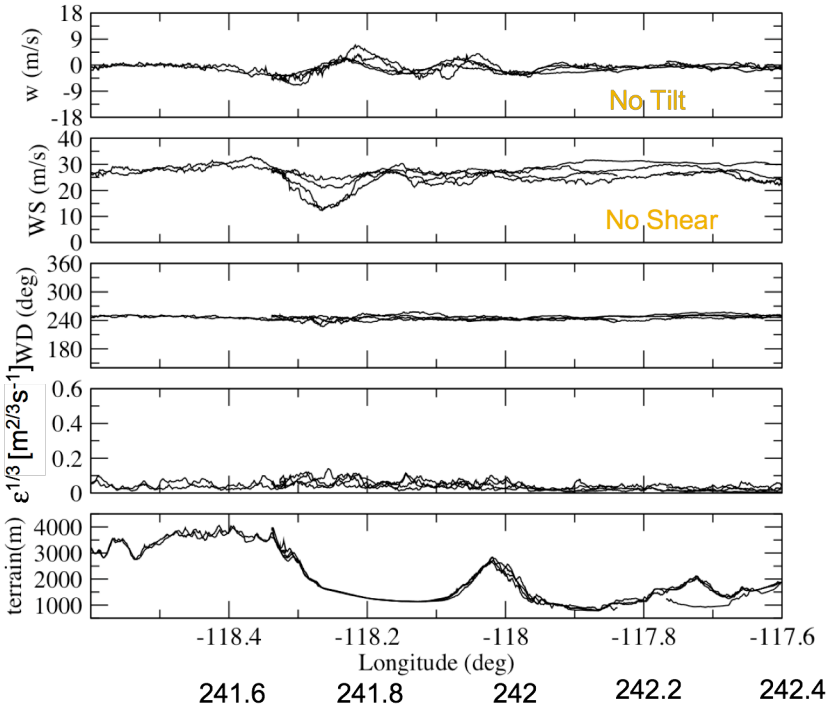


IOP 6 Aircraft Data

16:23 - 17:26 UTC

5.3 - 7.2 km ASL Track B

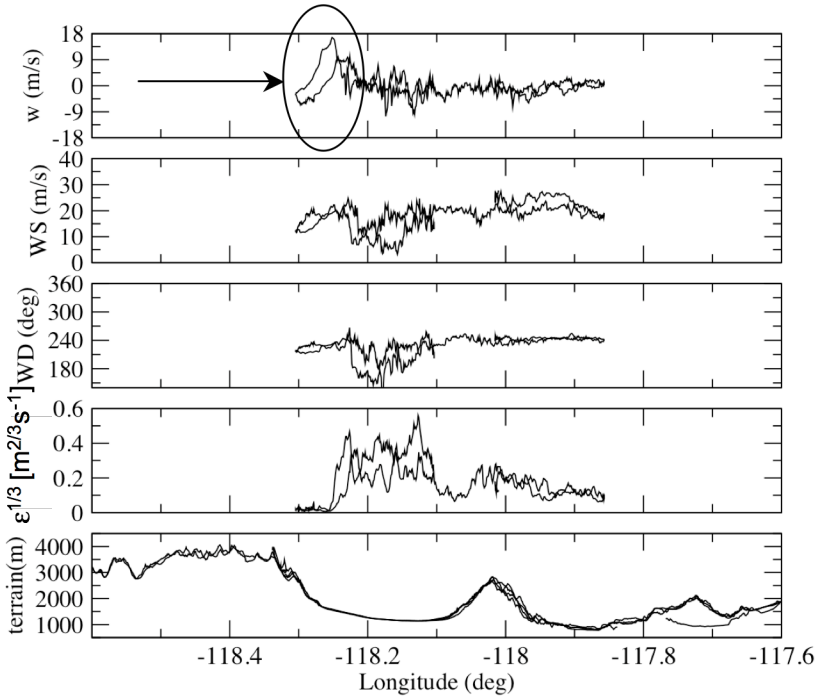
Above Rotor and Cap Clouds



17:41 - 17:59 UTC

3.9 km ASL Track B & Box

Below Rotor Cloud Base

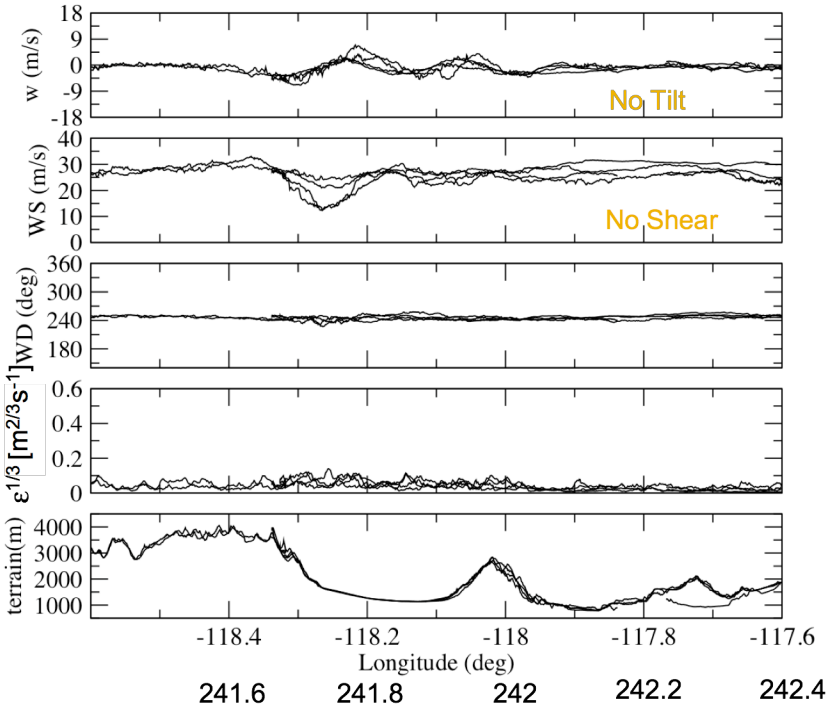


IOP 6 Aircraft Data

16:23 - 17:26 UTC

5.3 - 7.2 km ASL Track B

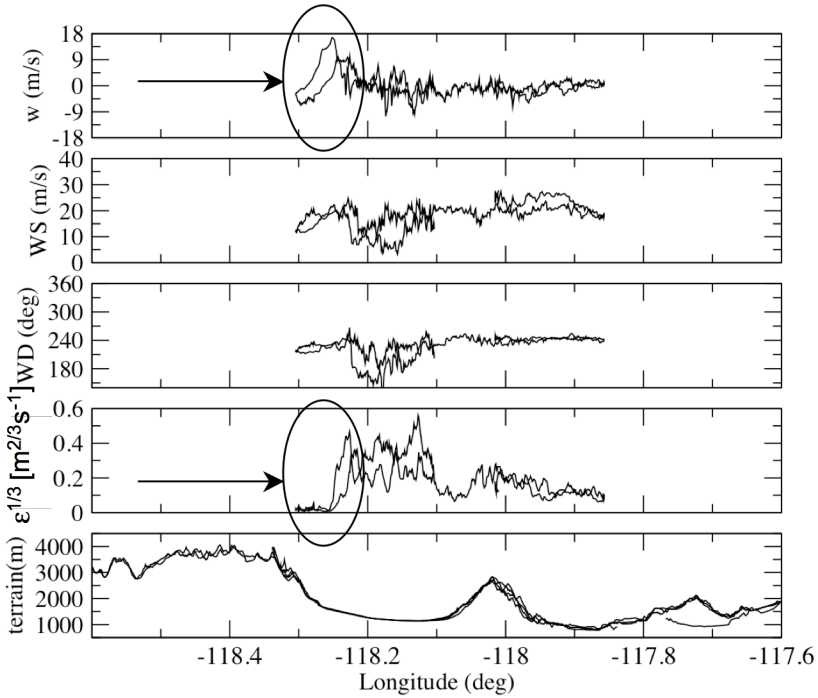
Above Rotor and Cap Clouds



17:41 - 17:59 UTC

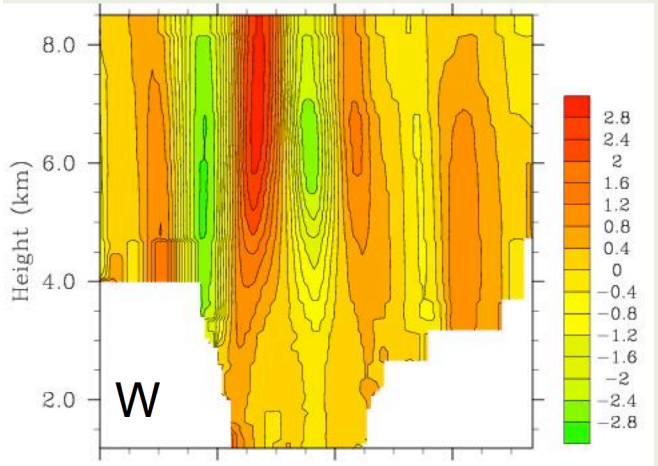
3.9 km ASL Track B & Box

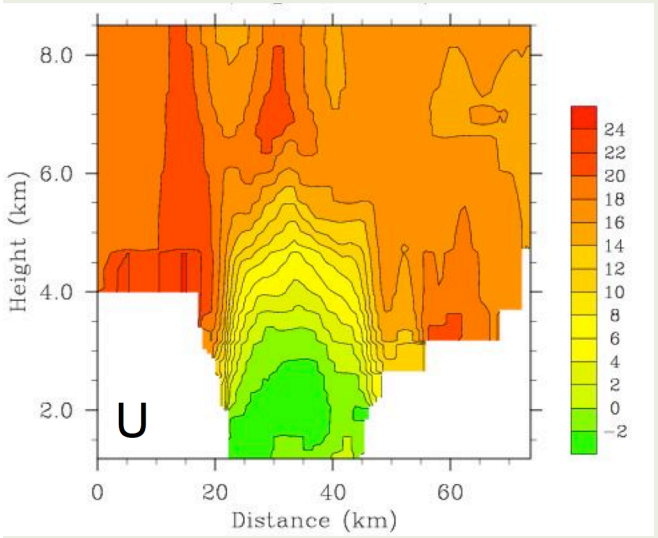
Below Rotor Cloud Base



Turbulence Characteristics Observed Over Owens Valley (IOP 1)

