Influences of Thunderstorms on Aviation Turbulence

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CoCoRaHS WxTalk Webinar
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Outline

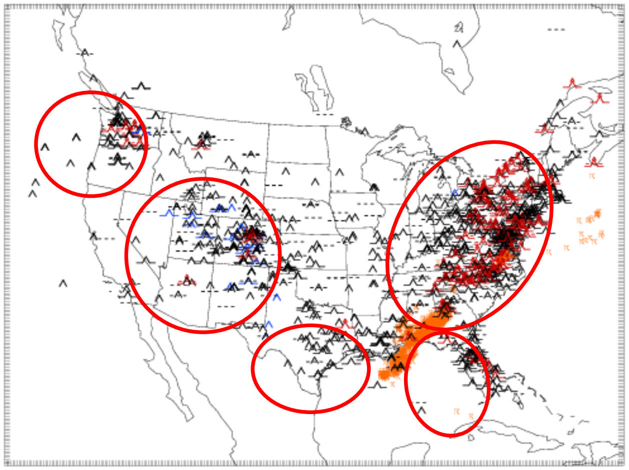
Objective: Explore different mechanisms for turbulence from research simulations

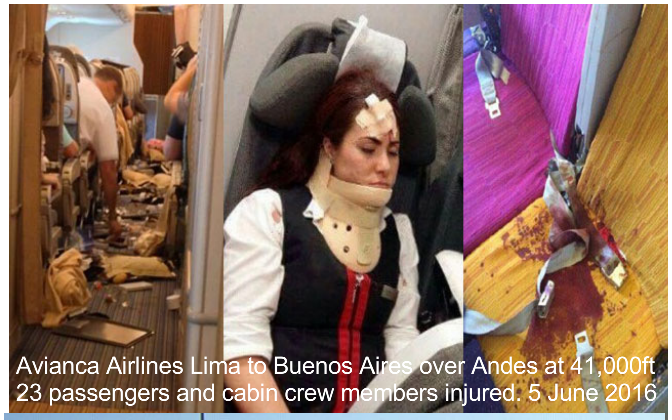
- common aspect is thunderstorms (near or far away) can strongly influence turbulence

1. Background (Effects of turbulence on airlines, turbulence reporting/measurements)
2. Thunderstorm-generated turbulence (emphasis on turbulence outside of clouds)
   - wave breaking above thunderstorms
   - waves moving horizontally away from thunderstorm regions
   - increased vertical wind shear in thunderstorm outflows near jet stream
3. Prediction of thunderstorm-related turbulence
   - research simulations (high-resolution, can capture processes leading to turbulence onset)
   - operational forecasting methods (lower-resolution, more statistically based)

Part 1. Background: Motivation for Aviation Turbulence Studies

- Turbulence has economic cost of ~ $200M/yr
- Accounts for 75% of air carrier accidents
- 10% of air carrier turbulence related accidents resulted in damage to the aircraft
- Causes aircraft fatigue and shorter airframe life
- Contributes to public perception that air travel is unsafe
- Second leading weather factor affecting air traffic controller workload



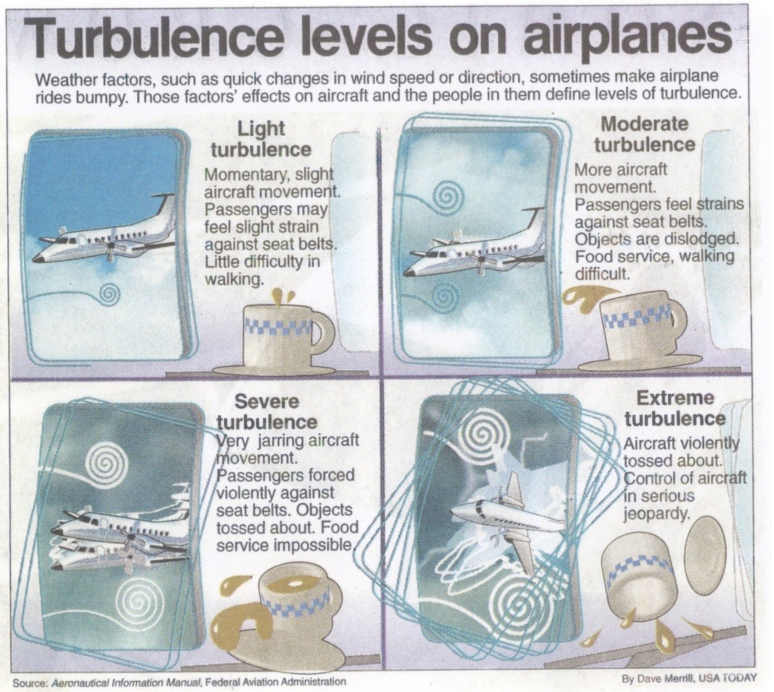


Avianca Airlines Lima to Buenos Aires over Andes at 41,000ft
23 passengers and cabin crew members injured. 5 June 2016

DC8 cargo jet encounter with
extreme turbulence over
Evergreen CO 9 Dec 1992

Turbulence Observations

- Aircraft response to turbulence is **aircraft dependent**
  - Complicated relationship between aircraft size, cruise speed, and aerodynamics.
- **So are pilot reports** (PIREPs/AIREPs): "light", "moderate", "severe"
  - Qualitative (not a number) and subjective (depends on a pilot opinion)
  - Location and time not always accurate
  - Not sampled well
- **CANNOT forecast these levels for every aircraft in the airspace**
- Instead need atmospheric turbulence measure (i.e. aircraft independent measure)



Turbulence levels on airplanes

Weather factors, such as quick changes in wind speed or direction, sometimes make airplane rides bumpy. Those factors' effects on aircraft and the people in them define levels of turbulence.

Light turbulence
Momentary, slight aircraft movement. Passengers may feel slight strain against seat belts. Little difficulty in walking.

Moderate turbulence
More aircraft movement. Passengers feel strains against seat belts. Objects are dislodged. Food service, walking difficult.

Severe turbulence
Very jarring aircraft movement. Passengers forced violently against seat belts. Objects tossed about. Food service impossible.

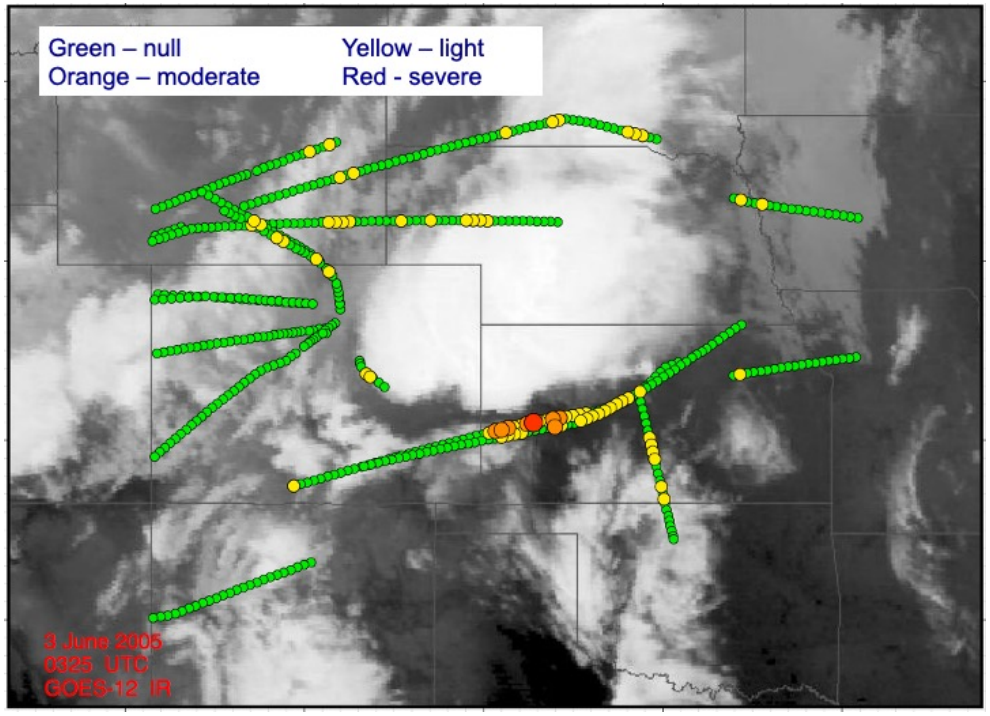
Extreme turbulence
Aircraft violently tossed about. Control of aircraft in serious jeopardy.

Source: *Aeronautical Information Manual*, Federal Aviation Administration

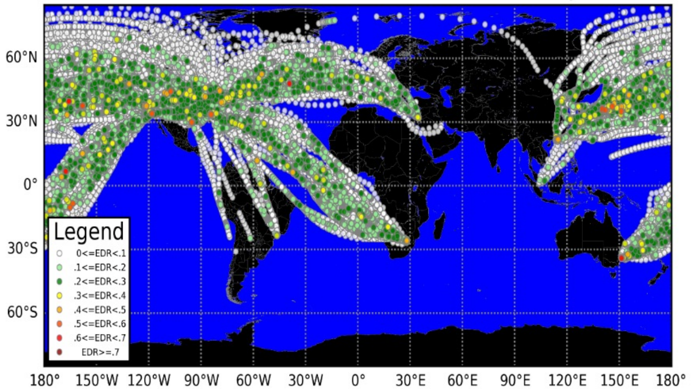
By Dave Merrill, USA TODAY

Airborne In Situ EDR Observations

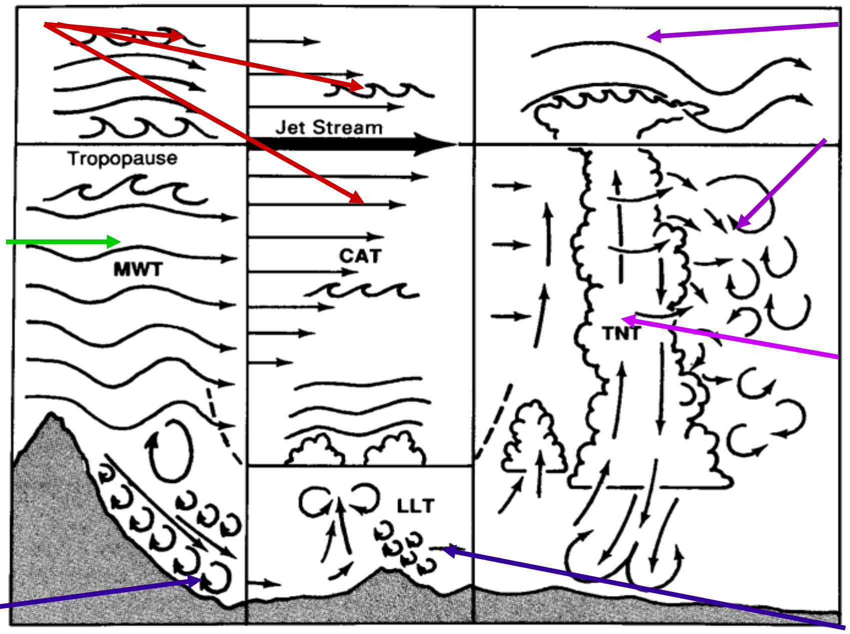
- In situ EDR (Energy Dissipation Rate) turbulence observations
  - Quantitative (numerical) and objective (pilot- and aircraft-independent)
  - Location and time is accurate
  - Software resides within avionics system
  - Records both average and peak (EDR) every minute
  - Reports are automatically generated (routine and event-driven by stronger turbulence)
  - Observations in meteo. data streams (e.g, AMDAR)



