Mountain Wave Turbulence and Predictability

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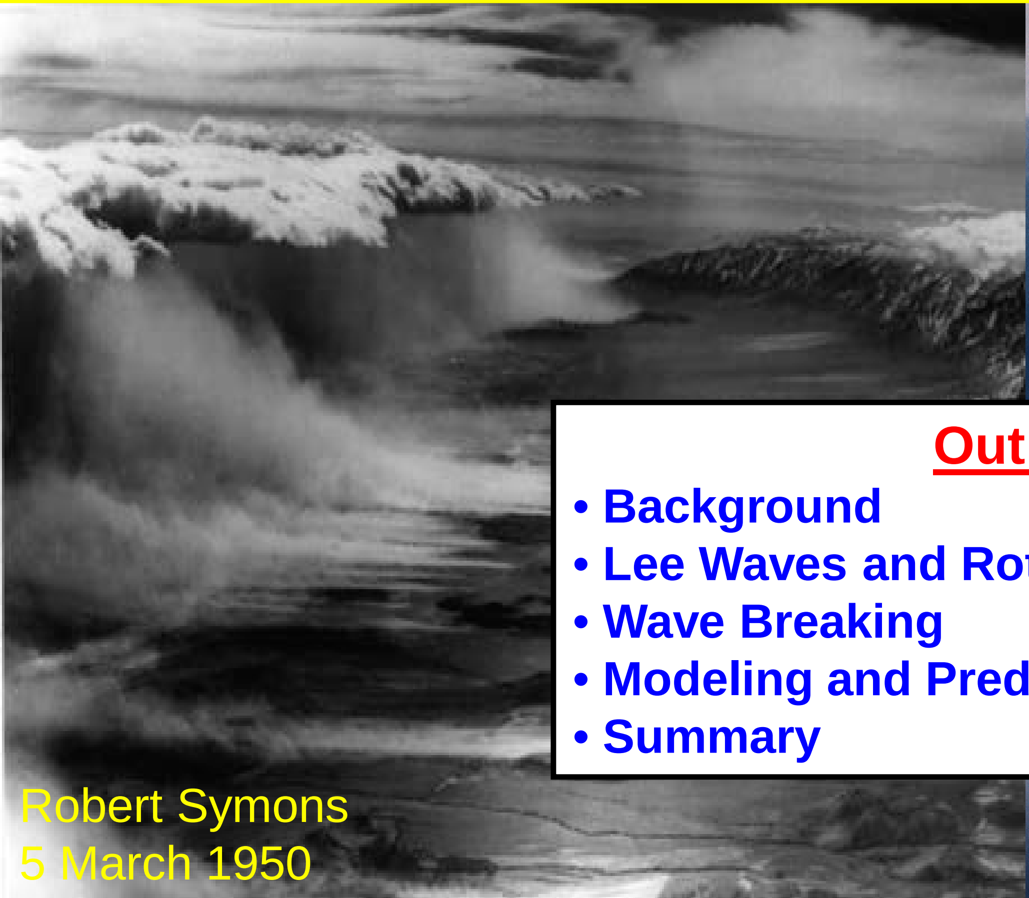


Robert Symons
5 March 1950

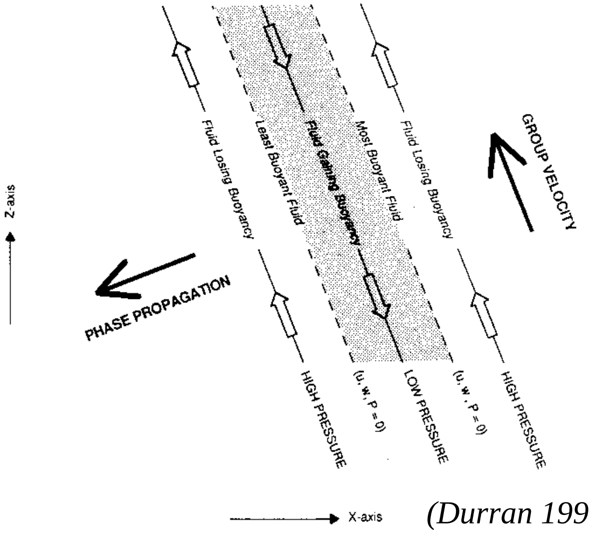
Outline

- **Background**
- **Lee Waves and Rotors**
- **Wave Breaking**
- **Modeling and Predictability**
- **Summary**

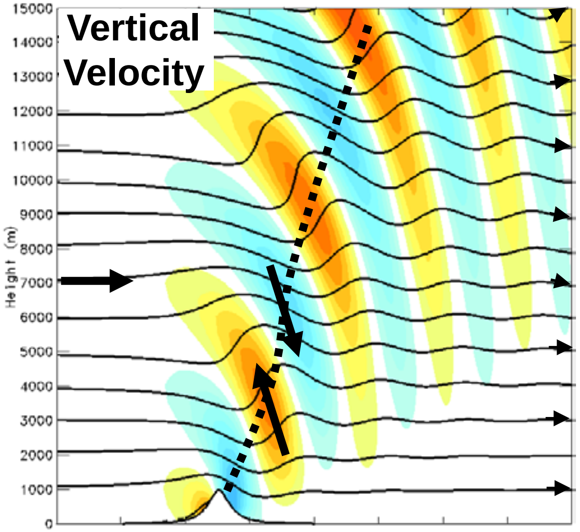
T. Henderson

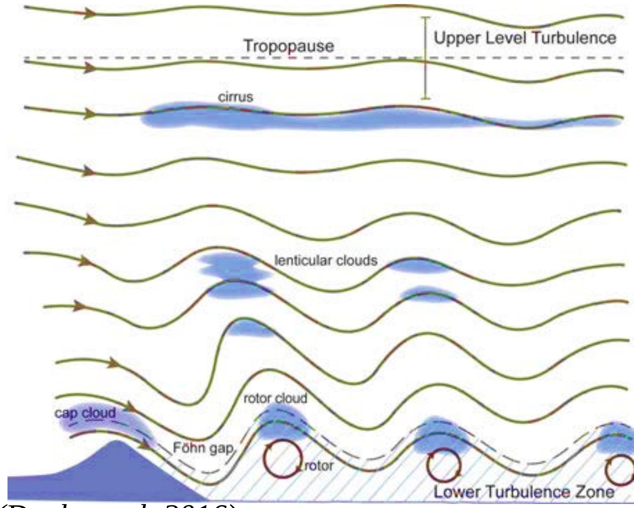
What is a Mountain Wave?

- When Stably Stratified Air is Forced Over a Barrier a Disturbance is Created
- Energy is Carried Away by Internal Gravity Waves
- Buoyancy is the Restoring Force
- Downward Phase Propagation ➔ Upward Energy Propagation (Group Velocity)



(Durran 1990)





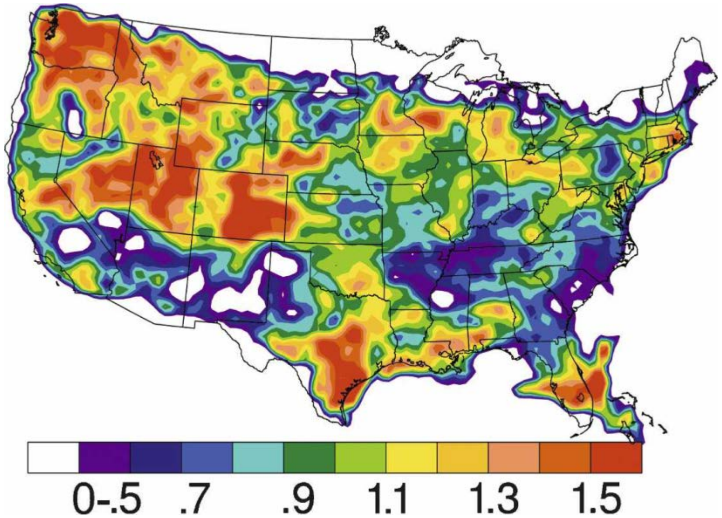
(Doyle et al. 2016)

- Gravity Waves May Steepen & Break
  - Nonlinearity, Critical Levels
  - Decreasing Mean Density
  - Breakdown via Secondary KH Instability

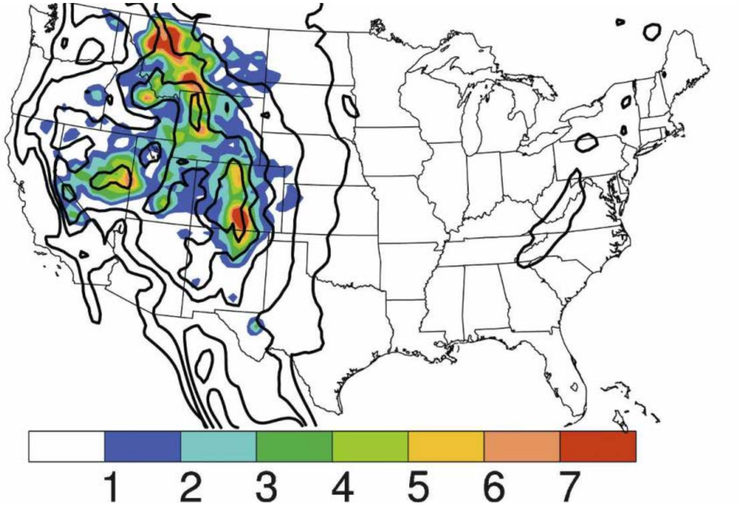
NCAR

Mountain Wave Turbulence Climatology

Normalized PIREPS (MOG/Total)
1995-2005 (Wolff and Sharman 2008)

