FAA, NASA, NOAA Turbulence R&D, products

Tri-Agency Review 24 Mar 2010

FAA – Tammy Farrar

NASA ASAP,ROSES – John Murray

NOAA – Steve Abelman

Bob Sharman
NCAR/RAL
sharman@ucar.edu

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NextGen major drivers for IOC

- **Populate the 4D data cube (e.g., OI-2010: Net-enabled common weather information infrastructure)**
- **Foundational Breakthroughs in Atmospheric Science to Enabler Improved Forecast Skill (EN-2510-2512)**
- **Near term IOC products (Level 1 – 2013)**

(1) *In situ* observations of turbulence

EN-2230: Network-enabled airborne-based sensor system level 1. This near-term observation sensor system includes connectivity to the net-centric environment (i.e., hardware, software and interfaces) and supports the collection of airborne-based observations (e.g., turbulence, icing, winds, temperature, solar radiation, volcanic ash) from the major passenger, regional and package carriers.

(2) Turbulence nowcasting/forecasting

EN-2430 Weather Forecasts - Consolidated Turbulence - Level 1. Near-term predictive models and current weather observations are fused to provide a consolidated turbulence forecast that is available to users over a network-enabled infrastructure. This capability will include North America from 10,000 feet to FL450, 0-18 hours, updated hourly, and will forecast clear air and mountain wave turbulence.

(3) Remote sensing of turbulence

EN-2220 Network-enabled Weather Observation System - Ground-based Level 1. Network-enabled ground-based sensor system level 1. This initial observation sensor system includes connectivity to the net-centric environment (i.e., hardware, software and interfaces) and supports the collection of ground-based observations.

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Turbulence nowcasting, forecasting NextGen drivers (from IWP)

- Near-term: "consolidated probabilistic turbulence forecast that is available to users over a network-enabled infrastructure. This capability will be for North America from 10,000 feet to FL450, 0-18 hours, updated hourly, and will forecast clear air and mountain wave turbulence"

- Mid-term: "use of improved models, increased resolution, higher refresh rates, and improved physics to meet user needs. This capability will include
  1) a North American diagnosis from 10,000 feet to FL 450 updated every 15 minutes,
  2) a North American forecast from 10,000 feet to FL450 covering time equal 0 to 18 hours, updated hourly,
  3) a Regional forecast over the Northeast Corridor that includes convective turbulence, and
  4) a Global forecast from 20,000 feet to FL 650 covering time equal 0 to 36 hours with a 6-hour update rate.

- Far-term: "use of improved models, increased resolution, higher refresh rates, and improved physics to meet user needs. This capability will include
  1) an integrated diagnosis and forecast covering North America, the North Pacific, and the North Atlantic from the surface to FL650 covering time equal 0 to 24 hours, updated hourly,
  2) high-resolution regional nests in North America,
  3) a Global diagnosis from the surface to FL 450 updated every 15 minutes, and
  4) a Global forecast from the surface to FL 650 covering time equal 0 to 36 hours updated hourly

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Functional requirements

- **"…the 4D Weather SAS shall provide NAS forecasts at 4 km horizontal resolution (non Oceanic FIRs)"**
- **"The 4D Weather SAS shall contain forecasts with vertical resolution of 500 ft from the surface to the top of the NAS…"**
- **"The 4D Weather SAS shall provide global forecasts at 10 km horizontal resolution (includes Oceanic FIRs)" (implementation date undefined)**
- **'…the 4D Weather SAS shall contain forecasts covering the NAS in 1-hour increments out to 60 hours."**
- **"The 4D Weather SAS shall contain global forecasts in 6-hour increments from 60 hours to 14 days"**
- **"The 4D Weather SAS shall contain a climatological forecasts out to 3 months"**
- **"The 4-D Weather SAS shall update the climatological forecasts monthly"**
- **"The 4D Weather SAS shall update 1-hour incremented forecasts every 30 minutes."**

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Aviation turbulence R&D in support of NextGen

- Develop, test, and implement quantitative turbulence measurement techniques
  - In situ edr measurements on commercial aircraft (FAA)
  - Remote sensing of in-cloud turbulence (FAA,NOAA)
  - On-board forward-looking instruments (NASA)
  - GPS scintillation measurements (NASA, NOAA)
  - Satellite-based turbulence detection algorithms (NASA)

- Develop, test, and implement routine turbulence nowcasting and forecasting products
  - EDR, later probabilistic gridded data over NA (FAA, NASA)
  - EDR, later probabilistic gridded data globally (NASA, FAA)
  - WAFS global turbulence forecasts (NOAA)
  - Provide HOL interface to forecast products (NOAA)

- R&D of free atmosphere turbulence genesis and cascade processes (NASA, NSF, Foreign)

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FAA turbulence products aimed at IOC

- *In situ* edr data
  - Atmospheric turbulence metric
  - Data received in near real time fed into 4D data cube
  - Used in DAL-FAA demo
  - Used in forecast/nowcast products
- Turbulence forecast product (Graphical Turbulence Guidance – GTG3)
  - Deterministic output of edr
  - Uses WRF-RR/CONUS
  - Hourly out to 18 hrs.
- Turbulence nowcast product (GTGN)-1
  - Deterministic output of edr
  - Updated every 15 min
  - Uses
    - In situ data
    - NTDA2 CONUS mosaic (edr)
    - DCIT
    - GTG3

