Improvements in Low Level Turbulence (LLT) forecasting for UAVs

Domingo Muñoz-Esparza & Robert Sharman

National Center for Atmospheric Research (NCAR)

3rd Turbulence Impact Mitigation Workshop

Advances in Detection, Forecasting, and Characterization of Aviation-scale Turbulence

5-6 September 2018, MITRE campus, McLean, VA

Unmanned Aerial Systems (UASs)

NCAR

NASA's concept for a possible UTM system

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

> 10 kg; > 2 m

< 0.1 kg
< 0.1 m

What is the relevant range of EDR when forecasting turbulence for UAS applications?

LLT implications for general aviation

NCAR

Wake vortices persist longer in weak-turbulence background environments

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

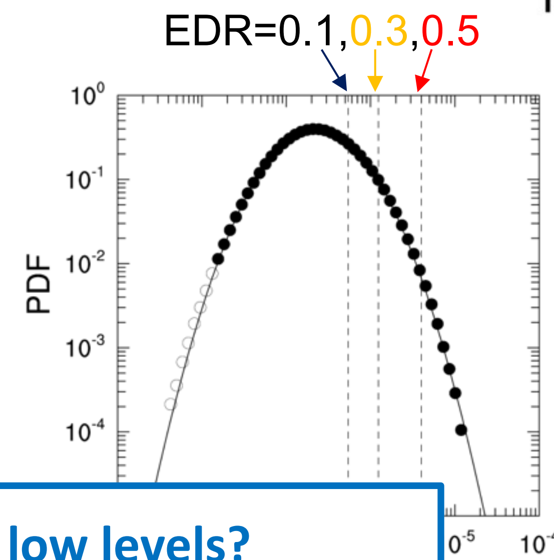
GTG: "turbulence indices" + "observations"

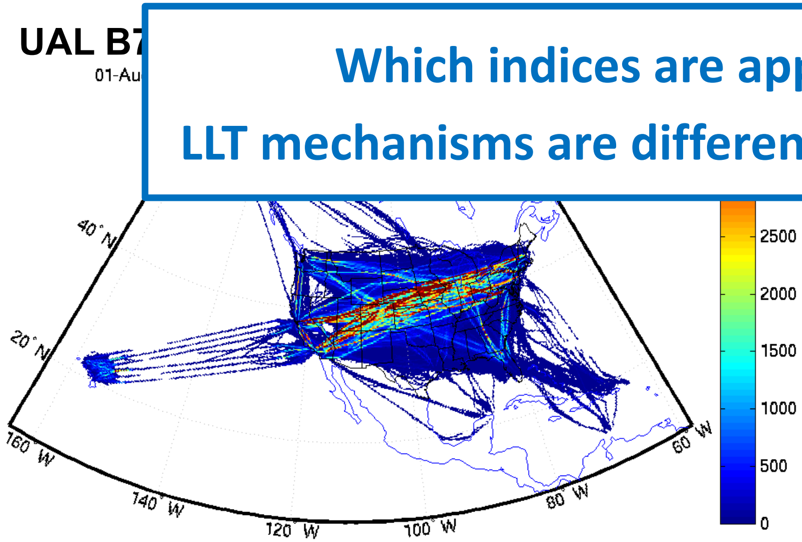
NCAR

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

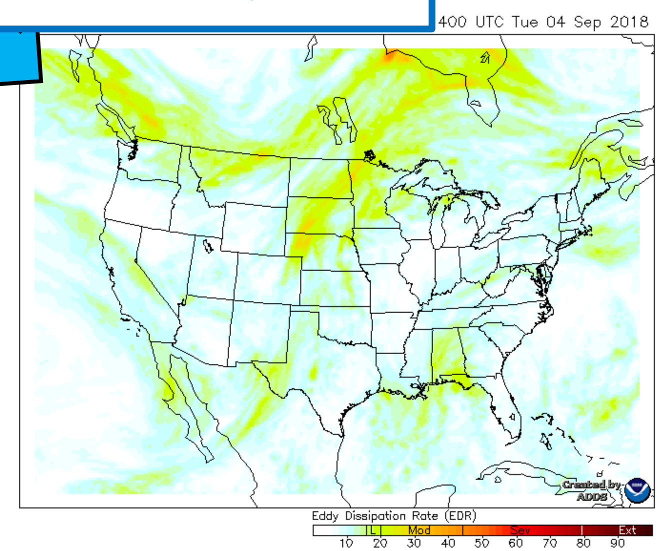




Which indices are appropriate at low levels?

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

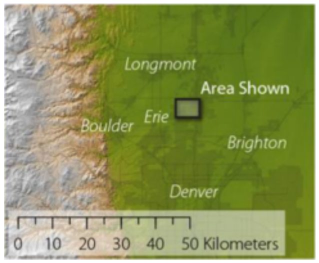
$n \sum_i w_i D_i^*$



Graphical Turbulence Guidance (GTG)
Sharman & Pearson (JAMC 2017)
Pearson & Sharman (JAMC 2017)
Muñoz-Esparza & Sharman (JAMC 2018)