DAL 777-200LR and UAL 777-300ER Turbulence Observations, Jan-Oct 5 2017



Different Turbulence Sources



Clear-air Turbulence (CAT)

Mountain wave Turbulence (MWT)

Low level Terrain-induced Turbulence (LLT)

Cloud-induced or Convectively-induced Turbulence (CIT)

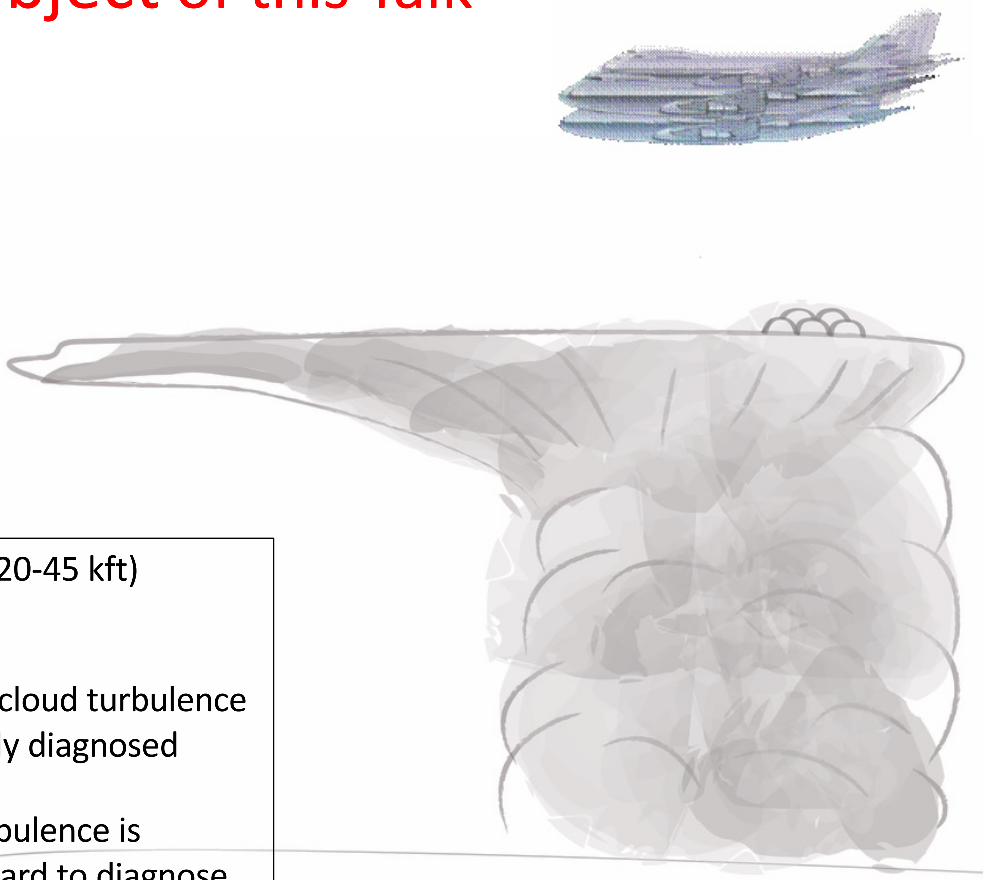
In-cloud turbulence

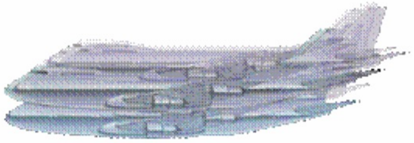
Convective boundary Layer turbulence

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

Subject of this Talk

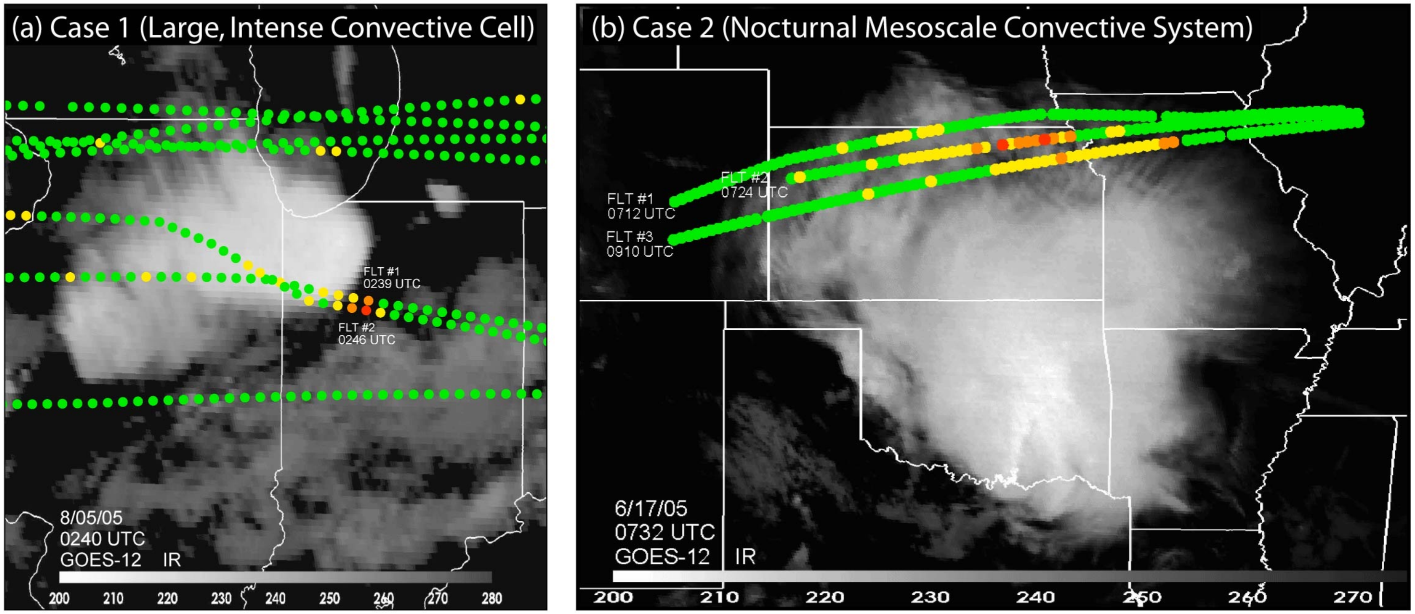




- Estimated that about 20% of upper-level (20-45 kft) turbulence is thunderstorm related
- Estimates would be much higher if out-of-cloud turbulence generated by thunderstorms could be easily diagnosed
- Out-of-cloud thunderstorm-generated turbulence is is invisible (like clear-air turbulence) and hard to diagnose using standard hazard identification technologies (e.g., radar, satellite, lightning detection networks)

Part 2: Mechanisms for Turbulence Adjacent to (but outside of) Thunderstorm Regions

IR Satellite and Flight Tracks for Example Cases of Convectively-Induced Turbulence



(a) Case 1 (Large, Intense Convective Cell)

(b) Case 2 (Nocturnal Mesoscale Convective System)

0200-0245 UTC 5 August 2005 175 km

0700-1000 UTC 17 June 2005 350 km

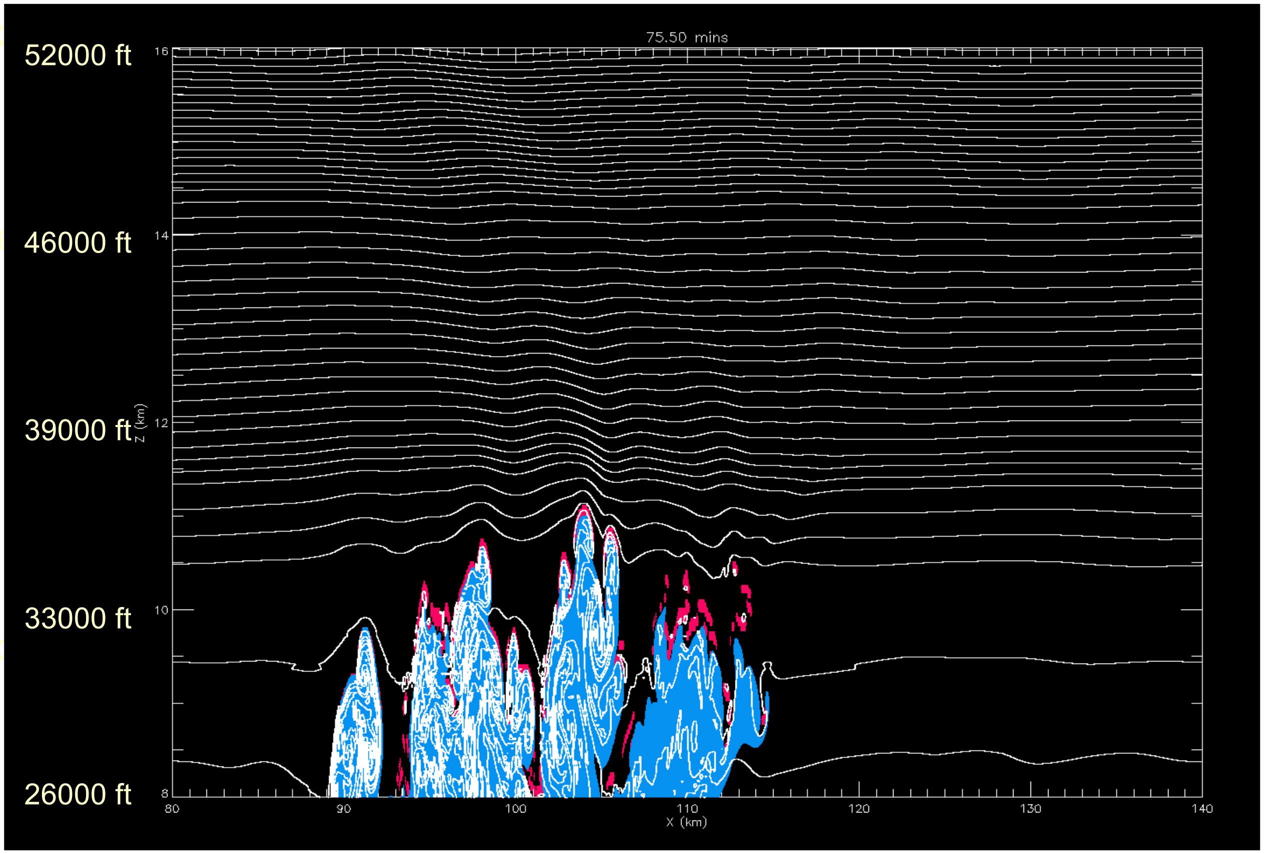
Turbulence intensities from in situ EDR:
Green = Smooth (EDR < 0.1)
Yellow = Light (0.1≤ EDR < 0.3)
Orange = Moderate (0.3 ≤ EDR < 0.5)
Red = Severe (EDR ≥ 0.5)

Reference:

Lane, T. P., R.D. Sharman, S.B. Trier, R.G. Fovell, and J. K. Williams, 2012: Recent advances in the understanding of near-cloud turbulence. *Bull. Amer. Meteor. Soc.*, **93**, 499-515,doi:10.1175/BAMS-D-11-00062.2.

