Methods for prediction of aircraft turbulence and their validation

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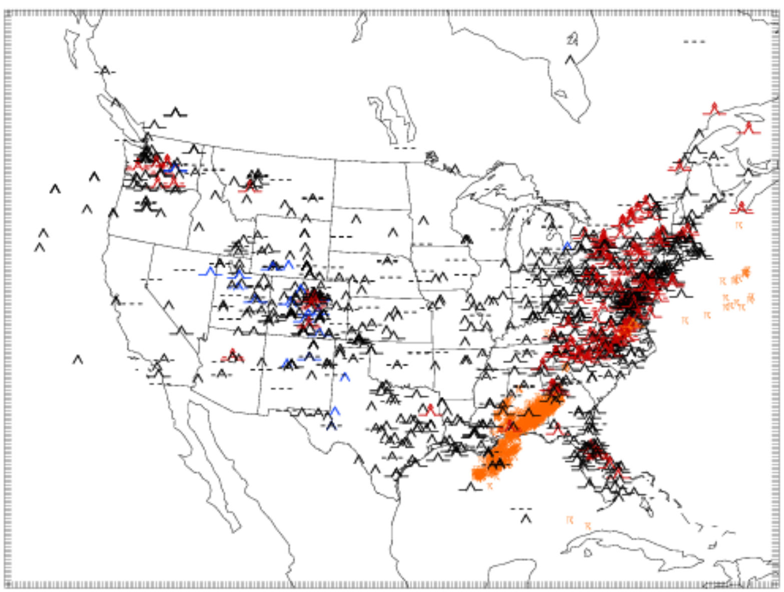
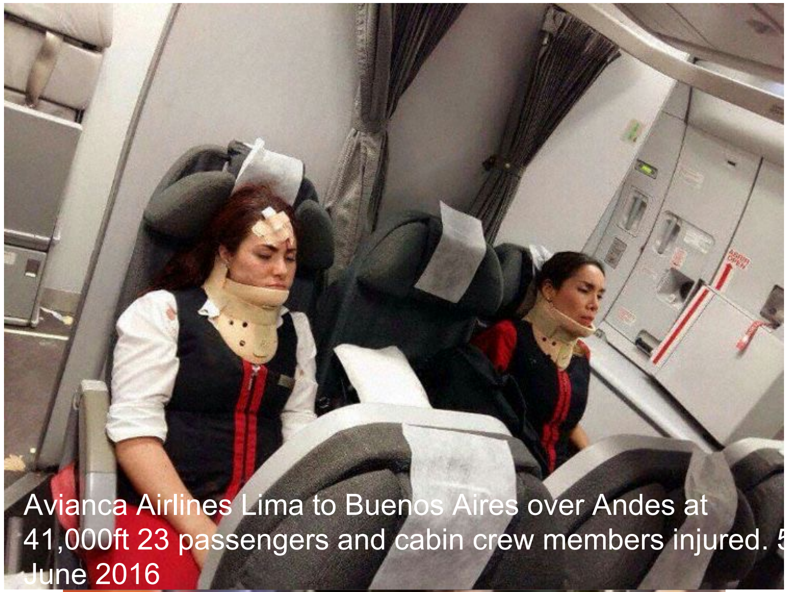
Aviation turbulence - Motivations

- Economic cost of ~ $200M/yr
- Accounts for 75% of air carrier accidents
- ~ 15 serious injuries, ~50 minor per year for air carriers (reported to NTSB)
- 10% of air carrier turbulence related accident resulted in damage to the aircraft
- Causes aircraft fatigue and shorter airframe life
- Second leading weather factor affecting air traffic controller workload



Motivations (cont.)

- Incidentally…
  - For 2022: 17 injuries, 13 crew or 76% (NTSB)
  - Est 4500/year
  - Most not wearing seat belts…
  - Large fraction due to convection
    - Kaplan et al. (2005) found 38 of 44 of severe turbulence encounters were in or near convection
    - Wolff and Sharman (2008) found about 40%
- Requirements for better turbulence avoidance from
  - FAA
  - ICAO (International Civil Aviation Organization)



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

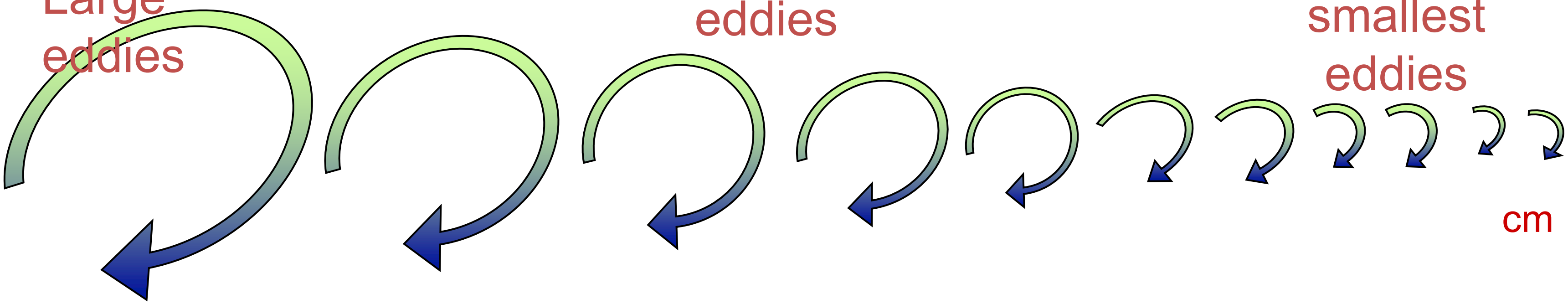
Extreme turbulence Aeroflot Moscow-Bangkok flight 2353 UTC 30 Apr 2017 B777 at FL350 (238 mb)

“Aircraft scale turbulence”=“fine-scale”

