Mountain Winds, Waves, and Turbulence

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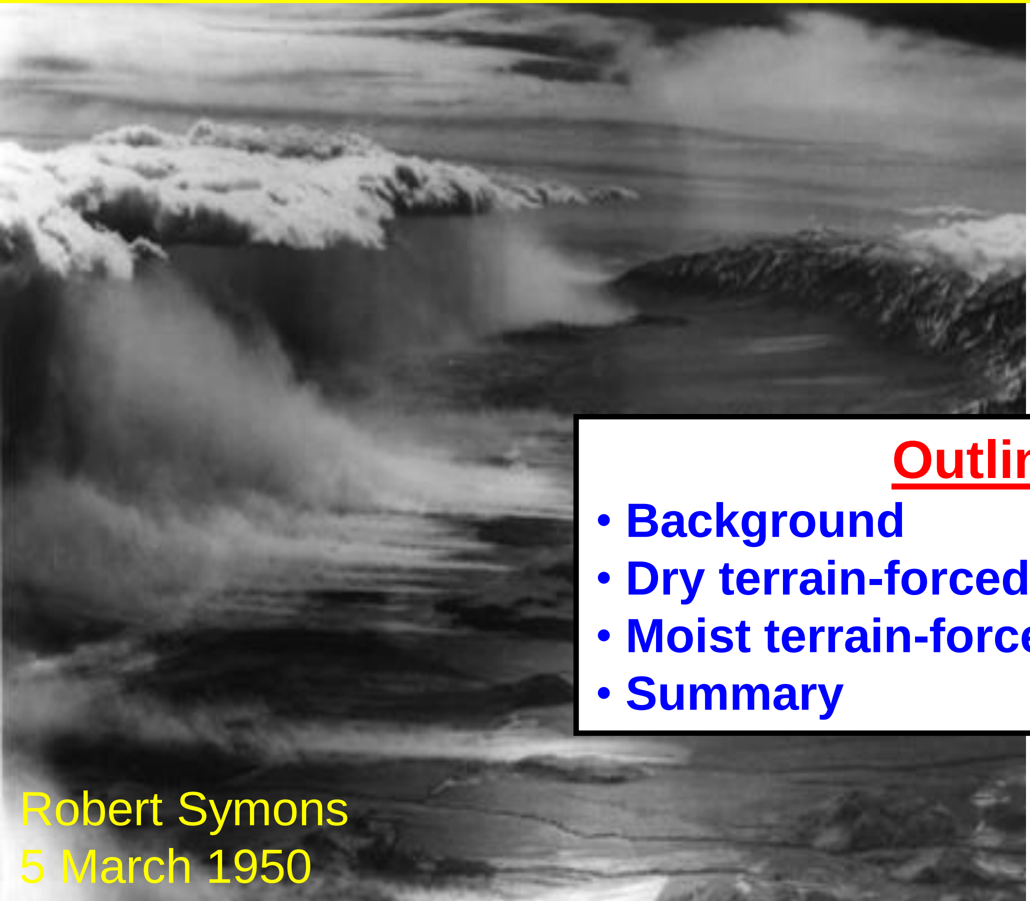
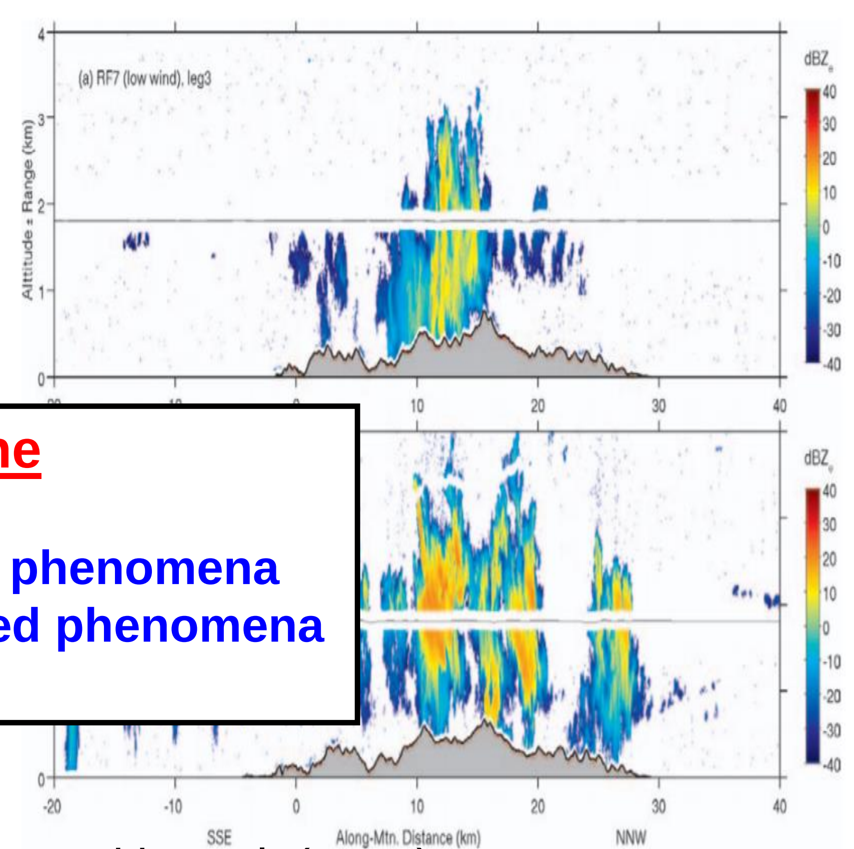


Robert Symons
5 March 1950



Smith et al. (2012)

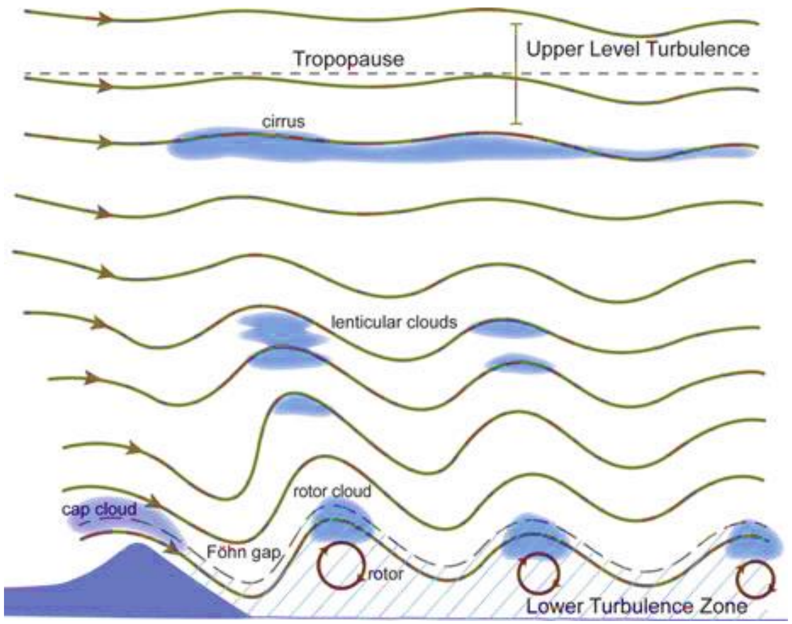
Outline

- Background
- Dry terrain-forced phenomena
- Moist terrain-forced phenomena
- Summary

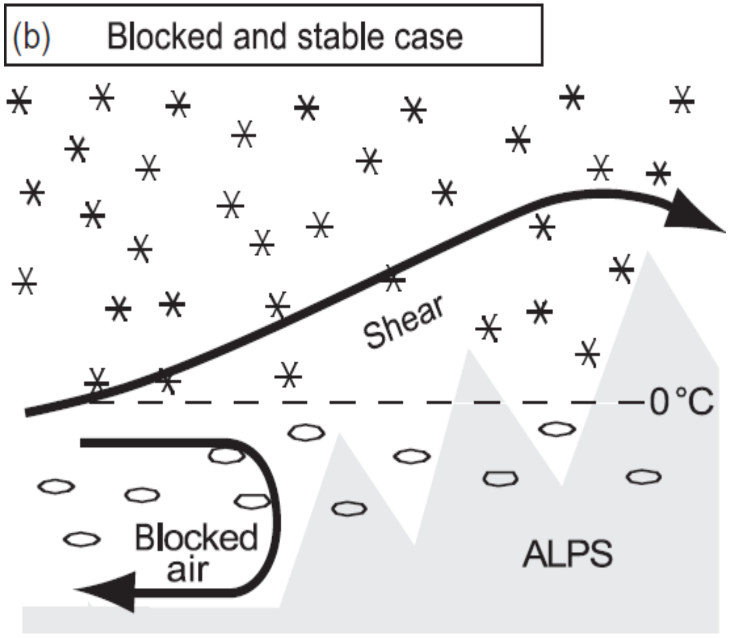
Background

- The nature of mountain flows (dry and moist) are very sensitive to turbulence
- Flow over/around terrain, breaking mountain waves are key generators of turbulence
- Our theories (dry and moist) typically do not include realistic PBLs and turbulence
- Model resolution has increased faster than we can verify with observations
- Observational gaps exist related to gravity wave characteristics, turbulent breaking
- Gravity wave drag parametrizations are known to be deficient and highly tuned. Crude GWD parameterizations lead to large systematic biases in weather/climate models.

