“Clear-air turbulence”

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Turbulence in the Free Troposphere

- Free troposphere =
  - above PBL
  - stratified shear flow (like SBL)
  - For many applications also consider lower stratosphere (i.e. UTLS)
  - “Clear-air” turbulence (CAT)
  - Often includes “mountain wave turbulence” (MWT)
  - Clouds still important
- Motivations
  - Important for understanding thermal and dynamic structure of the free atmosphere
  - Mixing of trace gases and pollutants
  - Trop-strat exchange
  - Affects EM/acoustic propagation
  - Affects safety and efficiency of flight
- Yet, not much scientific interest in this since the 1970s

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Aviation turbulence - Motivations

- Economic cost of ~ $200M/yr
- 75% of air carrier accidents
- Average 13.9 serious injuries and 47.2 minor per year for Air Carriers
- 10% of air carrier turbulence related accident resulted in damage to the aircraft
- Causes aircraft fatigue and shorter airframe life spans
- Second leading weather factor affecting air traffic controller workload

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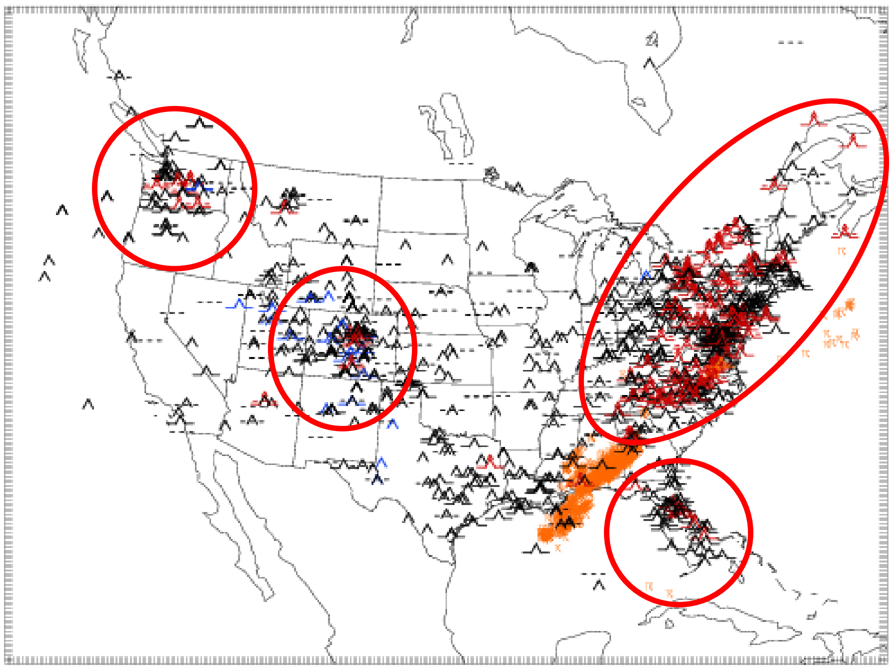
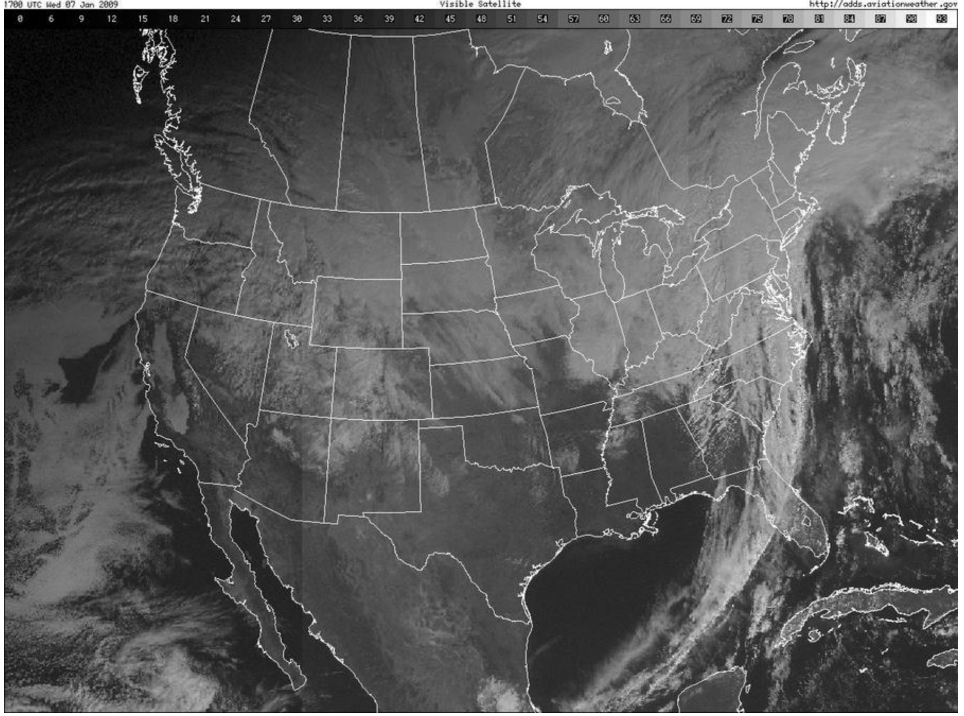
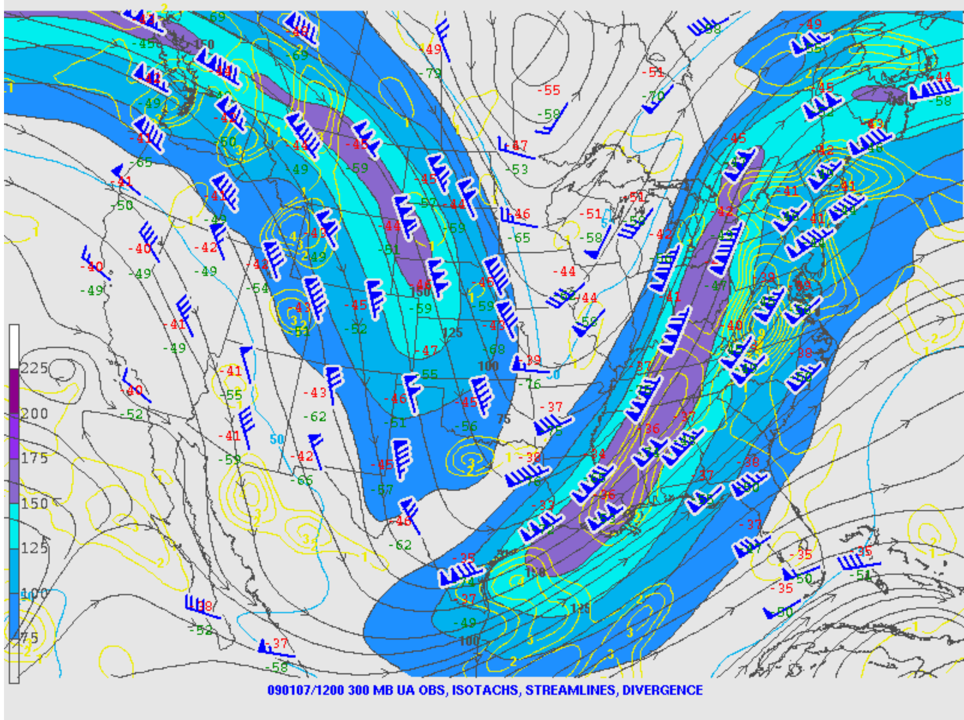
07 Jan 2009 – a big turbulence day in the NAS

pireps for 07 jan 2009 0000 to 2400 UTC
flight levels(ft) =   1. to 65000.