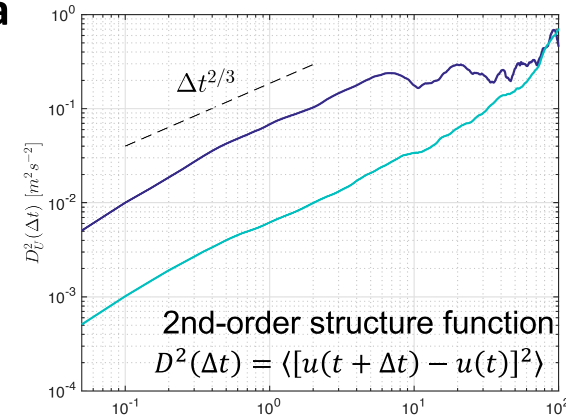
EDR observations at low-levels

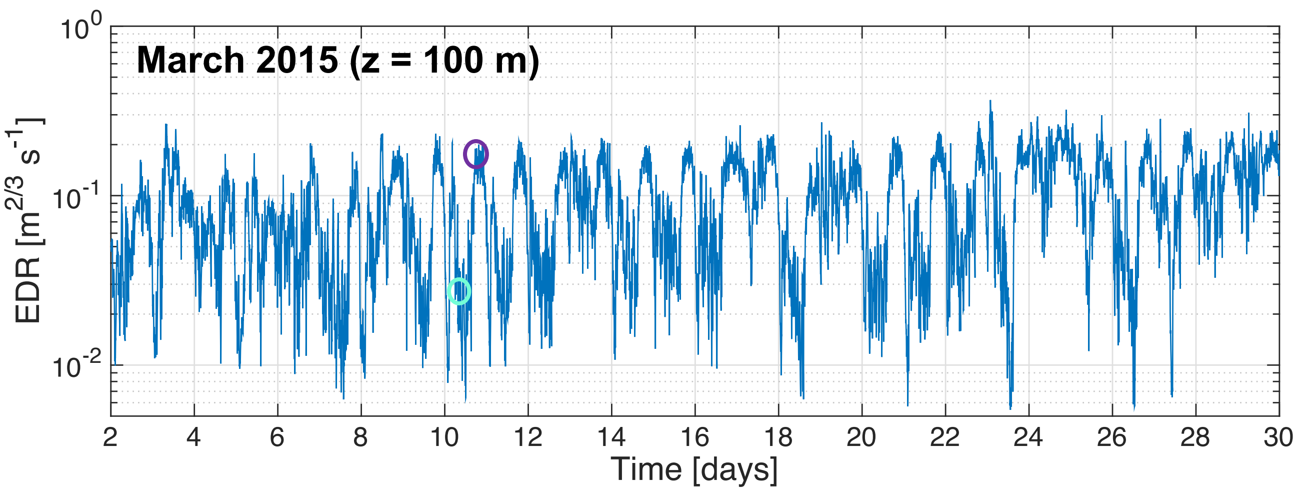
The e**X**perimental **P**lanetary boundary layer **I**nstrumentation **A**ssessment campaign (2015) (Lundquist et al. BAMS 2017) -> **high-frequency sonic anemometer data**



Kolmogorov's (1941) hypothesis:

$$\boxed{D^2(\Delta t) = U^{2/3} C_K \varepsilon^{2/3} \Delta t^{2/3}}$$





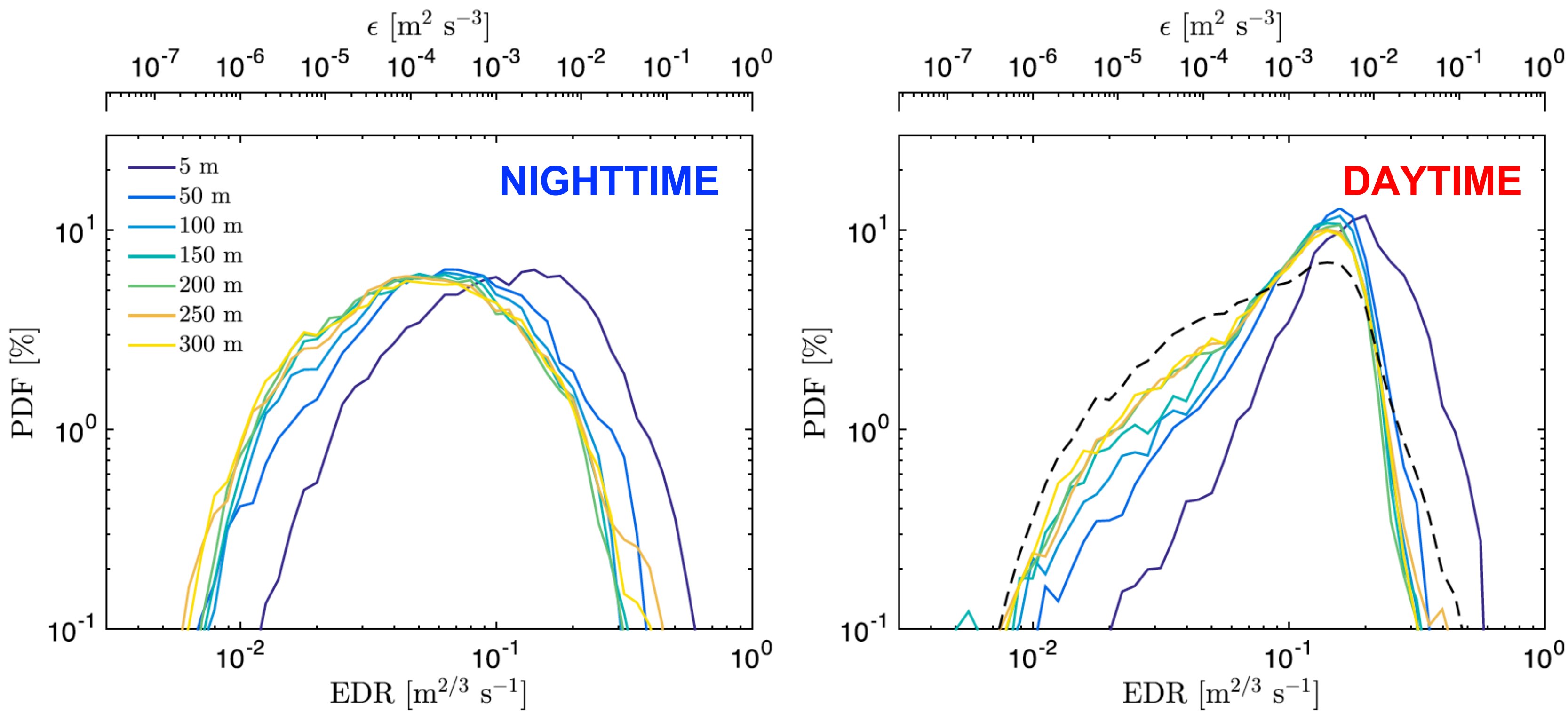
Automated algorithm developed to derive EDRs from sonic anemometers

