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Mountain Wave Turbulence and Predictability

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Outline

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

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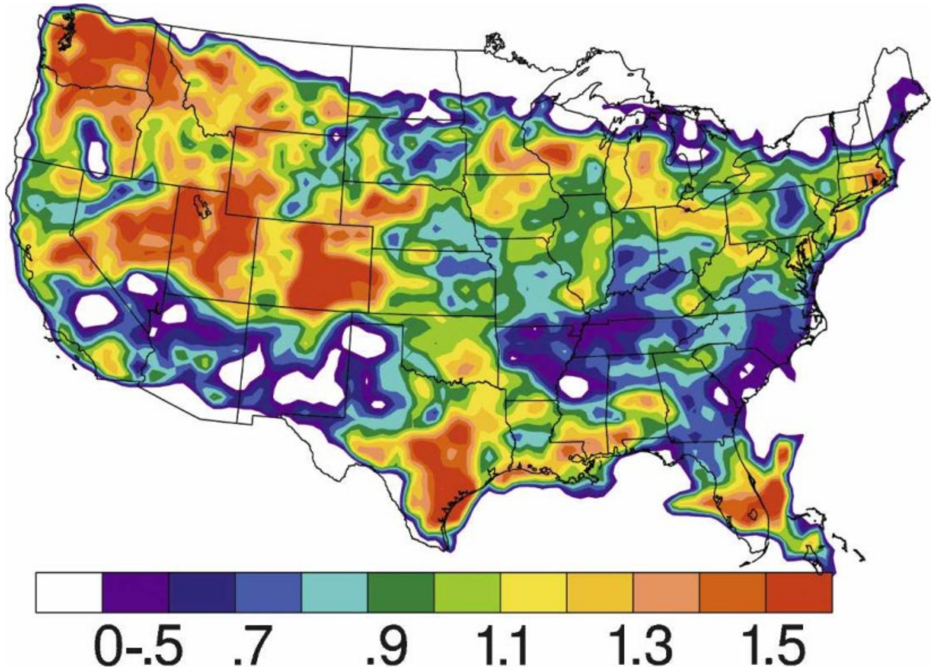
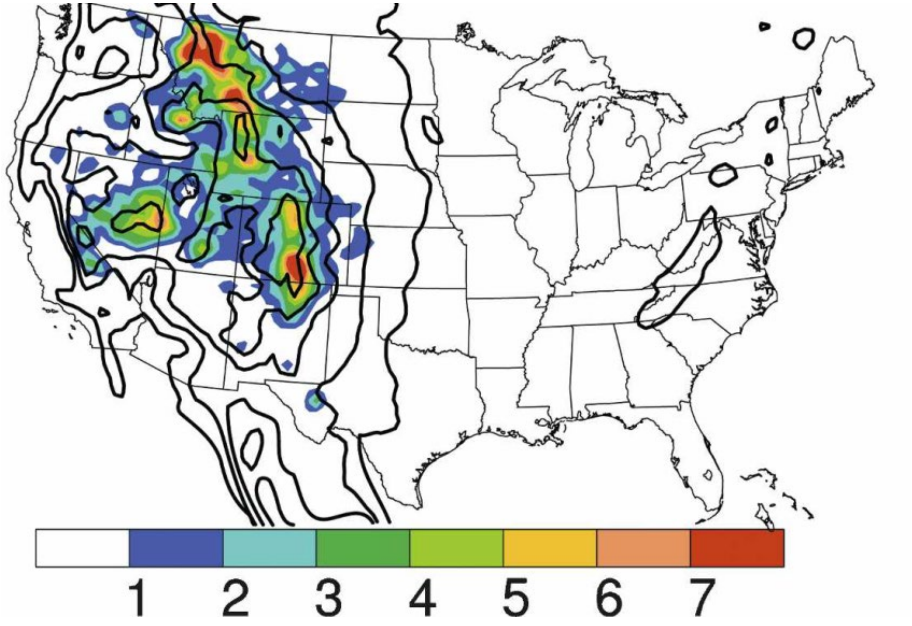
Mountain Wave Turbulence Climatology

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)



- When stably stratified air is forced over a barrier a disturbance is created and energy is carried away by internal gravity waves or mountain waves.
- Major source of turbulence over the western U.S. is due to mountain wave turbulence (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)

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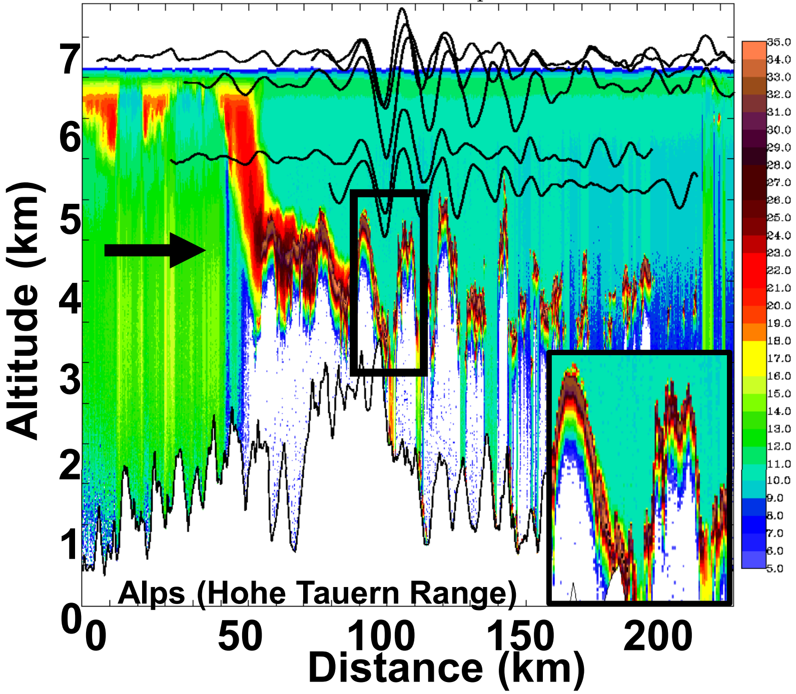
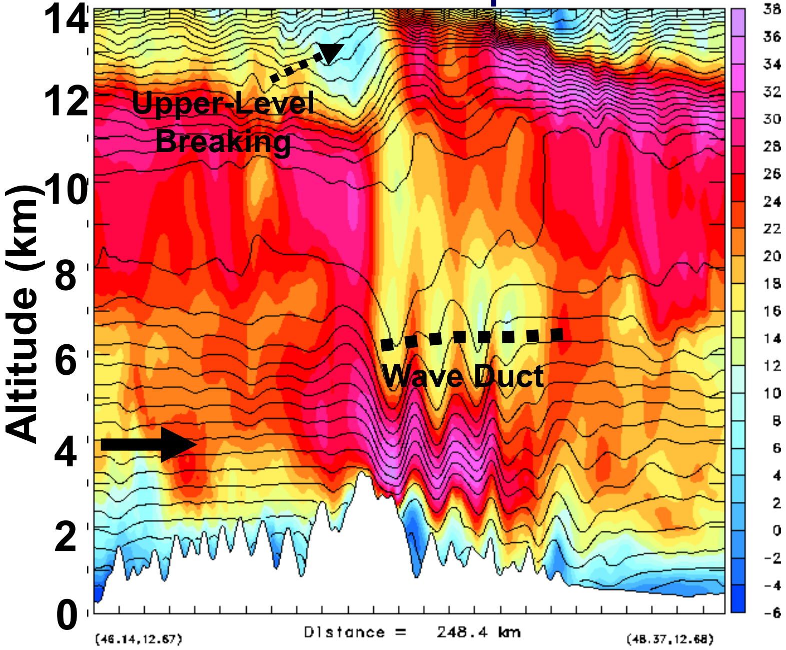
Lee Waves and Turbulence