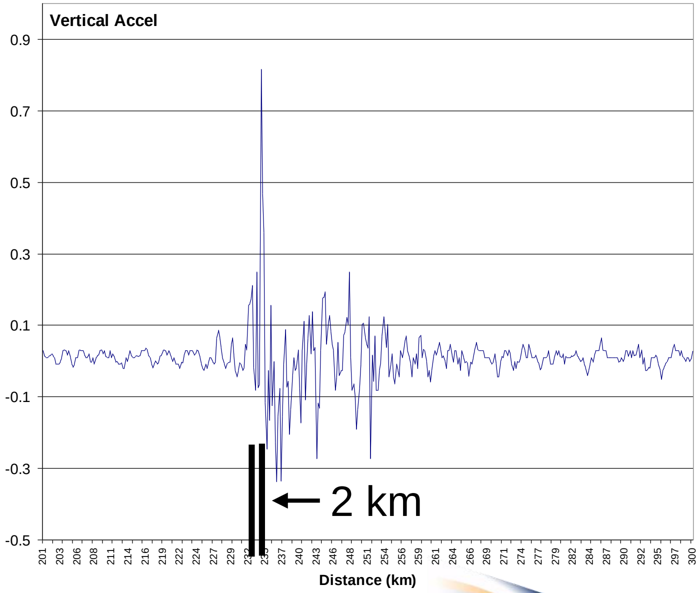






“Clear-air” turbulence (CAT)

- Associated with enhanced wind shears and reduced stabilities in the vicinity of jet streams, the tropopause and upper-level fronts (favored on cyclonic side and above and below the jet stream core)
- Definition: “all turbulence above the surface boundary layer, not directly associated with convective clouds” (Plan for U.S. clear-air turbulence research in GARP, 1971)
- Occurs in pancake-shaped “patches”
- – Median depth ~ 1km, length ~ 100 km
- Nonstationary and intermittent
- Sources (not so simple):
    - Kelvin-Helmholtz instability (KHI) occurs when background Ri is small (<~1)
    - Other instabilities
    - Gravity waves
        - Can perturb low Ri environment to lead to KHI
        - Critical level encounters (complicated in 3D)
        - Convection
        - Adjustment processes



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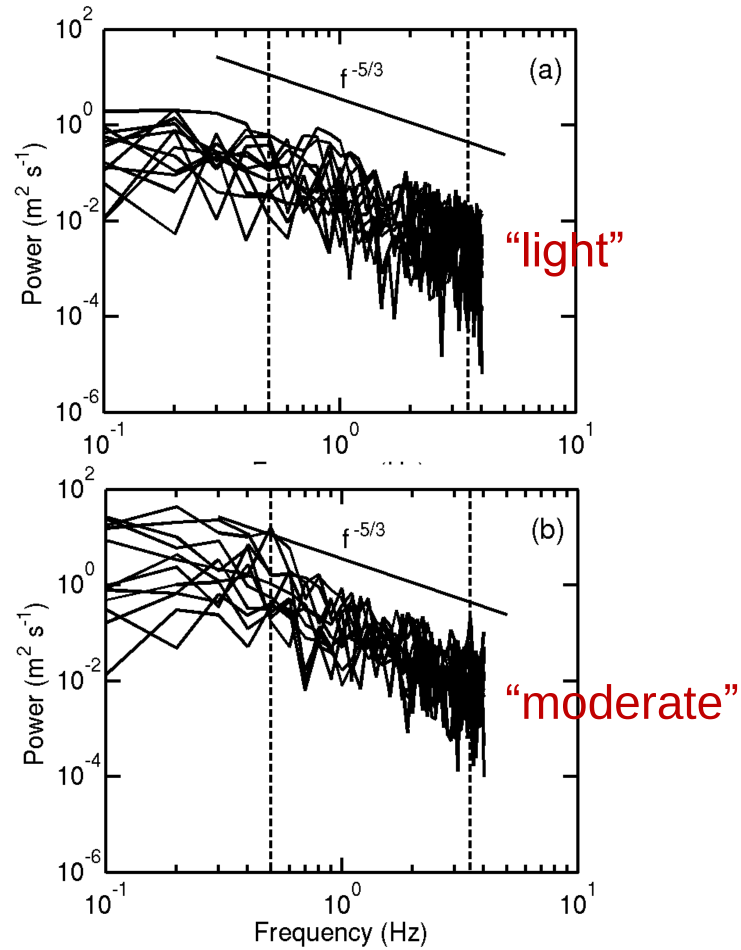
CAT character

- For aviation, eddy sizes of most importance are ~ aircraft size, i.e., in inertial subrange where

  $E(k) \sim \varepsilon^{2/3} k^{-5/3}$
- “Bumpiness” ~ $\varepsilon^{1/3}$ (=“EDR”)
- International Civil Aviation Organization (ICAO) standard for reporting turbulence intensity
  - EDR=0.10, 0.4, 0.7 for “light”, “moderate”, “severe”
- Aircraft response to vertical motion >> lateral/longitudinal
- Horizontal spectrum of *w* is most important
- NOT isotropic!
- Has implications for measurements



w spectra from B737 aircraft
Each 10 sec with 5 sec overlap @8 Hz = 12 spectra/min
Sharman et al JAMC 2014

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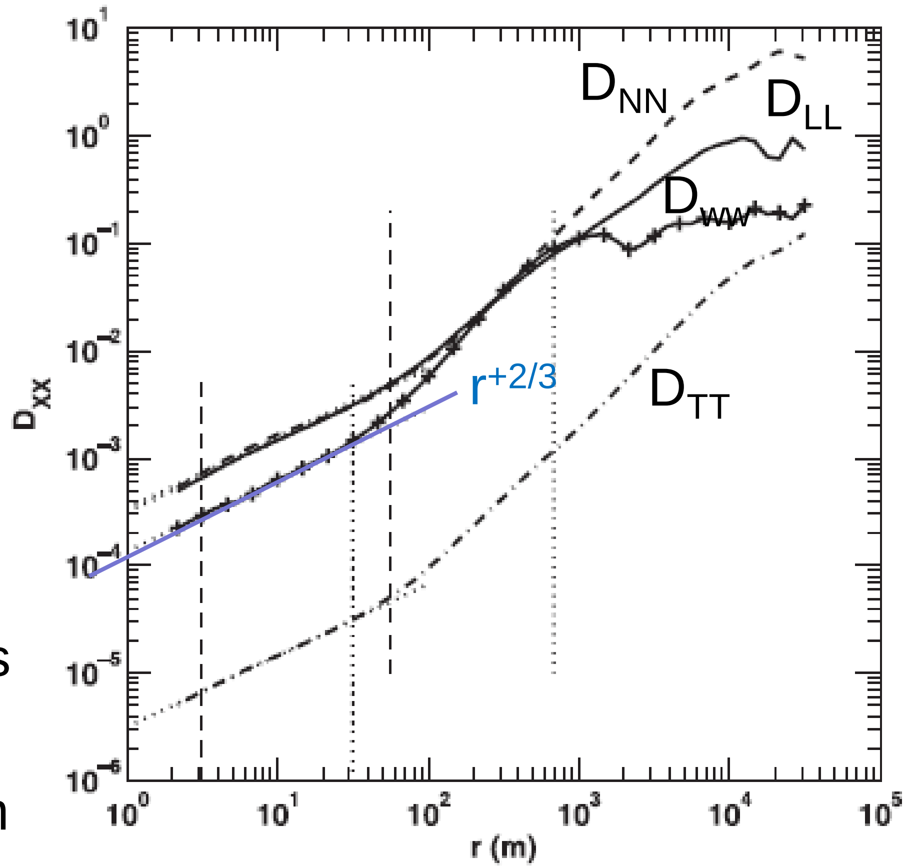
CAT character (cont.)