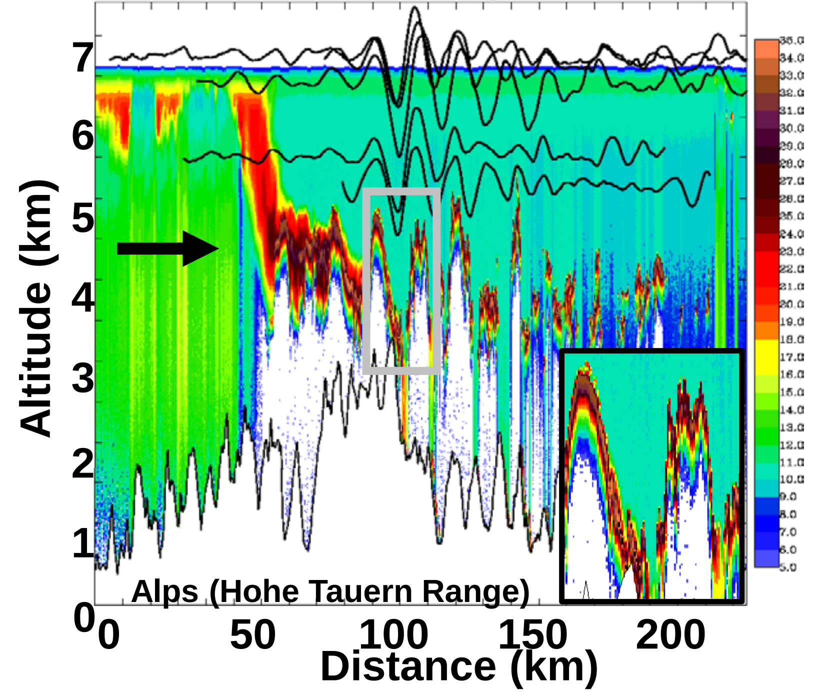


Percent of MOG MWT to Total PIREPs
above FL180 (5.5 km) (12 YR)
Wolff and Sharman (2008)

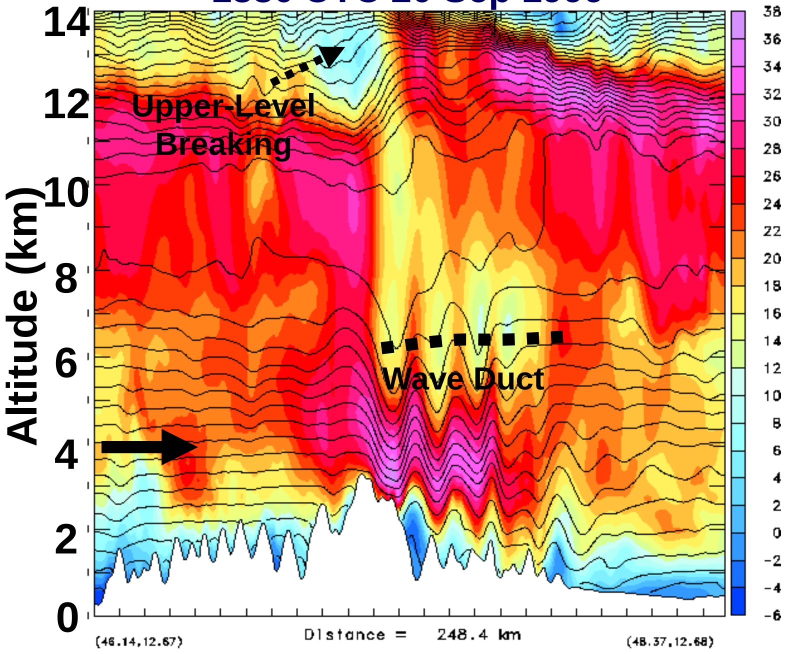


- **Major source of turbulence over the western U.S. is due to MWT**
- **Correlation of the normalized MOG MWT pattern is apparent with topographic heights greater than about 1.5 km, consistent with previous studies (Reiter and Foltz 1967; Nicholls 1973, Lee et al. 1984)**

Lee Waves and Turbulence



SABL Backscatter & Electra Displacement Height
1330-1400 UTC 20 Sep 1999



COAMPS (dx=1 km) Wind Speed (color) and θ
1330 UTC 20 Sep 1999

- Mountain lee waves are generally laminar though can be turbulent occasionally
- Trapped wave generated by wave duct and flow over narrow terrain of Alps.
- Wave duct enhanced by upstream moist processes.

Doyle and Smith (2003) QJRMS

Rotors: Sierra Wave Project

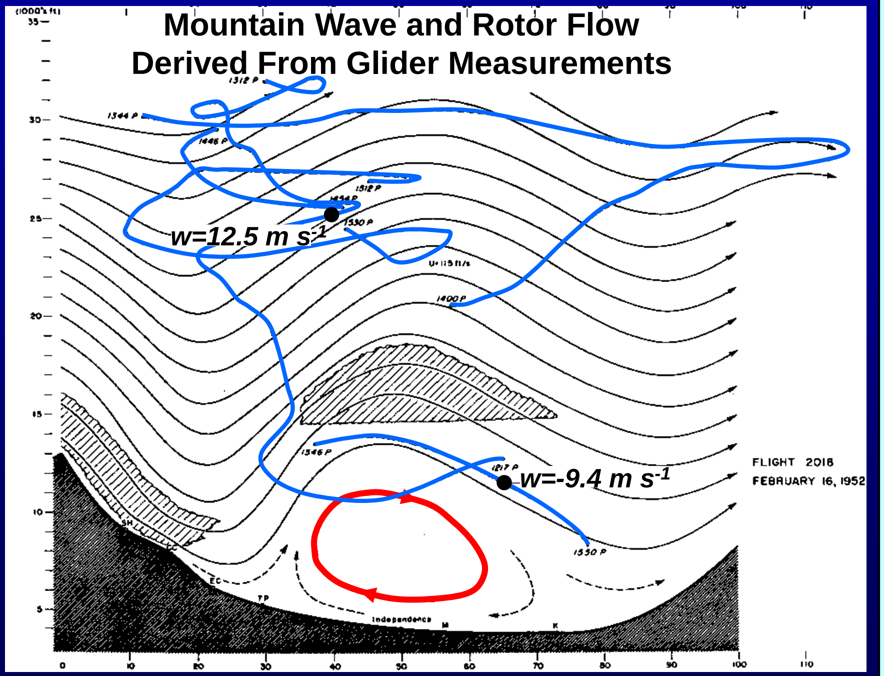
- Sierra Nevada Range is well known for spectacular mountain wave phenomena and rotors

Mountain Wave Clouds, Dust & Rotor Clouds From a P-38 With Engine Off (w_{max}~35 m s^{-1})
R. Symons

NOAA Archive

J. Kuettner

- Rotor structure and characteristics were documented in several cases during SWP



Mountain Wave and Rotor Flow Derived From Glider Measurements

Holmboe and Klieforth 1957

25 April 1955

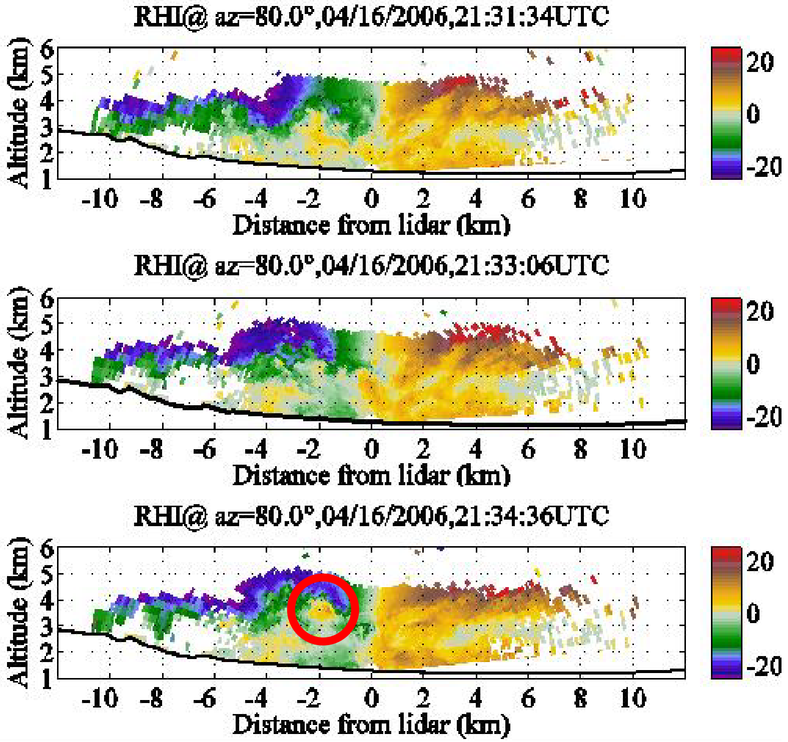
Dr. J.P. Kuettner Collection

- Sailplane destroyed in mid-flight during rotor encounter (~16Gs) at 4 km
- Surface gusts > 25 m s^{-1}