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

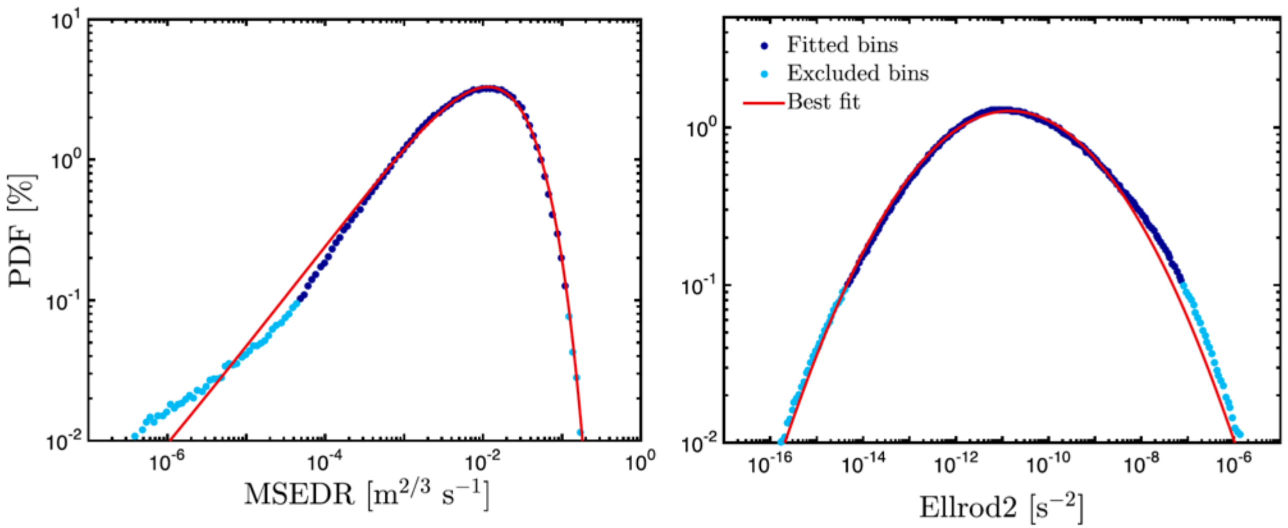
$$\boxed{\ln D^* = a + b \ln D}$$

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

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

$$\begin{cases} f(\ln x) = \frac{k}{\lambda}\left(\frac{\ln x}{\lambda}\right)^{k-1} e^{-(\ln x/\lambda)^k} & (log-Weibull) \\ f(\ln x) = \frac{1}{\sqrt{2\pi\sigma^2}} e^{-\frac{(\ln x-\mu)^2}{2\sigma^2}} & (lognormal) \end{cases}$$

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

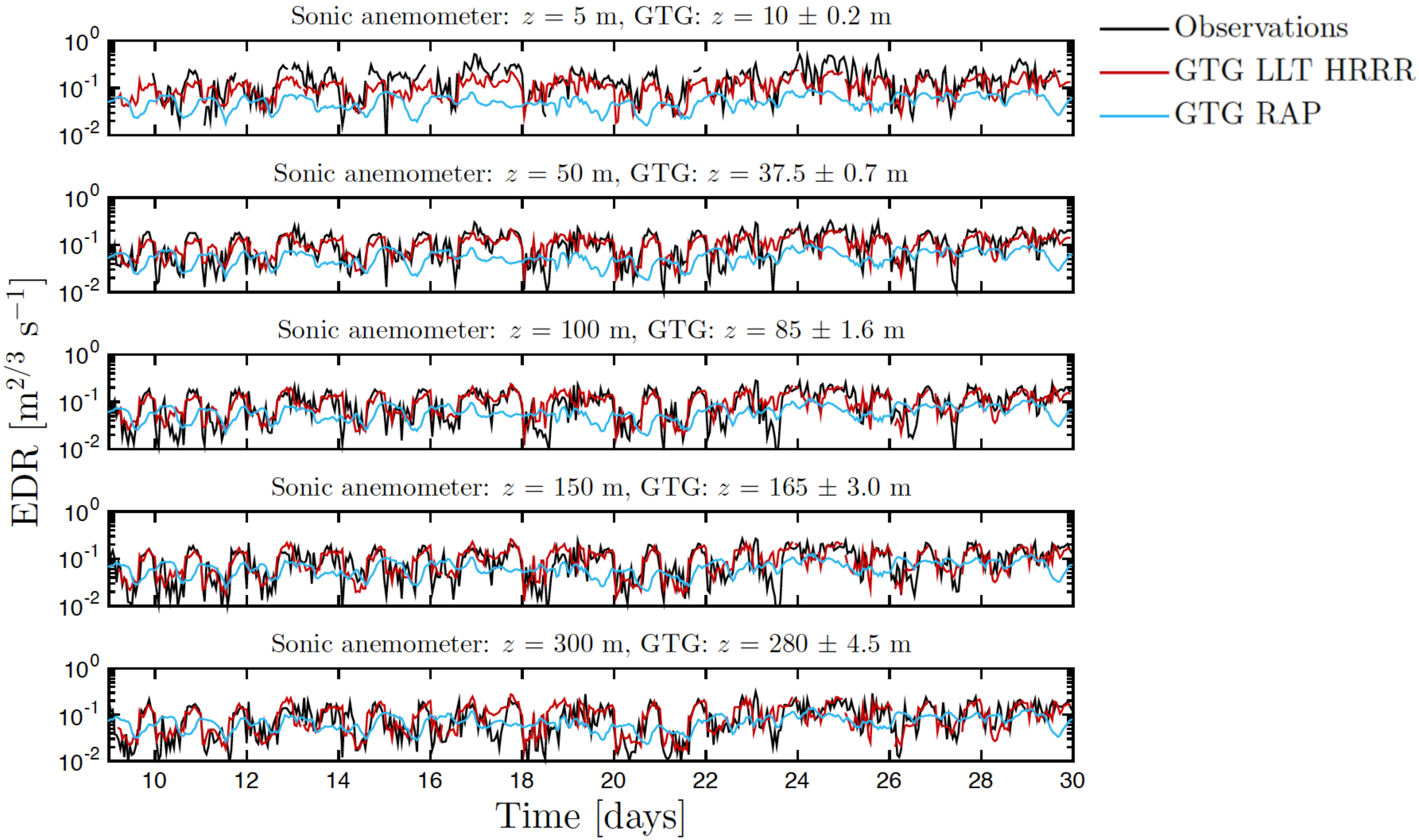


Muñoz-Esparza & Sharman (JAMC 2018)

GTG LLT validation & comparison to GTG v3 (I)