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



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



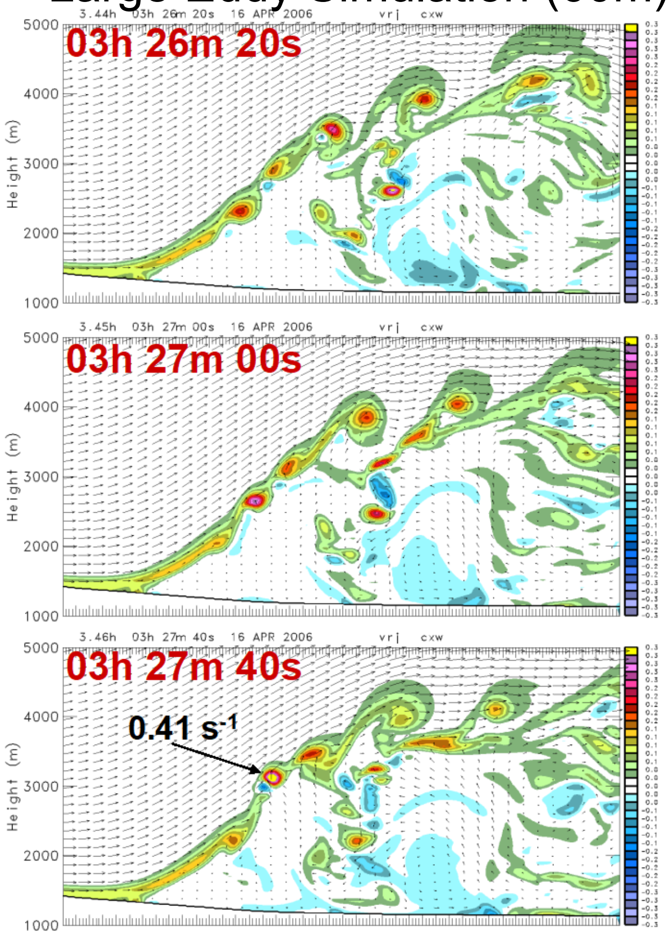
- Mountain lee waves are generally laminar though can be turbulent occasionally
- Trapped wave generated by flow over narrow terrain of Alps beneath a “leaky” wave duct.
- Wave duct enhanced by upstream moist processes.

Doyle and Smith (2003) QJRMS

Rotors: T-REX

Subrotor Vortices During the Terrain-Induced Rotor Experiment

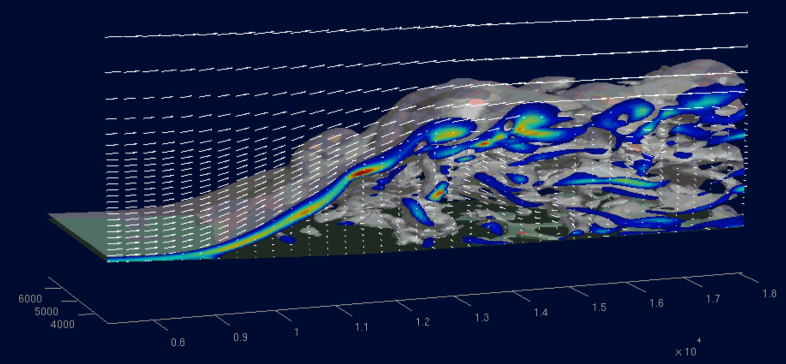
Large Eddy Simulation (60m)



COAMPS LES Simulation

2100 UTC 16 April 2007

[30 min. period, Δx=60 m]

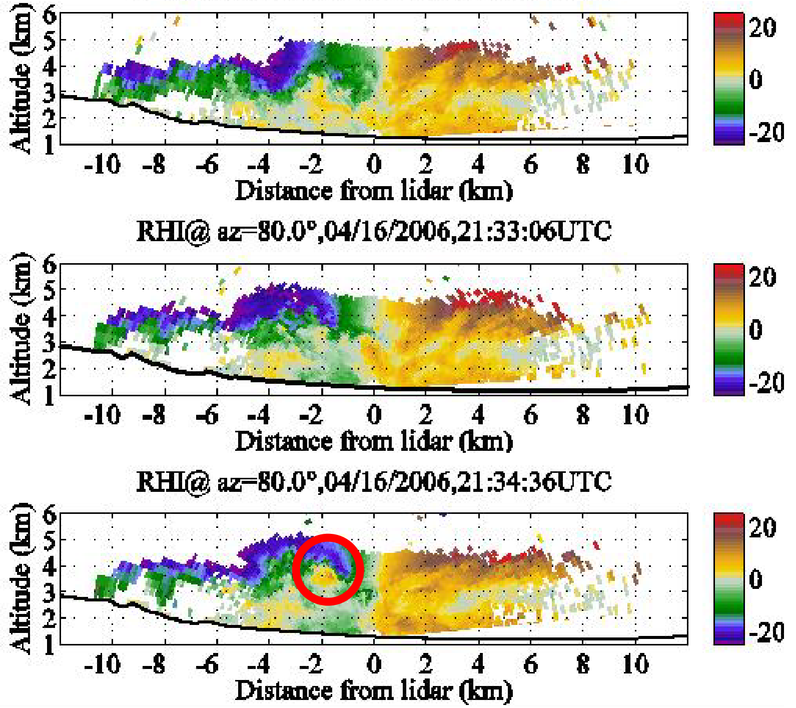


η Vorticity (color)

η = 0.15 s^{-1} (red)

η = 0.02 s^{-1} (gray)