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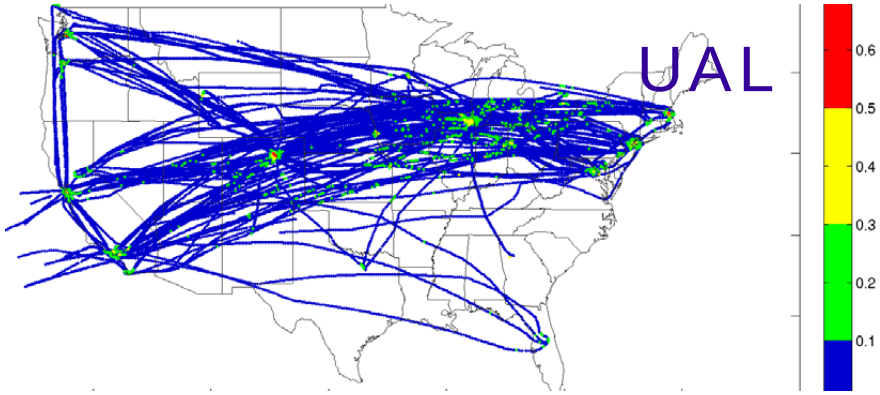
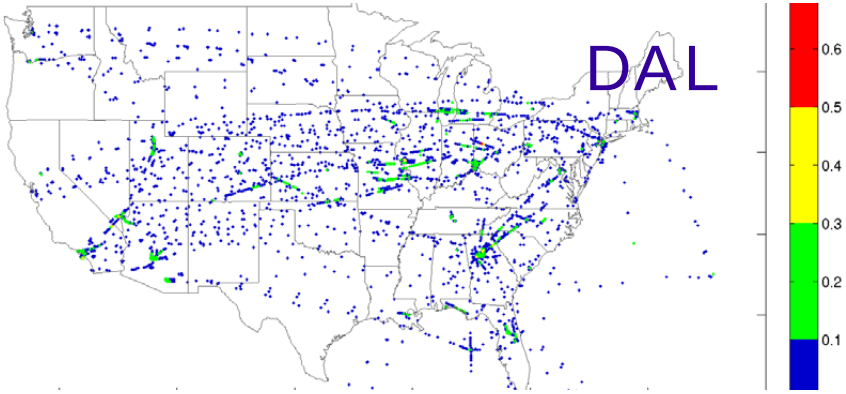
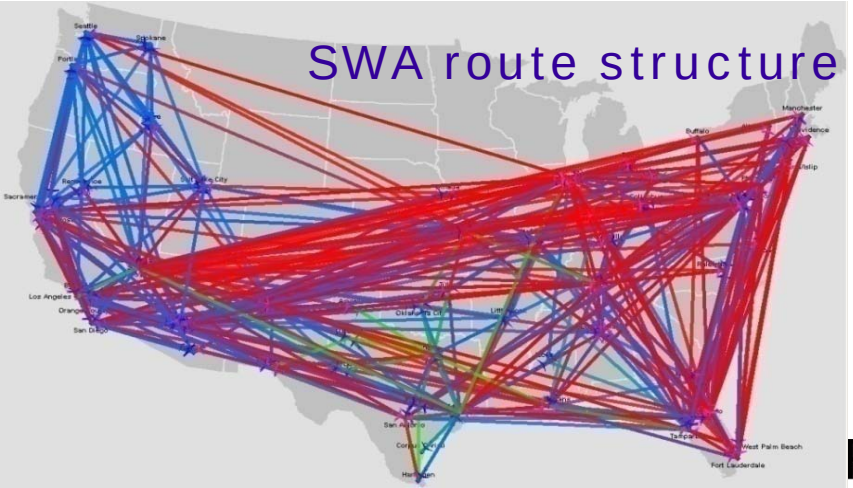
In situ edr measurements (FAA)

- Background
  - Provides atmospheric turbulence metric: eddy dissipation rate (edr), actually $\varepsilon^{1/3}$ ($m^{2/3}$ / s)
  - Records peak and mean
    - UAL every minute
    - Algorithm updated to event-based recording + heartbeat
- Status
  - 100 UAL 737s and 100 UAL 757s (accelerometer-based 1-min updates)
  - ~ 70 DAL 737-800s (event-driven vertical winds-based algorithm)
  - Final integration testing underway by SWA/Honeywell, full deployment expected Summer 2010 on ~ 340 737-700s)
- Future
  - UAL, DAL 767s
  - UAL 777s with Boeing?
  - AIRTRAN?

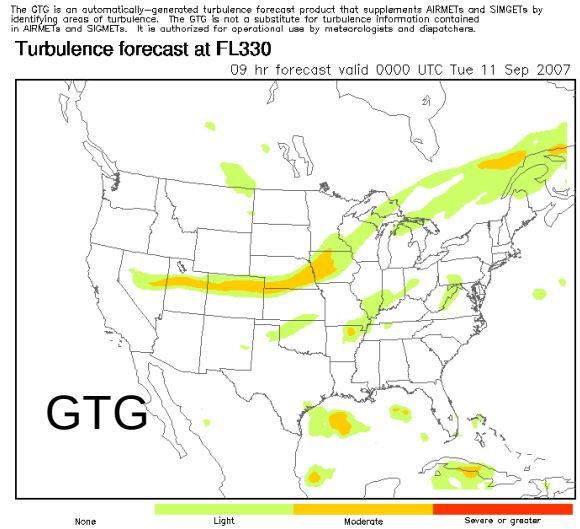


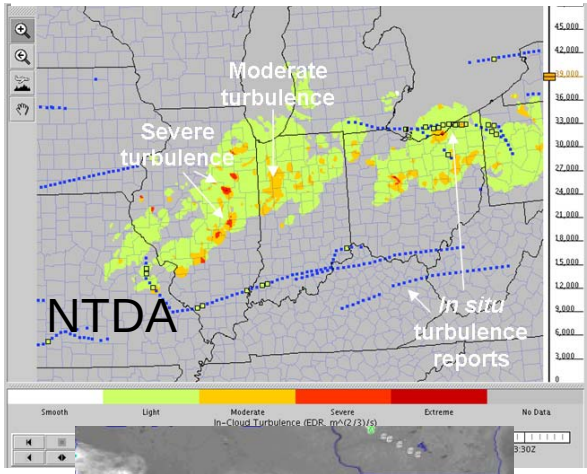


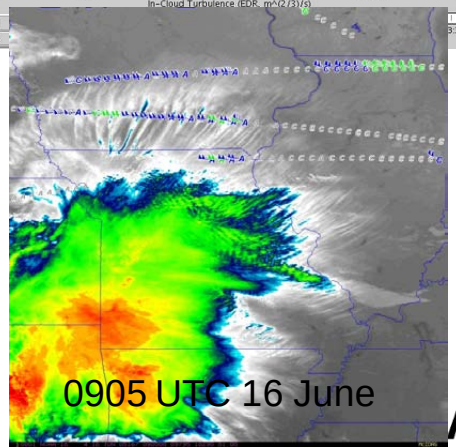


Turbulence nowcasting & forecasting products (FAA)

- **Forecasting (used for strategic planning)**
  - NWP model based
  - Updates hourly
  - Develop turbulence diagnostics from standard NWP model output fields
  - Depicts EDR on 3D grid
  - Graphical Turbulence Guidance (GTG)
- **Nowcasting (used for tactical avoidance)**
  - Observation based
    - In situ (edr + pireps)
    - Remote sensing (NTDA)
    - Inferences from CoSPA, satellite features
  - Merges all current turbulence observations with GTG
  - Depicts EDR on 3D grid
  - Updates ~ 15 min
  - Graphical Turbulence Guidance Nowcast (GTGN)







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Known turbulence sources (GTG)