- EDR = $\varepsilon^{1/3}$ (Cornman et al. 1995, *J. Aircraft*)
- ε = Energy dissipation rate at the smallest scales (units of de/dt: m^2/s^3)

Numerical Simulation: Turbulence generated above a growing thunderstorm arising from breaking waves in the lower stratosphere

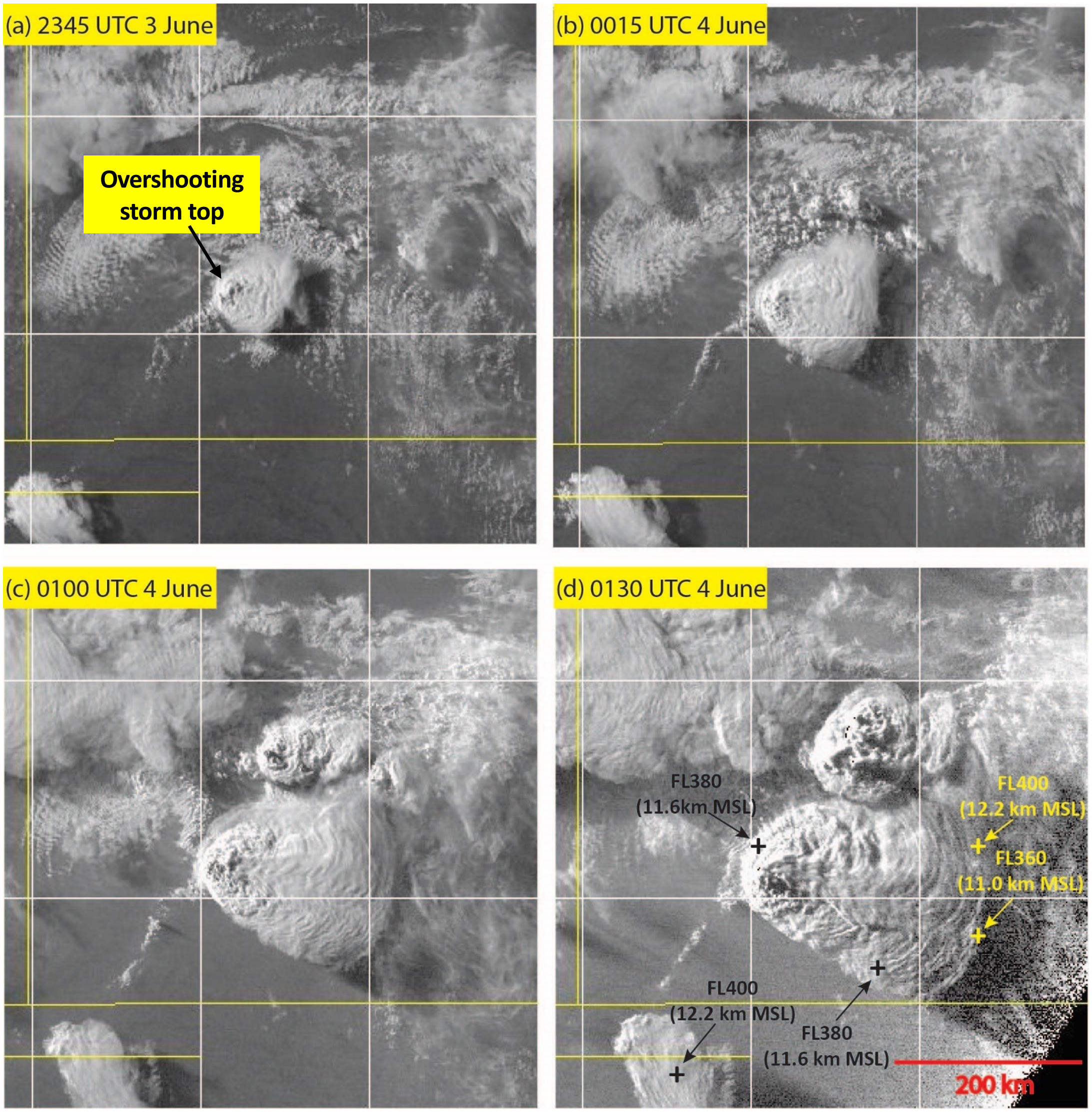


2-D simulation showing cloud in blue shading, gravity waves, and turbulence in red contours (courtesy of Todd Lane)

Observed case (10 Jul 1997) where severe turbulence is encountered near tropopause at Dickinson, ND with 22 injuries

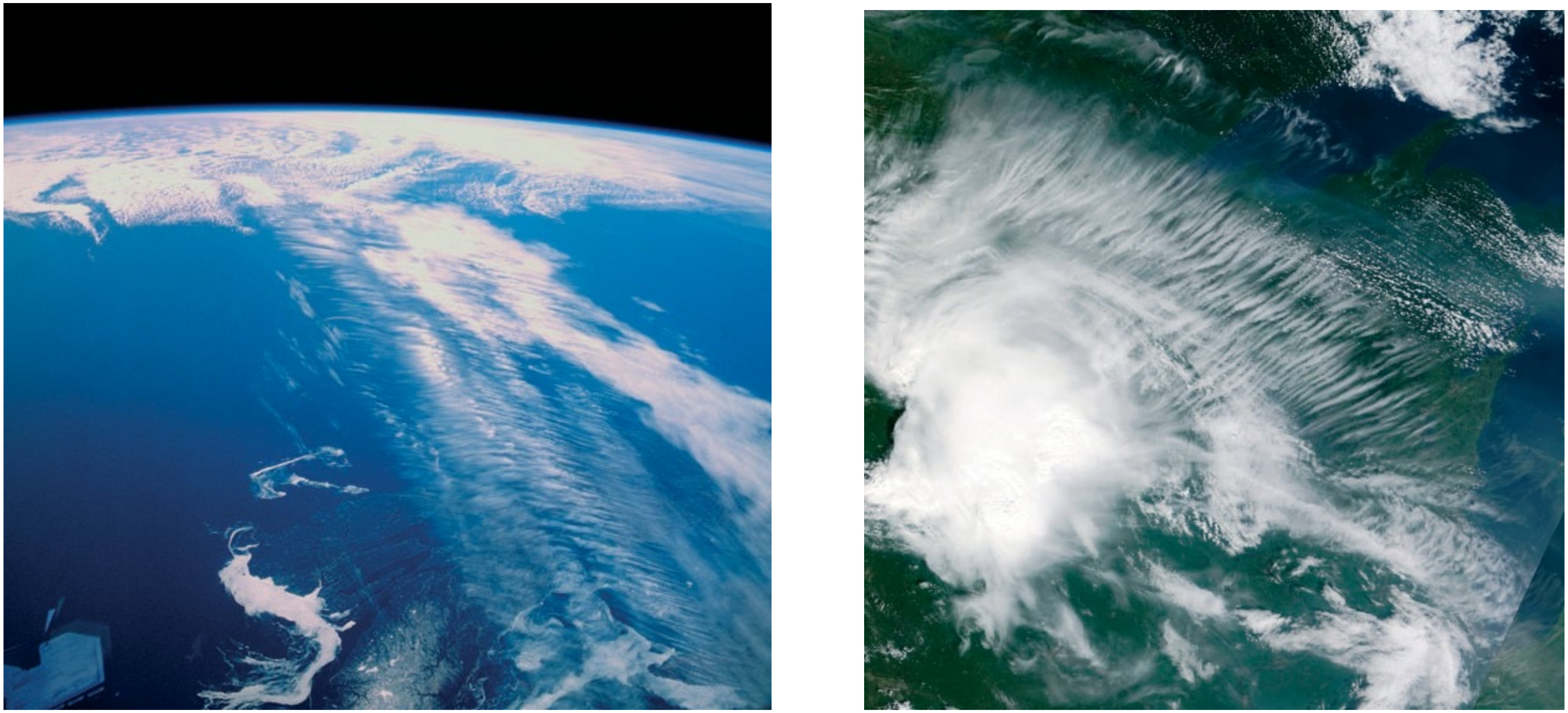
Lane, Sharman, Clark, and Hsu (J. Atmos. Sci., 2003)

Observed Horizontally Propagating Waves on 4 June 2015



- Waves generated by thunderstorm overshoots into the lower stratosphere on west side of storm
- Waves evident in satellite images of thunderstorm anvil cloud for up to 200 kilometers downwind of nearly stationary storm
- Nearly stationary upstream wave fronts also present (but fewer)
- Light turbulence reported at both downstream and upstream anvil edges during 2-hour period

Visible Satellite Images over 2-hour period



Taken from Knox et al. (Weather 2010)

- Regions of widespread turbulence are often associated with cirrus bands near jet stream level
- These cirrus bands can be influenced by outflows from large collections of thunderstorms (mesoscale convective systems)

Mesoscale Convective Systems (MCSs): Organized Thunderstorm Clusters

- Definition: A collection of thunderstorms together having > 100-kilometer horizontal scale (often linearly organized)

- Typical lifecycle of late afternoon initiation, maximum intensity during evening, maximum size overnight

