Aviation turbulence forecasting research challenges and needs

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Aviation Turbulence: Challenges

1. Nature of turbulent motion is not well-understood

- Sir Horace Lamb, *Hydrodynamics*, 1932, Art 365: "Turbulent Motion. It remains to call attention to the chief outstanding difficulty of our subject."
- Sir Graham Sutton, *The Challenge of the Atmosphere*, 1962, "turbulence, the state of motion which, by its complexity, constitutes the outstanding difficulty in hydrodynamics"
- J. S. Turner, *Buoyancy Effects in Fluids*, 1973, "Patches of turbulence in the ocean or atmosphere can arise as a result of the superposition of motions from many sources and on many scales. A completely deterministic theory is therefore unlikely…"

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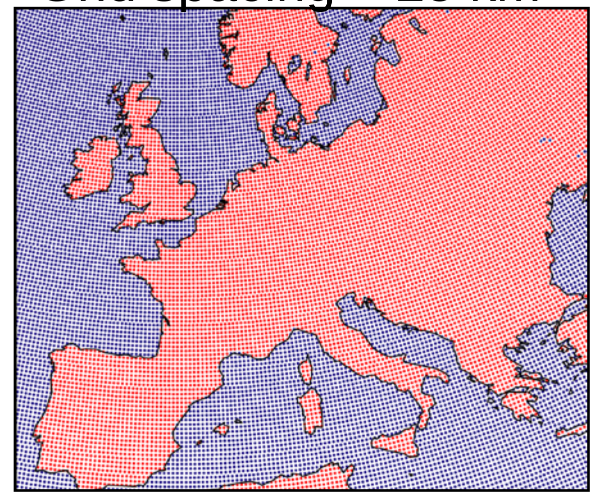
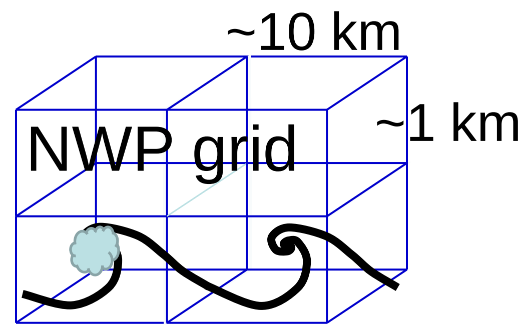
Challenges (cont.)

2. Scale of turbulence is too small to actually forecast

- Very small scale (10s m- few km) compared to other motions in the atmosphere that are routinely observed and forecast
- Forecasts typically use grid point model to represent continuous atmosphere
  - 10s km grid spacing so turbulence processes are subgrid scale and must be parameterized
  - No option to <u>directly</u> forecast
    - 5000km X 5000km X 25km CONUS domain @ 25m resolution = $2x10^5$ X $2x10^5$ X 10^3 = 40,000 Gigawords/variable!!
- Alternatively, can postprocess using operational NWP model to diagnose turbulence potential (implicitly assumes downscale cascade) -> GTG etc.

Grid spacing ~ 25 km





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Scales of aircraft turbulence

Energy Production

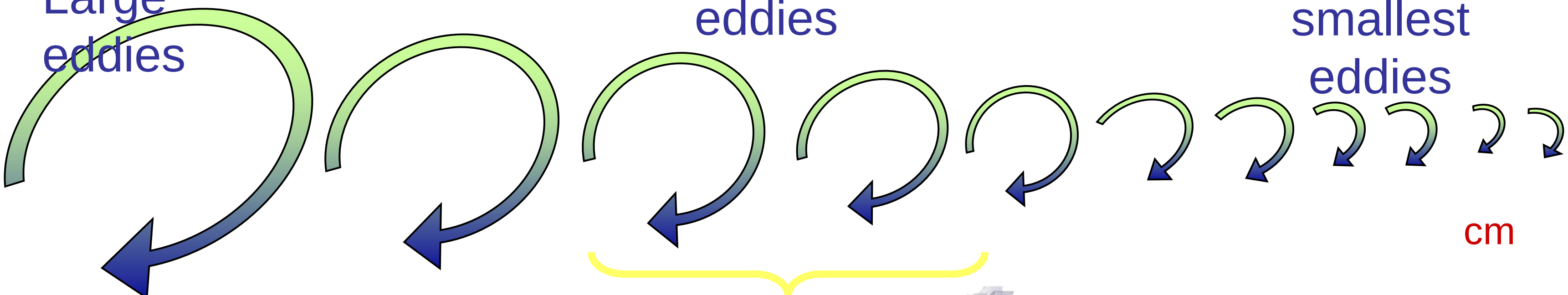
Energy flow (downscale cascade)

Dissipation by viscosity

Large eddies

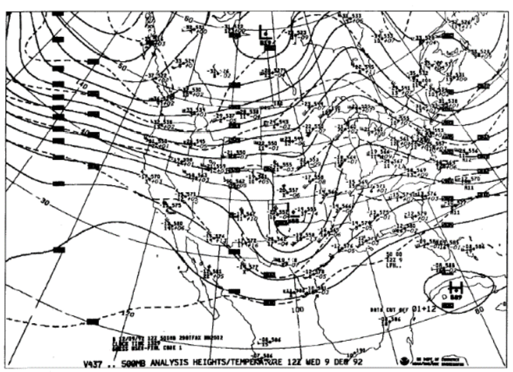
"turbulent" eddies

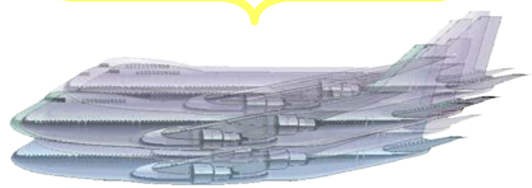
smallest eddies



cm

100s-1000s km





Aircraft responds to scales from few m - km

NWP resolution

Mesoscale model resolution

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Small scale nature of turbulent events

discrete

continuous

10 km

25 km

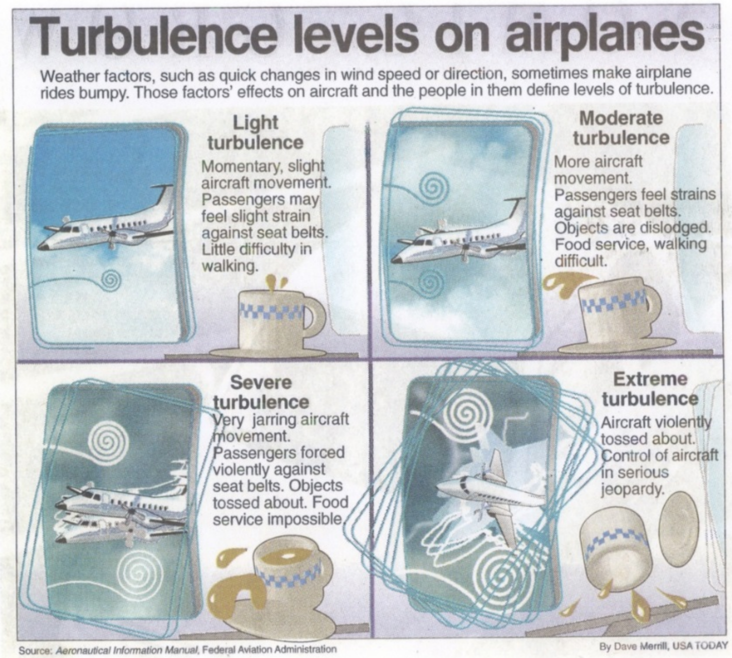
15 km

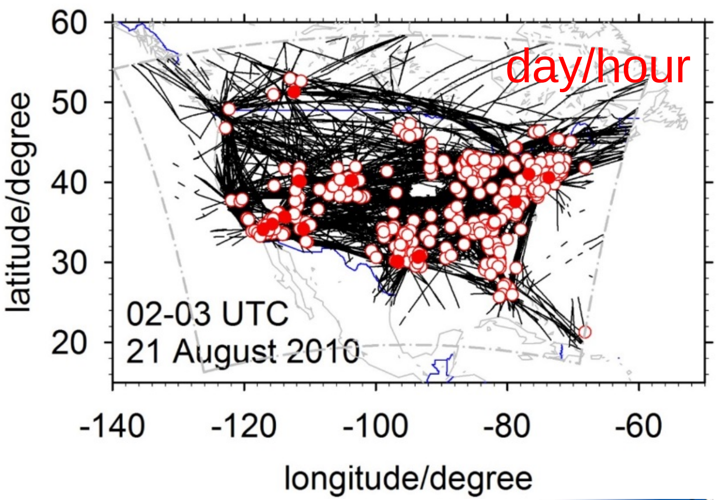
2 km

Challenges (cont.)