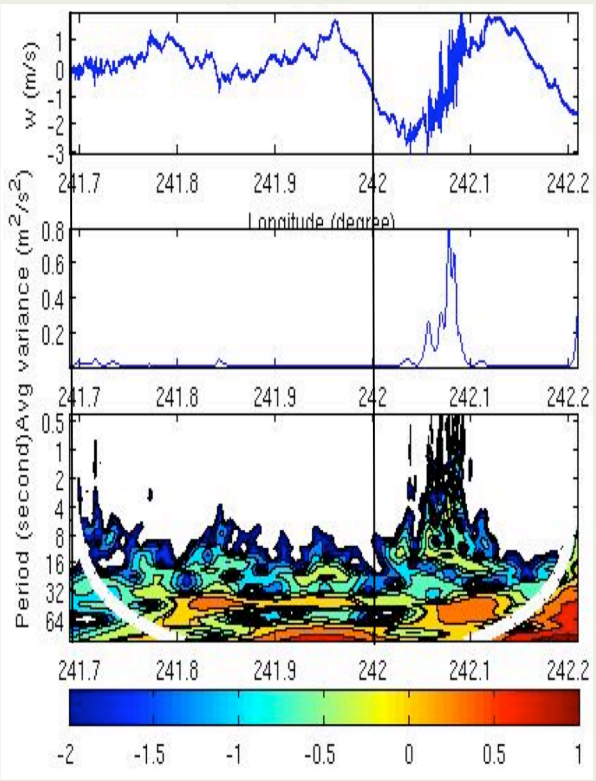
Objective Analysis of W and U of IOP 1a



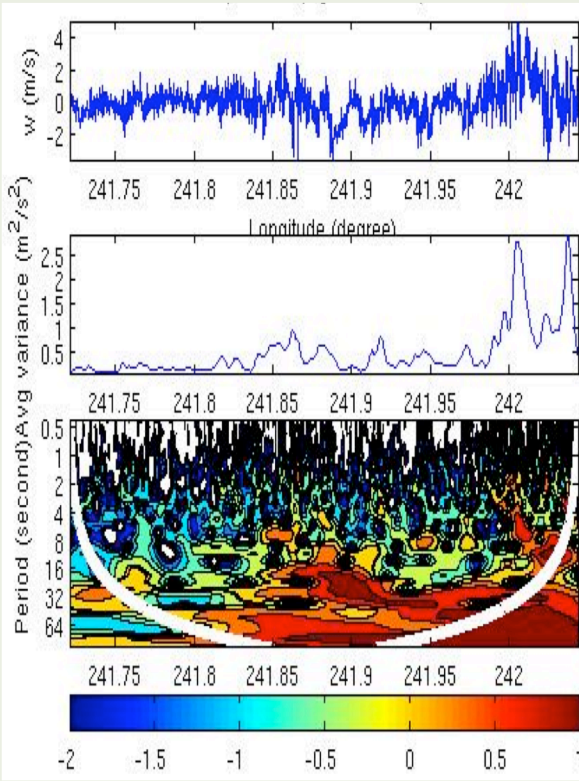


Wavelet Analysis: IOP 1a

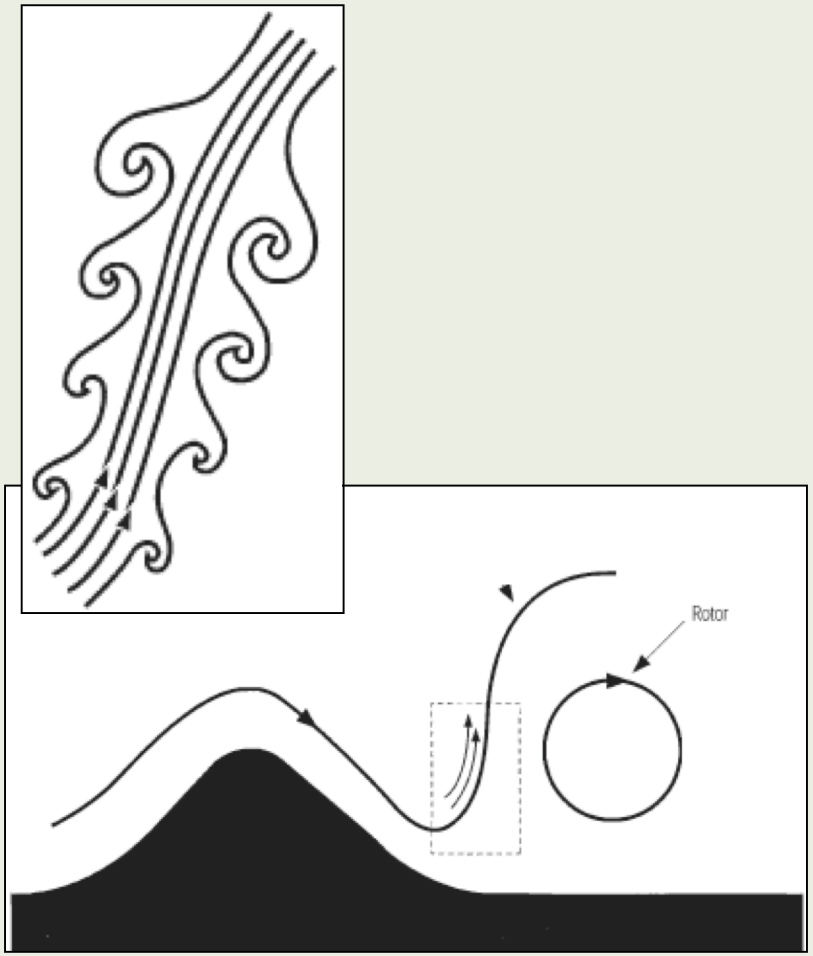
w (m s^{-1}) at 4900 m



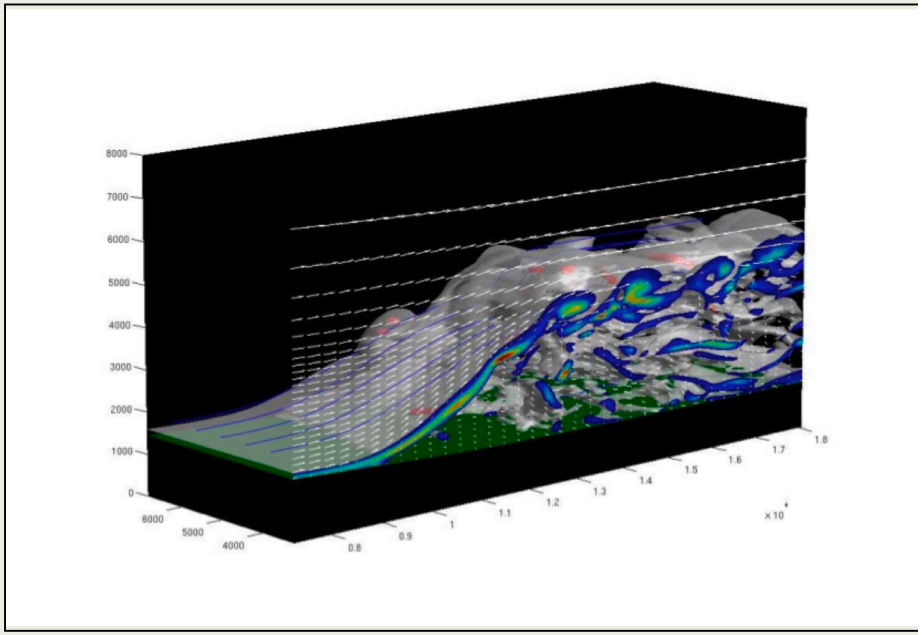
w (m s^{-1}) at 3600 m



Internal Rotor Structure: Subrotors



Doyle et al. (2008)



Radiosonde: Rise rate calculation

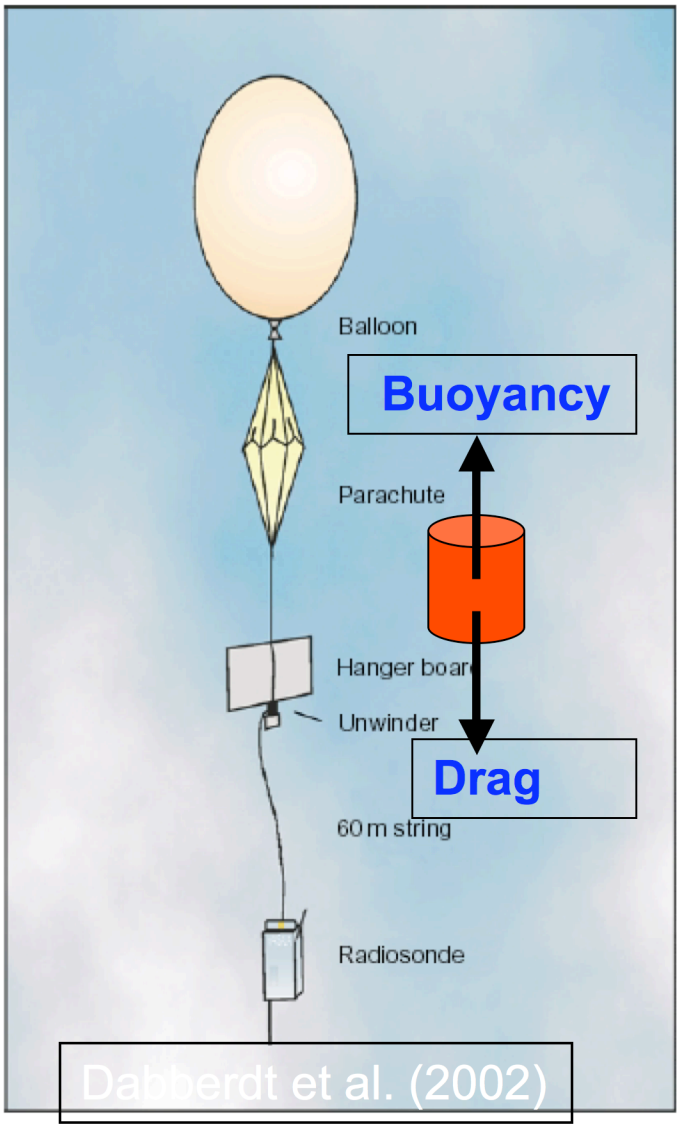


Figure 2 Typical radiosonde flight train, including balloon, parachute and hanger board, unwinder mechanism, separation line, and radiosonde.