- Another representation is through structure functions

$$D_u(s) \propto \overline{[u(x) - u(x+s)]^2} \propto \epsilon^{2/3}\, s^{2/3}$$

  - Inertial range ~ $s^{+2/3}$
  - "Bumpiness" ~ $\varepsilon^{1/3}$ (="EDR")
  - Can be longitudinal or transvers
  - Advantages
    - Does not require removal of m
    - No need to break up in sections
    - Provides direct connection to physical scales
    - Easy to compute
- Computation of reliable spectra/sfns requires accurate high resolution measurements of u,v,w,T



Computed structure functions from aircraft data at 12.3 km

Wroblewski et al. JAS 2010

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Larger scales

- Also contains a $k^{-5/3}$ (Nastrom and Gage Nature 1984) or $s^{+2/3}$ (Lindborg JFM 1999) range out to ~400km
- Not clear why, but seems to be a downscale cascade
- Important for forecasting

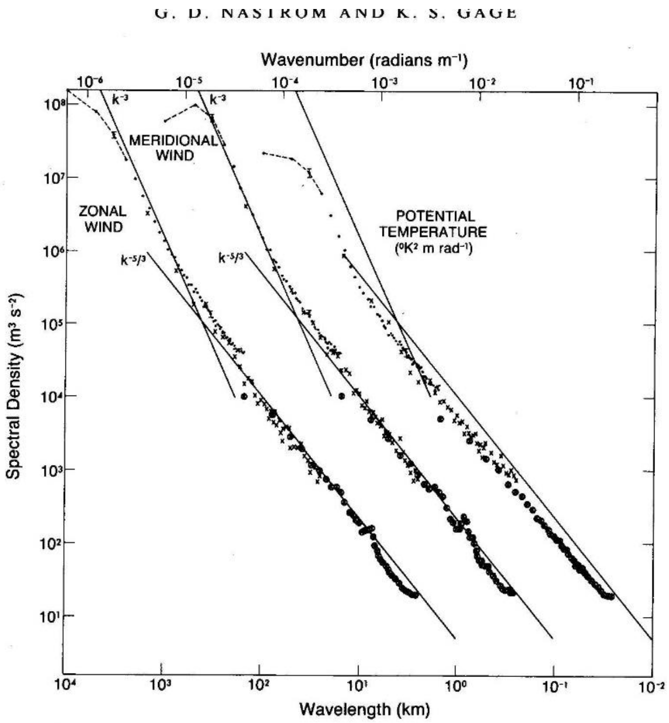
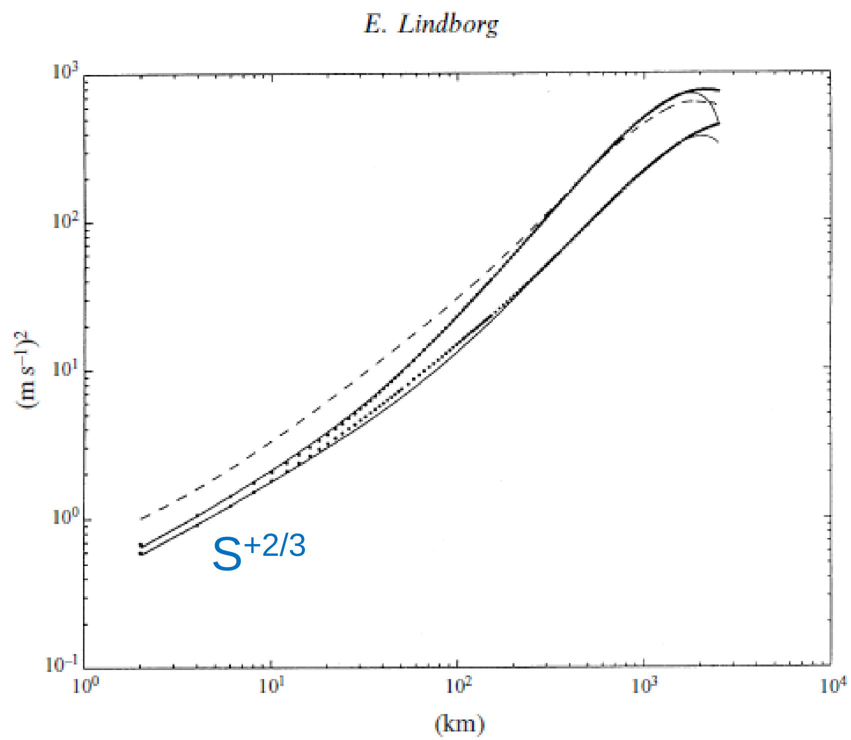
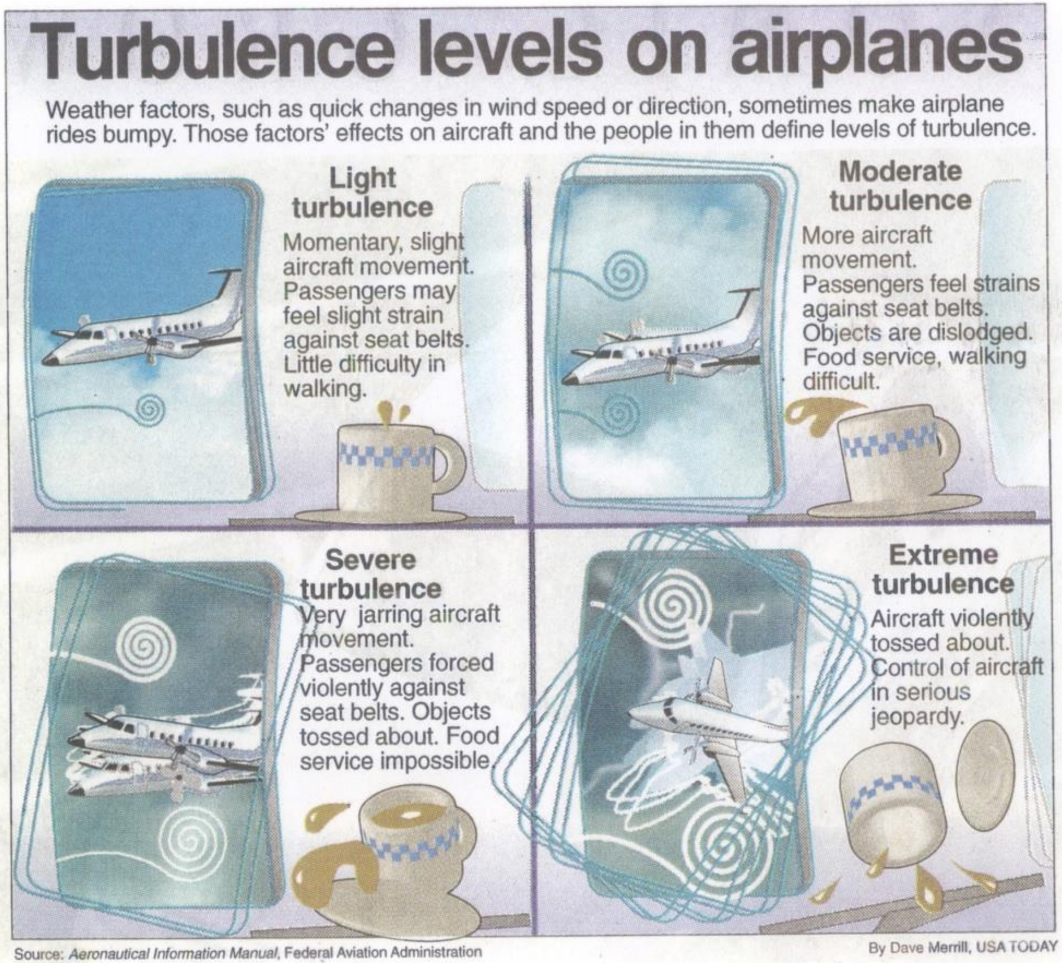


