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

Team: M.Fronzak, G. Jarrett, M.Tucker & B.Watts

3. Turbulence Measurements & EDR Standardization

Presenter Mike Emanuel

Team: T.Farrar, M.Fronzak, B.Sharman, M.Taylor, M.Wandishin, S. Catapano & M.Emanuel

4. Verification of Turbulence Forecasts

Presenter: Jennifer Mahoney

Team: J.Mahoney, M.Wandishin, B.Sharman, M.Taylor & B.Watts

5. Integration of Turbulence Info

Presenter: Mark Bradley

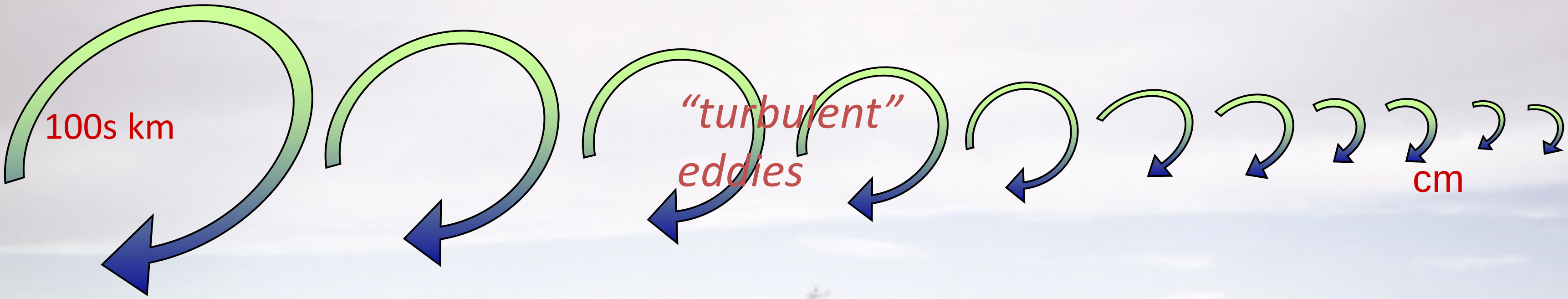
Team: M.Bradley, T.Fahey, M.Fronzak, J.Mahoney, B.Sharman, M.Taylor & M.Tucker

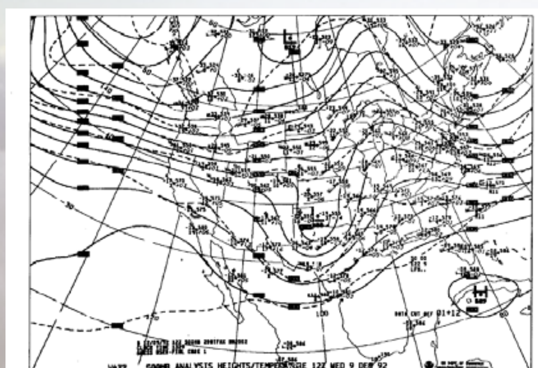
Turbulence Causes, Character, and Forecasting

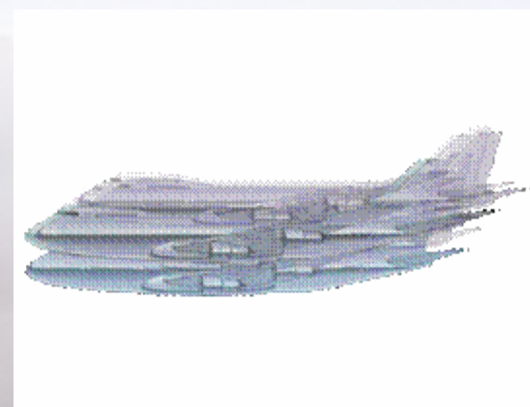
Scales of Aircraft Turbulence/ Turbulence Intensity Metric (EDR)

Largest eddies:
Energy Input

Smallest eddies:
Energy Dissipation







Aircraft responds to scales from

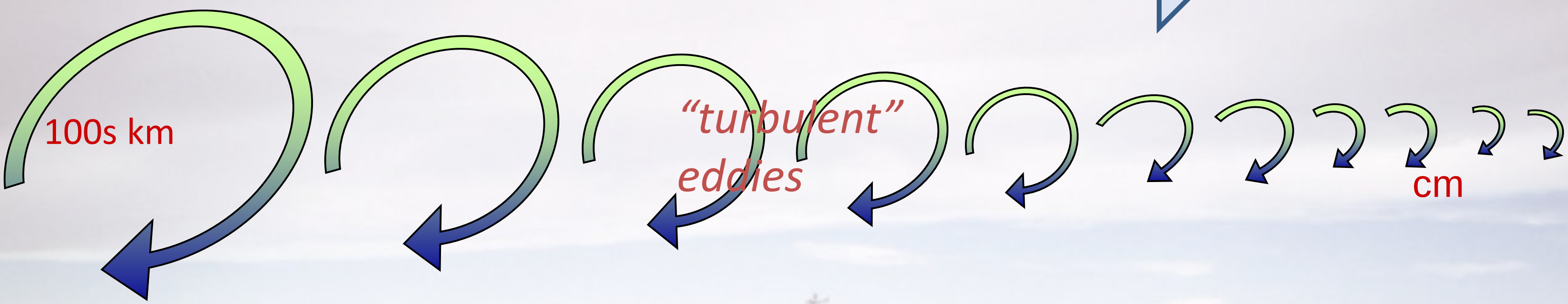
~100m – 3 km

Scales of Aircraft Turbulence/ Turbulence Intensity Metric (EDR)

Largest eddies:
Energy Input

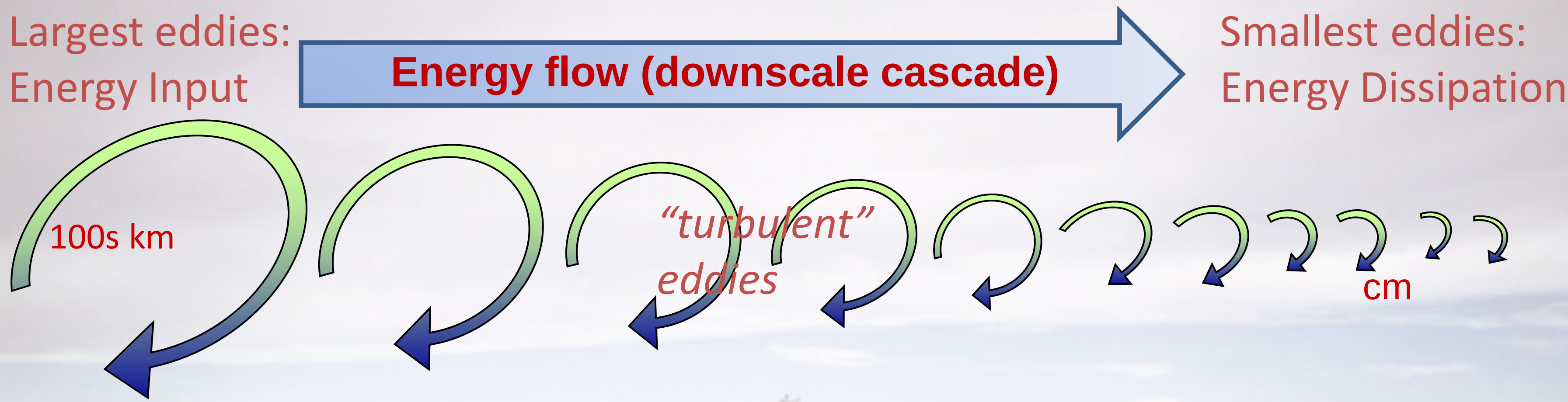
Energy flow (downscale cascade)

Smallest eddies:
Energy Dissipation



Faucet-sink analogy

Scales of Aircraft Turbulence/ Turbulence Intensity Metric (EDR)



- Energy production at largest scales
- Energy dissipation (into heat) at smallest scales. Depends on viscosity.
- ->"Downscale cascade"
- ε = Energy dissipation rate at the <u>smallest scales</u> (units of de/dt: m^2/s^3).
- Usually energy production at large scales ~ energy dissipation at small scales and ε 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 <u>exactly</u> at the small scales (but requires very high resolution), <u>approximately</u> 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)

Cloud-induced or Convectively-induced Turbulence (CIT)

In-cloud turbulence

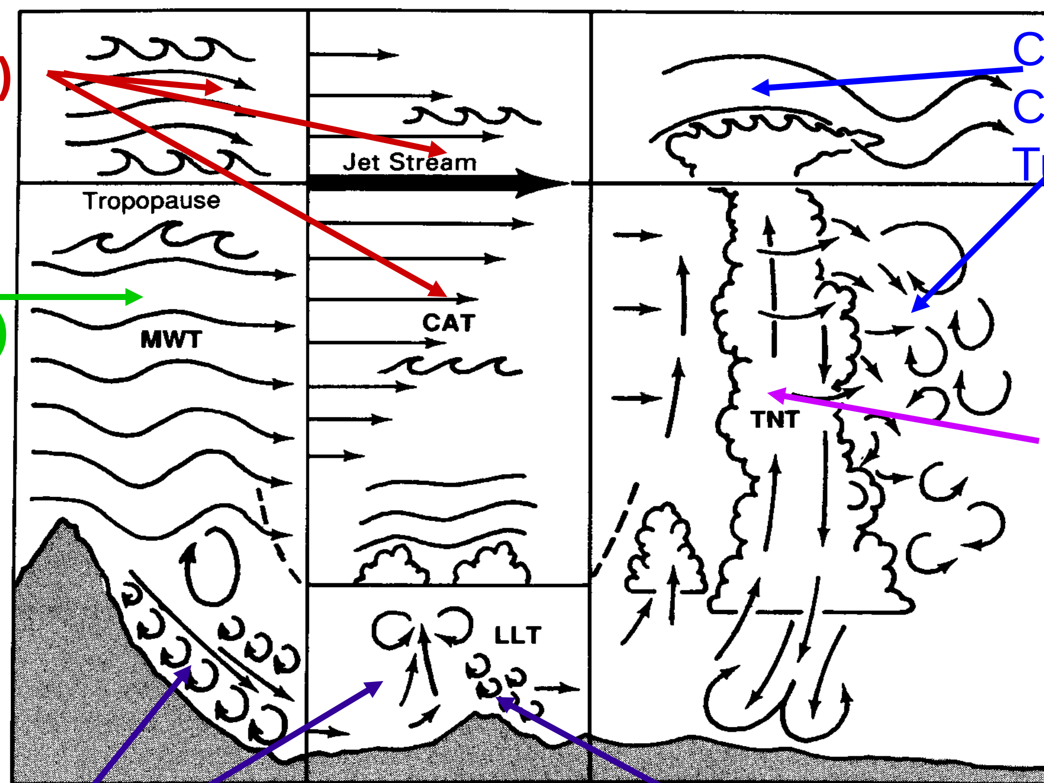


Figure 1-10. Aviation turbulence classifications. This figure is a pictorial summary of the turbulence-producing phenomena that may occur in each turbulence classification.

