Open Frontiers in Turbulence Forecasting and Detection

4th Turbulence Mitigation Workshop
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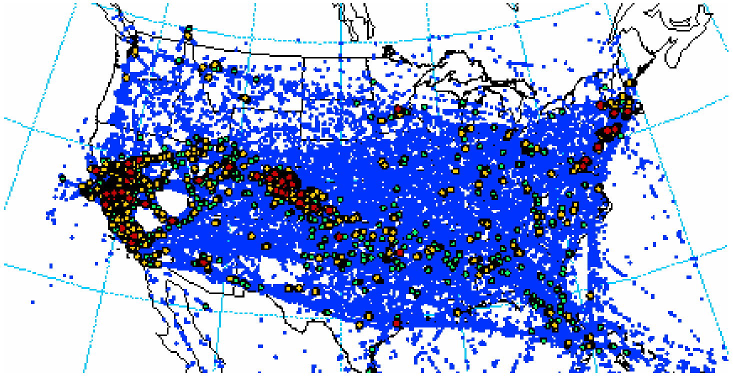
Turbulence Mitigation Workshop 4 Summary

- Can't really mitigate turbulence, so the workshop goal is to share latest turbulence research and operational advances to mitigate or at least minimize hazardous turbulence encounters

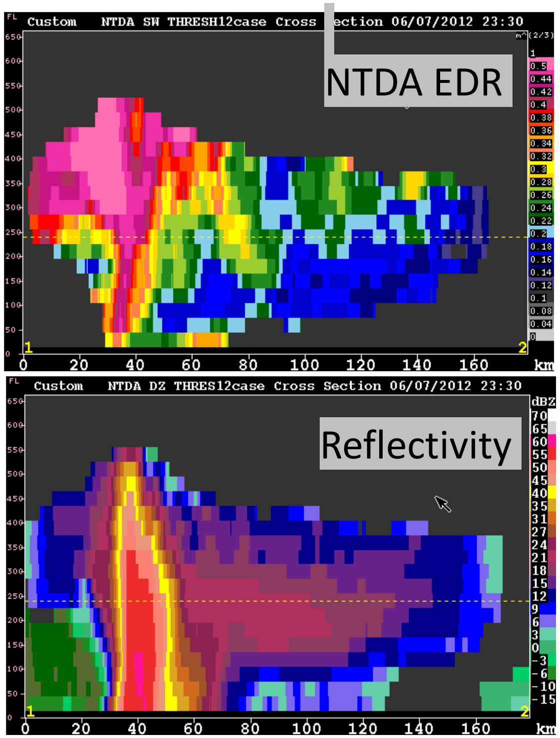
- Presentations clustered into 5 areas:
  - Develop better and more extensive turbulence observations/detection for routine dissemination, including public-private data sharing (Steve Bradford, Dean Lockett, Larry Cornman, Martin Gerber, Tim Rahmes, Nathan Polderman, Nathan Doble)
  - Develop better turbulence forecasting and nowcasting strategies and their verification (UKMO, Meteo France, Julia Pearson, John Williams, Walt Rogers)
  - Develop turbulence climatologies (Debi Turp, Paul Williams, Jung-Hoon Kim)
  - Perform fundamental and applied research to better understand the origin, life cycle, nature of turbulence, and feed back into forecasting and observation strategies (Andreas Dörnbrack and Ulrich Schumann, Paolo Imazio, Jim Doyle, Domingo Muñoz-Esparza, Hye-Yeong Chun)
  - Improve operational procedures that use observations and forecasts to promote avoidance of hazardous turbulence (Julia Pearson, Jason Craig, Stephanie Klipfel,, Matthias Steiner)