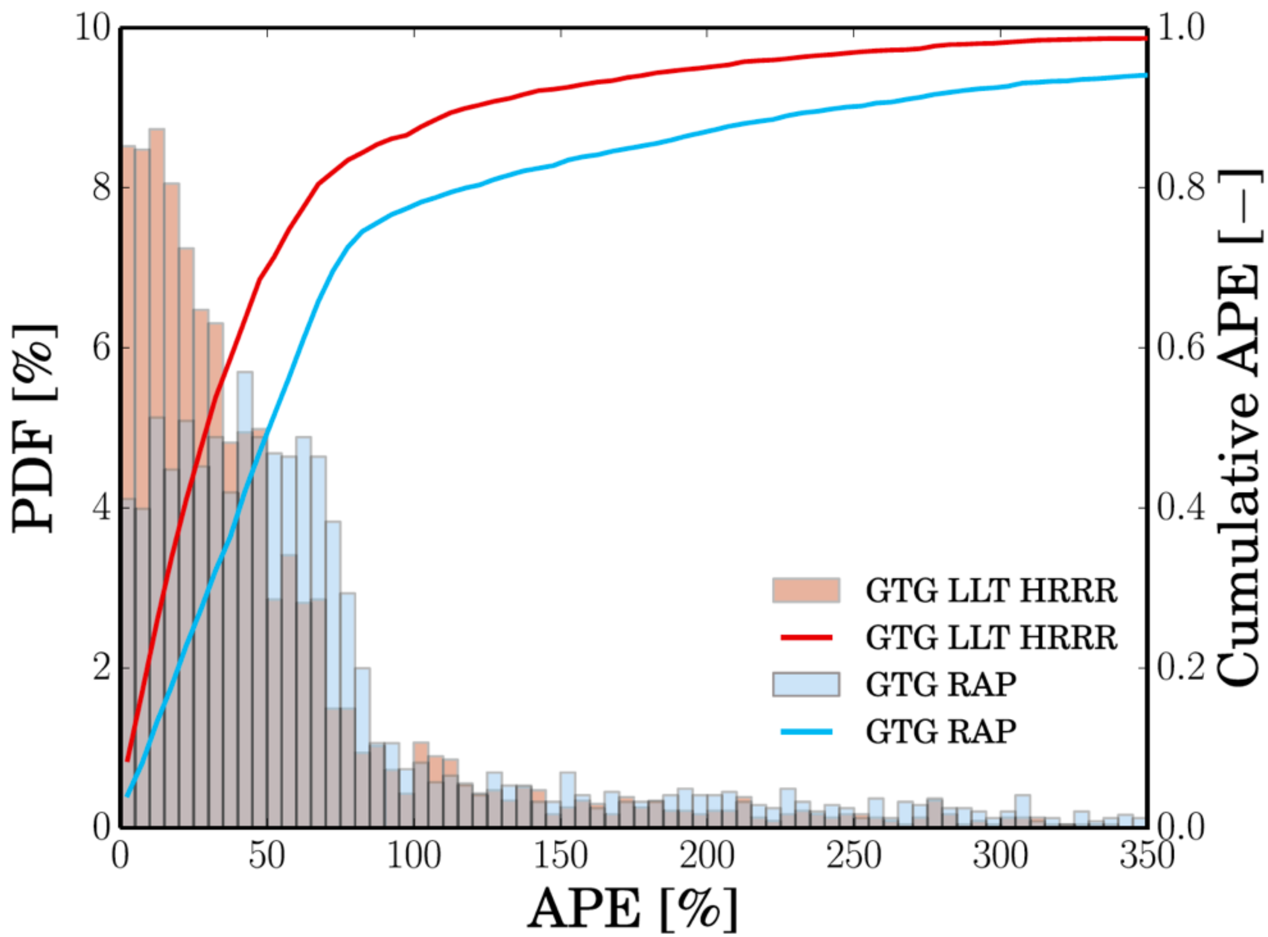
NCAR

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)

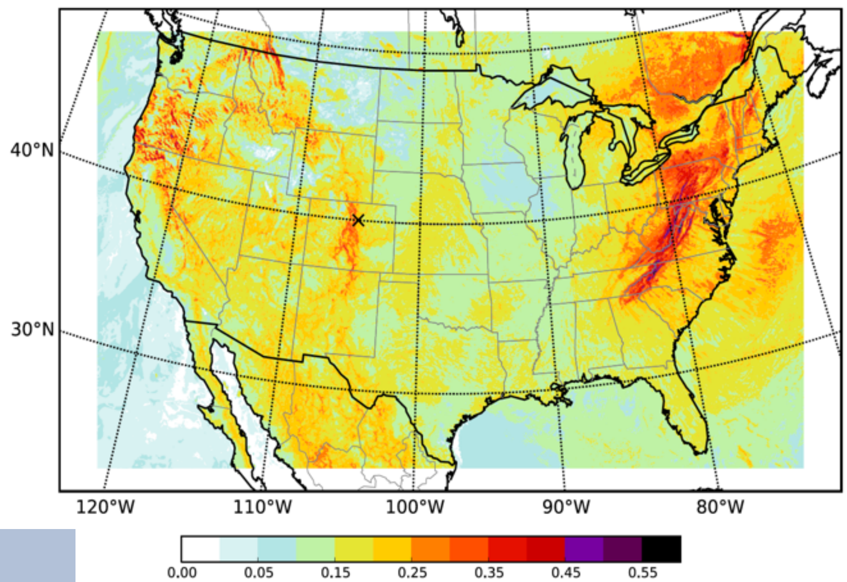
CAT error decreased by a factor of 2 (MAPE = 55%) and ~20% increased probability of detection of typical low and high EDR values



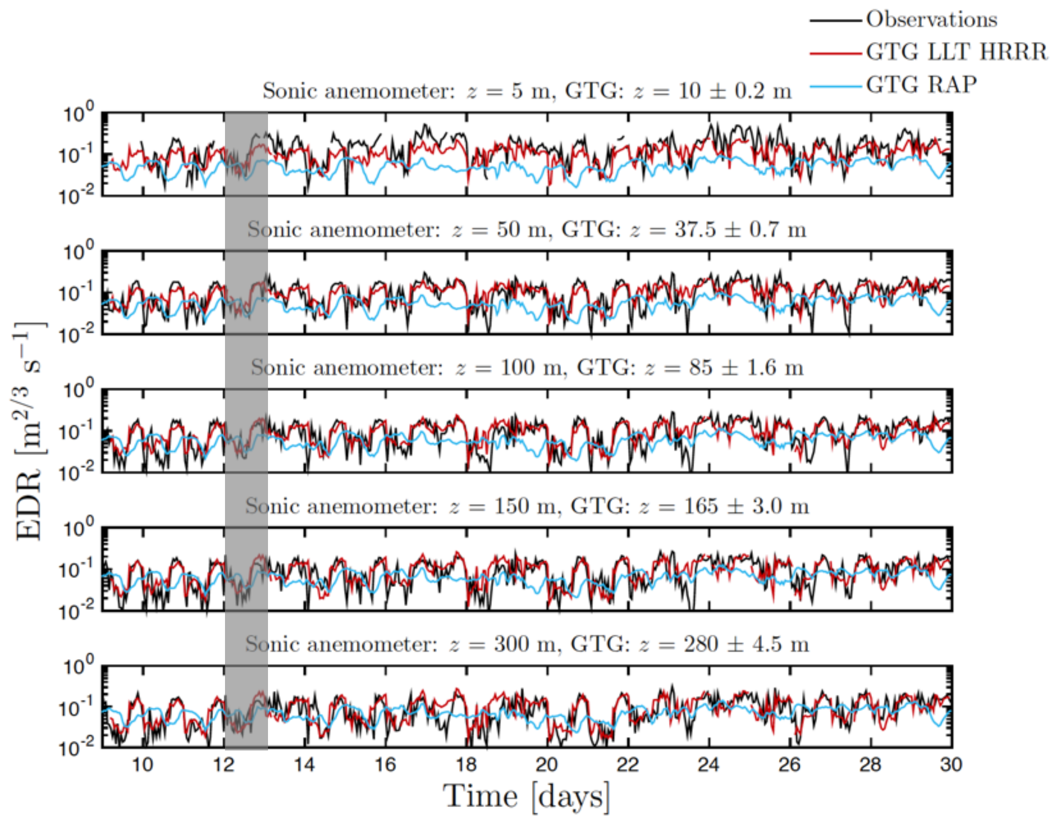
GTG LLT validation & comparison to GTG v3