Low level Terrain-induced Turbulence (LLT)

Convective boundary Layer turbulence

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

Background
Known Turbulence Sources

Kelvin-Helmholtz Instability

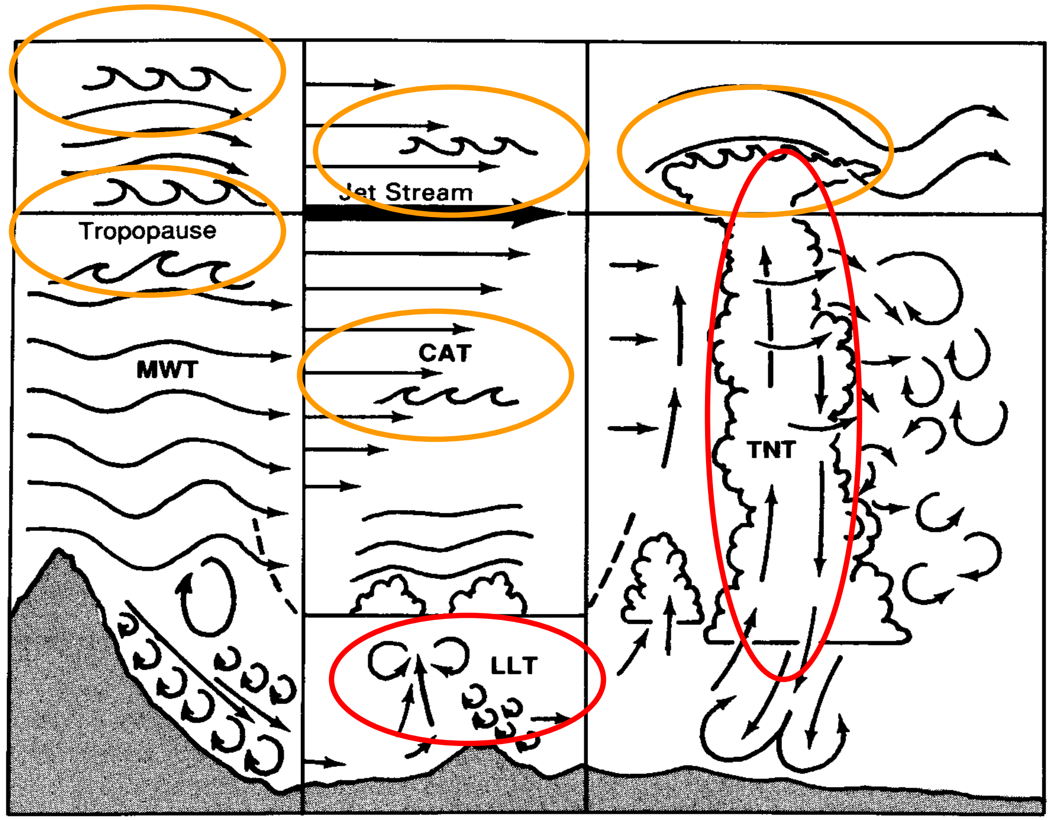
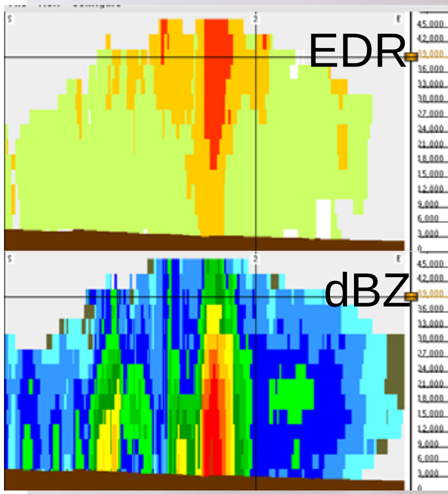


Figure 1-16. Aviation turbulence classifications. This figure is a pictorial summary of the turbulence-producing phenomena that may occur in each turbulence classification.

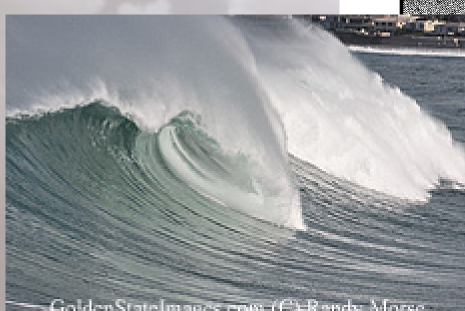
Convective Instability

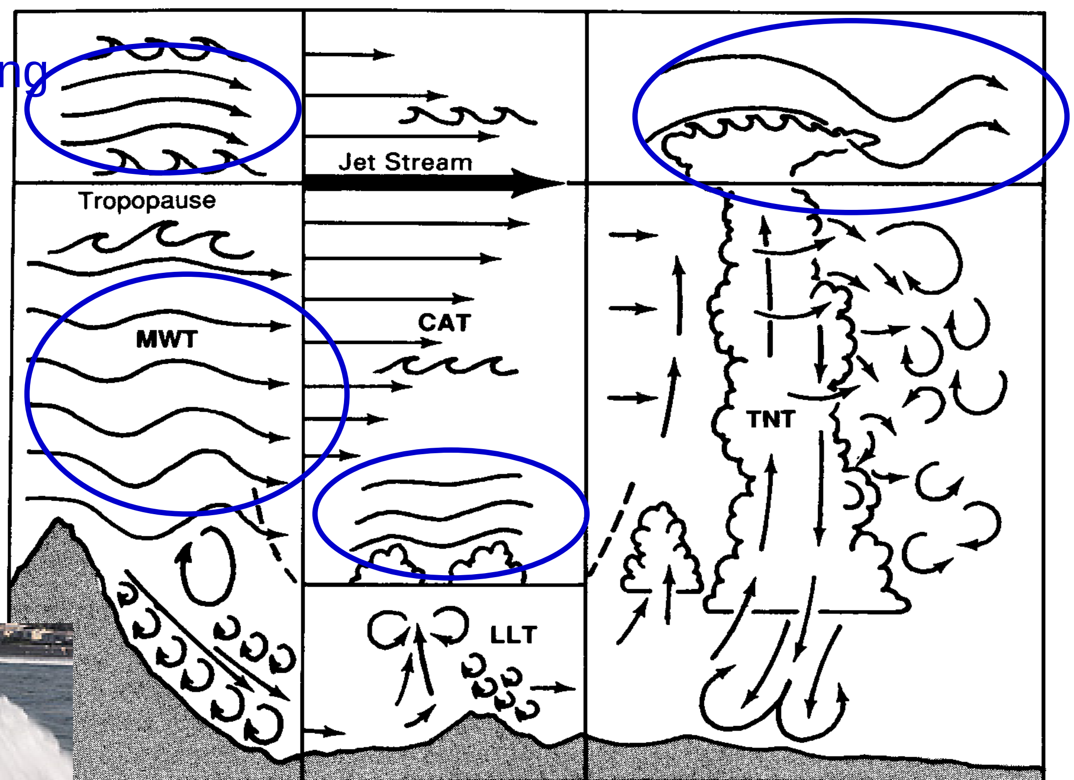


Source: P. Lester, "Turbulence – A new perspective for pilots," Jeppesen, 1994

Background
Known Turbulence Sources

Gravity waves and wave breaking





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

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

Convectively-Induced Turbulence (CIT)

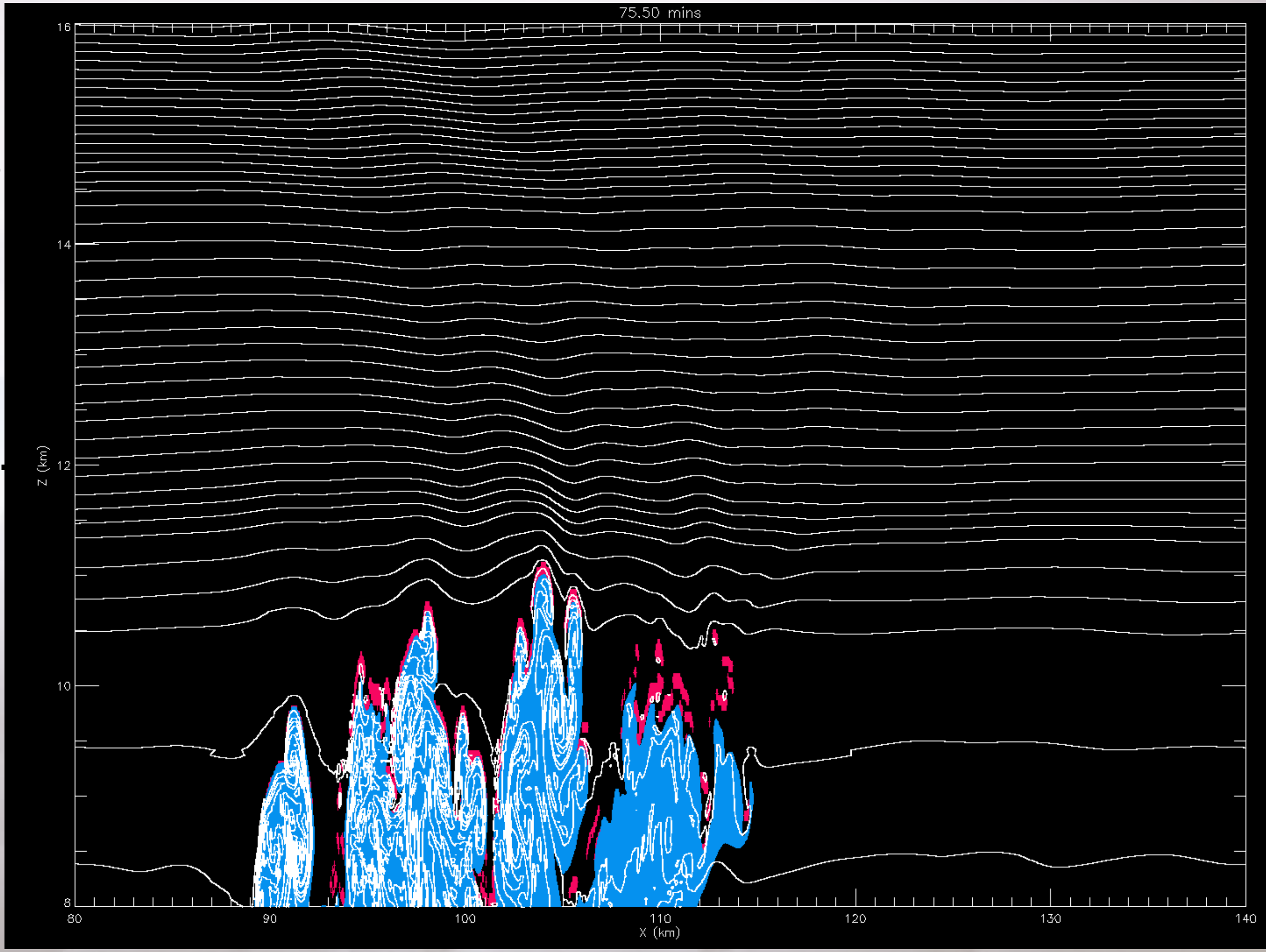
Some turbulence occurs in clear air near cloud (CIT)