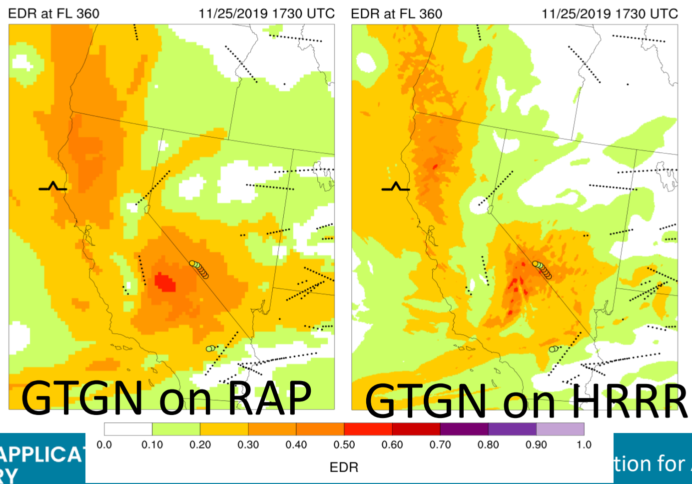
Progress Highlights: Observations and NWP model improvements

1. Better (quantitative, robust, high resolution, routine) observations
   - Moving to standard of energy dissipation rate (EDR) for all observations
   - EDR=$\varepsilon^{1/3}$ ($m^{2/3}\,s^{-1}$)
   - ~ aircraft loads (RMSG~EDR)
   - ICAO standard (for turbulence reporting) since 2001
   - NEXRAD Turbulence Detection Algorithm (NTDA)
2. More sophisticated/higher resolution NWP models provide better turbulence forecasts
   - Better resolves small-scale features due to waves and turbulence
   - Also improved numerics and parameterizations



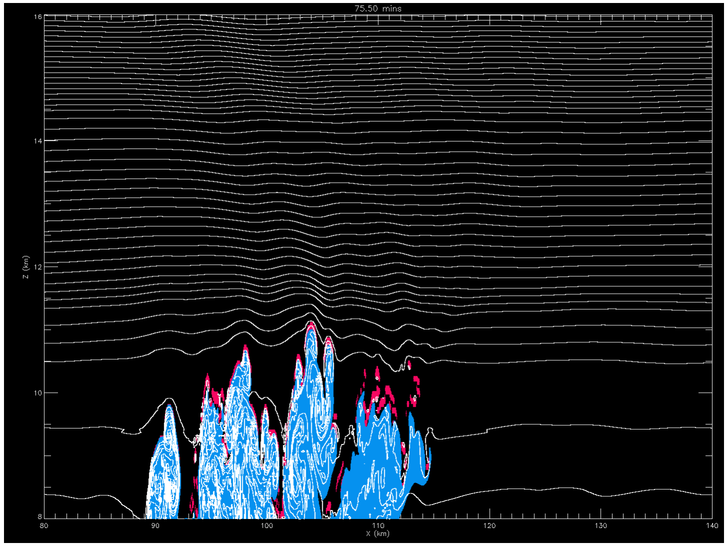
DAL+SWA EDR insitu 3 Dec 2019





Progress Highlights: Enhanced understanding

3. Use of observations coupled with high-resolution simulations and coarse resolution NWP models to
   - Better characterize turbulence
   - Identify sources of turbulence
   - Evaluate coarse-scale diagnostic performance
4. Identified importance of gravity waves in generating all forms of turbulence (CAT, MWT, CIT)
5. Identified the importance of deep convection in generating "CAT"
   - Gravity waves generated both above and laterally away from the cloud boundaries which can "break" leading to turbulence
   - Convection can significantly modify environment (e.g. by enhancing shear) that may induce turbulence far (>100 km) from the storm