Doppler Lidar Velocities

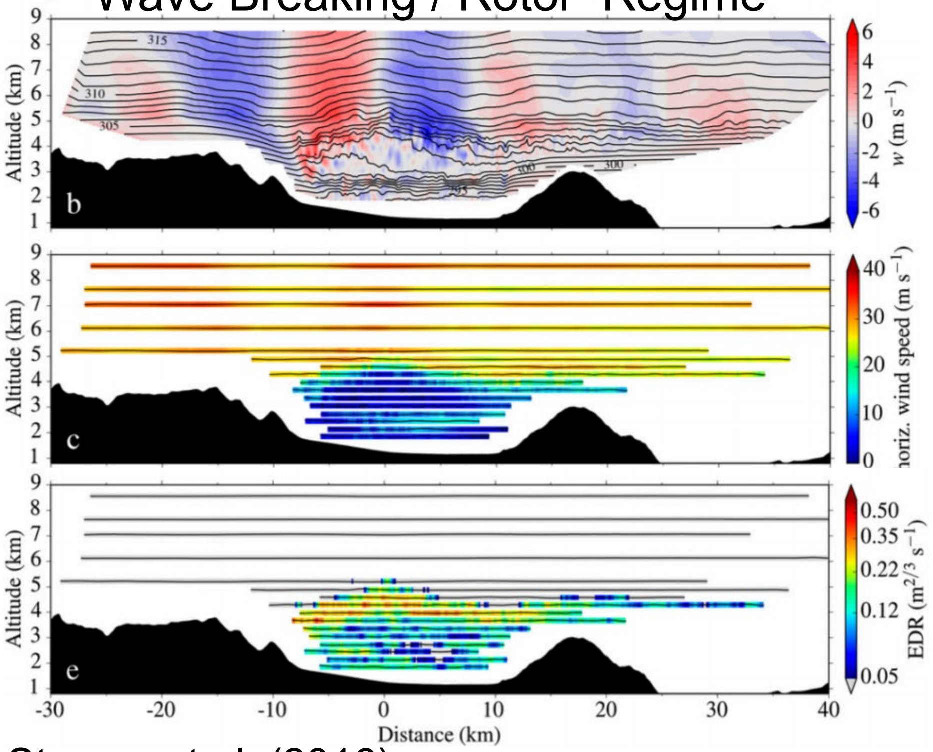


Large Eddy Simulations of rotors underscores the key characteristics including flow separation, elevation of vortex street, and development of KH billows or sub-rotors downstream

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

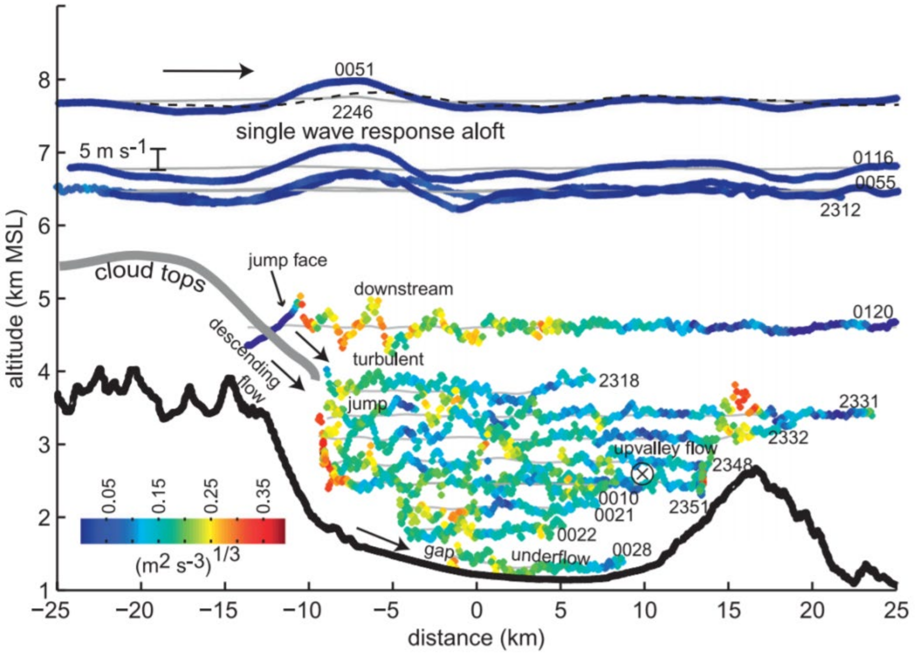
Hydraulic Jumps and Rotors

Wave Breaking / Rotor Regime



Strauss et al. (2016)

Hydraulic Analogue

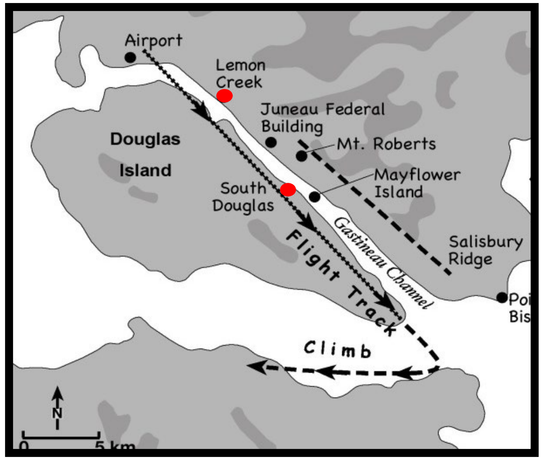


Armi and Meyer (2011)

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

Low-Level Wave Breaking

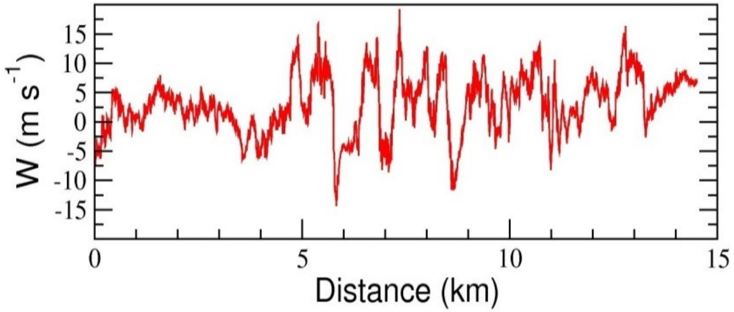
SARJET (Alaska)
UW KingAir Flight Path



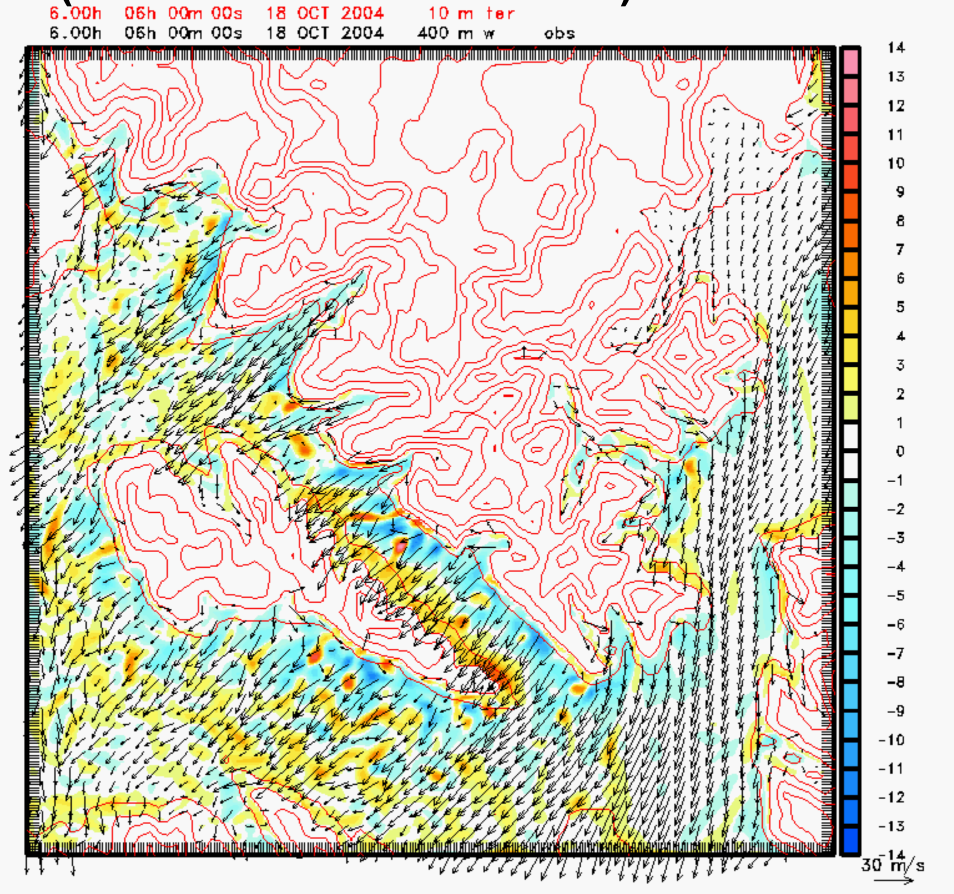
Bond et al. (2006)