FAA avoidance guidelines are inadequate

<u>Example</u>

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

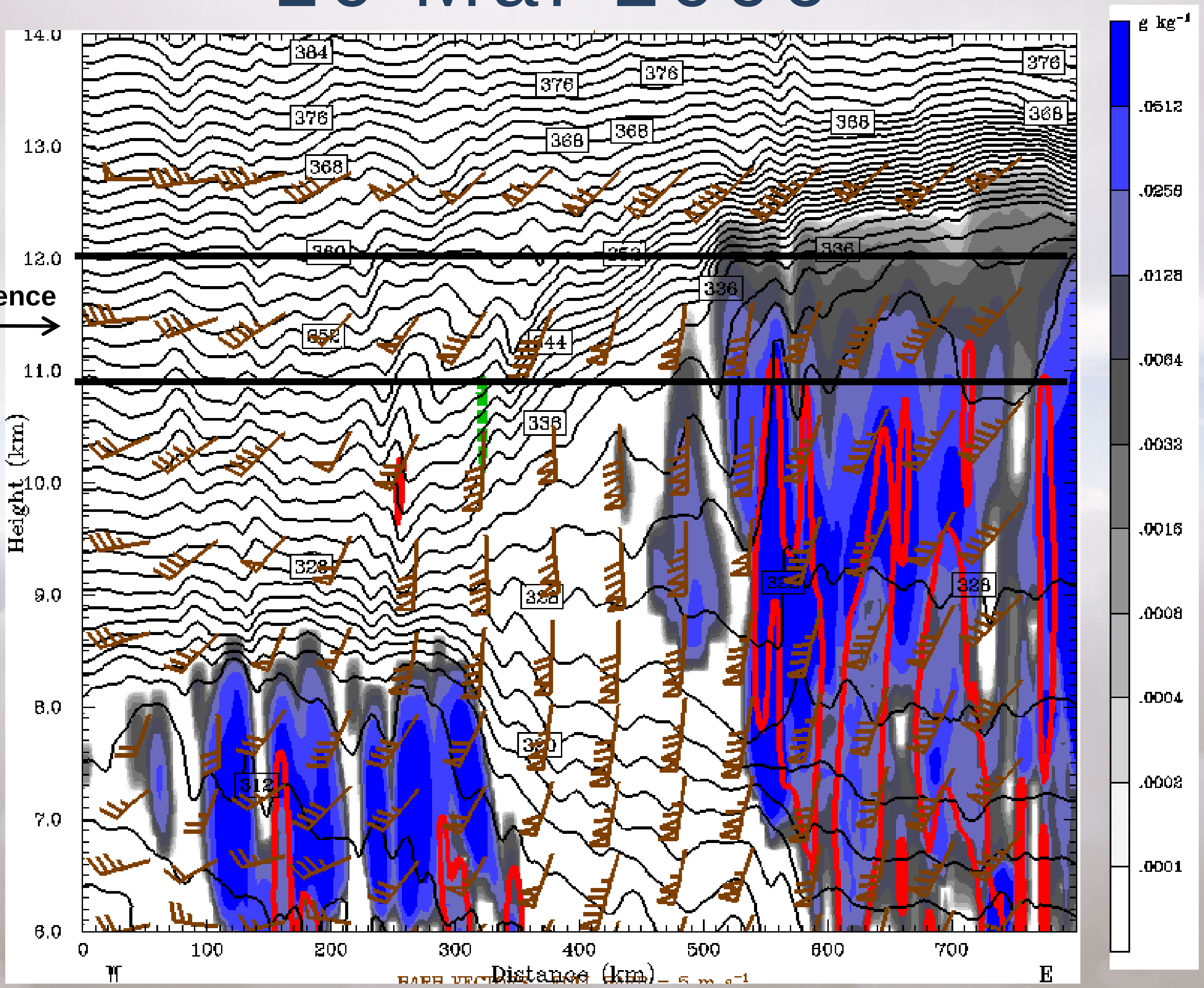


Courtesy Todd Lane, U. Melbourne

Lane and Sharman, JAMC 2008

"CAT" Outbreak
10 Mar 2006

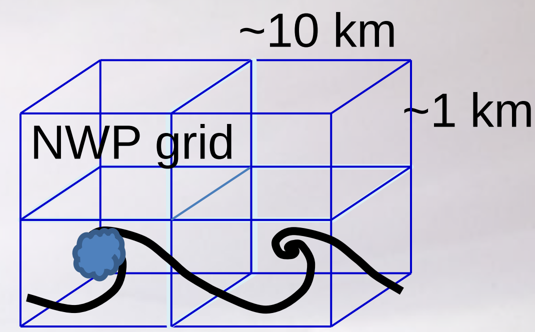
Reported Turbulence Layer →



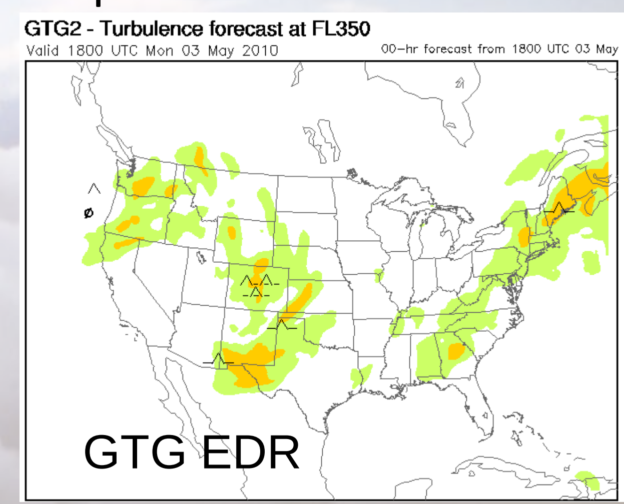
60-Min Animation (0020 to 0120 UTC 10 March 2006), Δ t = 5 min

Cloud (colorfill), θ (2-K contour interval), w (1 m/s contour interval; updrafts red, downdrafts, green)

Automated Turbulence Forecasting



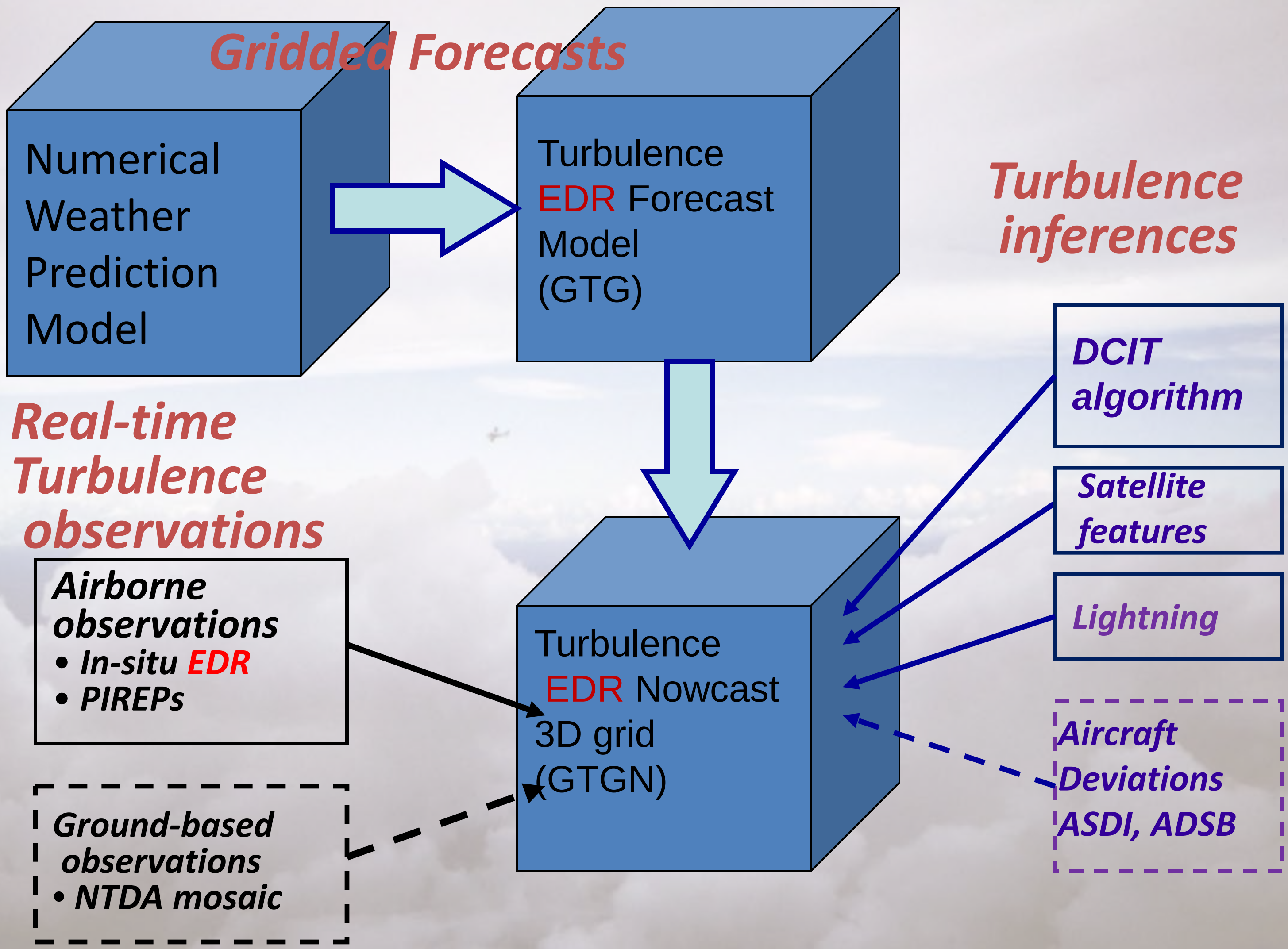
- Forecast EDR (atmospheric metric)
- Must use operational NWP model forecasts (~10 km)
  - Cannot capture aircraft scale turbulence (~100m)
  - Or gravity waves (~few km)
  - Or in-cloud convection (~ 10-100s m)
  - Does capture large scale turbulence sources -> downscale cascade -> aircraft scale turbulence 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

  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 <u>probabilistic</u> forecast (probability of exceeding a certain EDR value?)