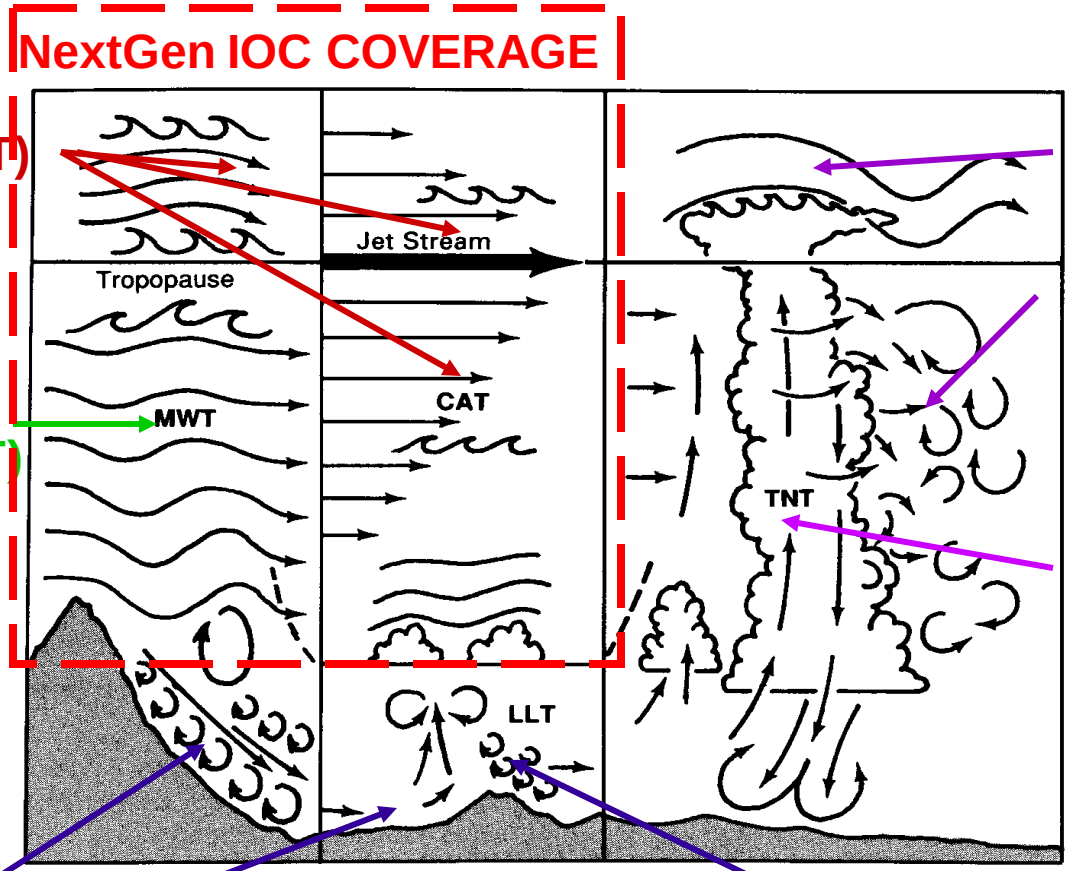

Figure 1-16. Aviation turbulence classifications. This figure is a pictorial summary of the turbulence-producing phenomena that may occur in each turbulence classification.

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

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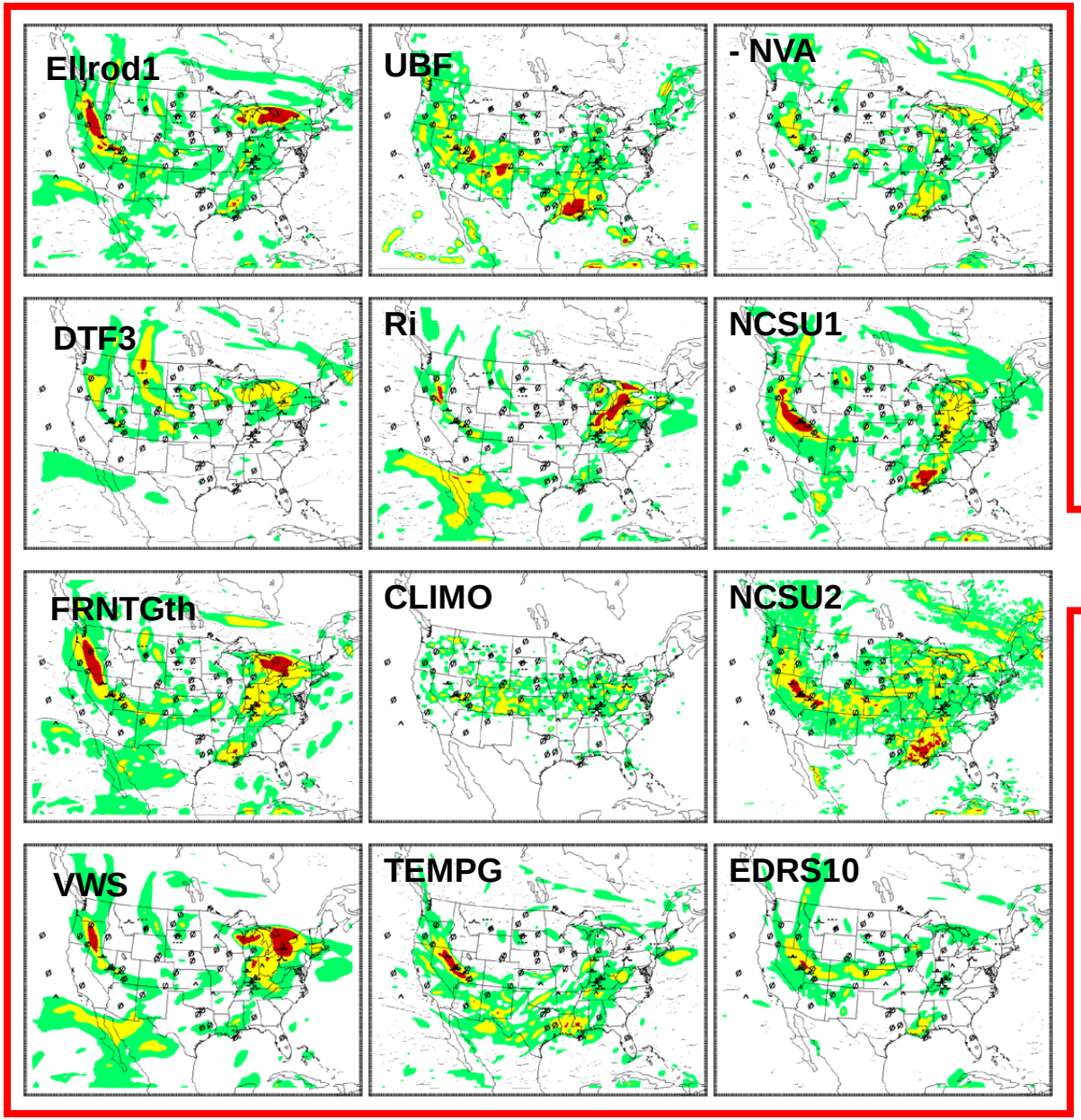
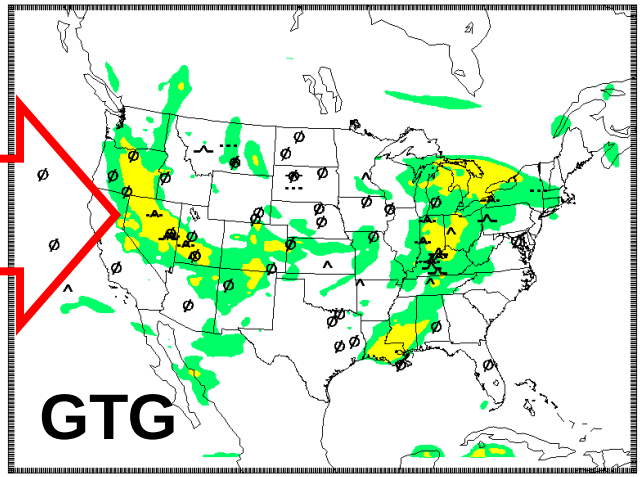