Buoyancy force = Drag force

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

$$m_h = BV * \rho *4.0026/28.9644$$

$$V_{rr} = (2*BF/ C_D*A*\rho)^{1/2}$$

BV0: ~20-40 ft^3 ?

m_s = 330g m_b=200g

C_D ~ 0.2-0.5 ?

$A = 4*\pi *[3*BV/(4*\pi)]^{2/3}$

ρ: density (kg m^{-3})

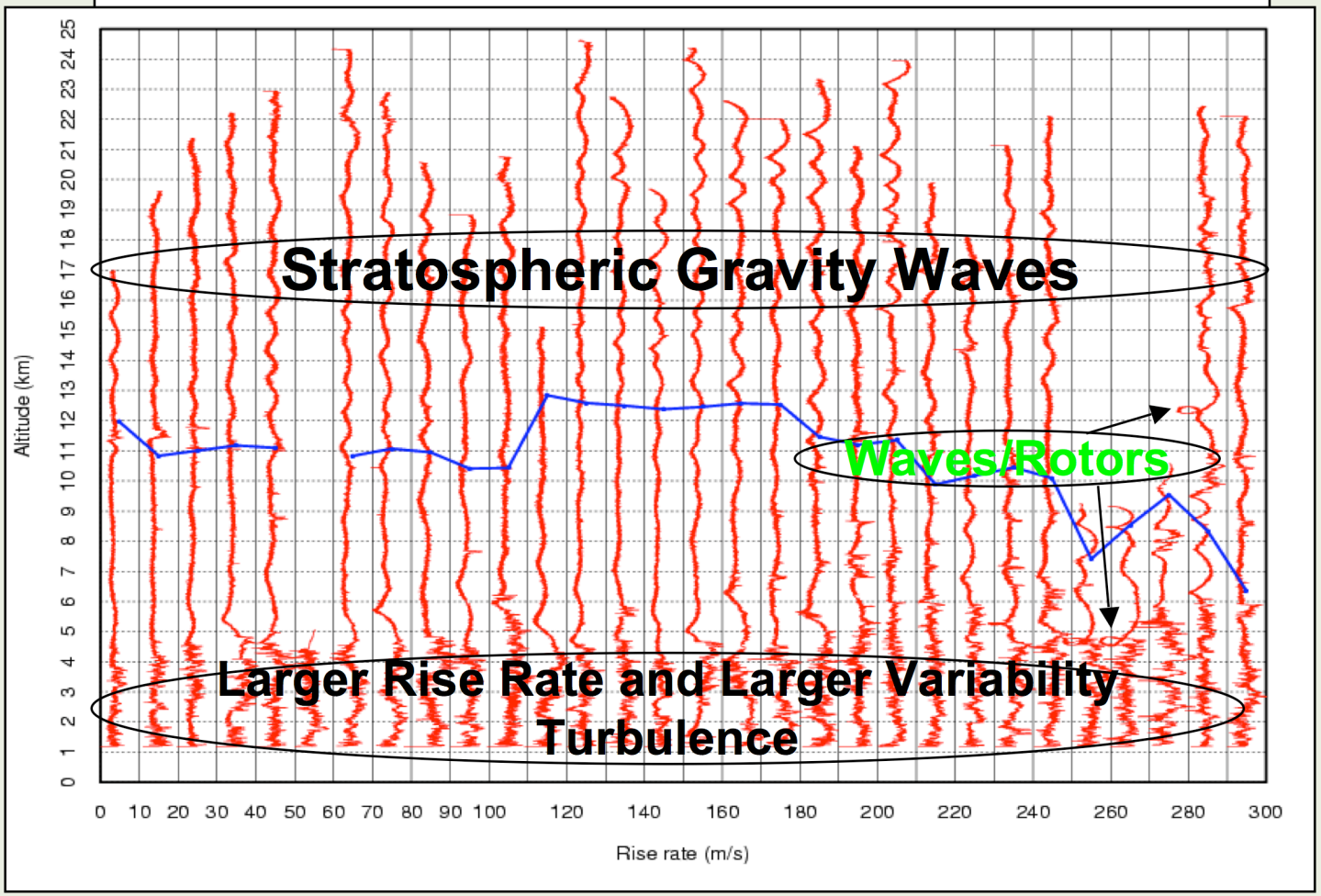
Vertical Wind = $V_{measured}$ - V_{rr}

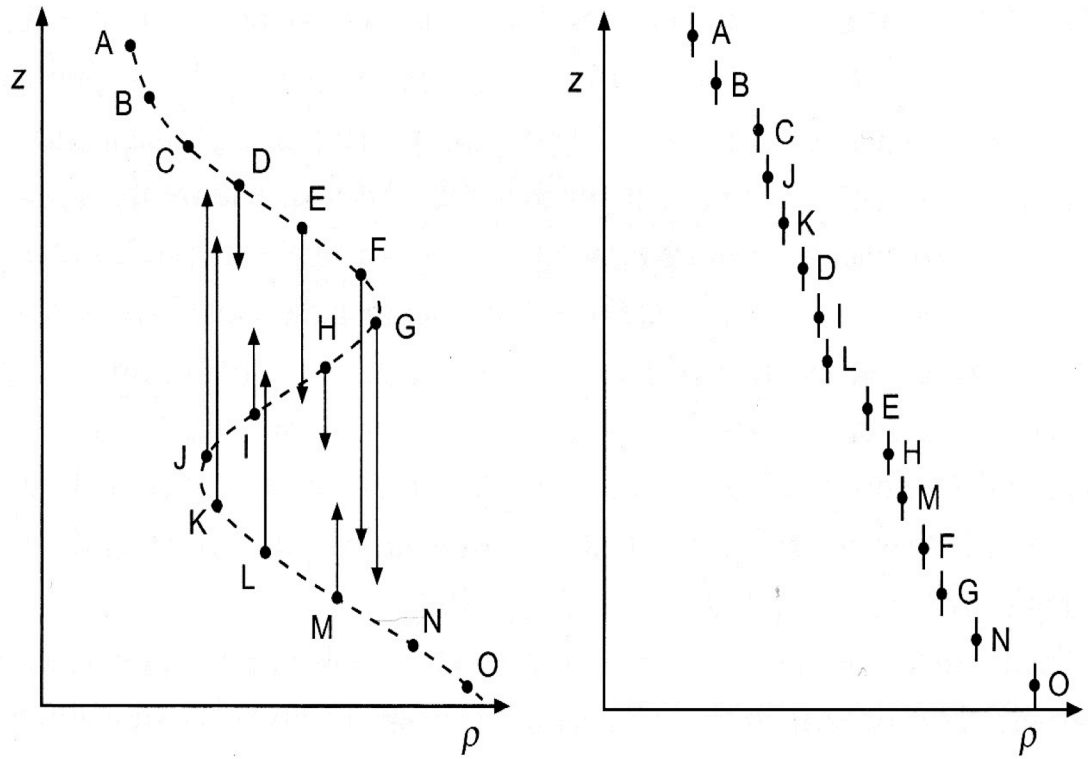
Factors affecting Cd (Lalas and Einaudi, 1980)