Large eddies

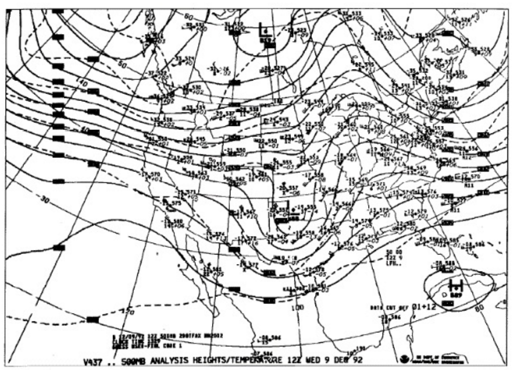
“turbulent” eddies

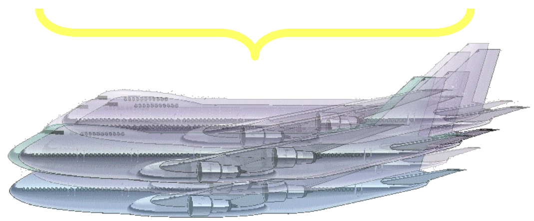
smallest eddies



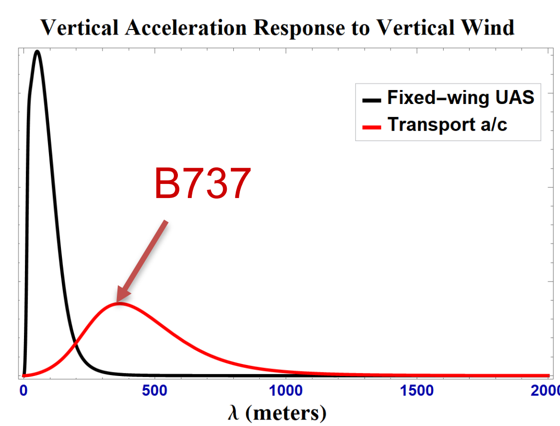
cm

100s-1000s km





Aircraft responds to scales from few m - km

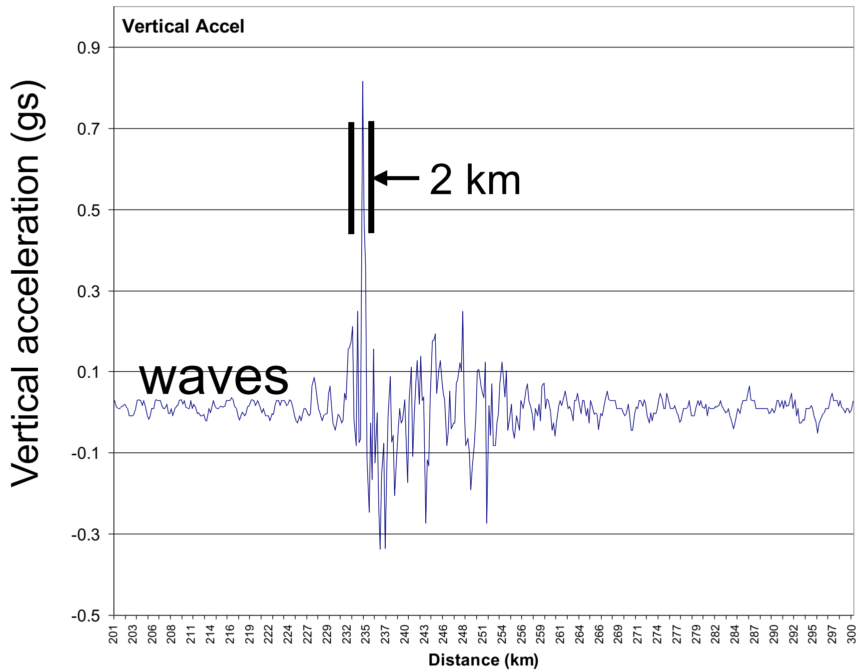


Courtesy Larry Cornman

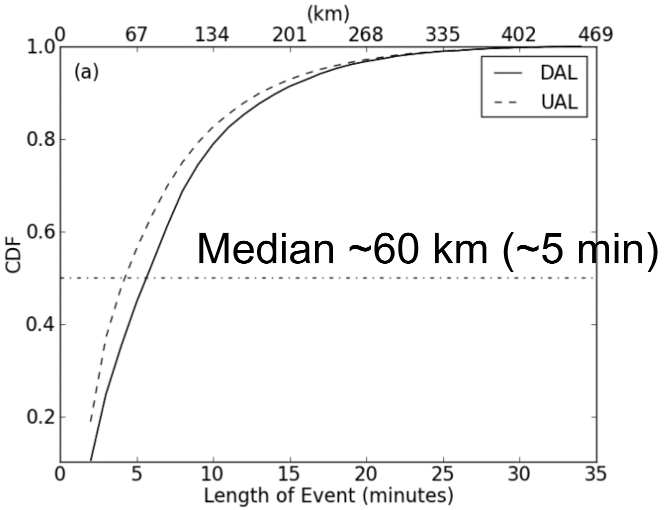
NWP resolution

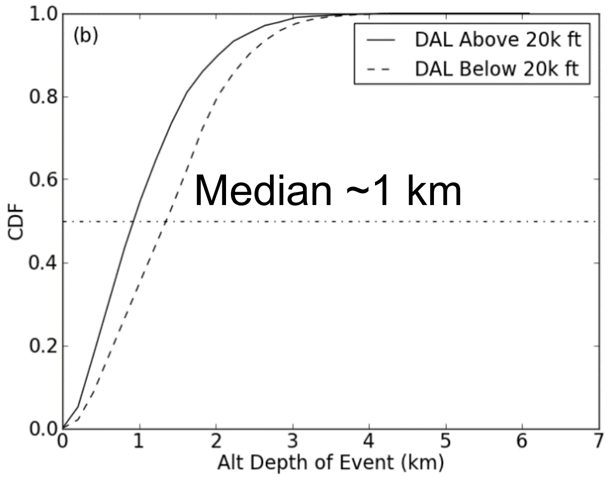
Mesoscale model resolution

Nature of turbulent events



Fine scale

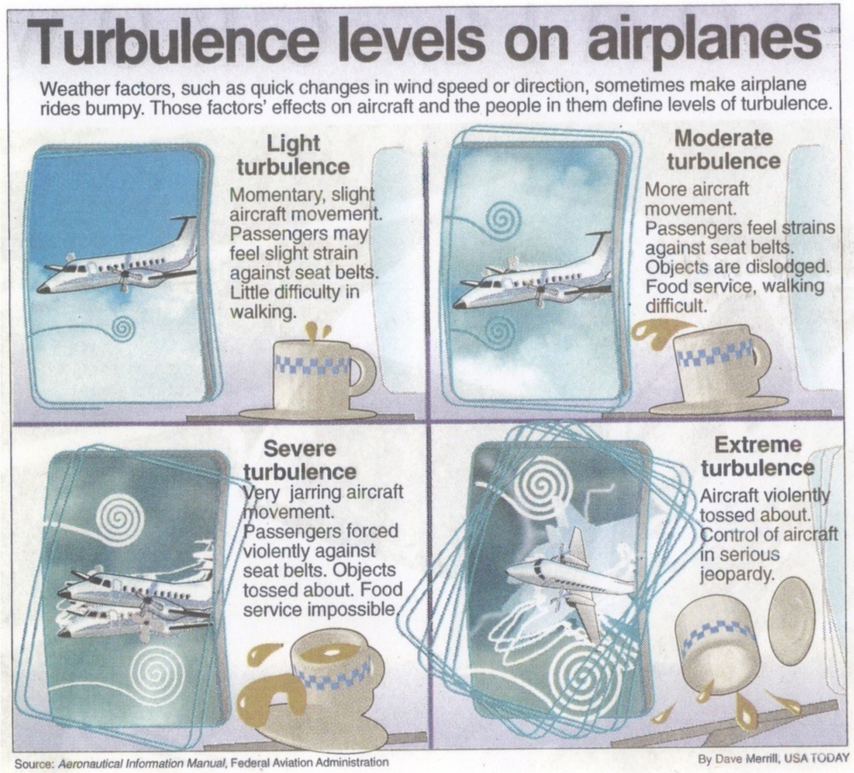




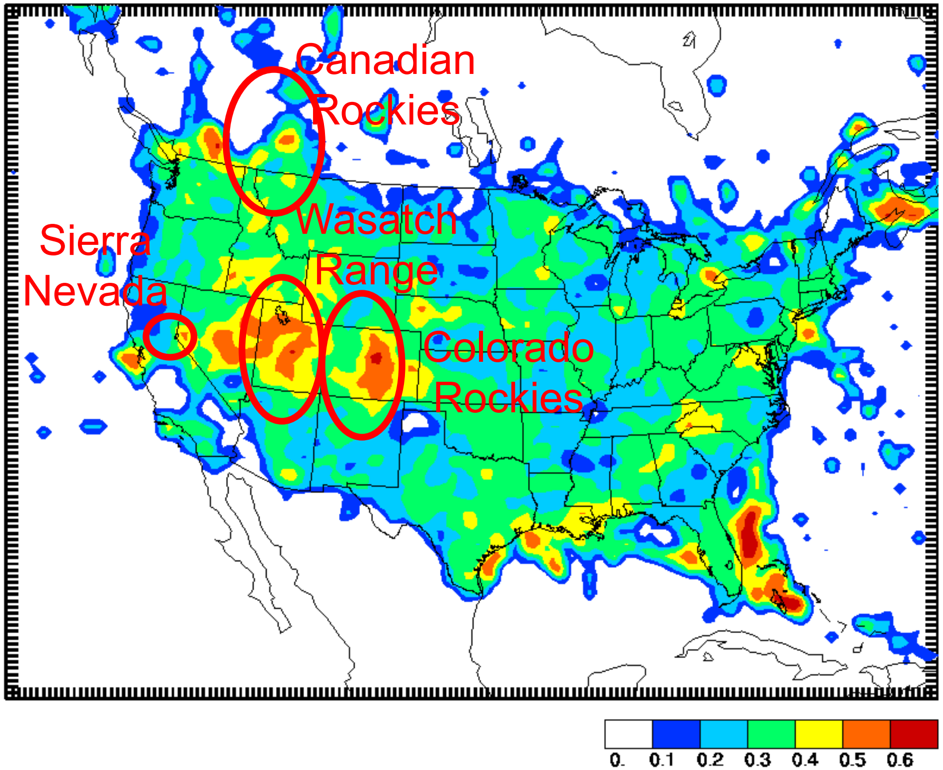
Continuous peak EDR≥0.1

Aviation turbulence intensity

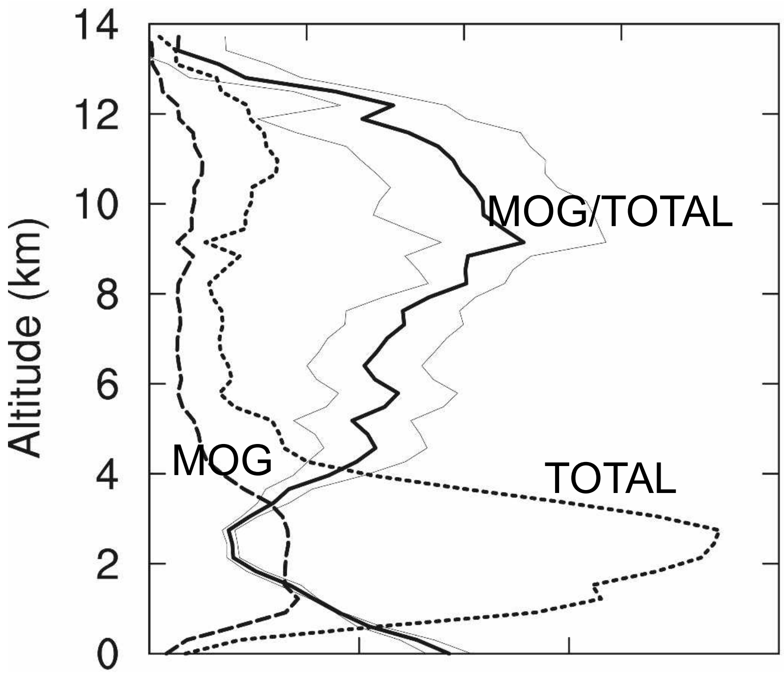
- Traditionally based on Pilot Reports (PIREPs/AIREPs)
  - Subjective opinion of pilot
    "none"
    "light"
    "moderate" (>1/2 g) may avoid
    "severe" (>1 g) must avoid
    "extreme" (>2 g) must avoid
  - Depends on the aircraft
- Moderate or greater (MOG) is an extremely rare event
  - ~ 1%
  - "severe" <~ 0.1%
- Not atmospheric intensity metric