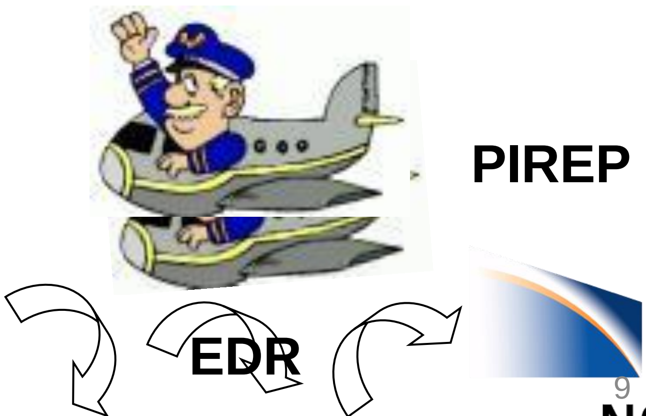
FIG. 3. Variance power spectra of wind and potential temperature near the tropopause from GASP aircraft data. The spectra for meridional wind and temperature are shifted one and two decades to the right, respectively; lines with slopes −3 and −5/3 are entered at the same relative coordinates for each variable for comparison.



Routine (operational) measurements

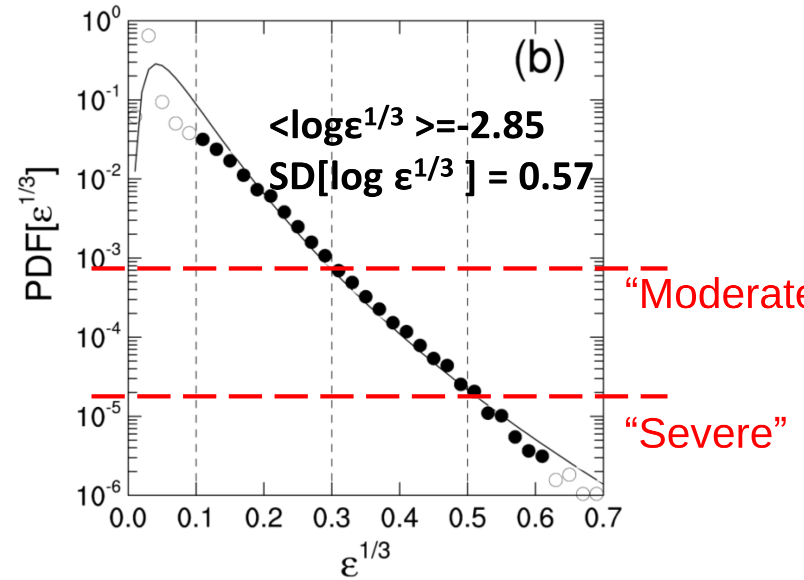
- Pilot reports (PIREPs), but
  - Nonuniform in space and time
  - Generally low occurrence
  - Subjective ("Light", "moderate", "severe", "extreme")
  - Aircraft dependent
  - Position and time inaccuracies
- In situ estimates of EDR (= $\varepsilon^{1/3}$ $m^{2/3}s^{-1}$) from commercial aircraft
  - Based on w spectra, fit to -5/3
  - Does not measure u,v,T
  - Cannot measure degree of isotrop
- Both subject to reporting bias
- High resolution rawinsondes or profilers or lidar are possible but
  - Not routine
  - Requires some assumptions and computations to get ε



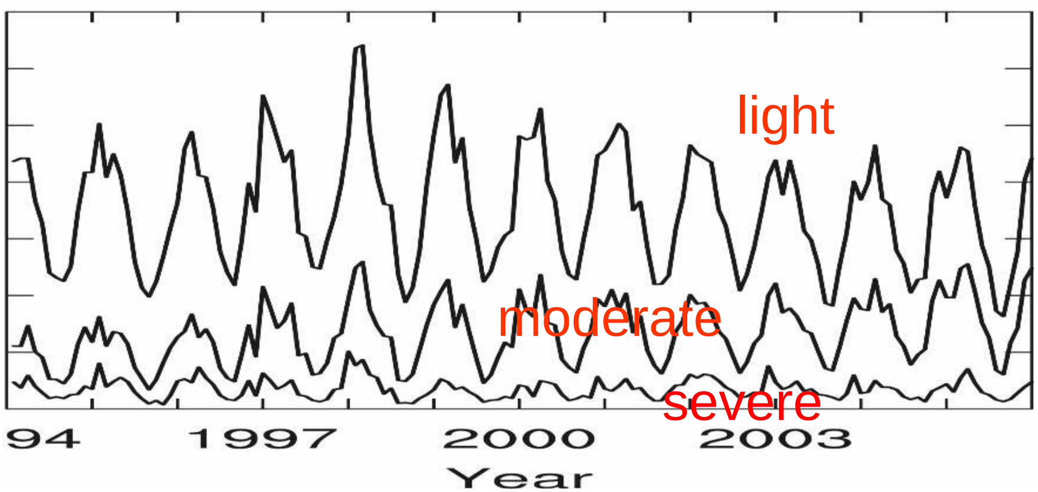


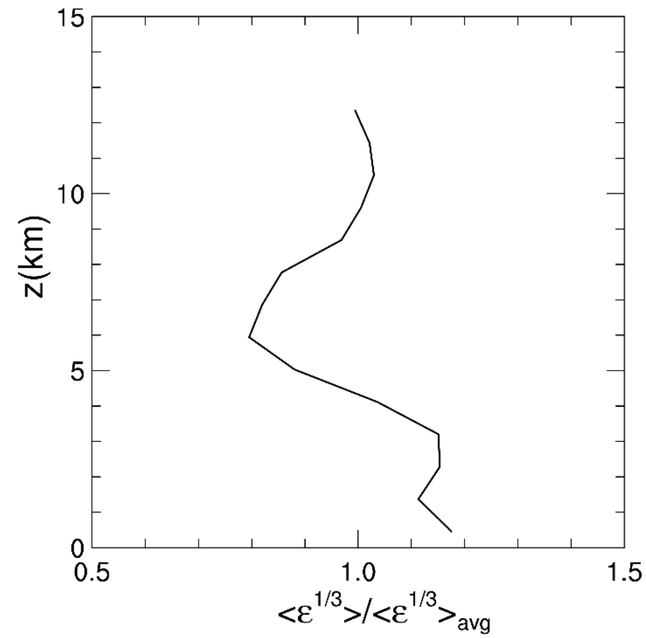
PIREP and In situ edr climatology

- PDF from in situ EDR measurements
  - Lognormal distribution of ε or $\varepsilon^{1/3}$
  - ~ 95% is "smooth"
  - "Moderate" <~ 10^{-3}
  - "Severe" <~ 10^{-4}
- Vertical distribution
  - maxima at low levels and UTLS
- Temporal variability
  - Maxima in winter (CAT and MWT) and spring (Convection)



