Segment 6: Turbulence

Friends and Partners of Aviation Weather

1 November 2012
Turbulence Session

Long Term Goals: Increase/Maximize Usable Airspace & Reduce/Minimize injuries and aircraft damage.
What can be done in the next 12-24 months to move toward this goal?

Topics

1. Turbulence Causes, Character & Forecasting for Aviation
   Presenter: Bob Sharman
   Team: T.Fahey, T.Farrar, B.Sharman & M.Taylor

2. Turbulence Issues for Aviation Decision Makers
   Presenters: Bill Watts & Matt Tucker

3. Turbulence Measurements & EDR Standardization
   Presenter Mike Emanuel

4. Verification of Turbulence Forecasts
   Presenter: Jennifer Mahoney

5. Integration of Turbulence Info
   Presenter: Mark Bradley
Turbulence Causes, Character, and Forecasting
Scales of Aircraft Turbulence/
Turbulence Intensity Metric (EDR)

Largest eddies:
Energy Input

Smallest eddies:
Energy Dissipation

100s km

“turbulent” eddies

cm

Aircraft responds to scales from
~100m – 3 km
Scales of Aircraft Turbulence/
Turbulence Intensity Metric (EDR)

Largest eddies:
Energy Input

Energy flow (downscale cascade)

Smallest eddies:
Energy Dissipation

100s km

“turbulent” eddies

Faucet-sink analogy

source

flow

sink

1 November 2012

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Segment 6
Scales of Aircraft Turbulence/Turbulence Intensity Metric (EDR)

Energy flow (downscale cascade)

Largest eddies: Energy Input
Smallest eddies: Energy Dissipation

100s km
“turbulent” eddies
cm

- Energy production at largest scales
- Energy dissipation (into heat) at smallest scales. Depends on viscosity.
- ->“Downscale cascade”
- $\varepsilon =$ Energy dissipation rate at the smallest scales (units of $\text{de/dt: m}^2/\text{s}^3$).
- Usually energy production at large scales $\sim$ energy dissipation at small scales and $\varepsilon$ is nearly constant across scales
- EDR = $\varepsilon^{1/3}$ is used because it is proportional to aircraft loads (0-1 m $^{2/3}$ / s)
- EDR can be calculated exactly at the small scales (but requires very high resolution), approximately at intermediate scales (with some assumptions about the statistical nature of the turbulence)
Background

Known 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.
Background

Known Turbulence Sources

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

Background

Known Turbulence Sources

Gravity waves and wave breaking

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

Convectively-Induced Turbulence (CIT)

Some turbulence occurs in clear air near cloud (CIT)

FAA avoidance guidelines are inadequate

**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
“CAT” Outbreak
10 Mar 2006

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

Reported Turbulence Layer

Cloud (colorfill), \( \theta \) (2-K contour interval), \( w \) (1 m/s contour interval; updrafts red, downdrafts, green)
Automated Turbulence Forecasting

- Forecast **EDR** (atmospheric metric)
- Must use operational NWP model forecasts (~10 km)
  - Cannot capture aircraft scale turbulence (~100m)
  - Or gravity waves (~few km)
  - Or in-cloud convection (~10-100s m)
  - Does capture large scale turbulence sources -> downscale cascade
    -> aircraft scale turbulence can be inferred
- Compute “turbulence diagnostics” (D) from NWP model output fields (e.g., winds, temperature)
- Ds are typically related to model spatial variations
- GTG approach: weighted ensemble mean of diagnostics
  \[ \text{GTG (EDR)} = W_1D_1 + W_2D_2 + W_3D_3 + \ldots \]
- R&D problems:
  - Develop Ds – requires better understanding of turbulence generation processes
  - Calibrate Ds in terms of **EDR**
  - Determine best way to use multiple diagnostics
  - Develop probabilistic forecast (probability of exceeding a certain EDR value?)
Turbulence nowcast system (GTGN)

Gridded Forecasts

- Numerical Weather Prediction Model
- Turbulence EDR Forecast Model (GTG)