	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

Aircraft Observations of w



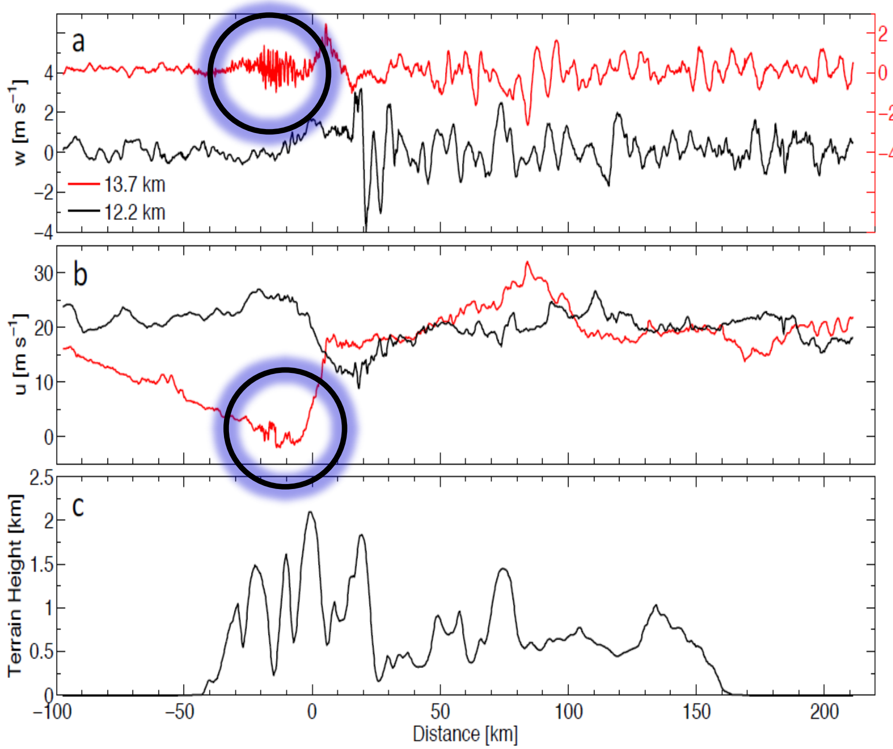
LES Wind and Vertical Velocity at 400 m (Terrain in Red Contours) Δx=150 m



- **LES modeling of wave breaking and turbulent eddy shedding**
- **Turbulent eddies embedded within the low-level breaking region**

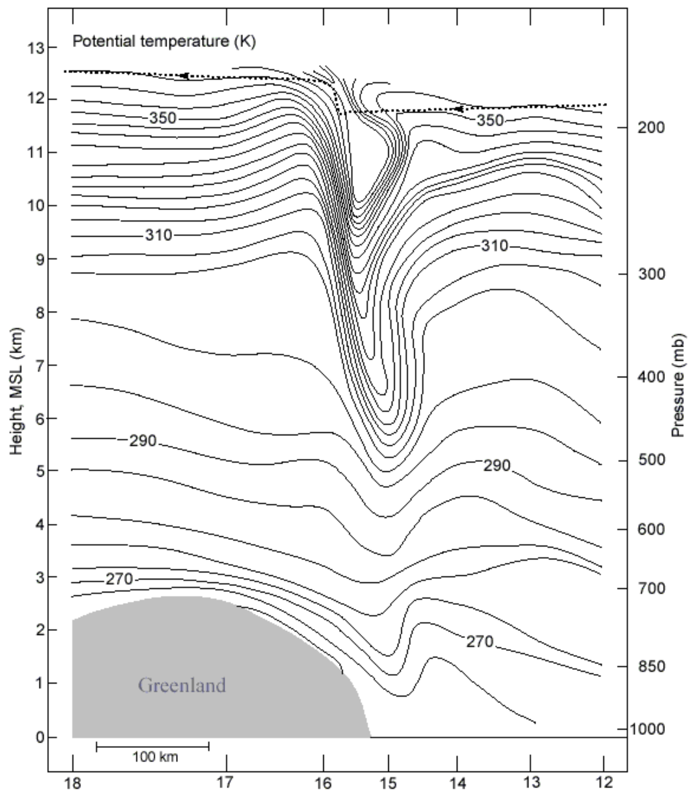
Upper-Level Wave Breaking and Turbulence

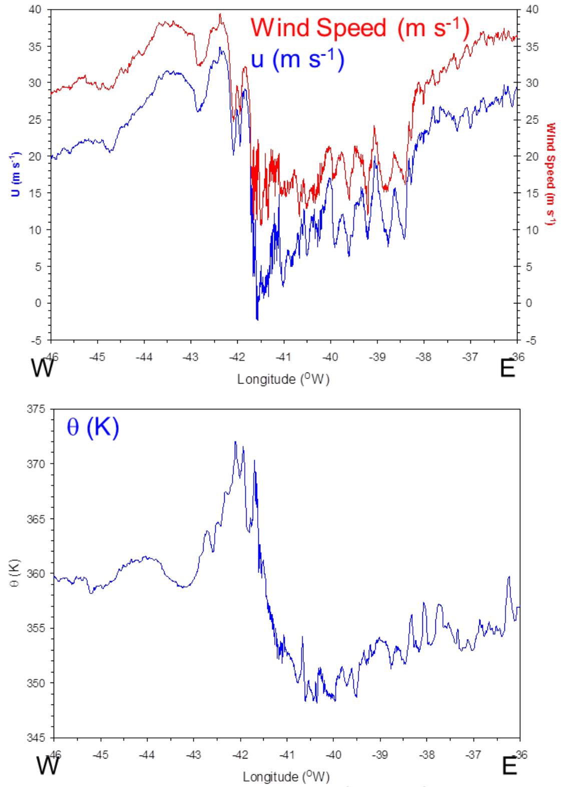
Wave Breaking over New Zealand (DeepWave)



Smith et al. (2016)