Dynamically-Driven Waves and Turbulence



Effects of Terrain on Clouds and Precipitation



Turbulent Flow over Terrain

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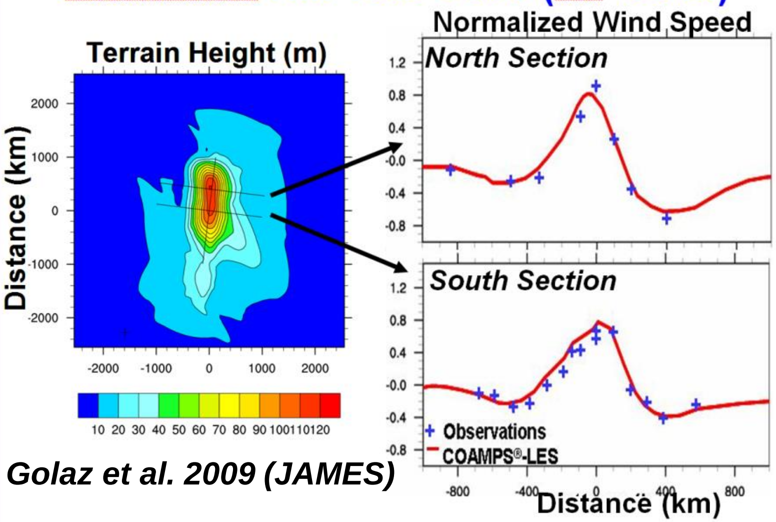
Askervein Hill (early 1980's)

Perdigão Experiment (2016-17)

6-week IOP using 47 instrumented towers, lidars, radiosondes

Askervein Hill Test Case (Δx=35 m)

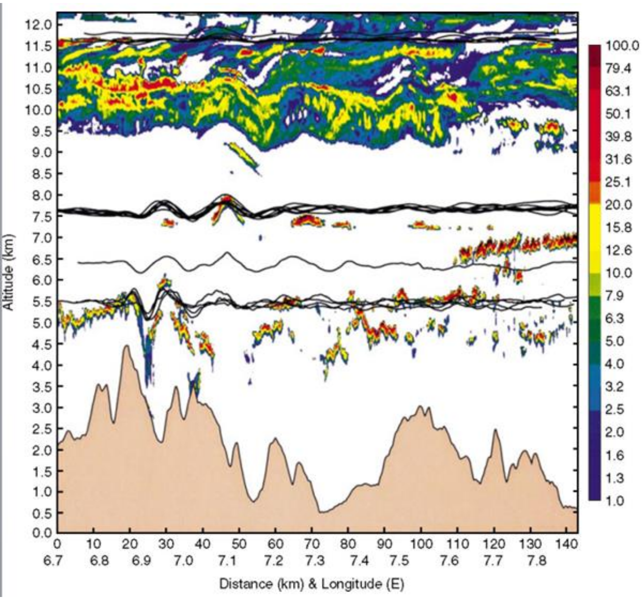


Golaz et al. 2009 (JAMES)

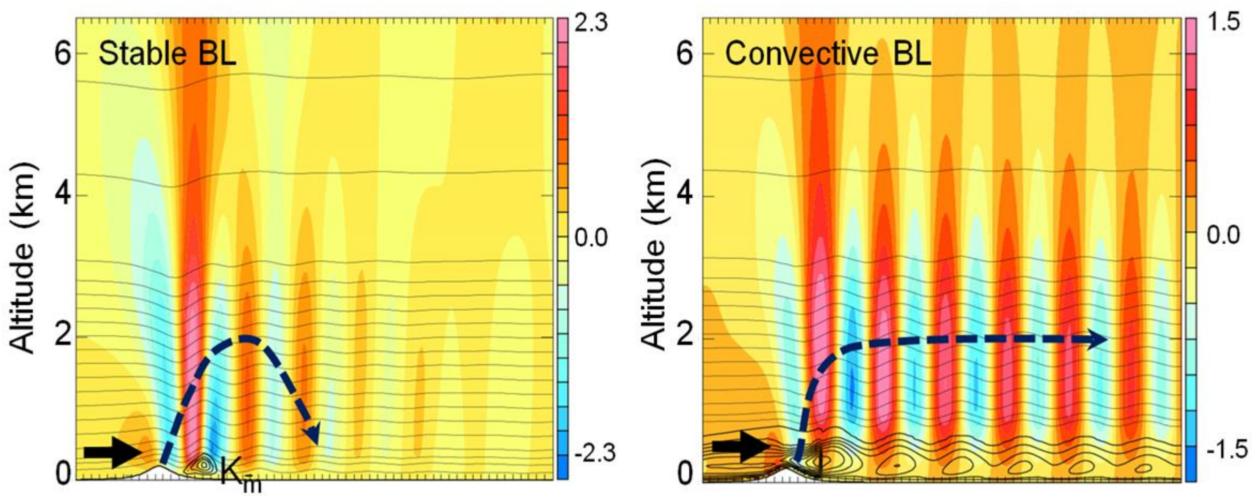
- **Frontiers**
  - **Complex terrain**
  - **Varying land surface characteristics**
  - **Flow dependence**
- **Key Science Questions**
  - **How much momentum is extracted?**
  - **How much heat and CO_2 are transferred between wind & landscape?**
  - **What degree of model sophistication is needed to simulate this with LES?**

Lee Waves and Turbulence

DIAL Lidar (Mt. Blanc)



Vertical Velocity and Potential Temperature



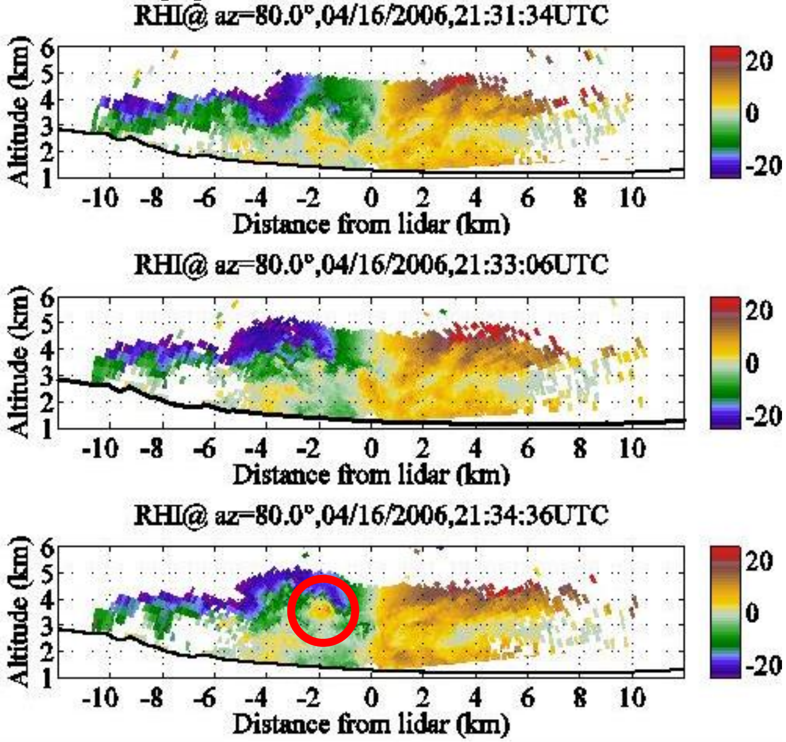
- Mountain lee waves are sensitive to nature of turbulence (theory/limited obs)
- Frontiers
  - Role of turbulence and PBL on: i) wave launching, ii) lee waves
  - Influence of varying land surface characteristics, diurnal cycle
- Key Questions
  - How does the PBL/turbulence influence lee waves and wave breaking?
  - How does upstream the mountain PBL influence waves and turbulence?

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 During the Terrain-Induced Rotor Experiment

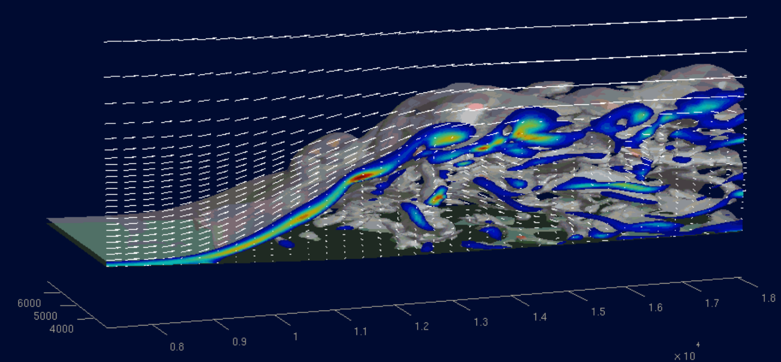
Doppler Lidar Velocities



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)

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

- **Frontiers**
  - **Characterization of low-level turbulence in rotors and wave breaking**
- **Key Questions**
  - **Under what conditions do subrotors form? Is this a KH instability?**
  - **What is the role of the PBL and heating/turbulence? Role of clouds?**

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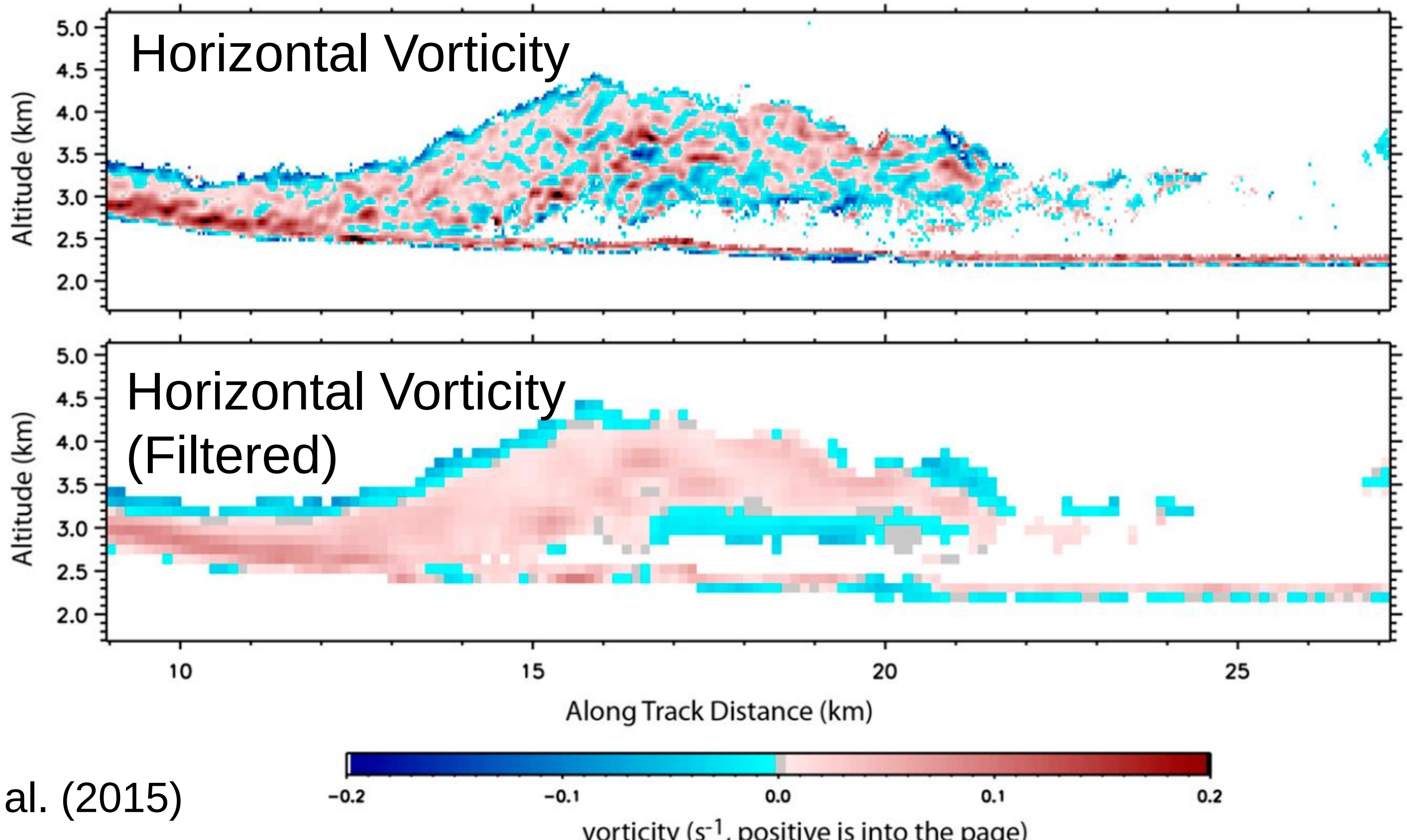
Rotors