- Better to use energy dissipation rate ε or EDR= $\varepsilon^{1/3}$ m $^{2/3}$s^{-1}
  - ICAO standard
  - Can relate EDR to aircraft loads (peak g ~ σ_g ~ $\varepsilon^{1/3}$)
  - Convenient scale 0-1



Aviation turbulence climatology based on PIREPS



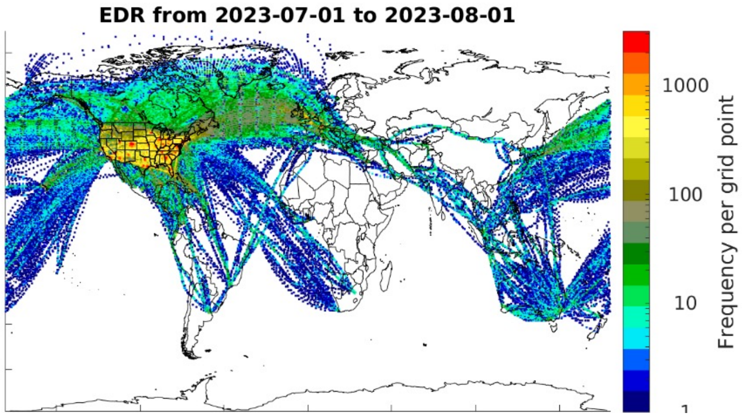
MOG/Total

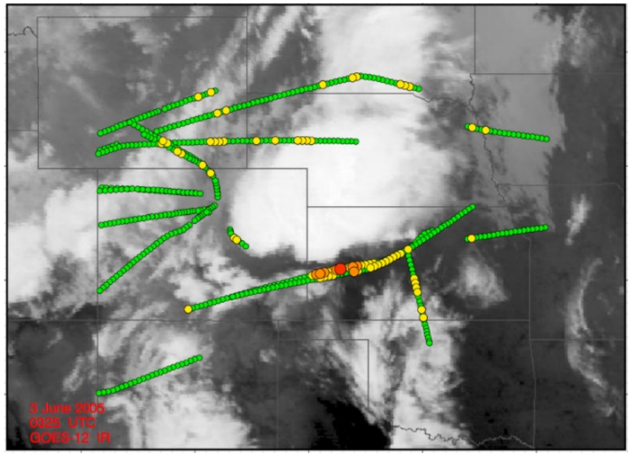


15 years of FOS pireps (1993-2007)

Aircraft in situ edr estimates

- NOAA AMDAR archive contains winds, T, qv on many aircraft at different observation frequencies
- Also have estimates of EDR from selected aircraft (DAL, SWA on AMDAR) – others are proprietary
- NCAR archive ~ 2000 ac from DAL, SWA, UAL, SWR, AAL; ~$5x10^4$ counts/day DAL, SWA
- 1 min sampling rate recording peak and mean EDRs but reporting/downlink frequency depends on airline
  - Communication costs are an issue
  - Airline nervousness about litigation
- Algorithm included on all new Boeing aircraft and also available for new Airbus aircraft
- IATA (International Air Transport Association) developing database to include all airlines (available for a fee!)