Lane et al. JAS 2003

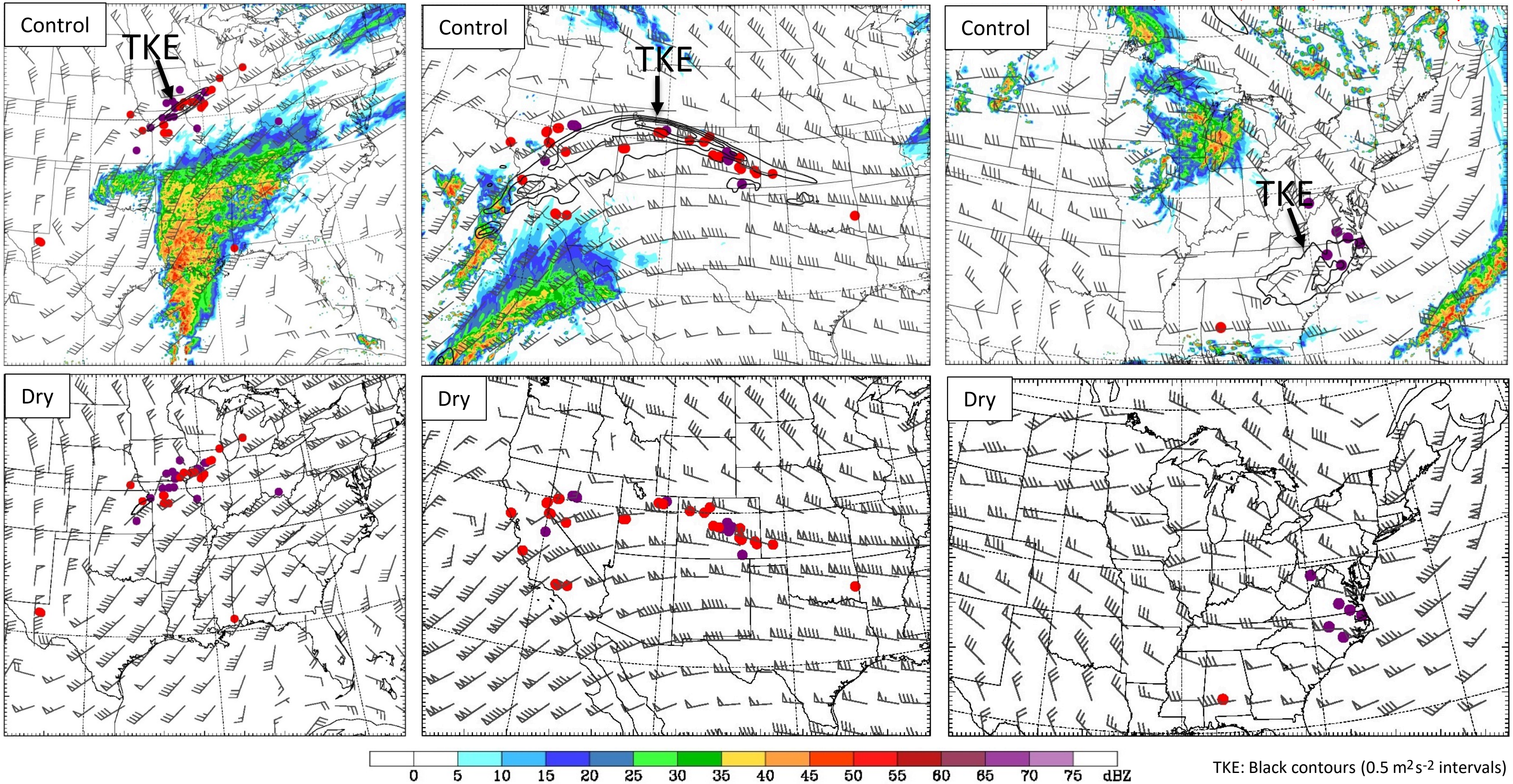
Progress Highlights: Enhanced understanding of “CAT”

WRF Simulations on d02 with Observed 20000-45000 ft Severe Turbulence Reports (red = in situ, violet = PIREPs)

