Inflow conditions and turbulence for distributed wind energy

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Outline

- Introduction
- Beyond turbulence intensity. But first turbulence intensity.
- Spectral characteristics of wind
- Wind direction changes

Distributed wind energy

Definition

- Wind energy close to the end user, rather than in centralised farms
- Generally smaller in size. Standard IEC61400-2 (small wind turbines) under revision: scope extended to RSA $= 1200$ m^2. Would cover most of distributed wind turbines (not all).
- Sometimes off-grid, remote locations

Turbulent environments

- Lower hub heights $\rightarrow$ lower wind speed and higher turbulence
- Generally closer to obstacles $\rightarrow$ higher turbulence

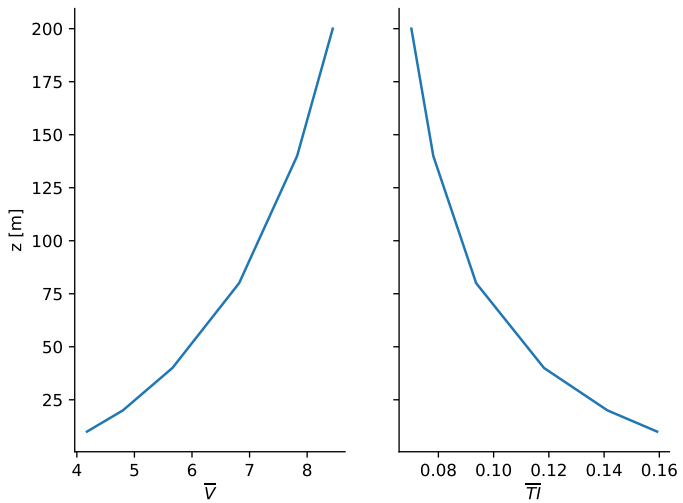

Figure: Mean wind speed and mean TI as a function of height. Cabauw dataset, 20 years

Turbine archetypes

- Wide variety of turbine archetypes
- Often passive yaw:
  - Upwind, with tail fin
  - Downwind
- Complex dynamics of response to changes in wind direction

Turbulence intensity

Definition

$$\mathrm{TI} = \frac{\sigma_V}{\overline{V}} \tag{1}$$

Averaging times

- IEC 61400 standard. Duration test: fill required wind speed bins with 10-min averages
- Filling with 1-min averages would be considerably faster. Could conceivably be allowed under next revision of IEC 61400-2 standard (SWT)
- Turbulence intensity depends on averaging time, with 1-min TI systematically lower than 10-min average.

Averaging times (cont.)

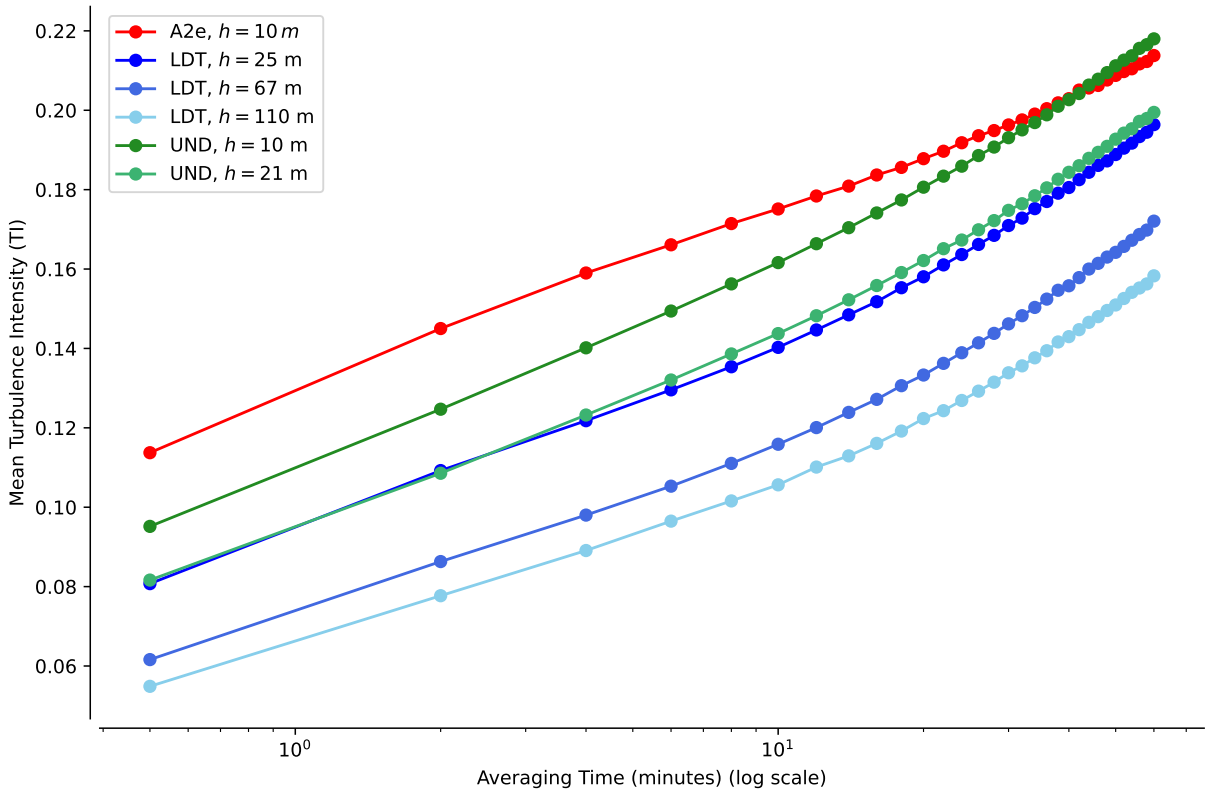

Figure: Mean turbulence intensities for different sites, as a function of averaging time.