3. Routine observations for verification are lacking

- Routine ground-based observations too sparse
- In situ observations (pilot reports or PIREPS)
  - Nonuniform in space and time
  - Subjective (“Light”, “moderate”, “severe”, “extreme”)
  - Position and time inaccuracies
  - Aircraft dependent
  - Pilots try to avoid it
  - Information about clouds is usually not recorded
  - Wake vortices contaminate results ($6x10^{-4}$ critical encounters/flight hr)





Schumann&Sharman JAircraft 2014

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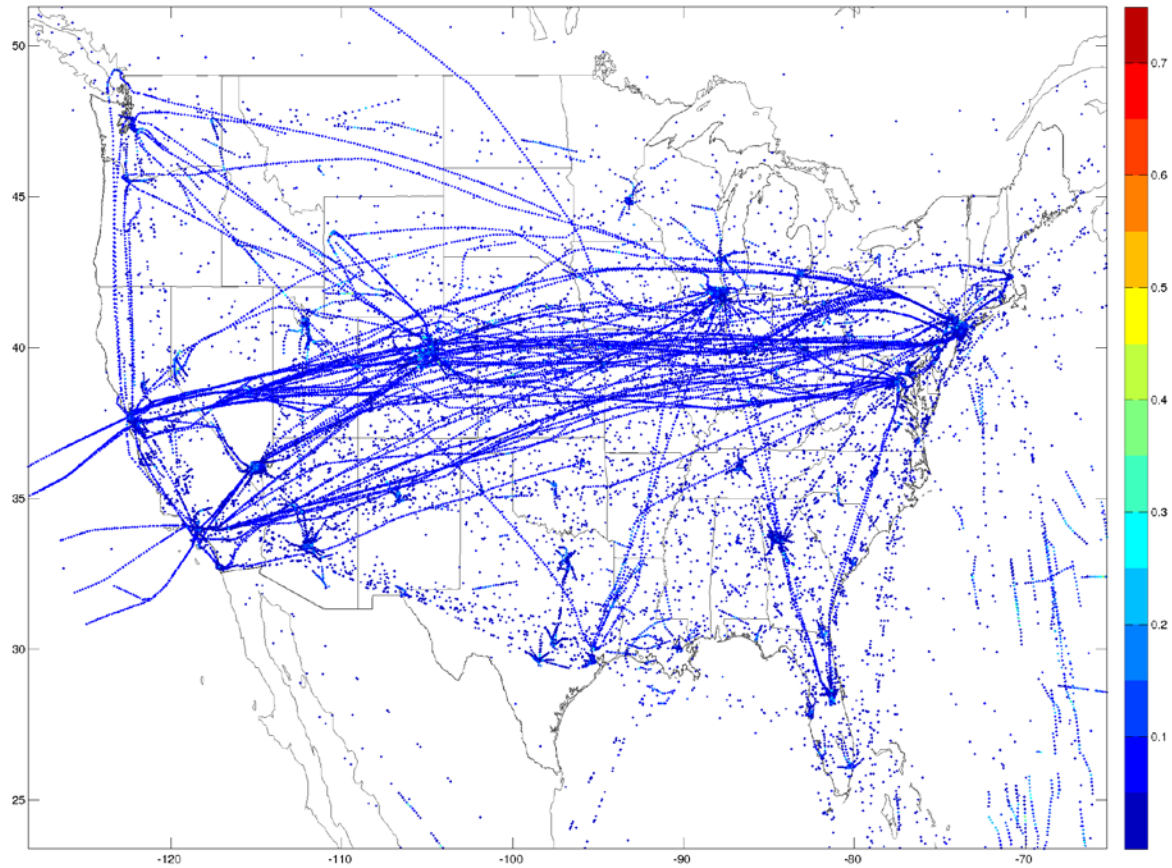
Challenges (cont.)

Current insitu EDR reports are also nonuniformly distributed and are insufficient density, don't report turbulence type



UAL 757+DAL737+DAL767+SWA737
24hrs 25 Aug 2014

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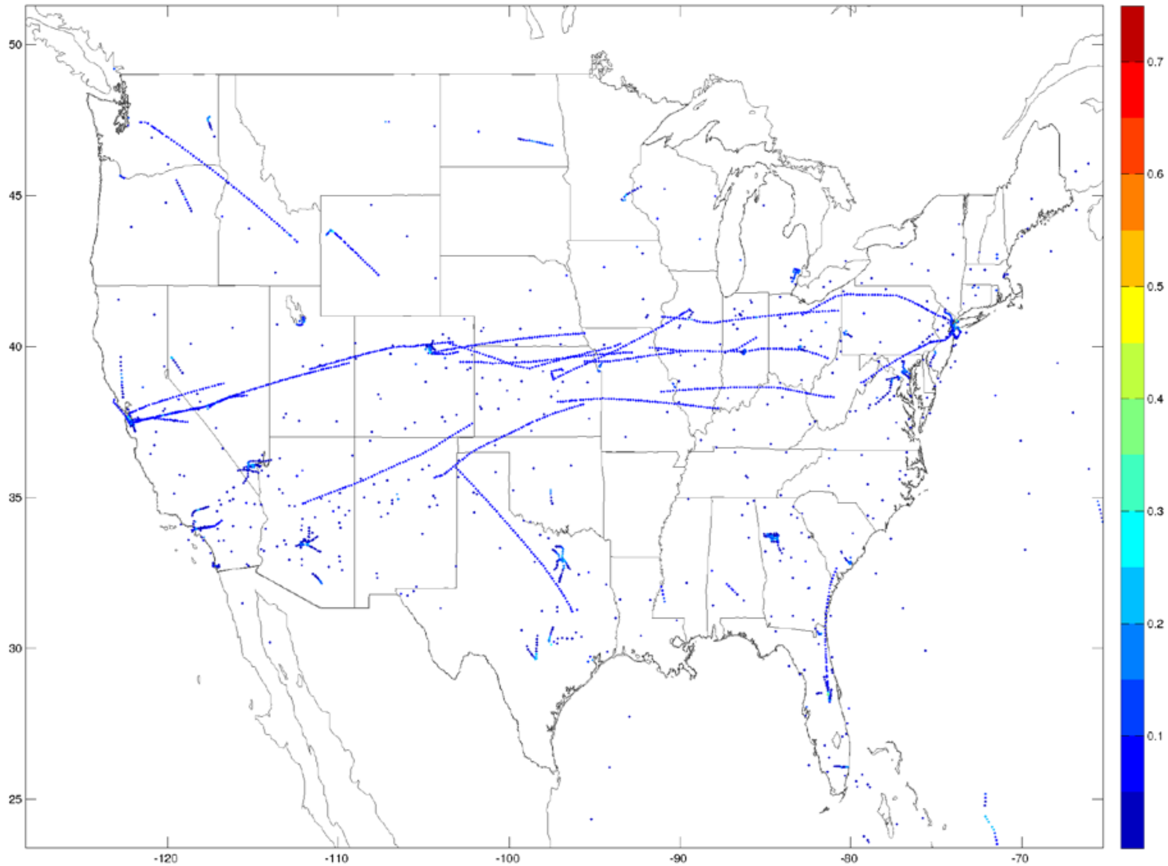
Challenges (cont.)