1800 UTC 25 Oct 2019 MREF, 9-km Winds, 8-km TKE, and 1500-2100 UTC Reports

2000 UTC 3 Dec 2019 MREF, 10-km Winds, 9-km TKE, and 1700-2300 UTC Reports

1800 UTC 28 Jun 2017 MREF, 12-km Winds, 11-km TKE, and 1500-2100 UTC Reports



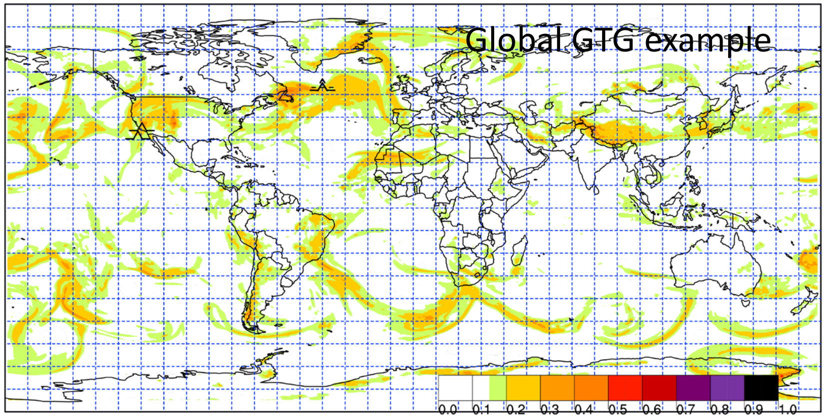
TKE: Black contours (0.5 $m^2 s^{-2}$ intervals)

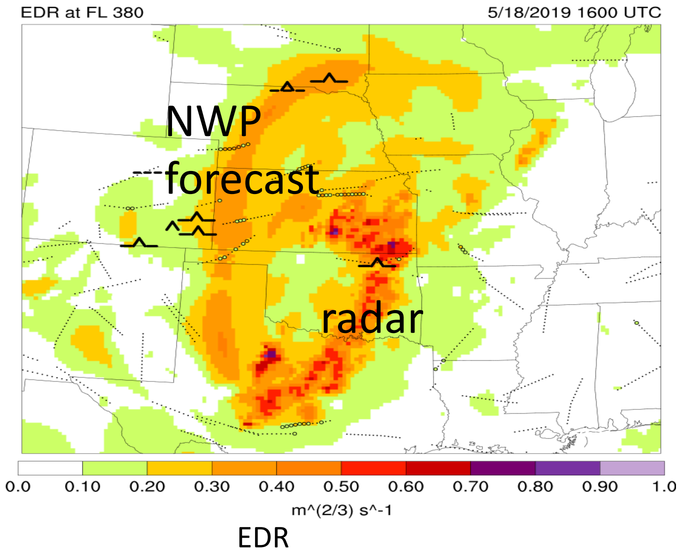
NEXRAD WSR-88D radar mosaic of maximum reflectivity in a vertical column (MREF, color shadings)

Courtesy Stan Trier, NCAR

Progress highlights: Advances in operational turbulence forecasting

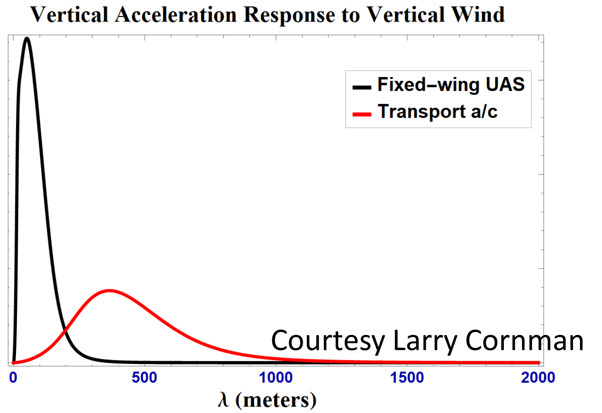
- Forecasts EDR NOT light, moderate, severe
  - Move from AIRMETS, SIGMETS to grid-based graphics
  - Turbulence potential -> severity (EDR)
- Requires inference of turbulence from larger resolved scales ->
- Turbulence diagnostics
  - SGS turbulence parameterizations are deficient at upper levels
  - Can use single or ensemble of diagnostics (**GTG**)
  - Different diagnostics for CAT,MWT,CIT
- Operational implementations of gridded products are now common
  - NOAA/NCEP
  - UK Met Office
  - Meteo France
  - Korean Meteorological Agency
  - Taiwan CAA/CWB
  - DWD
  - Private vendors
- Convection difficult to predict so must use a nowcasting approach (e.g., GTGN)