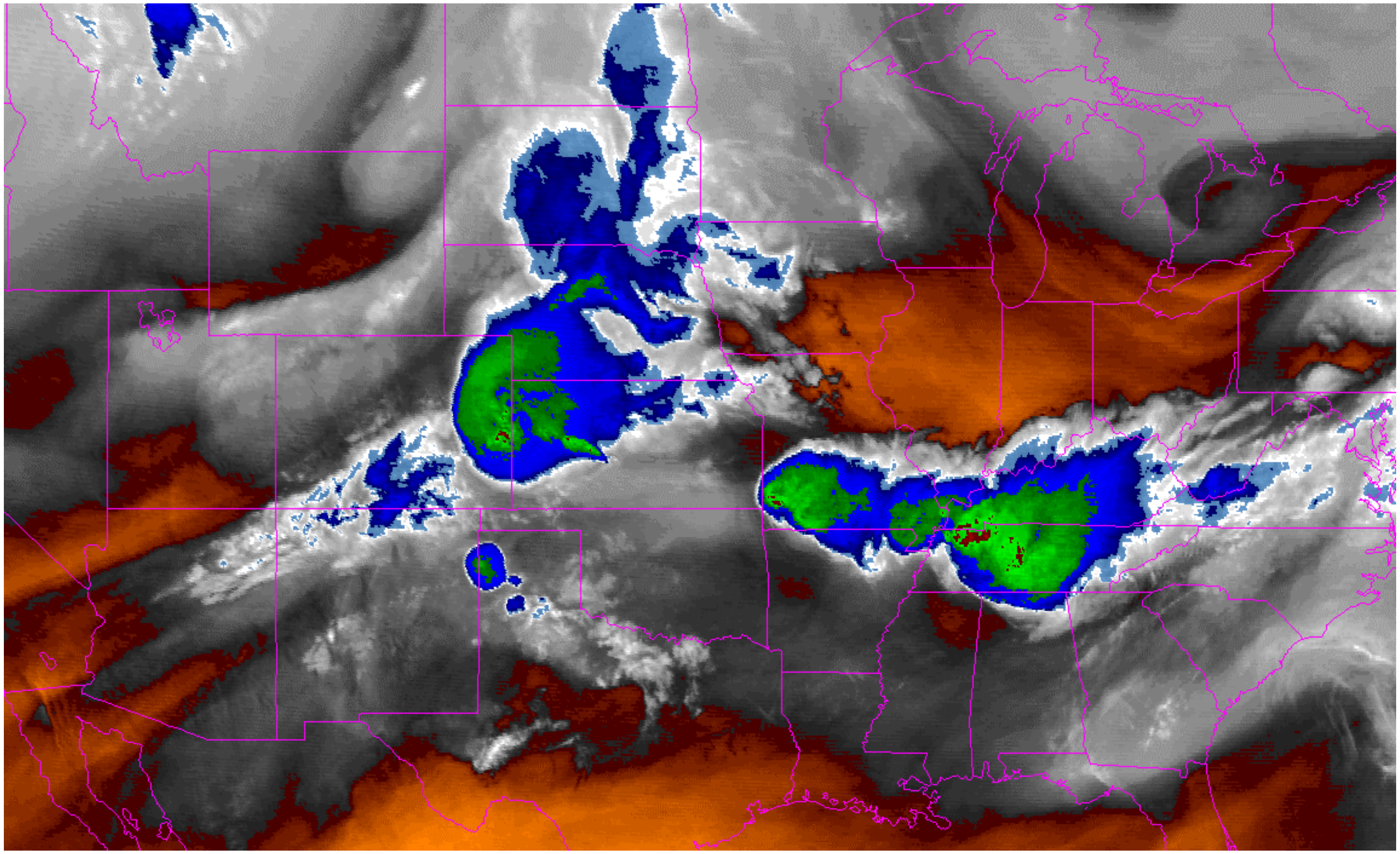
- Well organized internal circulations that can persist beyond decay of individual thunderstorms

  - Lower tropospheric outflow and cold pool
  - Midlevel vortex
  - Upper tropospheric outflow near jet stream level (i.e., at typical commercial aviation cruising altitudes)

- Individual thunderstorms (lifetime = 1 hour) move with mean flow but overall MCS (lifetime = 6-12 hour) motion deviates due to redevelopment of storms in preferential locations

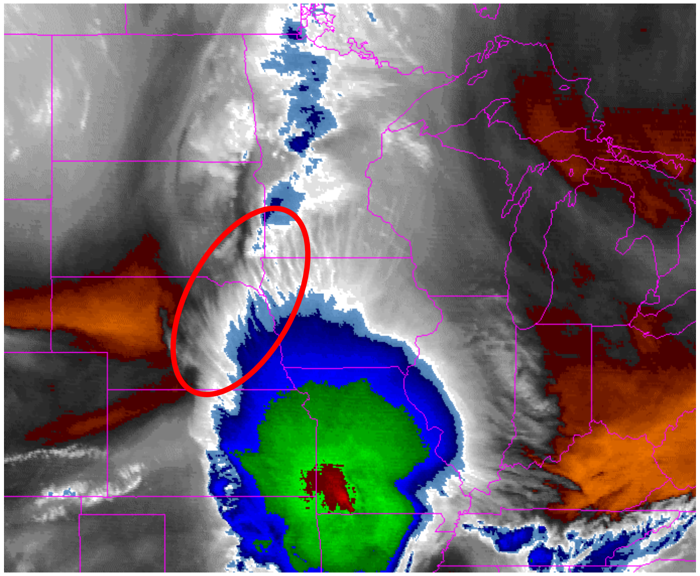
  - Transport of unstable air by low-level jet
  - Interaction of cold pool with environmental low-level vertical shear (storm regeneration in direction of vertical shear)

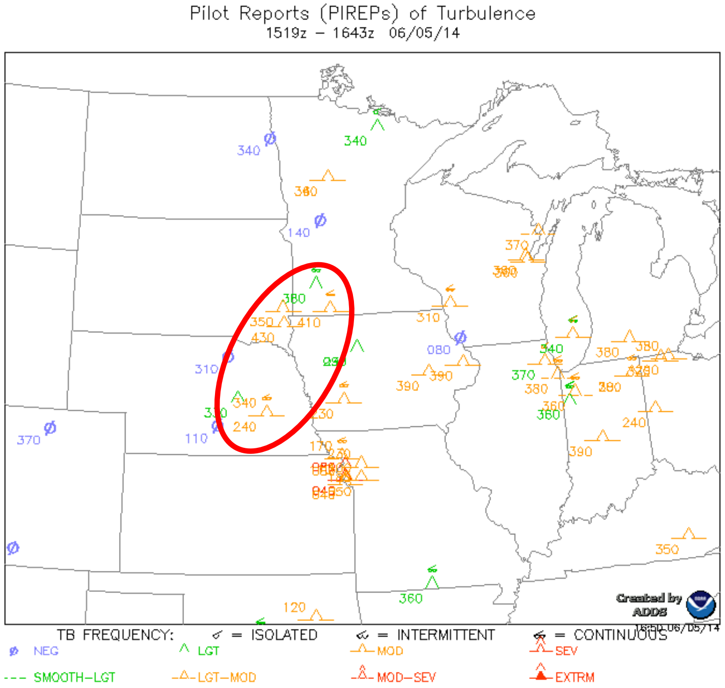
10-hour Loop of Water Vapor Imagery from 06-16 UTC 5 June 2014 (Δ t =30 min)



From CIRA, Courtesy of Russ Schumacher (CSU)

Association of Upper-level PIREPS of Moderate Turbulence with Cirrus Bands

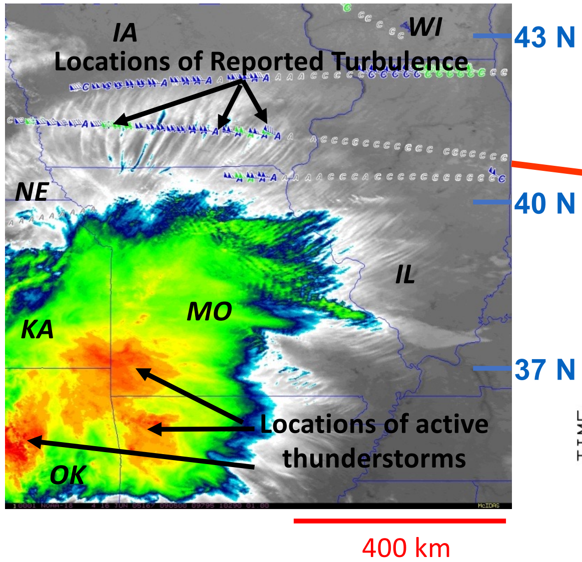




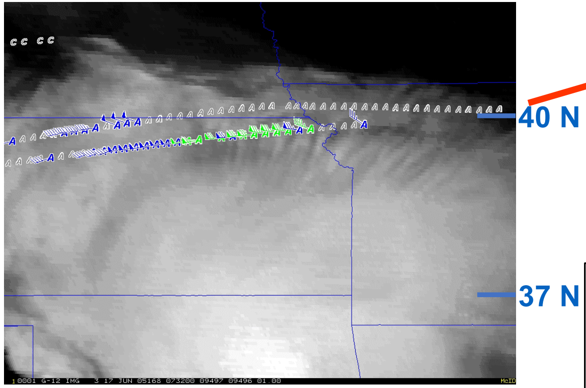
- Lenz et al. study (2009, *Wea. Forecasting*) found ~ ½ of large long-lived MCS over CONUS had cirrus bands oriented transverse to circular MCS cloud boundary
- At least one observation of light (moderate) turbulence for 93% (44%) of those transverse cirrus band cases