Turbulence nowcast system (GTGN)



Turbulence Problems that Aviation Decision Makers Face

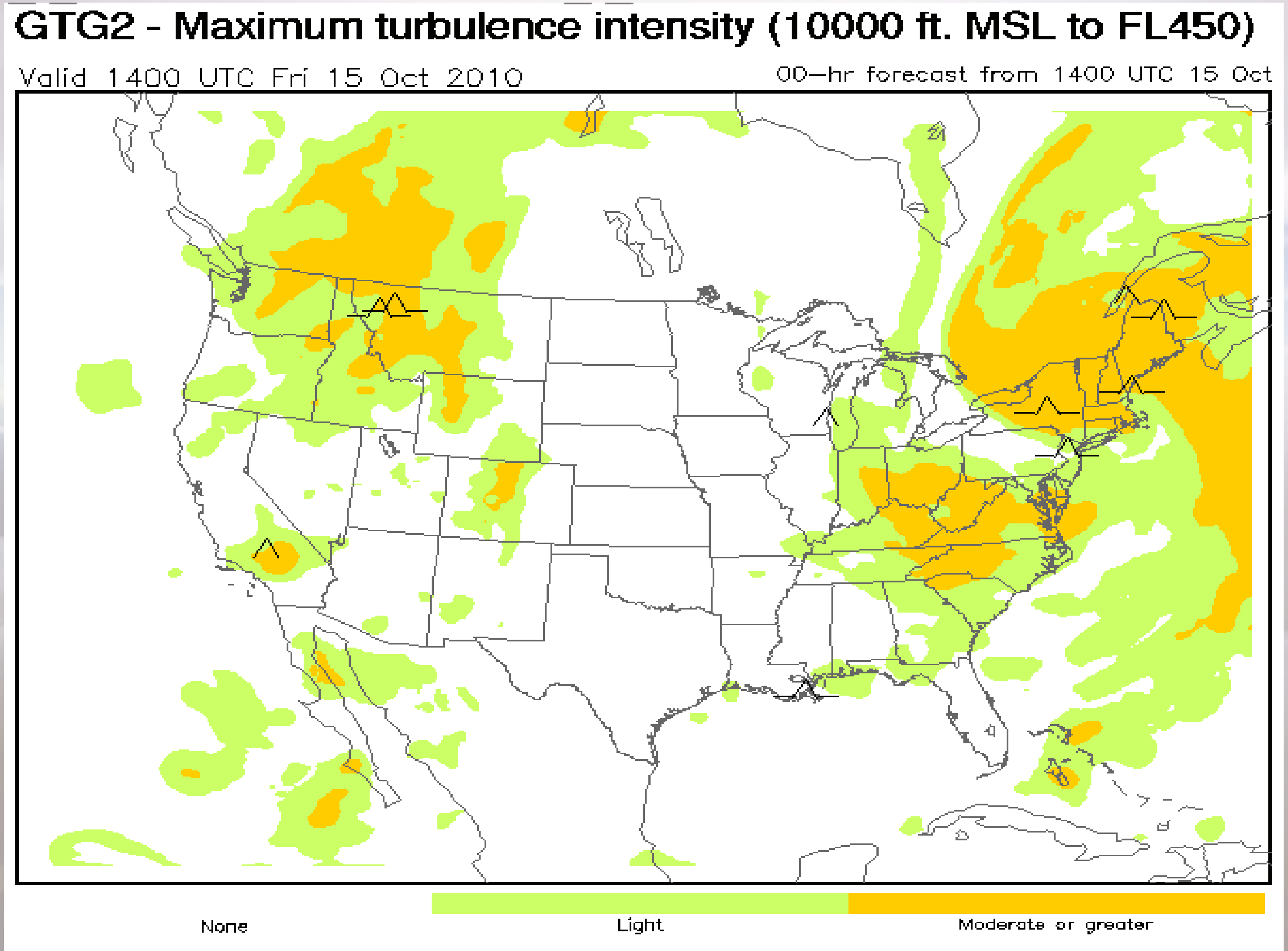
Turbulence Issues for End Users

- 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



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?

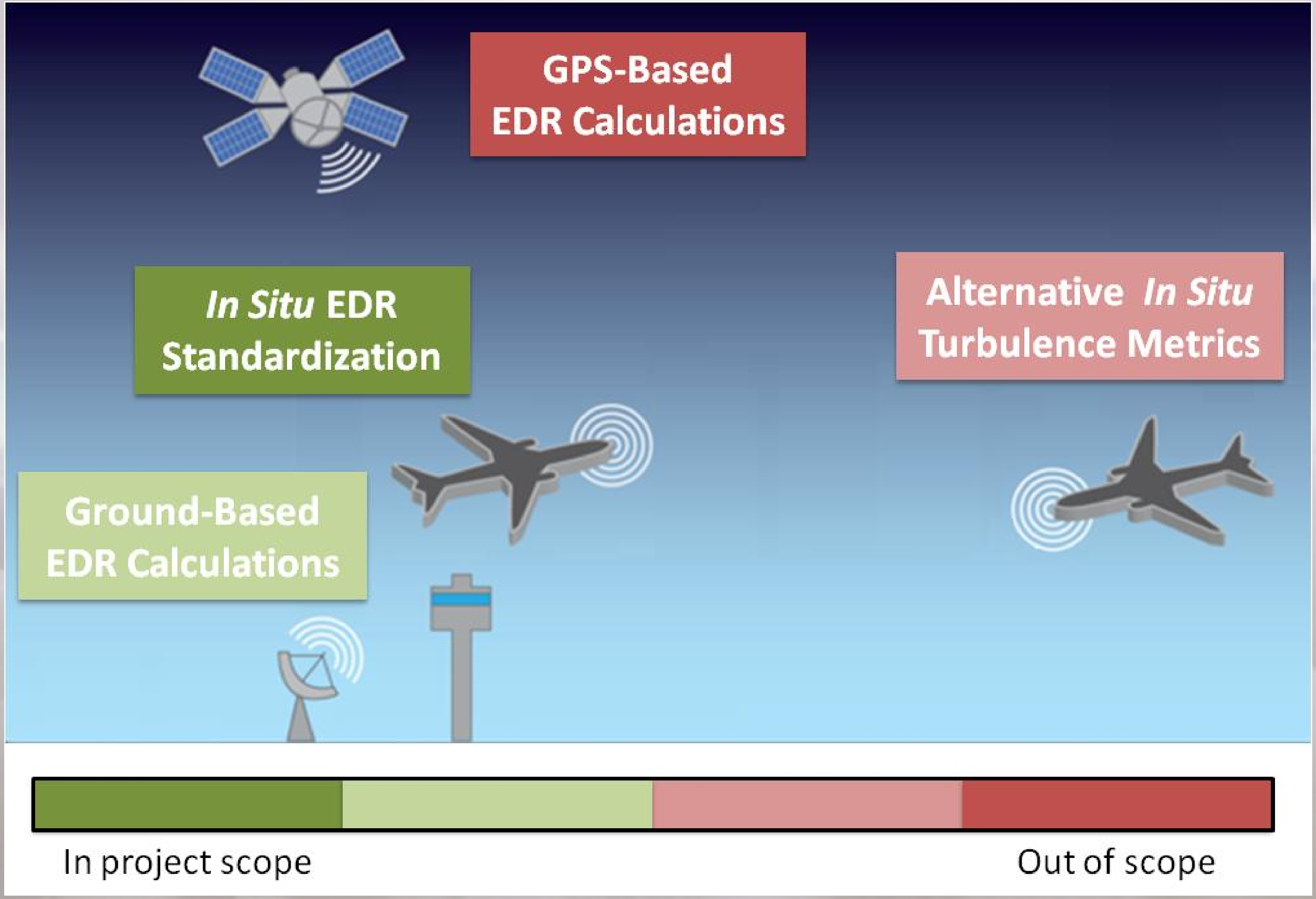
- EDR is a calculated metric (not measured)
  - Without a standard, differences in algorithmic approach and operational input could lead to unacceptable deviations in resulting EDR values

In Situ EDR Calculation

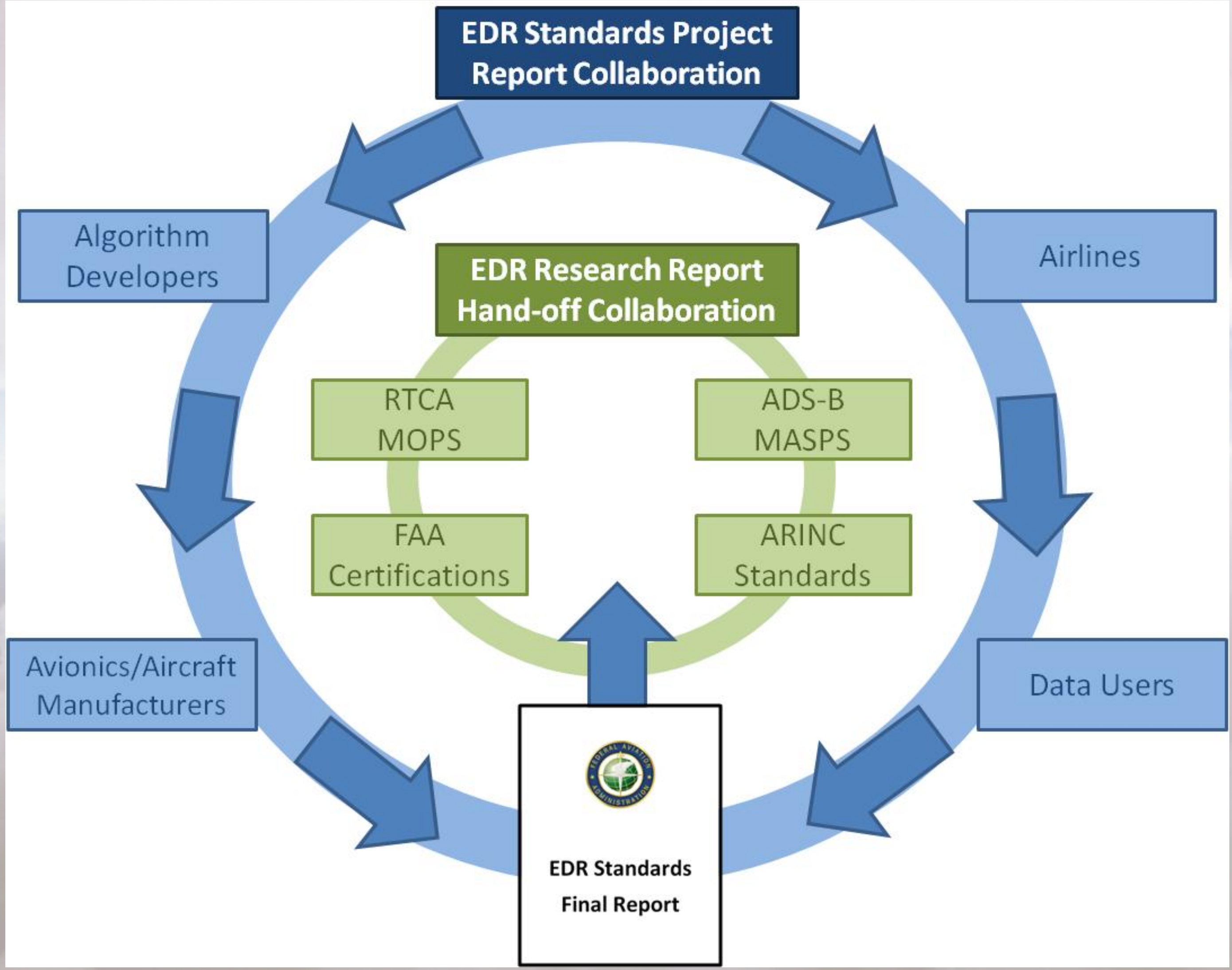
- Methods of calculation include: winds and vertical acceleration
  - Vertical Wind
    - Input: calculated vertical winds
    - Airlines: Delta and Southwest
  - Horizontal Wind
    - Input: longitudinal wind via true airspeed
    - Airlines: Regional airlines (via TAMDAR program)
  - Vertical Acceleration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

