Observations and simulations of turbulent processes in the upper troposphere and lower stratosphere

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Larry Cornman, John Williams

Upper troposphere-lower stratosphere turbulence: aviation perspective

- Commercial aircraft and business jets spend most of their time in cruise (~7 – 13 km)
- ~75% of all NTSB weather-related aviation accidents
- Therefore there is a real need for aviation turbulence nowcasts/forecasts
- But 3 major obstacles:
  - Routine observations are lacking
  - Fundamental understanding of turbulence processes in the UTLS is lacking
  - Operational NWP models have grid sizes much larger than scales that affect aircraft (eddies ~ 100m – several km >> inertial range (homogeneous isotropic))

Fundamental questions for UTLS turbulence

- What are the sources?
  - Large-scale forcing mechanisms
  - Turbulence genesis mechanisms
    - Any large-scale process that would allow KHI
    - Gravity wave “breakdown”
- What is the climatology?
  - Frequency
  - Spatial statistics
- How is it different from BL, esp. SBL turbulence?
- Is troposphere different than stratosphere?
- What is the degree of anisotropy?
- What are the length scales; are they the same as in the BL?
- What is the relation between velocity and thermal turbulence (ε vs C_T^2)?

Sources – pilot's perspective

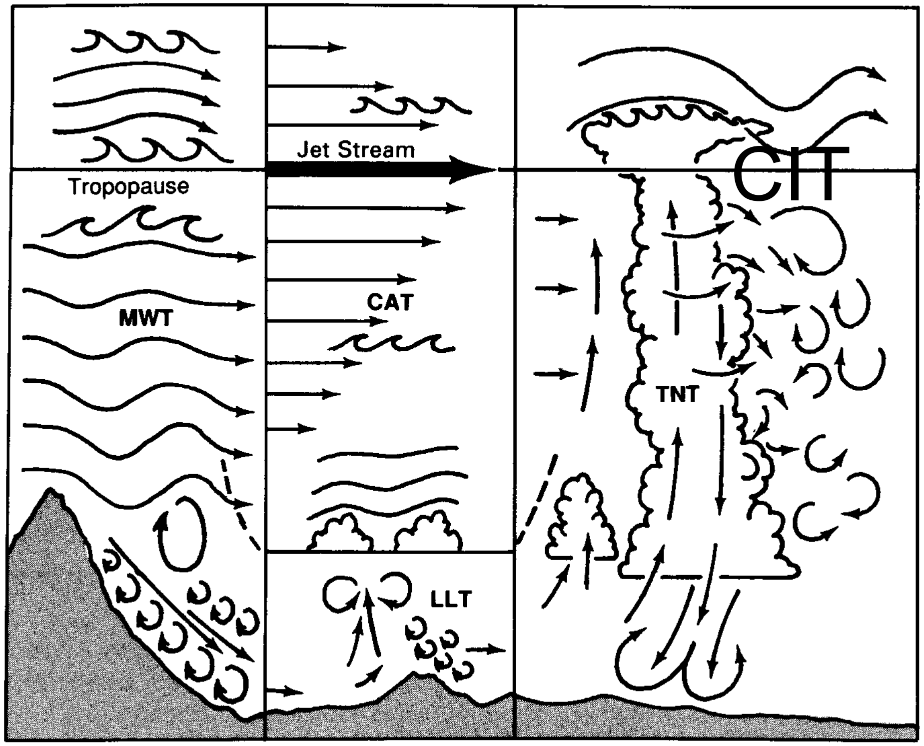


Figure 1-16. Aviation turbulence classifications. This figure is a pictorial summary of the turbulence-producing phenomena that may occur in each turbulence classification.

Source: P. Lester, "Turbulence – A new perspective for pilots," Jeppesen, 1994

Relation to upper-level fronts

RICHARD J. REED AND KENNETH R. HARDY

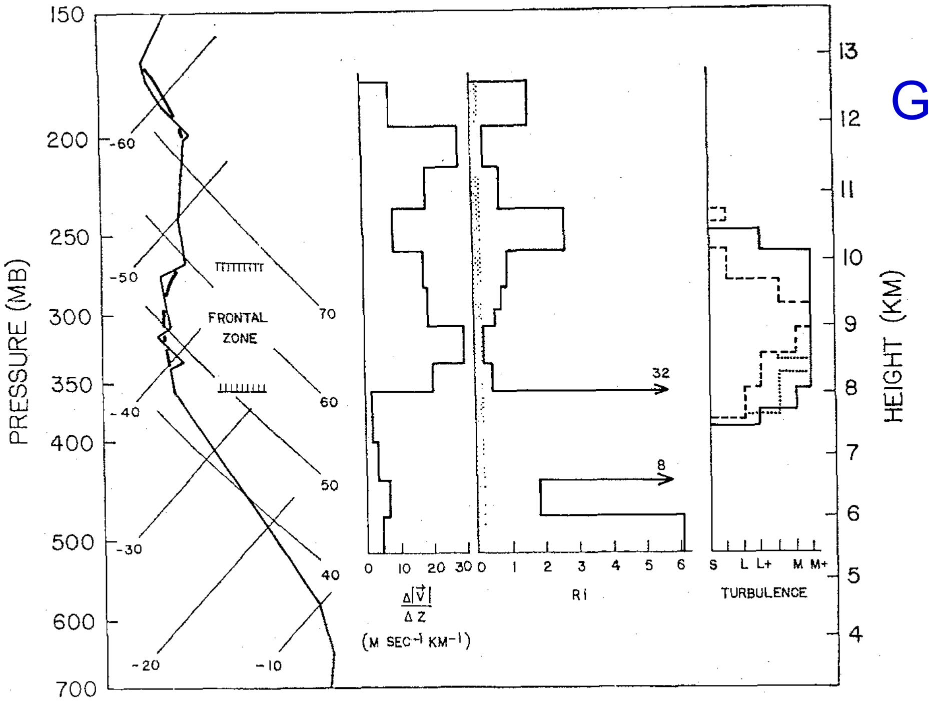
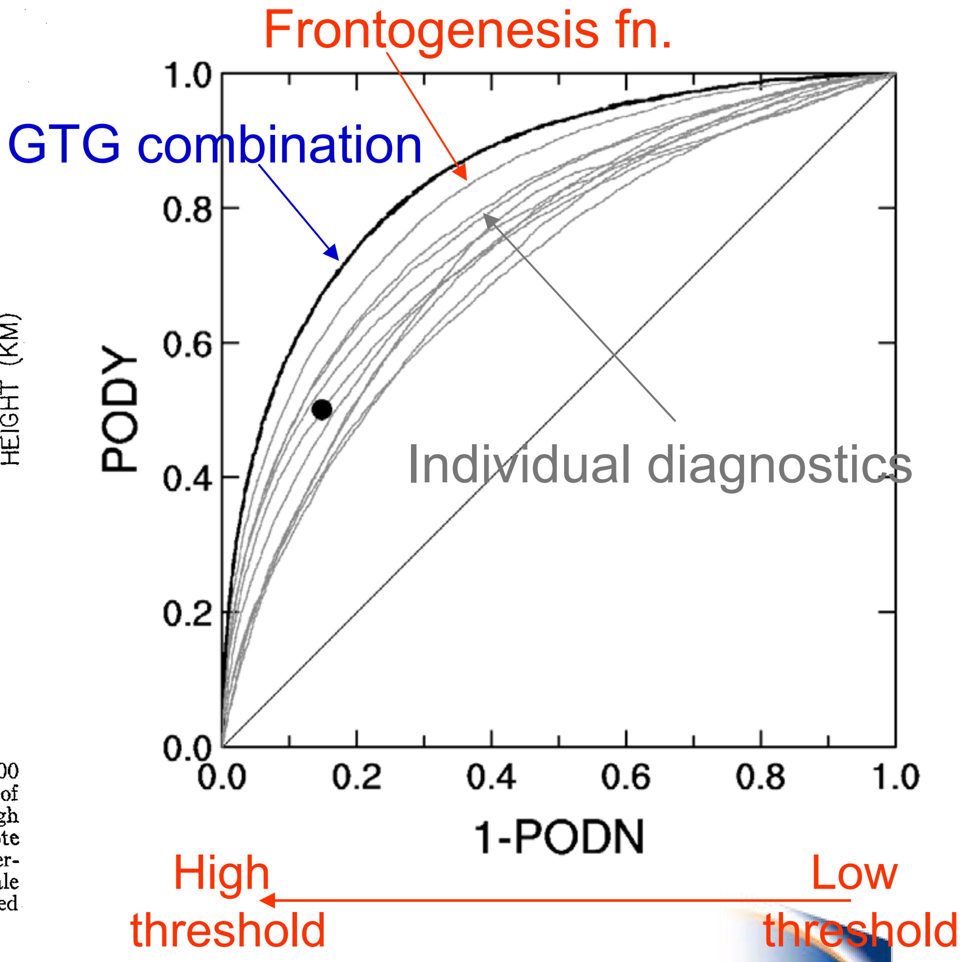


FIG. 8. Temperature, vector wind shear, and Richardson number (Ri) based on the 0000 GMT 18 March 1969 sounding at Wallops Island. Also plotted are the pilot's estimates of turbulence intensity for the NASA T-33 research aircraft during three traverses through the layer which were flown between 0230 and 0300 GMT. The letters S, L and M denote smooth, light and moderate turbulence, respectively, and the plus sign denotes an intermediate category. Note the coincidence of the turbulence with the low Ri and the small-scale temperature perturbations. Heavy segments of temperature sounding denote smoothed values used in computing Ri.

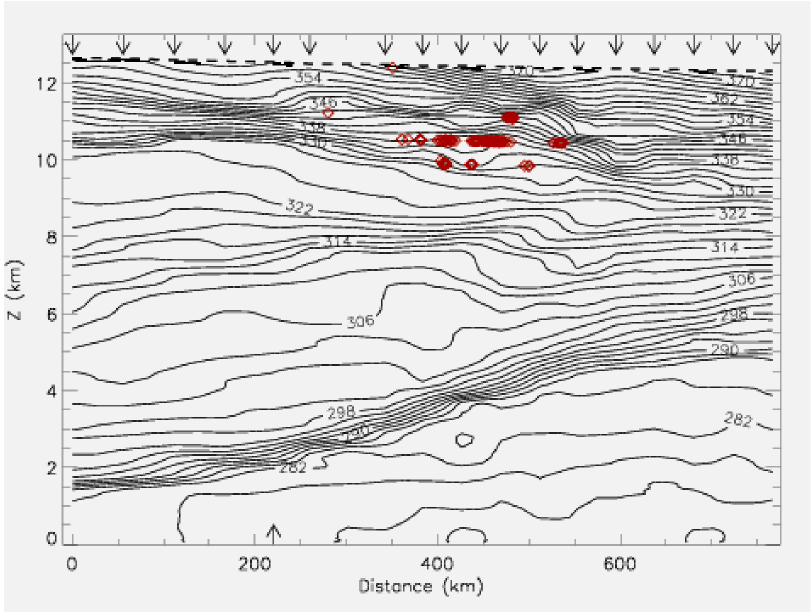
Reed and Hardy, JAM, 1972



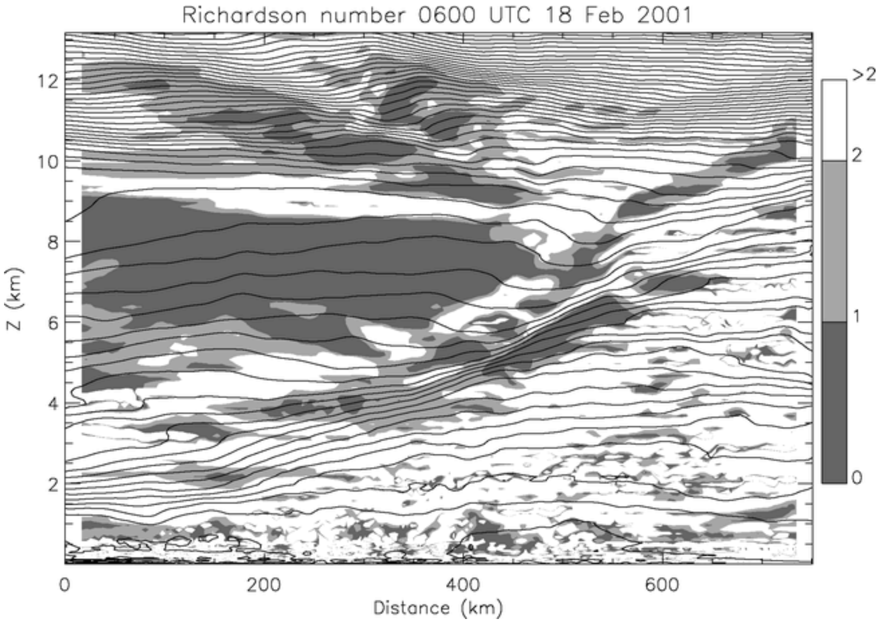
Wolff and Sharman, JAMC, 2008

Relation to inertia-gravity waves generated by upper-level fronts

- NOAA G-IV encountered patches of moderate turbulence over Pacific Ocean 17-18 Feb 2001 at ~10-11 km
- Observations and simulations showed this was related to breaking IGWs propagating through the strong shear above the jet, perturbing both the wind shear and stability – to reduce Ri <1