GTG =Weighted ensemble mean of n turbulence diagnostics



0 h forecast valid at 22 Sep 2006 15Z

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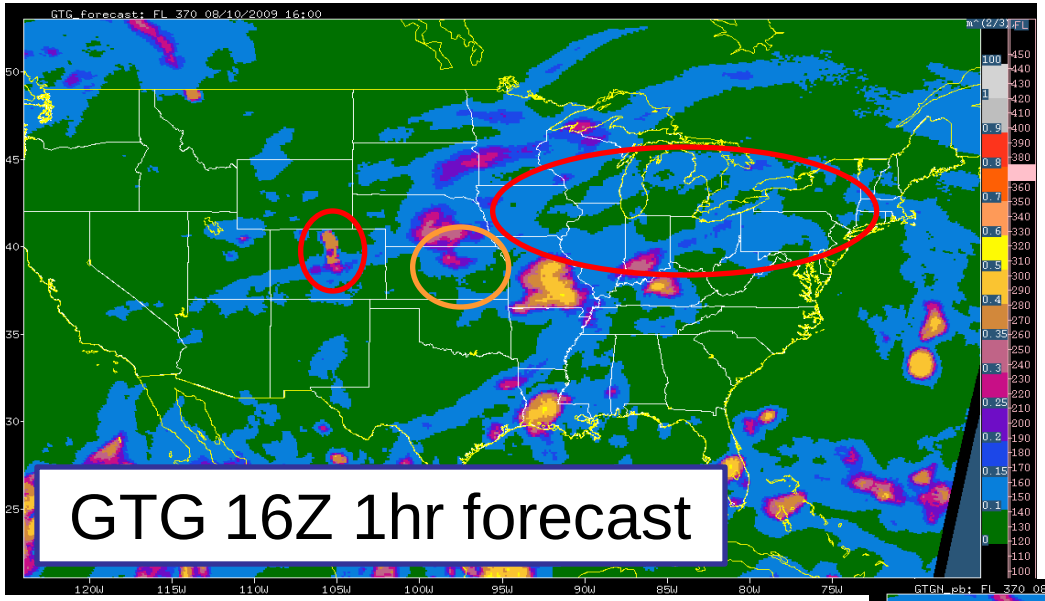
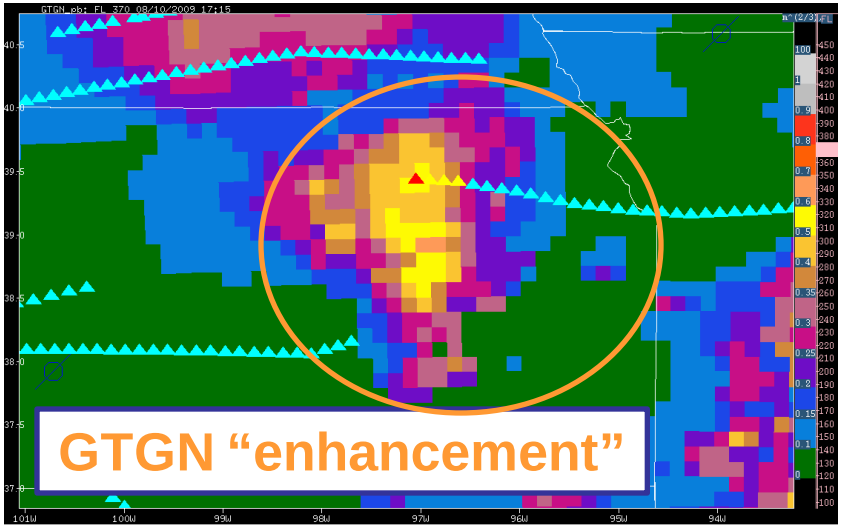
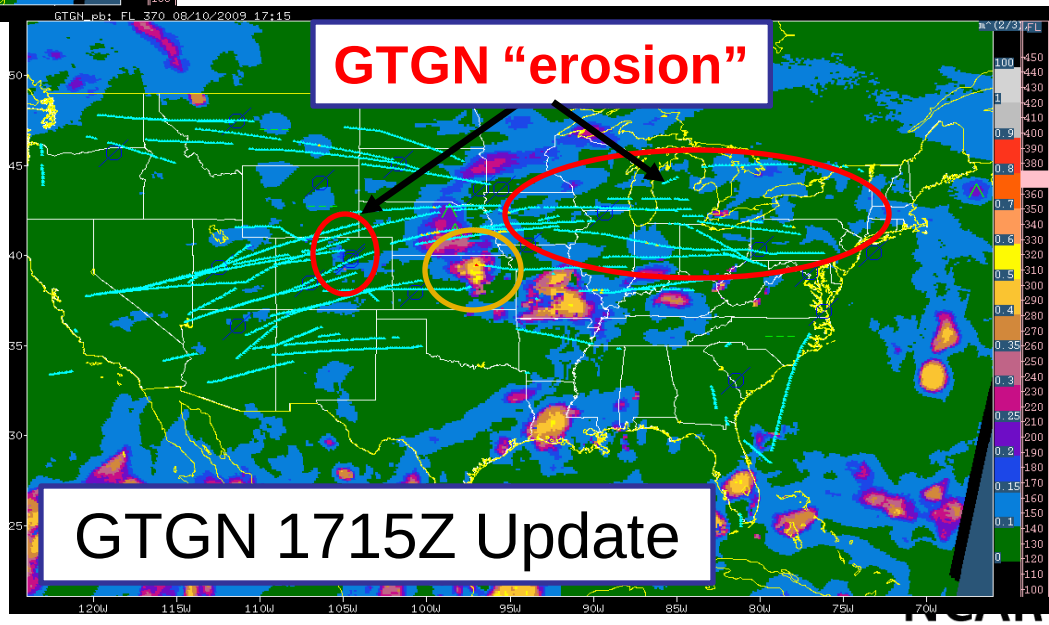
GTGN example: 08/10/2009 at 1715Z, FL 370





Blue tracks: UAL,DAL in situ measurements from previous hour



Current turbulence forecasting research areas

- Within the current GTG framework improvements are only possible through
  - Better NWP models
  - Better turbulence diagnostics
    - Requires better understanding of linkage between NWP scales and turbulence scales
    - Very little activity in this area
  - R&D better methods for combining diagnostics
    - Ensemble approach
    - Ultimately output needs to be probabilistic