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

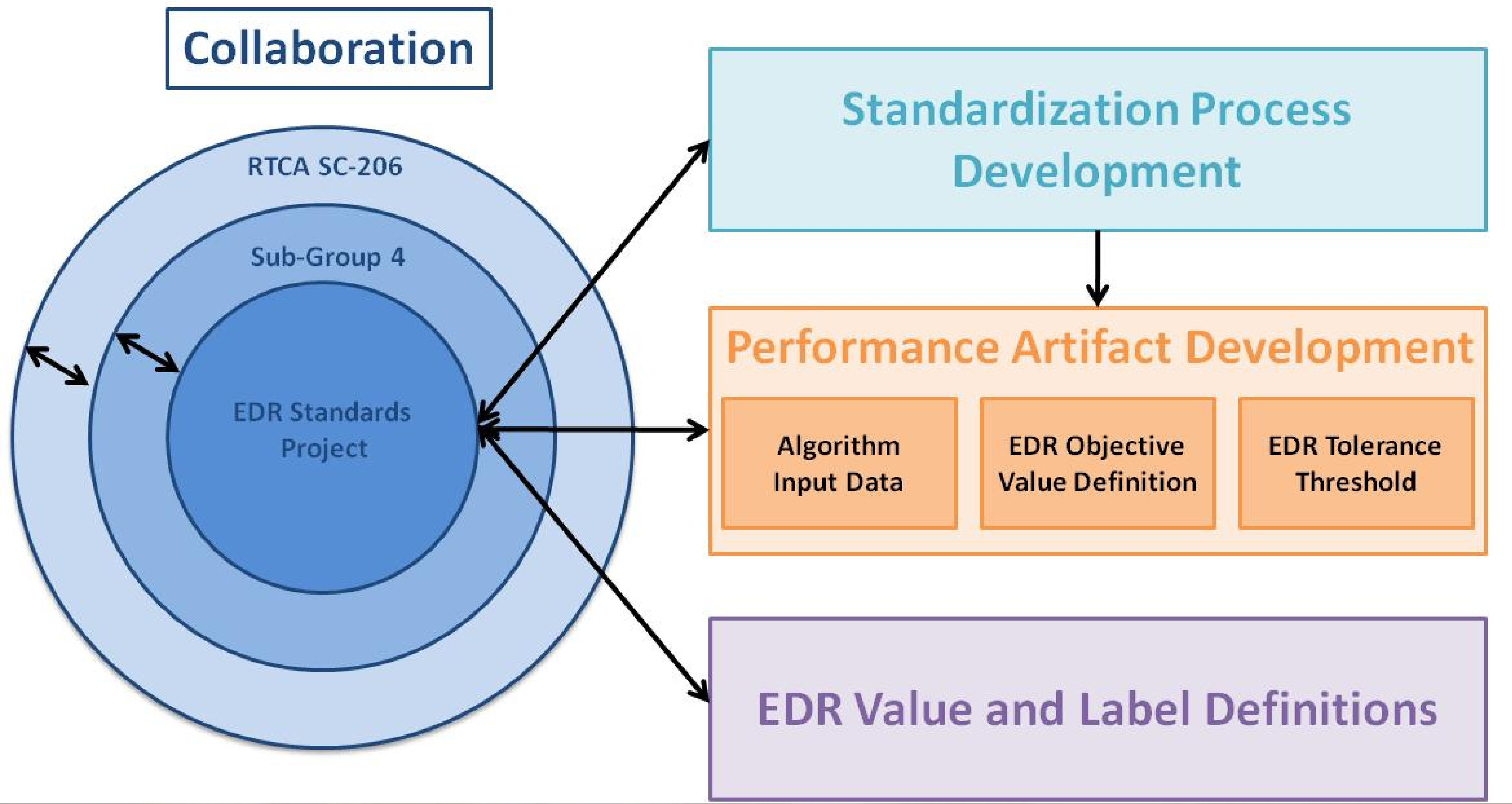
Scope


GPS-Based
EDR Calculations
In Situ EDR
Standardization
Alternative *In Situ*
Turbulence Metrics
Ground-Based
EDR Calculations
In project scope
Out of scope

Project Overview



Work Element Relationship



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

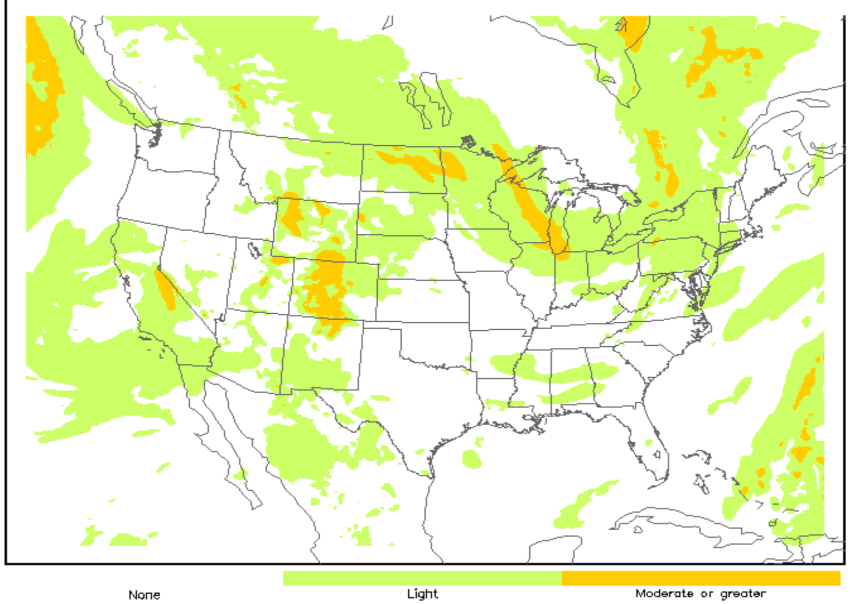
Name	Phone	Email
Michael Emanuel - FAA	609-485-4873	michael.emanuel@faa.gov
Joe Sherry - Exelis	202-651-7533	joseph.sherry@exelisinc.com
Sal Catapano - Exelis	202-651-7545	salvatore.catapano@exelisinc.com