1. The radiosonde balloon is not super-pressurized, so does not retain the spherical shape. For Re=10^5, C_d = ~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 2.5x10^5, 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

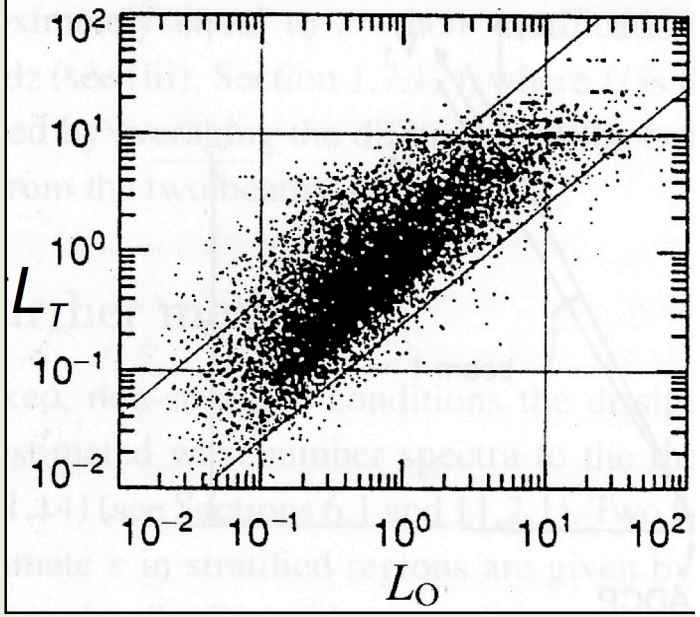
GAUS-ISS (March 2006; Soundings 1-30)





Thorpe (2005)

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 scal in a stably stratified fluid):