Wave Breaking over Greenland

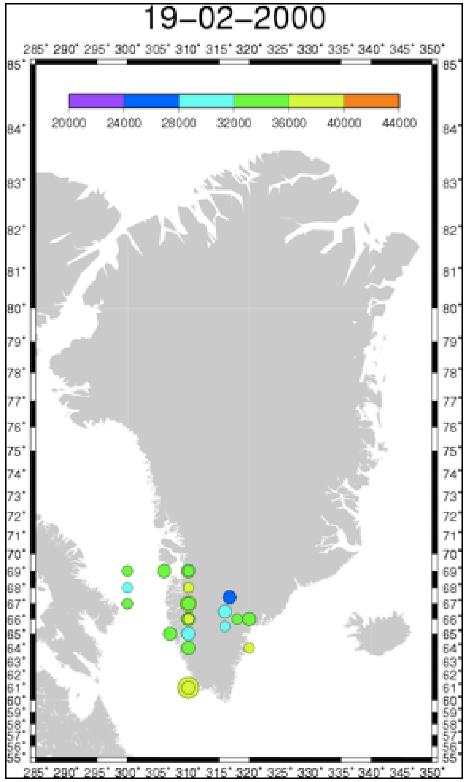




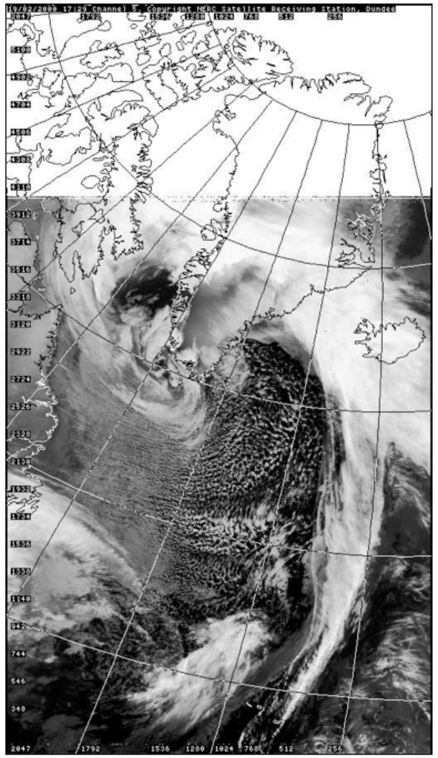
Doyle et al. (2005)

- Observed turbulent upper-level wave breaking (and mixing in UTLS)
- Real world complex flows (cyclones with time-dependent forcing)

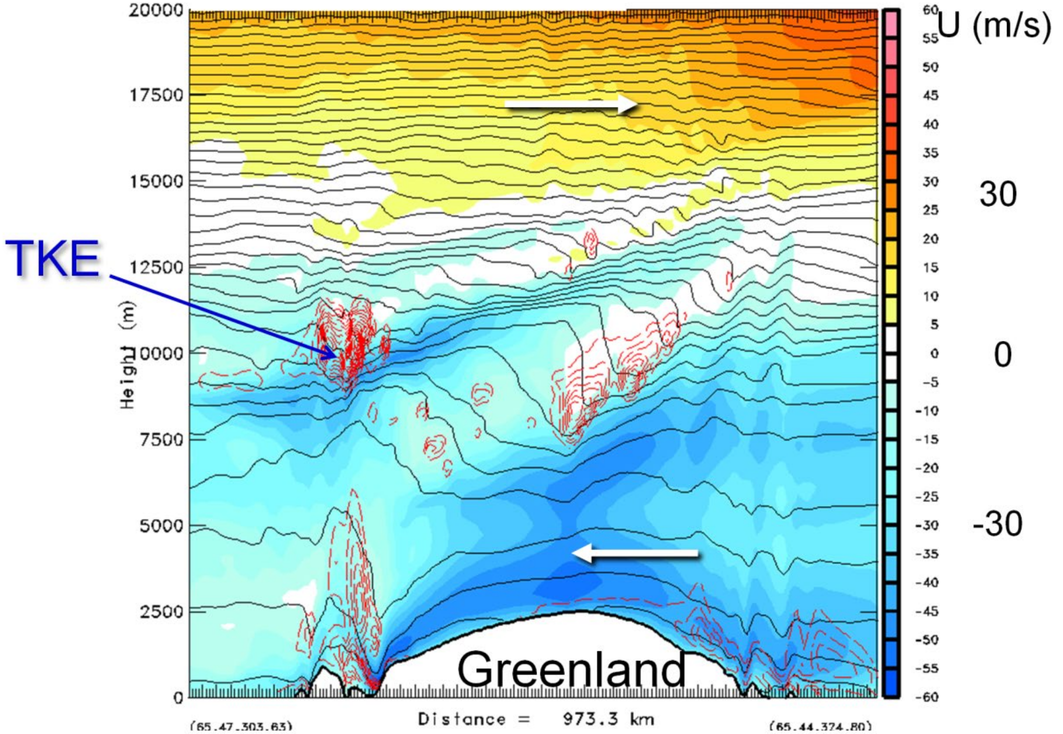
Critical Levels and Wave Breaking Turbulence

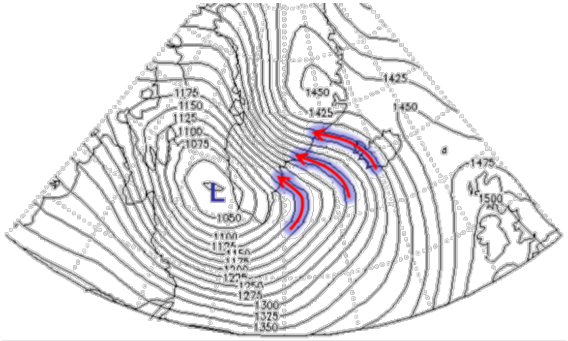


1729Z 19 Feb 2000

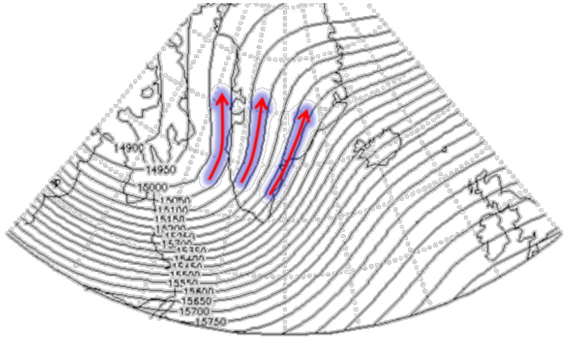


COAMPS Simulation (5 km)