Subrotor Vortices over the Medicine Bow Mountains

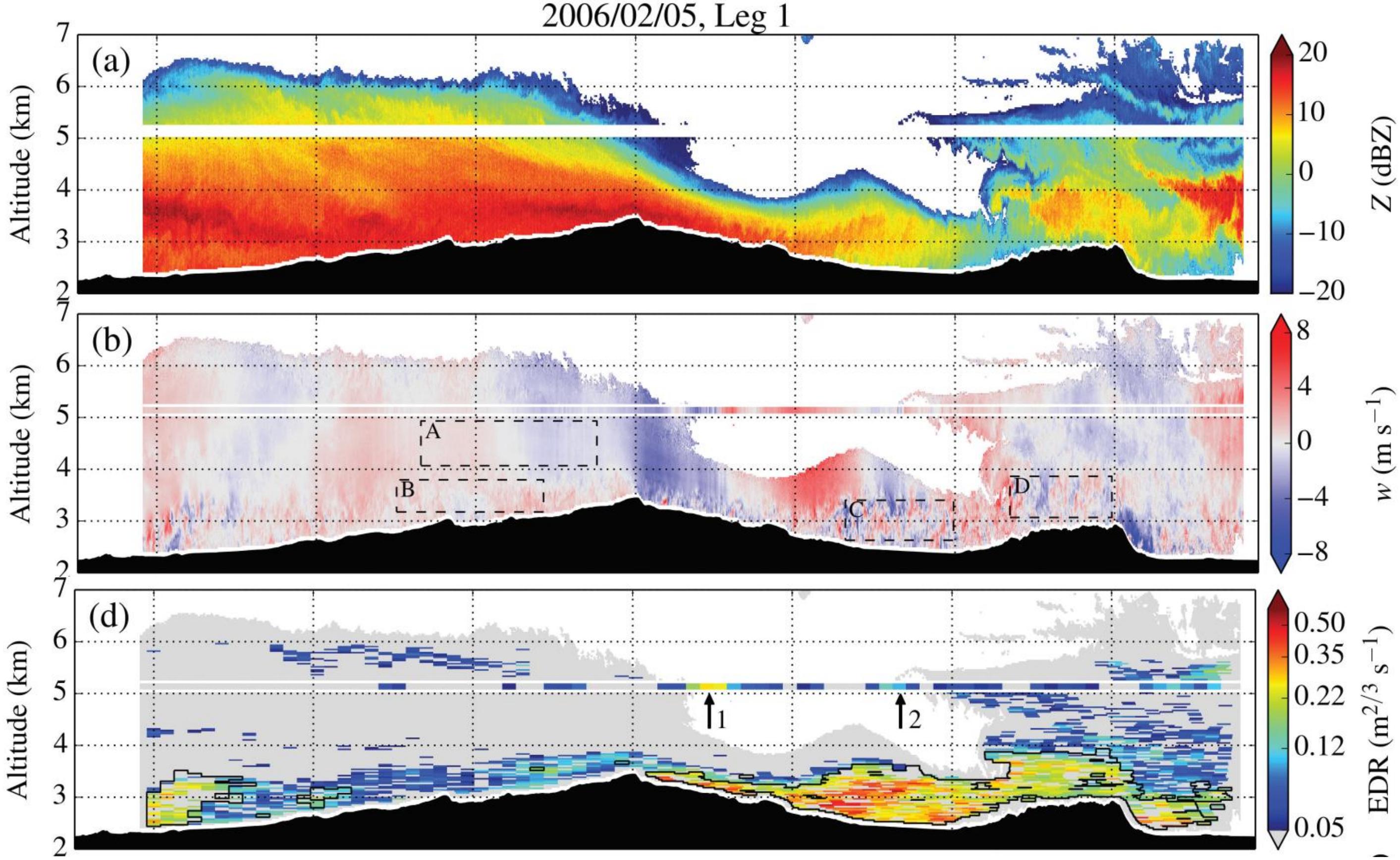


French et al. (2015)

- **Frontiers**
  - **Characterization of low-level turbulence in rotors and wave breaking**
- **Key Questions**
  - **Under what conditions do subrotors form? Is this a KH instability?**
  - **What is the role of the PBL and heating/turbulence? Role of clouds?**

Rotors

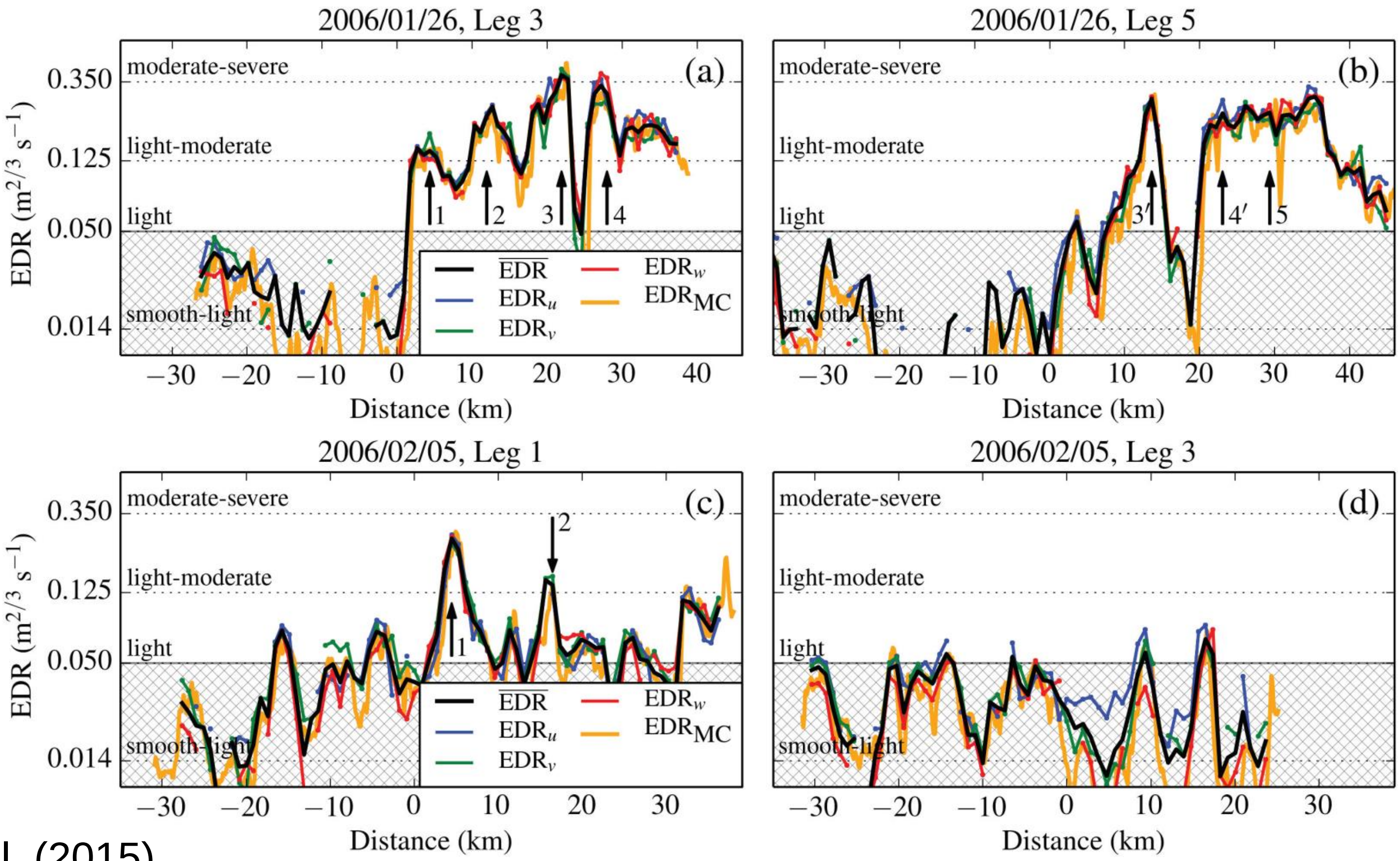
- Medicine Bow Mountains during the NASA Orographic Clouds Experiment
- Hydraulic jump type of rotor
- Severe turbulence is encountered in the downdraft, with maximum $\sigma^2 w$ and EDR_w of $16.4 m^2 s^{-2}$ and $0.77 m^{2/3} s^{-1}$



Strauss et al. (2015)

- **Frontiers**
  - **Characterization of low-level turbulence in rotors and wave breaking**
- **Key Questions**
  - **How does the turbulence differ between hydraulic-like jump rotors and lee wave rotors?**

Low-Level Wave Breaking

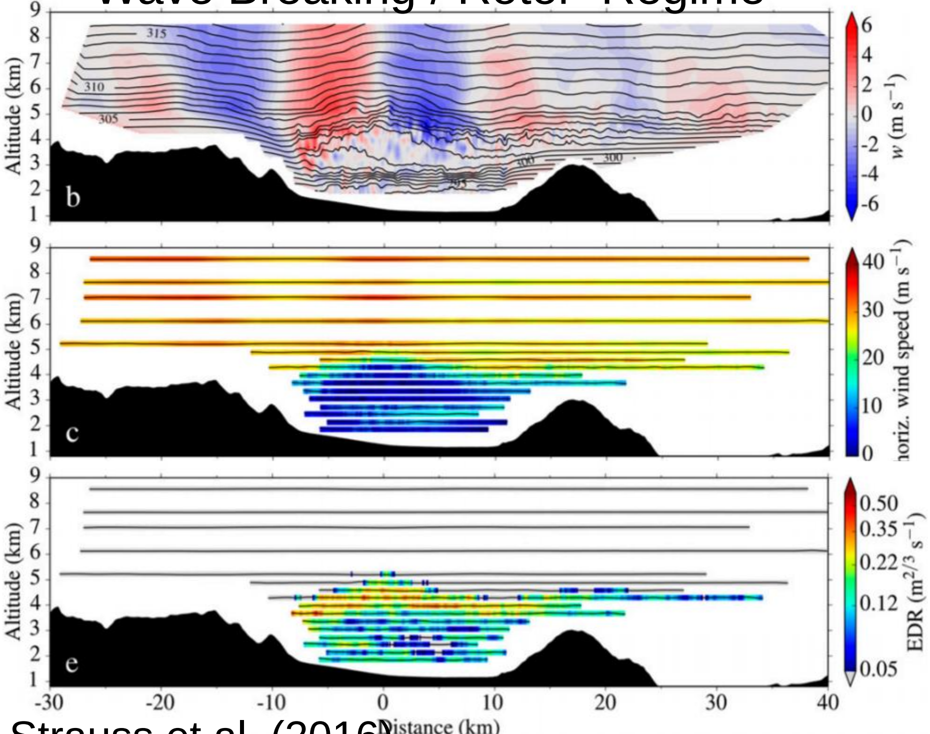


Strauss et al. (2015)