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

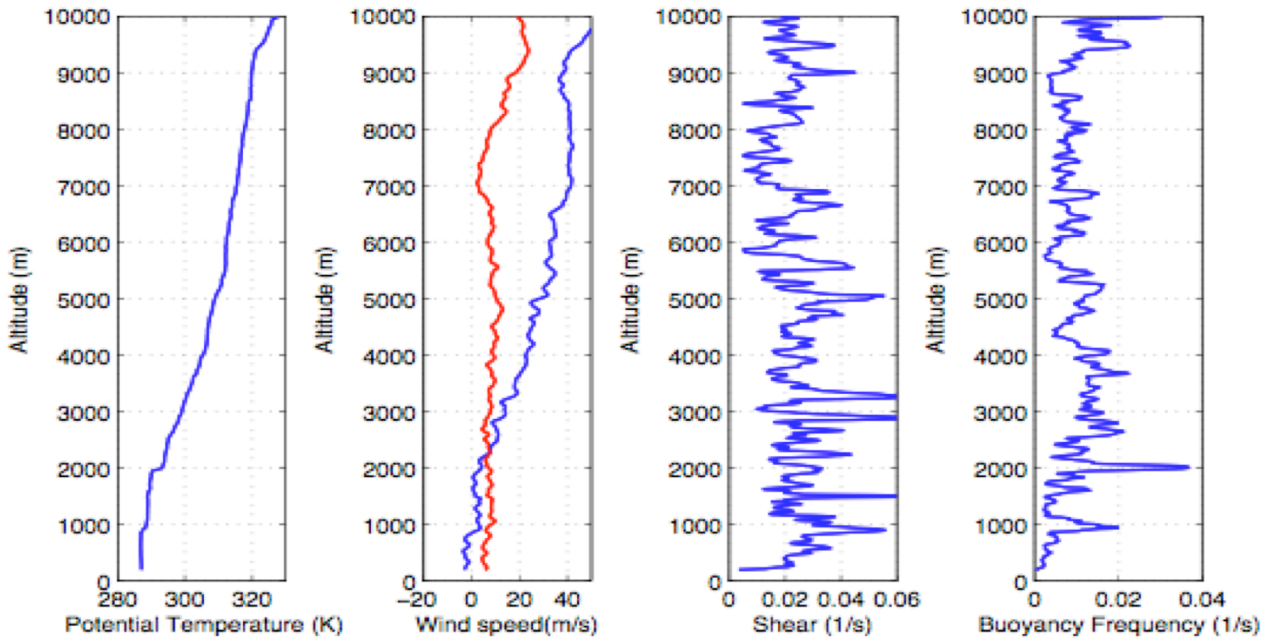
Thorpe scale $L_T \sim L_O$

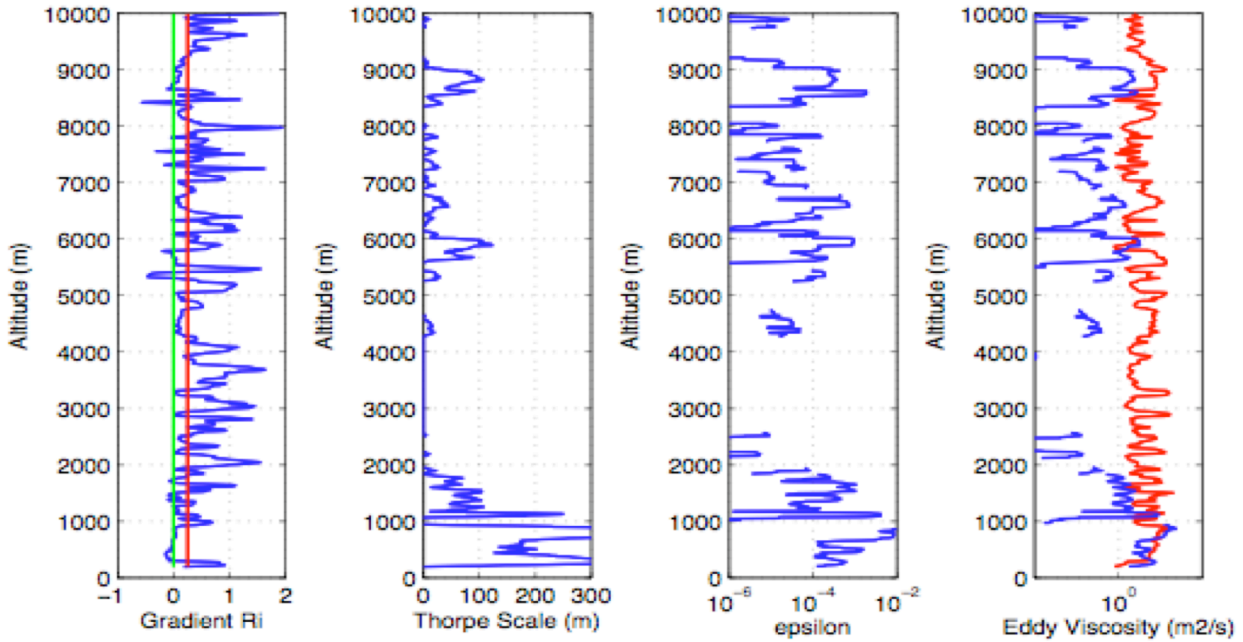
Therefore TKE dissipation ra