UAL 757+DAL737+DAL767+SWA737
1hr 1800 UTC 25 Aug 2014

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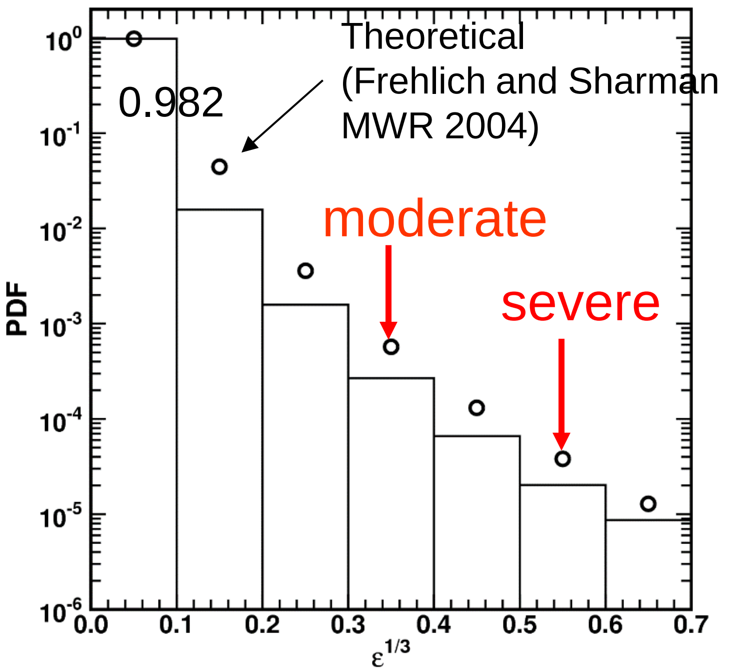
Challenges (cont.)

4. **Large scale forecasts errors**
   - There are inaccuracies in the large scale forecasts
   - These increase with lead time
   - Can use ensembles to help quantify errors
5. **Turbulence is a rare event!**
   - ~ 96% - 98% is "smooth"
   - "Moderate" <~ 10^{-3}
   - "Severe" <~ 10^{-4}
   - Based on insitu edr estimates
   - Biased since pilots avoid (possibly smooth ~ 85%?)*



Others….

*Sharman et al., JAMC 2014

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Aviation Turbulence R&D Needs

- **Better/more comprehensive observations of aircraft scale turbulence**
  - In situ turbulence estimates
  - Ground-based and airborne remote sensing techniques, including satellite-based technologies
- **Better nowcasting & forecasting products**
  - Need nowcast products for tactical avoidance of turbulence patches that were not properly forecast
  - This may be provided by human-over-the-loop checks
- **Better understanding of turbulence generation/ advection and propagation mechanisms**
  - Analyses of data gathered in field programs
  - Case studies using high-resolution simulations
  - Can be used to formulate improved turbulence forecast algorithms
- **Need to get information to the cockpit**
- **Need industry, govt labs, university collaborations**

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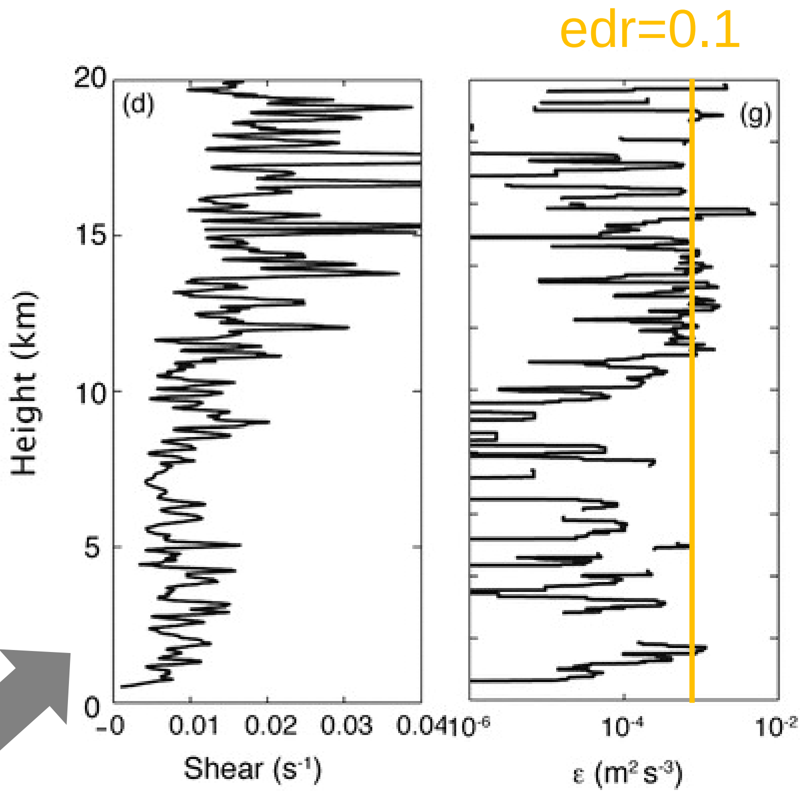
Candidate observation enhancements

- More reliable PIREPs
  - Need industry collaboration
- More in situ edr data
  - Global, night
  - Combine and standardize sources
  - Develop reliable PIREPs to EDR maps
  - Optimize data gathering
  - Need industry collaboration
- Provide access to on-board turbulence detection systems (forward looking radar)
  - Need industry collaboration
- Develop/implement lidar-based on-board detection systems, e.g. DELICAT
- High resolution rawinsondes
  - 800 globally, 90 US
  - 6-sec data is available (~25 m)
- Satellite feature detectors