- **Frontiers**
  - **Measurements of low-level turbulence in rotors and wave breaking are rare**
- **Key Questions**
  - **What are the characteristics of wave breaking and associated turbulence?**

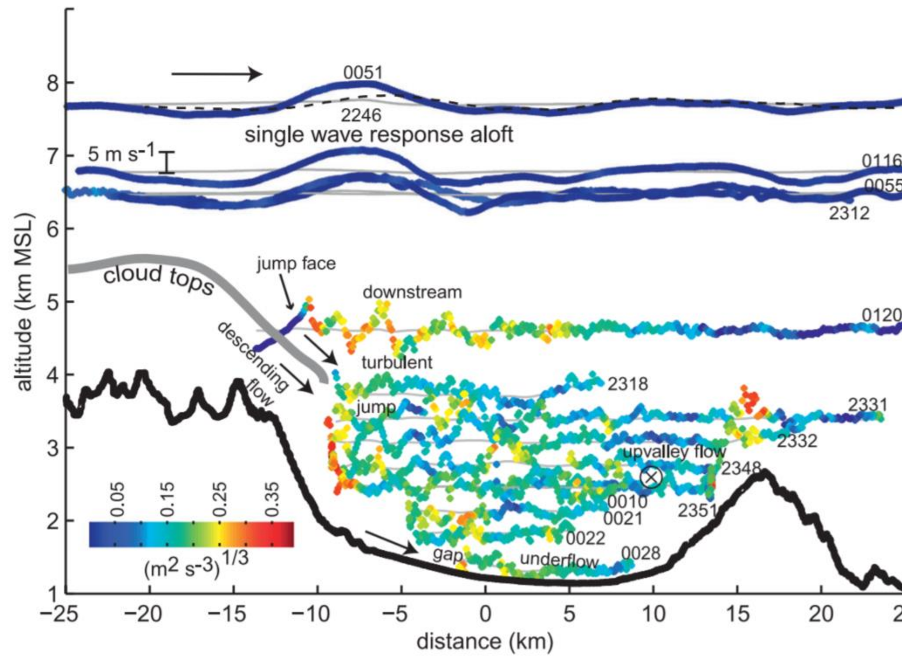
Low-Level Wave Breaking

Wave Breaking / Rotor Regime



Strauss et al. (2016)

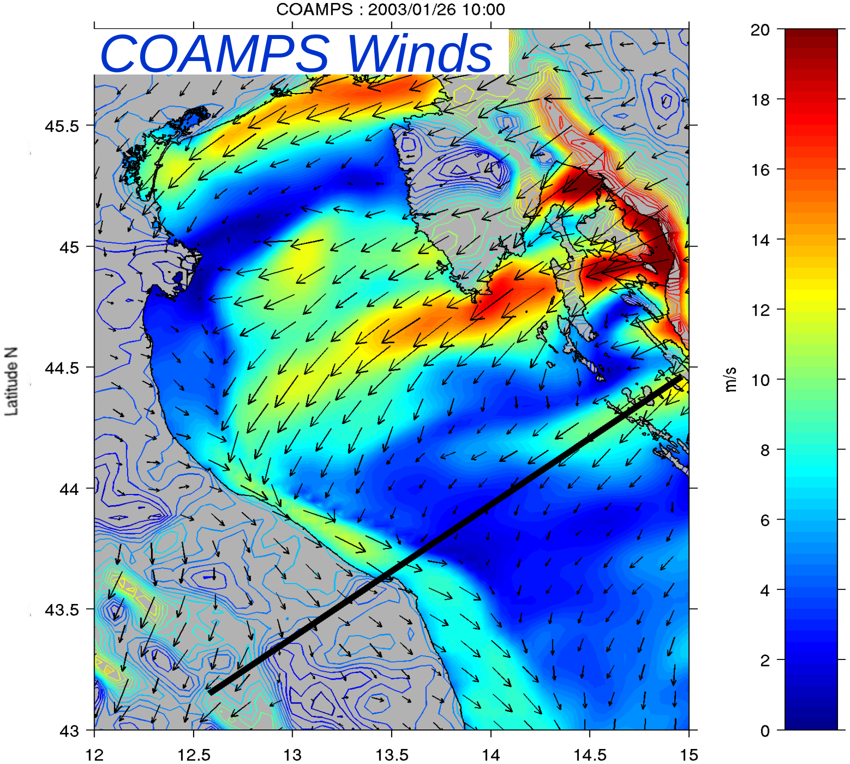
Hydraulic Analogue



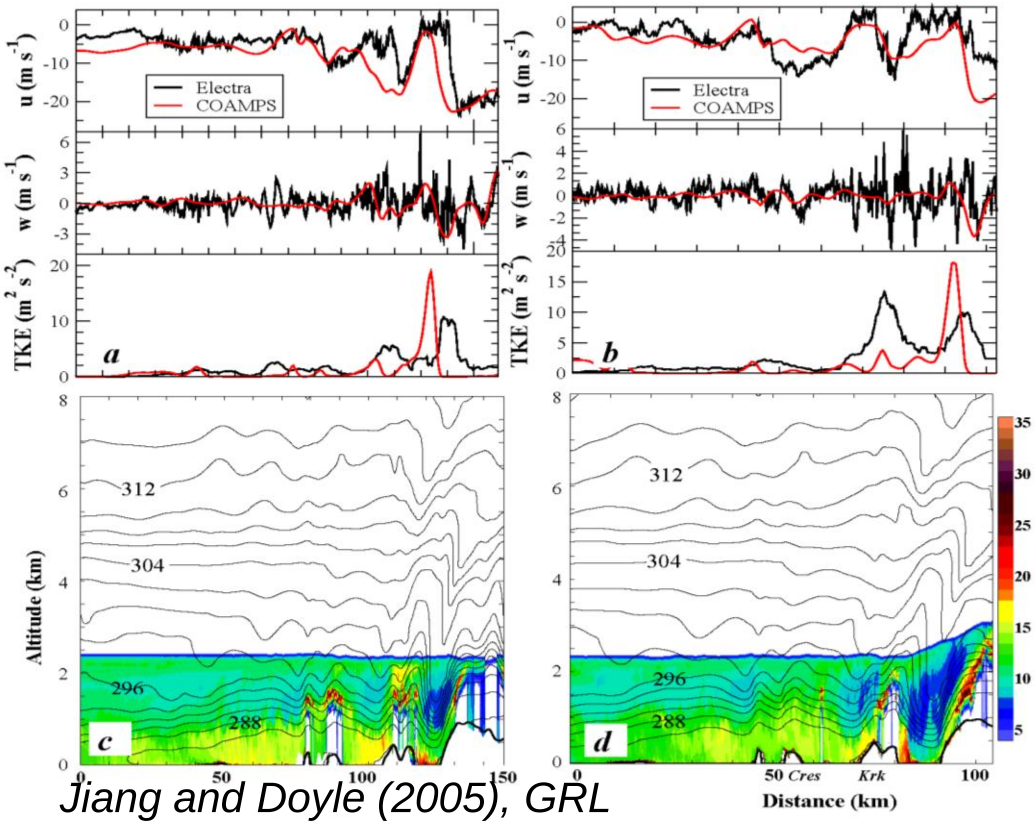
Armi and Meyer (2011)

- **Frontiers**
  - **Internal hydraulic jump vs. low-level wave breaking paradigms**
  - **Characteristics of turbulence and relationship to vortex breakdown**
- **Key Questions**
  - **What are the key dynamics and sources of turbulence?**
  - **What is the role of flow through high-level gaps, which are too turbulent to observe?**

Downslope Windstorms



Askari et al. (2006), JGR

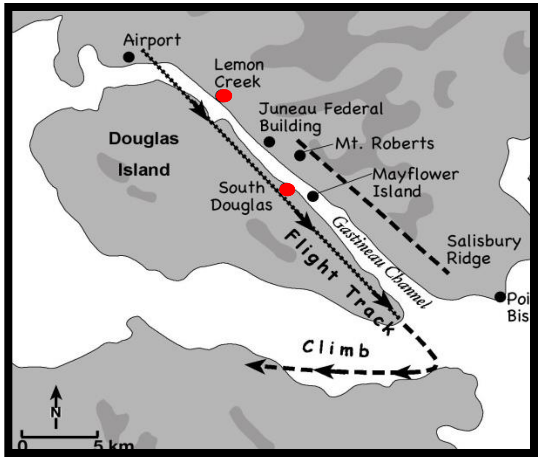


Jiang and Doyle (2005), GRL

- **Frontiers**
  - **Turbulent "shooting flow" in downslope windstorms**
  - **Air-sea interaction and reconnection with marine PBL (models are poor)**
- **Key Questions**
  - **What are the key dynamics and sources of turbulence?**
  - **What is the role of flow through gaps (too turbulent to observe)?**