$$\boxed{\varepsilon = c_K L_T^2 N^3}$$

Also Eddy Diffusivity

$$\boxed{K = \gamma \varepsilon N^{-2}}$$

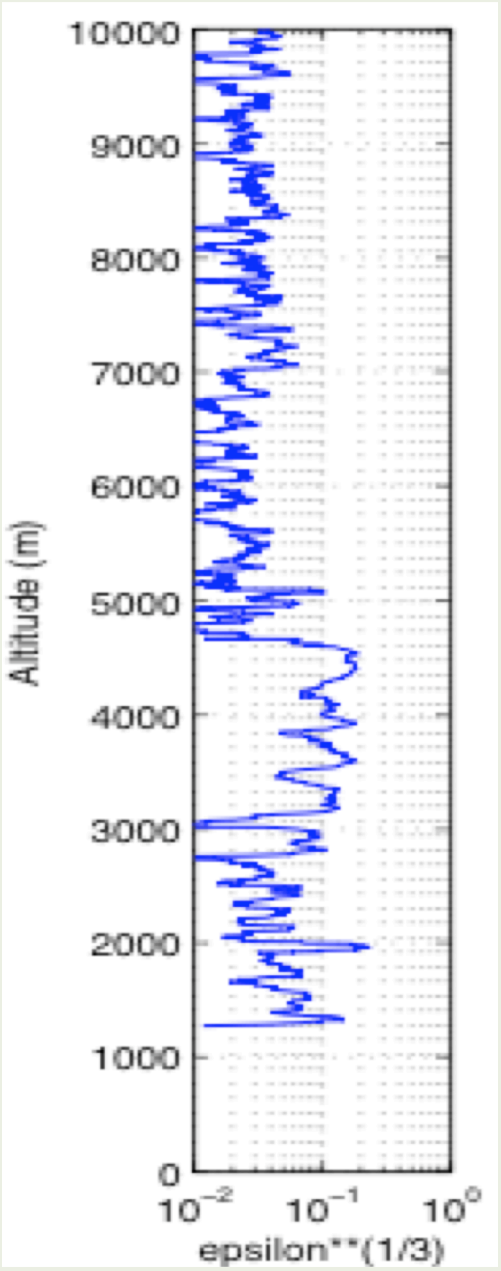


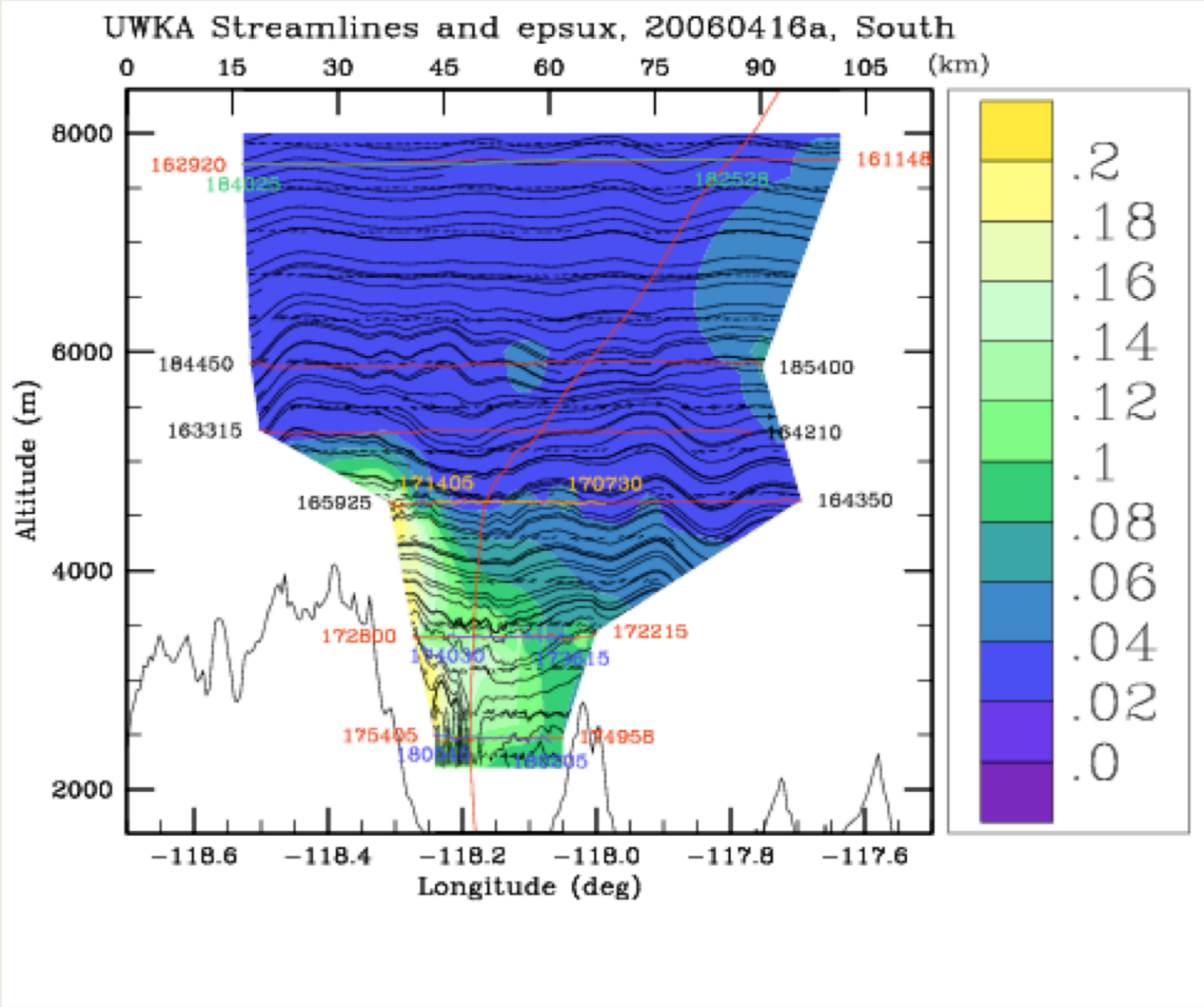


IOP 13
(April 16, 2006)