Observations – isentropes and dropsonde locations

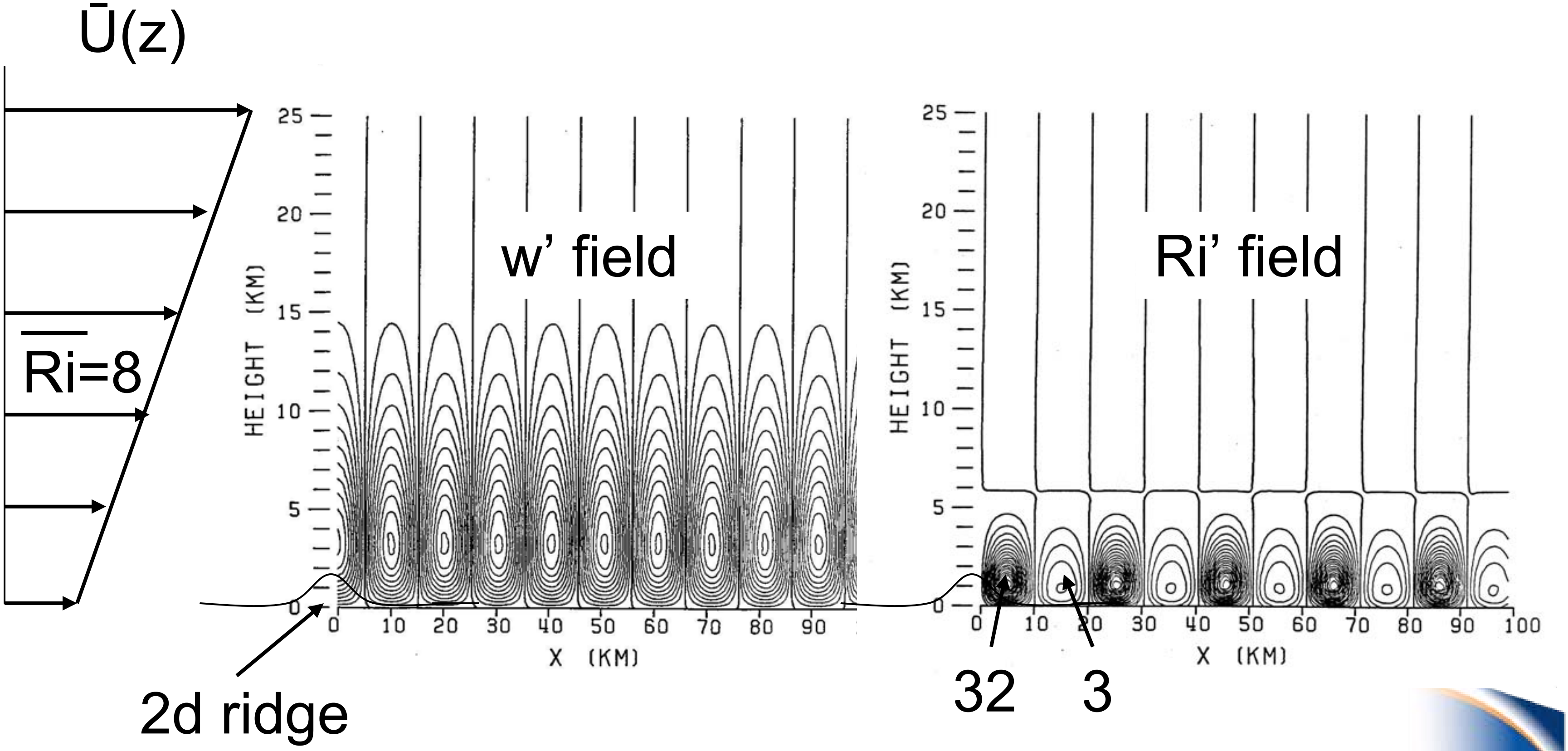


Simulation results COMAPS + C-H model Δx=3 km

From Lane et al. JAS 2004

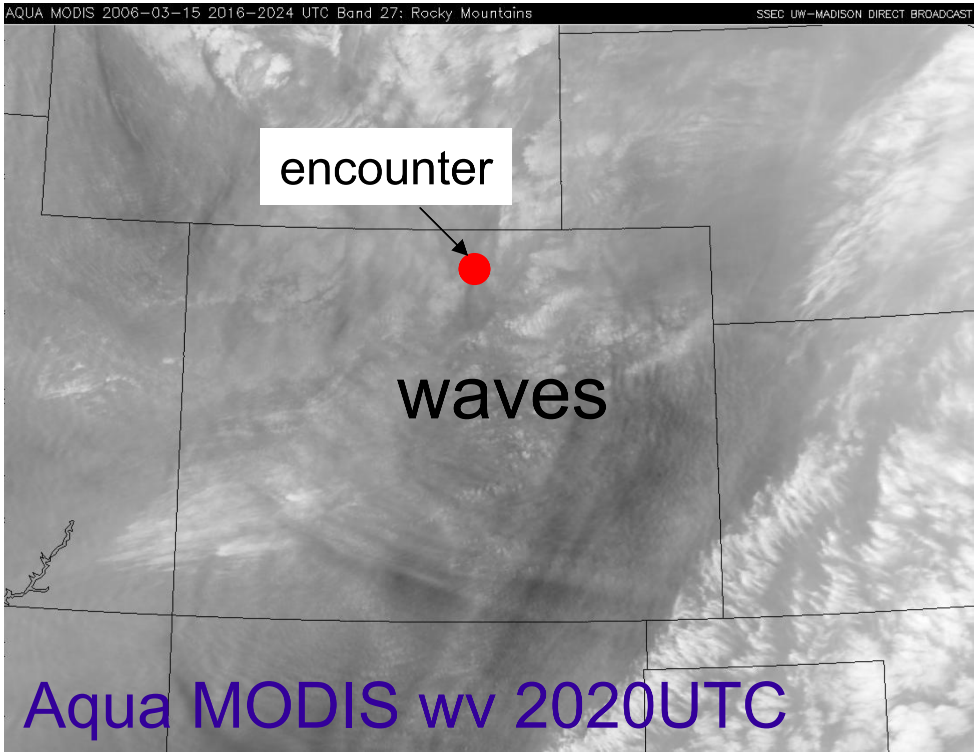
Gravity waves perturb background Ri

- Example: Trapped lee wave with linear shear, N=const., ($Ri=N^2/U_z^2$=const=8), Nh_0/U_0=.5

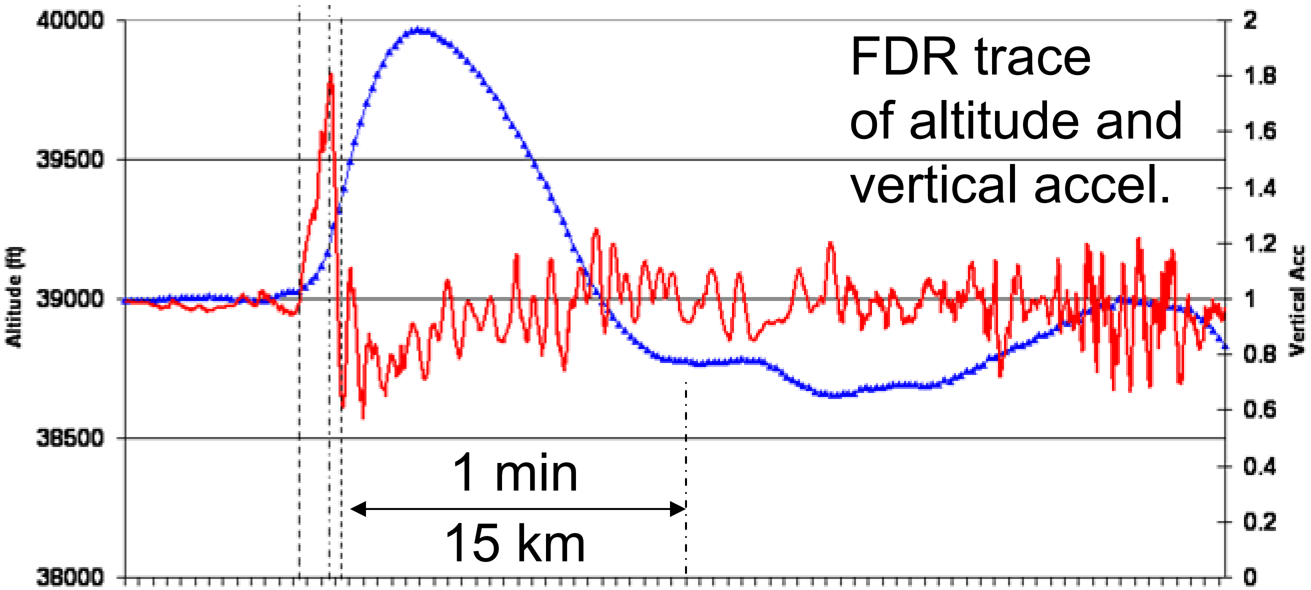


Relation to MWT

- Severe turbulence encounter 15 Mar 2006 lee of Rockies, N. Colorado, 22Z, 11.9 km, 1 injury, flight diverted



Aqua MODIS wv 2020UTC



FDR trace of altitude and vertical accel.