- 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)

5h-fcst EDR, z = 150 m (valid 18 UTC 15th March 2017)



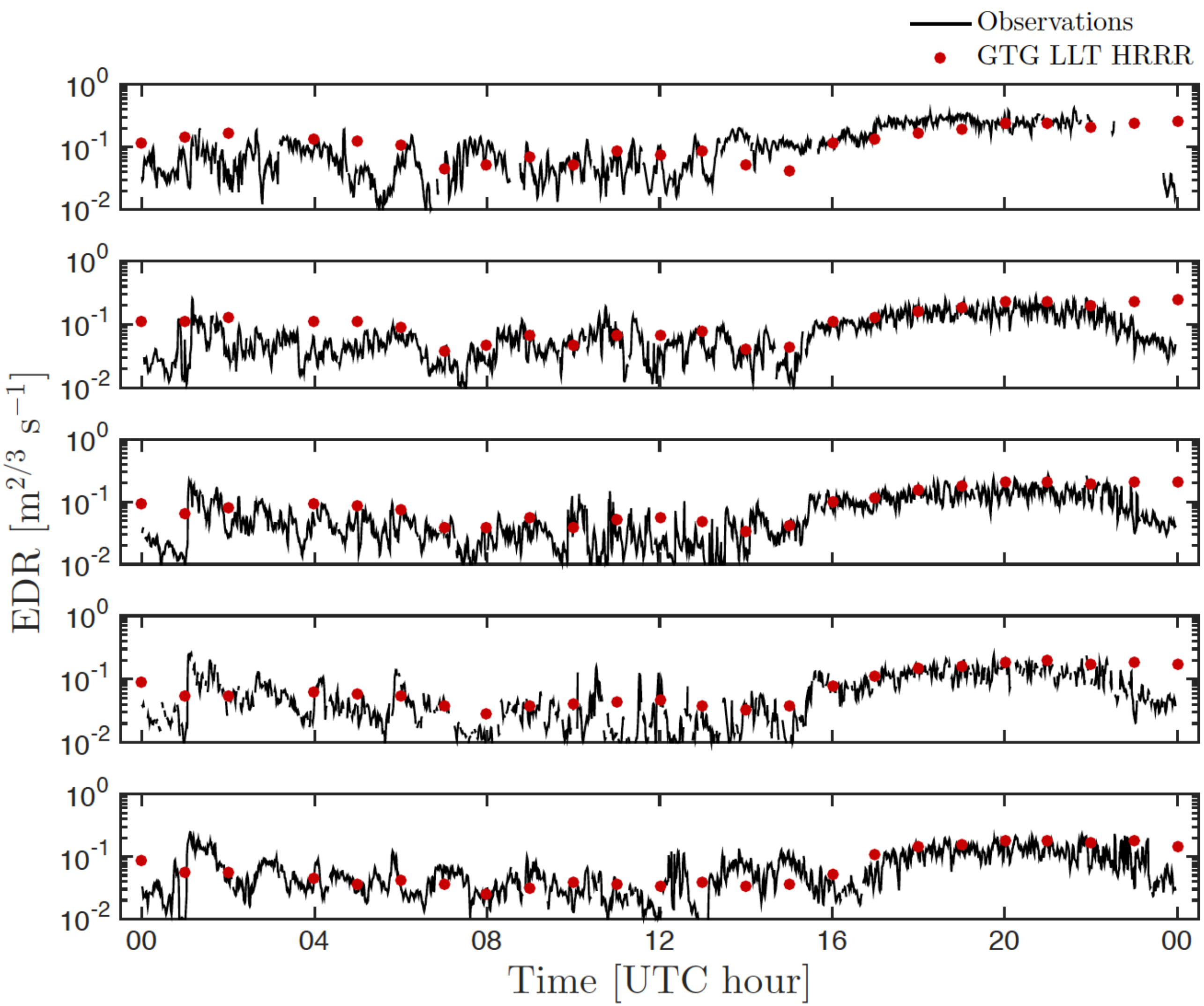
X BAO tower



Overall diurnal evolution of ABL turbulence is correctly captured