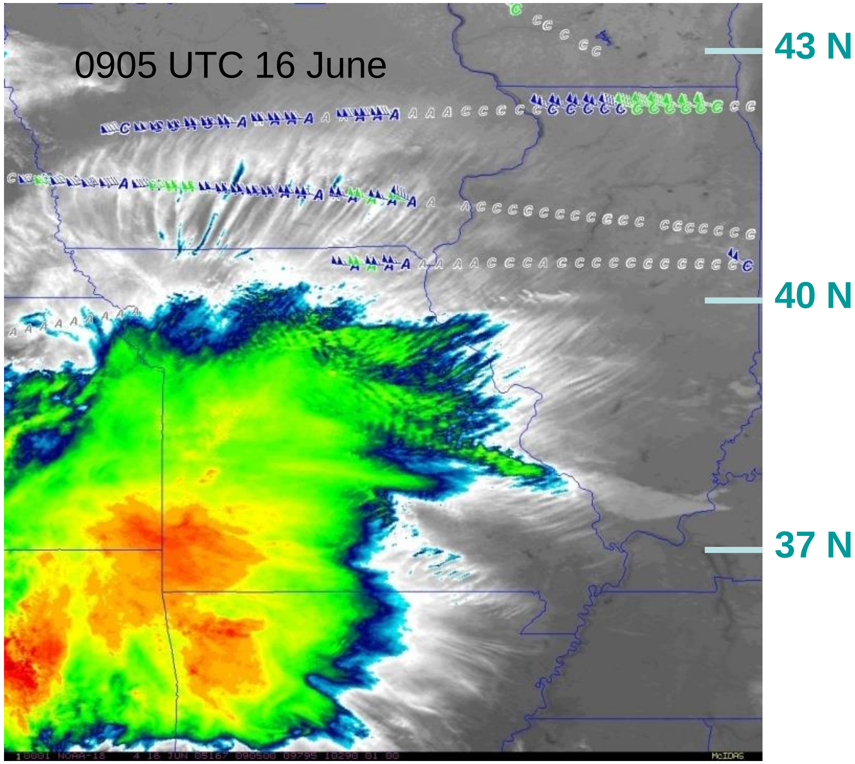
PIREPs climatology





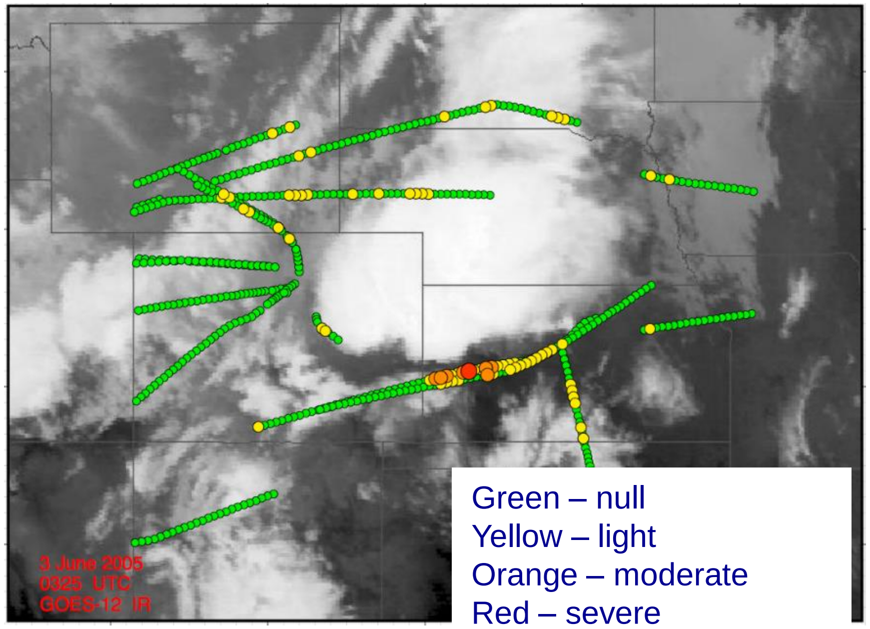
Effects of convective cloud

- Many reports of “CAT” are actually related to cloud
  - May be close or far from active convection
  - Some due to gravity wave or inertia-gravity wave breakdown emanating from convection
  - Cloud can modify Ri environment



Courtesy UW CIMMS

Actual EDR measurements
(1 hour, FL200-FL410)



Courtesy Dragana Zovko-Rajak, U. Melbourne

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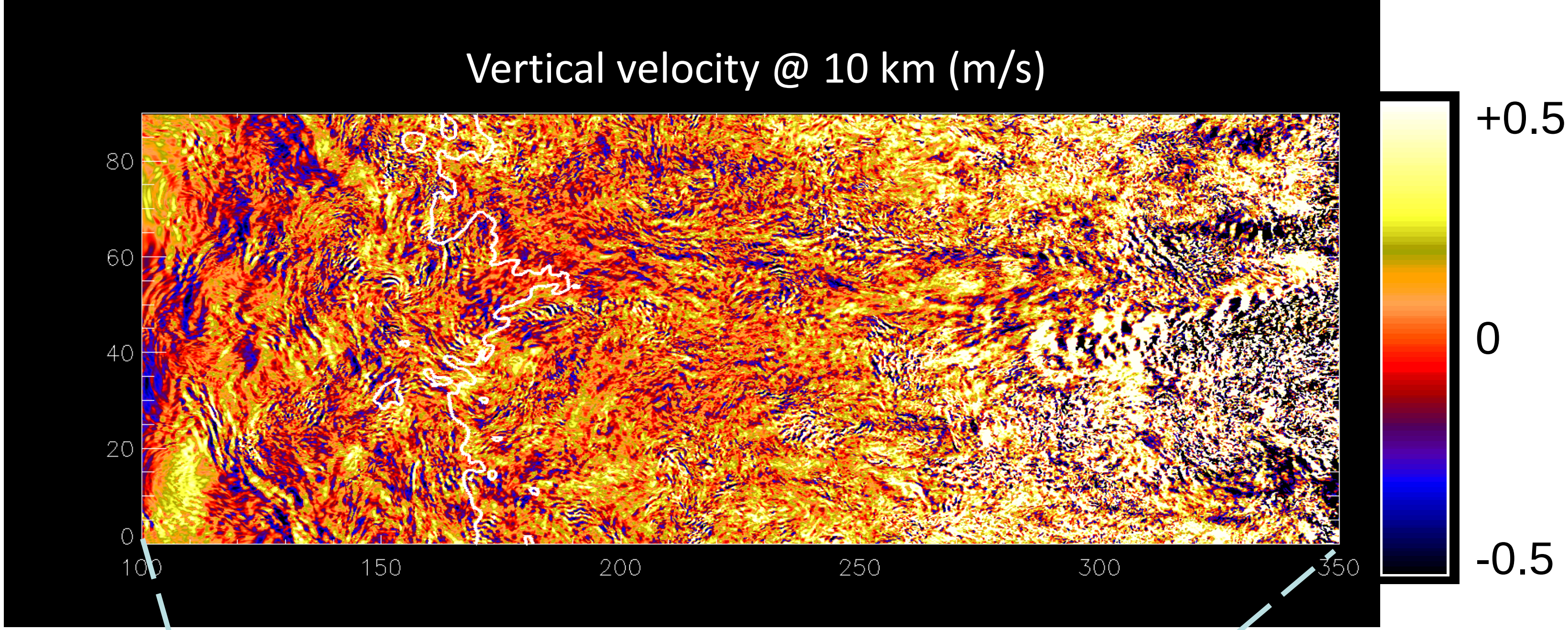
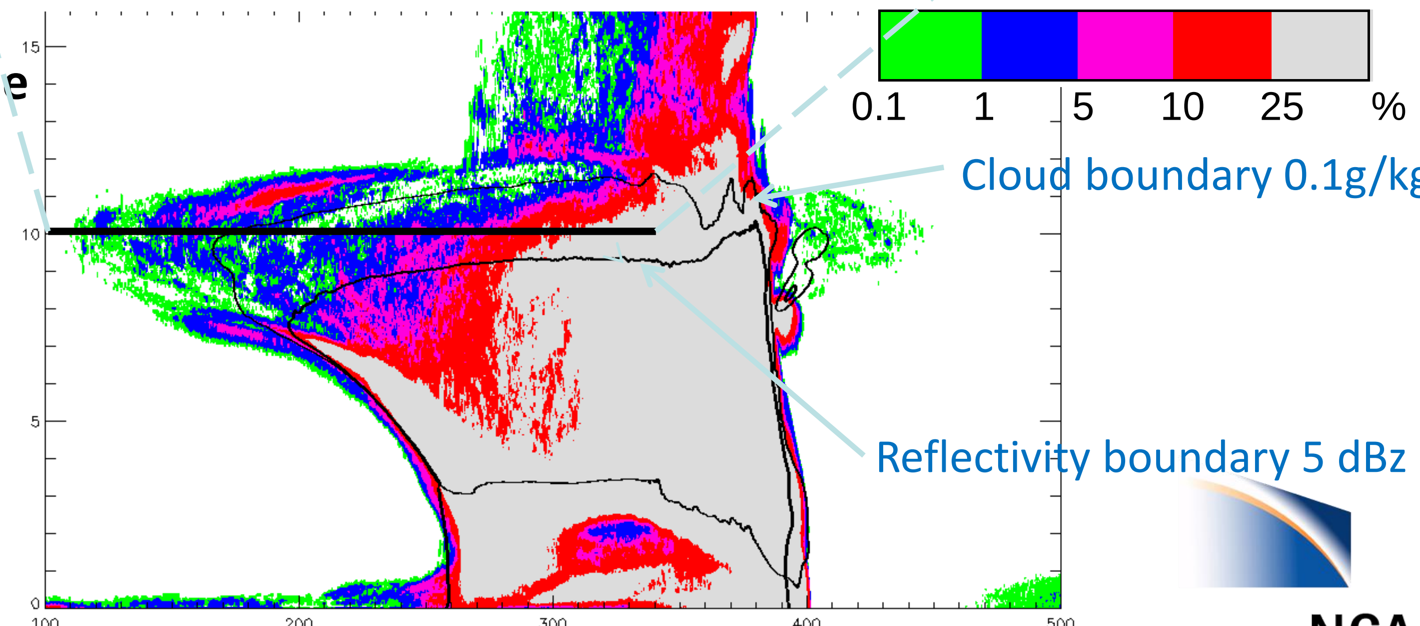