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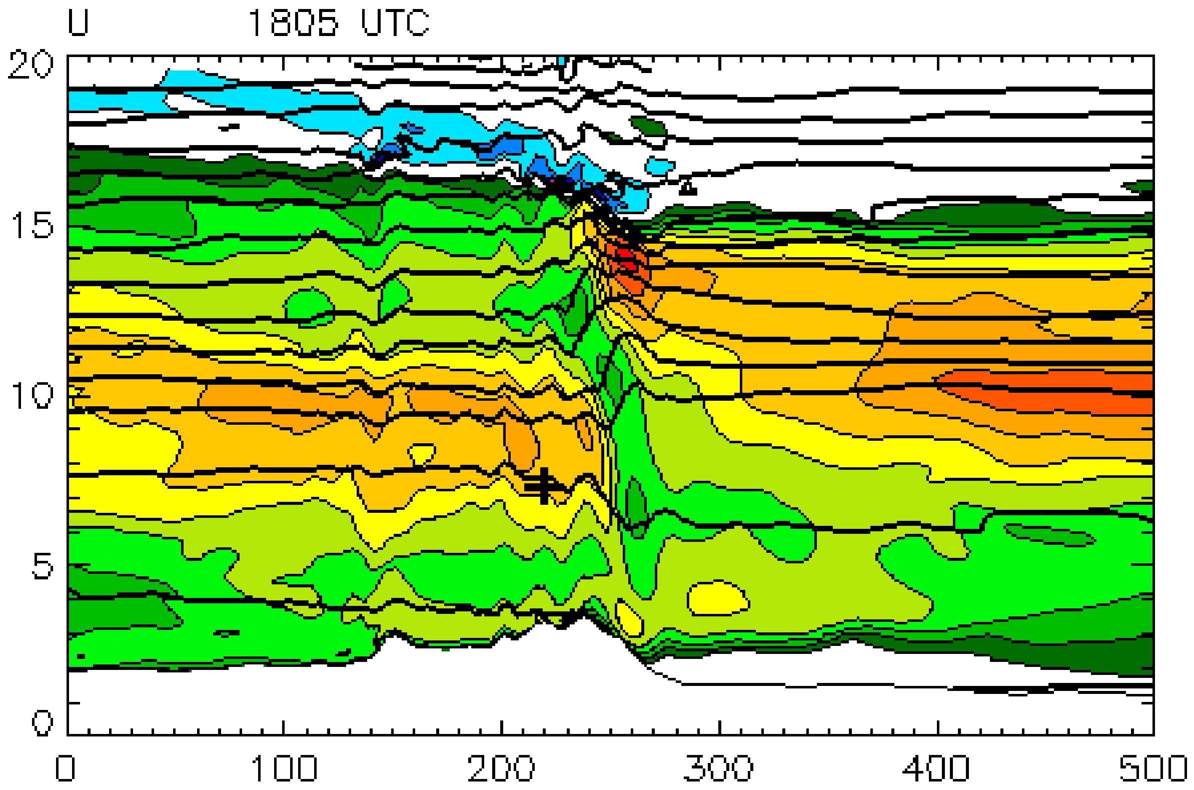
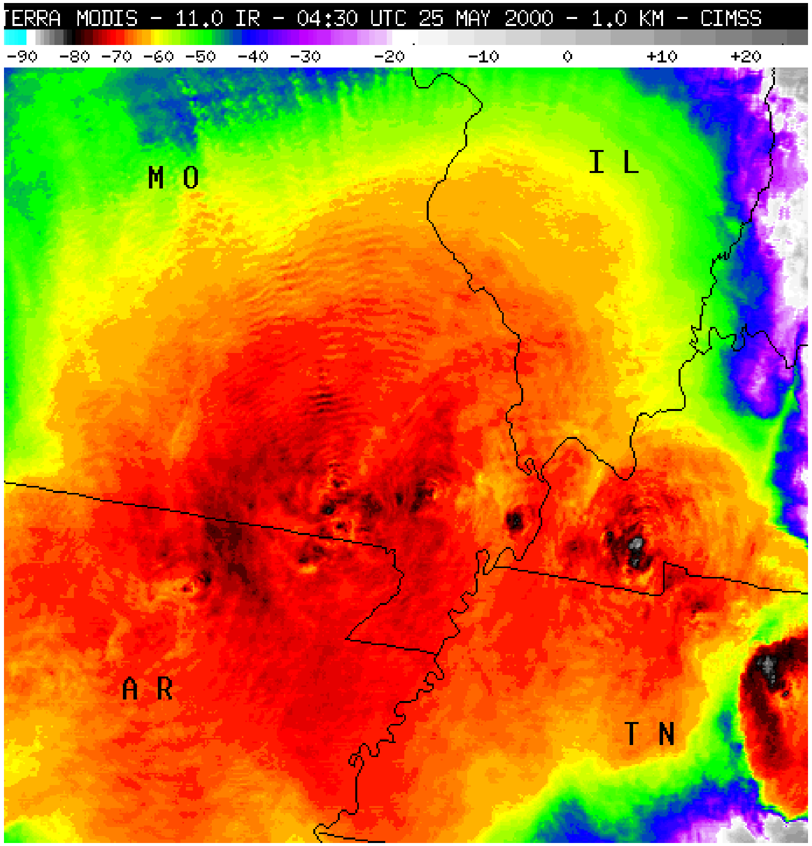
Simulation of event

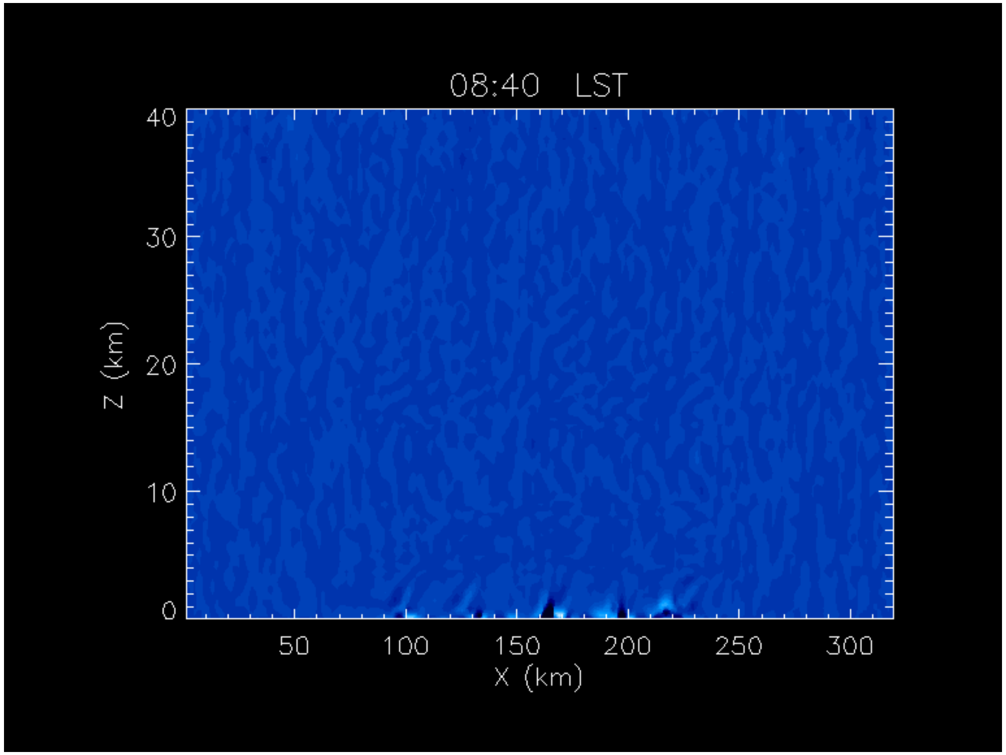
- Multi-nested Clark-Hall model, inner nest resolution 1 km
- Wave-induced critical level (U+u’=0)
- Not resolvable by NWP model



Another source: convectively-generated gravity waves



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



Simulation of convectively induced gravity waves above tropical convection. Courtesy Todd Lane U. Melbourne

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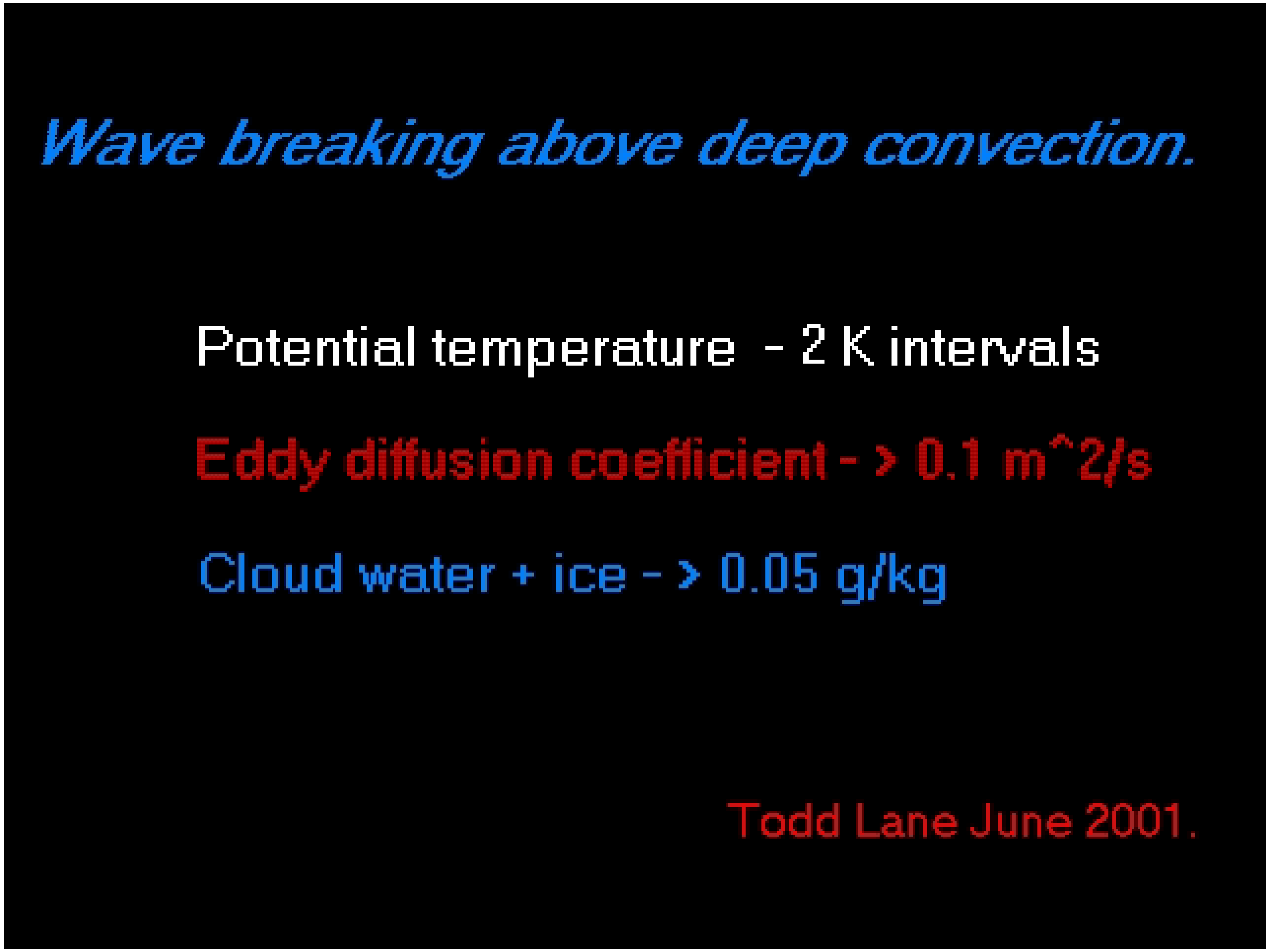
2D simulation* of wave propagation and breaking sequence (Lane et al. JAS 2003)



Wave breaking above deep convection.