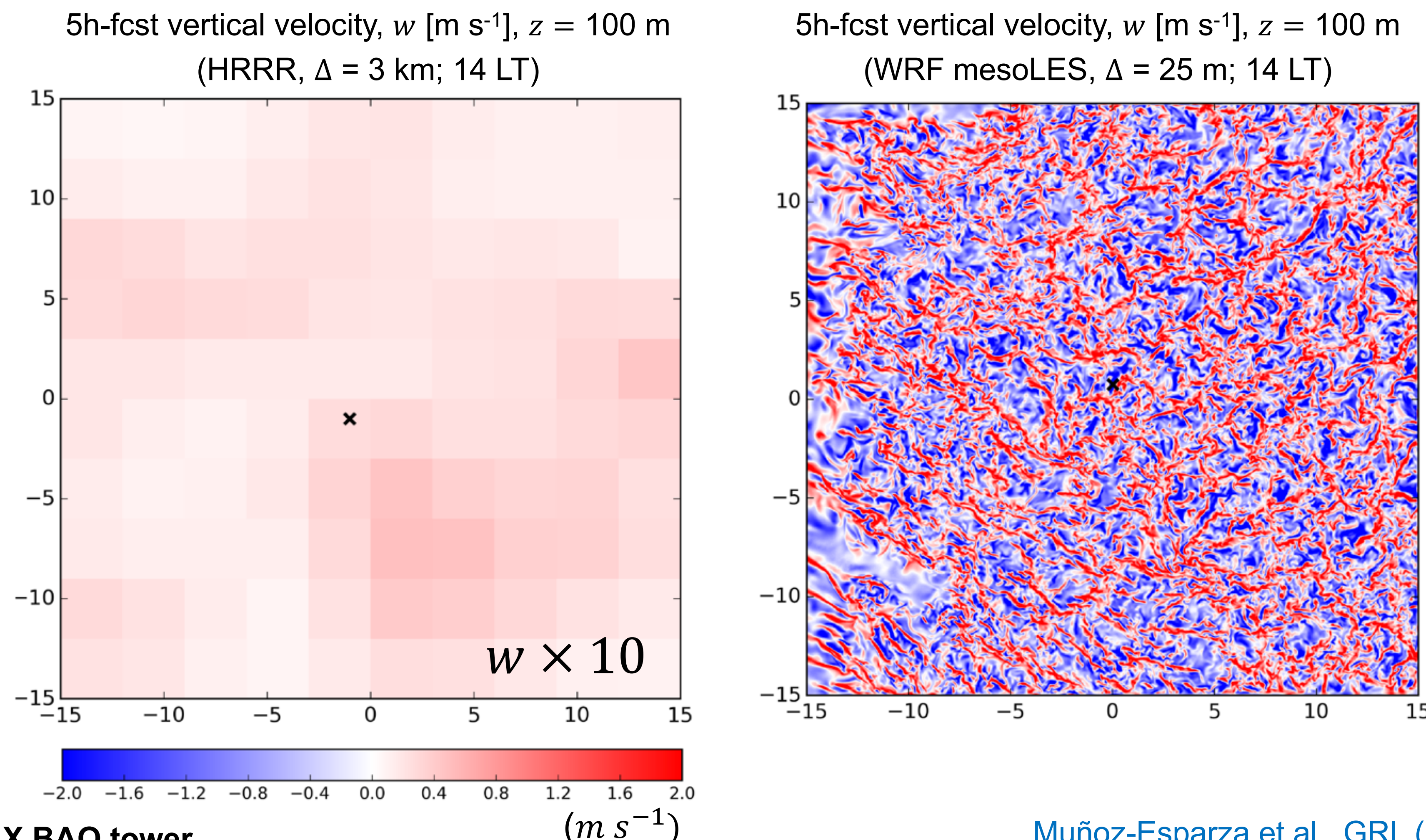
However…

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…

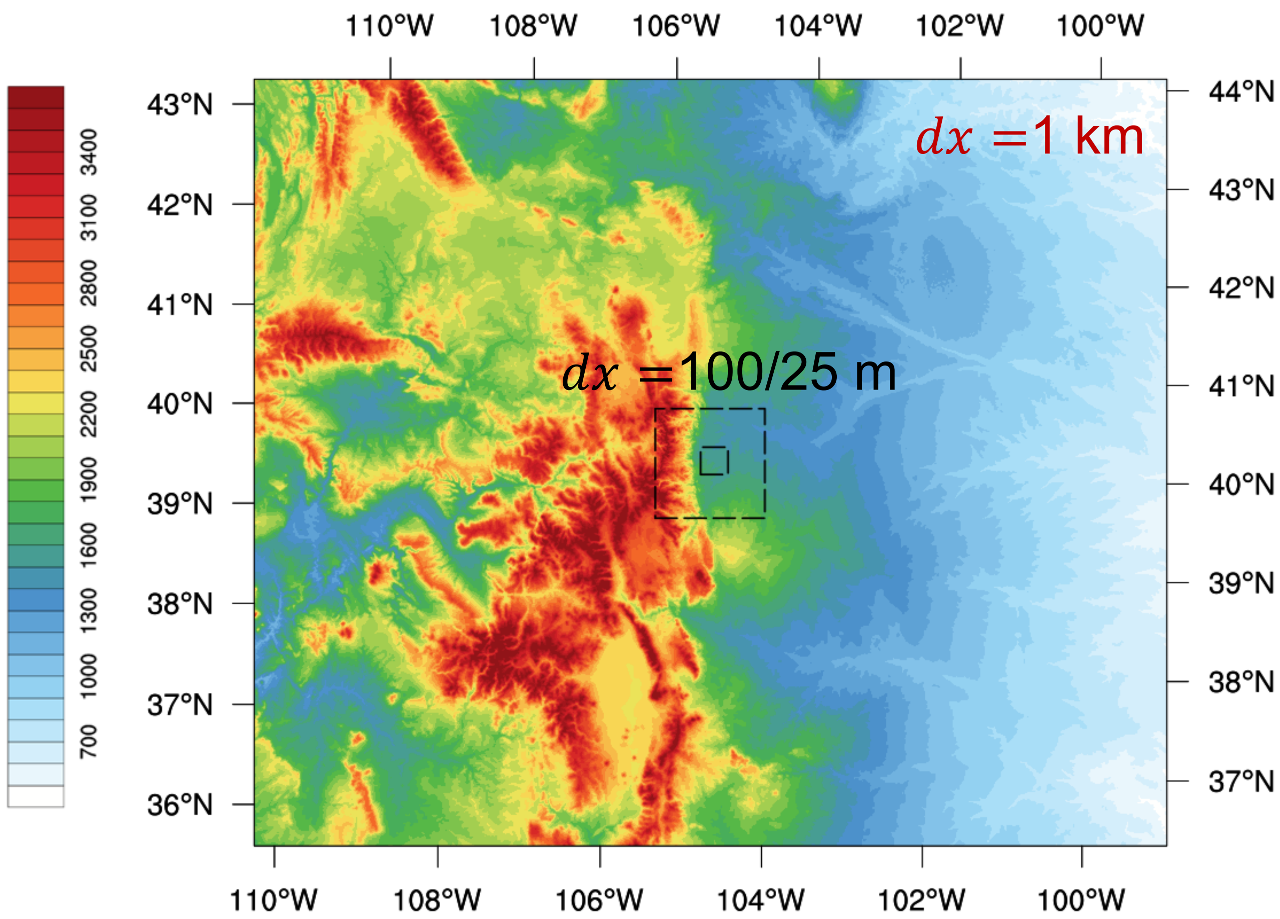


X BAO tower

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]