Proportion of along-line volume that is turbulent (TKE>0.25 m^2/s^2)



Thunderstorm line simulation 8000x1220x334 @75 m

Lane&Sharman, GRL 2014

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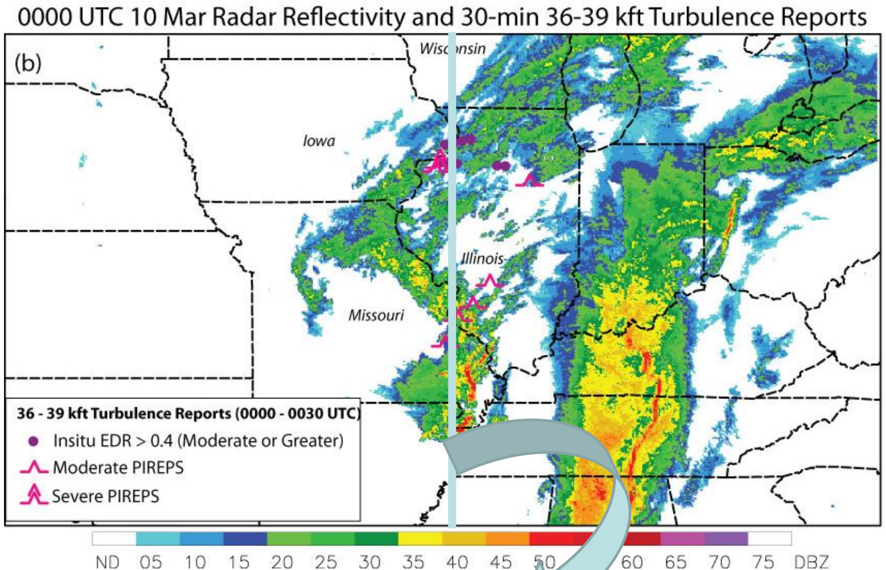
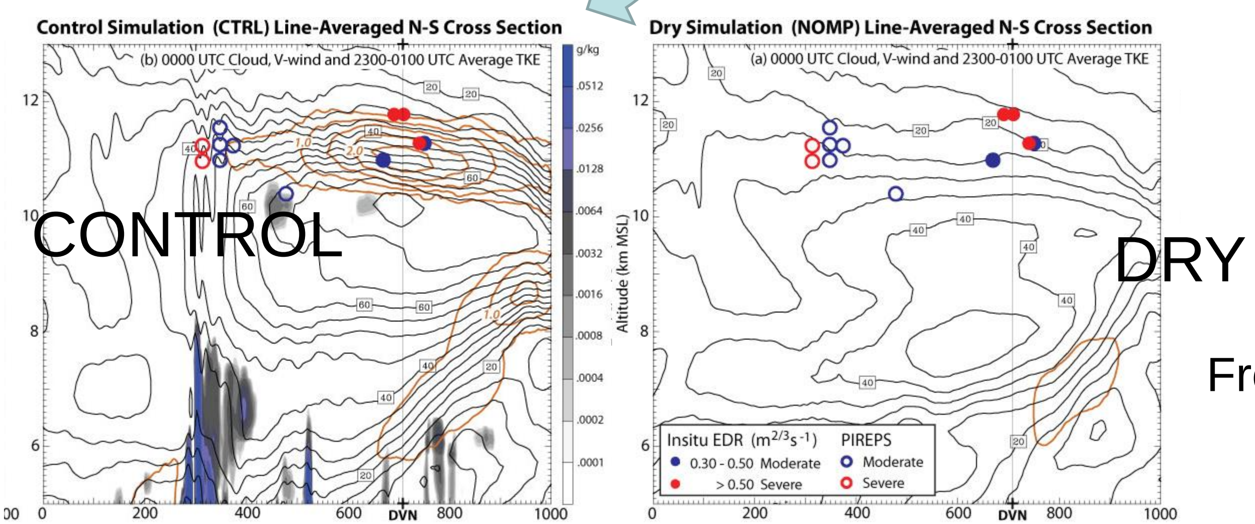
“CAT” outbreak on 10 Mar 2006



- Simulations of CAT events can now be accomplished using large domains to capture dominant forcing mechanisms nesting to smaller high resolution domains through to identify “turbulence” mechanisms
- Compare full physics run to “dry” run to identify effects of convection