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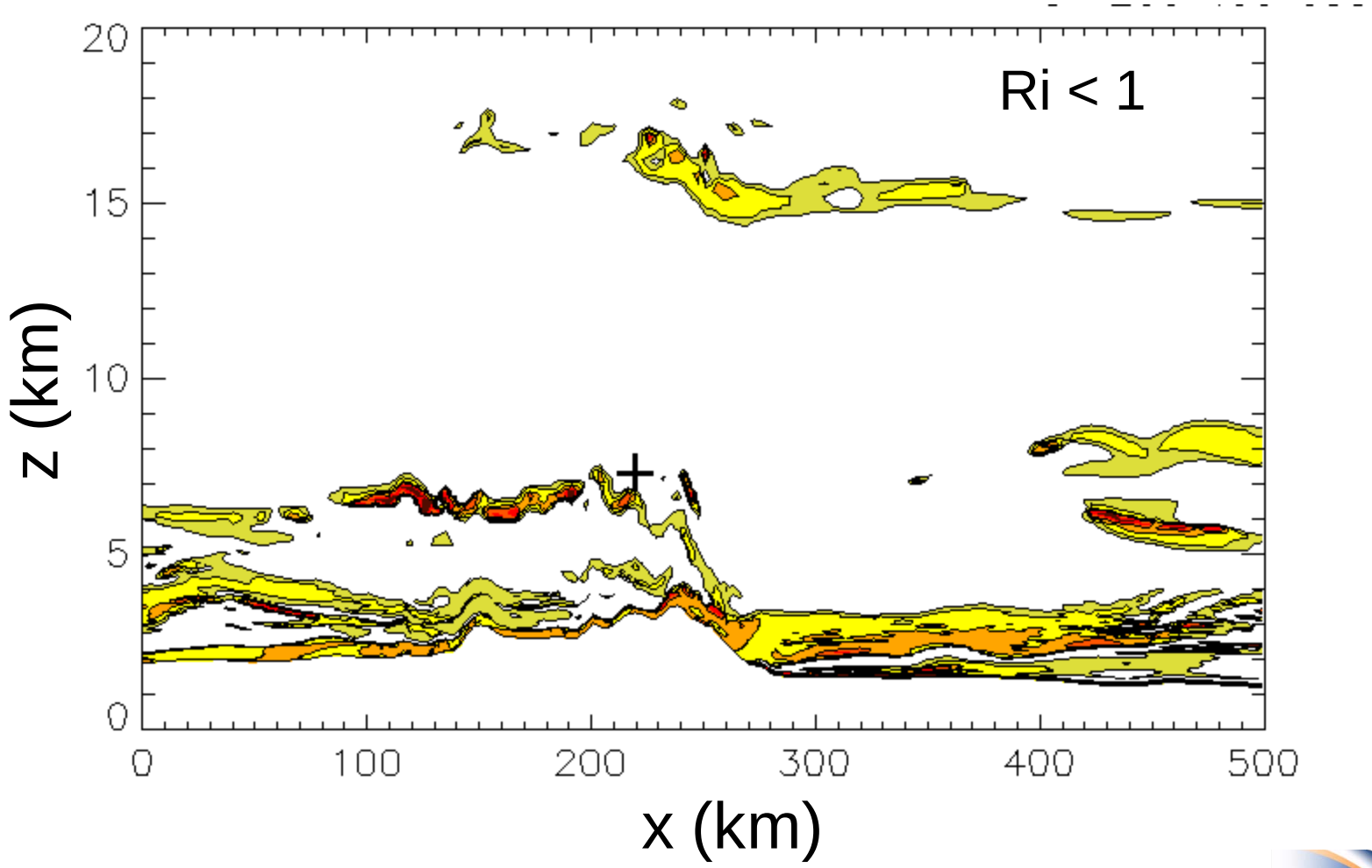
Need for probabilistic forecasts: Turbulence is very patchy and transient. Turbulence example diagnosed from high-resolution simulation



Clark-Hall simulation of severe mountain waves over Northern CO March 15, 2006
Turbulence in east-west cross-section, 15 min frames 18Z-20Z

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Turbulence nowcasting & forecasting R&D (NASA)

- **Provides R&D for development/ improvement of turbulence diagnostics which become part of GTG/N**
- **CIT diagnostics (CAN)**
  - Concentration of out-of-cloud turbulence detection
  - Satellite feature detectors
  - Case studies (numerical simulations)
  - Incorporate into GTGN-1 product
- **MWT diagnostics (ASAP)**
  - Climatologies, diagnostic development
  - Satellite feature detectors
  - Case studies (numerical simulations)
  - Incorporate into GTG3, GTGN-1 products
- **Global turbulence and convection (ROSES)**
  - Emphasis on oceanic convection -> turbulence
  - GFS-based forecast system
  - Hand-off to FAA in 2011

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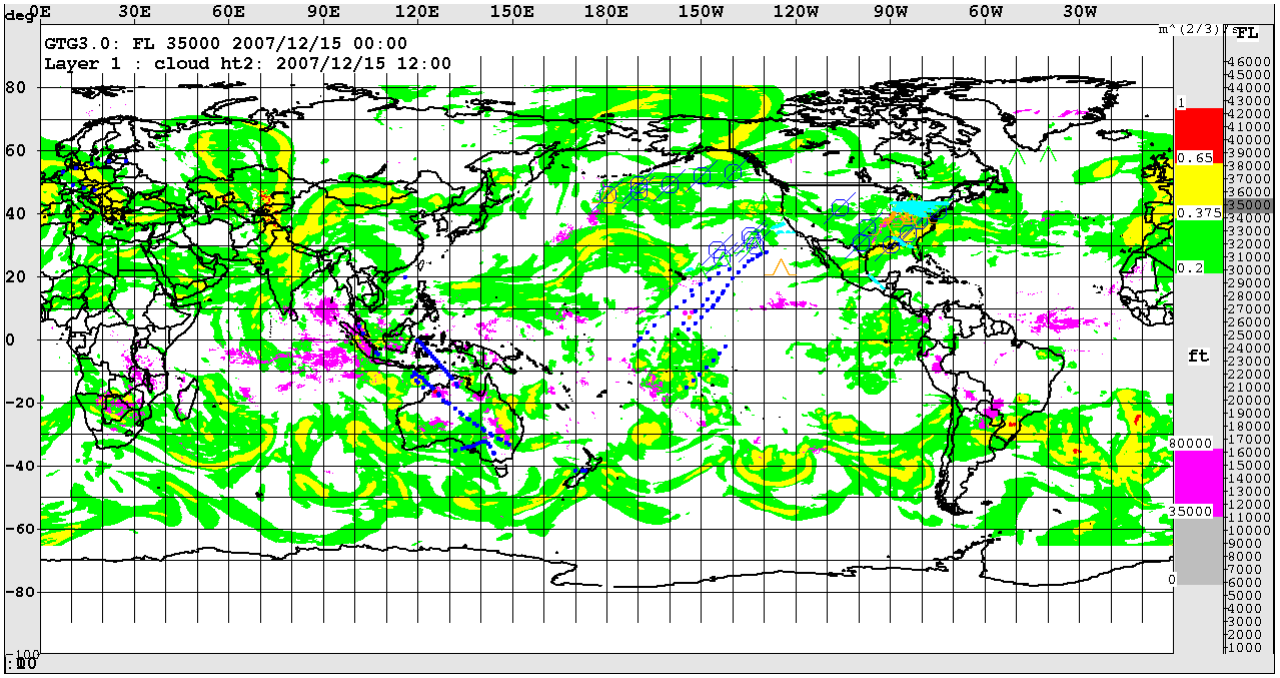
Turbulence nowcasting & forecasting R&D (NOAA)

- Human-over-the-loop
- Alaska low-level turbulence
- NASA global turbulence/WAFS