Clayson&Kantha, JTEC, 2008

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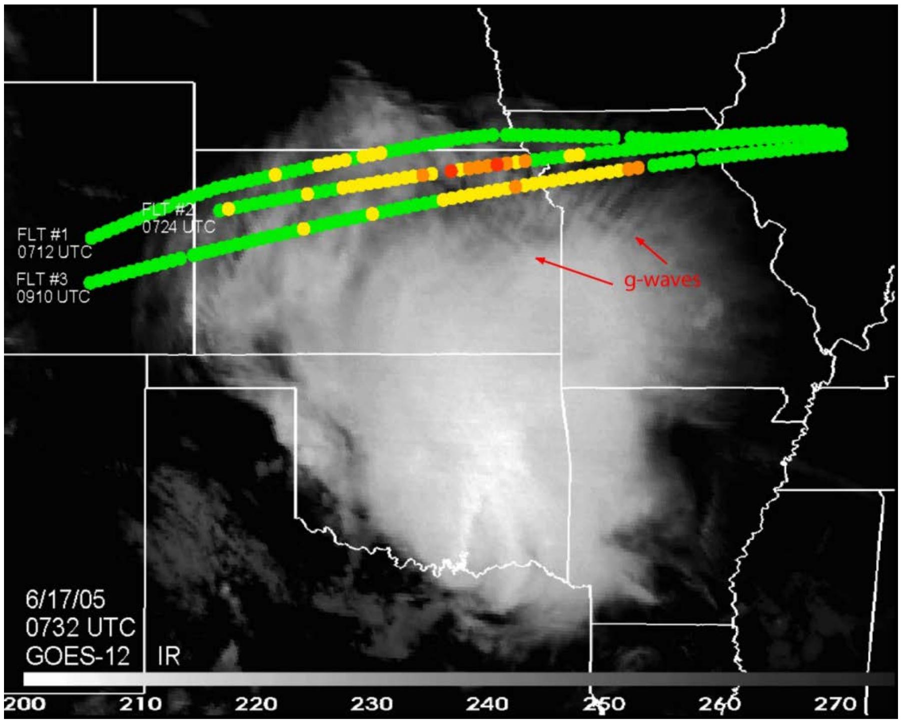
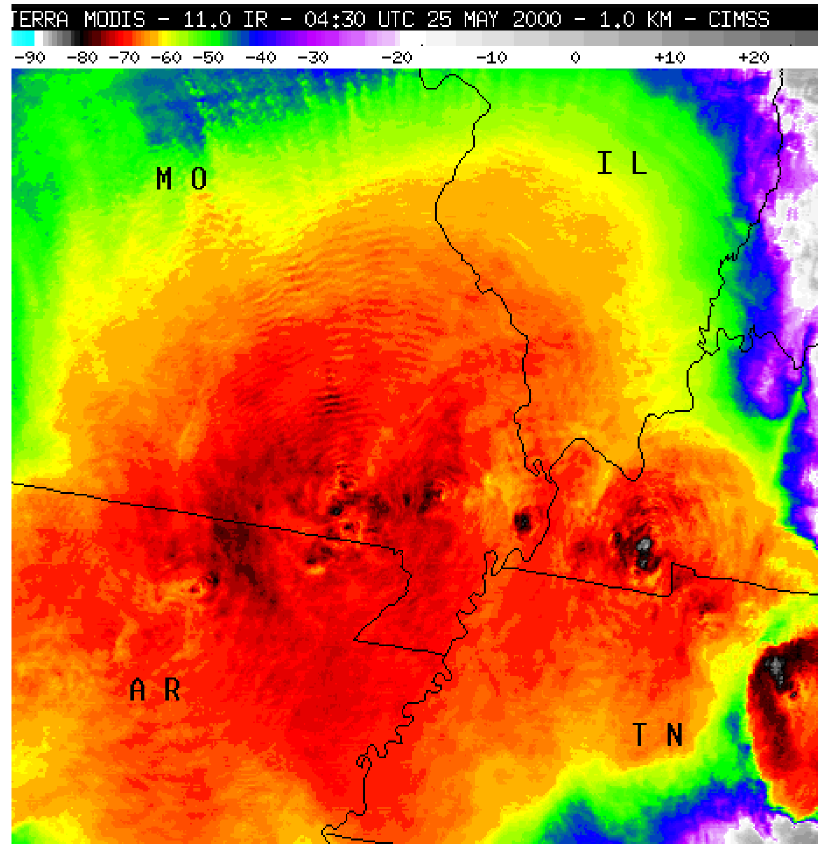
Satellite feature detectors: anvil bands and gravity waves





17 June 2005 Moderate and severe turbulence insitu EDR measurements near Transverse (Radial) MCS Outflow Bands over central US

- **Trier & Sharman (2009, MWR)**
- **Trier et al. (2010, JAS)**

MODIS image of convectively-induced gravity waves.
Courtesy Wayne Feltz UW CIMSS

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Better forecasting techniques

Forecast errors due to

1. NWP model errors
2. Errors in postprocessing algorithms

Which is more important?

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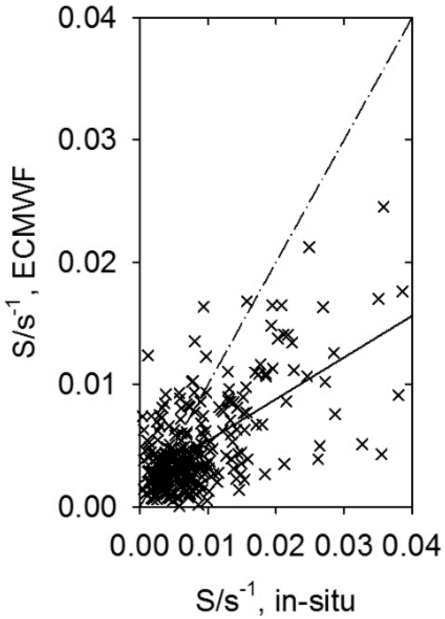


Courtesy Ulrich Schumann

Better forecasting techniques

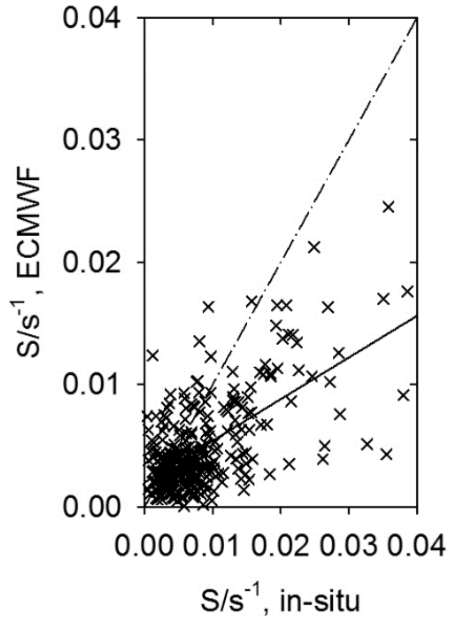
Forecast errors due to

1. NWP model errors
2. Errors in postprocessing algorithms

Which is more important?

1. NWP model errors (needs)

- Higher resolution
  - Grid nesting (horizontal and vertical)
  - Feature following grids
  - Regional models merged into global models
- Refine Turbulence Kinetic Energy (TKE) subgrid parameterizations for free atmosphere
- Sensitivity studies
  - To resolution
  - To various model configurations/ parameterizations