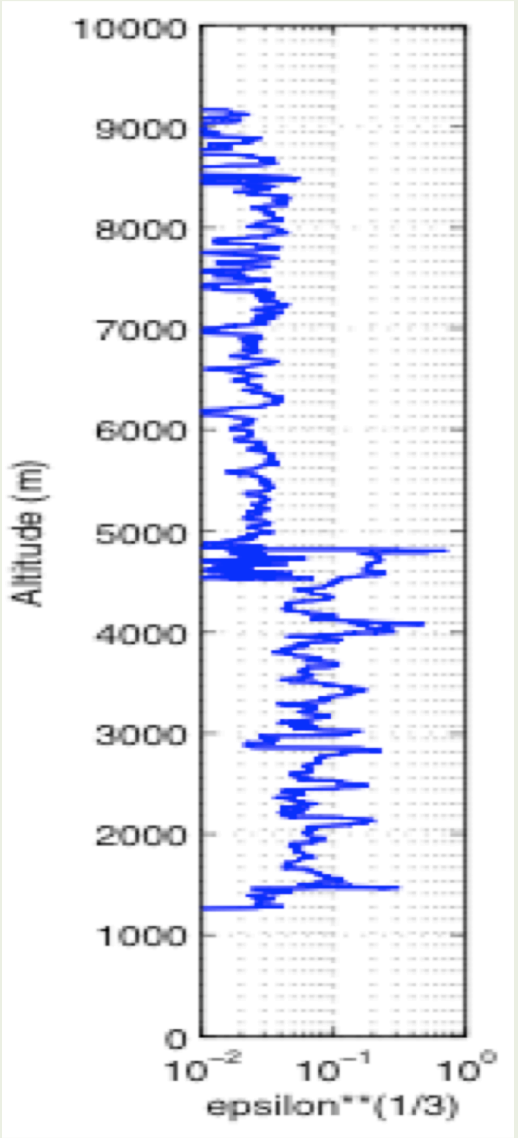
Upstream Sonde

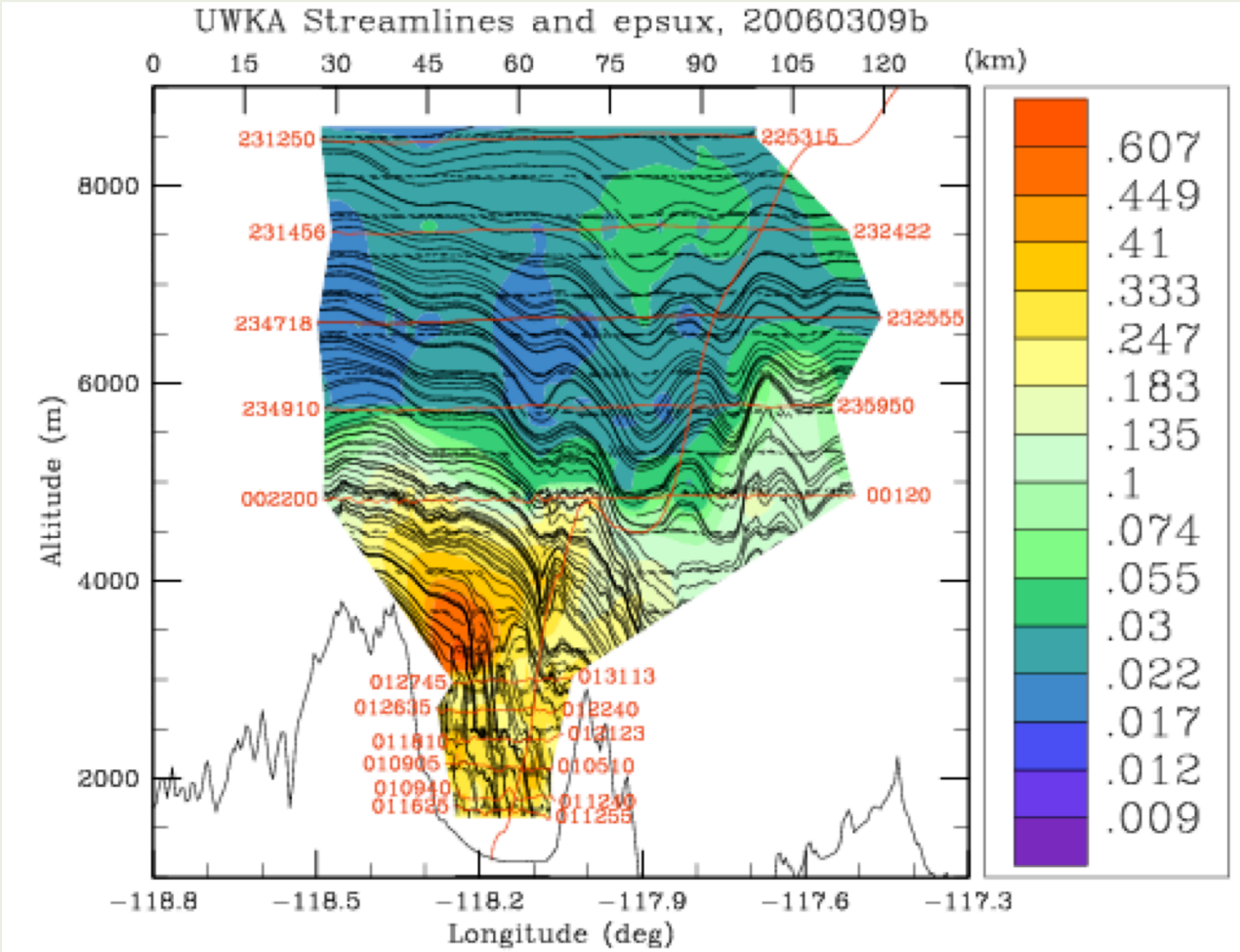
IOP 13 (April 16, 2006)