Verification of Turbulence Forecasts

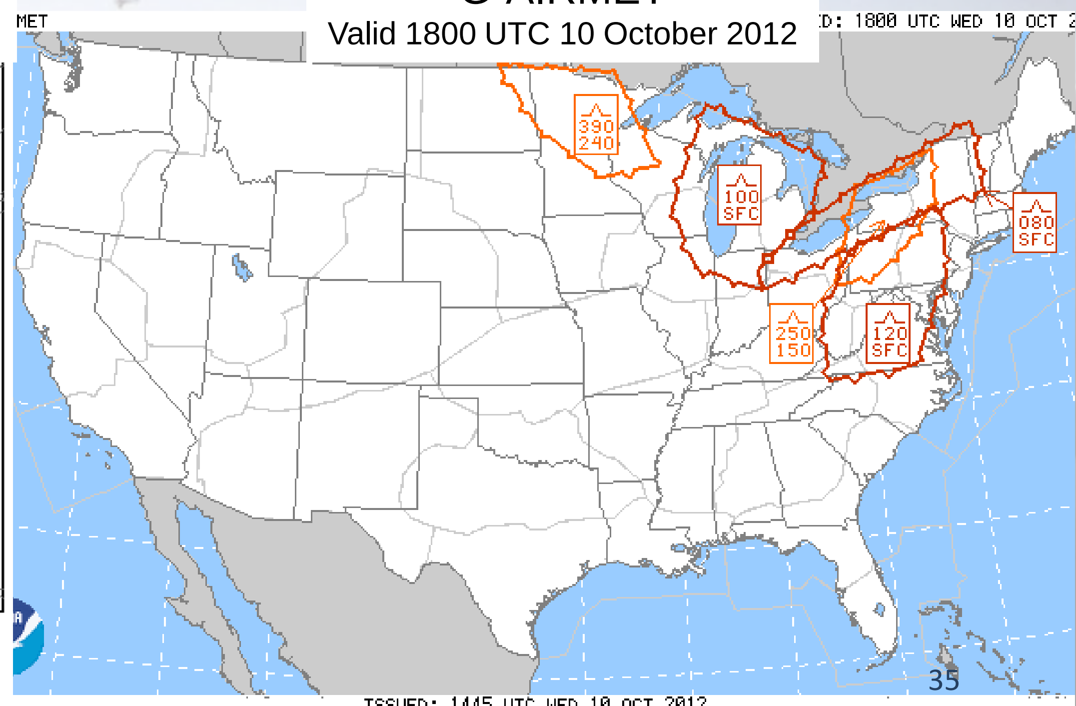
The Need for Forecast Evaluation

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

Graphical Turbulence Guidance
Valid 1800 UTC 10 October 2012



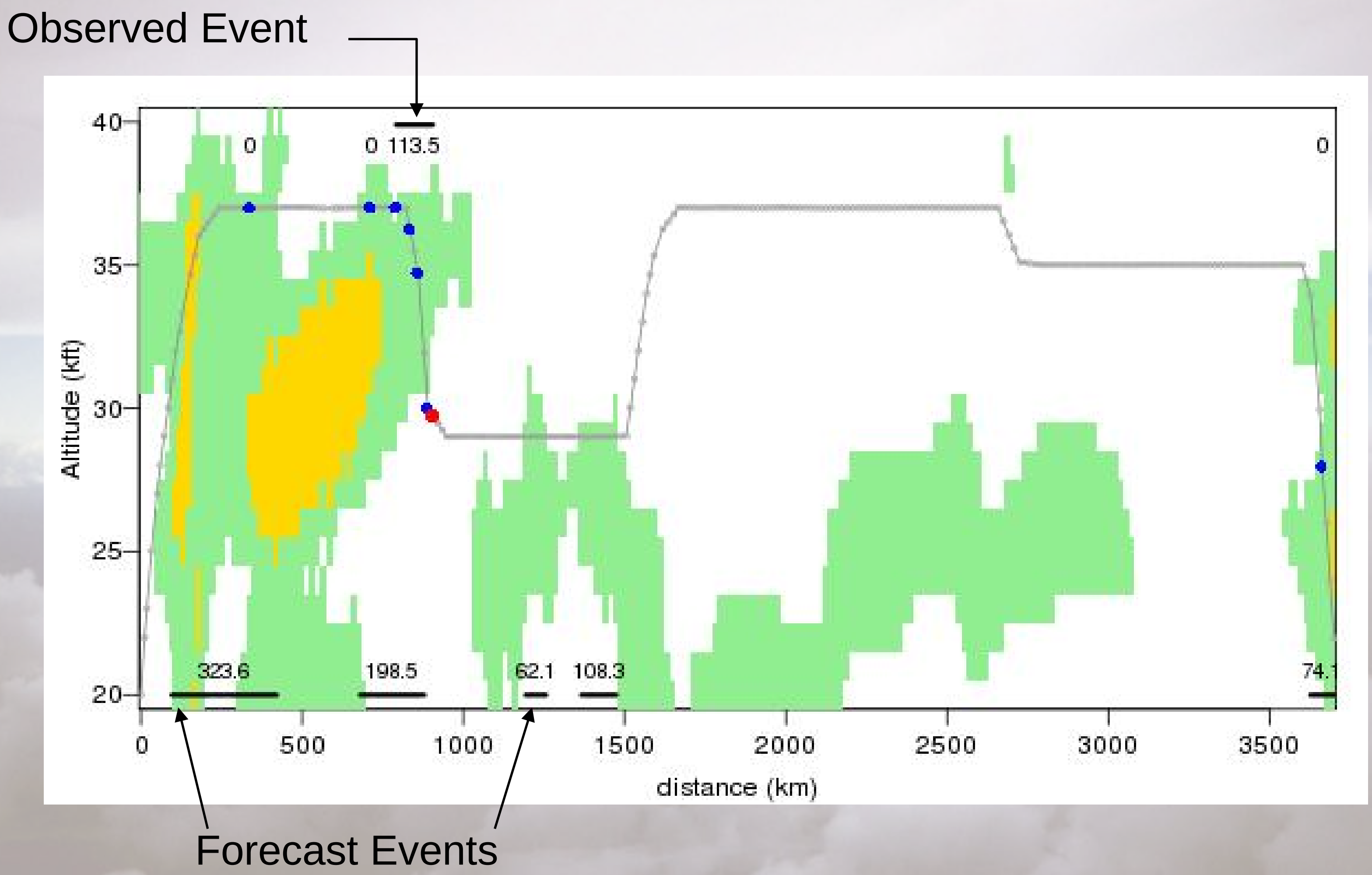
G-AIRMET
Valid 1800 UTC 10 October 2012



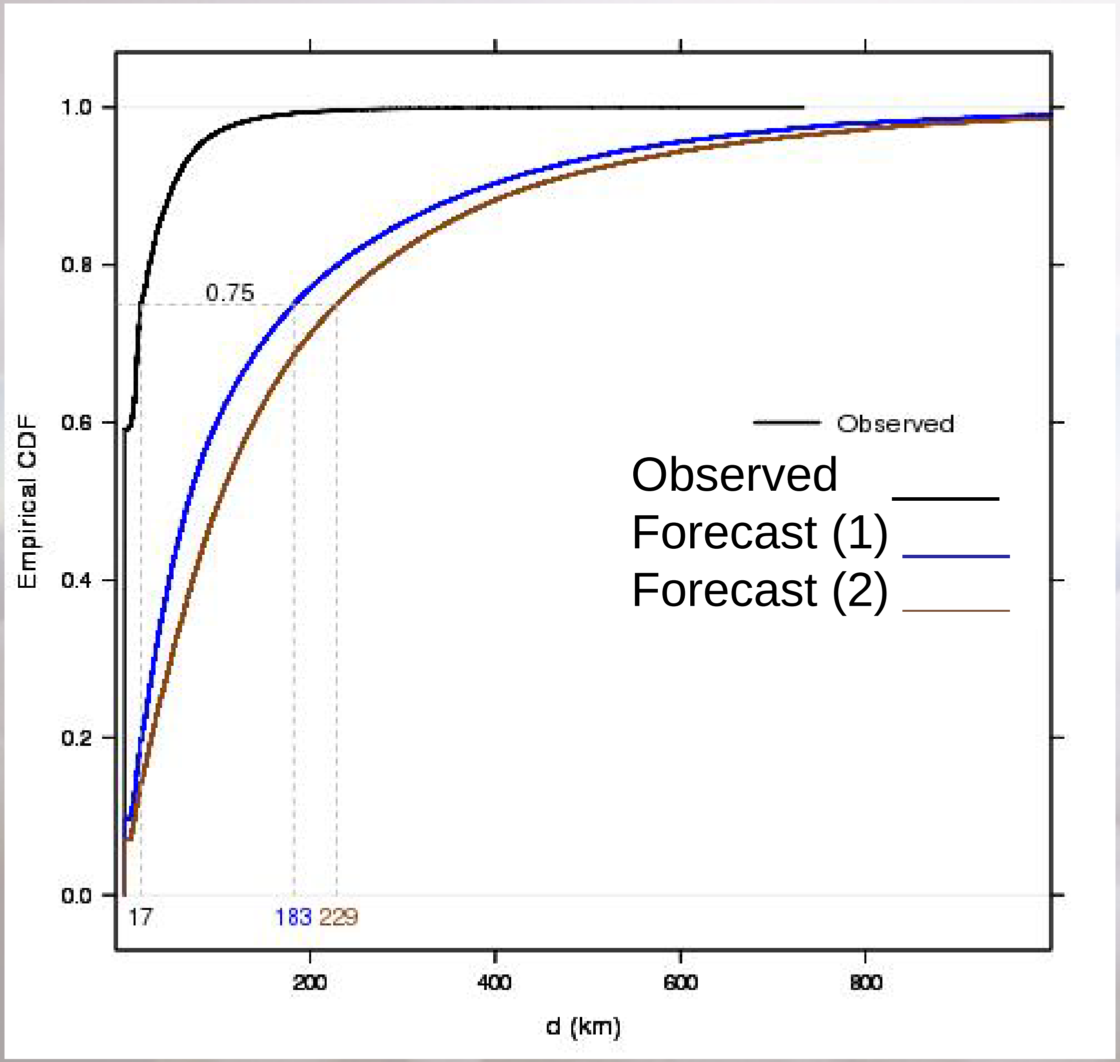
Untangling Observations for use in Verification

- 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



Event Length Analysis



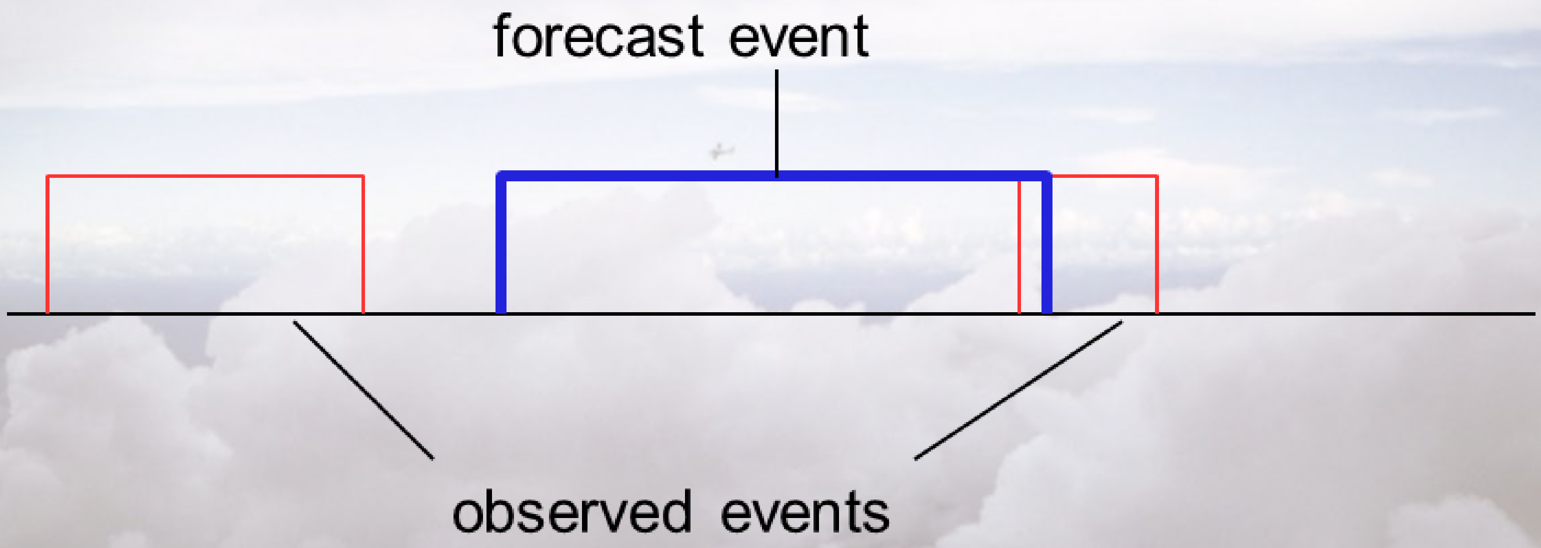
Forecasts produce turbulence events substantially longer than observed

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

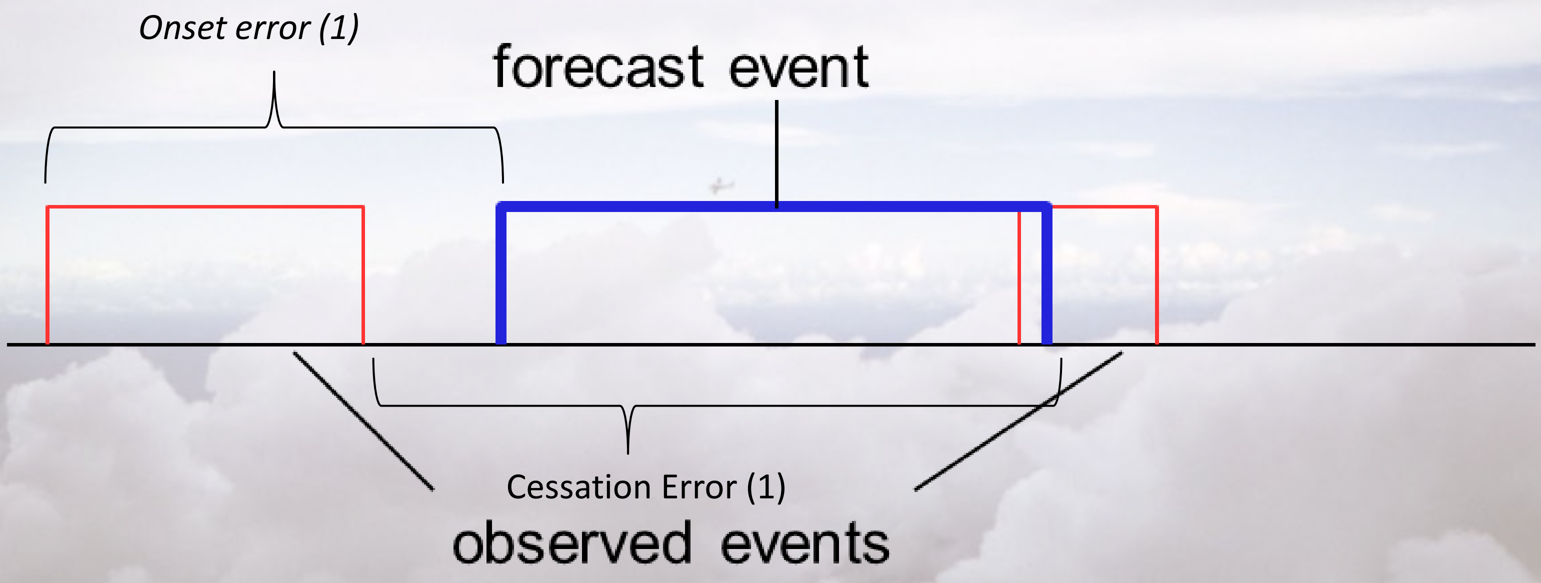
75% forecast (1) turbulence event length is 229 km