Potential temperature - 2 K intervals

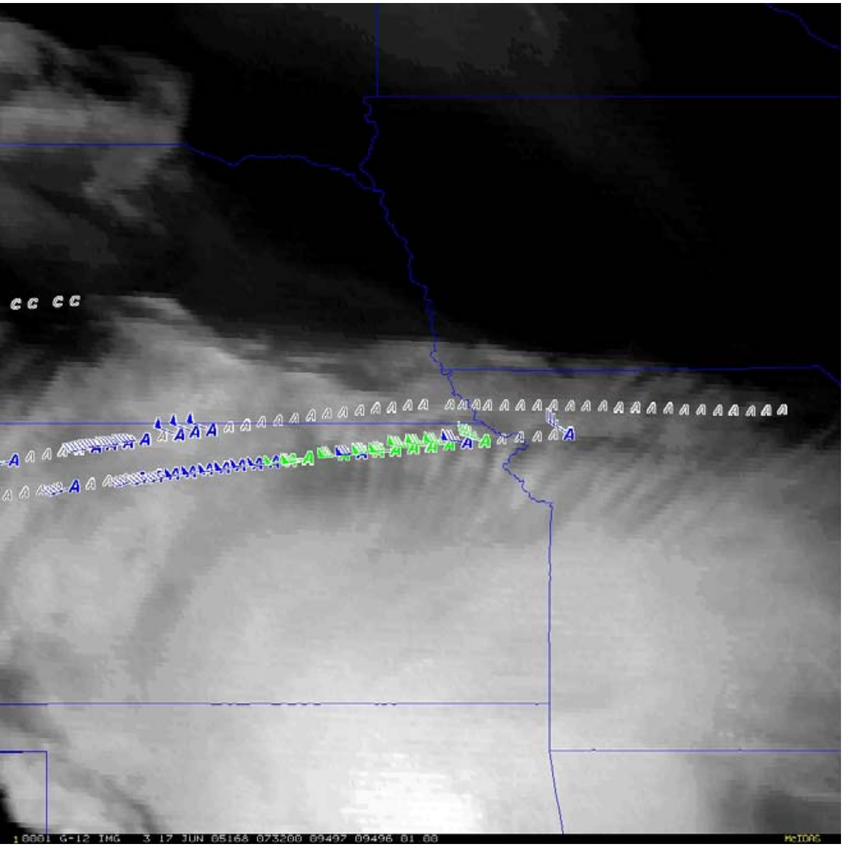
Eddy diffusion coefficient - > 0.1 m^2/s

Cloud water + ice - > 0.05 g/kg

Todd Lane June 2001.

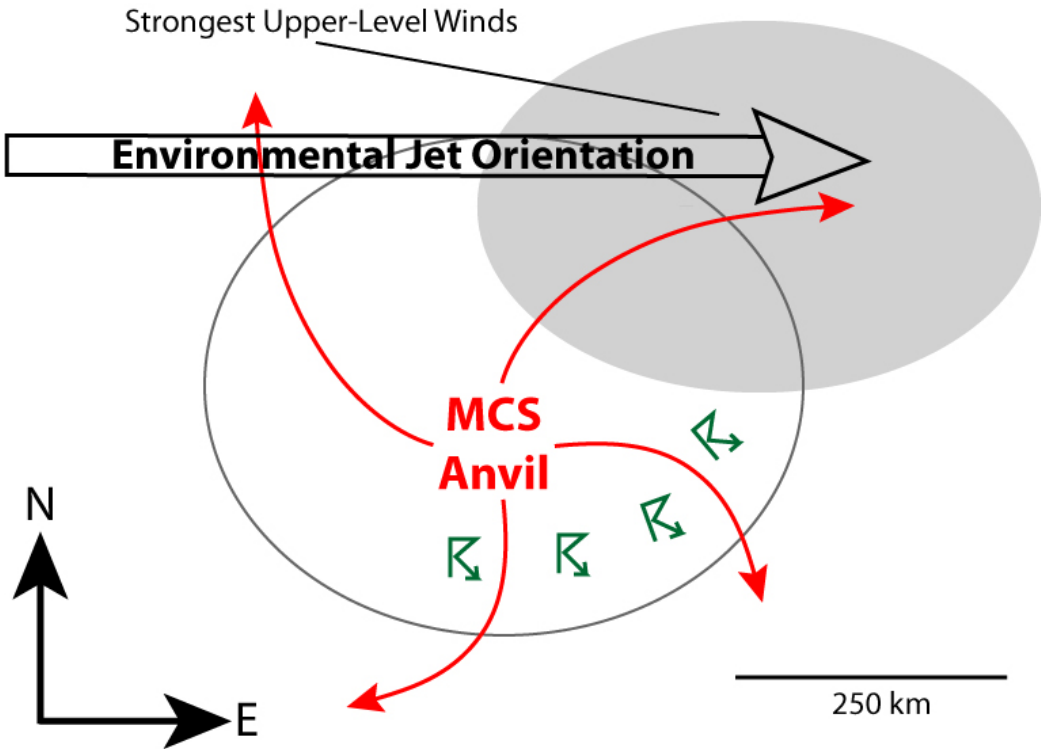
*Clark-Hall cloud model (Clark 1977,1979)

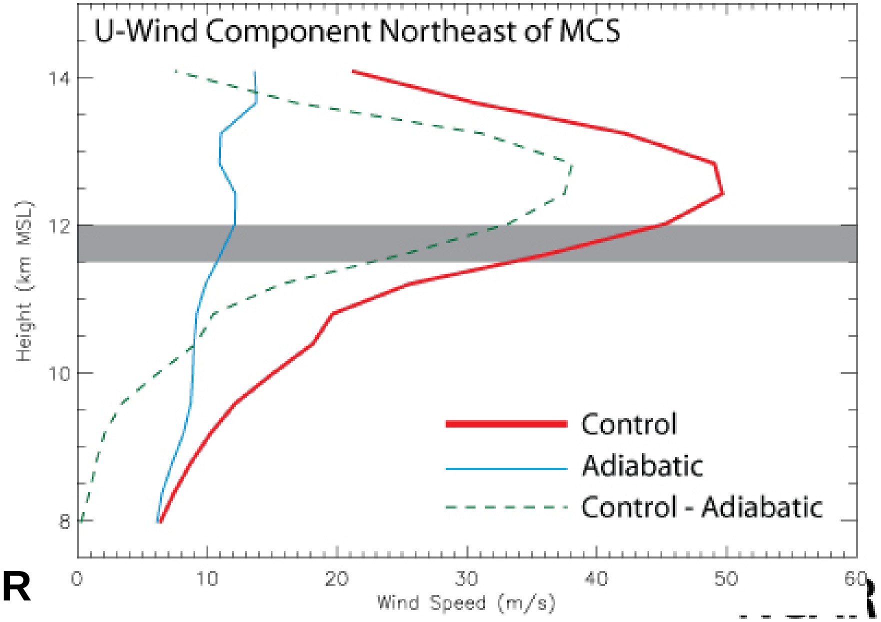
Relation to anvils



0730 UTC 17 June 2005 WV Imagery,
Flight Track Winds and Turbulence Reports

Green: Peak EDR = 0.25-0.45 (Moderate Turbulence)

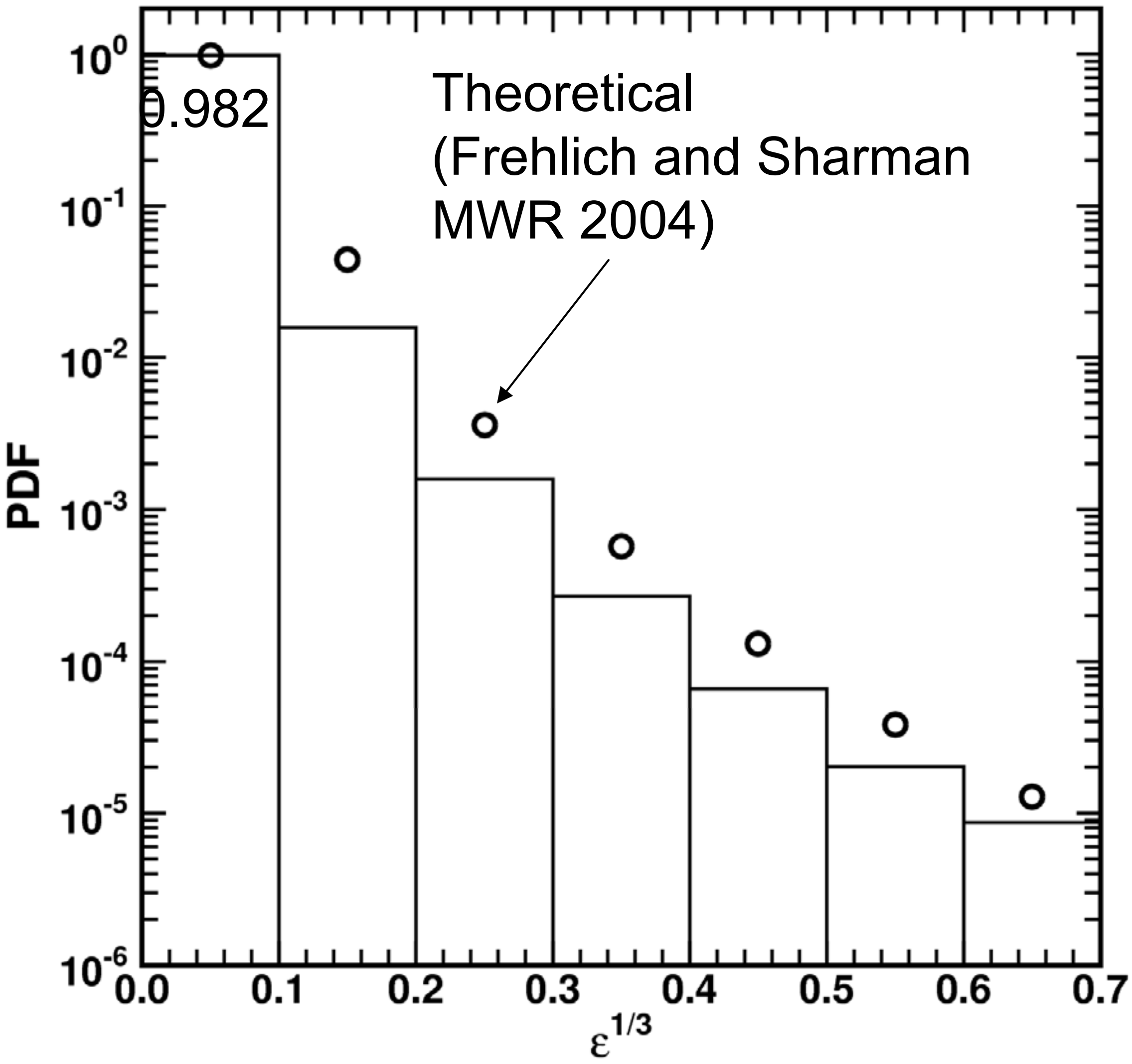




Courtesy Stan Trier, NCAR

UTLS turbulence climatologies – frequency

- Using ~ 16M UAL (~1 year) insitu peak edr measurements



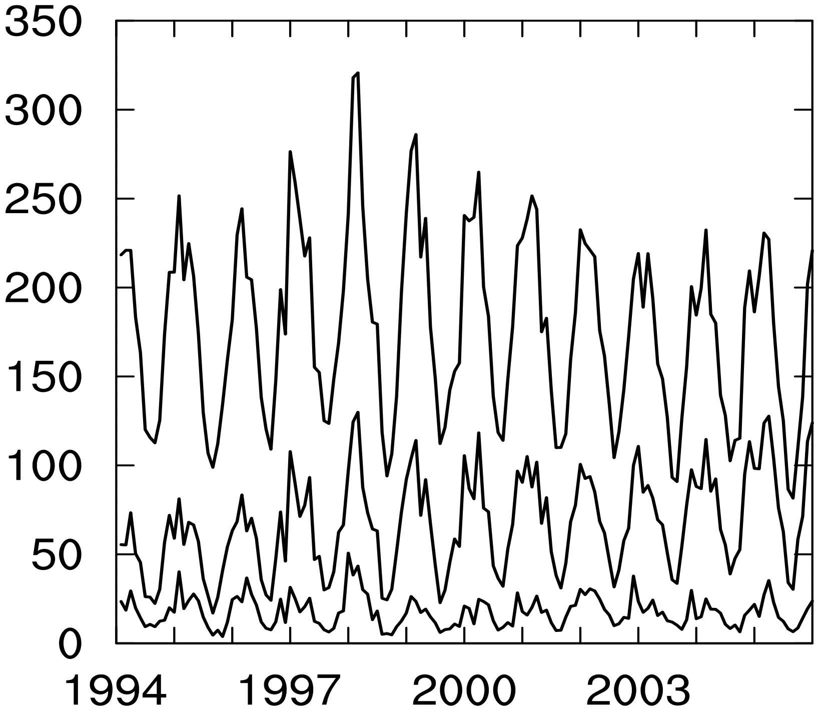
0.982

Theoretical (Frehlich and Sharman MWR 2004)