Rotors: T-REX

Subrotor Vortices During the Terrain-Induced Rotor Experiment

Doppler Lidar Velocities


RHI@ az=80.0°,04/16/2006,21:31:34UTC

RHI@ az=80.0°,04/16/2006,21:33:06UTC

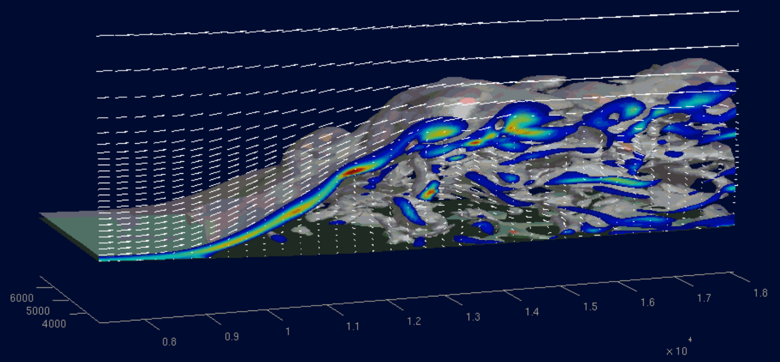
RHI@ az=80.0°,04/16/2006,21:34:36UTC

Doyle, Grubišić, Brown, De Wekker, Dörnbrack, Jiang, Mayor, Weissmann, 2009, JAS

COAMPS LES Simulation

2100 UTC 16 April 2007

[30 min. period, Δx=60 m]



η Vorticity (color)

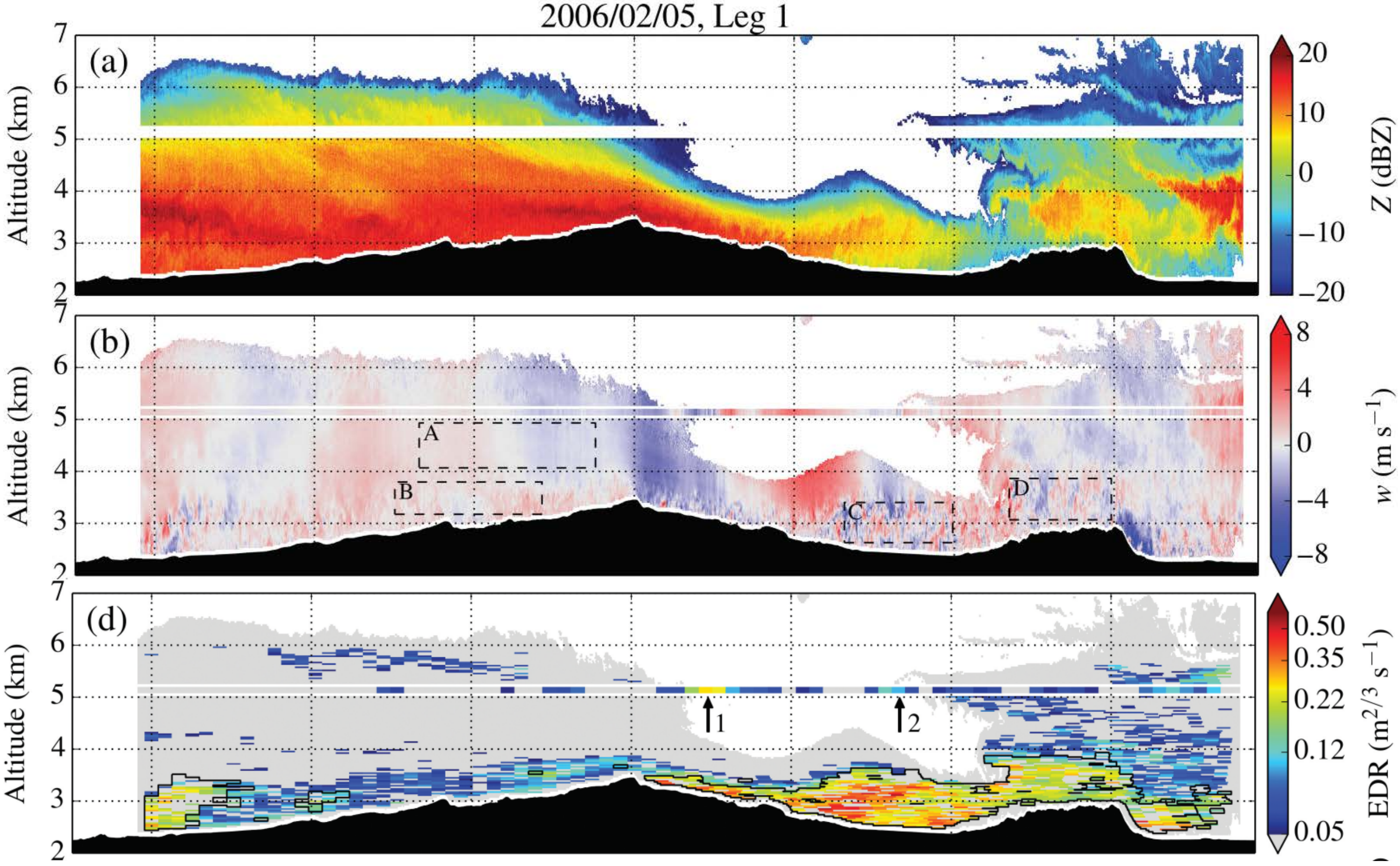
$\eta = 0.15\ s^{-1}$ (red)

$\eta = 0.02\ s^{-1}$ (gray)

Large Eddy Simulations of rotors underscores the key characteristics including flow separation, elevation of vortex street, and development of KH billows or sub-rotors downstream

Rotors

- Medicine Bow Mountains during the NASA Orographic Clouds Experiment
- Hydraulic jump type of rotor
- Severe turbulence is encountered in the downdraft, with maximum σ^2w and EDR$_w$ of 16.4m^{2}s^{-2} and 0.77m$^{2/3}$s^{-1}

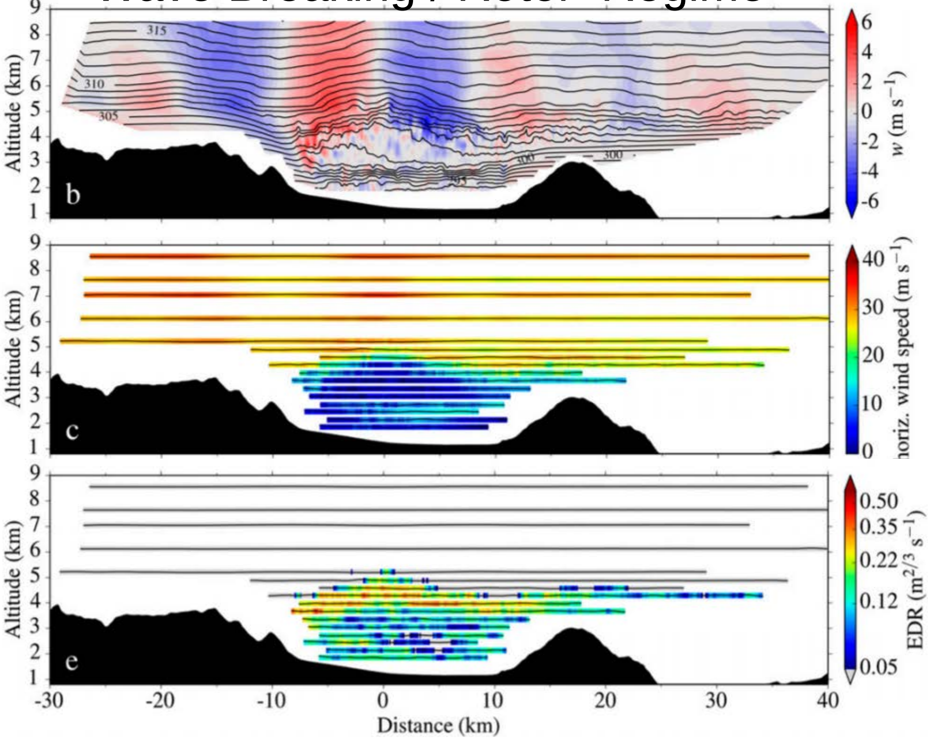


Strauss et al. (2015)

How does the turbulence differ between hydraulic-like jump rotors and lee wave rotors?

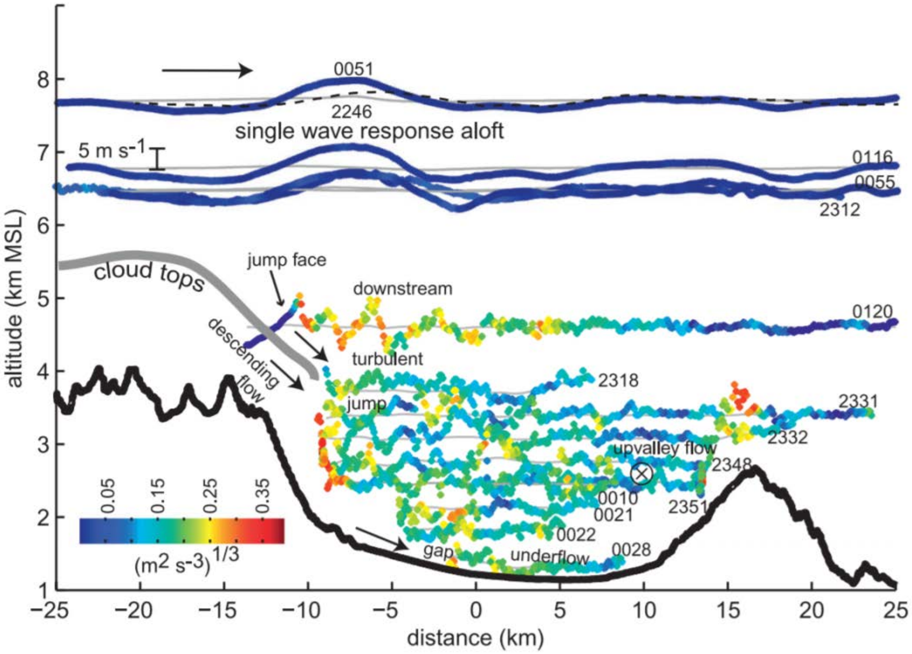
Hydraulic Jumps and Rotors

Wave Breaking / Rotor Regime



Strauss et al. (2016)