GFS GTG 12-hr fcst, magenta=cloud tops>35,000 ft, AIREPs, *in situ* turbulence measurements from Delta, United and Qantas aircraft, ± 90 min (blue =null, light, orange=moderate, red severe turbulence)

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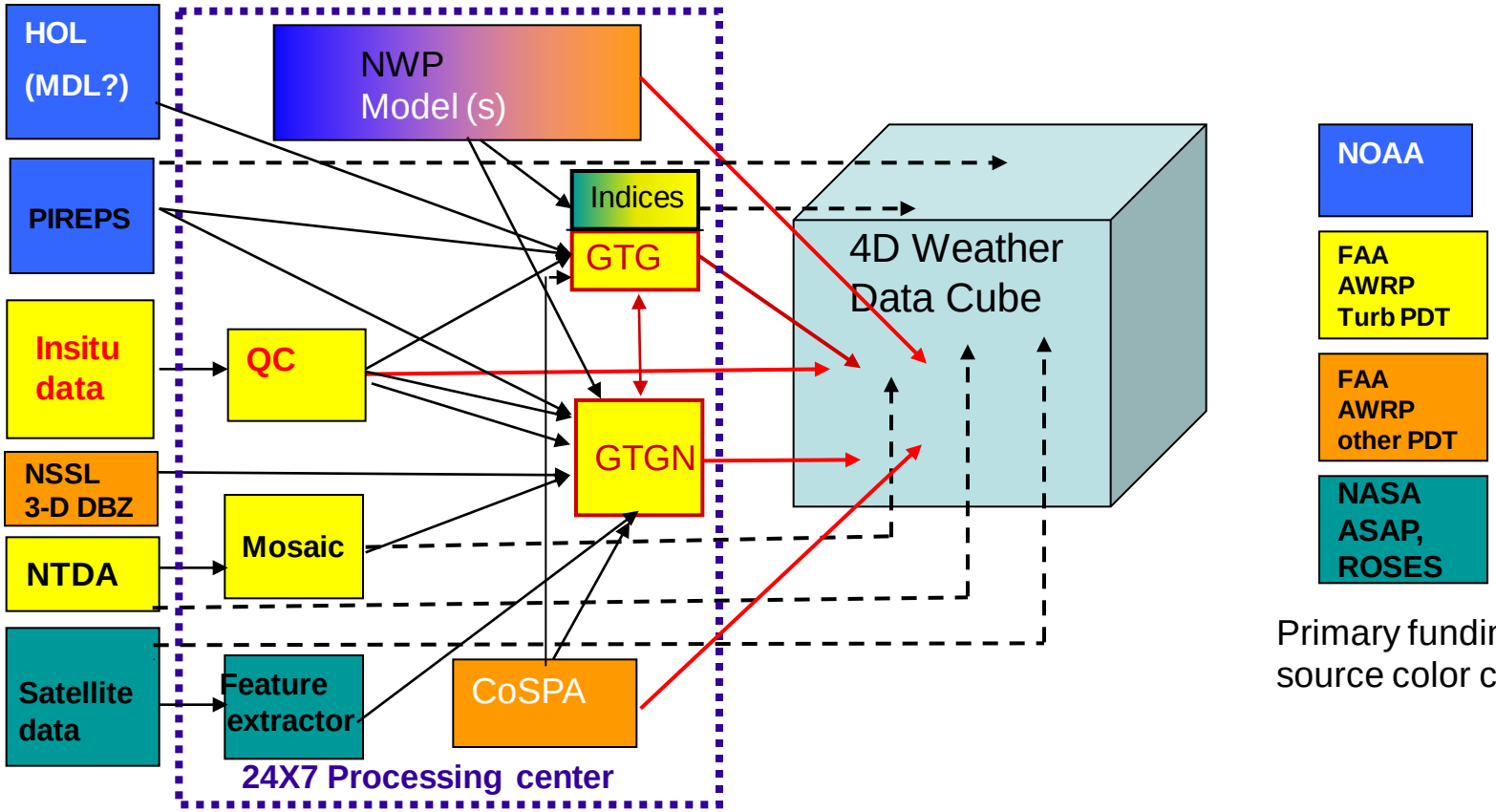
FAA/NASA/NOAA Turbulence efforts and Connection to NextGen 4D data cube



Primary funding source color code

Red → Candidates for "Single Authoritative Data Source" (SAS)

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Gaps or research opportunities

- **Lack of fundamental understanding of turbulence processes in the free (stable) atmosphere***
  - High resolution numerical simulations of turbulent events very instructive
  - What is the effect of gravity and gravity-inertio waves?
- **Need more and better observations over CONUS and globally***
  - More insitu measurements
    - Has been invaluable for R&D and accurate operational products
    - Need nighttime (package carriers), international coverage, with water vapor
    - Need benefits assessment of insitu/TAMDAR to GTG,GTG-N
    - Need edr -> aircraft loads maps (PIREPs)
  - Use of satellite data over remote areas to infer turbulence
    - Hyperspectral, GOES-R
    - Coupled atmospheric/satellite simulations
  - All observations can be used in GTGN

* "I have no data yet. It is a capital mistake to theorise before one has data. Insensibly one begins to twist facts to suit theories, instead of theories to suit facts." Sherlock Holmes to Dr. Watson in *A scandal in Bohemia*, A. Conan Doyle(1891)