R

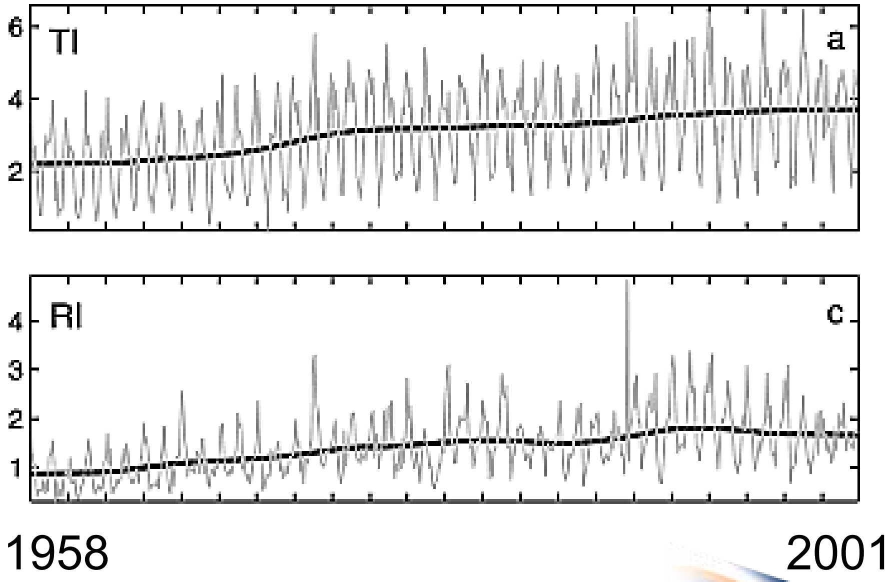
UTLS turbulence climatologies – marked seasonal dependence

- Using ~ 1M turbulence PIREPs from 1994-2007 over CONUS



Wolff and Sharman, JAMC, 2008

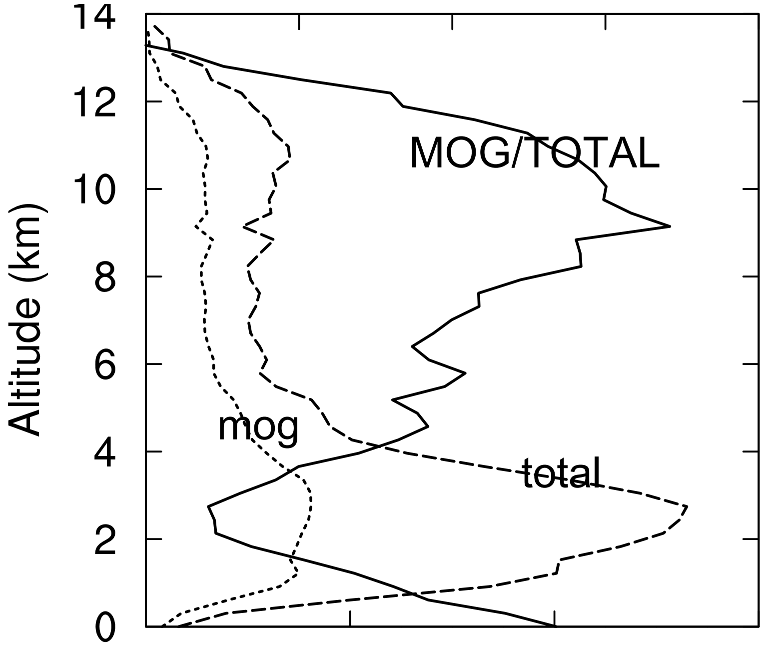
- Using ERA40 reanalysis from 1958-2001 globally



Jaeger and Sprengler, JGR, 2007

UTLS turbulence climatologies – vertical distribution

PIREP counts over CONUS



ε inferred from MU radar spectral width over Japan (35N)

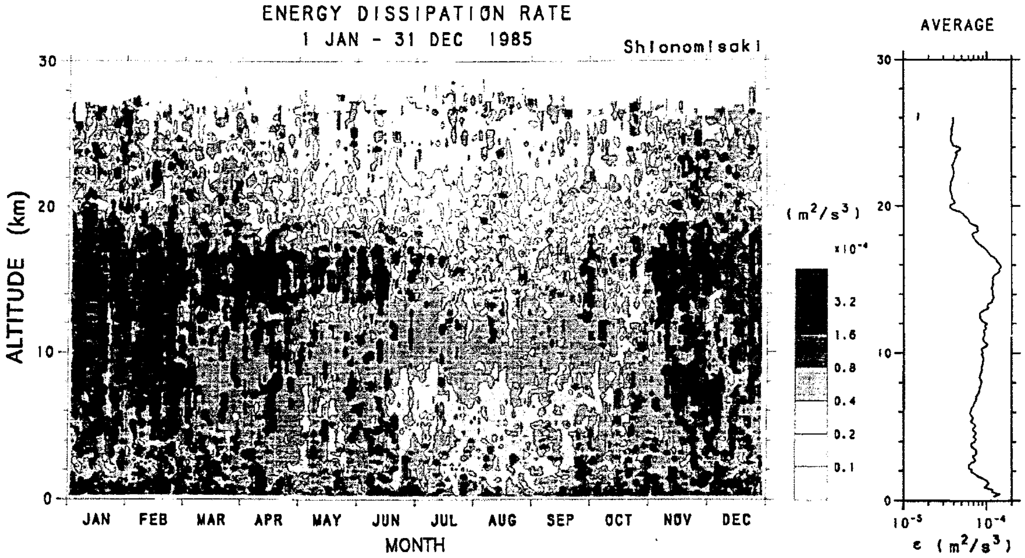


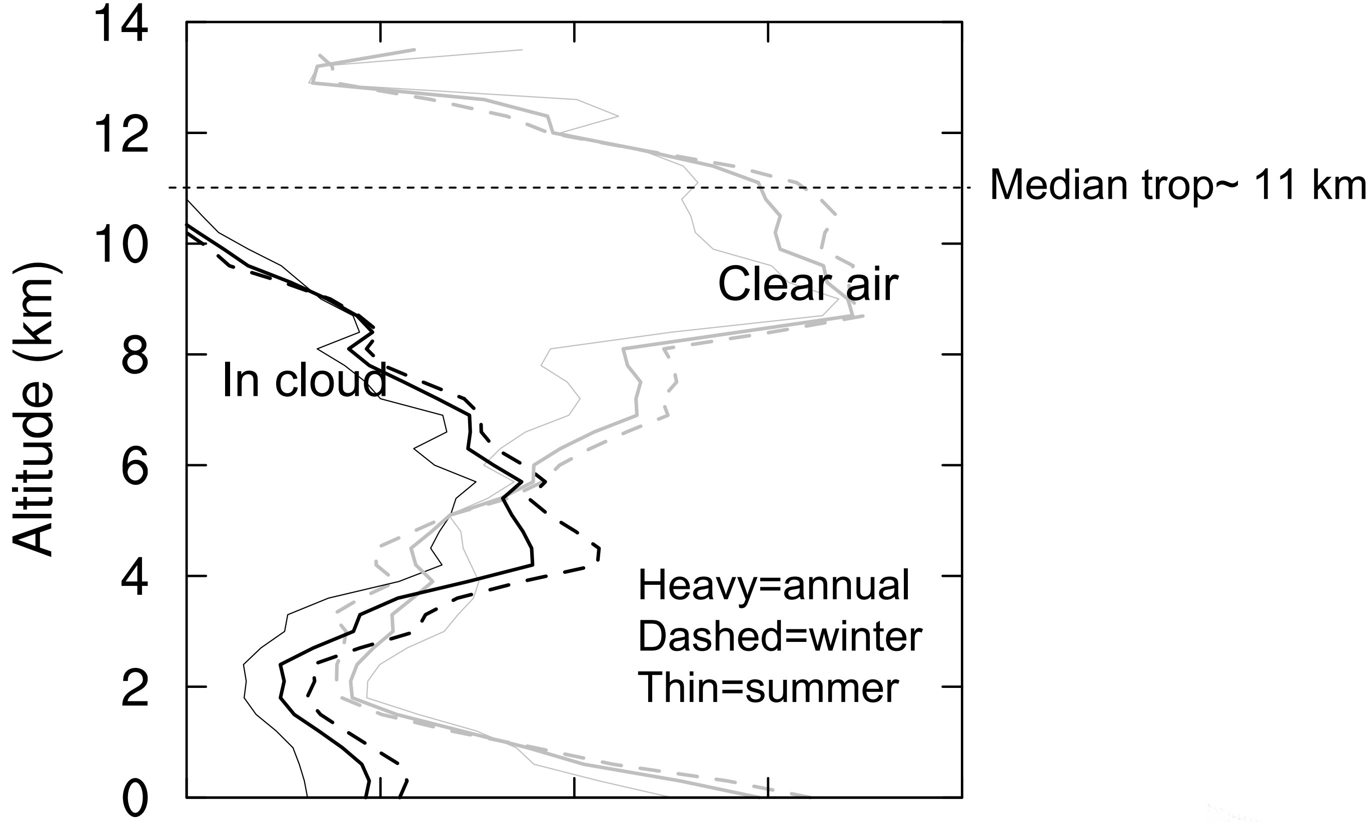
Figure 6. Seasonal-vertical variations of the mean kinetic energy dissipation rate ε calculated from routine meteorological observations (twice a day) at the Shionomisaki Weather Station of the Japan Meteorological Agency.