From Trier et al. MWR 2012

WRF simulation 3.3 km grid, 82 levels

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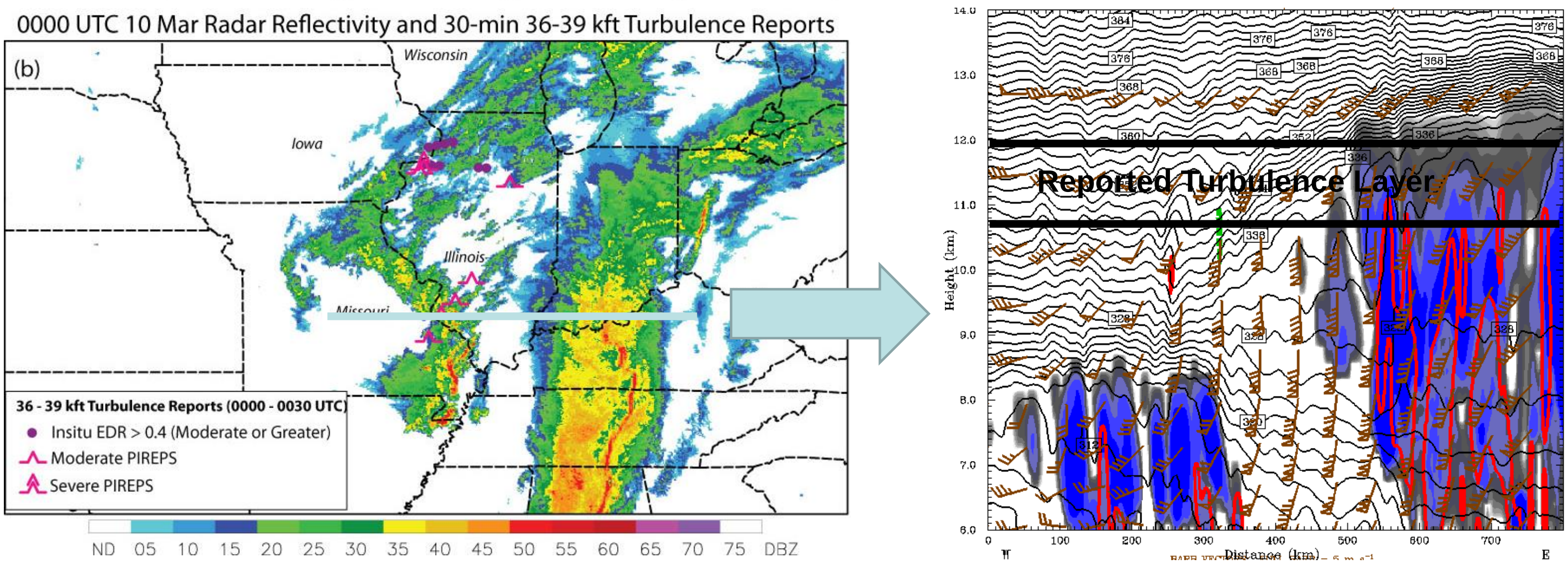
"CAT" outbreak on 10 Mar 2006 cont.



60-Min Animation (0020 to 0120 UTC 10 March 2006), Δ t = 5 min

Conclusions

- Cloud modification of the environment was crucial for the development of turbulence, esp in enhancing the environmental shear and lowering Ri
- Convectively-induced gravity waves even from shallow convection can be important
- Is this really an example of CAT?

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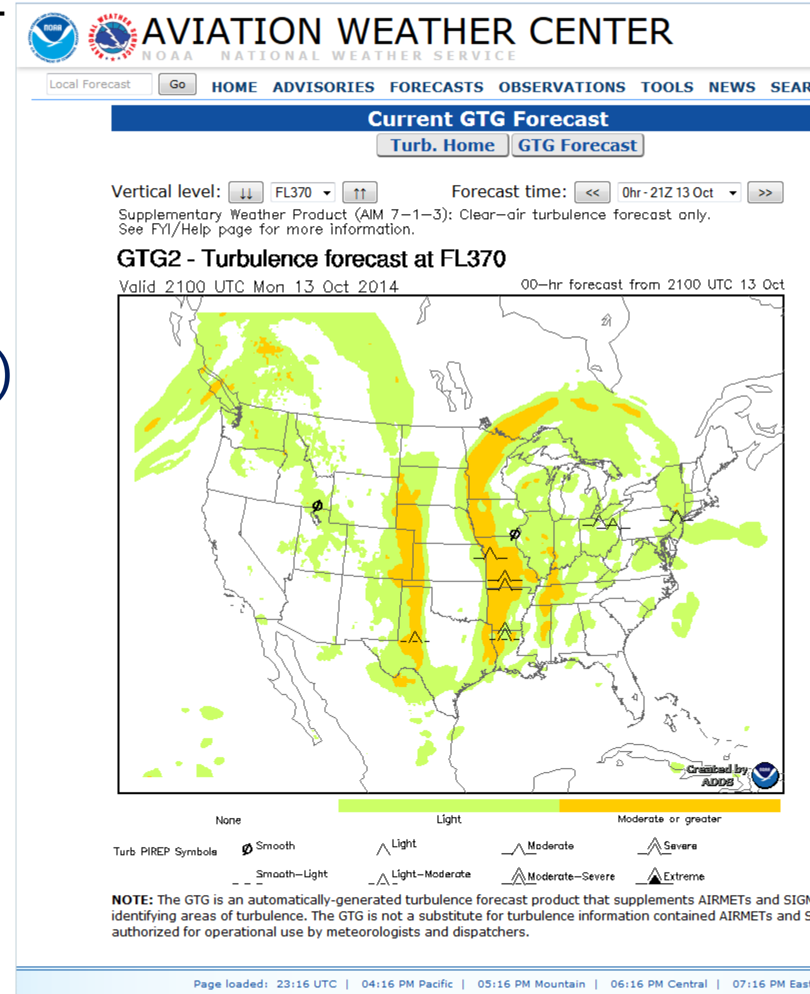
Turbulence Forecasting: Automated Approach

- Use operational NWP model (e.g. WRF RAP, GFS, ECMWF)
- TKE parameterization very poor
- Compute “diagnostics” of turbulence from spatial variability of model output
- Assume downscale cascade
- Each diagnostic is converted to $\varepsilon^{1/3}$ (D*) assuming lognormal distribution
- One approach is to use an ensemble mean of diagnostics*=

$$W_1D_1^* + W_2D_2^* + W_3D_3^* + \ldots.$$

- Use routine observations for calibration and verification
- PODs ~ 75-80%
- Misses due to
  - Unresolved or underresolved processes
  - NWP model errors
  - convective-related events
  - Unknown sources
  - …



*Sharman et al. JAMC 2016, WAF 2006

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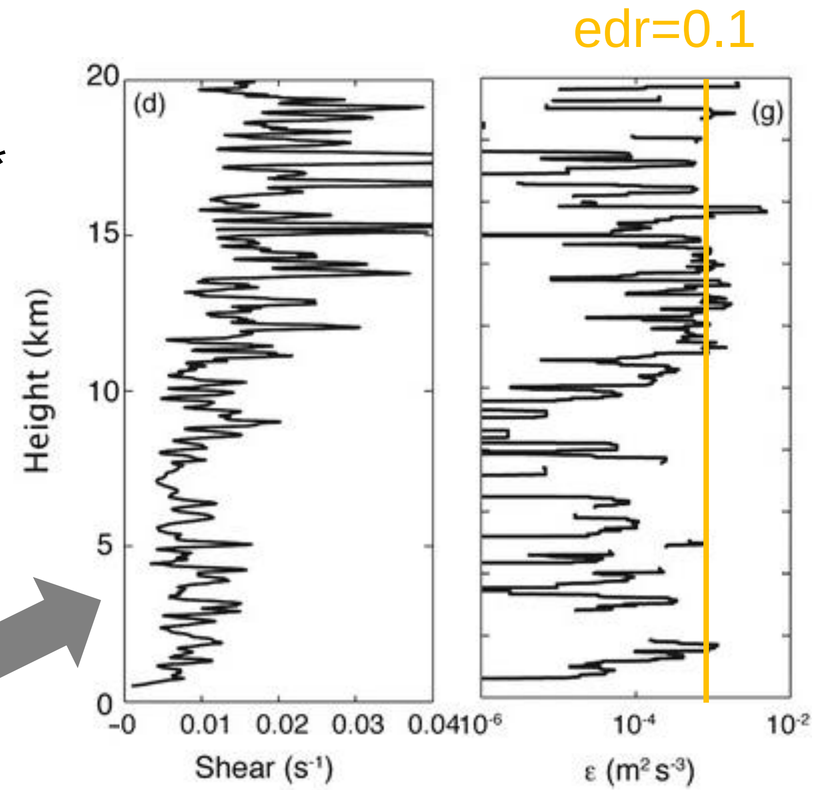
Scientific needs/challenges

- Need better understanding of causes and lifecycles of turbulence
  - What are the sources/damping mechanisms?
  - What is the role gravity waves, breaking, Ri reductions?
  - What is the role of spontaneous gravity wave emissions?
  - What about Rossby wave breaking?
  - What is the role of the tropopause and tropopause folds?
  - What is the relative importance of downscale and upscale cascades?
  - What processes contribute to the shape of the mesoscale spectrum?
  - What is the role of secondary gravity waves related to breaking gravity waves?
  - What is the role of Ci?
  - What is the prevalence of coherent horizontal vortex tubes (Clark et al. JAS 2000)?
- Modeling
  - Need better TKE subgrid parameterizations in free atmosphere -> ε
  - Nested simulations that include large (forcing) scale plus smaller scale have been highly successful
    - More cases based on accidents, elevated edr data
    - Resolution, parameterization, initialization sensitivity studies
- Need to establish climatology and assess effects of climate change
- How to use these insights to develop better diagnostics?
- Many good PhD topics here!!