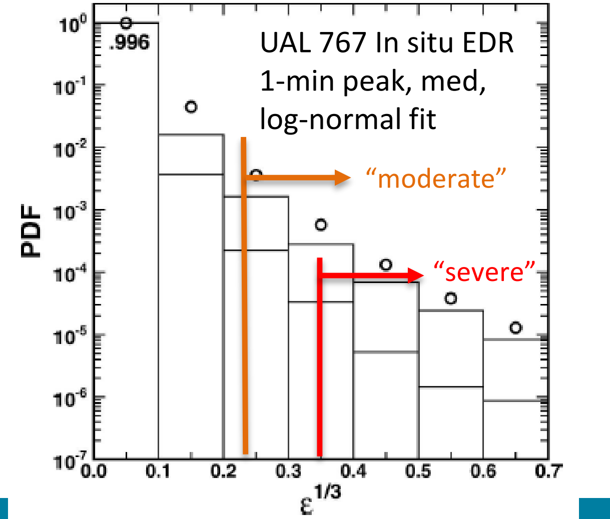




Frontiers

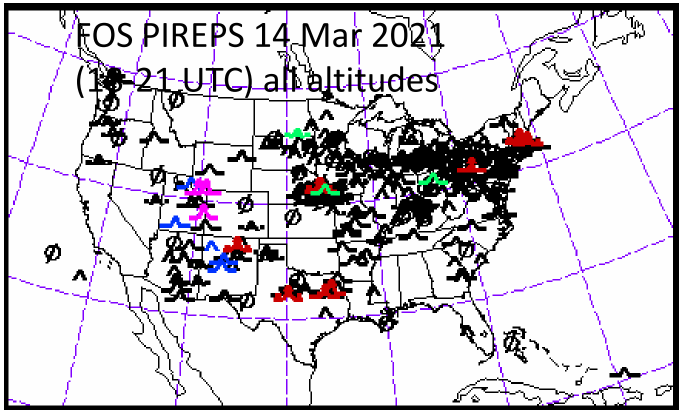
- Smaller, lighter aircraft are becoming an increasingly important component of operations
  - Unmanned aerial systems (UASs) and urban air mobility (UAM) respond to smaller scales
  - Higher loads for lighter aircraft
  - Response for quadcopters, etc?
  - Most fly in the atmospheric boundary layer
    - Urban effects
      - Extremely complex pattern even in the simplest cases
      - Depends on wind speed, direction, stability, building geometry, building-building interactions, etc
    - Low-level gusts including rotors
  - Also at high altitudes (Upper Class E airspace >FL600)
- Must deal with rare events (moderate freq ~ 0.01)
  - Need very large sampling of airspace
  - Forced to overforecast
  - Transitioning to probabilistic forecasts
  - Verification of rare events is not trivial!
  - Reliability estimates require robust turbulence climatology
  - How to disseminate rare events to users?
- Must respond to evolving climate effects
- Develop public-private data sharing policies