Wolff and Sharman, JAMC, 2008

Fukao et al., JGR, 1994

UTLS turbulence climatologies - relation to clouds

PIREP counts over CONUS



Wolff and Sharman, JAMC, 2008

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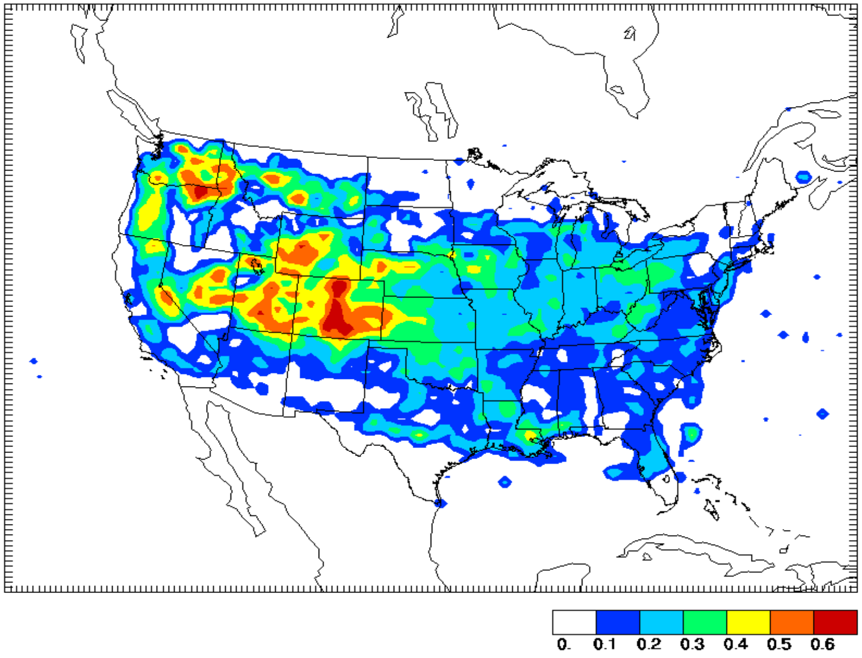
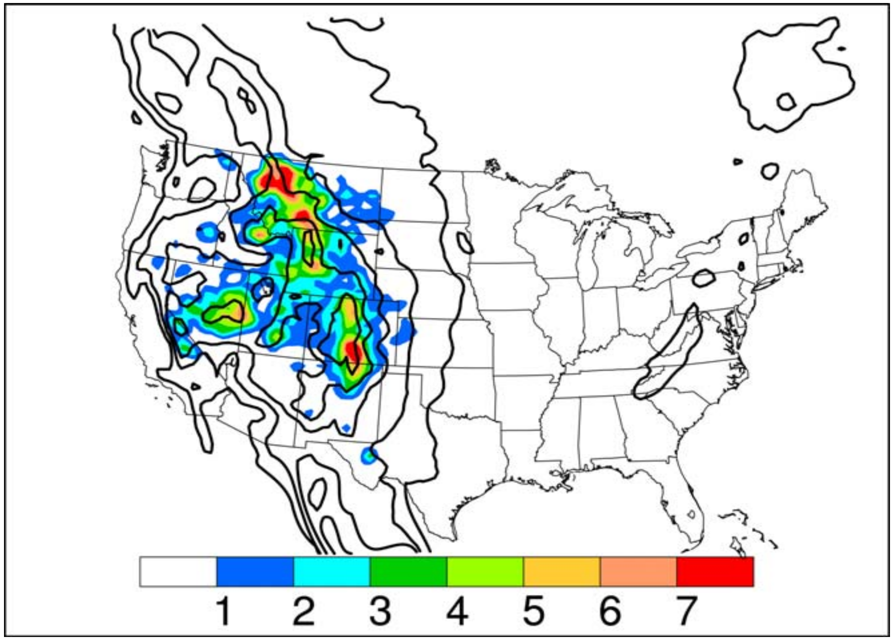
UTLS turbulence climatologies – relation to MWT



MOG/Total PIREPs > 20,000 ft
1994 – 2005



% MWT MOG/Total PIREPs > 20,000 ft
1994 – 2005

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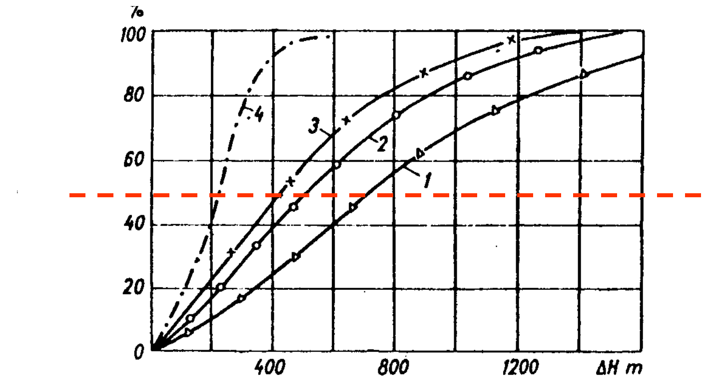
UTLS turbulence climatologies – dimensions of CAT zones

Based on limited observations

- **Shaped like "pancakes" or "blini"**
  - **Δh : 1/2 < 500m**
  - **L: 1/2 < 50 km**
- **Δt: 1/2 > 6 hrs, sometimes longer than a day**
- **within a patch, turbulence can be continuous or "discrete"**
- **continuous patches more likely to have strong bursts**



ıre 9.5. Integral frequency of thickness ΔH of turbulent zones in upper tropospher
3) and stratosphere (4). (1) Southern latitudes; (2, 4) temperate latitudes; (3) north

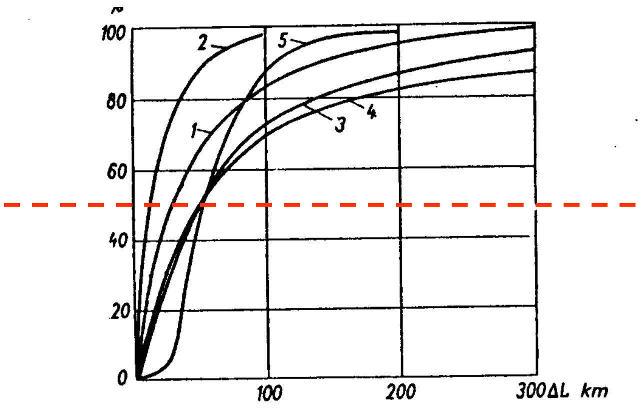
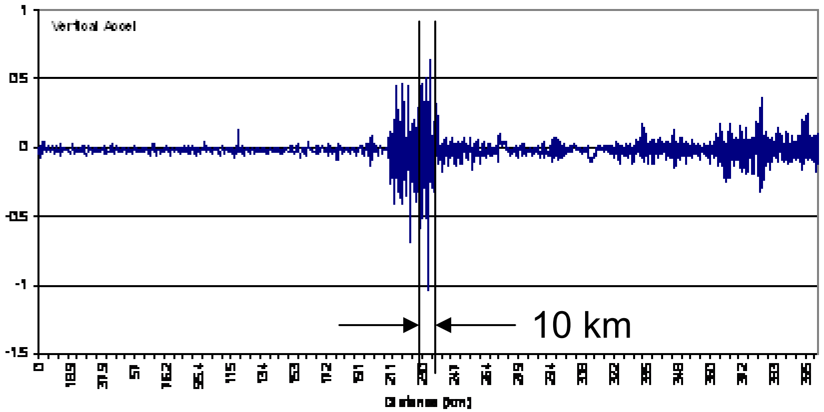


Figure 9.6. Integral frequency of horizontal dimensions ΔL of turbulent zones. (1) U.S
(upper troposphere); (2) U.S.A. (stratosphere); (3) USSR (upper troposphere, temperat
latitudes); (4) USSR (upper troposphere, southern latitudes); (5) USSR (stratosphere,
temperate latitudes)



From Vinnichenko, et al. "Turbulence in the Free Atmosphere"

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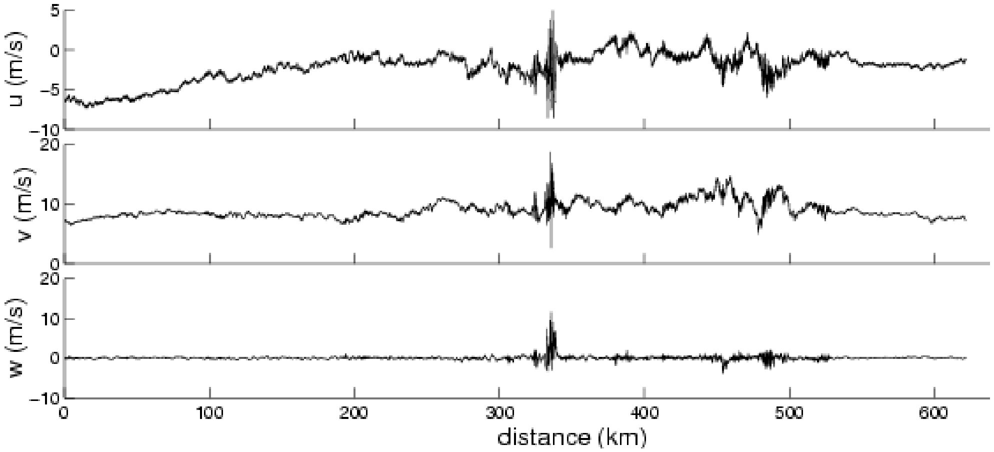
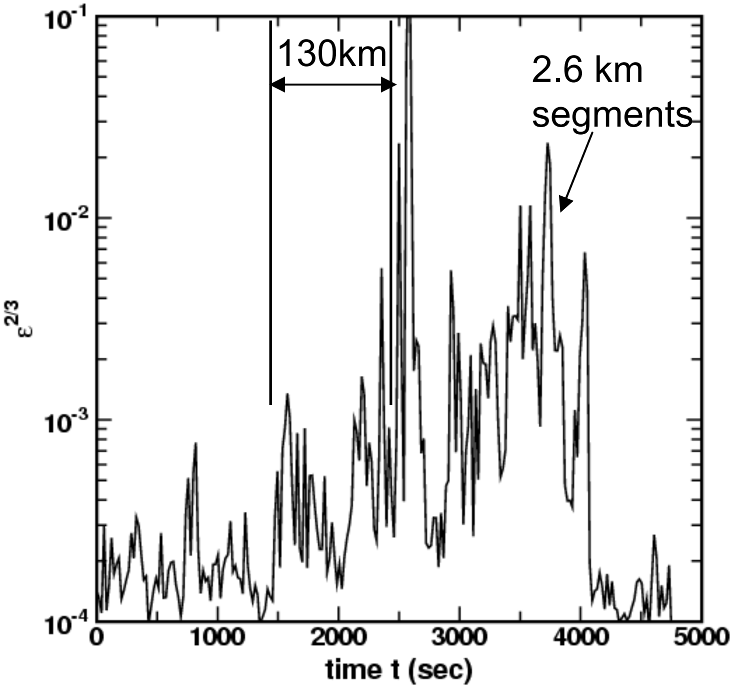
UTLS observations - intermittency

- Comparison to aircraft measured edrs show substantial edr variability





INDOEX NCAR C-130 4.8 km

Observed atmospheric spectra – GASP and MOZAIC data

- $k^{-5/3}$ behavior from ~3-4 km to ~400 km in mid to upper troposphere and lower stratosphere