Real-time Turbulence observations

Airborne observations
- In-situ EDR
- PIREPs

Ground-based observations
- NTDA mosaic

Turbulence inferences

DCIT algorithm
Satellite features
Lightning
Aircraft Deviations ASDI, ADSB

Aircraft Deviations ASDI, ADSB
Turbulence Problems that Aviation Decision Makers Face
Turbulence Issues for End Users

- ATC & ATM perspective
- Dispatch Perspective
  - Preflight-Strategic
  - En Route-Tactical
- Flight Attendant Perspective
- Pilot Perspective
- System Drivers
Turbulence Issues for End Users

- Controllers do not have access to turbulence data at the sector.
- PIREPS are entered into the system via sneaker net.
- Urgent PIREPS are the only PIREPS that get to the controller regularly at the sector.
- Ride reports are passed from controller to controller as they switch out.
- Altitudes are blocked when multiple reports for the same altitude come back bad or good.
Graphical Turbulence Guidance (GTG) Forecast

GTG2 - Maximum turbulence intensity (10000 ft. MSL to FL450)
Valid 1400 UTC Fri 15 Oct 2010
00–hr forecast from 1400 UTC 15 Oct
Dispatchers’ Issues

• Forecast
  – Model Selection
  – Forecaster Subjectivity

• Dispatcher / Pilots
  – Tool selection
  – Subjectivity / Risk Considerations
  – Workload drivers
Flight Attendants’ Issues

• Insufficient/ incomplete briefing from the flight crew on weather en route e.g. turbulence
• Inability to communicate effectively with flight deck about turbulence in the cabin
• Obligation to continue with service or compliance duties when the seatbelt sign is illuminated
• 300 lb. beverage cart that is a potential hazard
• Passengers disregard instructions and move about the cabin
Pilot Issues

• Current State
  – General forecast – Broad in scope
  – PIREPS – Wright Brother
  – ATC Chat Room

• Future State – Web viewer on a tablet
  – New turbulence metric
    • Existing A/C Sensors + Avionics’ box
    • Equals objective atmospheric state
  – Robust Forecast model using new metrics
Drivers

• Safety
  – If everyone is strapped in with carts stowed, NO ONE GETS HURT.
  – Key is not to cry wolf and F/A ignore warnings

• Efficiency/Emissions
  – Assumptions
  – Range of primary variables - %, Altitude, Time

• Capacity
  – FAA Focus

• Overall
  – The solutions for all 3 drivers might appear to conflict, but better turbulence knowledge can drive better solutions for all 3.
Turbulence Measurements and EDR Standardization

Presenter: Michael Emanuel
FAA Project Lead, EDRS

Panel: Matt Fronzak, Matt Taylor, Bob Sharman, Matt Wandishin, Sal Catapano
Turbulence Metrics

• State of Atmosphere
  – Eddy Dissipation Rate (EDR)
    • Aircraft-independent, universal measure of turbulence based on the rate at which energy dissipates in the atmosphere
    • Calculated using a variety of parametric data from aircraft avionics and computational algorithms
Turbulence Metrics

• G-Loads
  – Derived Equivalent Vertical Gust (DEVG) and Root Mean Square –Gravity (RMS-g)
    • Impact response for a given aircraft at specific and unique flight conditions

• Pilot Report (PIREP)
  – Voluntary report from a pilot of weather conditions encountered in flight reported to ATC and/or Flight Service
Origin of the In Situ EDR Standards Project

• In 2001, ICAO made EDR the turbulence metric standard

• In 2012, RTCA SC-206, developed an Operational Services and Environmental Definition (OSED) identifying the necessity for:
  – An international effort to develop performance standards for aircraft EDR values, independent of computation approach,
  – To set Minimum Operational Performance Standards (MOPS), and
  – To standardize aircraft EDR databus labels and encoding of EDR parameter values
Origin of the In Situ EDR Standards Project

• In response, the FAA initiated an In Situ EDR Standards Project in July, 2012 that will:
  – Provide the analysis, inputs, and recommendations required to adopt in Situ EDR performance standards
  – Provide supporting research required to adopt standards for EDR value and label definitions
• This project will not score EDR algorithms or calculation approaches
Why *In Situ* EDR Standards are Needed?