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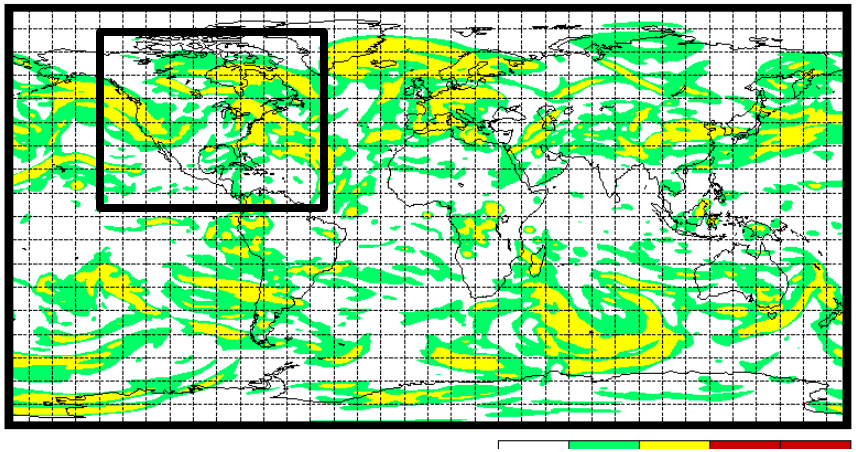
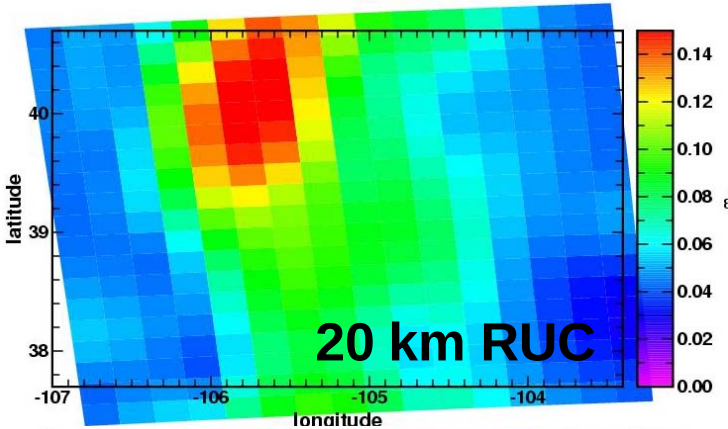
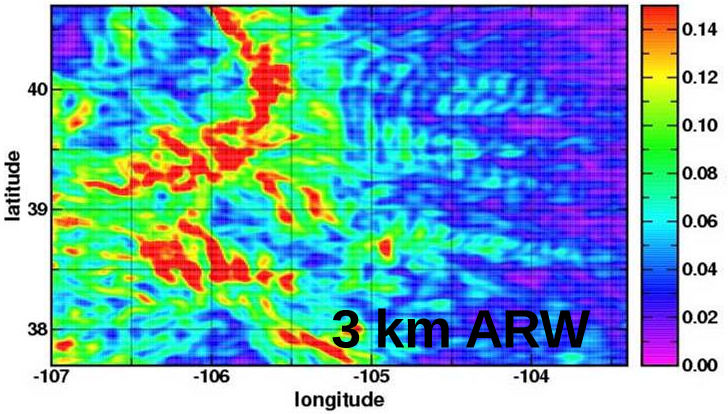
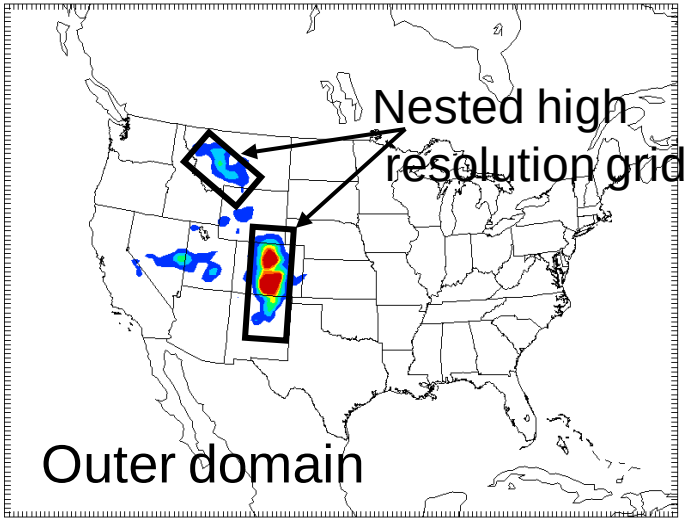
Gaps/research opportunities (cont.)

- **Improve probabilistic forecast techniques**
  - Lack definition
  - Need user input
  - Should be conditional (e.g. COSPA)
- **Explore NWP model dependencies**
  - What's best for convective precip may not be best for turbulence
  - Higher resolution will change optimal diagnostic suites -> use nesting?
  - Require blending between higher resolution NA grids and global grids
  - Also temporally (GTGN vs. GTG)









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backups

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Aircraft turbulence prediction - Motivation

- Turbulence has significant safety, economic and capacity impacts
  - In US, causes 75% of Part 121 accidents (OFCM Aviation weather Programs/projects 2004 update)
  - Economic cost of nearly $200 million per year (MCR Federal, 2003)
  - Second leading factor affecting the NAS (MOSAICATM/AvMET ARTCC/TRACON survey of wx factors impacting NAS)

Turbulence forecasting procedure

- Aircraft turbulence ~ few meters to couple km
- Much smaller than present operational NWP model resolutions
- Cannot directly predict aircraft scale turbulence
- Only hope is to infer turbulence potential from larger scale
  - Assumes downscale cascade of energy
  - Turbulence in mid-upper altitudes is in a stably-stratified environment where subgrid scale turbulence parameterizations do not work very well
- Multiple causes require multiple forecasting strategies →

  Graphical Turbulence Guidance Product (GTG)

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Turbulence Forecasting:
ITFA (Integrated Turbulence Forecasting Algorithm)
Graphical Turbulence Guidance Product (GTG)

- Aircraft turbulence ~ few meters to couple km
- Much smaller than present operational NWP model resolutions
- Therefore cannot directly predict aircraft scale turbulence - only hope is to infer turbulence potential from larger scale
- Multiple causes therefore multiple diagnostics (D)

$$ITFA = W_1D_1^* + W_2D_2^* + W_3D_3^* + \ldots.$$

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FAA Turbulence products aimed at MOC

- New in situ edr data
- GTG4
  - HRRR/WRF-RR/long range model(s)
  - Probabilistic (need definition)
  - Low-levels
- Global GTG
- Turbulence climatological grids
- GTGN-2
  - GTG4
  - Probabilistic
  - HRRR/ensemble based
  - New observations as available

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Turbulence Forecasting: Graphical Turbulence Guidance Product (GTG)

- Resolved scale "turbulence diagnostics" are automatically computed from standard weather model output (e.g., winds, temperature)
- Typically related to model spatial variations
- Must assume downscale cascade
- Multiple causes therefore multiple diagnostics (D)

$$GTG = W_1D_1^* + W_2D_2^* + W_3D_3^* + \ldots$$

- R&D problems:
  - Develop Ds
  - Assign weights W
    - Climatological
    - Dynamic
  - Performance is model dependent
- Rigorously tested against 100,000s of PIREPs and in situ EDR data