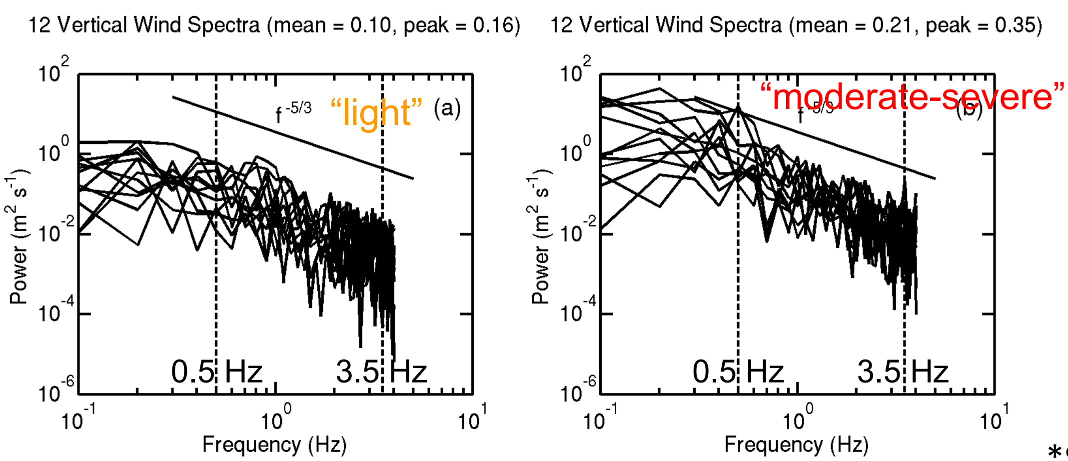




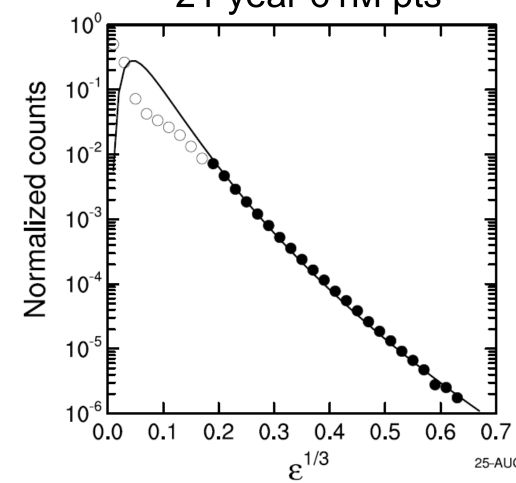
Zovko-Rajak et al. MWR 2019

Aircraft in situ edr estimates – algorithm*

- Accesses ~ 8 Hz avionics data from onboard computer (e.g. Aircraft Conditioning and Monitoring System ACMS)
- Compute spectra of w, 80 samples/spectrum
- Assume spectra follows $k^{-5/3}$ in 0.5-3.5 Hz frequency region
- Sliding 10 sec window with 5 sec overlap
- Within each window get best fit to $k^{-5/3}$ (Smalikho 1997)
- -> 12 EDRs/min
- Average and peak EDR levels recorded every minute (~12 km) from the 12 EDRs
- Rigorous QC applied
- Average and peak are binned at 0.02 EDR intervals



Insitu peak EDR data upper levels
~21 year 61M pts

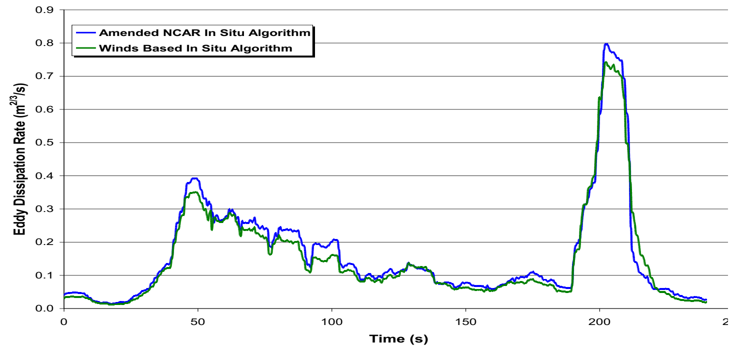


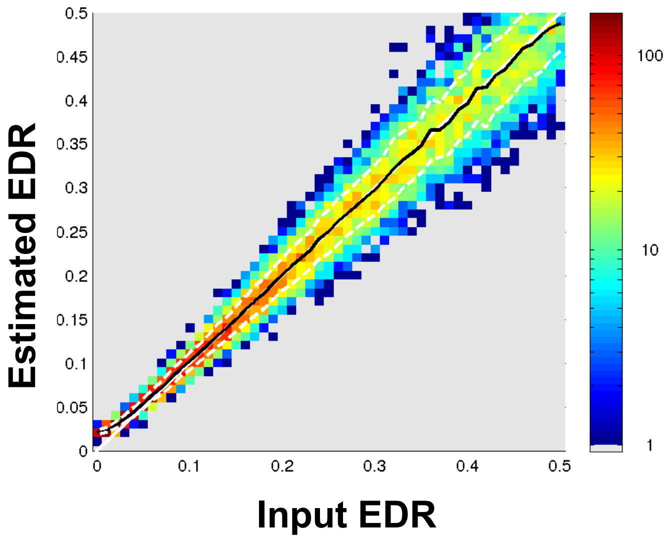
*Sharman et al. JAMC 2014

In situ edr estimates: caveats

- In situ verification exercises
  - Compare to accelerometer based methods from same aircraft
  - Simulations
    - Compare to von Karman turbulence simulation with known EDR and length scale (Frehlich et al., JAM 2001)
    - Use 2DOF response model to compute EDR and compare to input
- Caveats
  - Statistics contain an unknown avoidance bias
  - Daytime bias
  - Does not provide source (MWT, cloud)
  - Limited to ≤45,000 ft (lower stratosphere)
  - Some discrete events may not follow -5/3 assumed distribution (Rodriguez Imazio, JGR 2023)

  - Does not have to be perfect – Mainly need to distinguish between “smooth” and “moderate”
  - 0.02 EDR binning is adequate, 0.1 used on previous versions