16 – 17 June 2005 Case Study

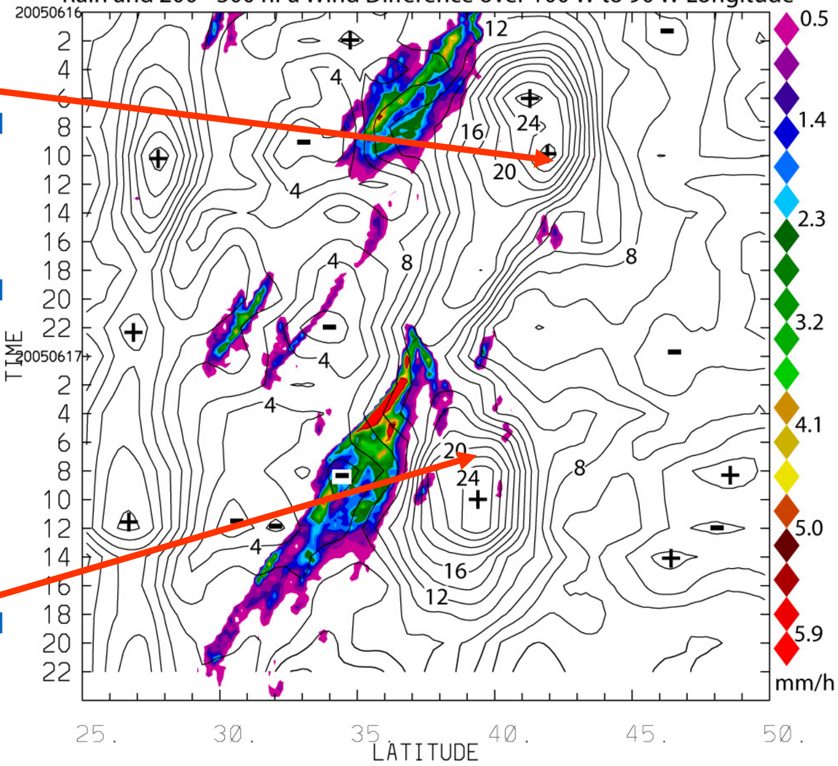
0905 UTC 16 June



0745 UTC 17 June

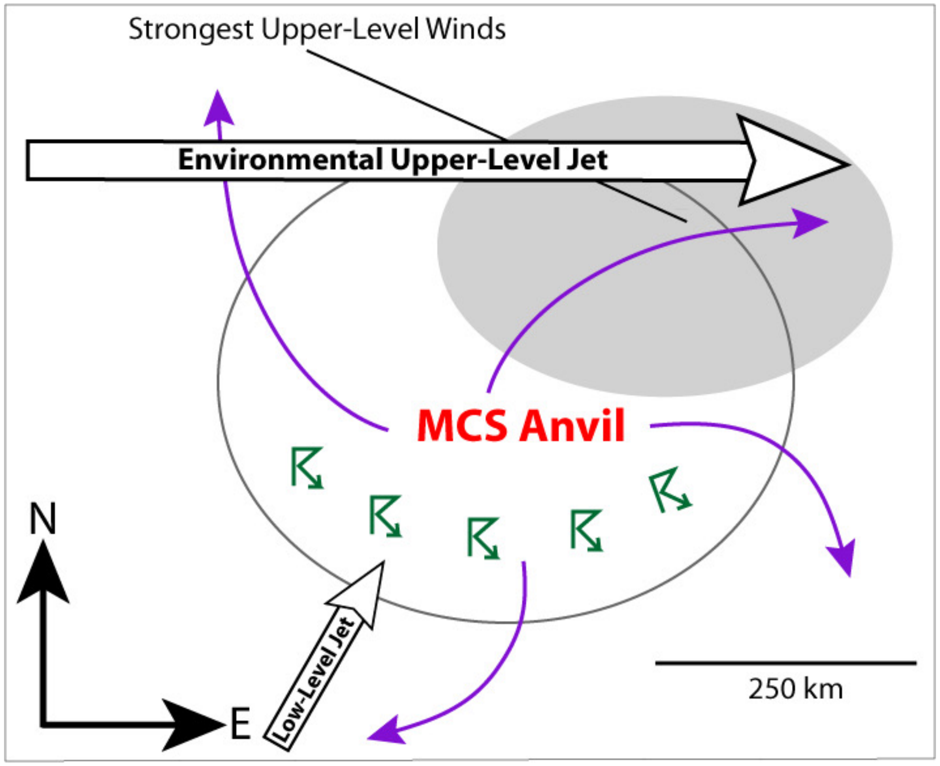


Rain and 200 - 300 hPa Wind Difference over 100 W to 90 W Longitude



- Wind shear strength (contours) is maximized hours later and several hundred kilometers north of heavy thunderstorm rain areas (colors)
- Jet stream winds increased by outflow coming from thunderstorm region

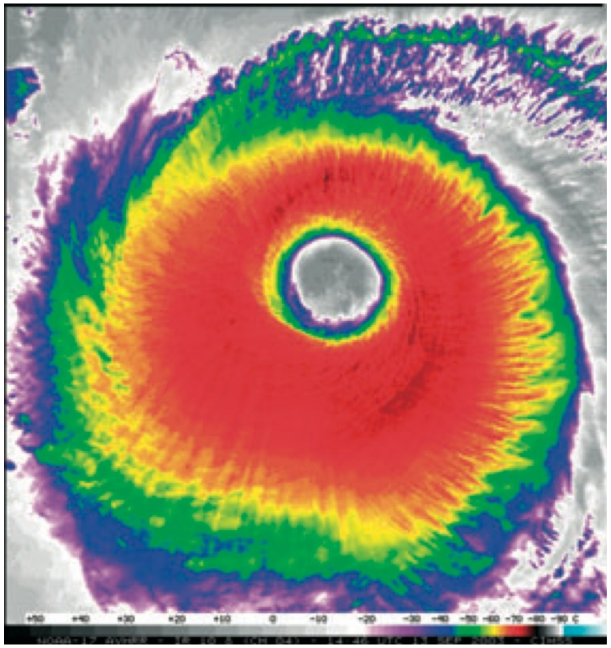
Upper-Level Flow Pattern in Typical Central U.S. Nocturnal MCS



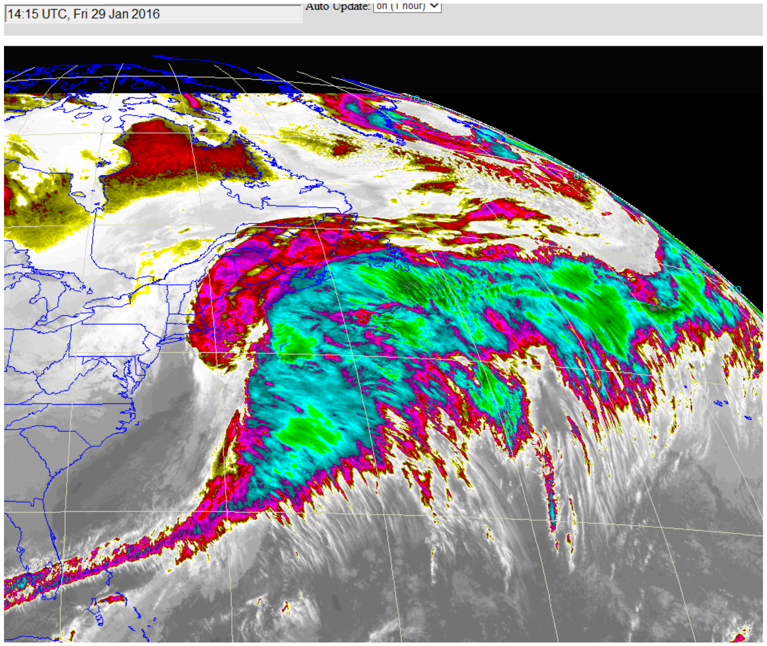
- Strongest flow (and vertical shear) in shaded region of MCS where anticyclonic outflow (purple arrows) is augmented by environmental flow

- On opposite side the outflow and environmental flow interfere with each other, and wind speeds/vertical shear are less

Other Examples of Transverse Banding in Weather Systems with Deep Convection (thunderstorms)



NOAA AVHRR 1-km IR imagery for Hurricane Isabel
at 1446 UTC 13 Sep 2003 (Knox et al. 2010, *Weather*)



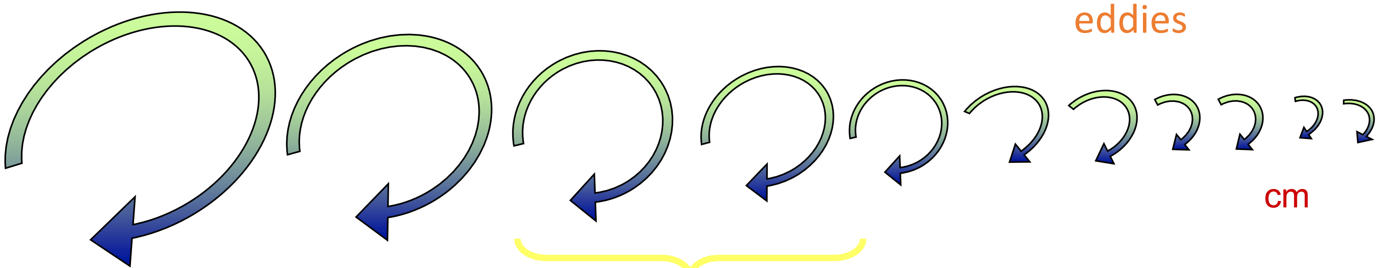
4-km IR imagery for oceanic cyclogenesis 28-29 Jan 2016
(Courtesy of Melissa Thomas, *Delta Airlines Meteorologist*)

Part 3. Turbulence Forecasting: Scales of aircraft turbulence

large

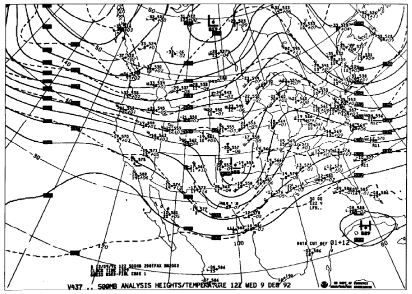
turbulent
eddies

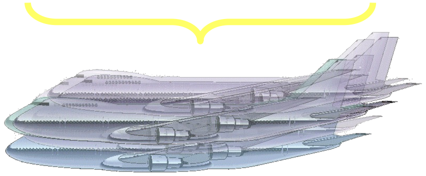
smallest
eddies



cm

100s km





Aircraft responds to scales
from few m - km

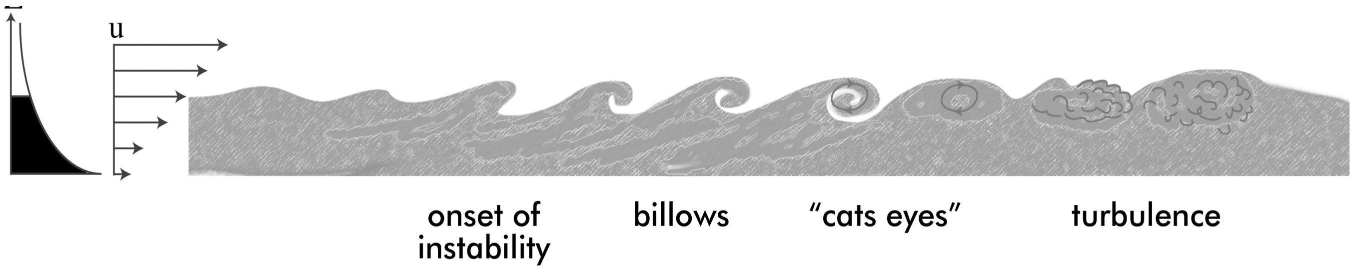
Operational
NWP
resolution

Research
NWP
resolution

linkage

Fundamental problem:
- **Scale**
- **Linkage**

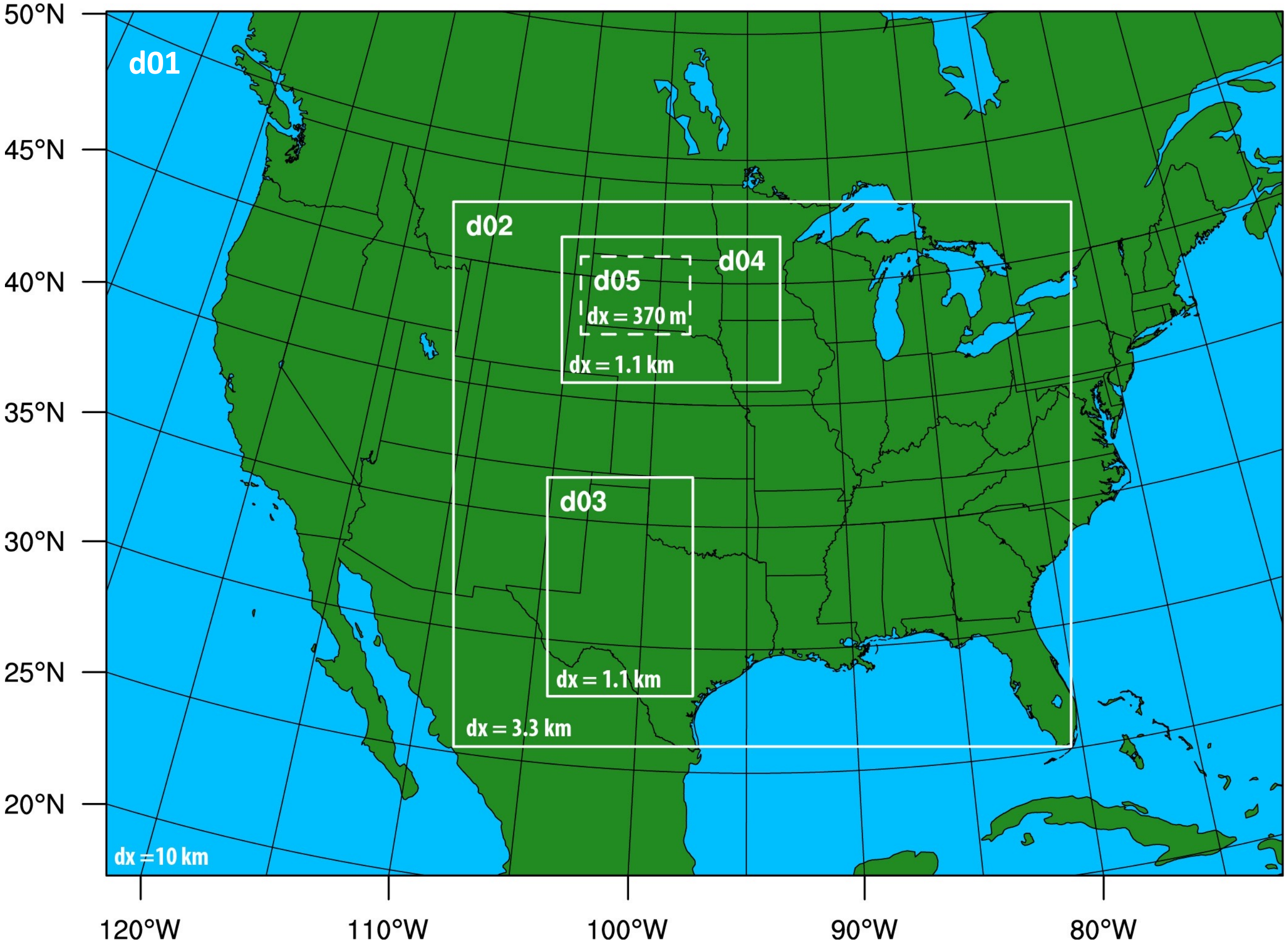
Turbulence generation mechanism – Kelvin Helmholtz instability (KHI)