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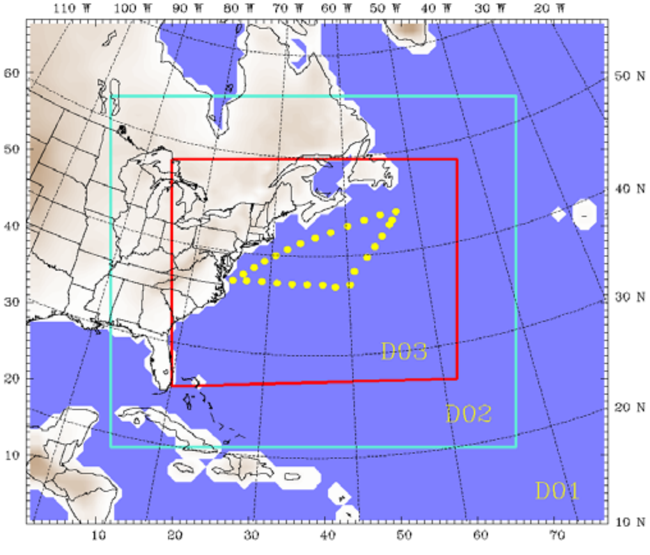
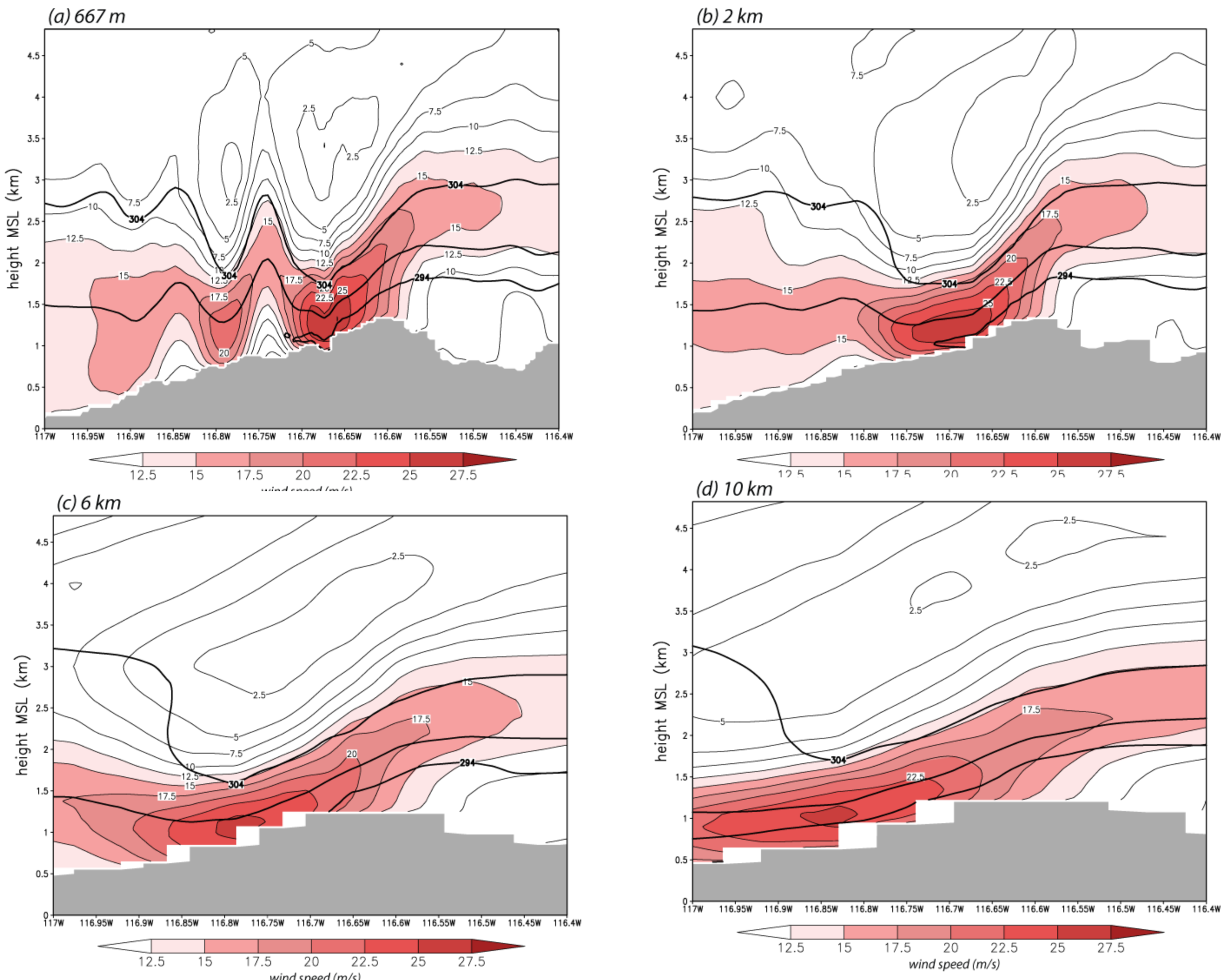


WRF Simulations of Santa Ana winds over San Diego, CA 15 Feb 2013: 4-hr average winds



Courtesy Rob Fovell, UCLA

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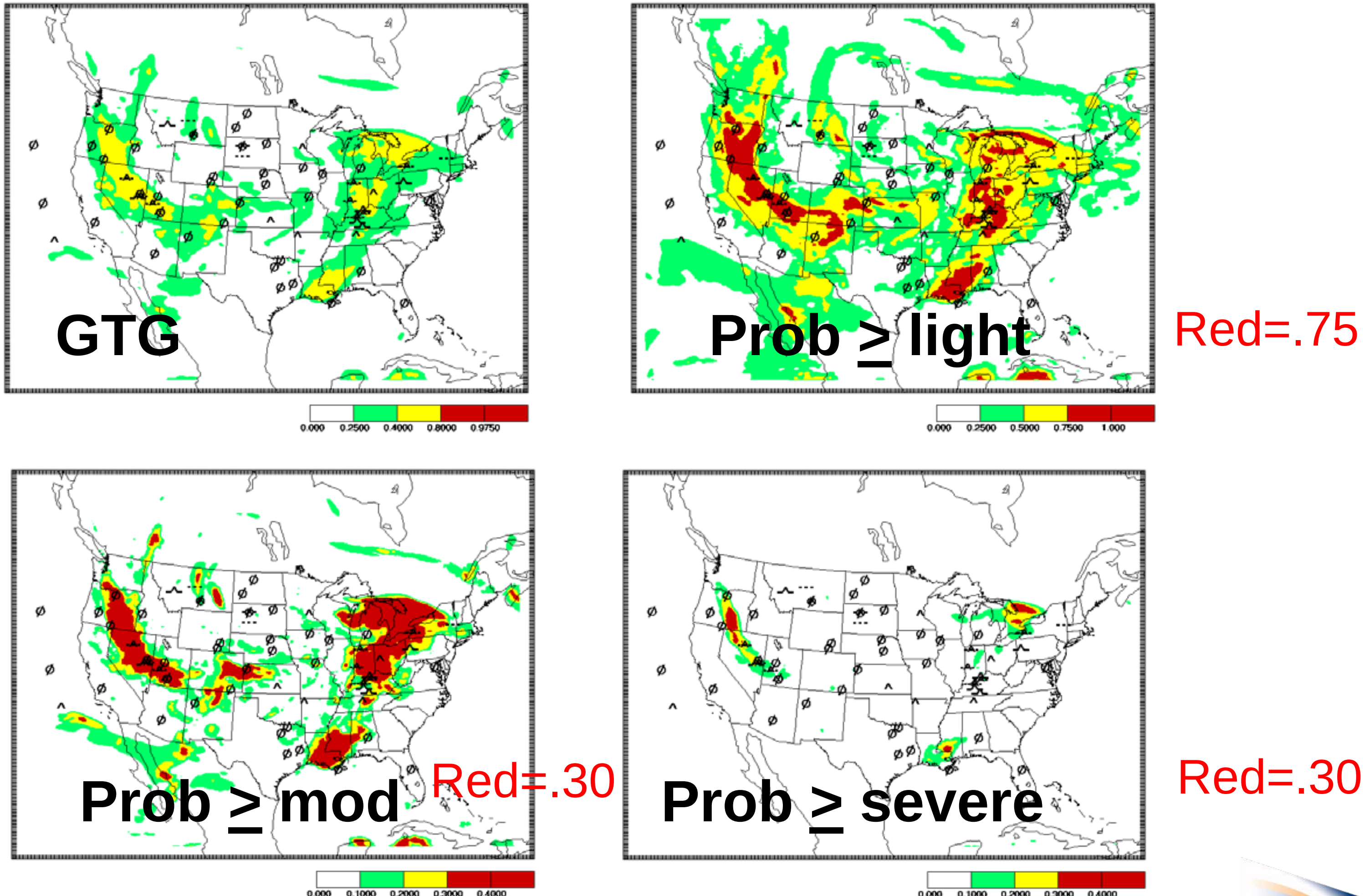
Better forecasting techniques (cont.)