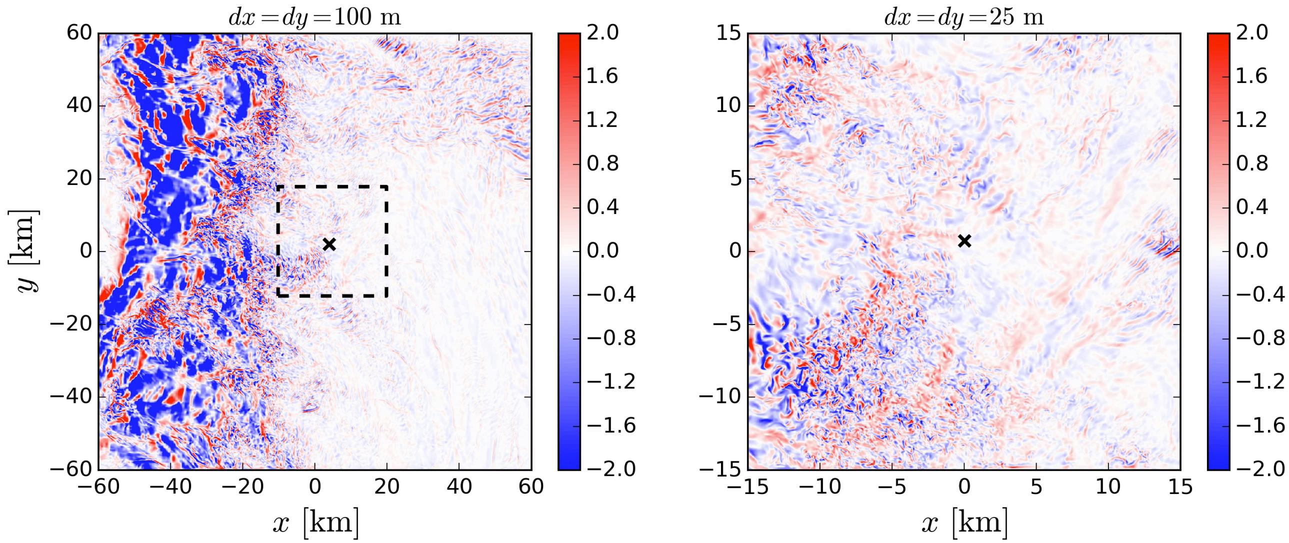


Toward eddy-resolving forecasts

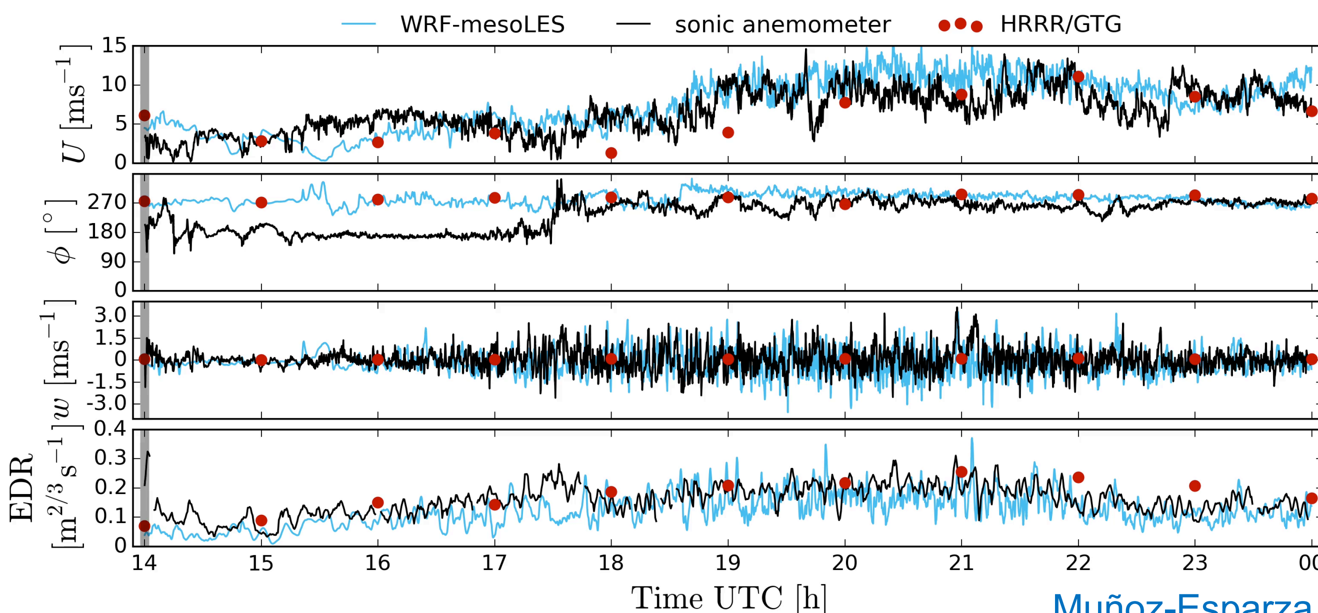
NCAR

Contours: vertical velocity [m s^{-1}]

(z = 100 m)