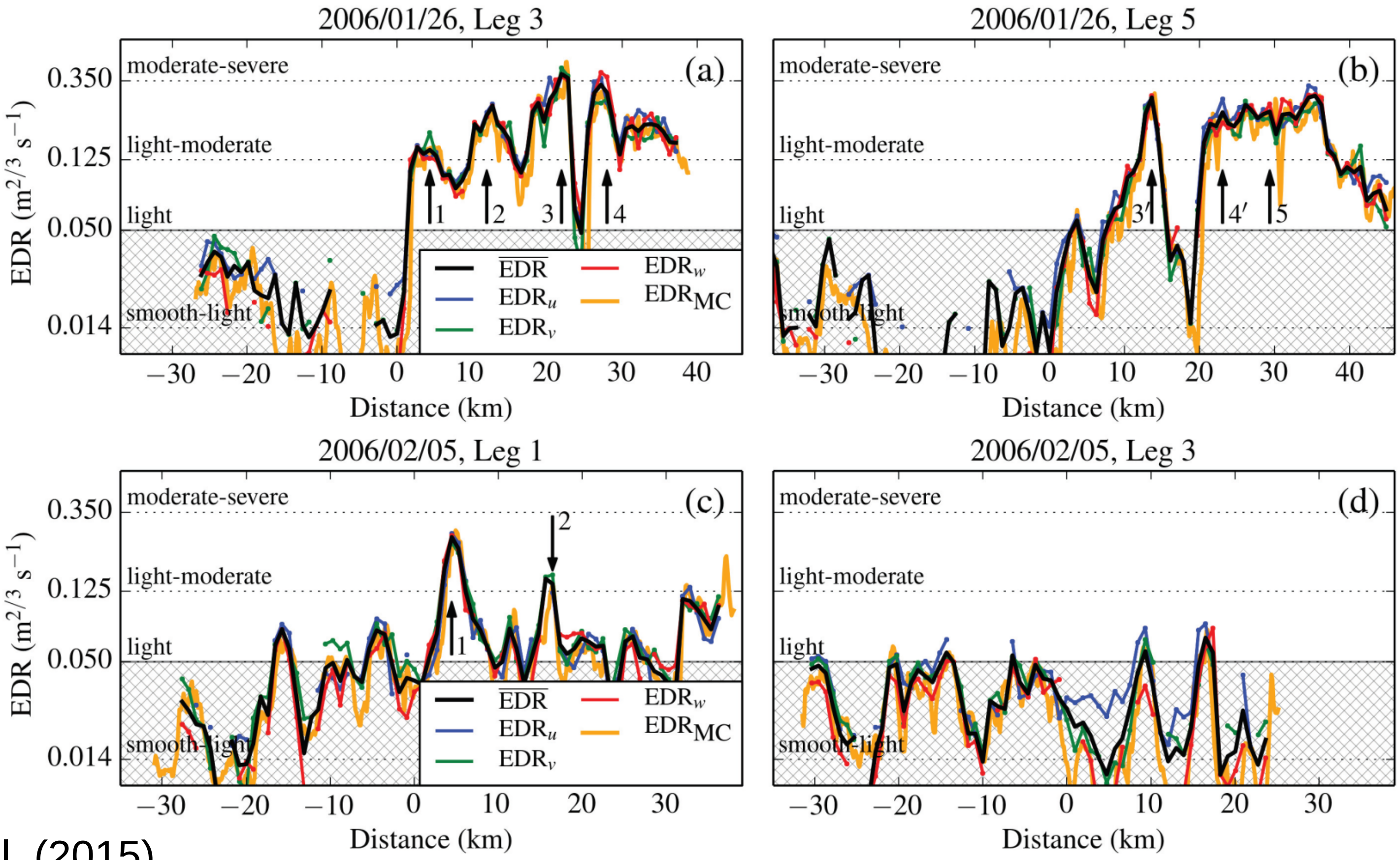
Hydraulic Analogue



Armi and Meyer (2011)

- **Internal hydraulic jump vs. low-level wave breaking paradigms**
- **Characteristics of turbulence and relationship to vortex breakdown are important**

Low-Level Wave Breaking

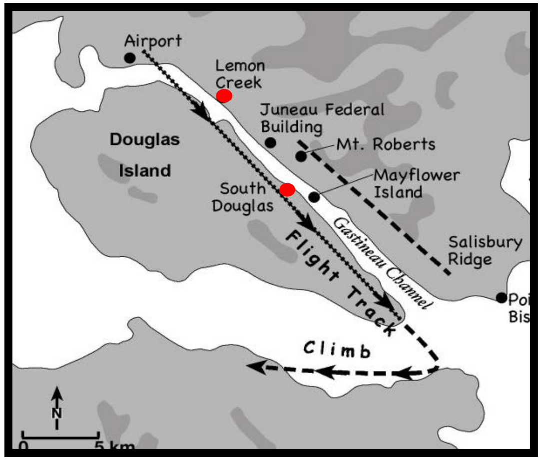


Strauss et al. (2015)

Measurements of low-level turbulence in rotors and wave breaking are rare

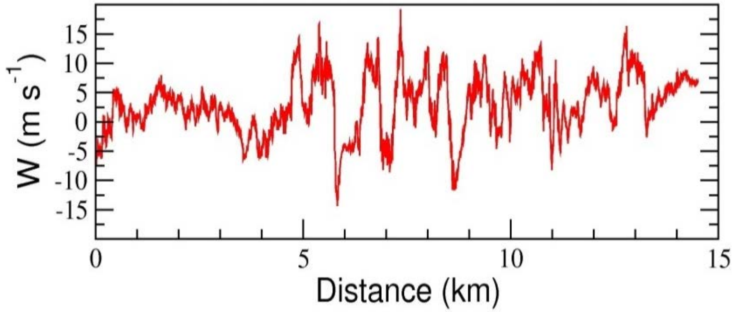
Low-Level Wave Breaking

SARJET (Alaska) UW KingAir Flight Path

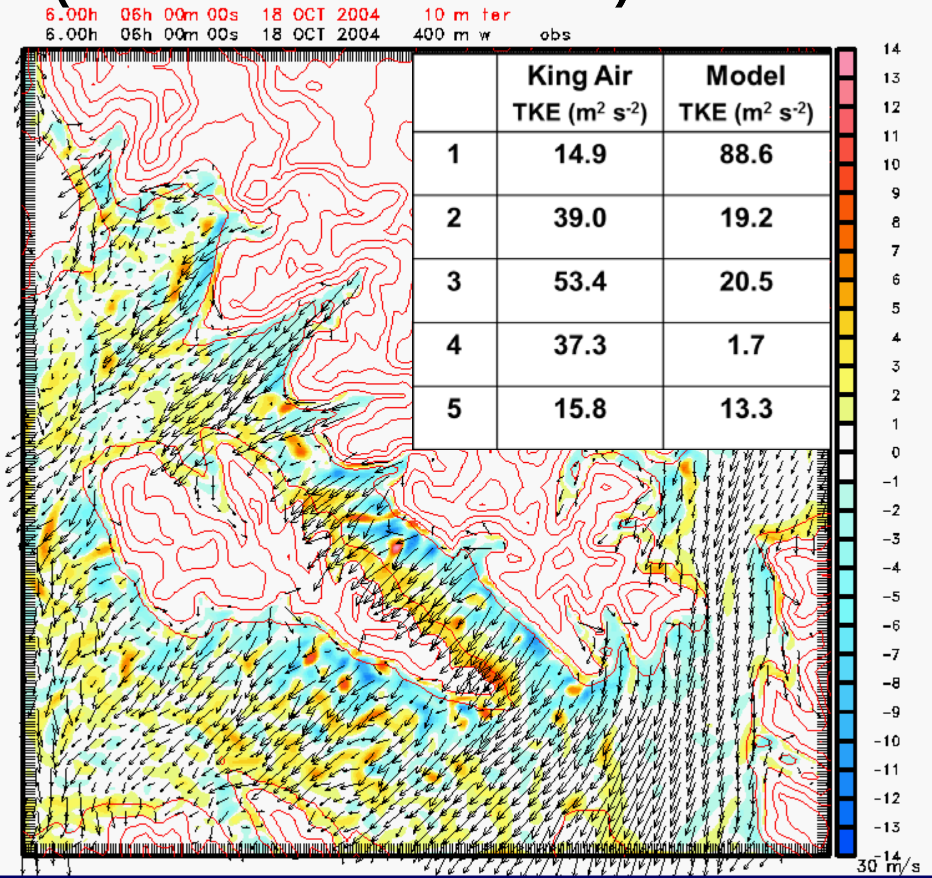


Bond et al. (2006)

Aircraft Observations of w



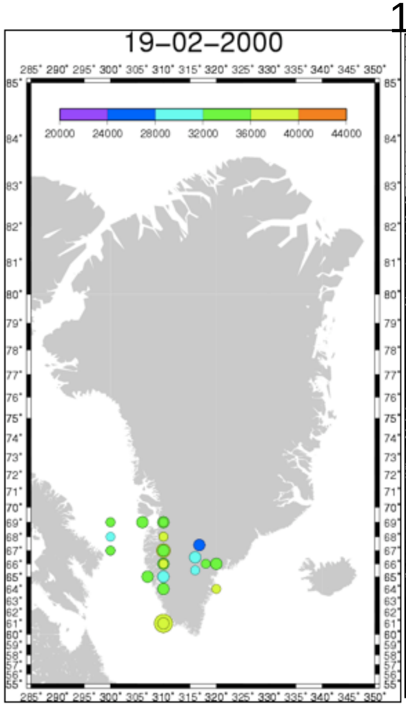
LES Wind and Vertical Velocity at 400 m (Terrain in Red Contours) Δx=150 m