- Instabilities favored by small Richardson number $Ri = N^2/(dU/dz)^2$
    - Includes convective unstable case $N^2 \leq 0$
    - Theoretically stability is guaranteed if $Ri > 1$
- So look for regions where Ri is small
- But |Ri| does not determine intensity of turbulence

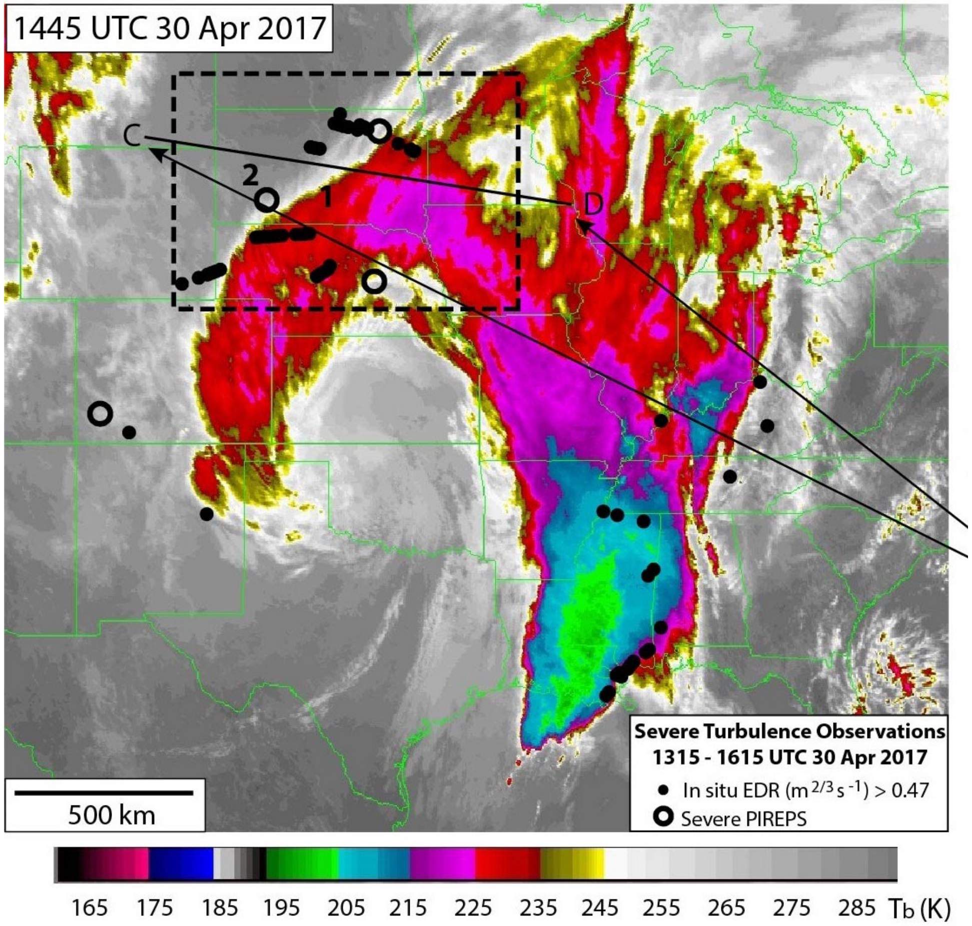
- Research NWP models can resolve scales influencing the onset of turbulence
- Operational NWP models can resolve large thunderstorms and MCSs, but not scales directly responsible for turbulence onset

Research NWP Model Domains for Simulation of Example Observed Aviation Turbulence Case (30 April 2017)

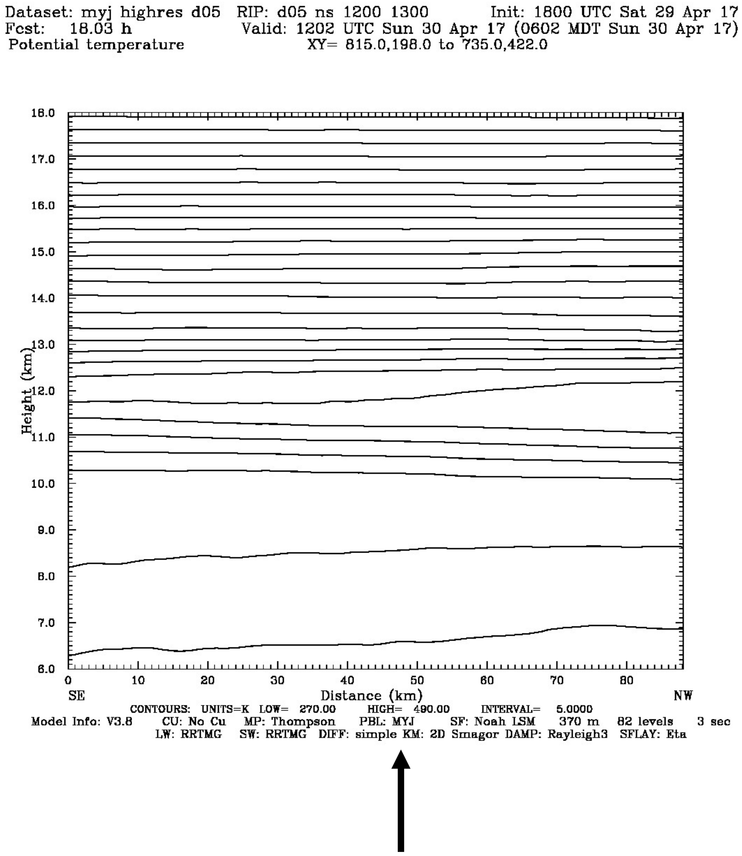


- Contains "nested" domains that communicate with each other
- Lowest-resolution outer domain d01 with horizontal grid spacing of 10 km resolves large-scale motions and basic weather pattern over continental U.S.
- Highest resolution inner domain d05, having 370-meter horizontal grid spacing, is located where the turbulence is observed.
- d05 can resolve motions (e.g., wave breaking) leading to turbulence, but it cannot resolve fully developed turbulence
- Highest-resolution operational model (the HRRR model) has horizontal spacing of 3 km and cannot resolve any turbulence

Example Case of Severe Turbulence due to KHI on Northwest Side (locations 1, 2) of Strong Low-Pressure System over Plains

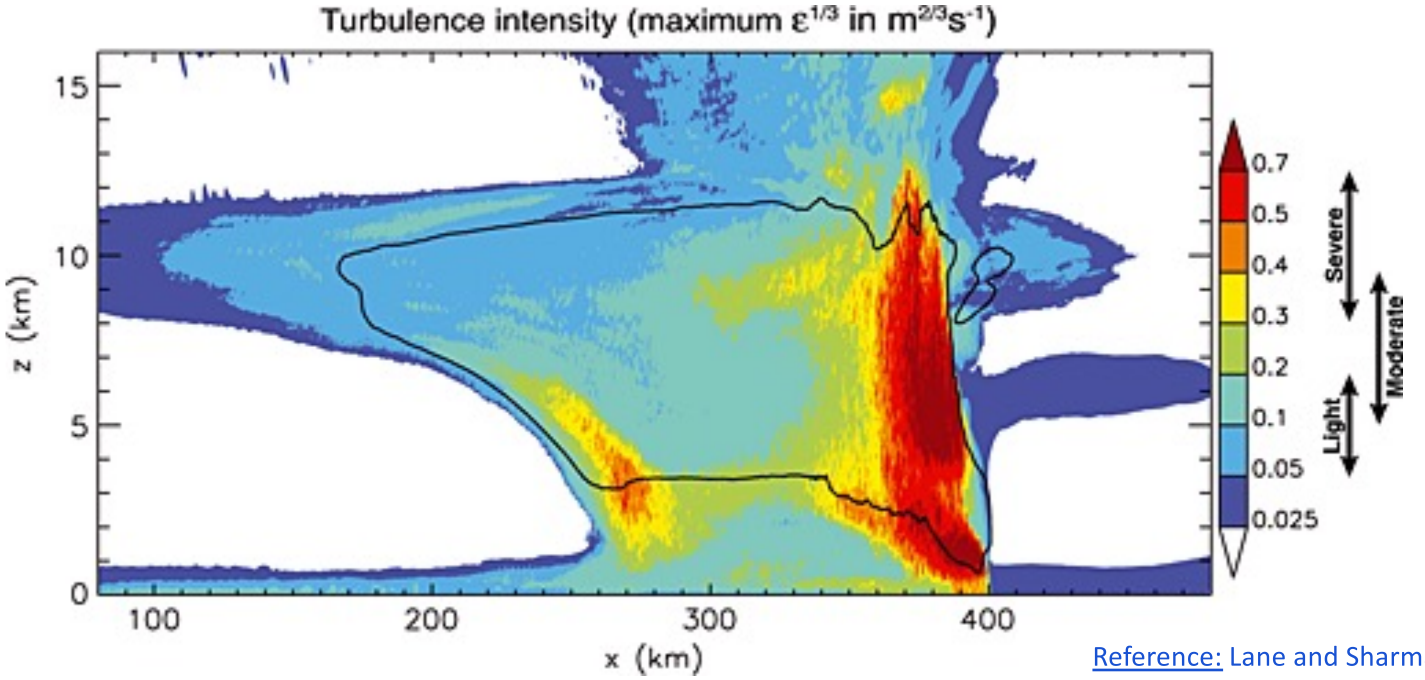


GOES-13 GVAR ch4 IR Satellite Brightness Temperature



30-minute animation from d05 of research NWP simulation

Large-Eddy Simulation (LES) Models



Reference: Lane and Sharman (2014, *GRL*)