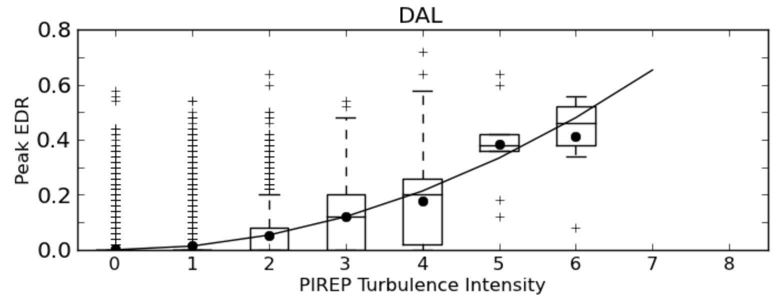


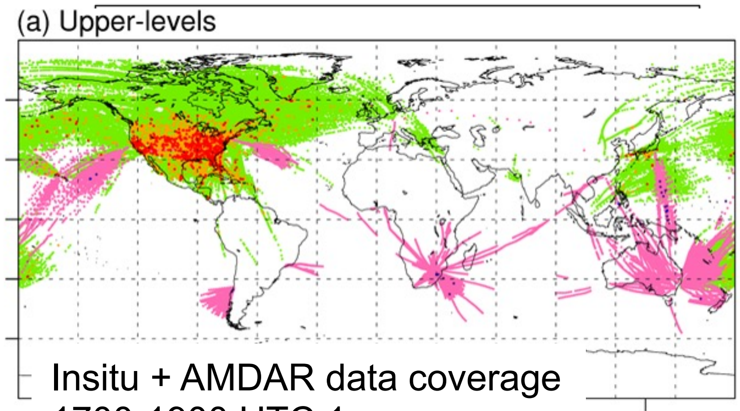


10,000 realizations of a von Karman turbulence wind field with known edr (Sharman et al. JAMC 2014)

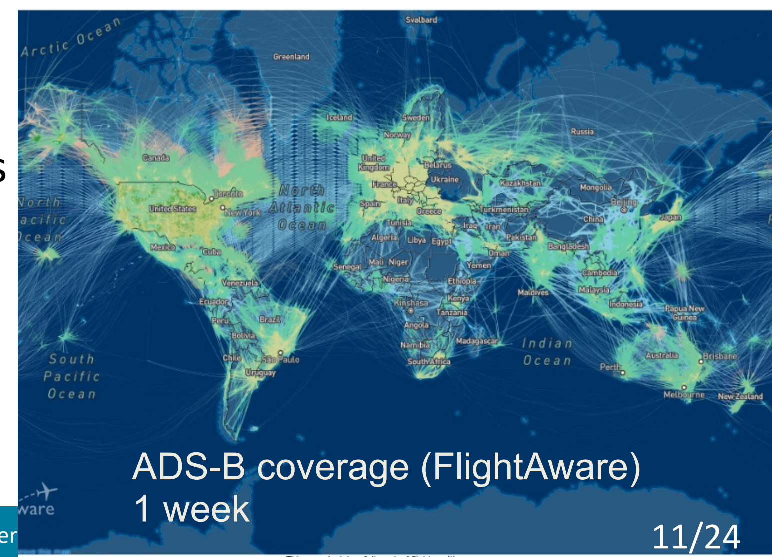
Other observations

- PIREPS
  - Must convert to EDR
  - Large position uncertainty (50% off by more than 23 km)
- AMDAR Ude
  - Must convert to EDR (Lee et al WAF 2022)
- ADS-B (Automatic Dependent Surveillance- Broadcast)
  - Use vertical rate converted to EDR
  - High density ~150,000 as of June 2022
  - No downlink costs
  - Challenging due to low sampling rate (~1Hz) and data quantization (e.g. ~0.3 m/s vertical rate)
  - Current research area at NCAR (L. Cornman PI)





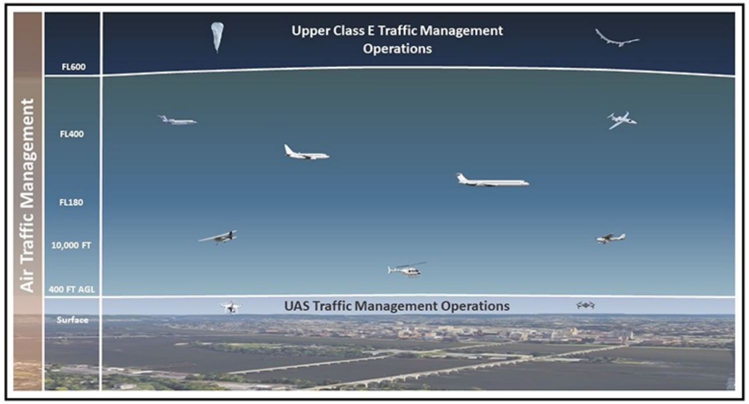
Insitu + AMDAR data coverage
1700-1900 UTC 1 year



ADS-B coverage (FlightAware)
1 week

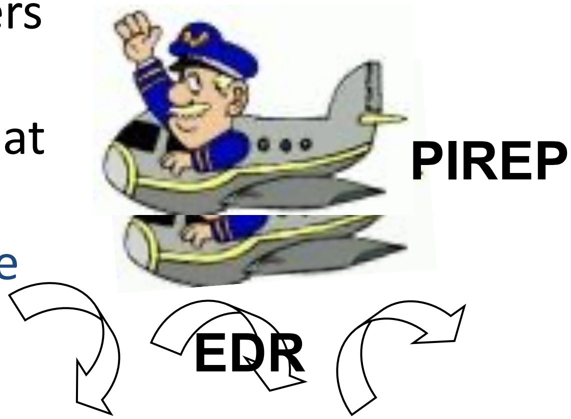
Other observations (cont.)

- HVRRD
  - Infrequent (2x day), sparse
  - But
    - Does include stratosphere
    - Does provide vertical distribution -> N^2 and shear
    - Which aircraft observations do not
  - Coming need for turbulence forecasts in Upper Class E air space (>60,000 ft) for UAS, military, SSTs, etc.
  - Ko et al. JGR 2023 showed EDR statistics were consistent for HVRRD derived EDR and in situ aircraft derived EDR in overlapping regions:
    - Both show occurrence frequency for mean MOG is very small
    - Data fit well by log normal



Aviation Turbulence Forecasting Approach

- Seek operational aviation turbulence forecast model
- “Aircraft scale” eddies that affect aircraft ~ few meters to couple km (smaller for UAS)
- Aircraft response is aircraft dependent but this is what pilot reports: “light”, “moderate”, “severe”
- CANNOT forecast these levels for every aircraft in the airspace
- Instead need to forecast atmospheric turbulence measure (i.e. aircraft independent measure)
  - We forecast EDR (= $\varepsilon^{1/3}$ $m^{2/3}s^{-1}$)
  - For reference ICAO standard thresholds (2001) for mid-sized aircraft are
    - EDR=0.10, 0.3, 0.5 for “light”, “moderate”, “severe”, resp.
  - We use EDR=0.15,0.22,0.34 $m^{2/3}s^{-1}$



Approach (cont.)

- No option to directly forecast globally or even regionally at say 25 m grid spacing operationally
- At lower resolutions current turbulence parameterizations don't work very well, esp. at upper-levels
- Use operational NWP model (e.g., WRF-RAP, HRRR, GFS)
- Compute "turbulence diagnostics" (D) from NWP output
- Assumes linkage between NWP resolvable scales and aircraft turbulence scales
- Ds are typically related to model spatial variations

For example: Ellrod Index=Deformation X shear

$$I = DEF\, S_V, \quad S_v = \left| \frac{\partial \vec{u}}{\partial z} \right|, \; DEF = \left(D_{SH}^2 + D_{ST}^2 \right)^{1/2}$$

$$D_{SH} = \frac{\partial v}{\partial x} + \frac{\partial u}{\partial y} \qquad D_{ST} = \frac{\partial u}{\partial x} - \frac{\partial v}{\partial y}$$

Approach (cont.)