2. **Reduce errors in postprocessing algorithms**
   - Requires more fundamental research
   - Requires better understanding of linkage between large scale represented in NWP models and smaller scales (waves, turbulence)
   - Need for autotuning of postprocessing algorithms when underlying NWP model changes
   - Better combination strategies using AI techniques (e.g. GTG, UKMet)
   - Use ensembles of diagnostics, possibly combined with NWP ensembles
     - Gives users some idea of confidence in results
     - Makes more sense given random nature of turbulent processes

Use of diagnostics as ensembles provides confidence values (or uncalibrated probabilities)



0 h forecast valid at 22 Sep 2006 15Z

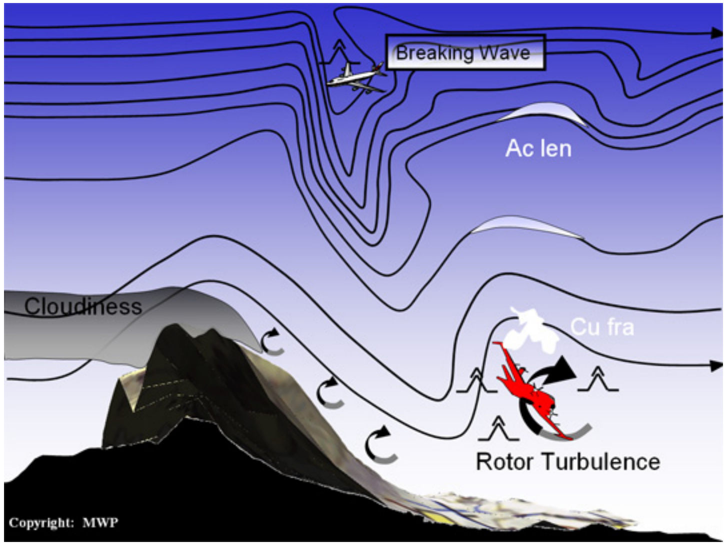
Better understanding of turbulence processes

- Need more national & international collaboration, esp. with university community
- Use combination of theoretical studies, field programs, and high resolution numerical simulations
- Case studies based on reported incidents or accidents, elevated edr data
  - Need airline cooperation
- Investigate importance of gravity waves and gravity wave breaking…

Gravity waves and gravity wave "breaking"

- Gravity waves may be generated in free atmosphere when air is displaced vertically:
  - Flow over mountains
  - Flow over fronts
  - Rapidly growing convection
  - Numerous other processes

- Gravity waves may break leading to turbulence



- Or may be a hazard itself

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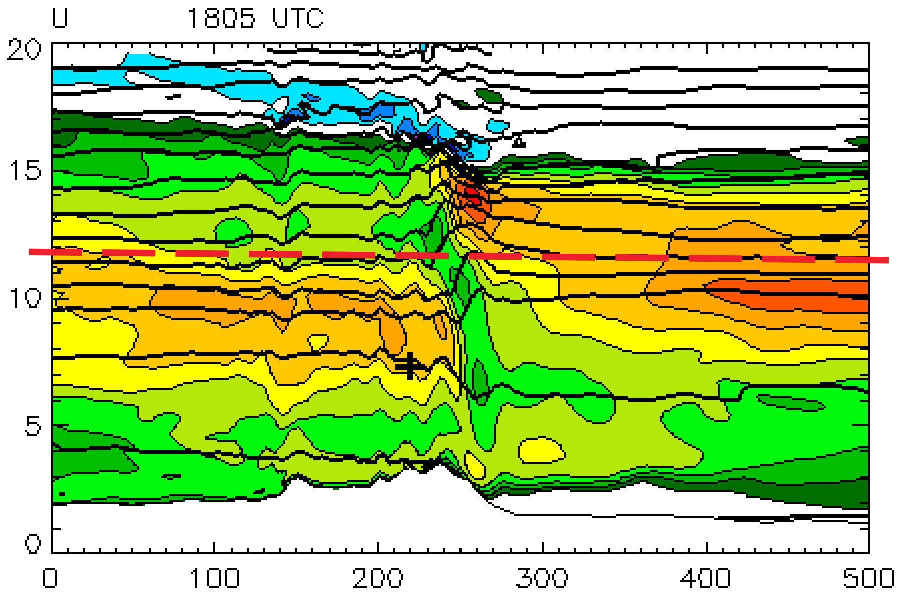
Simulation shows turbulence associated with gravity wave steepening and breaking



15 Mar 2006 over Northern CO at FL390: + .8g acceleration, Flight attendant broke wrist, Flight diverted to Nebraska
Clark-Hall simulation of mountain waves and turbulence

East-west cross-section, 15 min frames 18Z-23Z 3 km resolution (event – 22:14).

Lines=isentropes
U (m/s) white |U|<5 m/s cint 5 m/s

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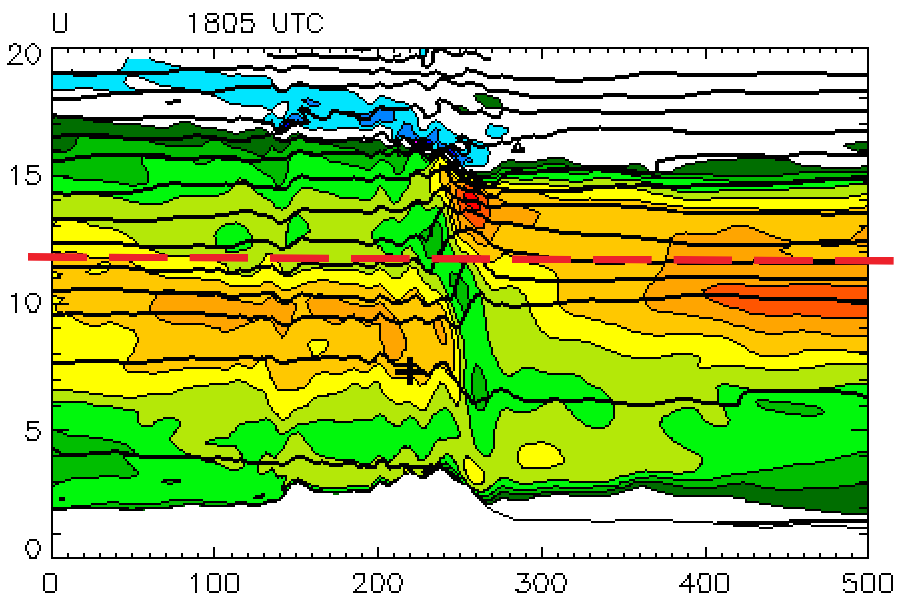