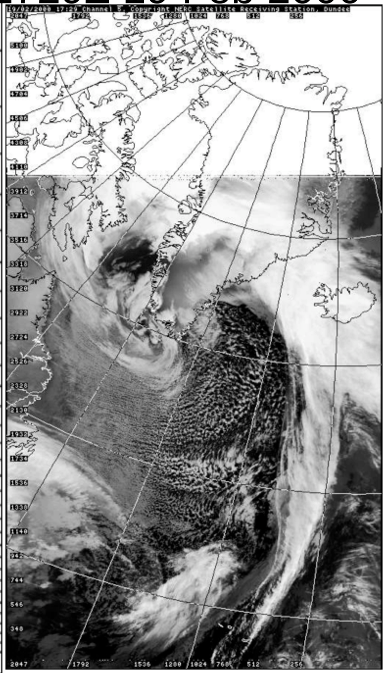
	King Air TKE (m^2 s^{-2})	Model TKE (m^2 s^{-2})
1	14.9	88.6
2	39.0	19.2
3	53.4	20.5
4	37.3	1.7
5	15.8	13.3

- **Explicit and LES modeling of wave breaking and secondary wave generation**
- **What observations are needed of turbulent downslope winds to constrain models?**

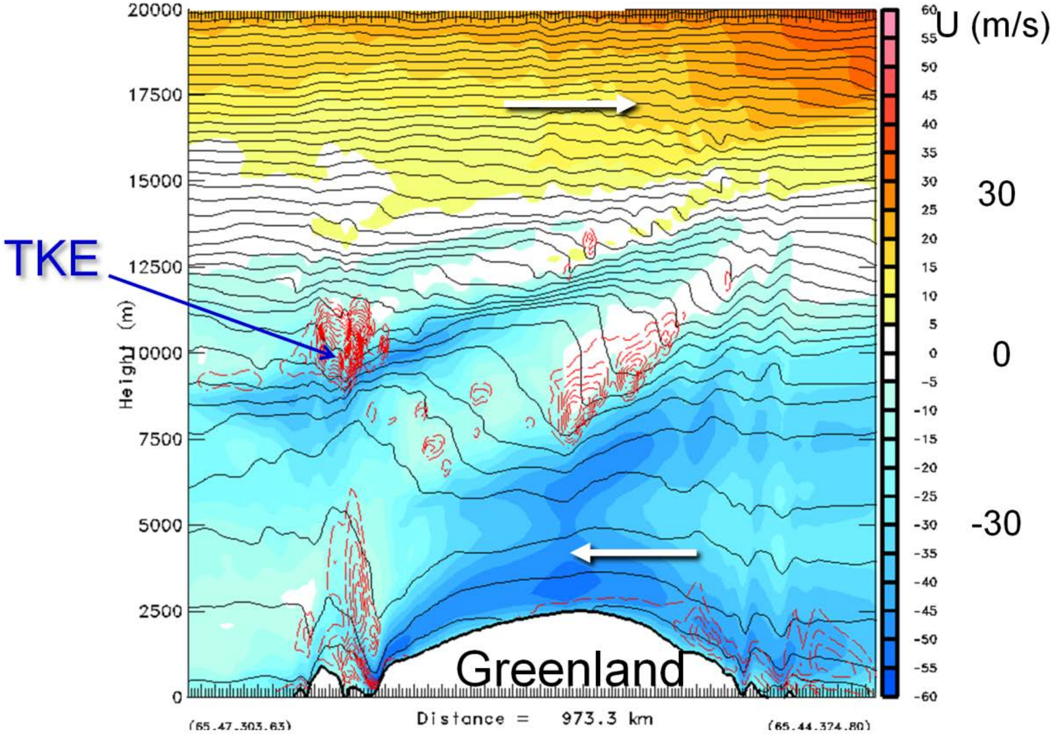
Critical Levels and Wave Breaking



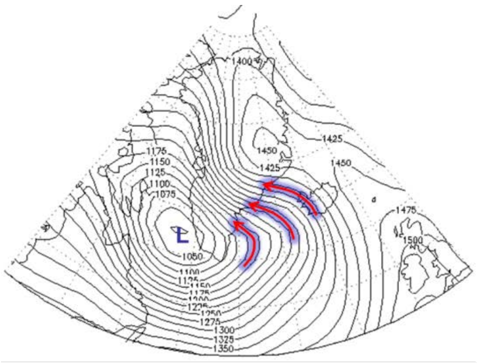
1729Z 19 Feb 2000



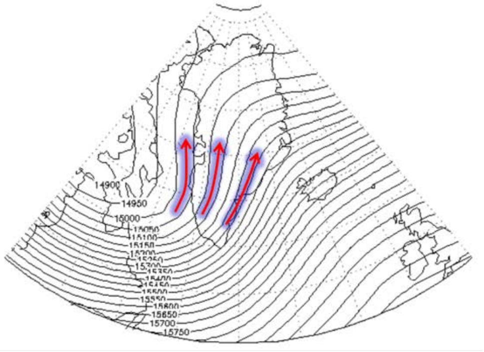
COAMPS Simulation (5 km)



- Low-level easterly flow and critical level (background) present.
- Sloping layers of wave overturning and turbulent breaking.



850 hPa



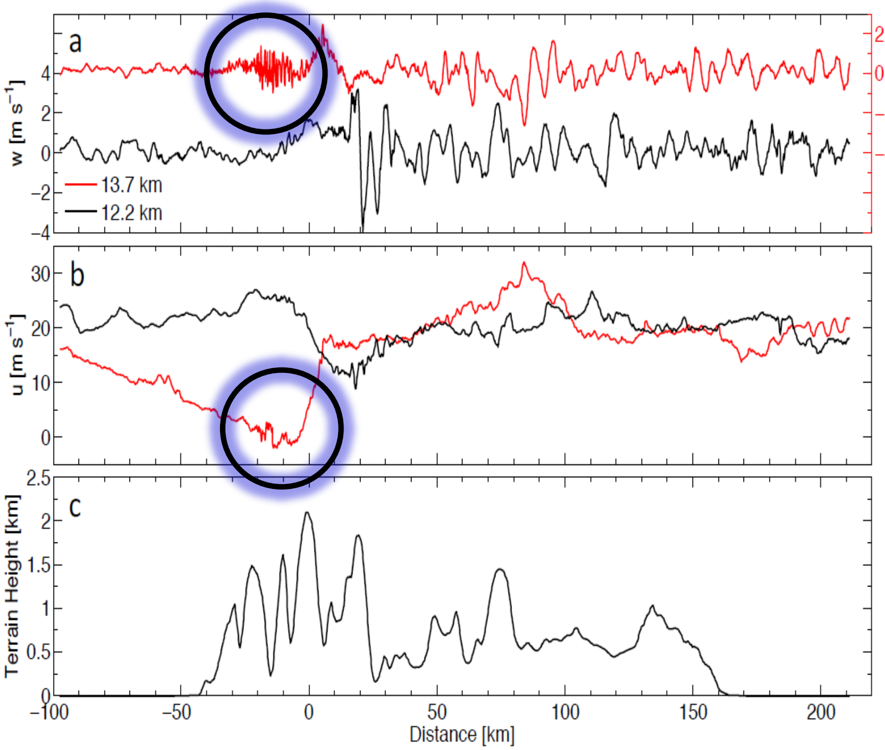
100 hPa

Lane et al. 2009

U.S. NAVAL RESEARCH LABORATORY

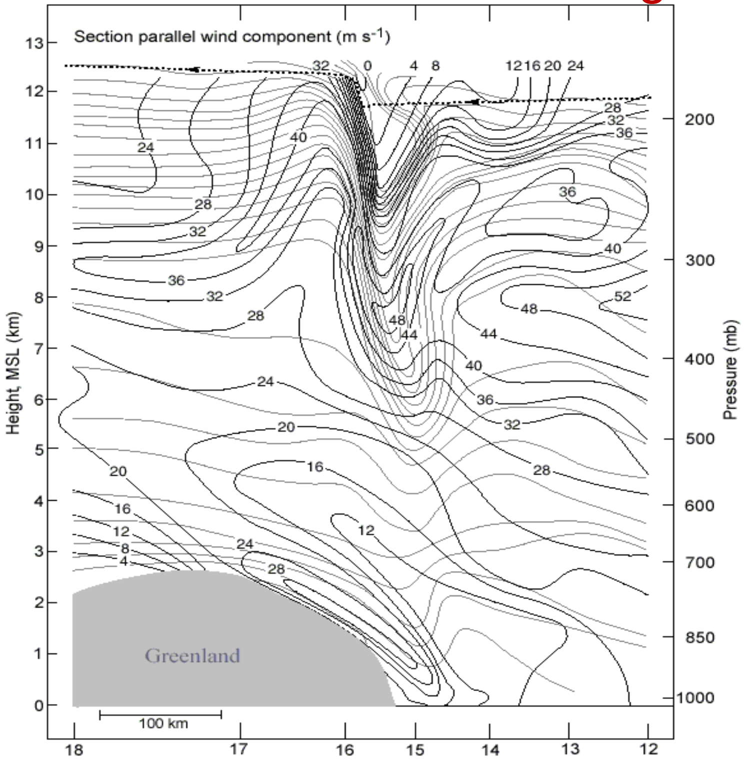
Upper-Level Wave Breaking

DEEPWAVE Wave Breaking (29 June)



Smith et al. (2016)