- Multiple causes require multiple forecasting strategies →
- Graphical Turbulence Guidance (GTG)*
- Compute suite of turbulence diagnostics (D) converted to EDR (D*)
- GTG = ensemble weighted mean

$$GTG = W_1 D_1^* + W_2 D_2^* + W_3 D_3^* + \ldots.$$

- Ws and D*s are turbulence source and altitude dependent
- PBL, troposphere, stratosphere separately
- GTG=MAX(GTG CAT + GTG MWT + GTG CIT) EDR, all separately available

*Sharman et al. *Weather & Forecasting* 2006
Sharman and Pearson, *J Appl Met Clim*, 2016

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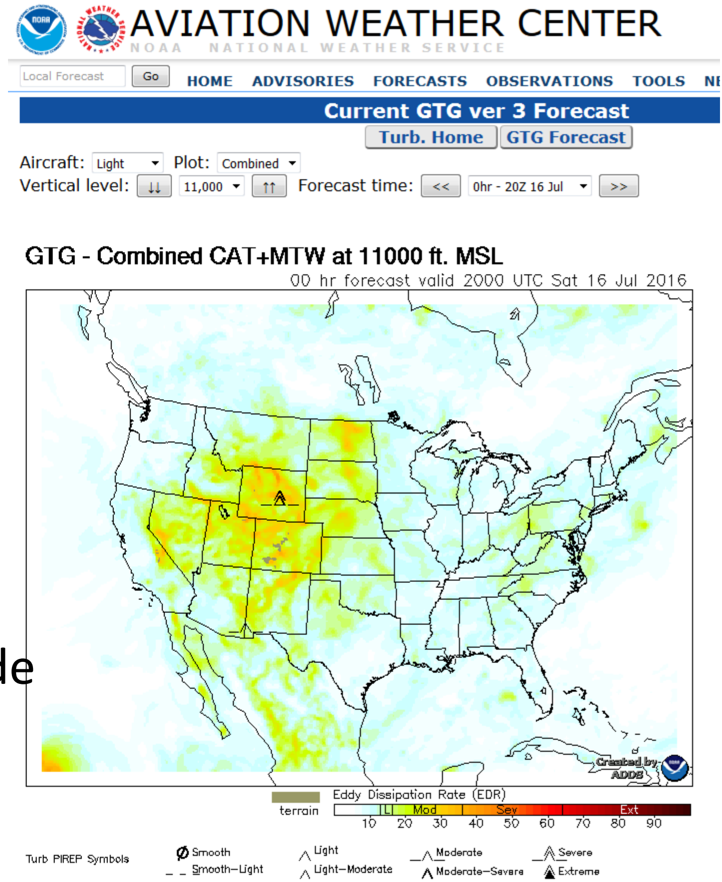
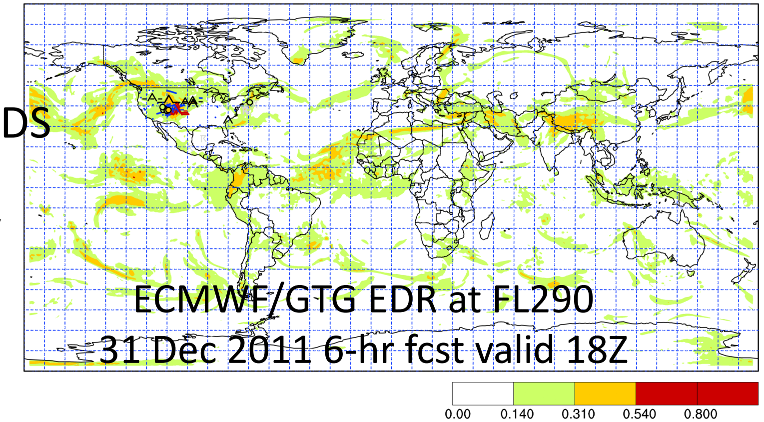
- GTG=MAX(GTG CAT + GTG MWT + GTG CIT) EDR, all separately available
- Operational
  - Currently available 24x7 on Operational ADDS (http://aviationweather.gov/adds)
  - Uses WRF-RAP NWP model updated hourly
  - Global on WAFS (GFS and UKMO), ECMWF updated every 6 hrs





ECMWF/GTG EDR at FL290
31 Dec 2011 6-hr fcst valid 18Z

*Sharman et al. *Weather & Forecasting* 2006
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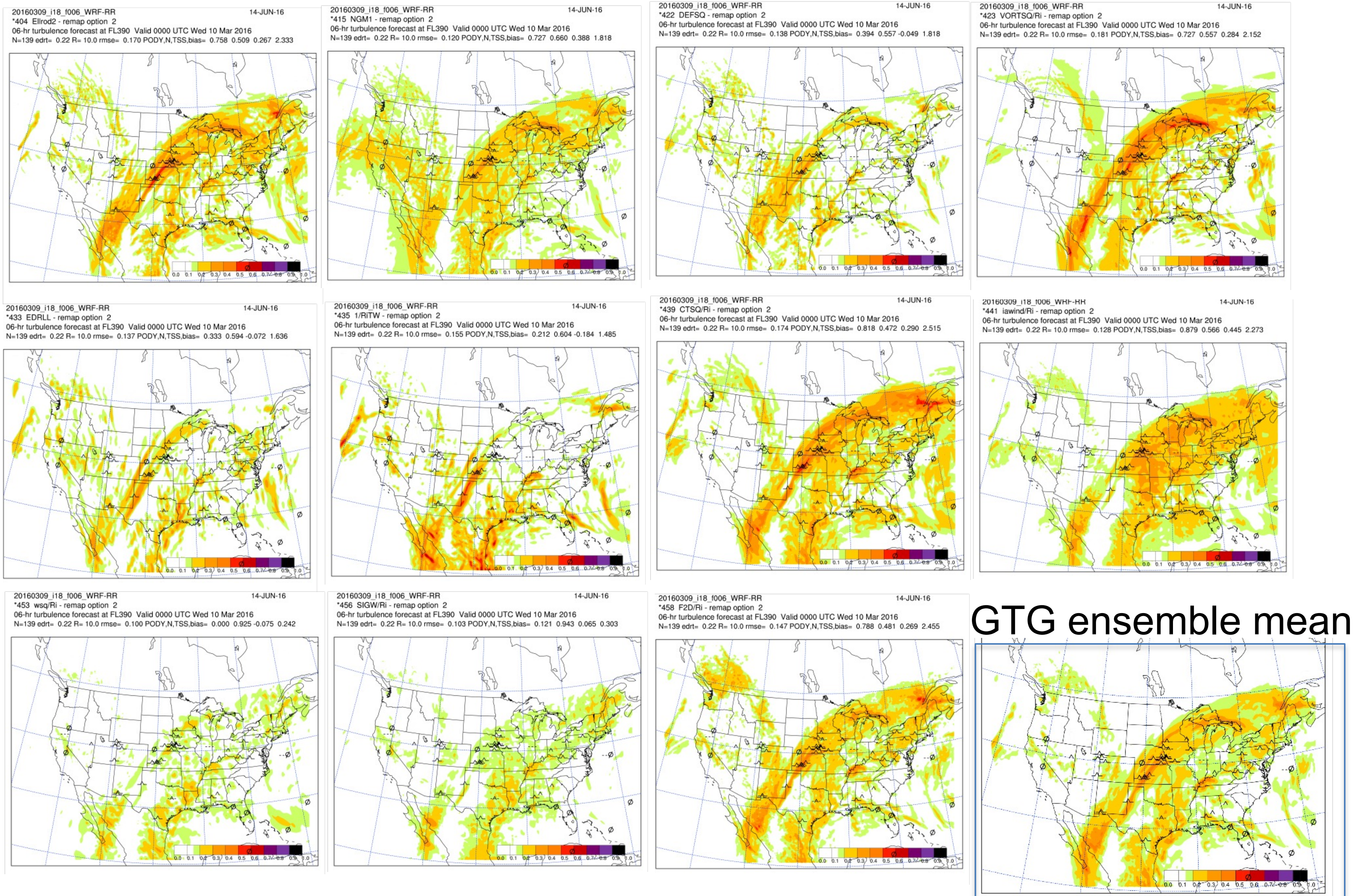
Example GTG diagnostics – GTG/RAP FL390