- Has finer horizontal resolution than research NWP models and uses horizontal grid spacings of 10 – 100 meters
- Better at examining details of the turbulence, but lacks potentially important details on the large-scale environment, so less suitable for examination of specific cases

Operational Forecasting of Turbulence

- Real-time operational forecasting of turbulence doesn't have the luxury of hindsight that research simulations of turbulence benefit from

- Operational NWP models typically cover large areas, have time constraints, and therefore must use much larger minimum horizontal grid spacings (which are unable to predict turbulence onset)

- Therefore, real-time (operational) forecasting of turbulence requires more of a statistical approach

  - output from a lower-resolution operational NWP model is used to drive a statistical model

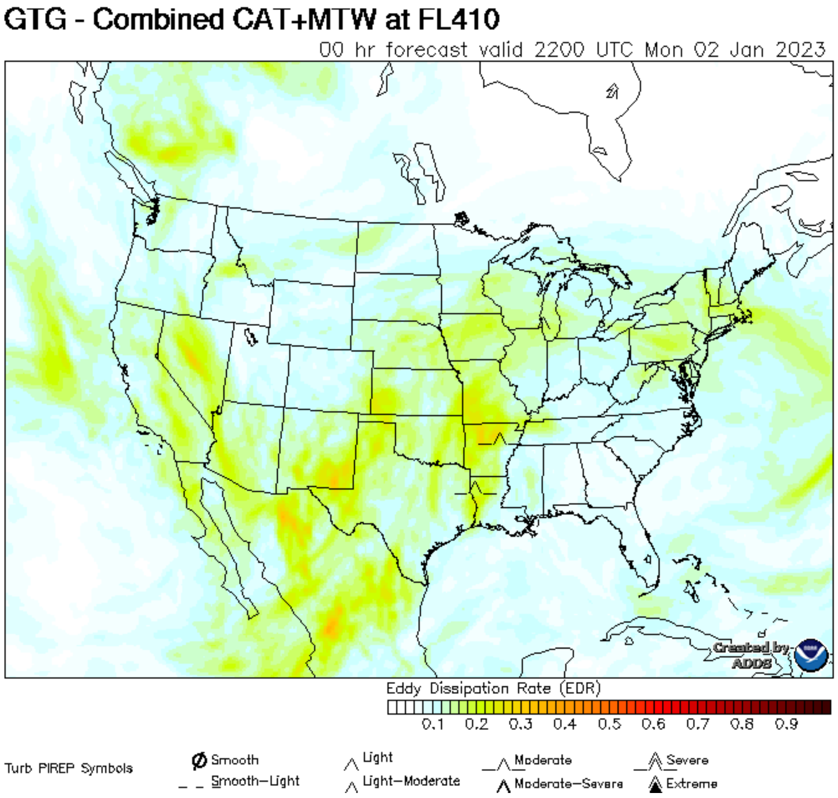
  - larger-scale parameters from the NWP model (e.g., wind shear, temperature), which are predictable, are then weighted based on past correlations with turbulence to estimate likelihood of turbulence in the forecast

  - can work well for thunderstorm-generated turbulence if the operational NWP model reliably forecasts the timing, intensity, and location of the thunderstorms

Graphical Turbulence Guidance

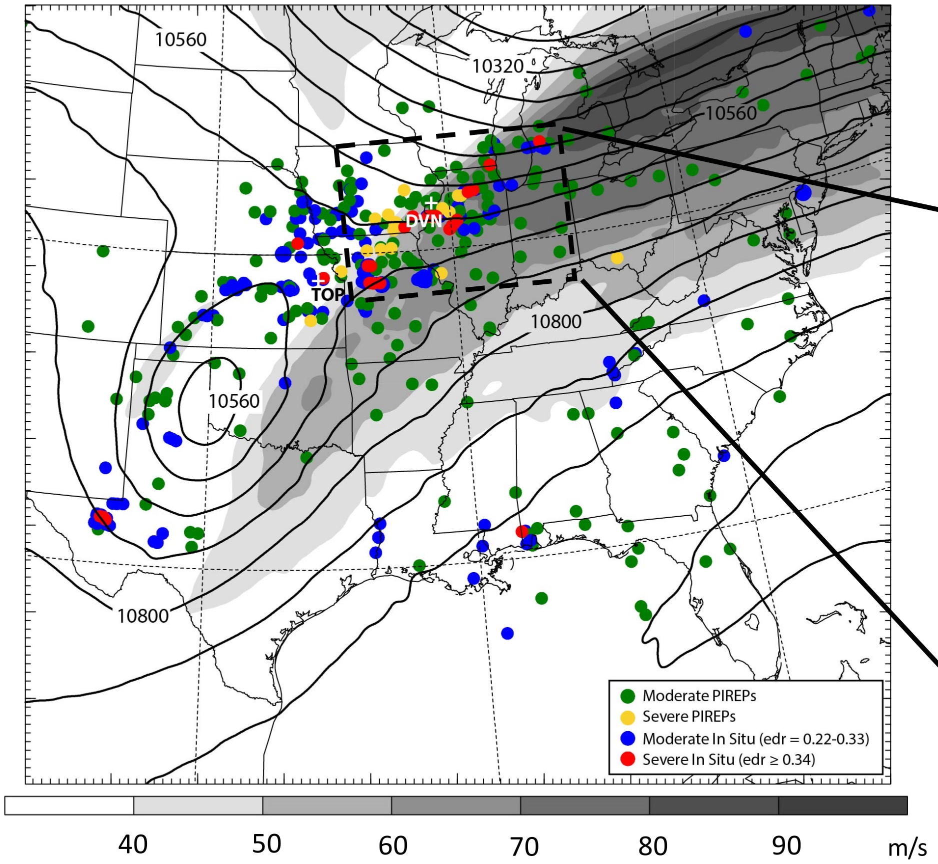
- Turbulence Forecast system is called the Graphical Turbulence Guidance (GTG)*
  - Based on various NWP models that include RAP, WRF, GFS, UK-Met, ARPEGE, HRRR, etc.
  - Runs regionally in US, Taiwan, S. Korea
  - Globally based on GFS, UKMet
- Provides strategic turbulence forecasts of turbulence intensity metric termed “EDR” (energy dissipation rate$^{1/3}$)
- Assumes large scale NWP model resolves turbulence sources linked to aircraft scale turbulence
- Outputs a ***combined*** turbulence forecast field as well as
  - **Mountain Wave Turbulence** (**MWT)**
  - **Clear Air Turbulence (CAT) & Low-Level Turbulence (LLT)**
  - **Thunderstorm-Generated Turbulence (CIT)**

Sharman et al. *Weather & Forecasting*, 2006
Sharman and Pearson, *J Appl Met Climate*, 2017
Pearson and Sharman, *J Appl Met Climate*, 2017

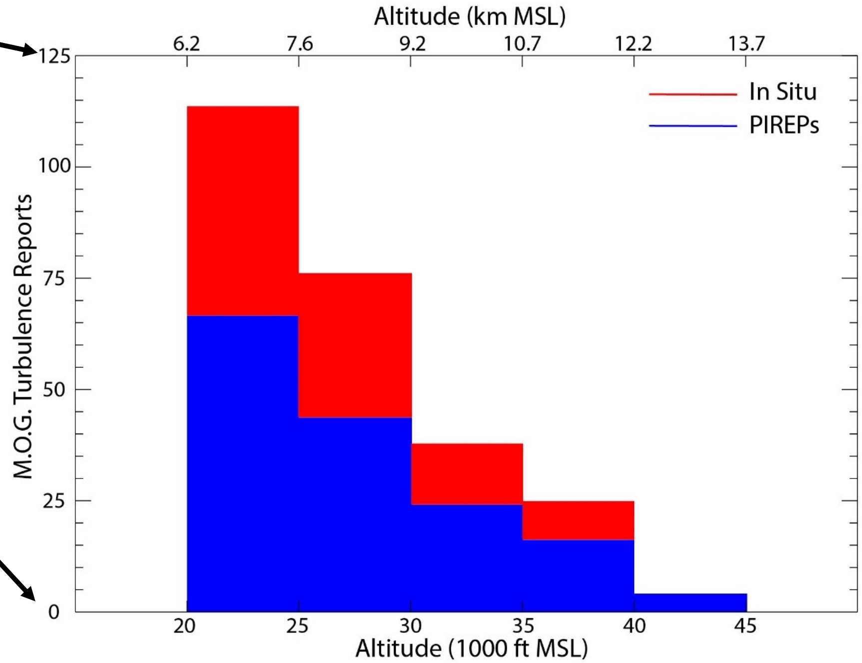


Example Case 1: 25 October 2019 (Jet-Entrance Region East of Strong Synoptic Trough)

