Improvements in Low Level Turbulence (LLT) forecasting for UAVs

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Small size/weight of UASs makes them more susceptible to turbulence variability & magnitude [expected low-altitude operations: \( z \approx 50 - 150 \, \text{m} \)]

> 10 kg; > 2 m

What is the relevant range of EDR when forecasting turbulence for UAS applications?
LLT implications for general aviation

Require accurate LLT forecasting & have a direct impact in take-off and landing maneuvers

Wake vortices persist longer in weak-turbulence background environments
GTG: “turbulence indices” + “observations”

Each turbulence index $D_i$ is rescaled to an EDR assuming a log-normal distribution of EDR

$$\log D_i^* = a + b \log D_i$$

where “a” and “b” are chosen to give best fit to expected log-normal distribution at upper levels and depend on climatology.

Which indices are appropriate at low levels?

LLT mechanisms are different: do we need to modify GTG?

Graphical Turbulence Guidance (GTG)
Sharman & Pearson (JAMC 2017)
Pearson & Sharman (JAMC 2017)
Muñoz-Esparza & Sharman (JAMC 2018)
EDR observations at low-levels

The eXperimental Planetary boundary layer Instrumentation Assessment campaign (2015) (Lundquist et al. BAMS 2017) -> high-frequency sonic anemometer data

Kolmogorov’s (1941) hypothesis:

\[ D^2(\Delta t) = U^{2/3}C_k\varepsilon^{2/3}\Delta t^{2/3} \]

Automated algorithm developed to derive EDRs from sonic anemometers

Large dataset generated!!! (3 months, 7 heights, ~1.5Million EDRs)

Muñoz-Esparza, Sharman, Lundquist (MWR 2018)
Insights into low-level turbulence

Statistical behavior

Strong diurnal and height dependence
- **Daytime turbulence**: Weibull distribution
- **Nighttime turbulence**: log-normal distribution (same as upper-levels)
New GTG LLT algorithm & calibration

Extended statistical re-mapping approach from GTG to ABL stability (2 distributions: log-normal/Weibull) dependence for low-level EDR forecasting

\[
\ln D^* = a + b \ln D
\]

\[
a = \langle \ln \varepsilon^{1/3} \rangle - b \langle \ln D \rangle
\]

\[
b = \frac{SD[\ln \varepsilon^{1/3}]}{SD[\ln D]}
\]

\[
f(\ln x) = \frac{k}{\lambda} \left( \frac{\ln x}{\lambda} \right)^{k-1} e^{-(\ln x/\lambda)^k}
\]

\[
f(\ln x) = \frac{1}{\sqrt{2\pi}\sigma^2} e^{-\frac{(\ln x-\mu)^2}{2\sigma^2}}
\]

- 1-year long calibration using the High-Resolution Rapid Refresh (HRRR, 3 km)
- Optimization based on Mean Absolute Percentage Error (MAPE) minimization

Muñoz-Esparza & Sharman (JAMC 2018)
Improved ABL predictions based on specific “indices” and observation-derived understanding of climatological behavior of turbulence dissipation rate in the ABL.
GTG LLT validation & comparison to GTG v3 (II)

CAT error decreased by a factor of 2 (MAPE = 55%) and ~20% increased probability of detection of typical low and high EDR values
GTG LLT validation & comparison to GTG v3

- Improved ABL predictions based on specific “indices” and observation-derived understanding of climatological behavior of EDR in the ABL
- Implemented in operational G-GTG based on FV3 (code already delivered)
- GTG LLT will be part of GTG v4 (additionally supporting HRRR and RAP)

Overall diurnal evolution of ABL turbulence is correctly captured
However...

Significant variability is present at smaller spatiotemporal scales [s – min]
Toward eddy-resolving forecasts

Operational NWP forecasts are too coarse to capture the required turbulent scales of interest…

**5h-fcst vertical velocity, \( w \,[\text{m s}^{-1}], \, z = 100 \, \text{m} \)**

(HRRR, \( \Delta = 3 \, \text{km}; \, 14 \, \text{LT} \))

**5h-fcst vertical velocity, \( w \,[\text{m s}^{-1}], \, z = 100 \, \text{m} \)**

(WRF mesoLES, \( \Delta = 25 \, \text{m}; \, 14 \, \text{LT} \))

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\( w \times 10 \)

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Muñoz-Esparza et al., GRL (2018)
Toward eddy-resolving forecasts

Dynamic downscaling from the RAP fcst (~13.2km) to nested 1 km mesoscale and 100m/25m LES [1200 x 1200 x 80 grid points]
Toward eddy-resolving forecasts

Contours: vertical velocity [m s⁻¹] (z = 100 m)

Muñoz-Esparza et al., GRL (2018)
Both probability of EDR and its temporal rate of change are well reproduced by the eddy-resolving forecasts!
Near-future directions: urban environment

Significant interest on urban scenarios
- High resolutions and building-resolving capabilities are required
- Accelerated GPU-LES to enable real-time forecasting applications

NCAR-RAL team is developing an accelerated GPU-LES code: “FastEddy”

Lee & Muñoz-Esparza (JAMC 2018, submitted)
Conclusions

✓ We have enhanced GTG with the development of a LLT-specific algorithm → accurately represents diurnal evolution of EDR in the ABL

✓ GTG LLT forecasting in the ABL has the potential to benefit: UAVs, wake turbulence …

✓ Meter-scale coupled WRF mesoscale-LES realistically reproduces turbulence in the ABL [dissipation rate validated through comparison to sonic anemometer data] → need to move toward “probabilistic” LES-scale forecasts

✓ NCAR’s GPU-accelerated LES model FastEddy will enable a path toward high-resolution eddy-resolving forecasts in the near term [including building-resolving urban capabilities]
Thanks for your attention!!!