75% forecast (2) event length is 183 km

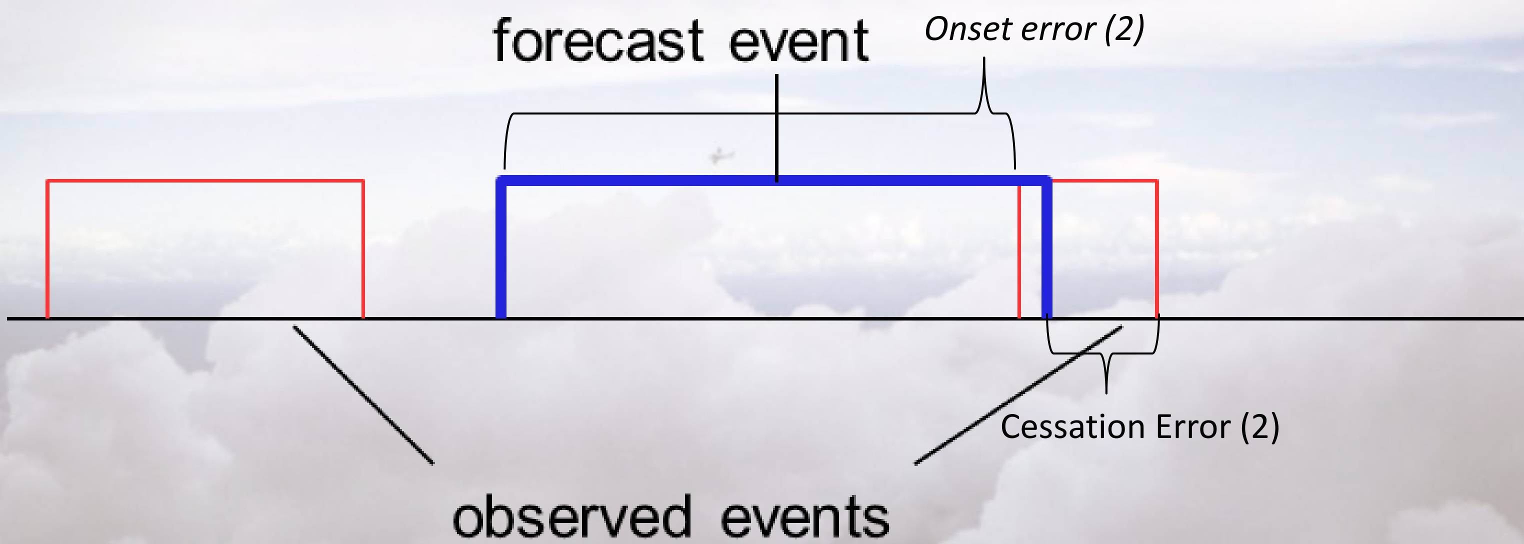
Event Comparison



Event Comparison

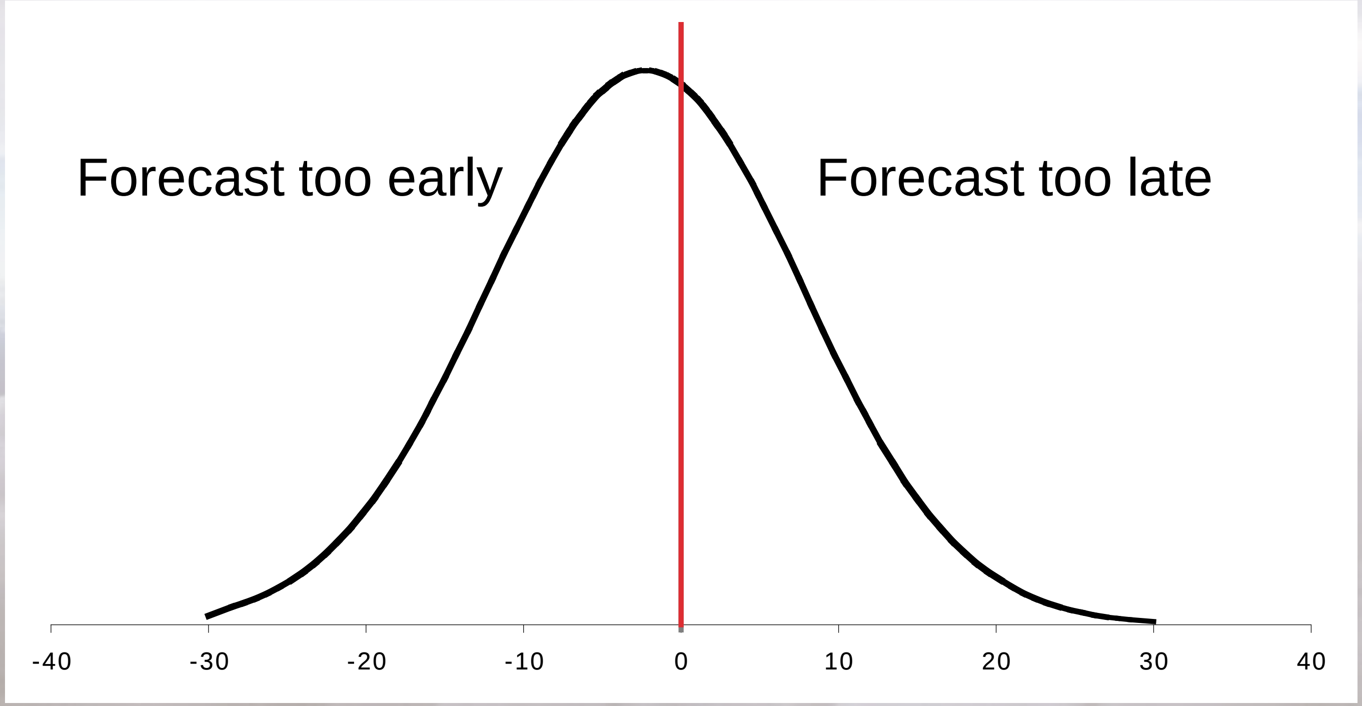


Event Comparison



Event Comparisons

Distribution event onset errors



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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

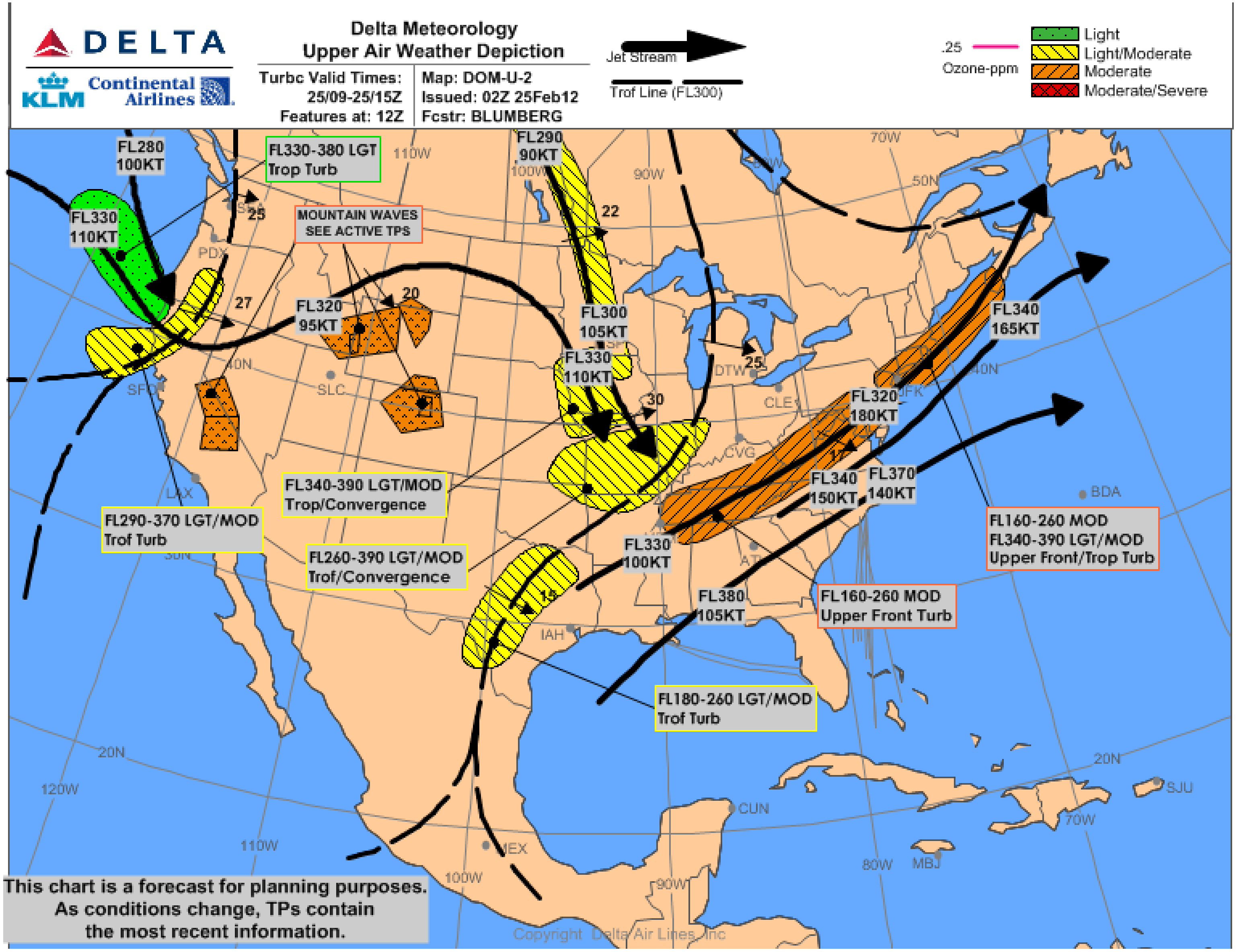
An Integrated Turbulence Avoidance System