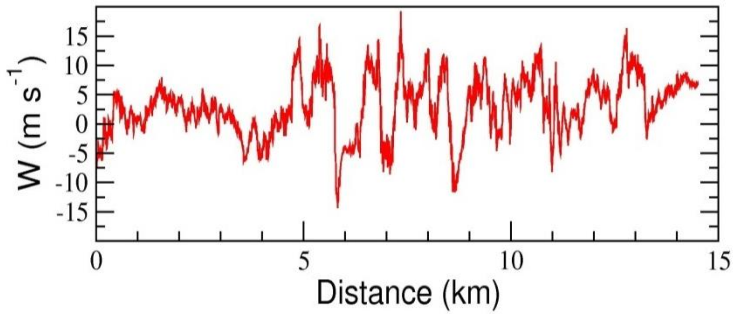
Downslope Windstorms

SARJET (Alaska) UW KingAir Flight Path

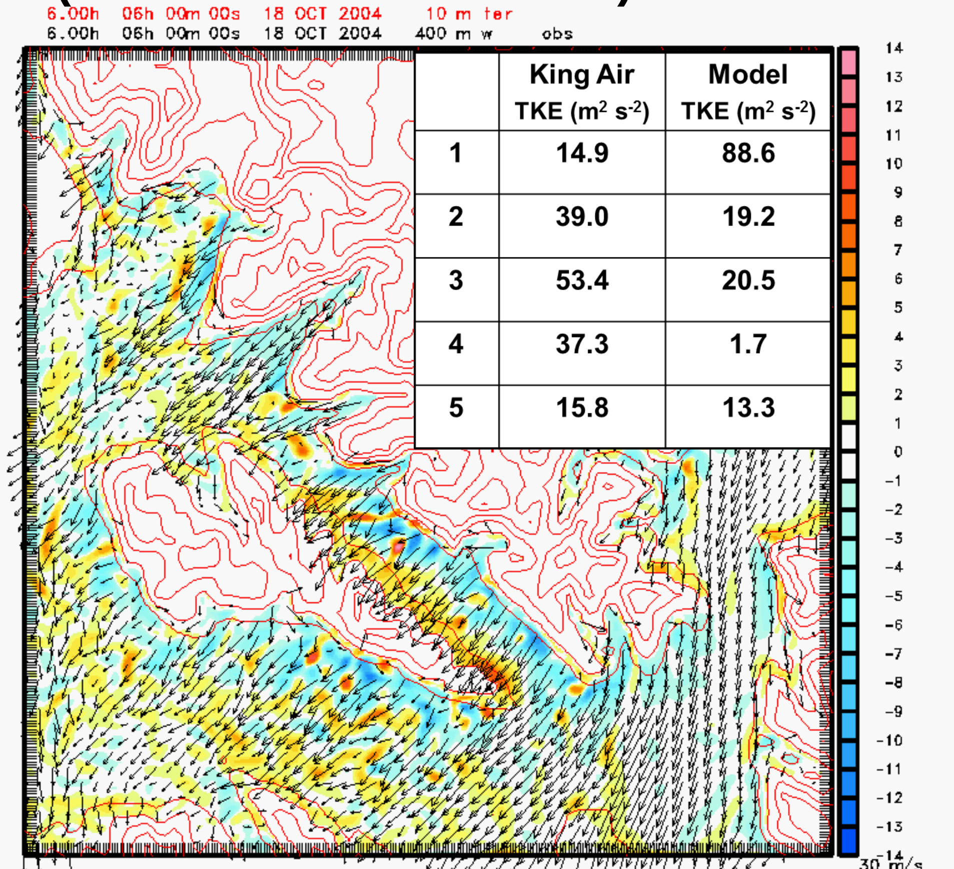


Bond et al. (2006)

Aircraft Observations of w



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

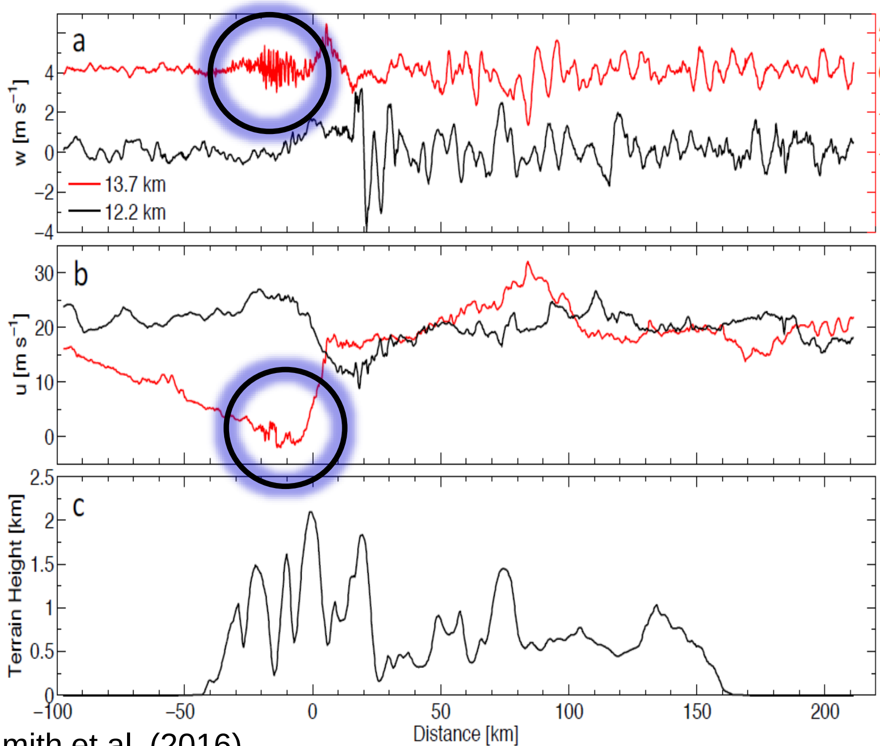


	King Air TKE (m^2 s^{-2})	Model TKE (m^2 s^{-2})
1	14.9	88.6
2	39.0	19.2
3	53.4	20.5
4	37.3	1.7
5	15.8	13.3

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

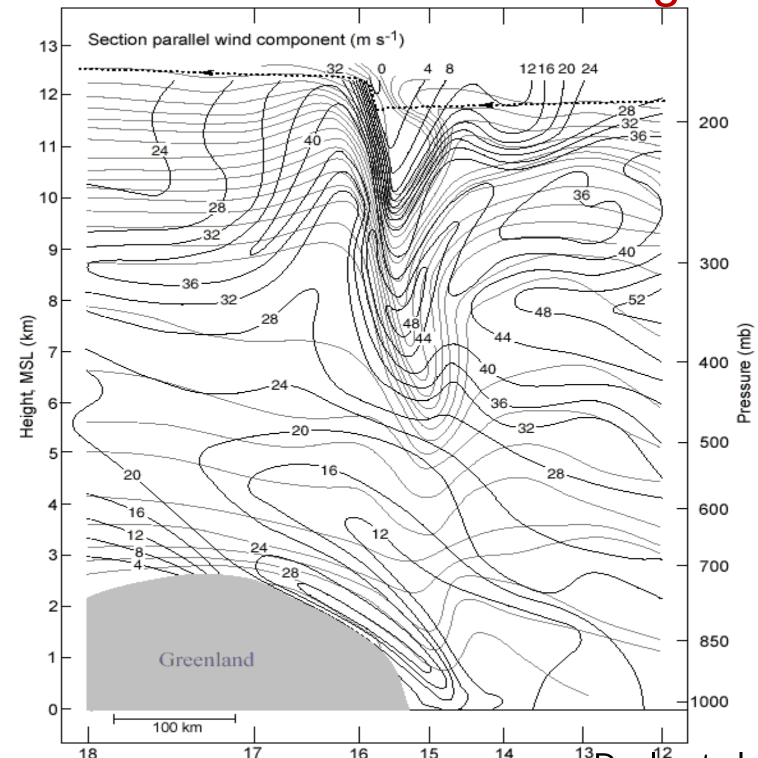
Upper-Level Wave Breaking

DEEPWAVE Wave Breaking (29 June)



Smith et al. (2016)

FASTEX Wave Breaking

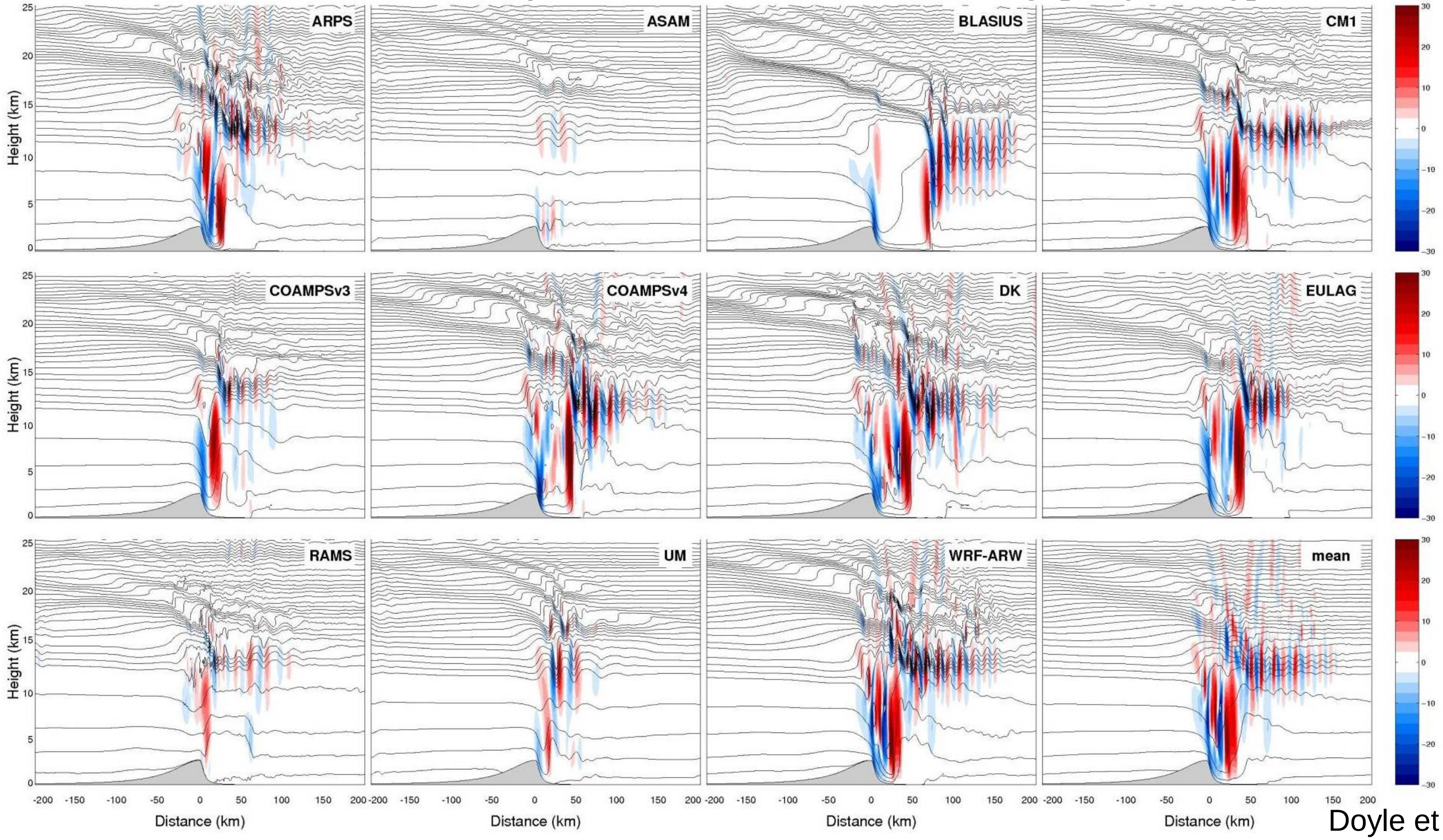


Doyle et al. (2005)