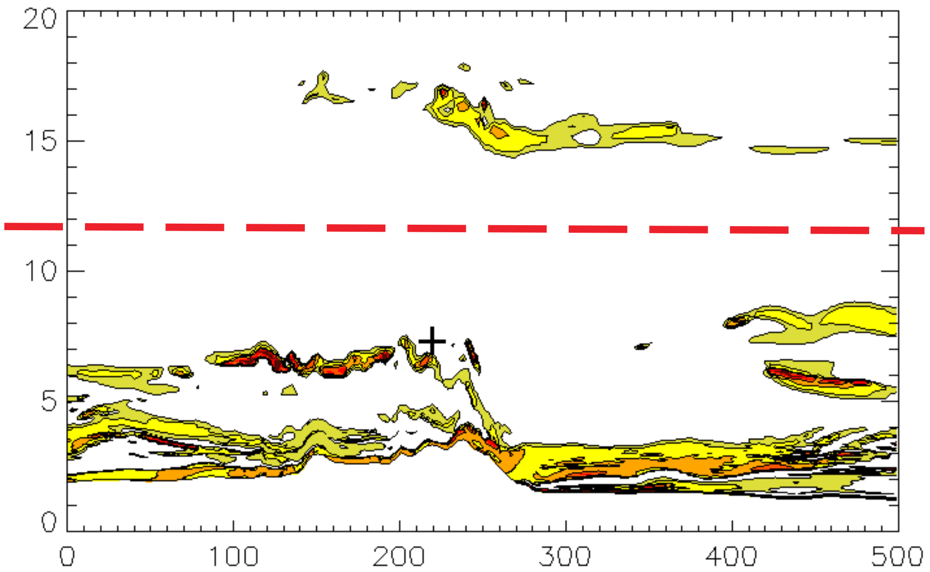

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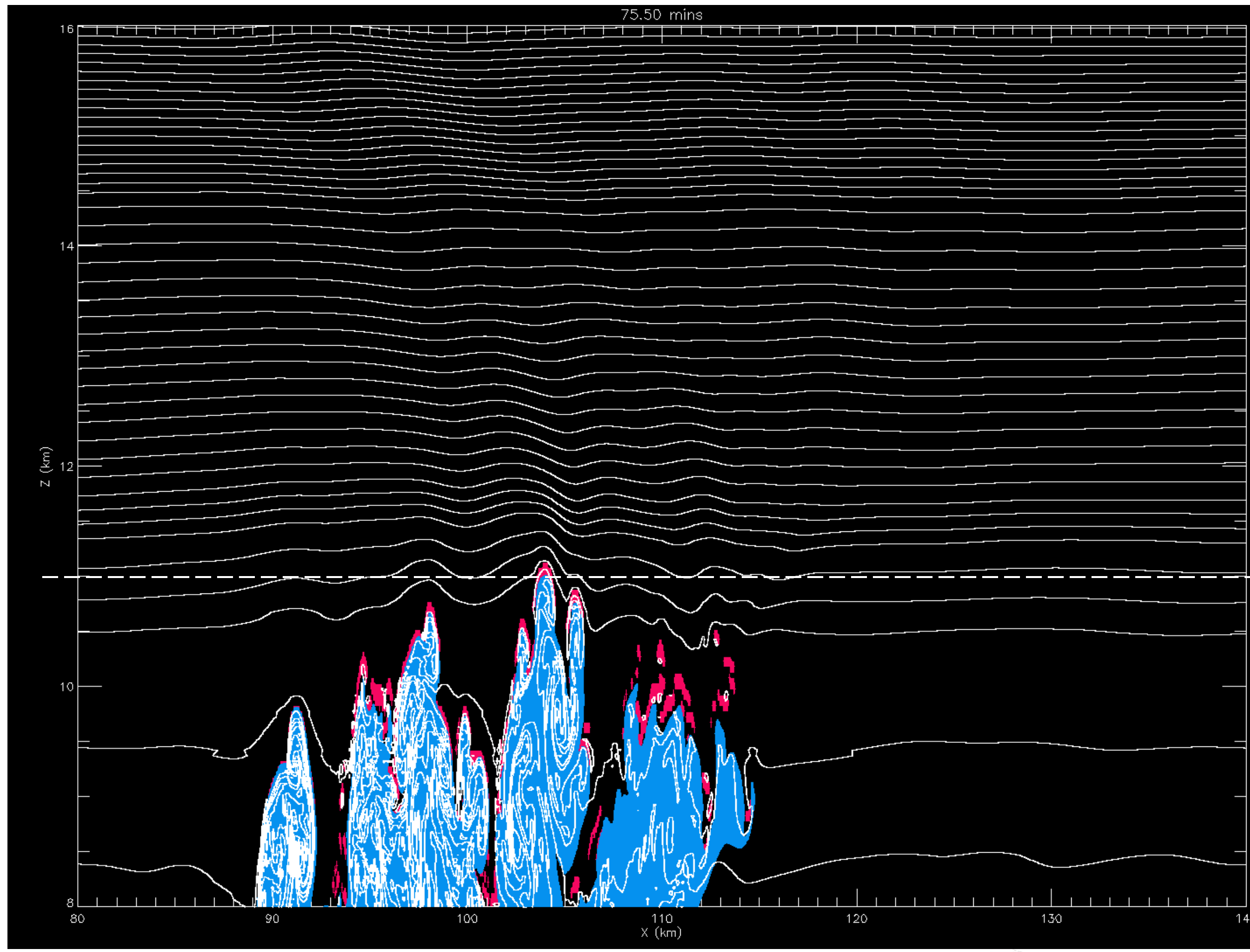
Example of gravity wave propagation and breakdown over a developing thunderstorm

Some turbulence occurs in clear air near cloud

- Termed convectively-induced turbulence (CIT)
- Related to gravity breaking

Example

- 10 July 1997 near Dickinson, ND. (En-route Seattle to JFK). Boeing 757 encountered severe turbulence while flying above a developing thunderstorm (and between thunderstorms)
- FL370 (approx 11 km)
- 22 injuries.
- +1 to -1.7 g's in 10 sec



Courtesy Todd Lane, U. Melbourne

Lane and Sharman, JAMC 2008

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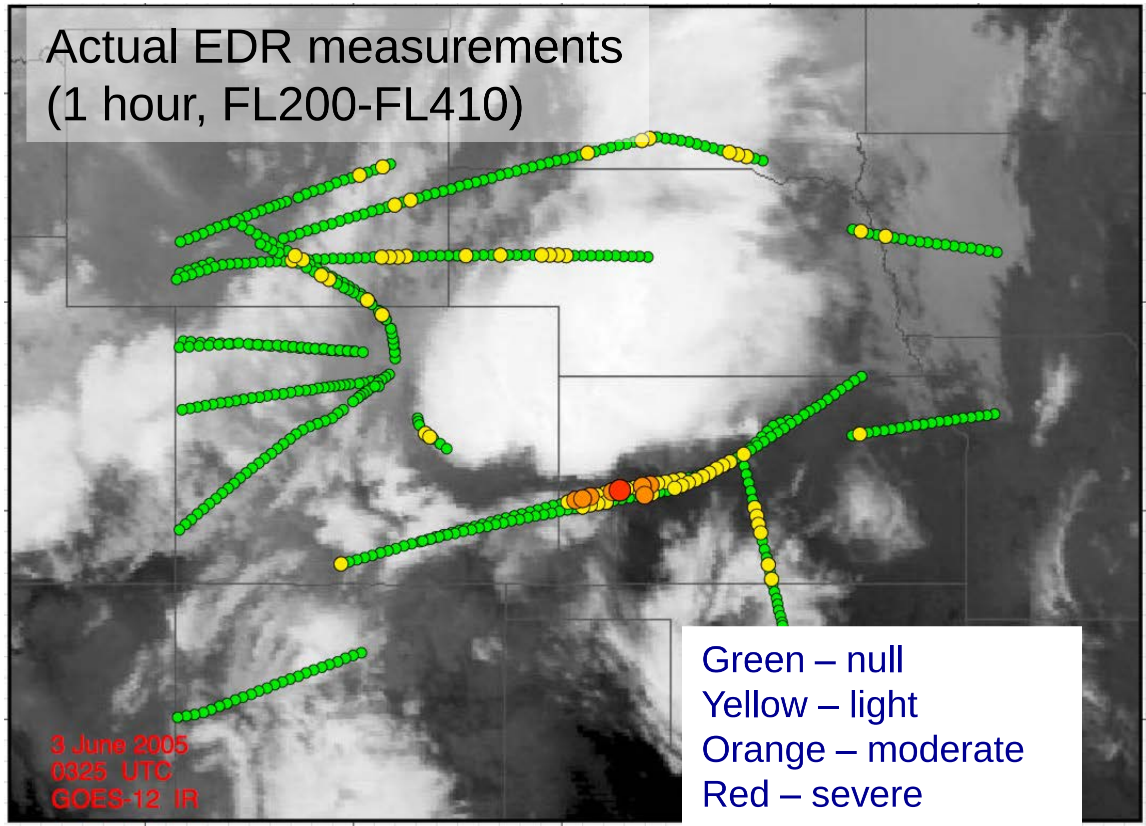
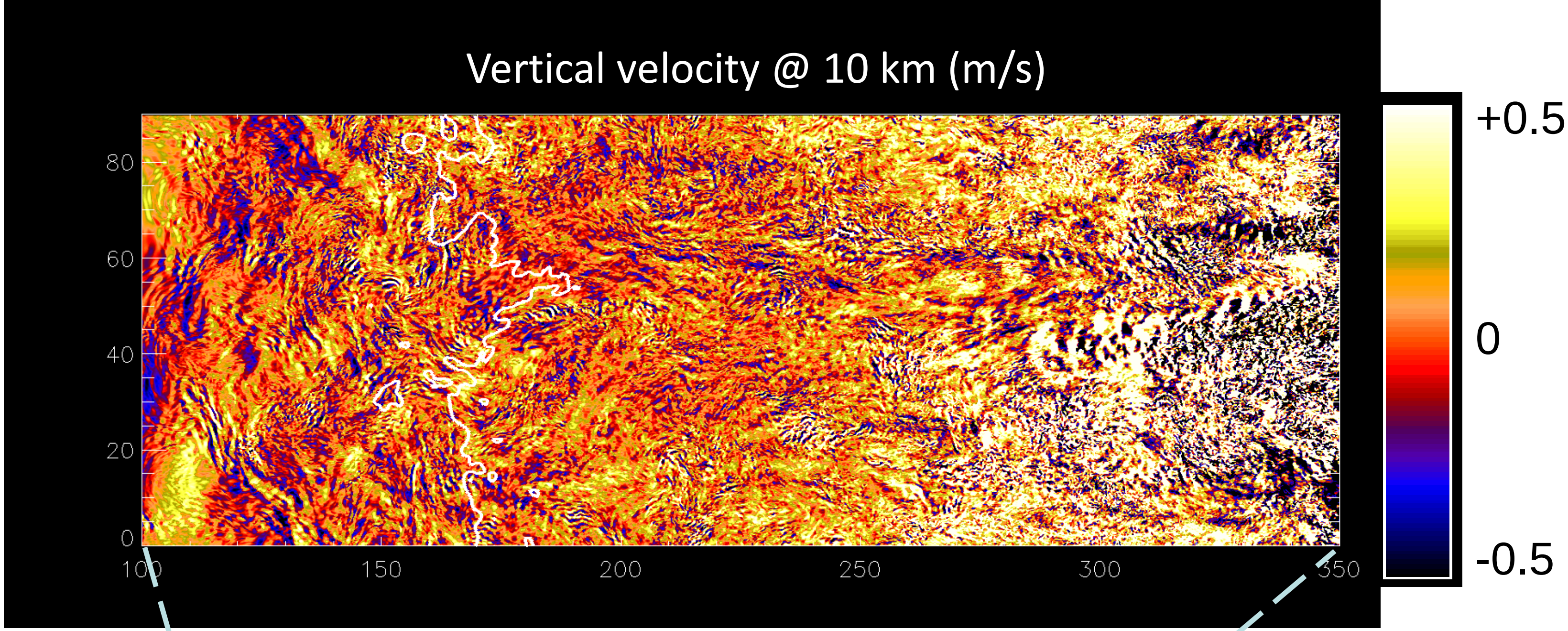
Better understanding of turbulence processes (cont.)