But certainly not perfect

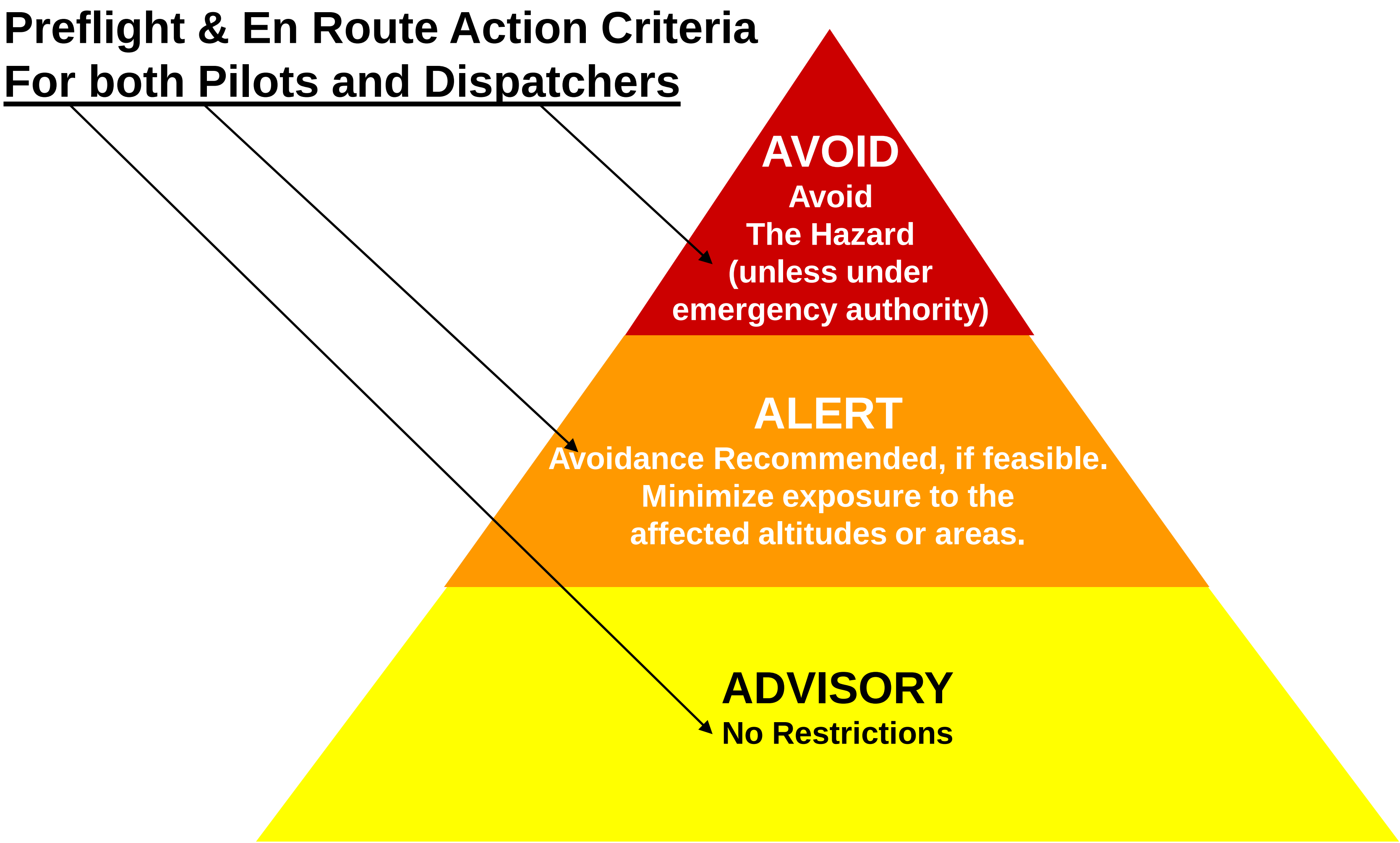
The Delta weather hazard avoidance system includes 4 components for both preflight planning and en route ops:

- **C**ommunication Capabilities
  (manual and automated text and graphics distribution)
- **A**voidance Policies & Procedures
  (implemented jointly by pilots and dispatchers)
- **P**roducts
  (automated &/or generated by Delta Meteorology)
- **S**ystem Familiarization via Training
  (ongoing process for both users and producers)

Depictions (Preflight) & TPs (En Route)

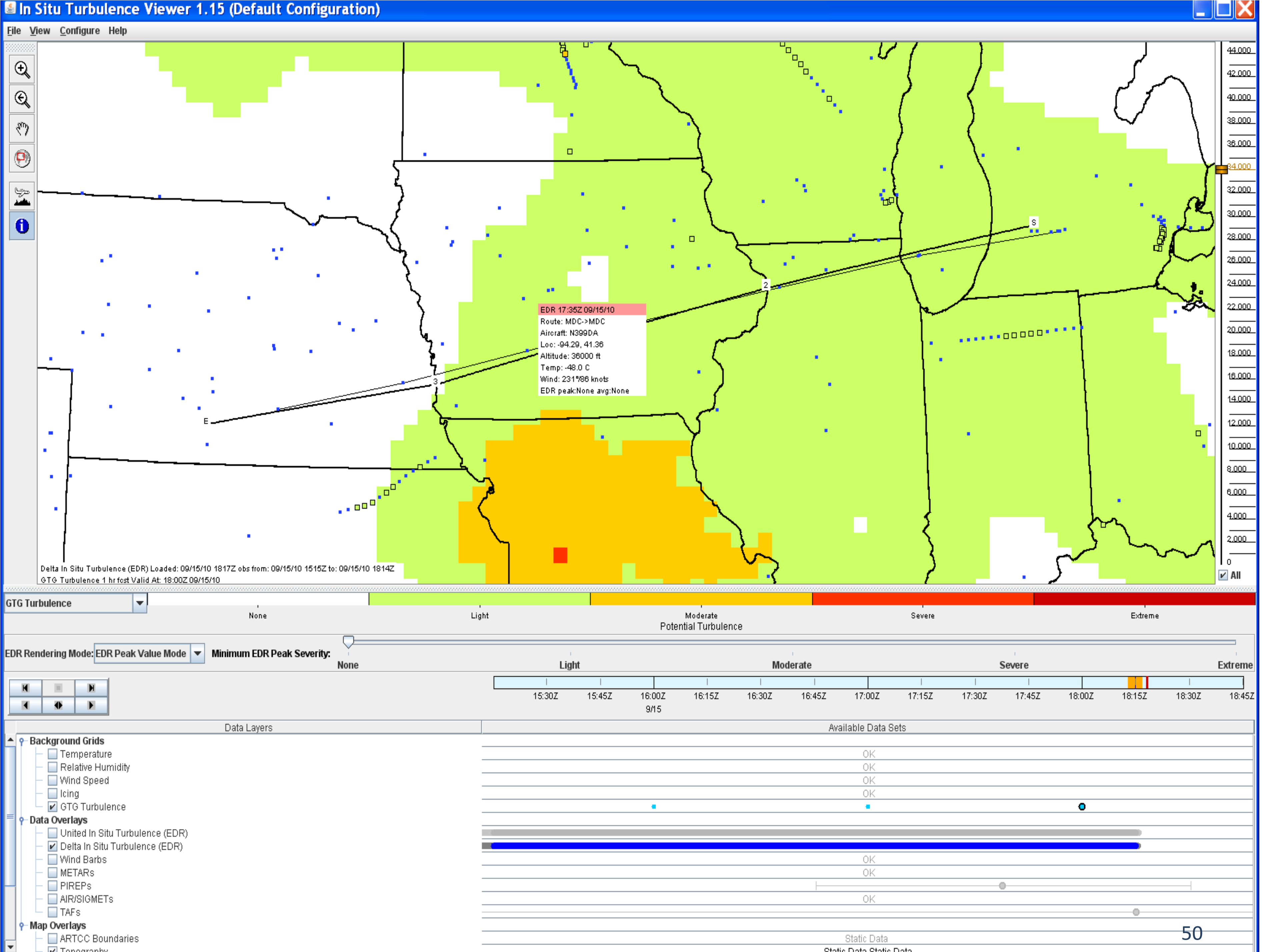


General Avoidance Policy & Procedures



Future State

- Drivers
  - Safety
  - Efficiency
  - Capacity
- Web viewer on a tablet
  - New turbulence metric
    - Existing A/C Sensors + Avionics' box
    - Equals objective atmospheric state
  - Robust Forecast model using new metrics


In Situ Turbulence Viewer 1.15 (Default Configuration)
File View Configure Help
EDR 17:35Z 09/15/10
Route: MDC->MDC
Aircraft: N399DA
Loc: -94.29, 41.36
Altitude: 36000 ft
Temp: -48.0 C
Wind: 231°/86 knots
EDR peak:None avg:None
Delta In Situ Turbulence (EDR) Loaded: 09/15/10 1817Z obs from: 09/15/10 1515Z to: 09/15/10 1814Z
GTG Turbulence 1 hr fcst Valid At: 18:00Z 09/15/10
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EDR Rendering Mode: EDR Peak Value Mode
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GTG Turbulence
Data Overlays
United In Situ Turbulence (EDR)
Delta In Situ Turbulence (EDR)
Wind Barbs
METARs
PIREPs
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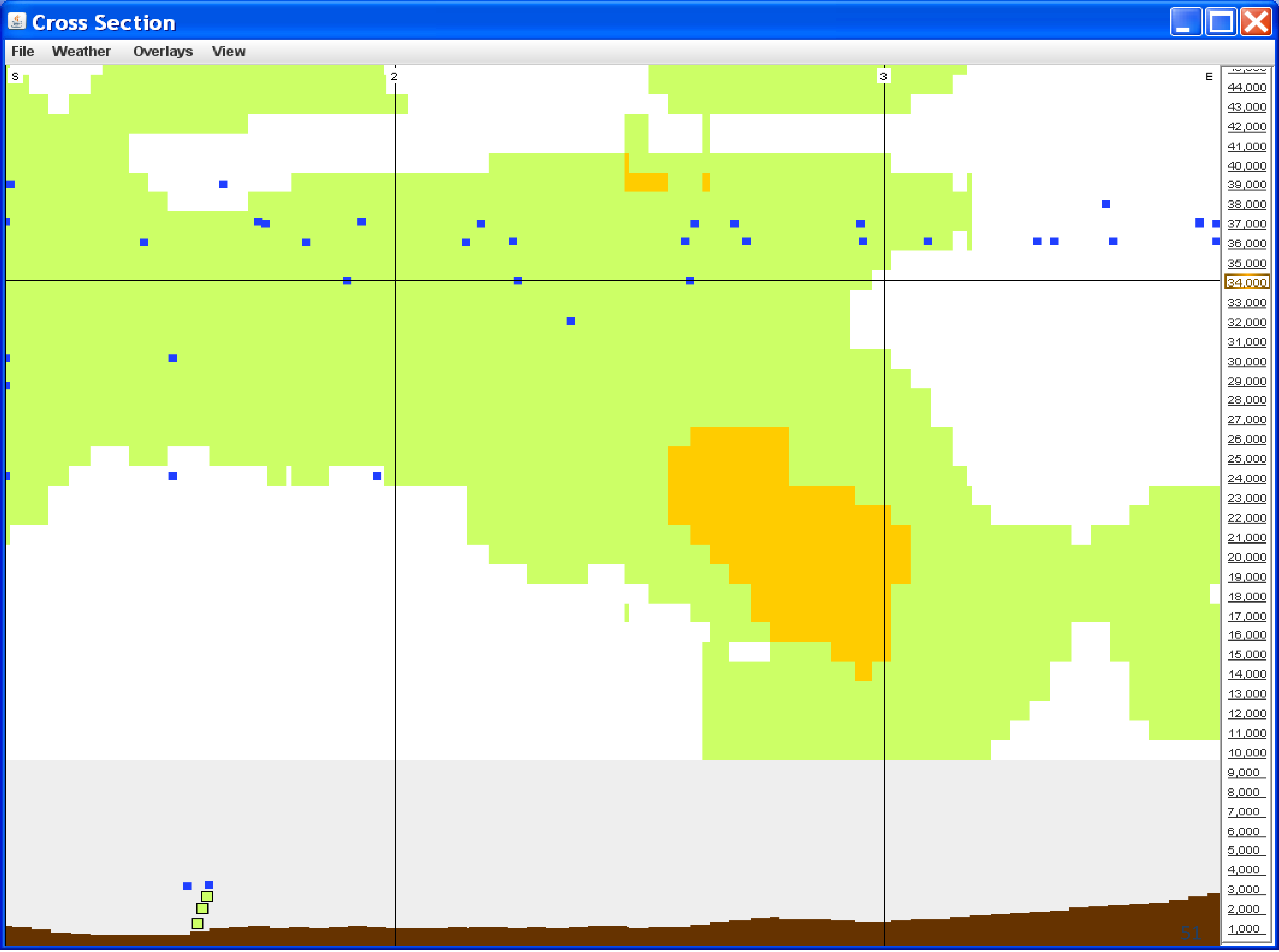
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