- **Frontiers**
  - **Observe 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)**
- **Key Questions**
  - **What are fine-scale (spectral) characteristics of wave breaking?**
  - **How does the momentum flux depend on the turbulence evolution?**

Upper-Level Wave Breaking

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



Doyle et al. (2011)

- **•Frontiers**
  - **Explicit and LES modeling of wave breaking and secondary wave generation**
  - **Models still disagree radically for relatively simple problems**
- **•Key Questions**
  - **What obs. of wave breaking are needed to constrain models/parameterizations?**

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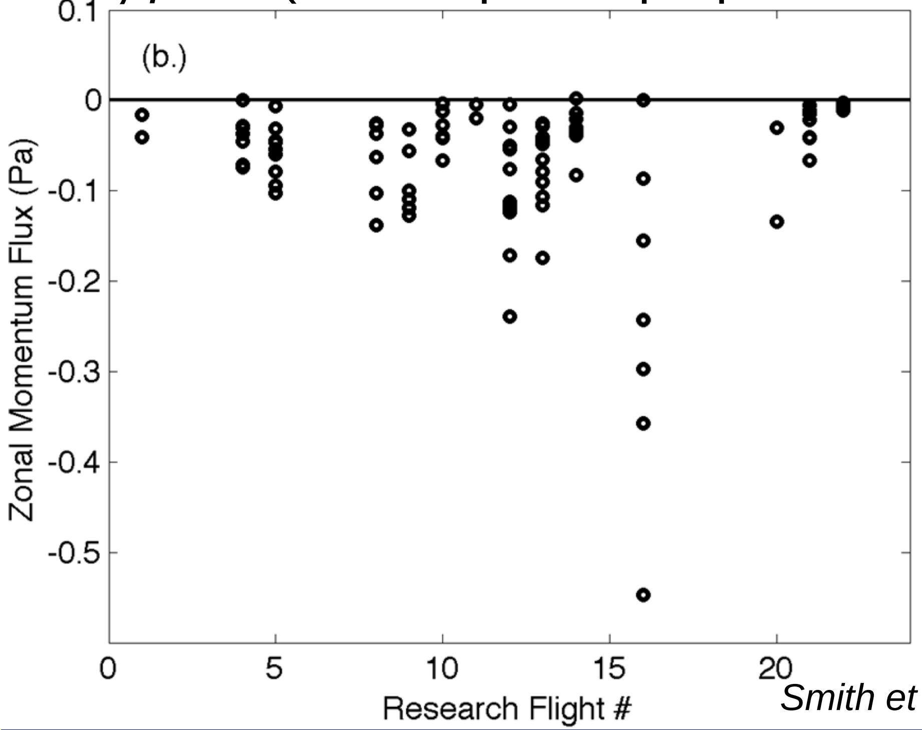
Mountain Waves and Fluxes

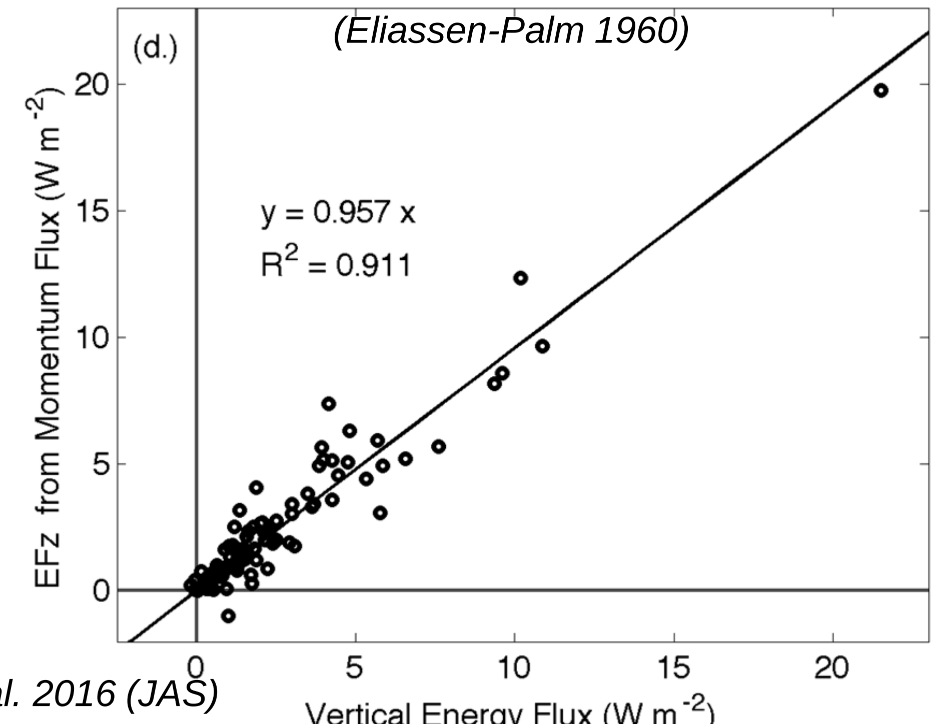
DEEPWAVE G-V Zonal Momentum Fluxes

$<\rho p'u'>$ (<0 for upward prop. waves)



Eliassen-Palm Relationship

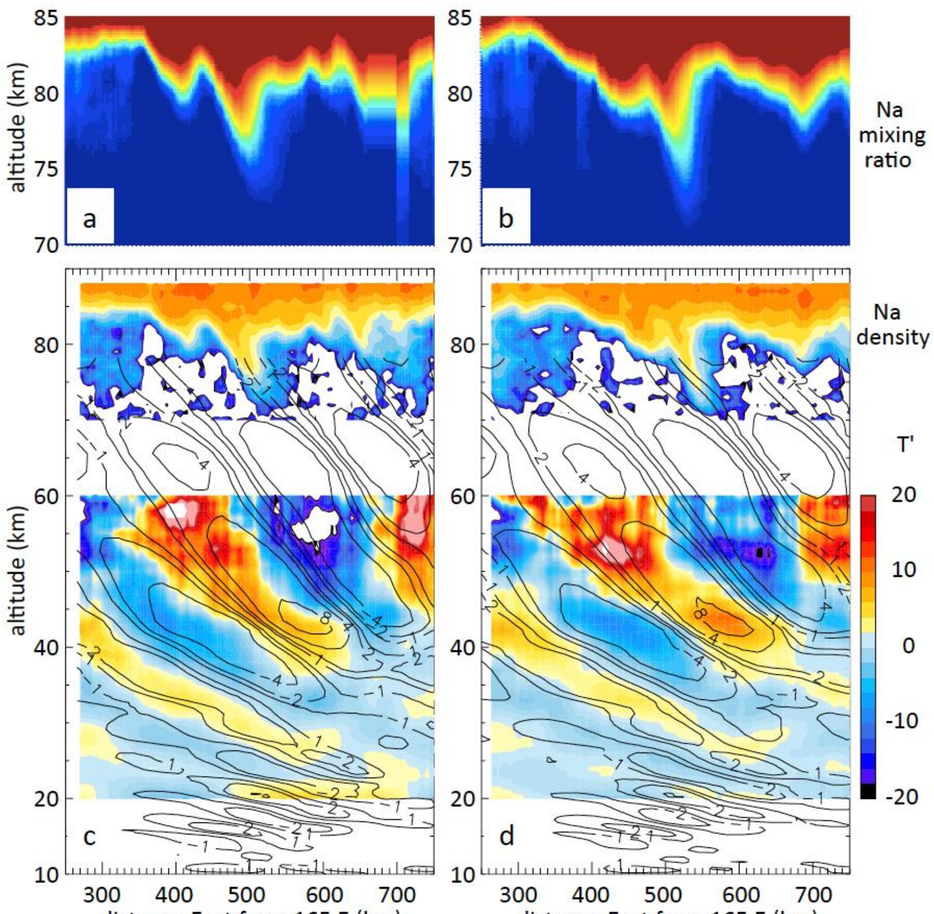
EFz = -U·MF =EFzM



Smith et al. 2016 (JAS)

- **•Frontiers**
  - **Observing needs: Differential GPS needed for accurate fluxes; long aircraft legs needed**
  - **Momentum fluxes under varying conditions (terrain, large-scale flow)**
  - **Gravity wave drag parameterizations are still poor (models extremely sensitive)**
- **•Key Questions**
  - **What causes the variability in momentum fluxes?**
  - **How can we obtain obs. of wave breaking to constrain models/parameterizations?**

Upper-Level Wave Breaking



Rayleigh Lidar Na Density

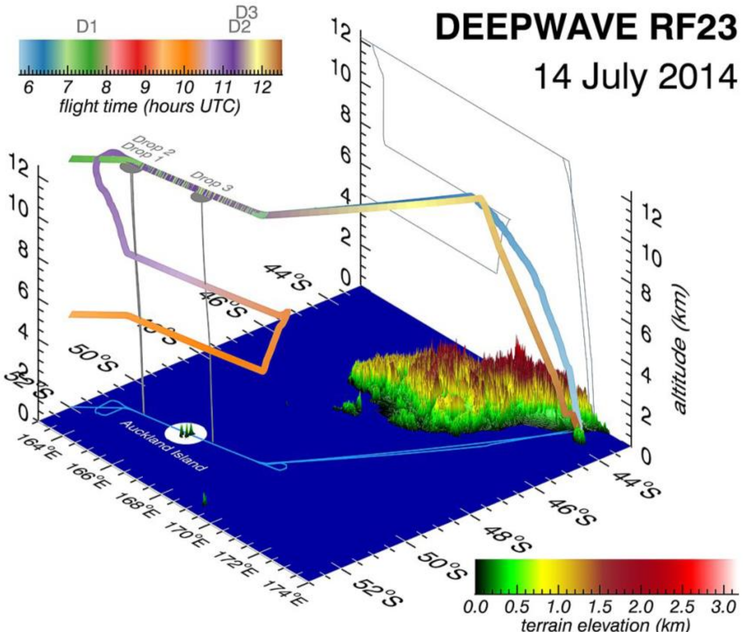
Rayleigh Lidar T' (color) ECMWF T' (contours)

Fritts et al. 2016 (BAMS)

- **Frontiers**
  - **Observations of upper-level (mesosphere-lower thermosphere) of wave breaking**
- **Key Questions**
  - **What are the wave characteristics that propagate to deep altitudes?**
  - **What are the momentum flux characteristics?**