850 hPa



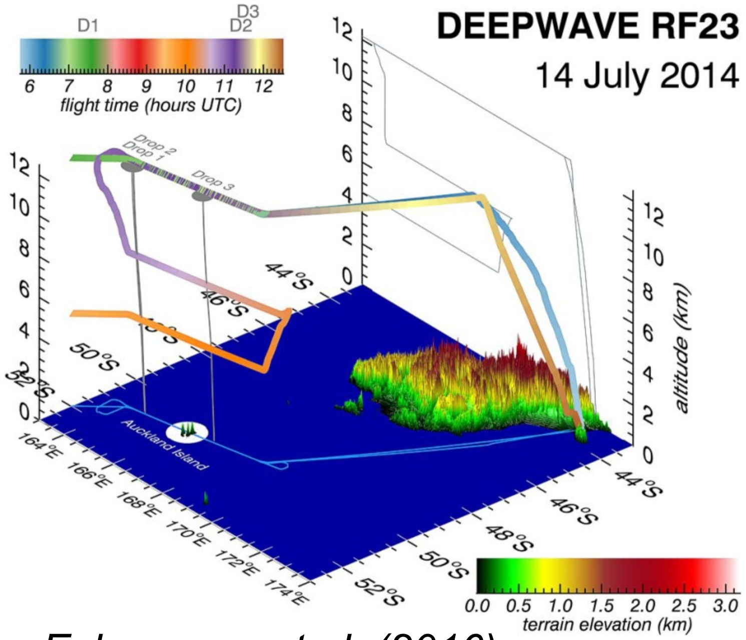
100 hPa

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

Lane et al. 2009

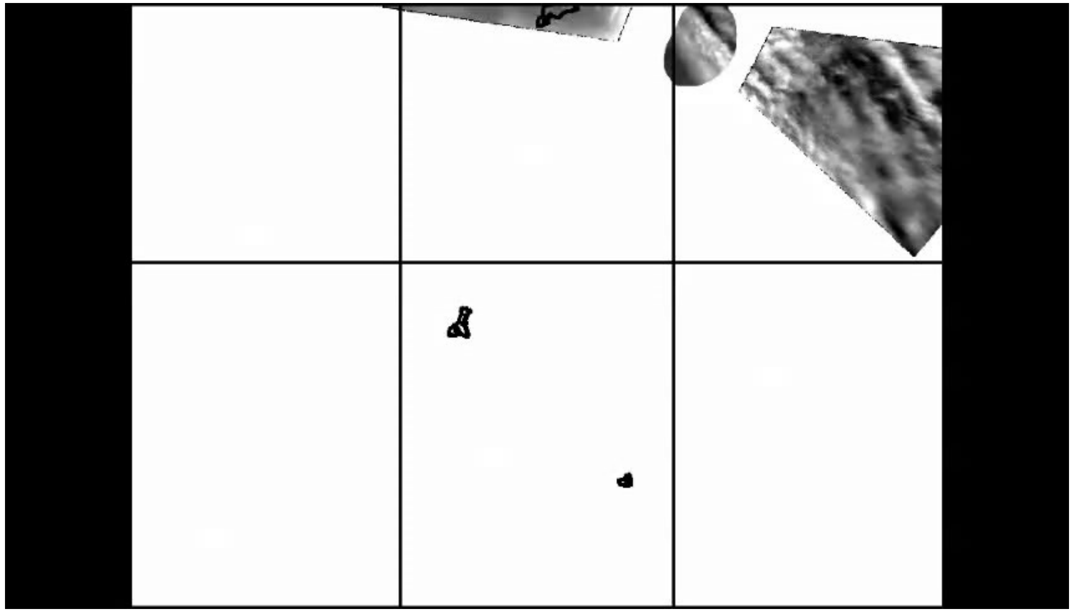
High-Altitude Wave Breaking and Turbulence

DEEPWAVE G-V Flight Over Auckland Island



Eckermann et al. (2016)

G-V AMTM Observations (~87 km)

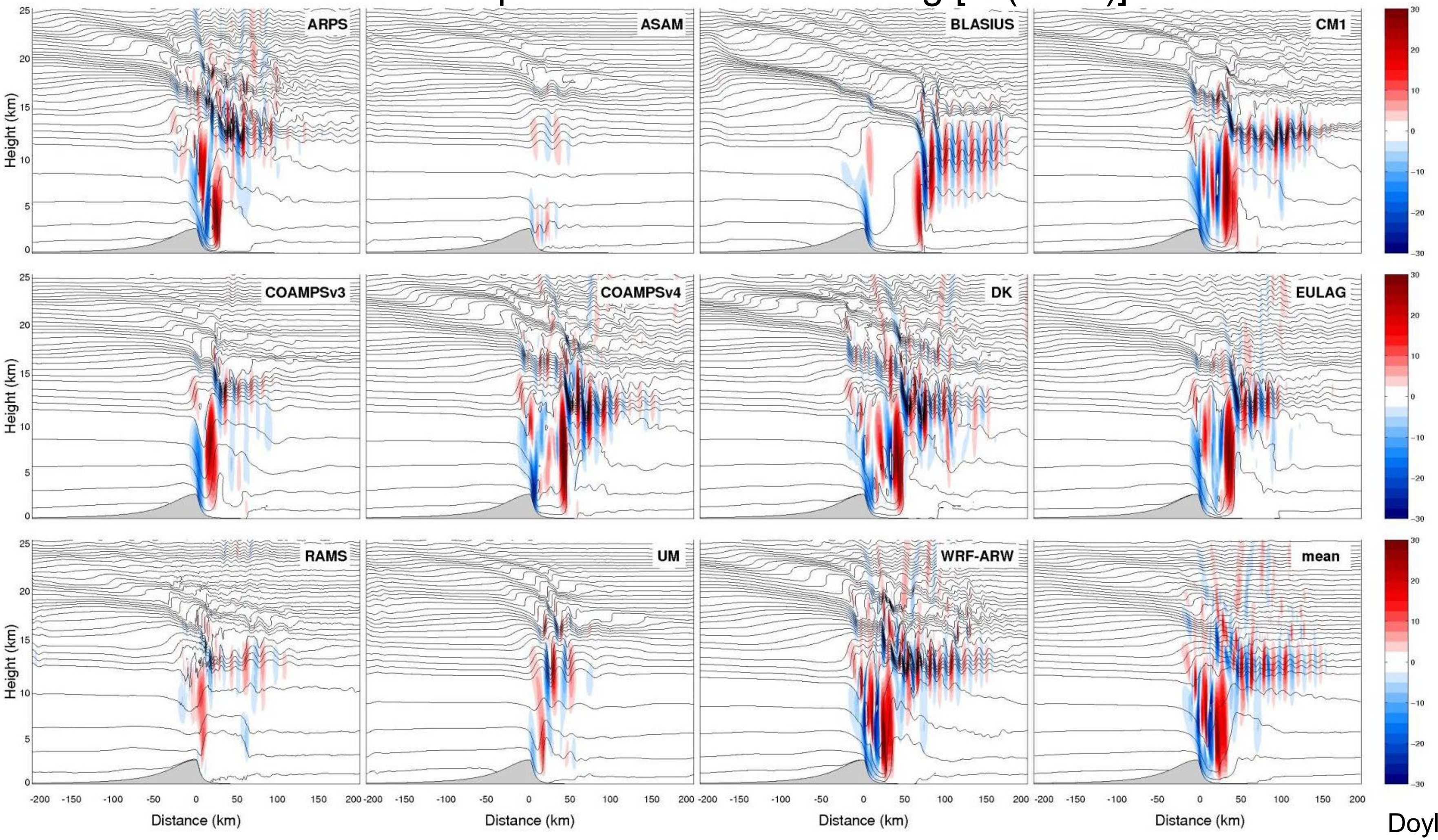


Pautet et al. 2015 (JGR)

Relatively small mountains and terrain may be important sources of gravity waves and upper-level turbulence