- EDR is a calculated metric (not measured)
  - Without a standard, differences in algorithmic approach and operational input could lead to unacceptable deviations in resulting EDR values
In Situ EDR Calculation

- Methods of calculation include: winds and vertical acceleration
  - Vertical Wind
    - Input: calculated vertical winds
    - Airlines: Delta and Southwest
  - Horizontal Wind
    - Input: longitudinal wind via true airspeed
    - Airlines: Regional airlines (via TAMDAR program)
  - Vertical Acceleration
    - Input: turbulence level is inferred from aircraft response (indirect method)
    - Airlines: United and American

A literature search has not identified any international *in situ* EDR operational implementations (E-AMDAR/UK Met Office confirmed)
Scope

In Situ EDR Standardization

Ground-Based EDR Calculations

GPS-Based EDR Calculations

Alternative In Situ Turbulence Metrics

In project scope

Out of scope
Project Overview
Work Element Relationship

Collaboration

RTCA SC-206

Sub-Group 4

EDR Standards Project

Standardization Process Development

Performance Artifact Development

Algorithm Input Data
EDR Objective Value Definition
EDR Tolerance Threshold

EDR Value and Label Definitions
Upcoming Events & Collaboration

• AMS Annual Meeting Paper / Briefing January, 2013 will provide details on:
  – approach EDR Standards Project will use to develop standards
  – information learned from EDR Literature Search (e.g. algorithms, applications, implementations)

• Project places a heavy focus on leveraging collaboration opportunities that provide mutual benefits
Focal Points

We would like to invite you to contact us and identify areas of the project for which you would like to offer your expertise

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Verification of Turbulence Forecasts
The Need for Forecast Evaluation

Build trust in the quality of turbulence forecasts to allow for an increase in usable airspace and reduce injuries and aircraft damage.
Untangling Observations for use in Verification

- Different instruments recording EDR
  - Limits use of data at some altitudes
- Different reporting approaches
  - Impacts categorization of turbulence severities
  - Introduces complexities with defining the event
Measuring Turbulence Events

Observed Event

Forecast Events
Event Length Analysis

Forecasts produce turbulence events substantially longer than observed.

75% of all observed turbulence runs as measured by EDR are shorter than 17 km.

75% forecast (1) turbulence event length is 229 km.
75% forecast (2) event length is 183 km.
Event Comparison

forecast event

observed events
Event Comparison

Onset error (1)

forecast event

Cessation Error (1)

observed events
Event Comparison

forecast event

observed events

Onset error (2)

Cessation Error (2)
Event Comparisons

Distribution event onset errors

Forecast too early  Forecast too late

\[ f - o \]
Highlights

• Definition of the ‘operational weather problem’ for aviation provides the foundation for the evaluation
• Forecasts must be translated to a common framework in order to adequately compare quality and accuracies
• Observation datasets need to be deeply investigated for adequate use in an evaluation
• Taking advantage of new observation datasets allows for advancements in methodologies and metrics
Turbulence Integration
Integration of Turbulence Information

• Reports
  – Collection - automated & manual sources
  – Evolution – PIREPS (Orville) to A/C sensors
  – Ingesting reports into computer models
• Turbulence Forecasts & Verification
• Distribution of reports or forecasts to users
• Display for decision makers
An Integrated Turbulence Avoidance System

The Delta weather hazard avoidance system includes 4 components for both preflight planning and en route ops:

- **Communication Capabilities**
  (manual and automated text and graphics distribution)
- **Avoidance Policies & Procedures**
  (implemented jointly by pilots and dispatchers)
- **Products**
  (automated &/or generated by Delta Meteorology)
- **System Familiarization via Training**
  (ongoing process for both users and producers)

But certainly not perfect
Depictions (Preflight) & TPs (En Route)
General Avoidance Policy & Procedures

Preflight & En Route Action Criteria
For both Pilots and Dispatchers

AVOID
Avoid The Hazard (unless under emergency authority)

ALERT
Avoidance Recommended, if feasible. Minimize exposure to the affected altitudes or areas.

ADVISORY
No Restrictions
Future State

• Drivers
  – Safety
  – Efficiency
  – Capacity

• Web viewer on a tablet
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