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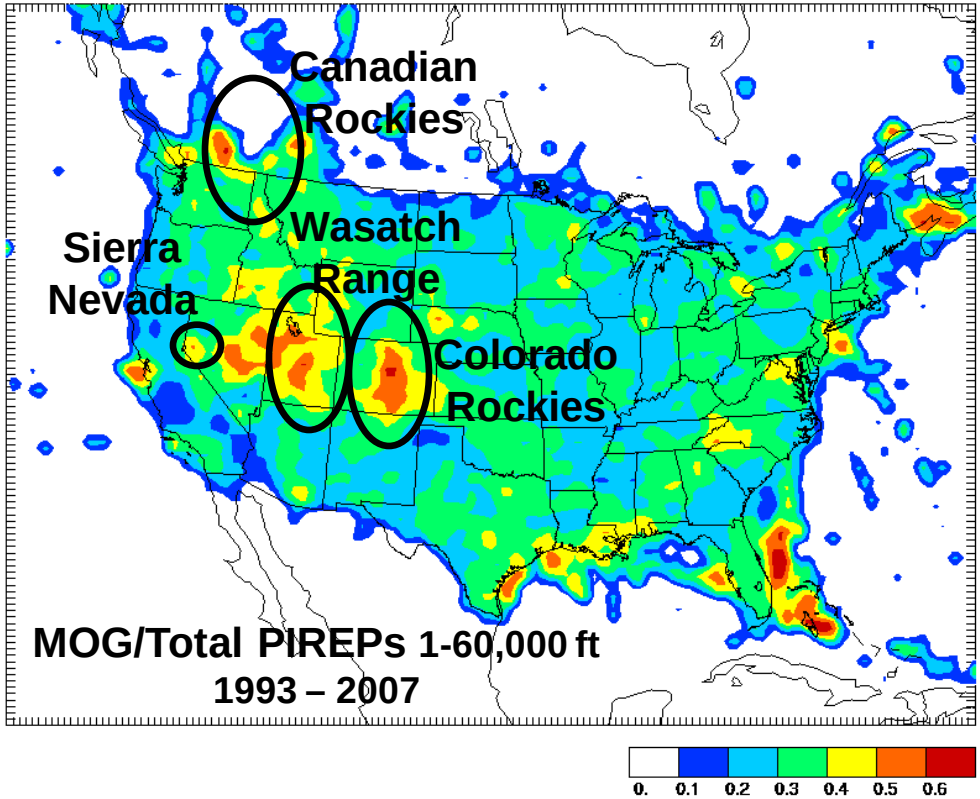
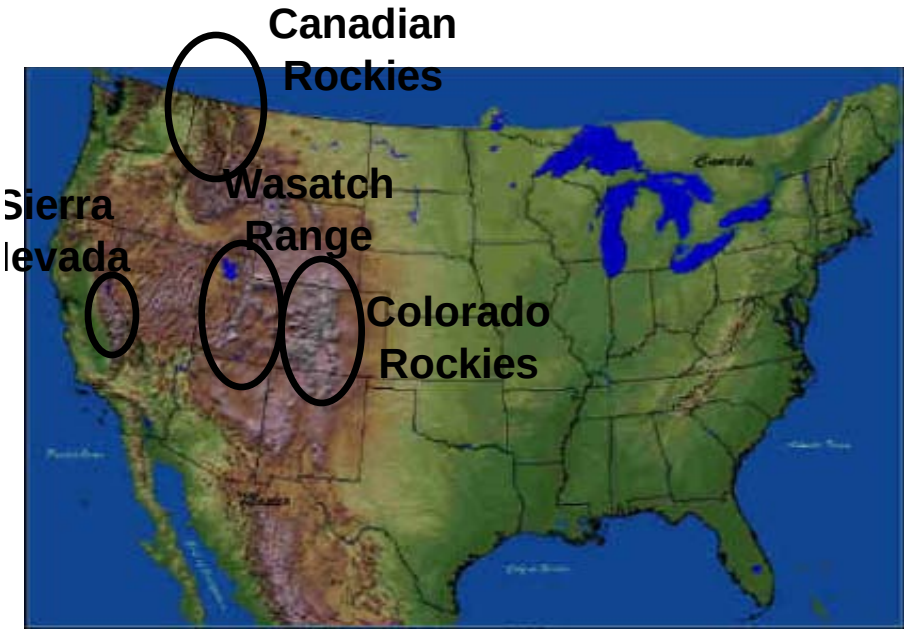
Turbulence levels are significantly higher over mountainous terrain





Topography

Climatology – 15 years of Pilot reports (PIREPs)

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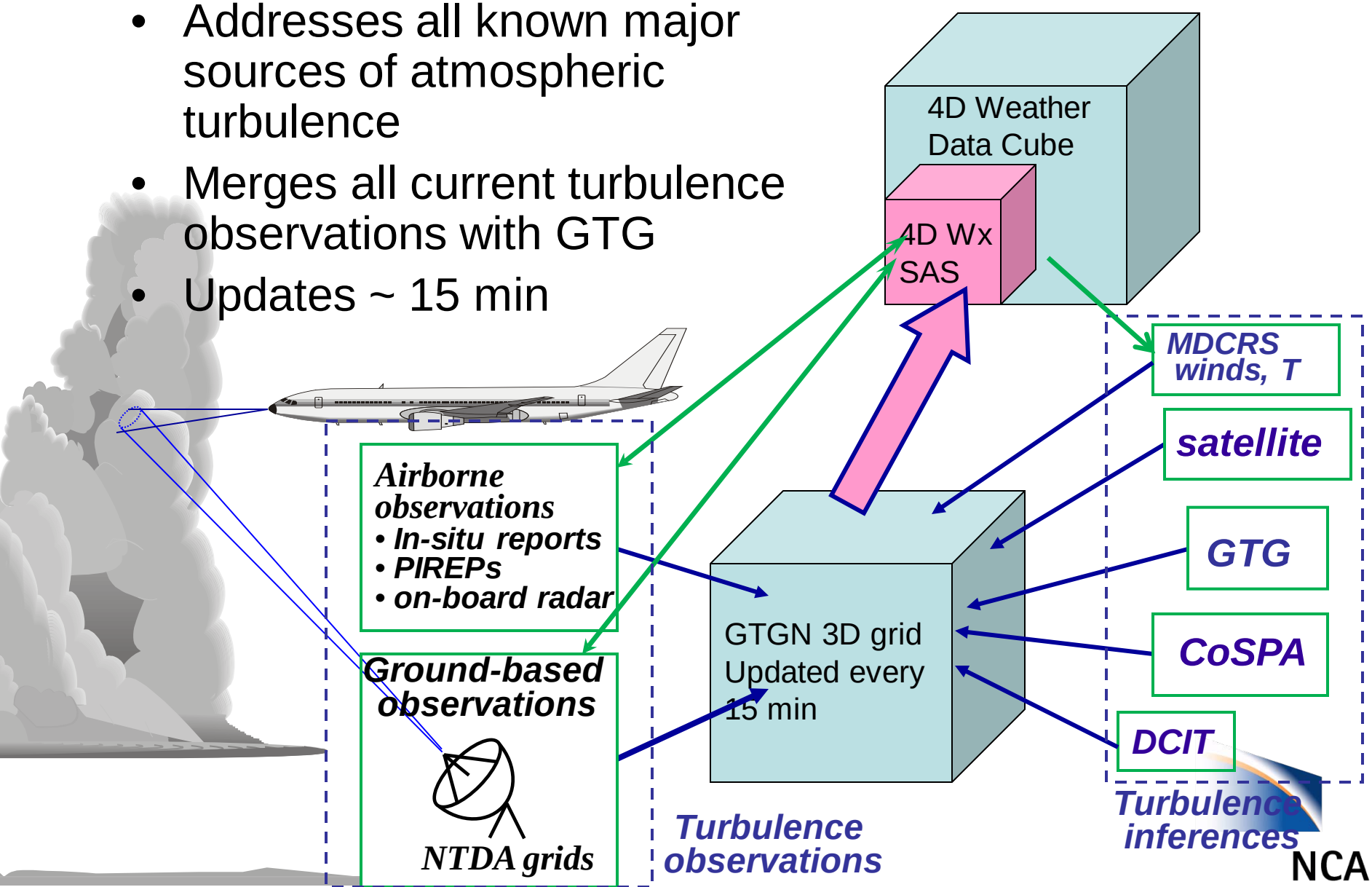
GTG-N: Turbulence nowcast system

- Addresses all known major sources of atmospheric turbulence
- Merges all current turbulence observations with GTG
- Updates ~ 15 min