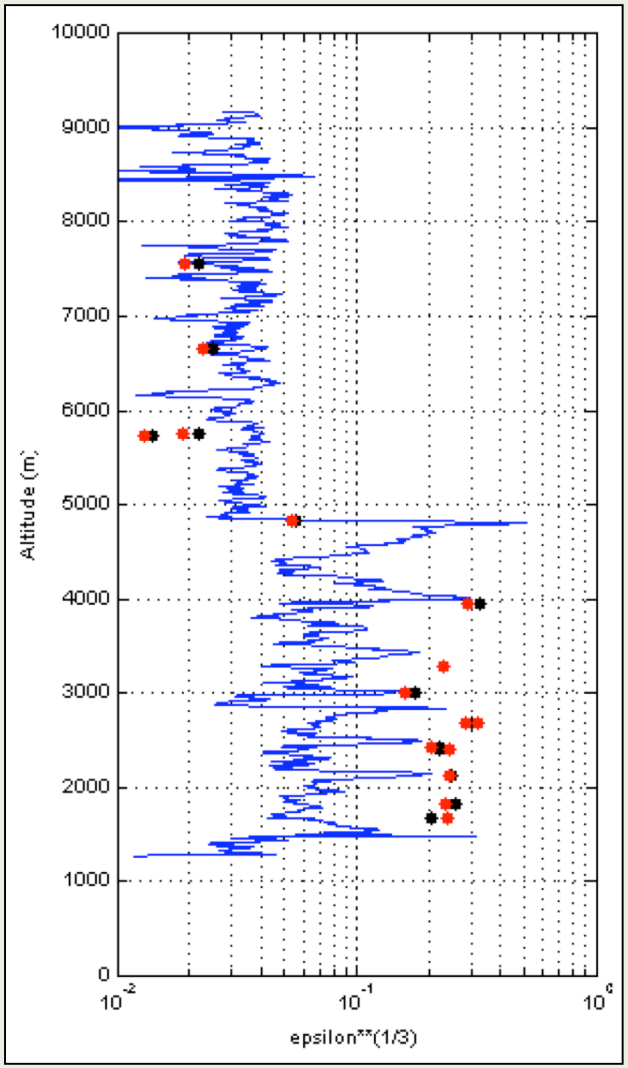


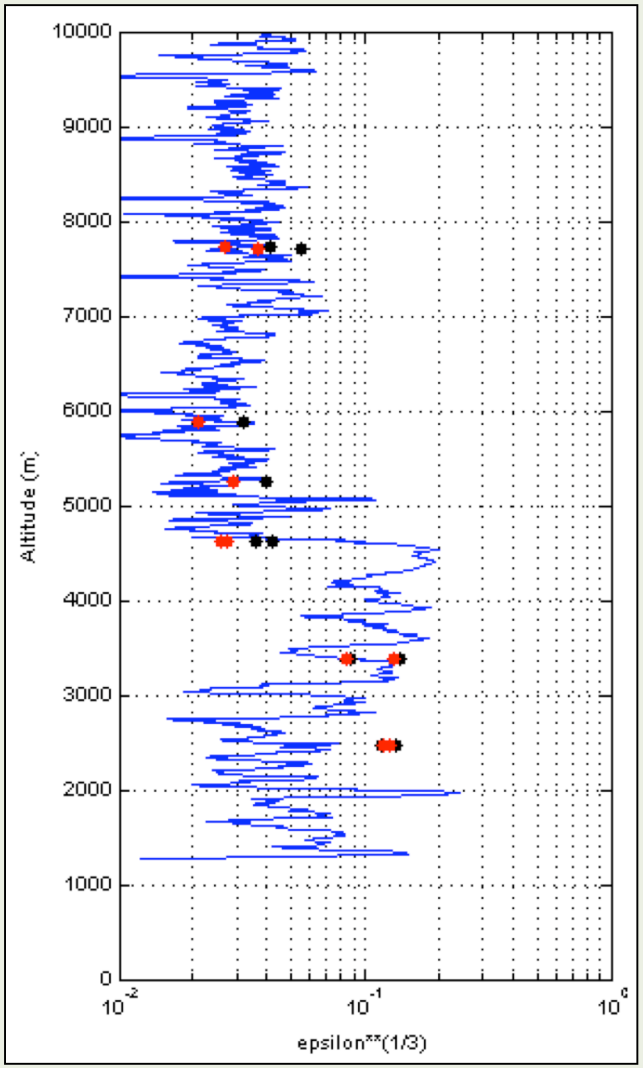
IOP 03 (March 9, 2006)

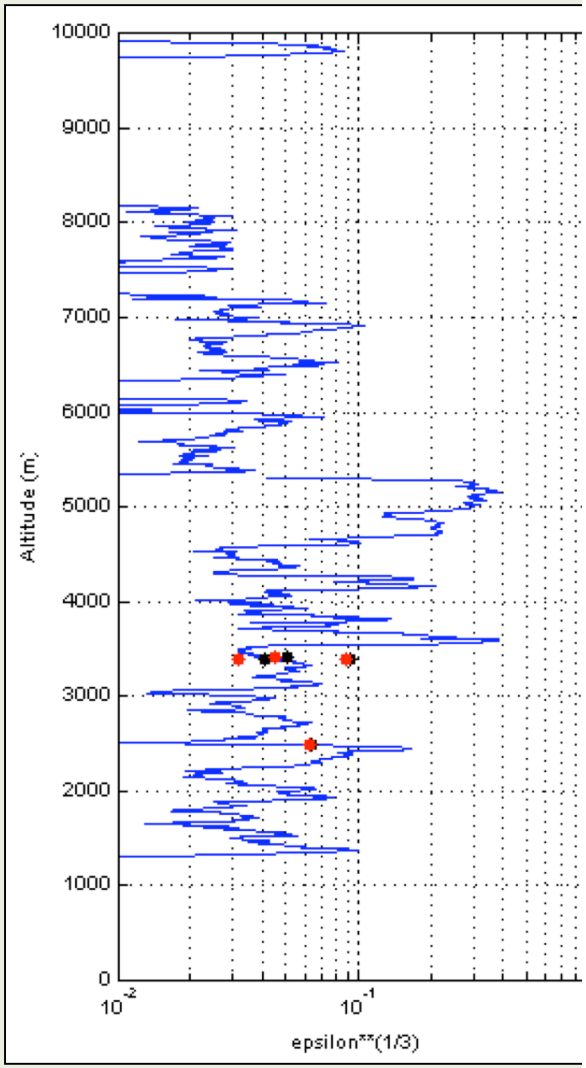




Comparison with Aircraft Data along the Sonde Track







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