Machine Learning and Probabilistic Approaches

- Machine learning (ML)
  - Avoids some of the calibration issues
  - But requires large amounts of observational data for training
  - Initial results are encouraging (Muñoz-Esparza et al. 2020, Kaluza)

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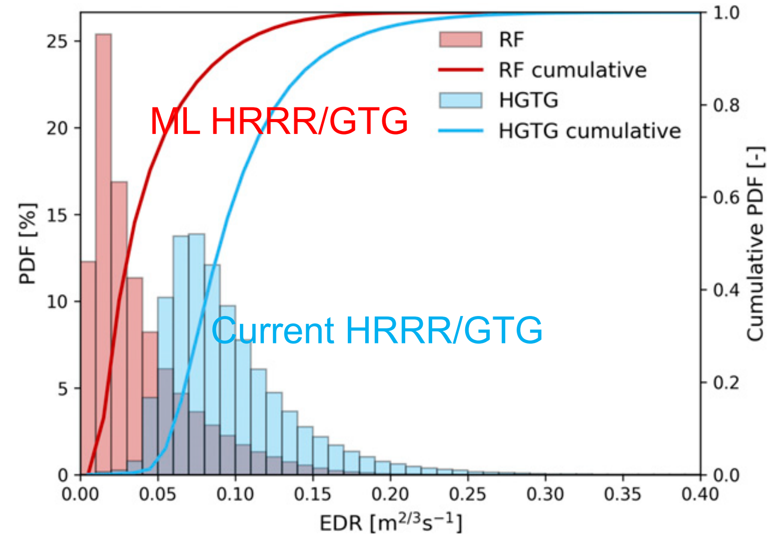

Muñoz-Esparza et al. 2020

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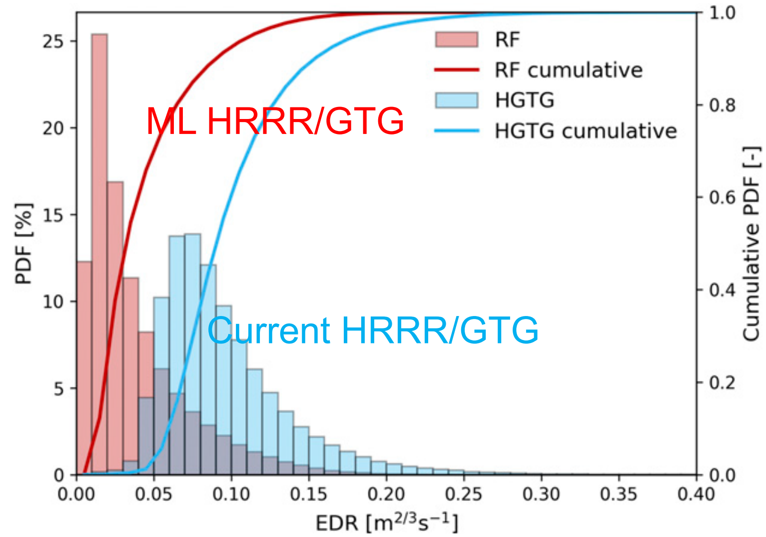
- Probabilistic approaches
  - Multiple diagnostics as an ensemble (MDE)
  - Multiple NWP ensembles (FME)
  - Time-lagged NWP output (TLE)
  - Some combination (Shin et al. WAF 2023)



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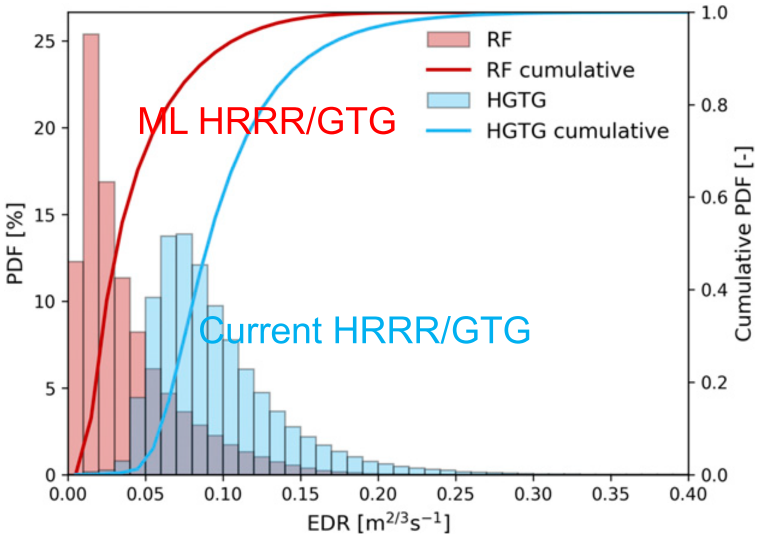

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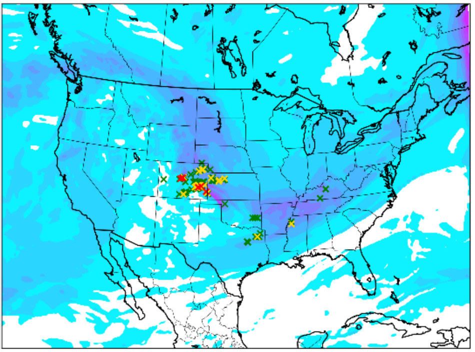
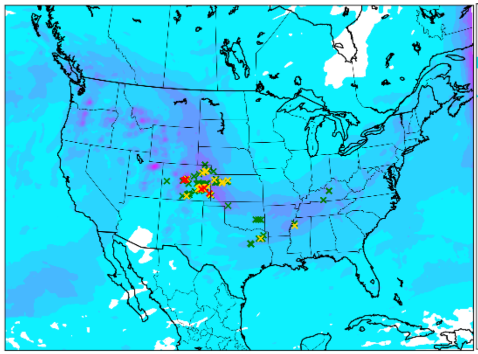
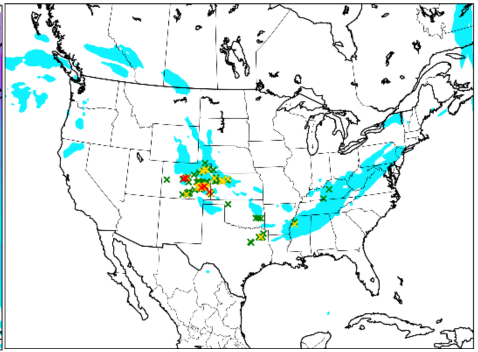