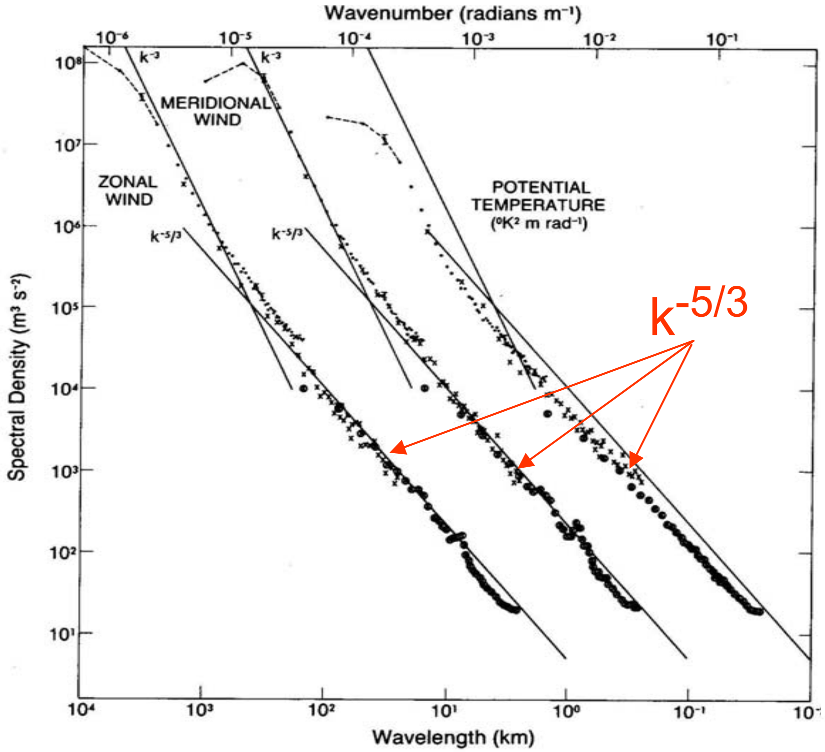
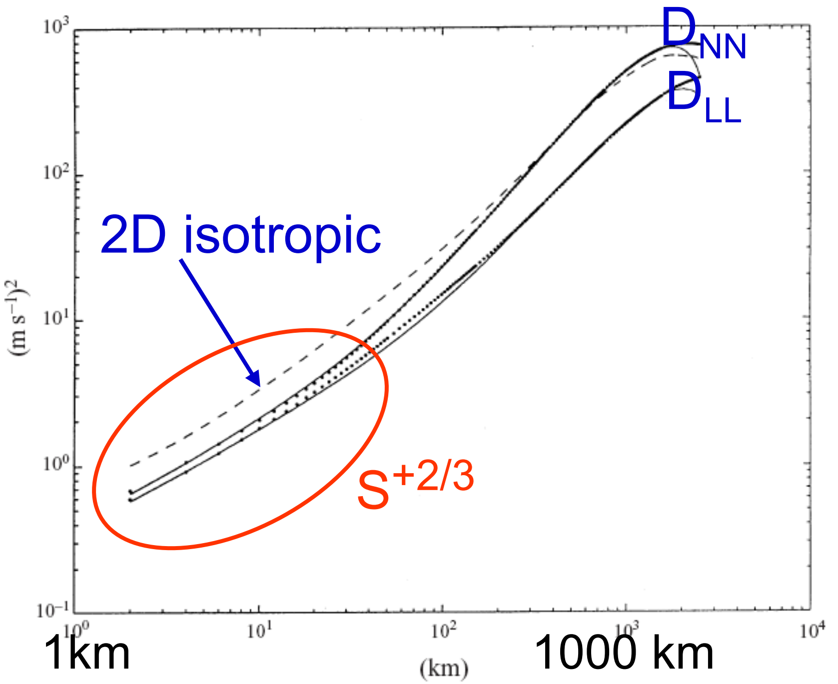


FIG. 3. Variance power spectra of wind and potential temperature near the tropopause from GASP aircraft data. The spectra for meridional wind and temperature are shifted one and two decades to the right, respectively; lines with slopes −3 and −5/3 are entered at the same relative coordinates for each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

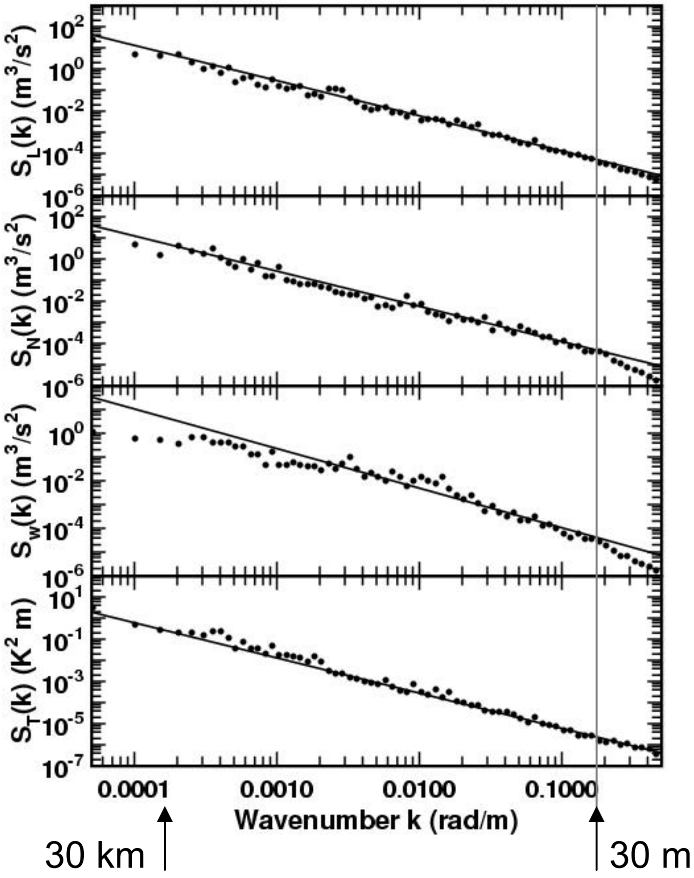


MOZAIC from Lindborg, JFM 1999

GASP from Nastrom et al., Nature 1984

Observed atmospheric spectra – research aircraft data

- Almost every flight examined shows
  - $k^{-5/3}$ behavior from 10s m to ~10s km in mid to upper troposphere and lower stratosphere
  - No rollover except perhaps for w (i.e. not von Karman-like)



spectra from INDOEX campaign NCAR C130
from Frehlich, QJRMS, 2006

UTLS turbulence climatology summary

- Occurrence of elevated turbulence very rare based on PIREPs, in situ data
  - But since based on encounters and pilots try to avoid this is probably biased low
  - Background <ε> ~ 7-8 x 10^{-5} from Lindborg model (Frehlich, JTEC 2001)
- Highly intermittent
- Marked seasonal dependence
- Mostly in clear air above about 6 km
  - Usually stably-stratified with shear
  - Some correlation with breaking gravity waves or IGWs
    - Wave perturbations drive already low background Ri to unstable values
    - Gravity wave-critical level interactions
  - Patchy, “pancake” structure: similar to observations of SBL
- Background spatial statistics show robust $k^{-5/3}$ or $s^{+2/3}$ behavior from 10s m to ~400-500 km
- No outer scale!!

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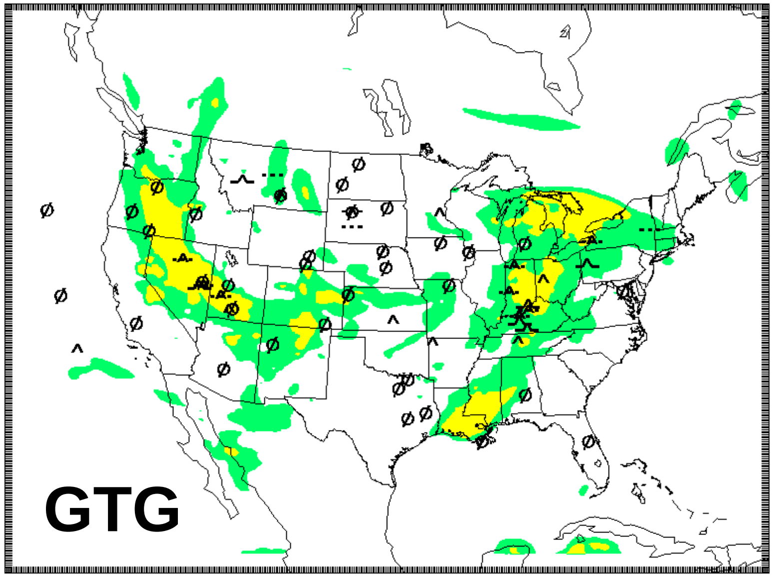
Nowcasts/forecasts of aircraft scale turbulence

Approach

- Use (relatively) large scale NWP model output (~10 km horizontal resolution) to predict likelihood of aircraft scale turbulence
- Since NWP model scales >> aircraft scales must understand linkage of large scales (model resolved) to small scales (unresolved)
  - Assume energy sources are associated with large scale (resolved) features:
    - Jet streams
    - Upper-level fronts
    - Tropopause
    - Strongly ageostrophic flows
  - Assume downscale cascade to aircraft scales



Example prediction based on 13 km RUC

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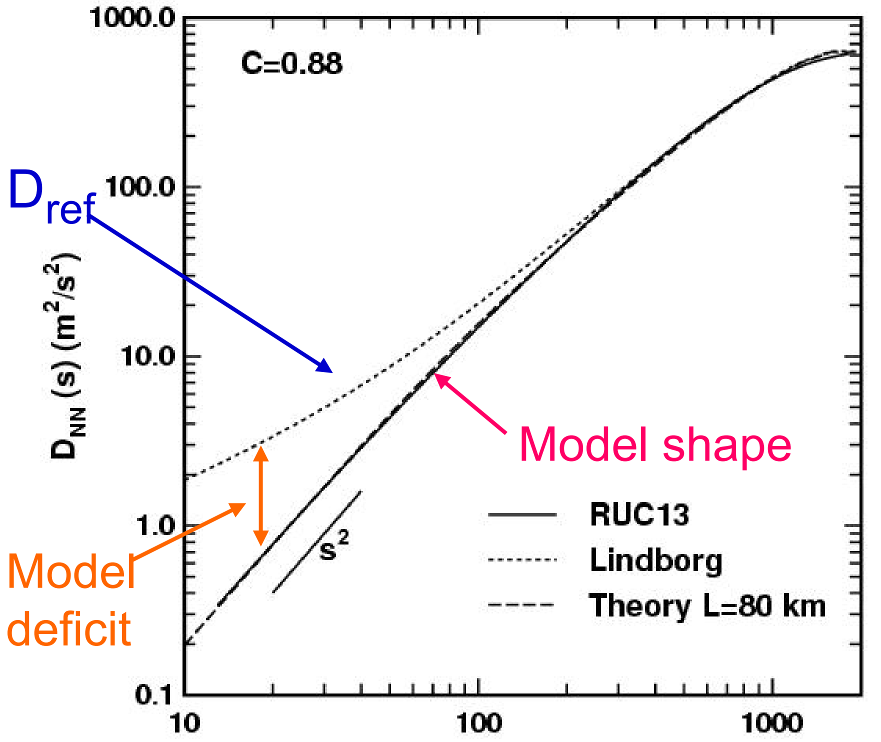
Development of edr diagnostic

- Eddy dissipation rate (Frehlich and Sharman, MWR, 2004)
  - Assumes UTLS turbulence follows GASP/Lindborg scaling
  - Derive edr from 2nd order structure function computed from NWP <u>resolved</u> model output fields
  - Account for NWP model specific smoothing and filtering



$$D_q(s) = <\left[q(x) - q(x+s)\right]^2> = C_K \varepsilon^{2/3} D_{cor}(s) D_{ref}(s)$$

$$D_{ref}(s) = s^{2/3} + \frac{b_1}{a_1} s^2 - \frac{c_1}{a_1} \ln s \quad \text{(derived from GASP data)}$$

$$\varepsilon^{2/3} = \frac{D_q(s)}{C_K D_{cor}(s) D_{ref}(s)} \quad \text{averaged over several lags } s$$