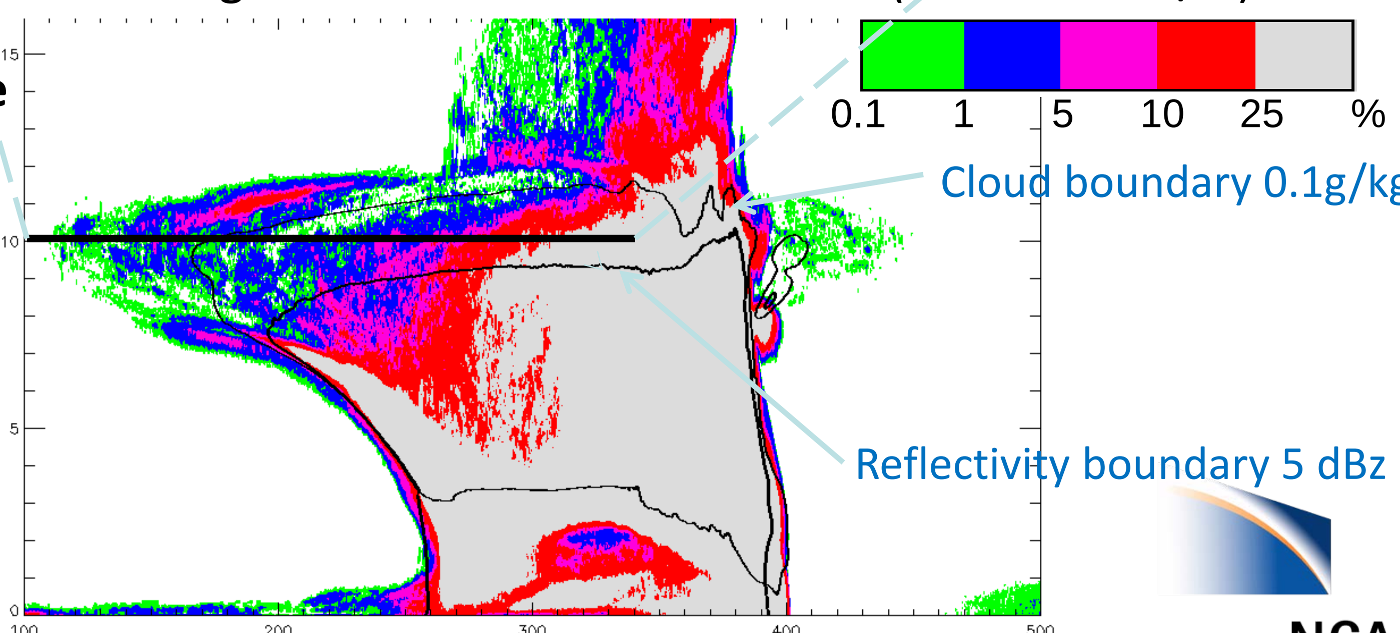
- More generally, what is the relation between turbulence in-cloud and out-of-cloud?
  - Gravity waves
  - Wake effects
  - What are optimum avoidance strategies?



Courtesy Dragana Zovko-Rajak, U. Melbourne



Proportion of along-line volume that is turbulent (TKE>0.25 m^2/s^2)



Thunderstorm line simulation 8000x1220x334 @75 m

Lane&Sharman, GRL 2014

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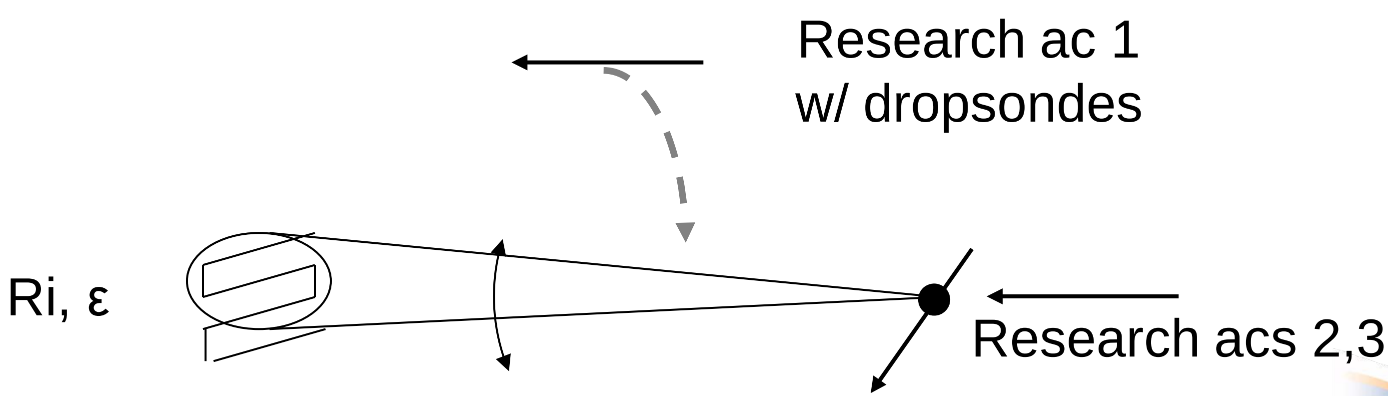
Need for field programs

- Need high resolution observations to better understand and quantify turbulence processes
- Ideally this would involve multiple aircraft with high-rate measurements and a forward-looking scanning Doppler lidar + radiometer, one with dropsondes
- Should be international collaborative effort
- Upward-looking radar would also be useful
- Use GTG forecasts to identify conducive areas/times
- Compare with simulations after the fact



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