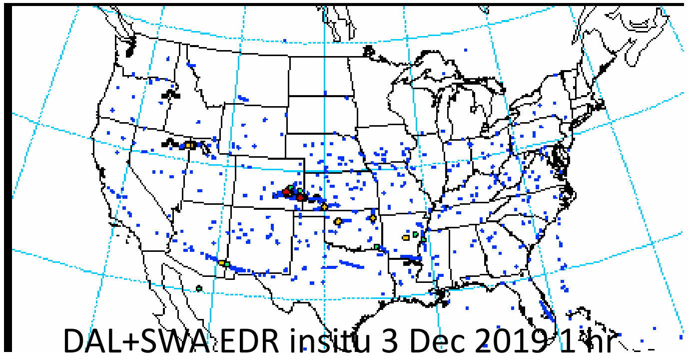




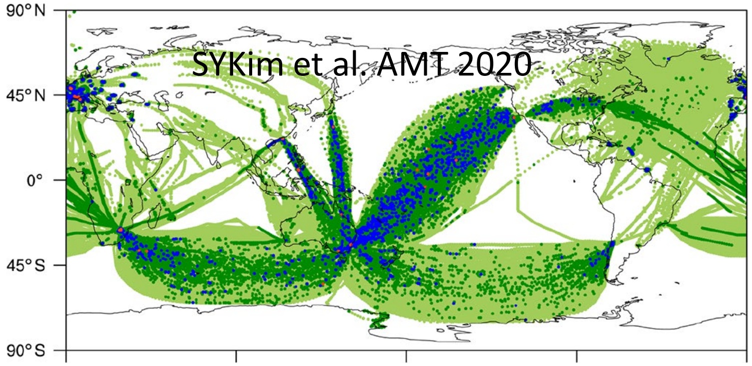
Frontiers: Observations

- Need more data
  - Make PIREPs more precise
  - Expand in situ EDR estimates
    - Current on-board (IATA)
    - Include water vapor estimates -> CIT
    - New on-board from Boeing and Airbus (?)
    - Implement QC'd AMDAR DEVG estimates
- Work towards accessing other observations
  - Implement ADS-B EDR estimates
  - Implement UAS EDR estimates
  - Implement HVRRD EDR estimates
  - Develop automated satellite feature detectors
  - Explore acceleration-based on-board measurements provided by some vendors (convert to EDR?)
  - Others…
- R&D areas
  - Ideally would like other information to better identify turbulence nature (CAT, CIT, waves)
  - How to verify EDR implementations?
  - Develop climatologies
  - Develop *in situ* <u>wave</u> detection algorithms



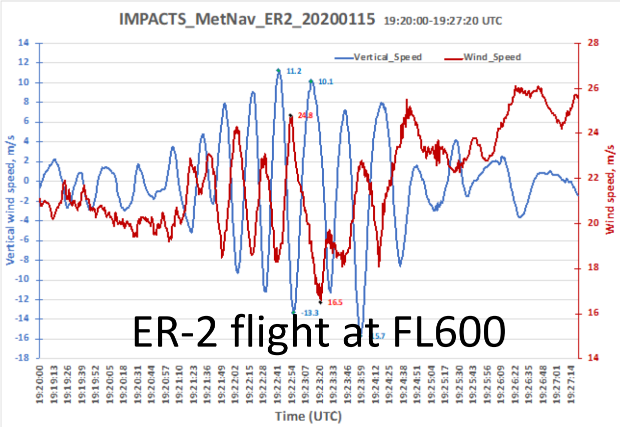


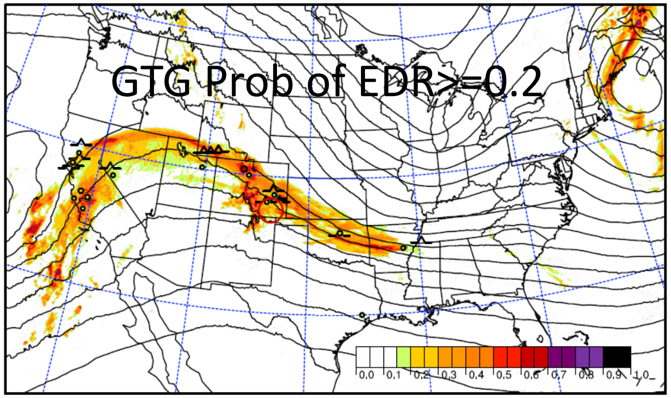
DAL+SWA EDR insitu 3 Dec 2019 1 hr
(18-19 UTC) FL360-380