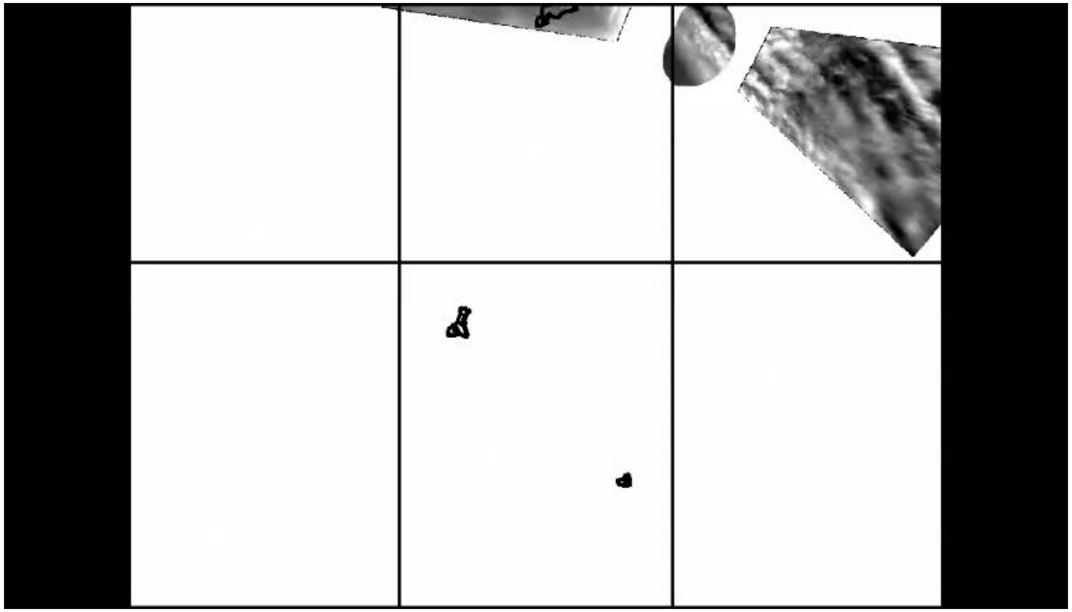
Upper-Level Wave Breaking

DEEPWAVE G-V Flight Over Auckland Island



Eckermann et al. (2016)

G-V AMTM Observations (~87 km)



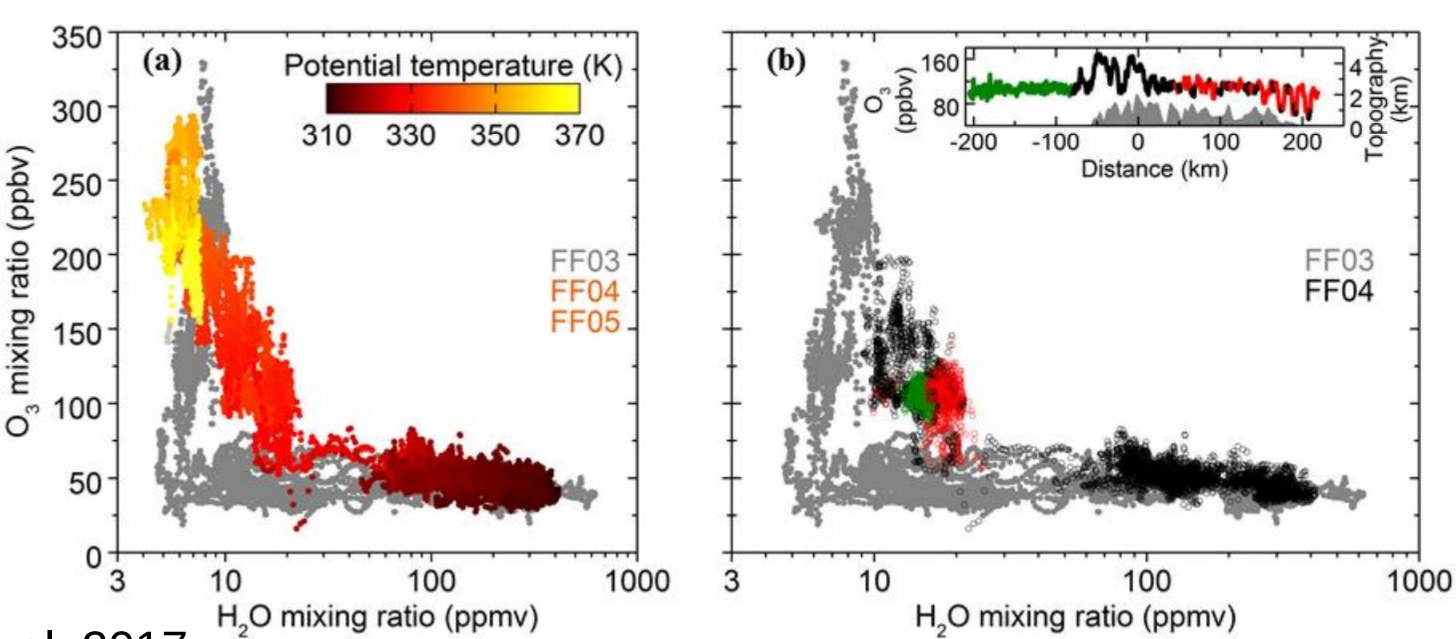
Pautet et al. 2015 (JGR)

- **Frontiers**
  - **Growing evidence that gravity waves generated by small islands are important contributors to momentum fluxes and missing from GCMs (Alexander et al. 2009)**
- **Key Questions**
  - **What are the wave characteristics that propagate to deep altitudes?**
  - **What are the momentum flux characteristics?**

Upper-Level Wave Breaking

DEEPWAVE DLR Falcon Flights

O_3 vs. H_2O Mixing Ratio in Upper Troposphere/Lower Stratosphere

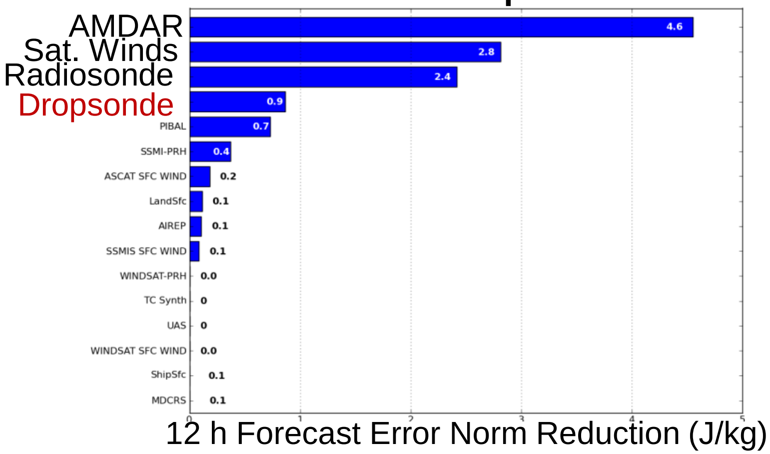


Heller et al. 2017

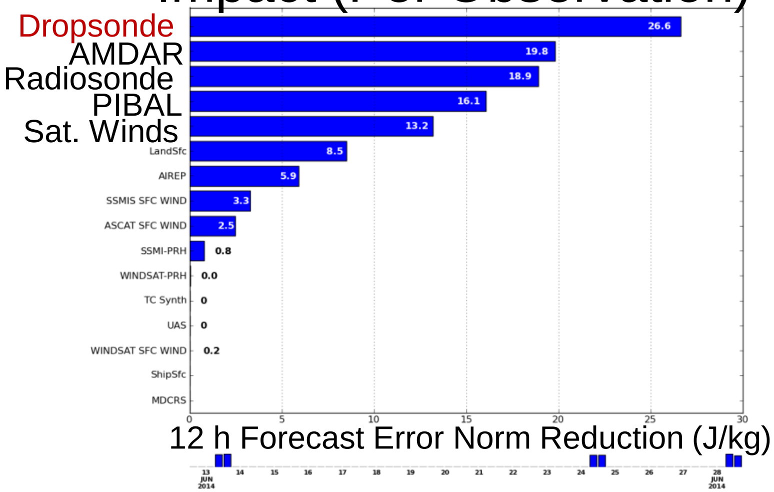
- **Frontiers**
  - **UTLS mixing due to gravity waves and wave breaking**
- **Key Questions**
  - **What are the turbulence characteristics important for mixing in the UTLS region?**

Observations Impact on Mountain Wave Launching

Total Impact

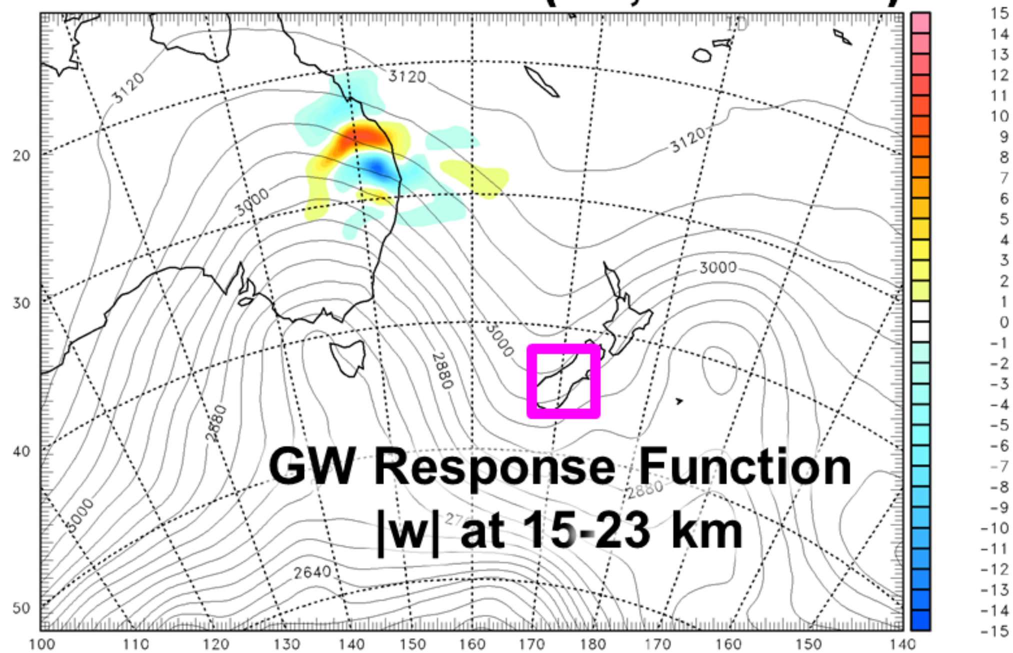


Impact (Per Observation)