FASTEX Wave Breaking

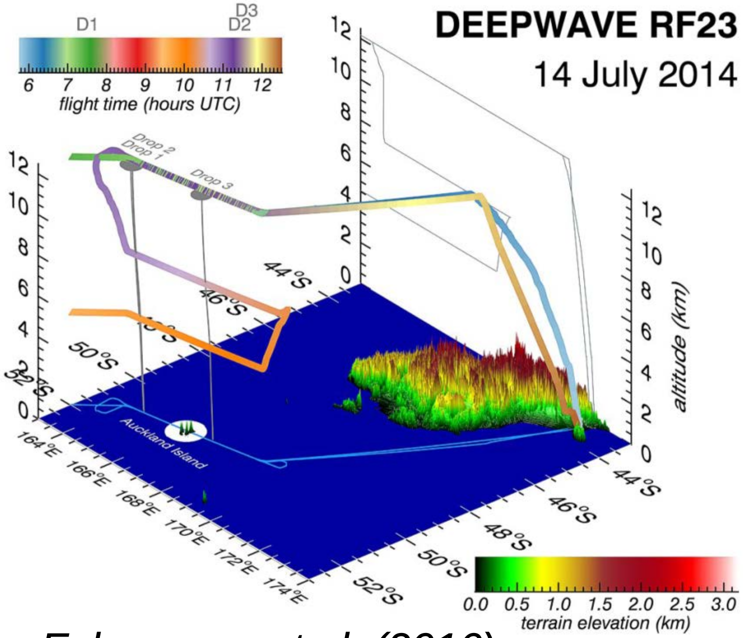


Doyle et al. (2005)

- **Observed turbulent upper-level wave breaking (and mixing in UTLS)**
- **Momentum flux diagnostics (including stratosphere - middle atmos.)**
- **Real world complex flows (cyclones with time-dependent forcing)**

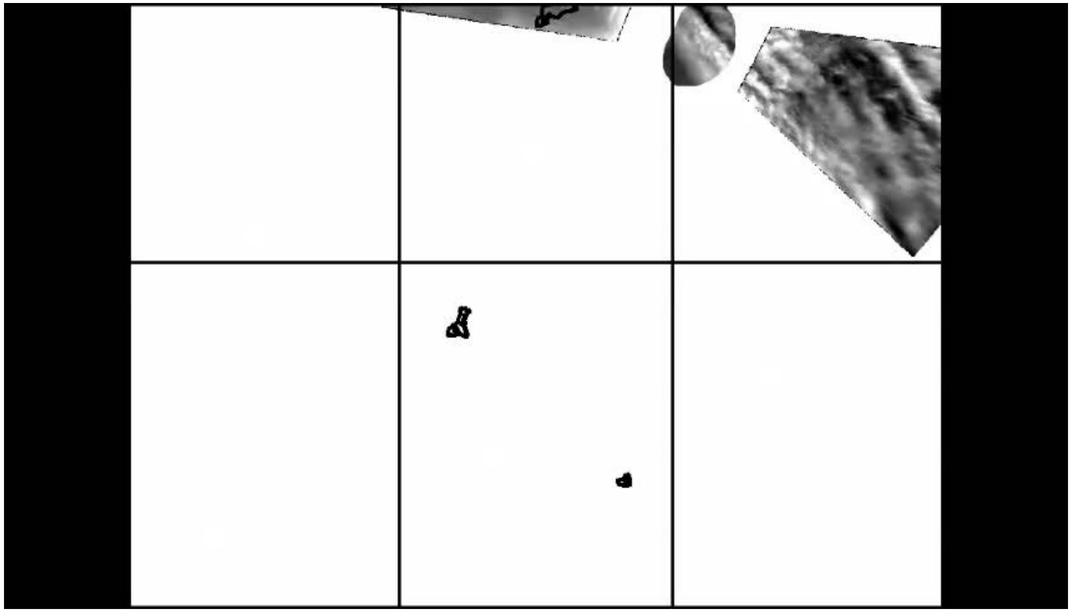
Upper-Level Wave Breaking

DEEPWAVE G-V Flight Over Auckland Island



Eckermann et al. (2016)

G-V AMTM Observations (~87 km)



Pautet et al. 2015 (JGR)

Growing evidence that small islands may be important sources of gravity waves and upper-level turbulence

MWT Predictability

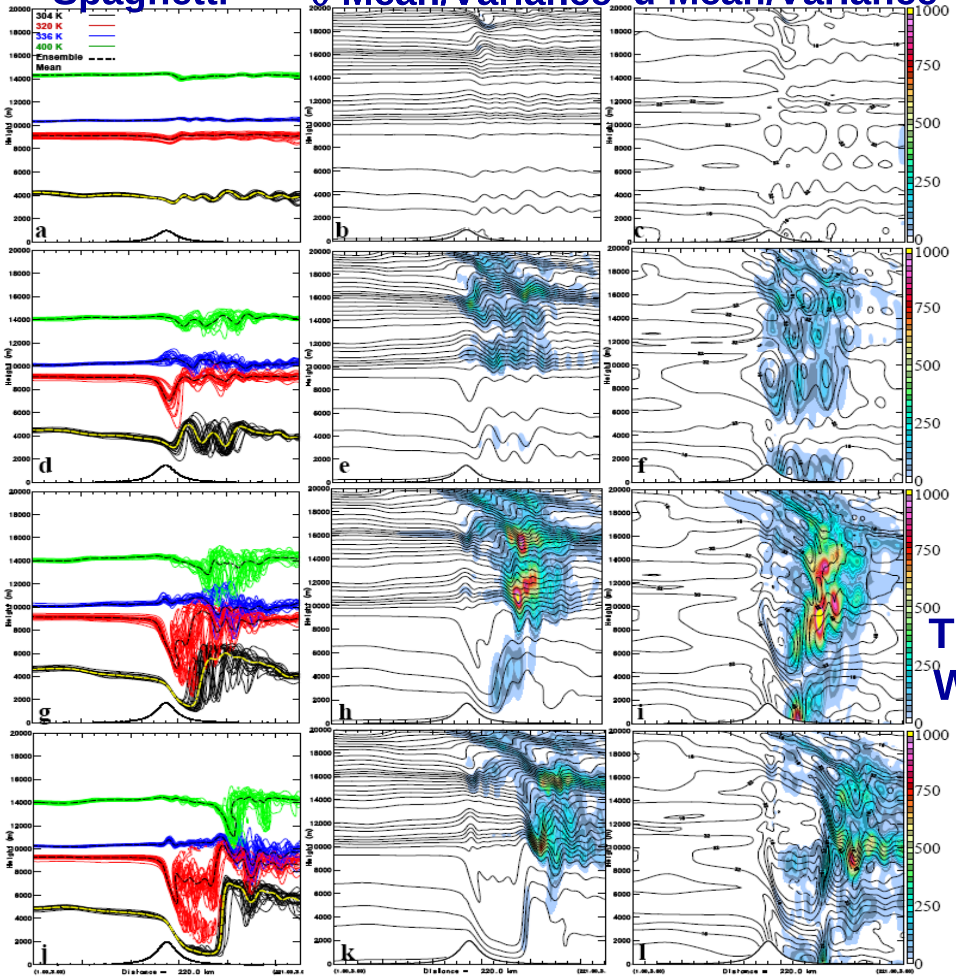
Spaghetti θ Mean/Variance u Mean/Variance

h_m=1000 m

h_m=1500 m

h_m=1750 m

h_m=2000 m



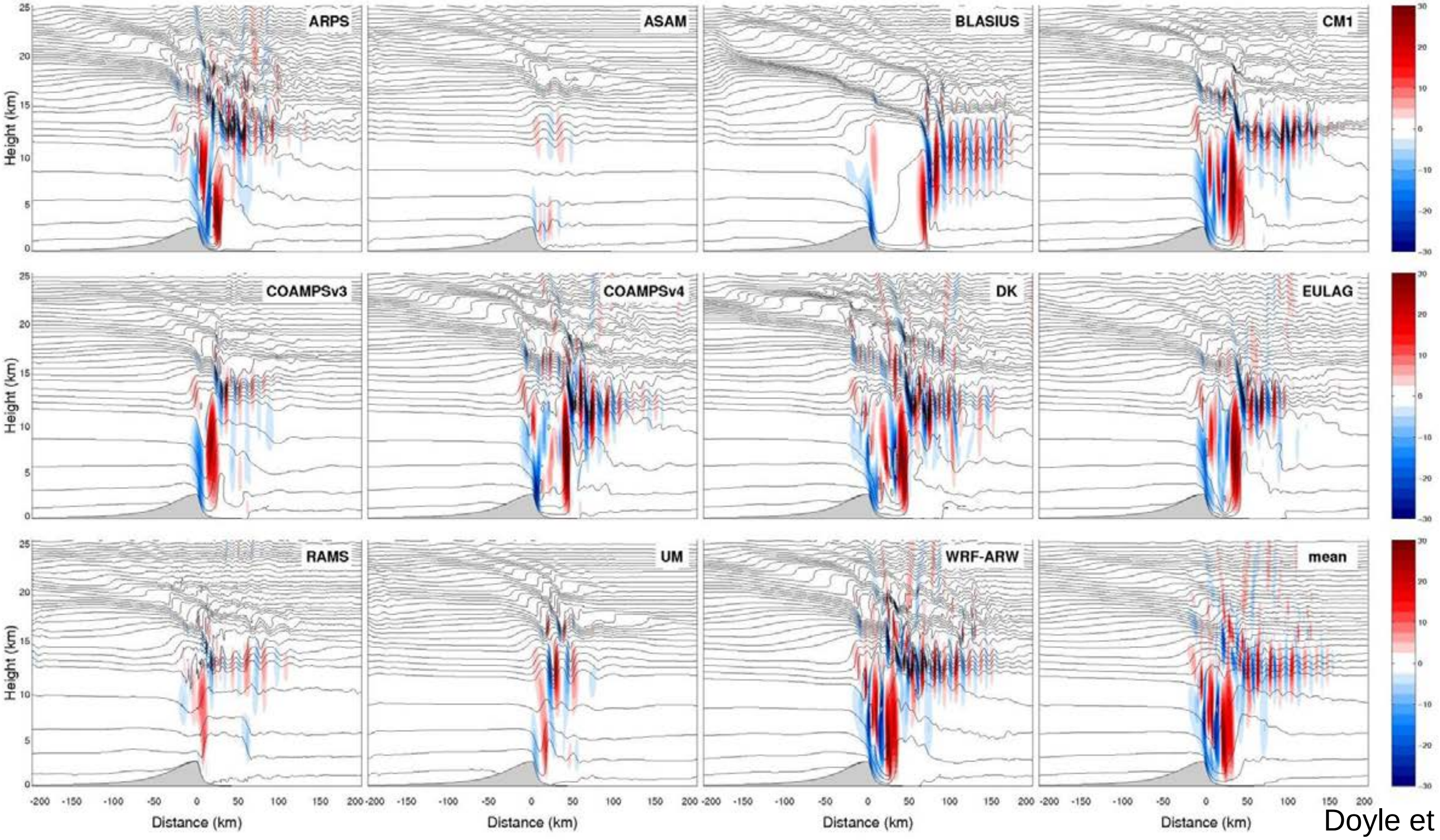
Bifurcation State
Trapped Waves
Wave Breaking