Mountain Wave Turbulence Predictability

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



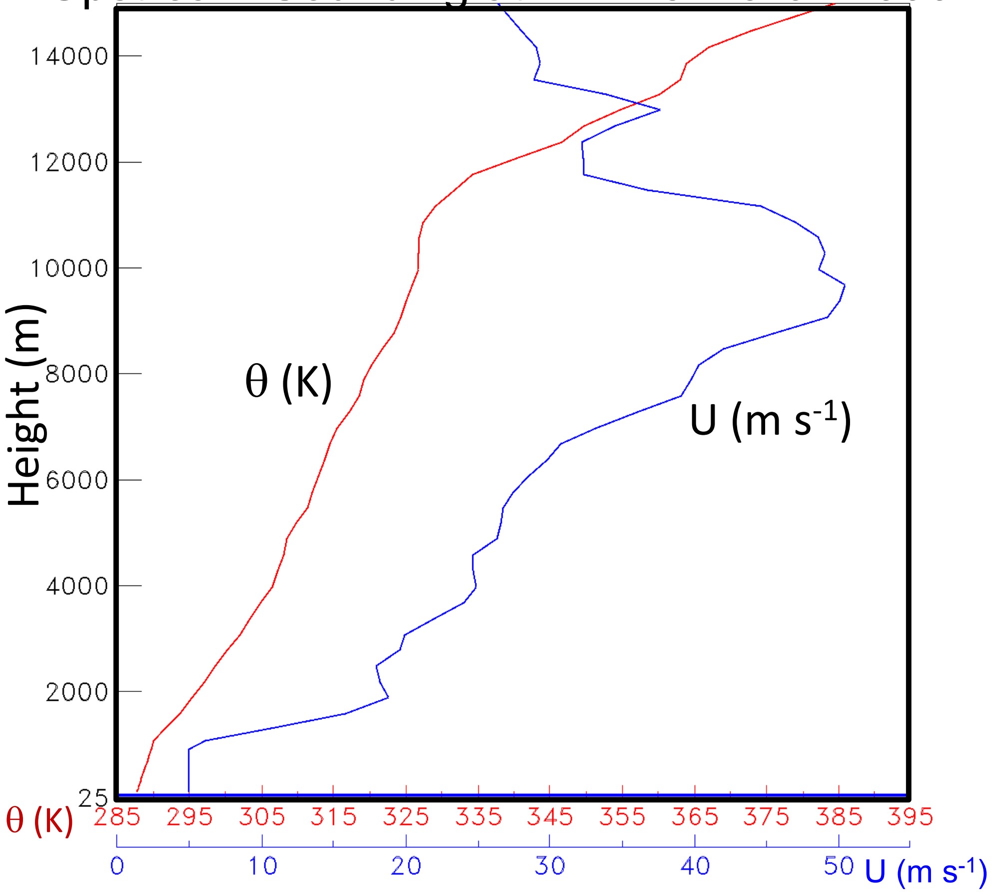
Doyle et al. (2011)

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

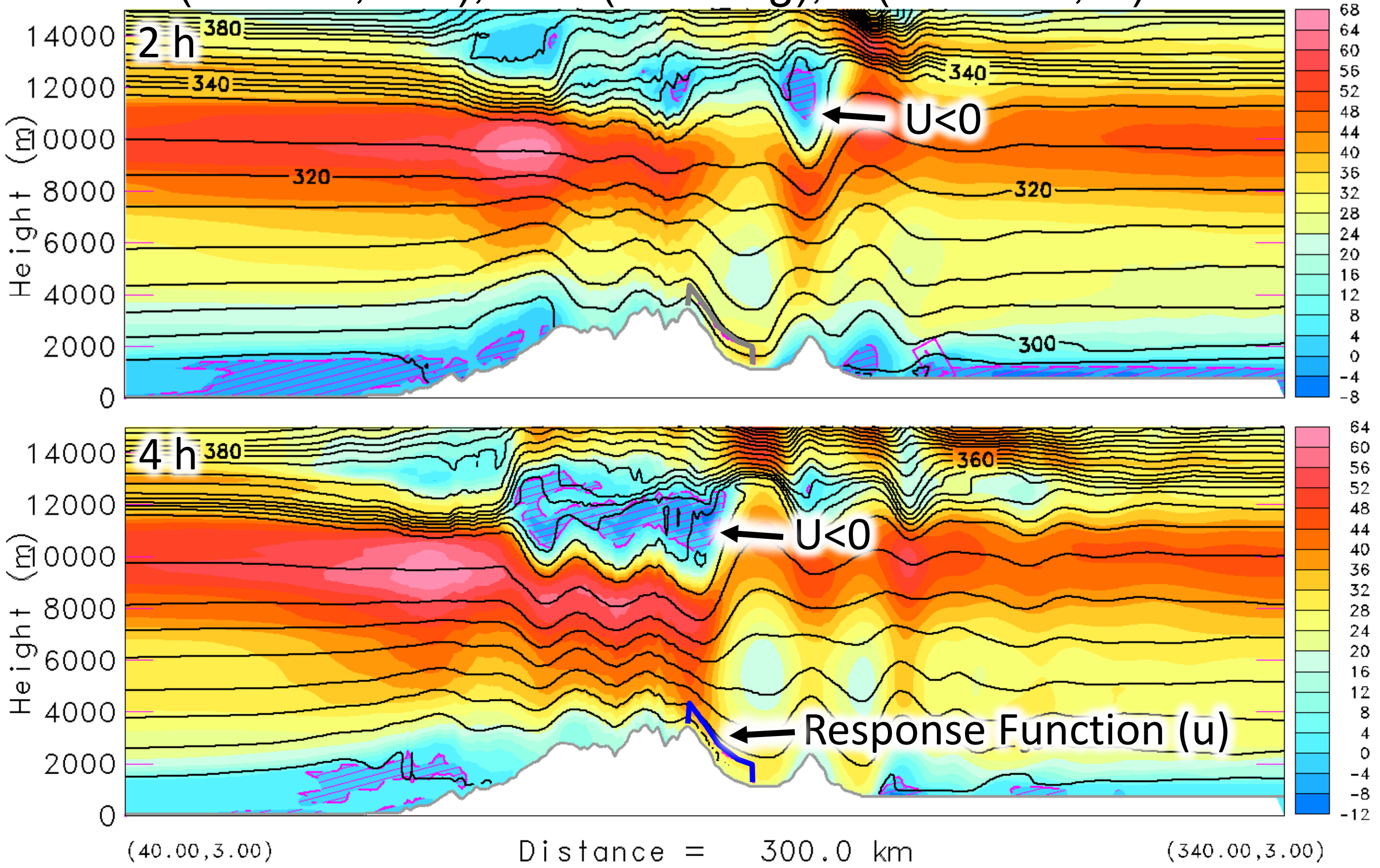
Mountain Wave Turbulence Predictability

2D Dry COAMPS (Δx=1 km, 95L) (Adjoint 2-4h)