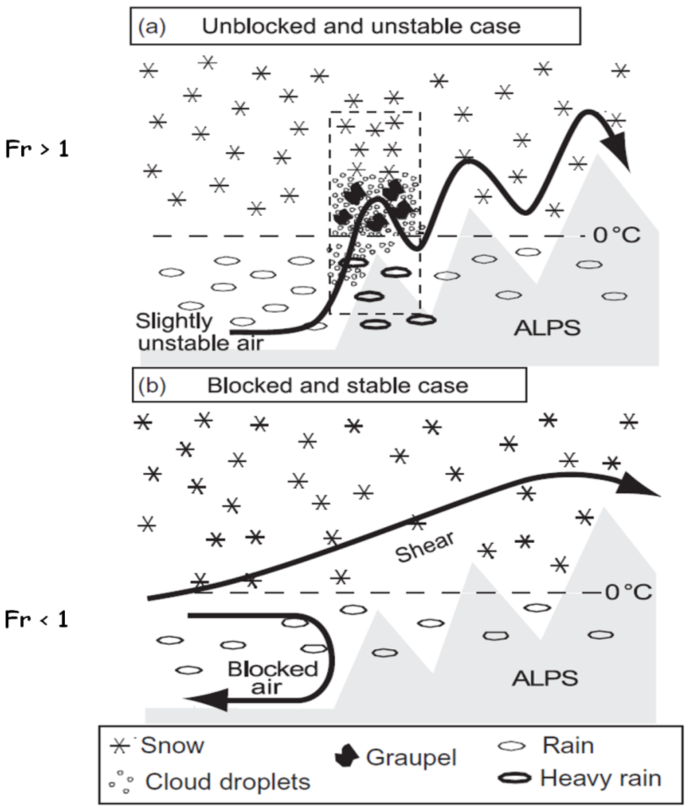
C. Amerault

700-hPa U Sensitivity (36h) & Heights 06Z 28 June 2014 (0h, RF11-12)

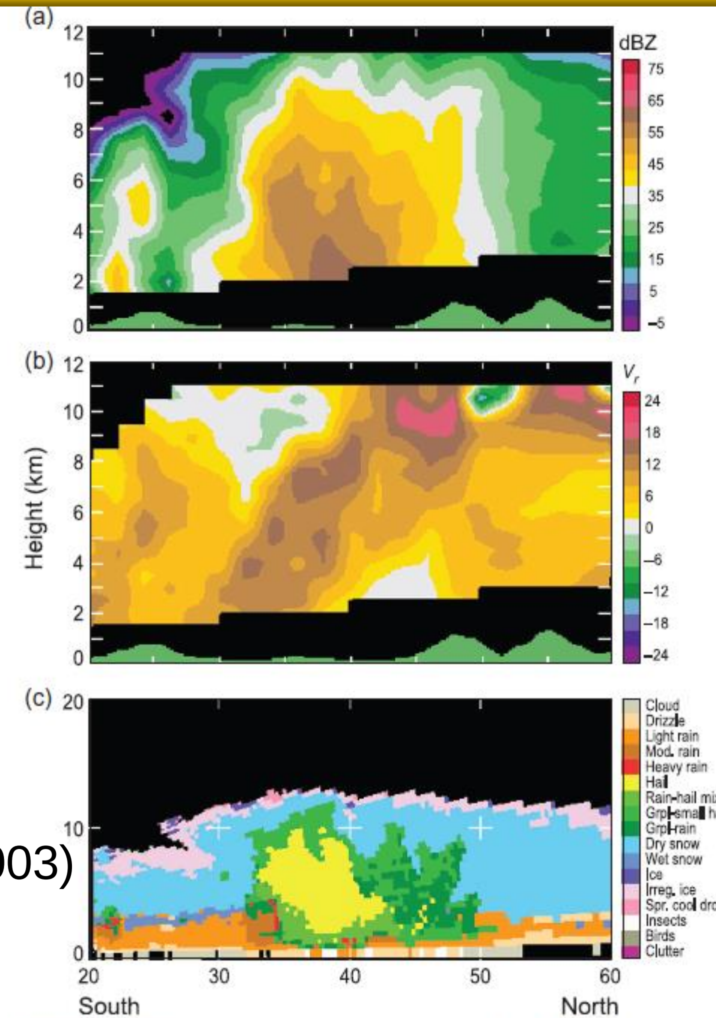


- **Adjoint (model+DA) observation impact on 12-h forecasts during DEEPWAVE.**
- **Targeted dropsondes have the largest impact on a per observation basis.**
- **Adjoint shows large impact of remote upstream regions of q (especially) and t, u**

Blocked Moist Flow



Rotunno and Houze (2007)

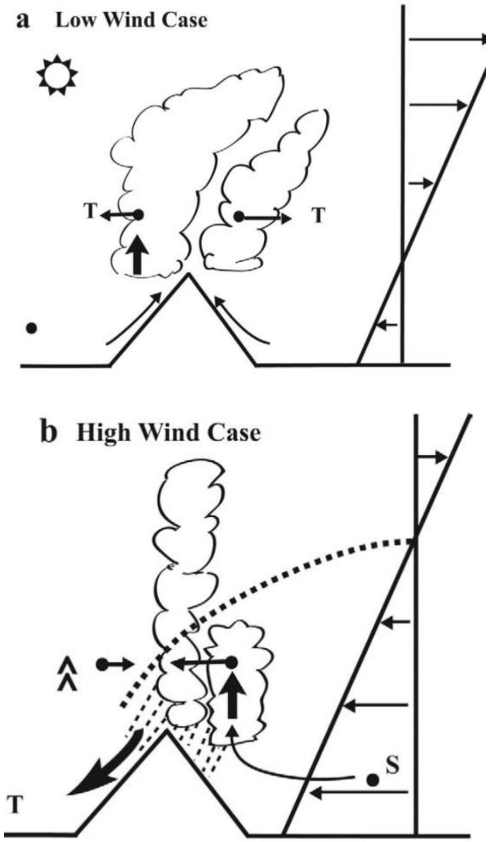


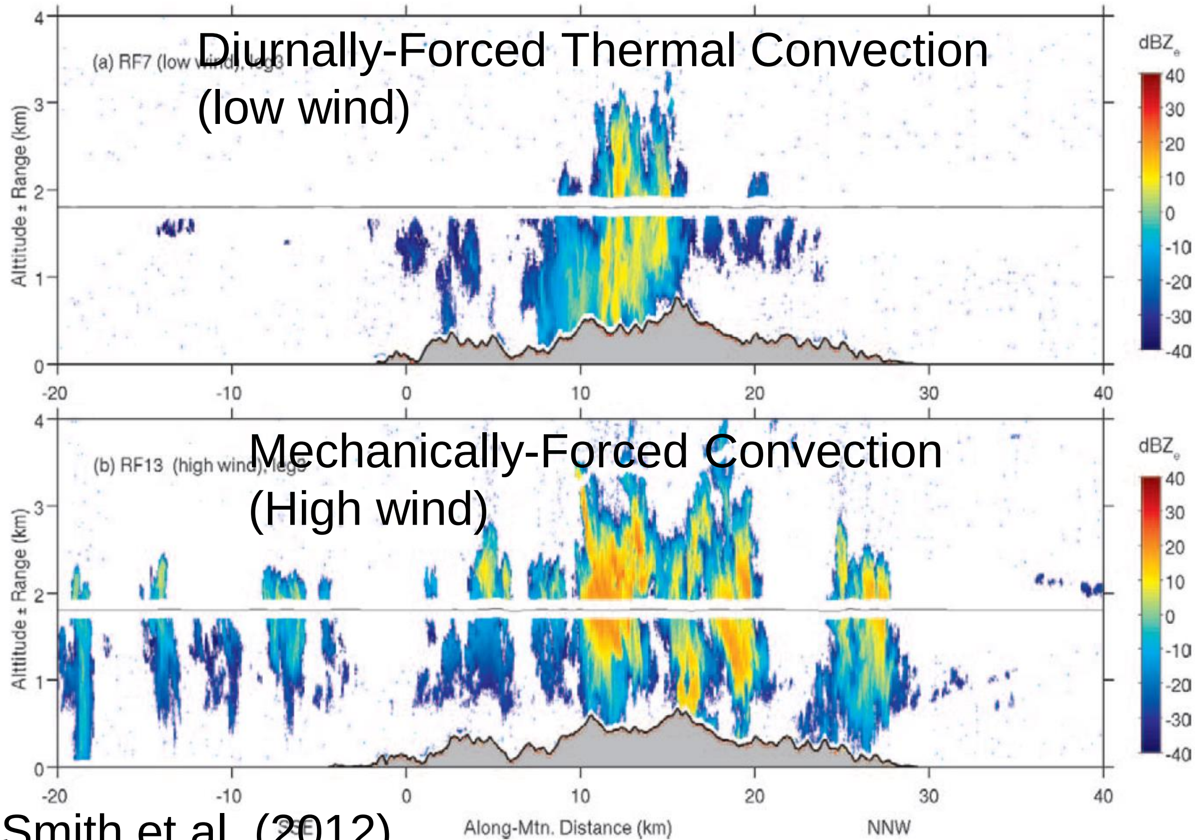
Seity et al. (2003)

FIGURE 12.30 Data obtained over the foothills on the Mediterranean side of the Alps at 1830 GMT, 17 September 1999 by the National Center for Atmospheric Research S-Pol radar: (a) equivalent radar reflectivity (dBZ); (b) Doppler radial velocity (m s^{-1}), with positive values indicating flow from left to right; (c) particle type inferred from dual-polarimetric radar data. For further description of this storm, refer to the summary at

- **Frontiers**
  - **Turbulence generated by terrain-induced blocking and microphysical processes**
- **Key Questions**
  - **How does blocking and shear modulate the orographic precipitation?**

Terrain-Induced Convection





Smith et al. (2012)

- **Frontiers**
  - **Mechanical convection over small scale terrain, and generation of clear air turbulence**
- **Key Questions**
  - **What are the key processes governing mechanically-driven convection and associated turbulence?**

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Mountain Winds, Waves, and Turbulence Summary

- Improved understanding and modeling of mountain waves, winds, breaking are needed, particularly bridging the gap between theory and the real world
- Theory builds on simple flows and terrain with no or simple PBLs & turbulence
- Model parameterizations for gravity wave drag are known to be deficient and highly tuned. Significant source of model biases in weather/climate models.
- Observational Gaps (e.g., characteristics, spectra, time dependence, mixing)
  - Mountain PBL: strongly modulates gravity wave launching
  - Multi-scale (dynamics and predictability studies): Atmospheric profiles upstream, over, downstream of terrain (time continuity)
    - i. Wave breaking and turbulence (low-levels to UTLS to MLT)
    - ii. Rotors, subrotors, shear instabilities, rotor clouds
    - iii. Downslope windstorms / “shooting flow”, vortex sheet, separation pts
    - iv. Wide/narrow gap flows and airflow through passes
    - v. Accurate u’, v’, w’, p’ for flux calculations (need long aircraft legs)
    - vi. Turbulence in moist flows: i) important for precipitation, ii) caused by terrain-forced convection