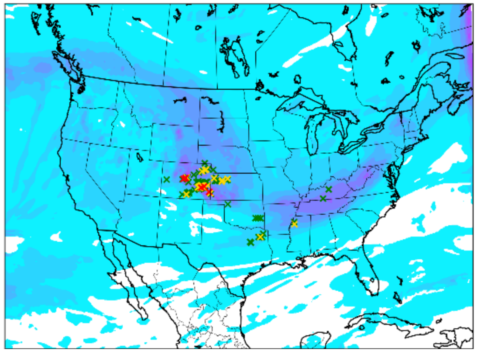
MDE 19 diagnostics



MDE 77 diagnostics



GEFS FME 31 ensembles

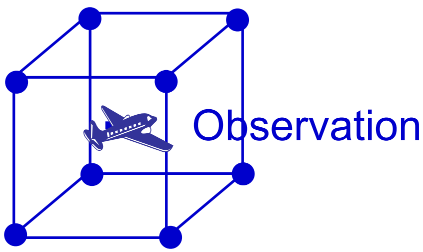


5 FME x 19 diagnostics

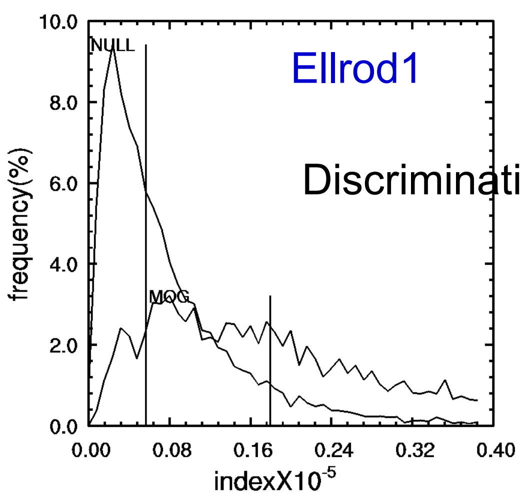
GTG verification: sample results

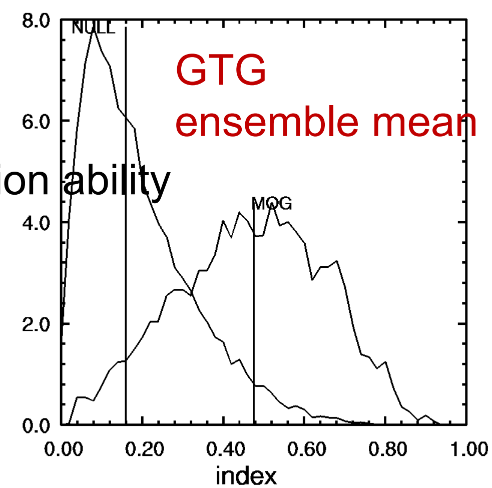
Develop verification metrics from many cases

- Compare observation to GTG surrounding grid points
- Use in situ “peak” EDR (~1 km uncertainty)
- Compute skill statistics to evaluate diagnostics/suite
  - MAE, RMSE, bias, ROC curves (Kaluza presentation)…
  - Discrimination ability
  - **Cannot distinguish between NWP and diagnostic errors**
  - All show deterministic ensemble mean has superior skill to individual diagnostics

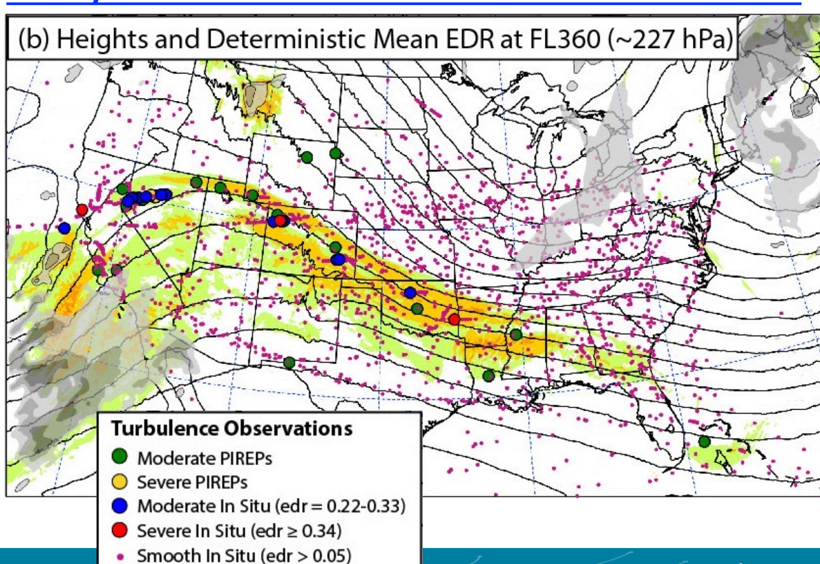


Discrimination ability





HRRR/GTG 6-hr Forecast Valid 2000 UTC 3 Dec 2019



Summary

- Semi-empirically based diagnostics can provide operationally useful forecasts of CAT and MWT using coarse resolution NWP model output
  - For aviation, $\varepsilon^{1/3}$=EDR is preferred observation/forecast metric
  - Using an ensemble of turbulence diagnostics instead of one diagnostic gives more robust statistical performance
  - Could also be used with an ensemble of NWP models
  - ML techniques show promise
  - Ultimately, approach must be probabilistic
  - CIT (convectively-induced turbulence) is challenging -> must nowcast

- Use of in situ EDR data allows more reliable tuning and verification
- HVRRD is useful to compare statistics of observational data, esp. in stratosphere

Longer term research needs

- Need better understanding of causes and lifecycles of turbulence
  - What are the sources/damping mechanisms?
  - What is the role of inertia-gravity waves, breaking, Ri reductions?
  - What is the role of the tropopause and tropopause folds?
  - How to handle wave-turbulence interactions?
  - Establish turbulence current and future climatology (P. Williams talk)
  - Need dedicated multiple aircraft field programs (dropsondes + penetrations)
- Modeling
  - What is "optimal" resolution for turbulence forecasting?
  - Need better subgrid turbulence parameterizations in free atmosphere -> ε
  - Nested simulations that include large (forcing) scale plus smaller scale have been highly successful
    - Need more cases based on accidents, elevated edr data
    - Need resolution, parameterization, initialization sensitivity studies

Many good PhD topics here!! For more see Sharman, Lane, Schumann (2017)