Upstream Sounding at 21Z 25 March 2006

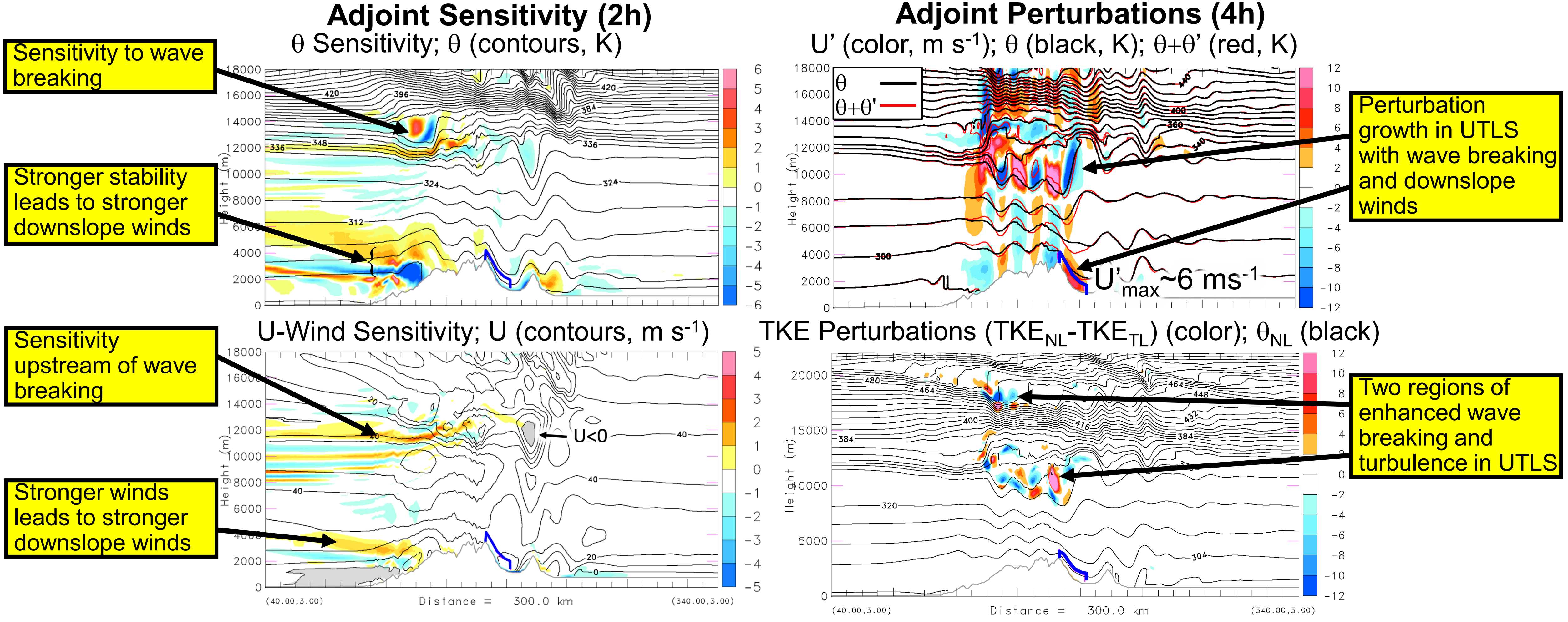


U (color fill, m/s), U<0 (hatching), θ (contours, K)



- Upstream sounding used to initialize 2D COAMPS (dry) with surface friction (NH/U~2.5-3.0)
- Strong downslope winds (~25 ms-1) and wave breaking in the lower stratosphere at 4-h time
- Adjoint allows for the mathematically rigorous calculation of forecast sensitivity of a response function to initial state
- Response function is the u-wind along the lee slopes in the lowest 725 m (lowest 9 levels)

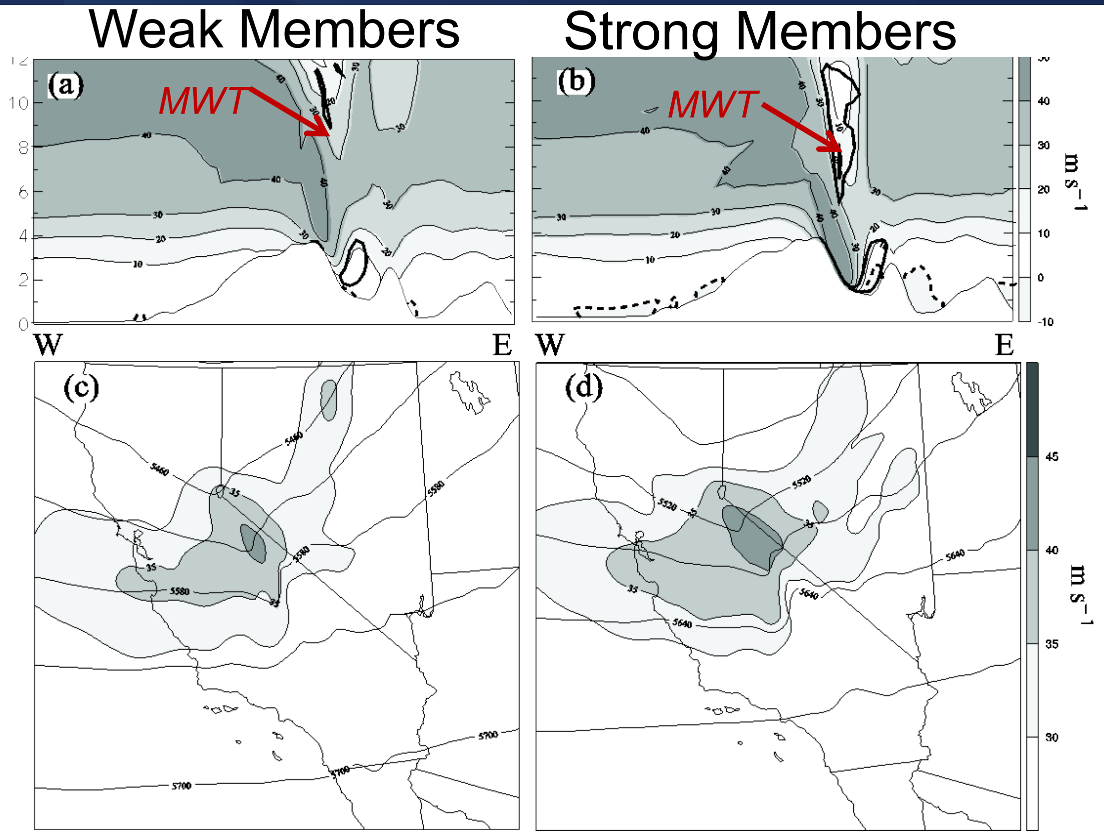
Mountain Wave Turbulence Predictability



Sensitivity of downslope winds during T-REX highlight the key role of:

- Upstream stability (key sensitivity), wind at crest height, in UTLS upstream of breaking, and the boundary layer
- 1°C warming upstream of crest leads to a ~50% larger increase in downslope winds than a 1 m s^{-1} wind increase
- Increased turbulence (TKE) in the UTLS in wave breaking layers

Mountain Wave Turbulence Predictability



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, New Zealand Alps).
- Rotors occur when strong downslope flow in the boundary layer along the lee slopes separate from the surface as a turbulent vortex sheet creating strong turbulence and sub-rotors.
- Adjoint model results indicate that mountain wave turbulence is highly sensitive to stability and winds upstream of the mountain crest and in the UTLS upstream of breaking layers.
- 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.