X BAO tower

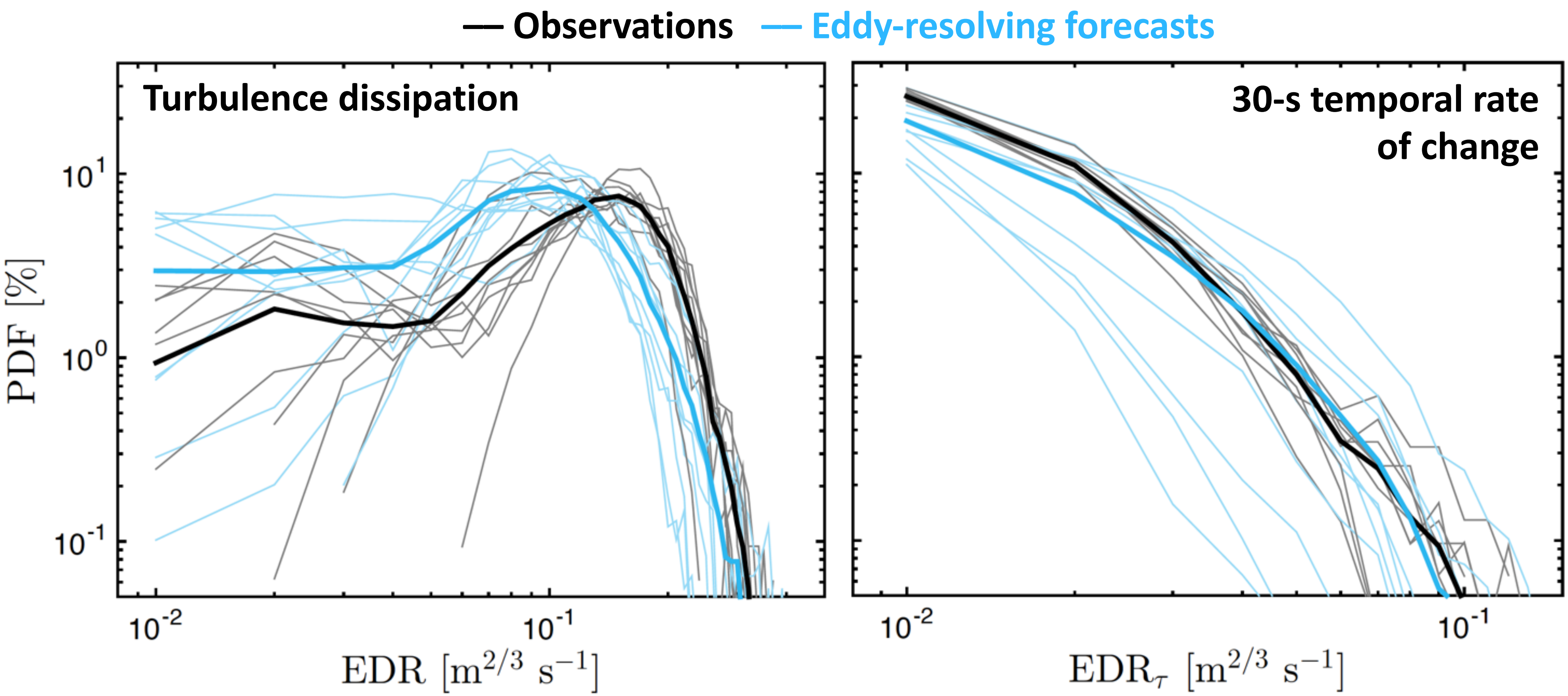


Muñoz-Esparza et al., GRL (2018)

Probabilistic turbulence forecasts

NCAR

<u>Daytime portion (8am – 6 pm) of 10 days</u> during the XPIA campaign with coupled WRF meso-LES [100 h total]



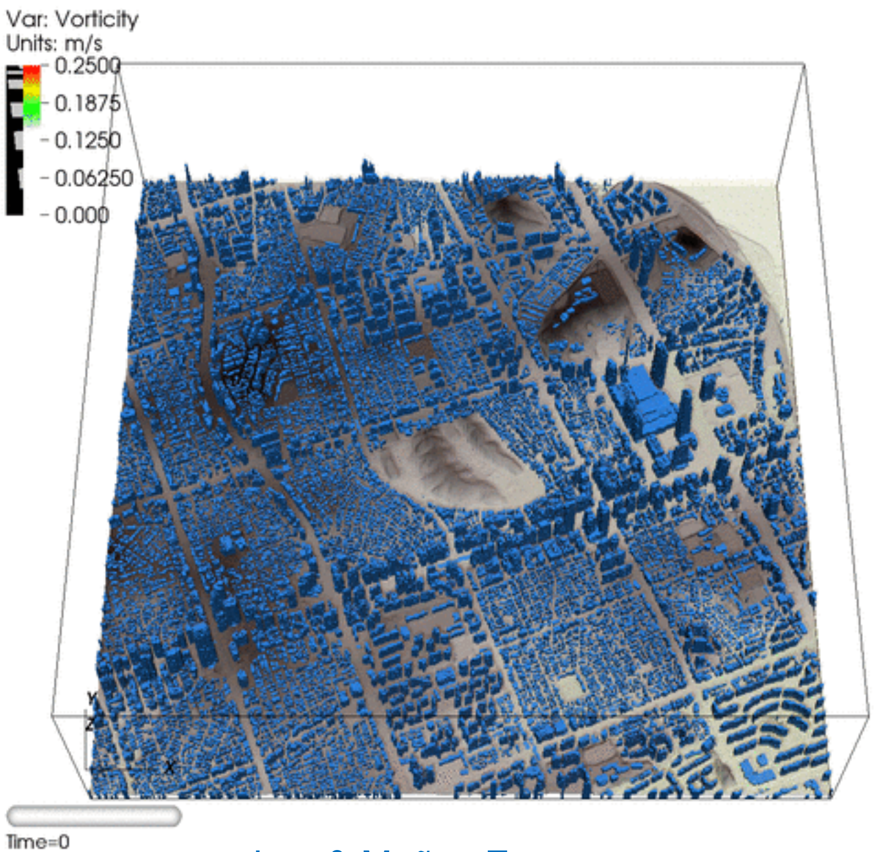
Both probability of EDR and its temporal rate of change are well reproduced by the eddy-resolving forecasts!

Near-future directions: urban environment

NCAR

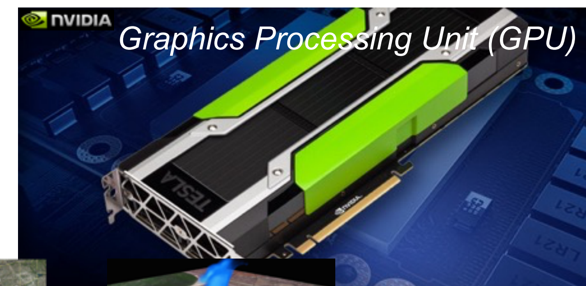
Significant interest on urban scenarios

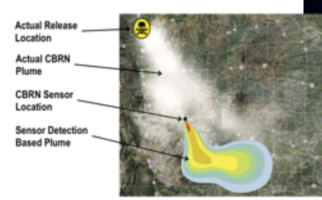
- High resolutions and building-resolving capabilities are required
- Accelerated GPU-LES to enable real-time forecasting applications

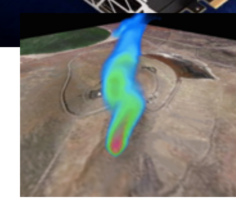


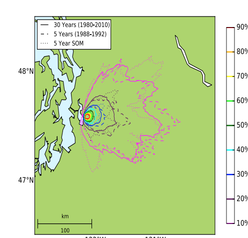
Lee & Muñoz-Esparza
(JAMC 2018, submitted)

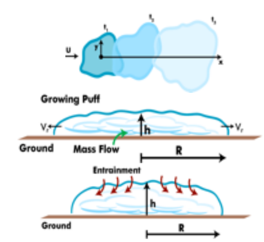
NCAR-RAL team is developing an accelerated GPU-LES code: "FastEddy"











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!!!

"Improvements in Low Level Turbulence (LLT) forecasting for UAVs"

Dr. Domingo Muñoz-Esparza

domingom@ucar.edu

NCAR
NATIONAL CENTER FOR ATMOSPHERIC RESEARCH

3rd Turbulence Impact Mitigation Workshop

Advances in Detection, Forecasting, and Characterization of Aviation-scale Turbulence

5-6 September 2018, MITRE campus, McLean, VA