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…”
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 directly forecast
       - 5000km X 5000km X 25km CONUS domain @ 25m resolution = \(2 \times 10^5 \times 2 \times 10^5 \times 10^3\) = 40,000 Gigawords/variable!!
   - Alternatively, can postprocess using operational NWP model to diagnose turbulence potential (implicitly assumes downscale cascade) -> GTG etc.
Scales of aircraft turbulence

Energy Production

Large eddies

100s-1000s km

“turbulent” eddies

“turbulent” eddies

Energy flow (downscale cascade)

Energy Production

Aircraft responds to scales from few m - km

Mesoscale model resolution

NWP resolution

Dissipation by viscosity

smallest eddies

cm
Small scale nature of turbulent events

- Discrete
- Continuous

Vertical Accel

- 10 km
- 2 km
- 25 km
- 15 km
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)
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
Challenges (cont.)

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

Forecast errors due to
1. NWP model errors
2. Errors in postprocessing algorithms

Which is more important?
Better forecasting techniques

Forecast errors due to
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Which is more important?

Courtesy Ulrich Schumann
Better forecasting techniques

Forecast errors due to
1. NWP model errors
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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

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

 Courtesy Rob Fovell, UCLA
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)

GTG

Prob > light
Red=.75

Prob > mod
Red=.30

Prob > severe
Red=.30
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
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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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
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?

Actual EDR measurements (1 hour, FL200-FL410)

Green – null
Yellow – light
Orange – moderate
Red – severe

Courtesy Dragana Zovko-Rajak, U. Melbourne
Proportion of along-line volume that is turbulent (TKE>0.25 m²/s²)

Thunderstorm line simulation
8000x1220x334 @75 m

Lane & Sharman, GRL 2014
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

\[ \text{Ri, } \varepsilon \quad \text{Research acs 2,3} \]

\[ \text{Research ac 1 w/ dropsondes} \]