1800 UTC 250-hPa GFS Heights/Wind Speeds, 1500-2100 UTC Turbulence Reports

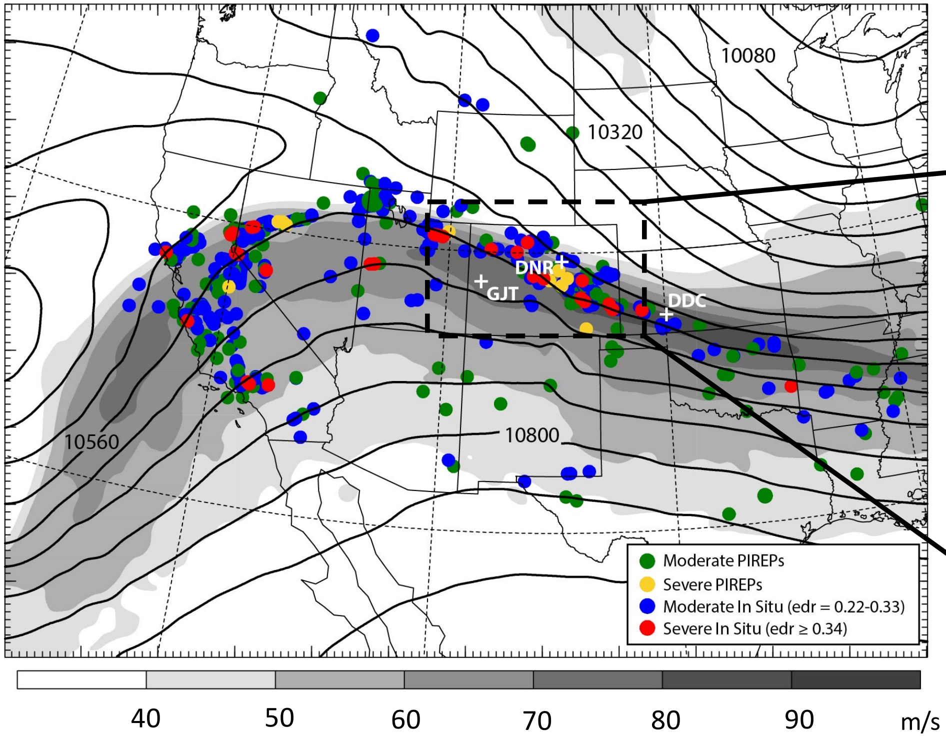


Altitudes of M.O.G. Turbulence (95-85W, 38-43N) 1500-2100 UTC

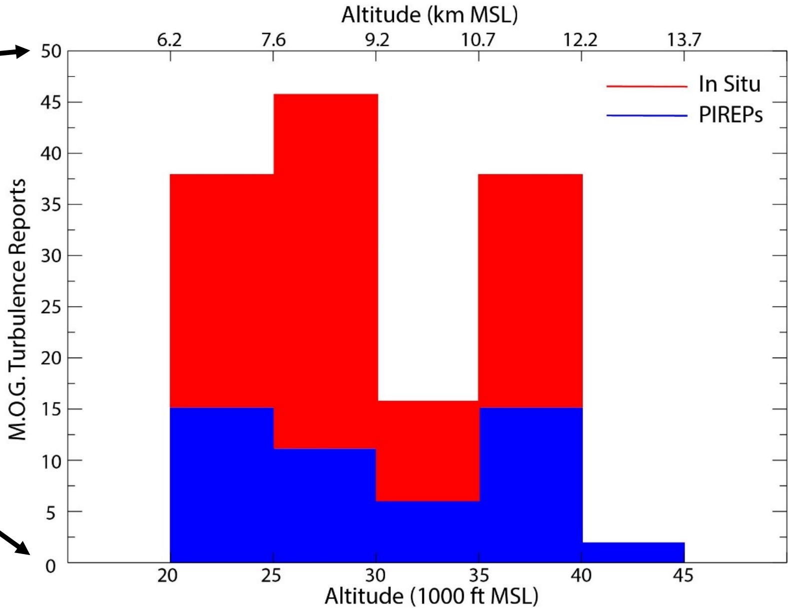


Example Case 2: 3 December 2019 (Strong Flow Downstream of Weak Synoptic Ridge)

1800 UTC 250-hPa GFS Heights/Wind Speeds, 1700-2300 UTC Turbulence Reports

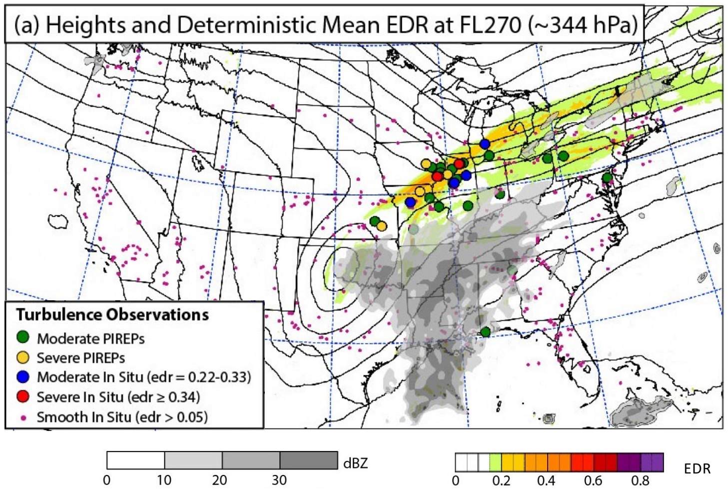


Altitudes of M.O.G. Turbulence (111-101W, 37-42N) 1700-2300 UTC

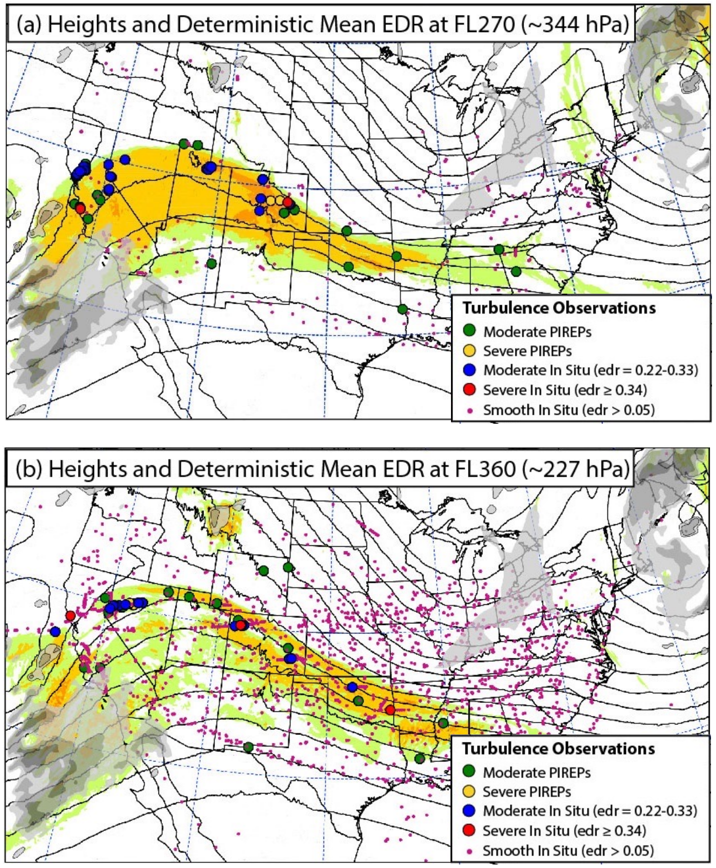


Operational Forecast Implications for Thunderstorm-Influenced Widespread Turbulence Events

Case 1 Six-Hour Forecast Valid 1800 UTC 25 Oct 2019



Case 2 Six-Hour Forecast Valid 2000 UTC 3 Dec 2019



GTG Forecasts of Cases 1 and 2 Driven with HRRR Model Output

- GTG forecasted EDR values within moderate-to-severe range in locations coinciding with observed turbulence reports
- Expert forecasting systems, such as GTG, show promise in anticipating widespread thunderstorm-influenced turbulence when upper-level outflows are realistically represented in output from highest-resolution operational NWP models (e.g., HRRR)

Reference: Trier, Sharman, Munoz-Esparza and Keller (2022, *Mon. Wea. Rev.*)

Summary

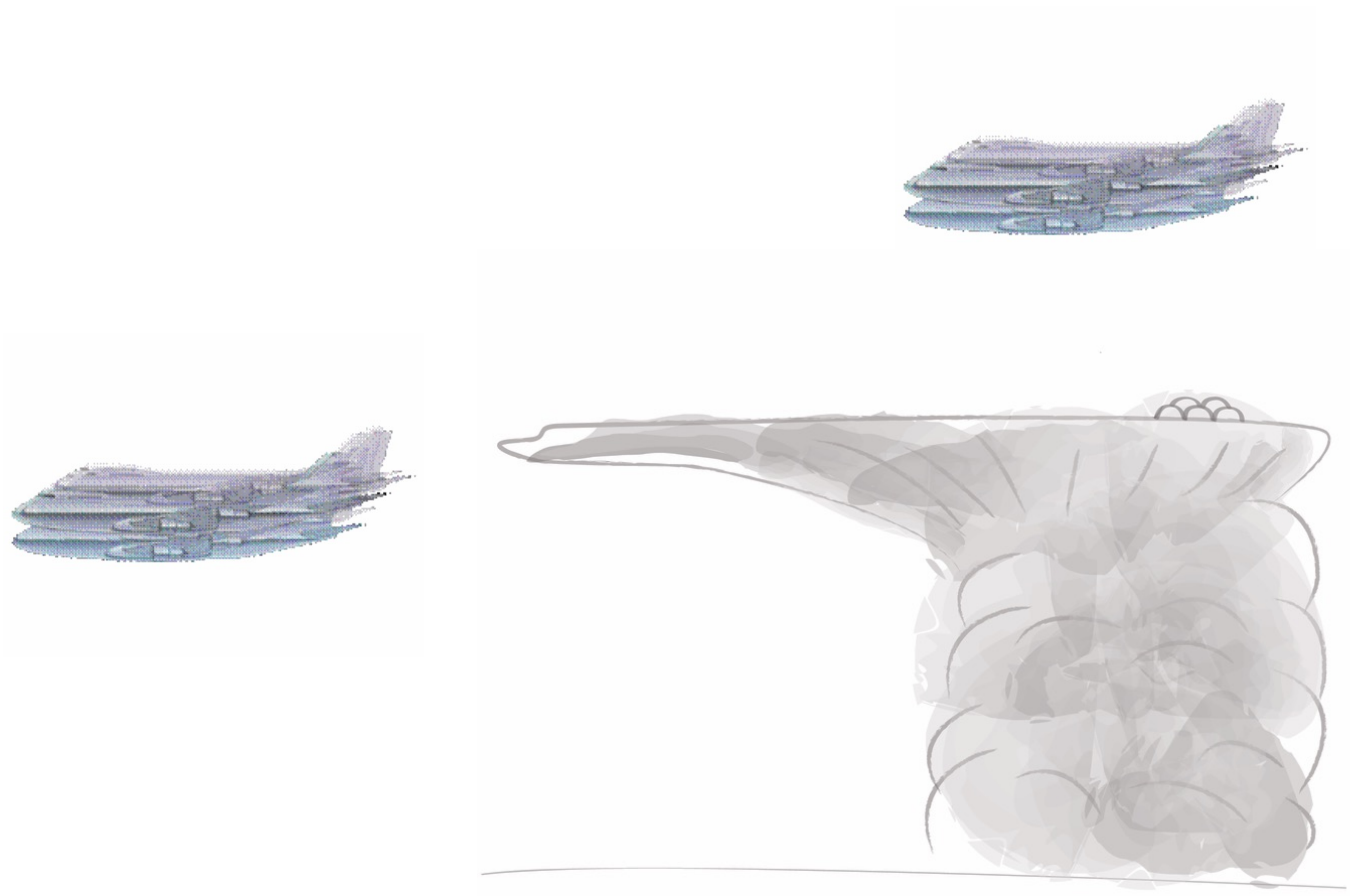
- Thunderstorm-generated turbulence presents a major hazard to commercial aviation both inside and for significant distances above (up to several kilometers) and laterally (up to several hundreds of km) from storms

- Multiple different linkages between thunderstorms and related distant turbulence, including waves and enhancement of jet stream winds due to storm outflows

- Thunderstorm-related turbulence more favored under certain large-scale atmospheric conditions (e.g., enhanced vertical wind shear, cold denser air overlying warmer air)

- High-resolution NWP and LES research models used to enhance physical understanding of the causes of turbulence related to thunderstorms, and where (relative to thunderstorms) it is most likely to occur

- Lower-resolution operational NWP models (e.g., HRRR) cannot simulate turbulence, but when used to drive statistically based “expert” systems (e.g., GTG) they show promise in forecasting thunderstorm related turbulence when they can accurately forecast the thunderstorms



Thank You!

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