- **2D ensemble initialized with a sounding from Jan 11, 1972 Boulder windstorm**
- **Maximum variance (uncertainty) occurs near the wave breaking threshold (h_m=1750 m)**

Doyle and Reynolds (2008)

MWT Predictability

Model Intercomparison of Wave Breaking [w (m s^{-1})]

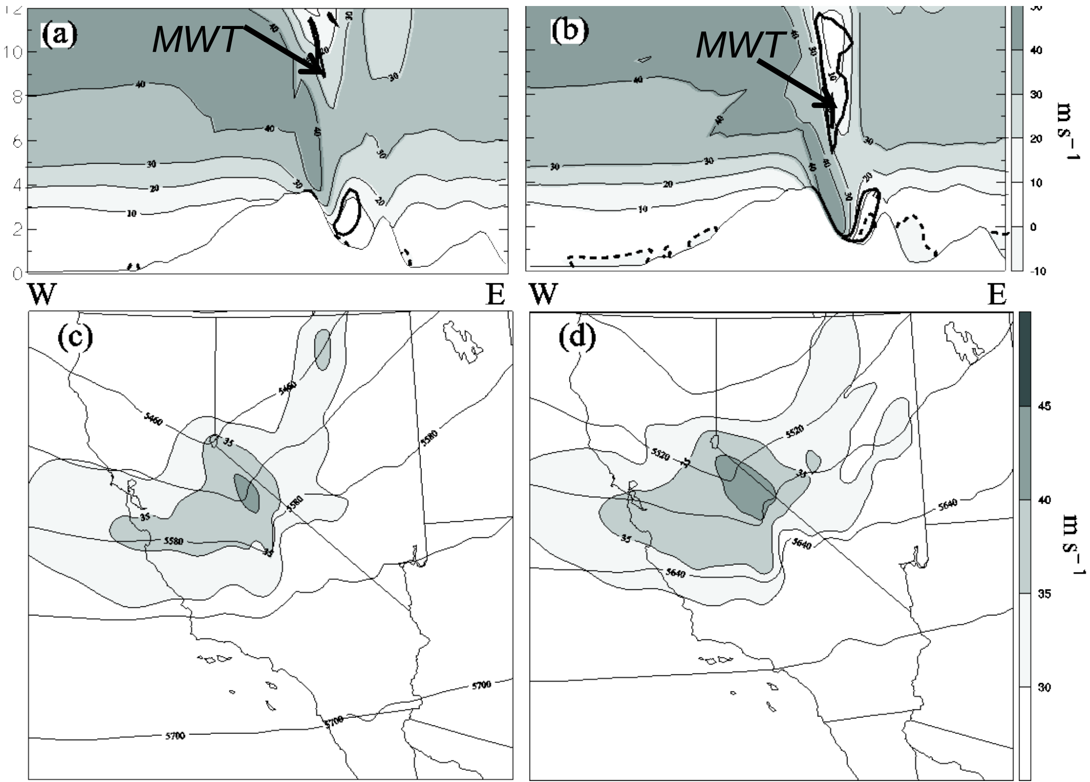


Doyle et al. (2011)

- **Explicit and LES 2D modeling of wave breaking and secondary wave generation**
- **Models still disagree radically for relatively simple problems (e.g., model error)**

MWT Predictability

Weak Members Strong Members



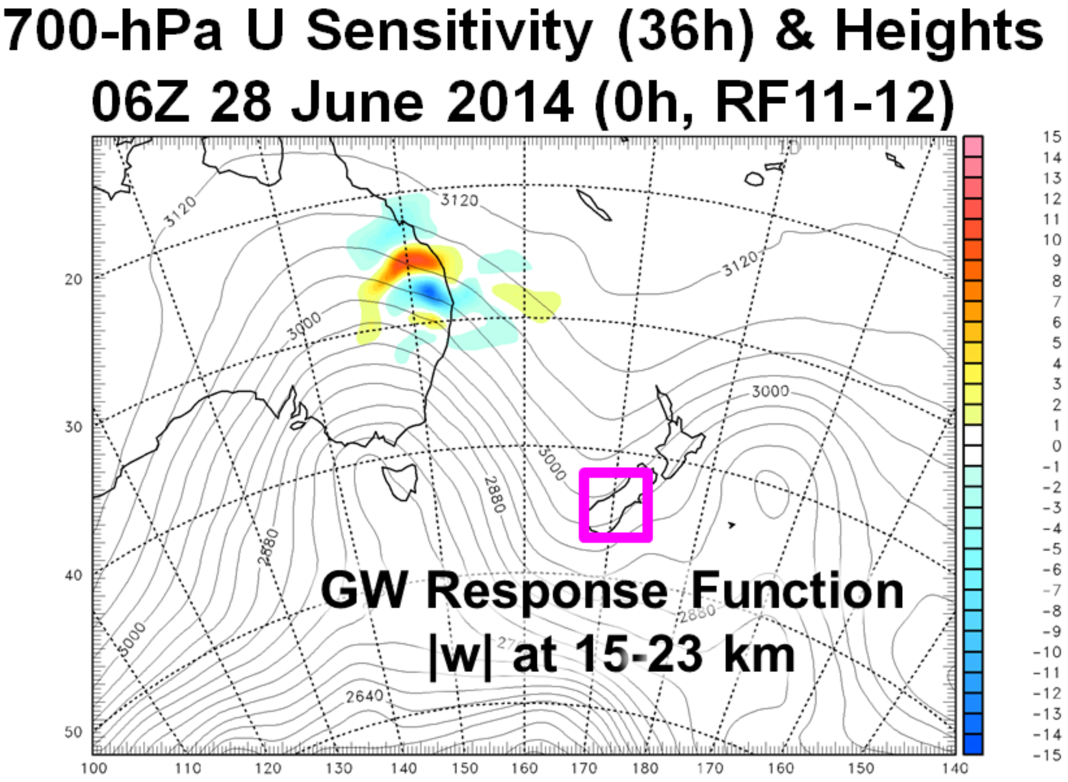
Reinecke and Durran (2009)

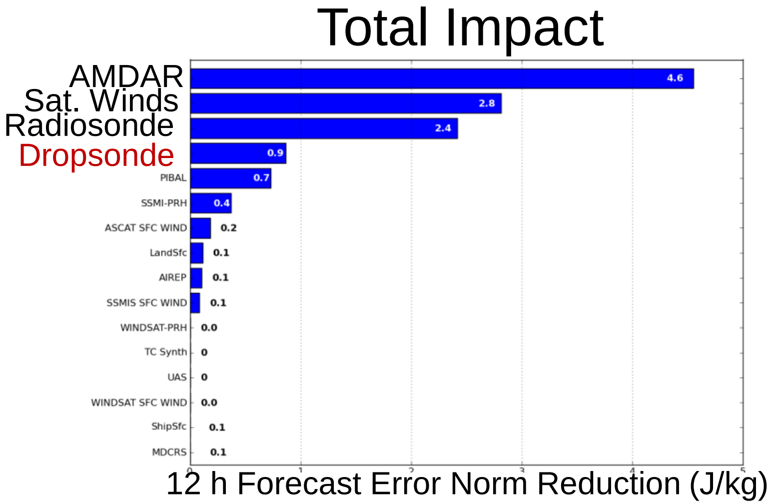
- **70-member ensemble simulation of a large-amplitude mountain wave during T-REX**
- **Strong-member subset: Large-amplitude breaking mountain wave with an extensive region of turbulent mixing directly above and to the lee of the Sierra.**
- **Weak-member subset: Wave breaking and turbulence are limited to a small region in the upper troposphere lower stratosphere**
- **Differences in the synoptic-scale forcing are small**