Observation needs: Expand routine observations

- Expand in situ $\varepsilon^{1/3}$ reporting system on commercial aircraft
  - Avoidance bias
  - W only
- Develop on-board turbulence detection systems (forward looking)*
  - Aerosol (coherent Doppler) lidars suffer from limited range due to low aerosol concentration
  - Rayleigh scattering lidars
  - Air density UV lidar
  - All are not currently cost feasible for commercial use
  - Measures horizontal component along a horizontal path
- High resolution rawinsondes
  - 800 globally, 90 US
  - 6-sec data is available (~25 m)
  - Also have vertical acceleration packages
  - Certain locations at certain times only
  - Measures vertical component along a vertical track
- Upward pointing high-resolution radars



Clayson&Kantha, JTEC, 2008

*Vrancken in Sharman and Lane 2016

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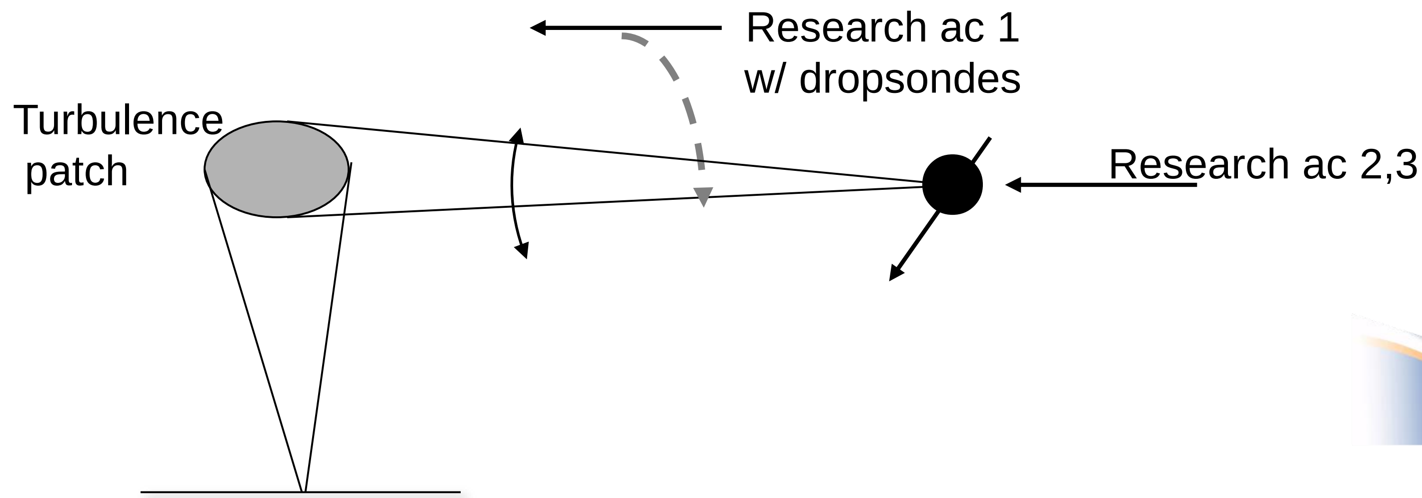
Need for field programs

- No systematic field campaigns dedicated to study CAT since early 1970s (USAF "ALLCAT")
- Need high resolution observations to better understand and quantify turbulence processes (difficult in low turbulence levels)
- Also need observations of environment (stability, shear)
- Ideally would involve multiple aircraft with high-rate measurements and forward-looking scanning Doppler lidar + radiometer, dropsondes + upward-pointing ground-based
- UAVs?
- Use forecasts to identify turbulence conducive areas/times
- Compare with simulations after the fact



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Overview References

Bedard, A. J. Jr.: Atmospheric turbulence aloft: A review of possible methods for detection, warning, and validation of predictive models. 31st Aerospace Sciences Meeting & Exhibit, AIAA 93-0847, Reno, NV, January 11-14 (1993)

Camp, D. W., Frost, W.: Atmospheric Turbulence Relevant to Aviation, Missile, and Space Programs. NASA Conf. Pub. 2468 (1987)

Dutton, J.: Clear-air turbulence, aviation, and atmospheric science. Rev. Geophys. Space Phys. **9**, 613-657 (1971). doi:10.1029/RG009i003p00613

Fedorovich, E., Rotunno, R., Stevens, B. (eds.): Dynamic processes contributing to the mesoscale spectrum of atmospheric motions. In Atmospheric Turbulence and Mesoscale Meteorology: Scientific Research Inspired by Doug Lilly. Cambridge University Press, Cambridge UK (2004)

Lane, T. P., Sharman, R. D., Trier, S. B., Fovell, R. G., Williams, J. K.: Recent advances in the understanding of near-cloud turbulence. Bull. Amer. Meteor. Soc. **93(**4**)**, 499-515 (2012). doi:10.1175/BAMS-D-11-00062.1.

Hoblit, F. M.: Gust Loads on Aircraft: Concepts and Applications. AIAA Education Series, American Institute of Aeronautics and Astronautics, Washington, D. C. (1988)

Hocking, W. K., Mu, P. K. L.: Upper and middle tropospheric kinetic energy dissipation rates from measurements of C_n^2 - review of theories, *in-situ* investigations, and experimental studies using the Buckland Park atmospheric radar in Australia. J. Atmos. Sol.-Terr. Phys. **59**, 1779-1803 (1997)

Hopkins, R. H., 1977: Forecasting techniques of clear-air turbulence including that associated with mountain waves. WMO Technical Note No. 155 (1977)

Honomichl, S.B., Detwiler, A.G., Smith, P.L.: Observed hazards to aircraft in deep summertime convective clouds from 4-7 km. J. Aircraft **50**(3), 926-935 (2013).

Lester, P. F.: Turbulence: A new perspective for pilots. Jeppesen Sanderson, Inc., Englewood CO. (1993)

National Academy of Sciences: Plan for U. S. clear-air turbulence research in the Global Atmospheric Research Program, H. A. Panofsky (ed), 36 pp. (1972)

Pao, Y.-H., Goldburg, A.: Clear Air Turbulence and Its Detection. Plenum Press, New York (1969)

Sharman, R. D., Trier, S. B., Lane, T. P., Doyle, J. D.: Sources and dynamics of turbulence in the upper troposphere and lower stratosphere: A review. Geophys. Res. Lett. **39**, L12803 (2012b). doi:10.1029/2012GL051996

Sharman, R. D. and T. P. Lane (eds): Aviation Turbulence Processes, Detection, Prediction, Springer (2016)

Vinnichenko, N. K., Pinus, N. Z., Shmeter, S. M., Shur, G. N.: Turbulence in the Free Atmosphere. Plenum, New York (1980)

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