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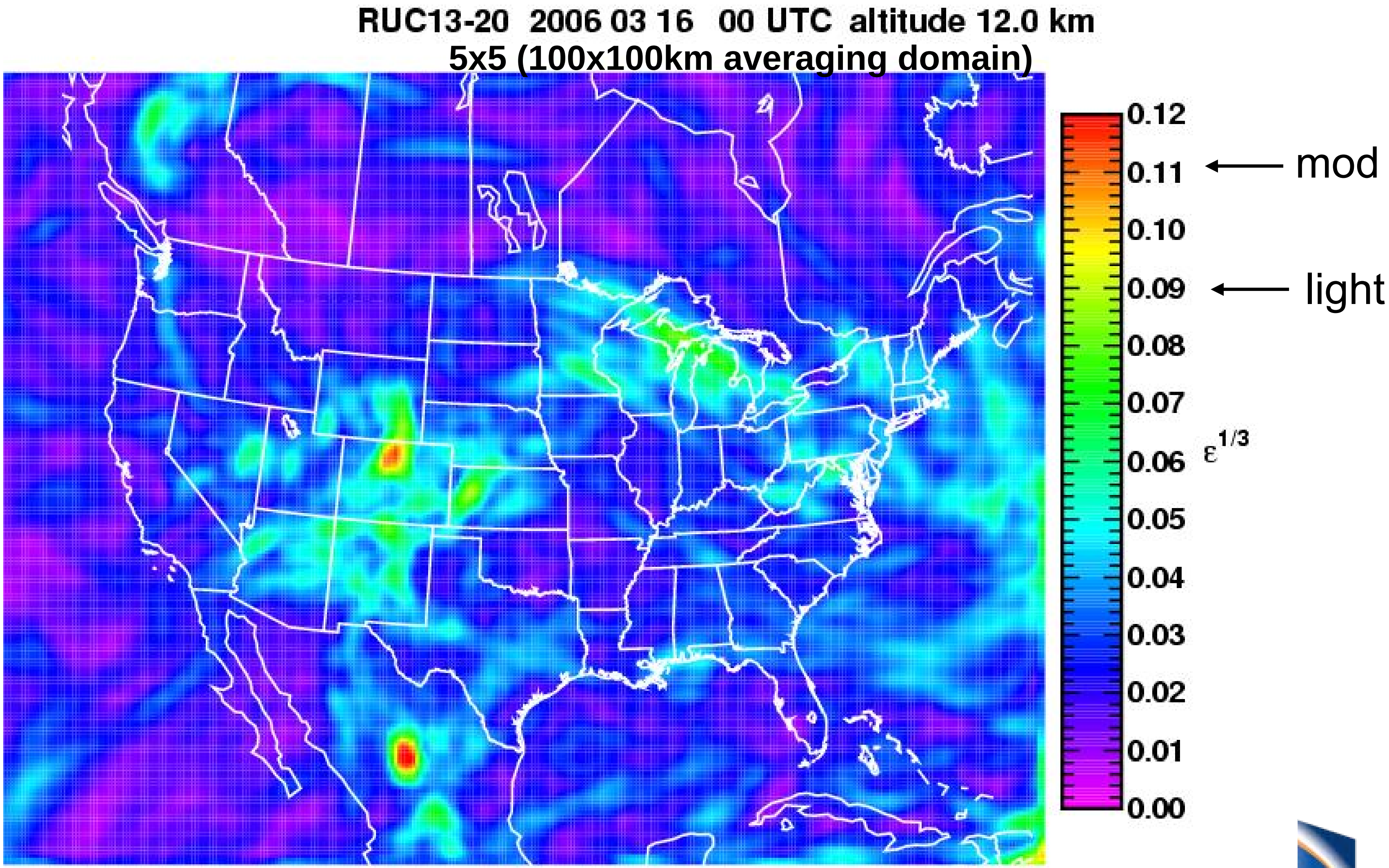
Edr calibration: comparison to pireps



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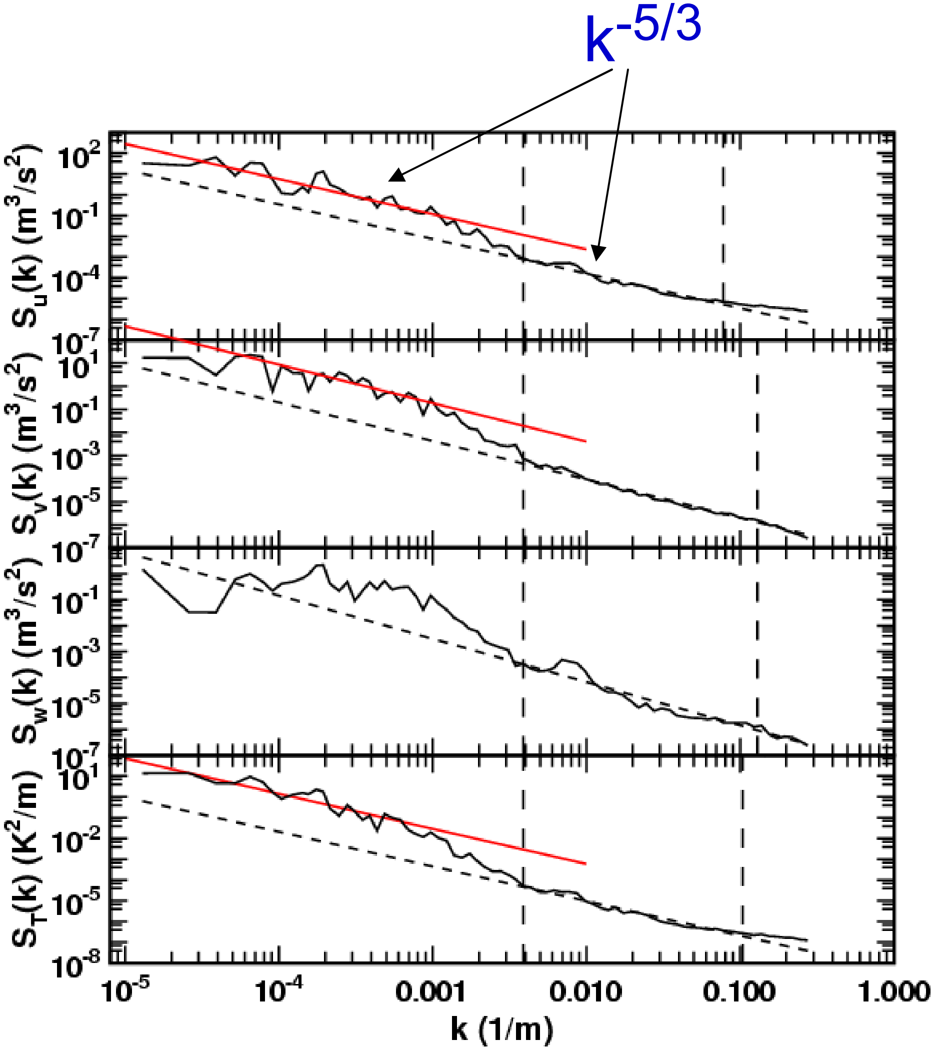
Spectra over mountains

- Examined spectra from HIAPER TREX ferry legs over Colorado Rockies
- Two regions:
  - (1) Classical inertial range turbulence 60m-2 km ($k^{-5/3}$)
  - (2) Gravity wave enhancement > 2 km (also $k^{-5/3}$)
- Observed in 22/24 ferry flights
- Also observed in
  - – original GASP data (Jasperson et al., JAS 1990)
  - – Enhanced east-west edr levels from RUC and other NWP models



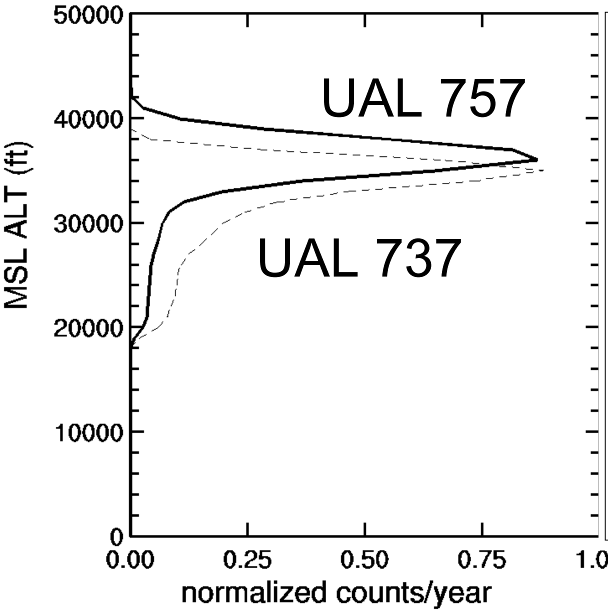
Flight 3 3/10/2006

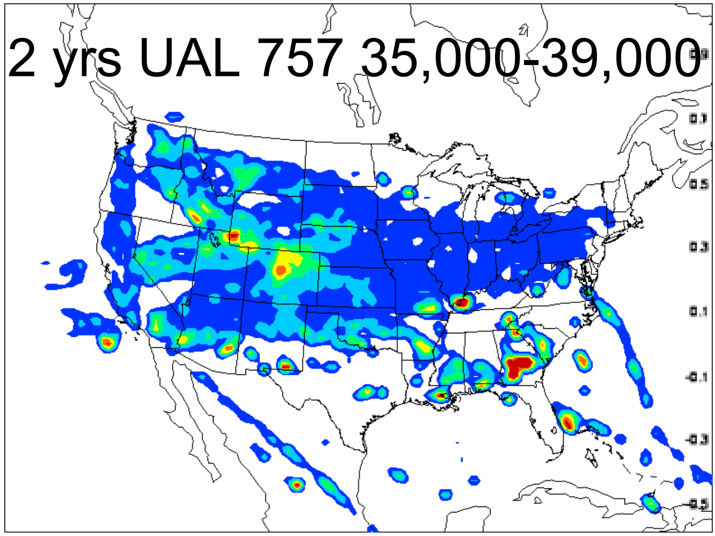
Implications

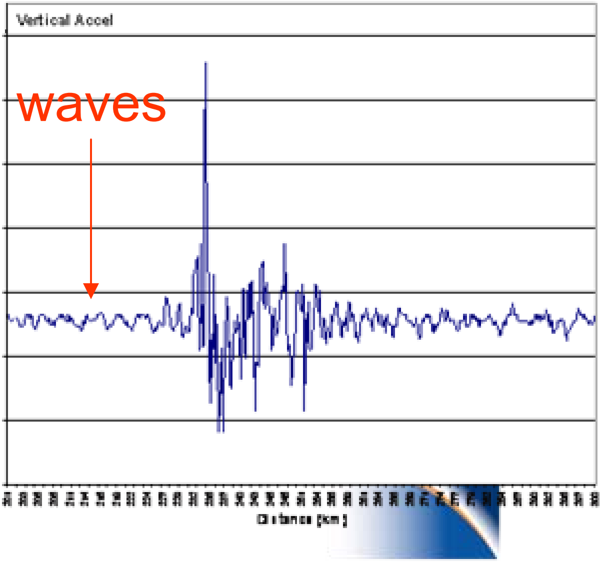
- Suggests $k^{-5/3}$ or $s^{+2/3}$ behavior is due to a superposition of gravity waves and a downscale cascade resembling 3D isotropic turbulence
  - Consistent with speculations of Dewan (1979,1997), VanZandt (1982), others
  - Successful in oceans (Garret-Munk spectrum)
  - i.e., a history of gravity waves produces $k^{-5/3}$ spectra
  - But does not identify the specific cascade mechanism
- Then:
  - The problem of forecasting turbulence is really one of forecasting gravity waves and gravity wave “breaking”
  - Higher resolution NWP models (~10 km or less) start to resolve part of the spectra
  - Models such as the edr diagnostic account for the downscale cascade (and also model smoothing effects) and have been particularly successful in predicting turbulence over mountains terrain

Future – *in situ* measurements

- Need to include other types of aircraft/airlines to get more coverage vertically and horizontally
- Need other simultaneous measurements to help identify source
  - Humidity or liquid water content
  - Waves?







Future –dedicated field program?

- Nothing since late 1970's
- Ideally should involve an aircraft (perhaps a UAV?) with high-rate measurements and a forward-looking scanning Doppler lidar + radiometer to get Ri in the vicinity of the aircraft – allows intercomparisons of ε
  - Need to establish accuracy requirements for stability and shear
- Upward-looking radar would also be useful to test ε – C_N^2 relations
  - Tradeoff studies of range, resolution
- Upward-looking lidar probably has inadequate range
- Use GTG forecasts and ground-based radar to identify conducive areas/times