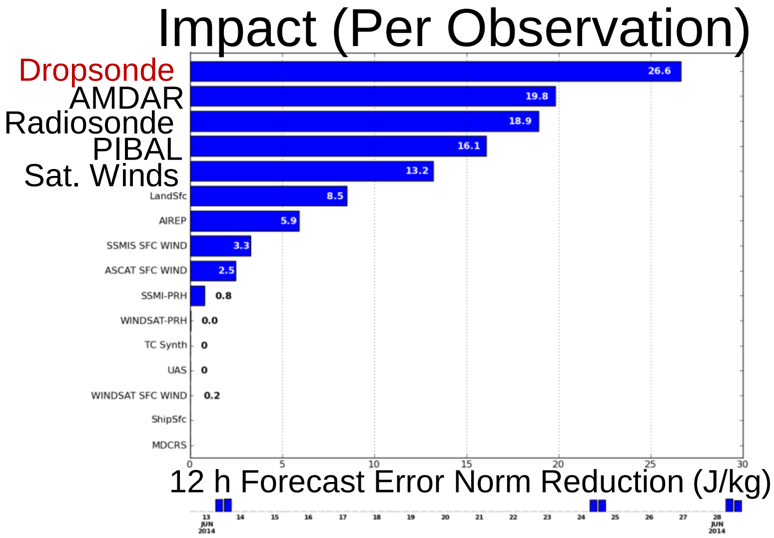
Summary

- Measurements (research aircraft, PIREPS) and numerical simulations show a rich spectrum of responses including MWT (wave breaking) that results from flow over large-scale (e.g., Greenland) and complex terrain (e.g., Alps,Sierra).
- Rotors and hydraulic jumps occur when strong downslope flow in the boundary layer along the lee slopes separate from the surface as a turbulent vortex sheet (and subrotors) creating strong turbulence.
- The predictive skill of numerical forecasts of MWT observed in nature is encouraging and has improved with increases in fidelity of the models.
- Ultimately, high-resolution ensemble methods that are capable of explicitly resolving mountain waves should be used to provide probabilistic forecasts of turbulence needed for aviation hazard mitigation.

Observation Impact on Mountain Wave Launching





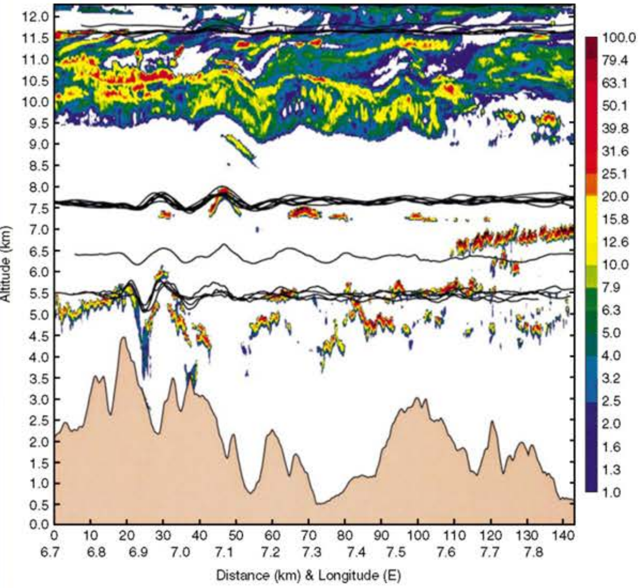


- **Adjoint highlights remote upstream sensitive regions important for MWs**
- **Adjoint (model+DA) observation impact on 12-h forecasts during DEEPWAVE.**
- **Targeted dropsondes have the largest impact on a per observation basis.**

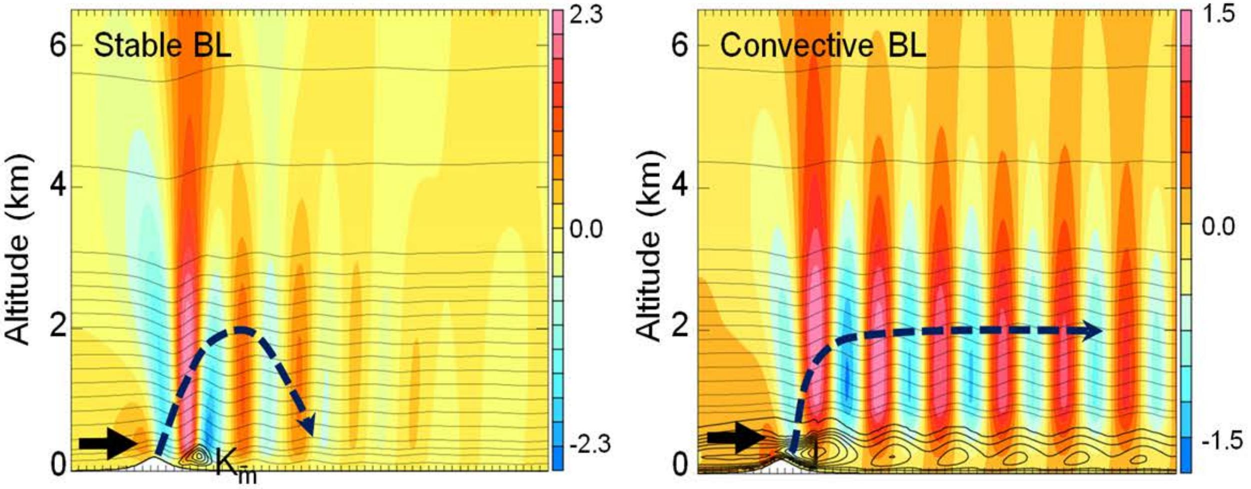
C. Amerault

Lee Waves and Turbulence

DIAL Lidar (Mt. Blanc)



Vertical Velocity and Potential Temperature

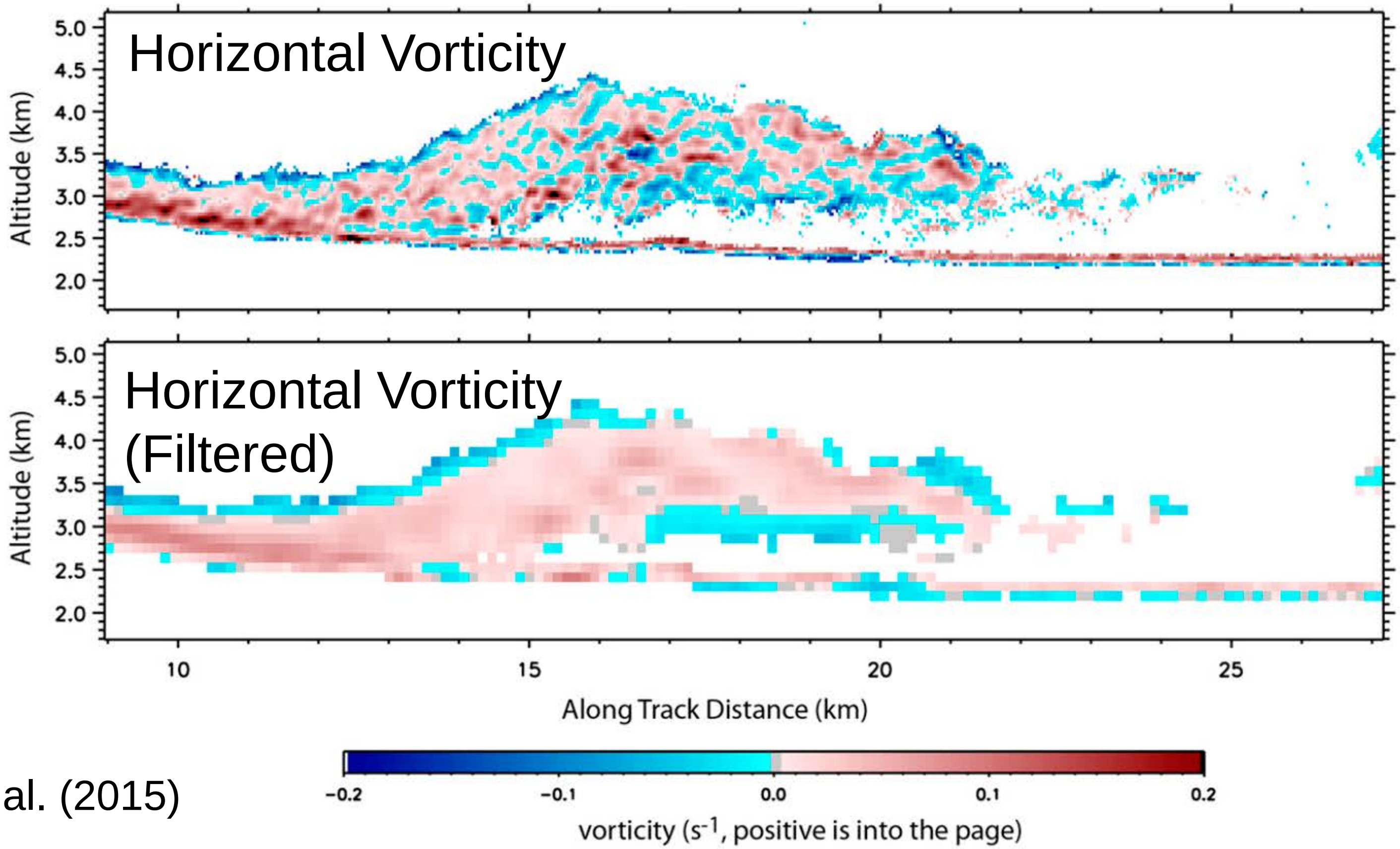


- Mountain lee waves are generally laminar though can be turbulent occasionally
- Lee waves are sensitivite to the PBL characteristics (stable vs. convective)
- Lee wave sensitive to land surface characteristics, diurnal cycle, upstream conditions (stability, moisture, winds)

Jiang, Doyle, Smith (JAS 2006); Smith, Jiang, and Doyle (JAS 2006); Jiang, Doyle, Wang, and Smith (JAS 2007), Jiang and Doyle (JAS 2008); Jiang, Smith, Doyle (JAS 2008)

Rotors

Subrotor Vortices over the Medicine Bow Mountains



French et al. (2015)

Unique observations of subrotor vortices over the Medicine Bow Mtns