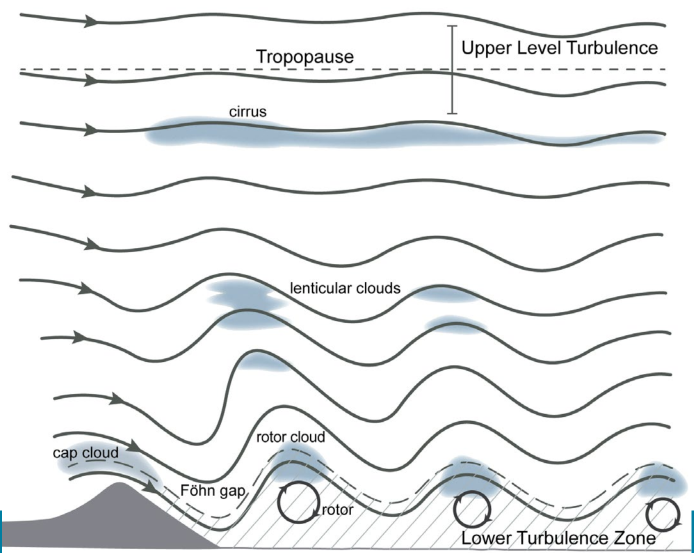


Frontiers: forecasting and nowcasting

- Develop turbulence diagnostics to accommodate:
  - low-level urban environments
  - complex terrain including rotors
  - higher altitudes (Upper Class E airspace >60,000 ft)
  - in-cloud and near-cloud turbulence
  - Results from research
- Develop probabilistic forecasts
  - Must deal with inherent predictability issues
  - NWP spread small for short-term forecasts
  - Explore alternatives, e.g. multi-diagnostic ensemble
- Apply AI/ML forecasting techniques
- Address verification issues
  - What is best metric or metrics for rare events ?
  - NWP errors vs diagnostic errors
  - Poor reliability due to overforecasting
  - What forecast lead times are most important to users?
- Need for rapid updates (nowcasts) globally
- Develop mountain <u>wave</u> forecasts (working group?)







From Doyle et al. 2016

Frontiers: Fundamental 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 climatology (through observations over along period of time and NWP model archives) and assess effects of climate change
  - **Need dedicated multiple aircraft field programs (dropsondes + penetrations)**
- **Modeling**
  - Need better subgrid turbulence parameterizations in free atmosphere -> ε
  - Address convection timing and displacement errors
  - Move to turbulence prediction within NWP framework (has direct access to tendencies)
  - Nested simulations that include large (forcing) scale plus smaller scale have been highly successful
    - Need more cases based on accidents, elevated edr data, field programs
    - Need resolution, parameterization, initialization sensitivity studies

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

Summary

- Reviewed 5 progress highlights mentioned in the Workshop
  1. Wide-spread implementation of in situ observations
  2. Development of sophisticated higher resolution NWP models
  3. Use observations coupled with high-resolution simulations
  4. Better understanding of the role of deep convection in “CAT”
  5. Better understanding of the role of gravity waves in free atmosphere turbulence

- Identified short term operational and research needs
  - Provide low-level turbulence forecasts in complex terrain and urban environments
  - Include more observations for verification and nowcasting, perhaps from ADS-B, satellite features, high-resolution soundings
  - Provide global nowcasts that include CIT
  - Case studies using high-resolution simulations
  - Develop private vendor – research community collaborations
  - Establish mechanisms for data sharing

- Identified some longer term and more fundamental research needs
  - Enhance fundamental understanding of genesis and character of aircraft-scale turbulence through
    - high-resolution simulations
    - Field programs
  - Establish effects of climate change
  - NWP directly predicts ε or EDR