Reference wind speed

- IEC 61400-2: turbulence intensity to be reported at $V = 15\,\mathrm{m/s}$
- Lower reference wind speeds would be easier to report, statistical more sound and more meaningful for actual operating conditions

Reference wind speed (cont.)

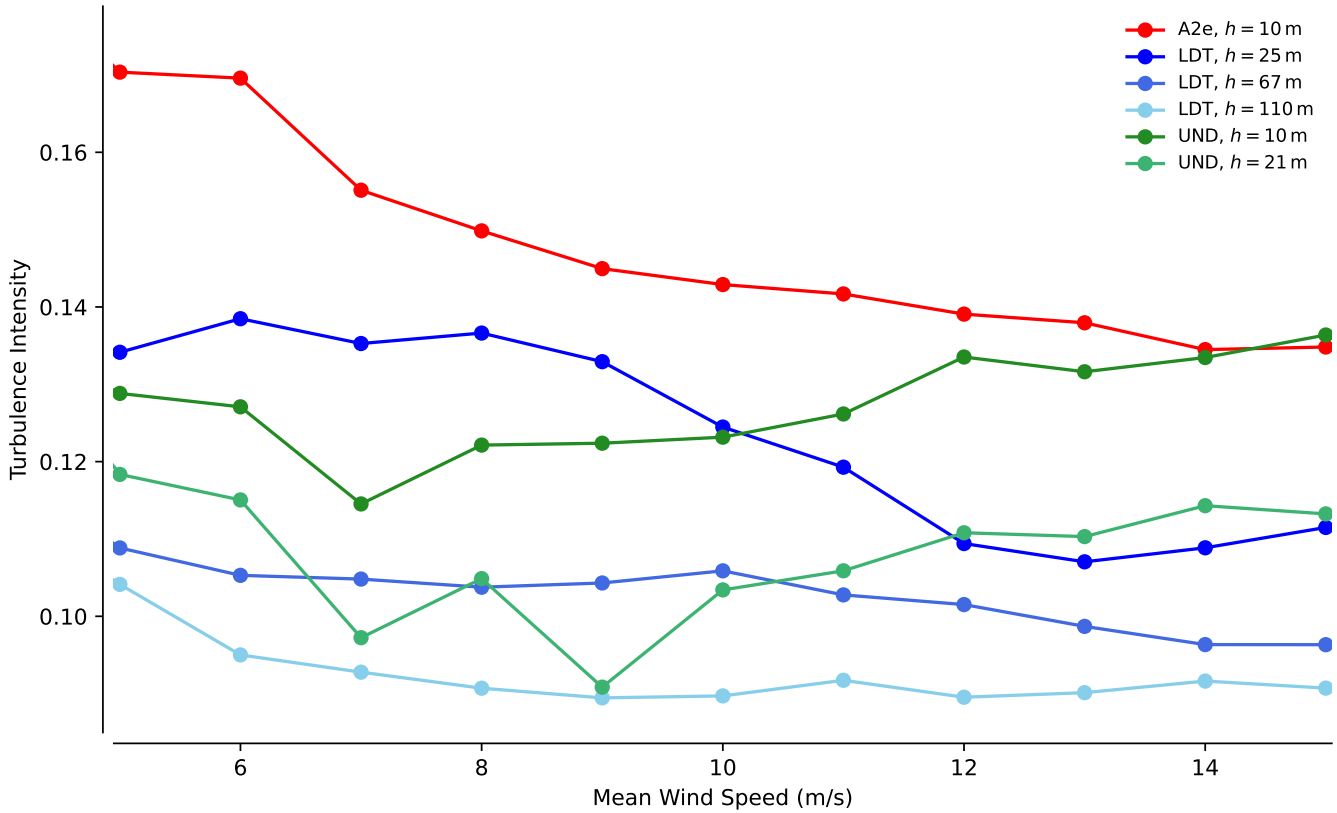

Figure: Turbulence intensities for different reference speeds, for an averaging time of 10 minutes. The values are reported as decimal fractions (so 0.12 corresponds to 12 %, etc).

Spectral characteristics

Spectra are important

- Information about importance of different atmospheric drivers (seasonal, synoptic, diurnal, turbulent, ...)
- Averaging times
- Structural loads and control systems design
- Turbulence models: synthetic times series generators assume a spectral shape

The spectral gap: van der Hoven spectrum

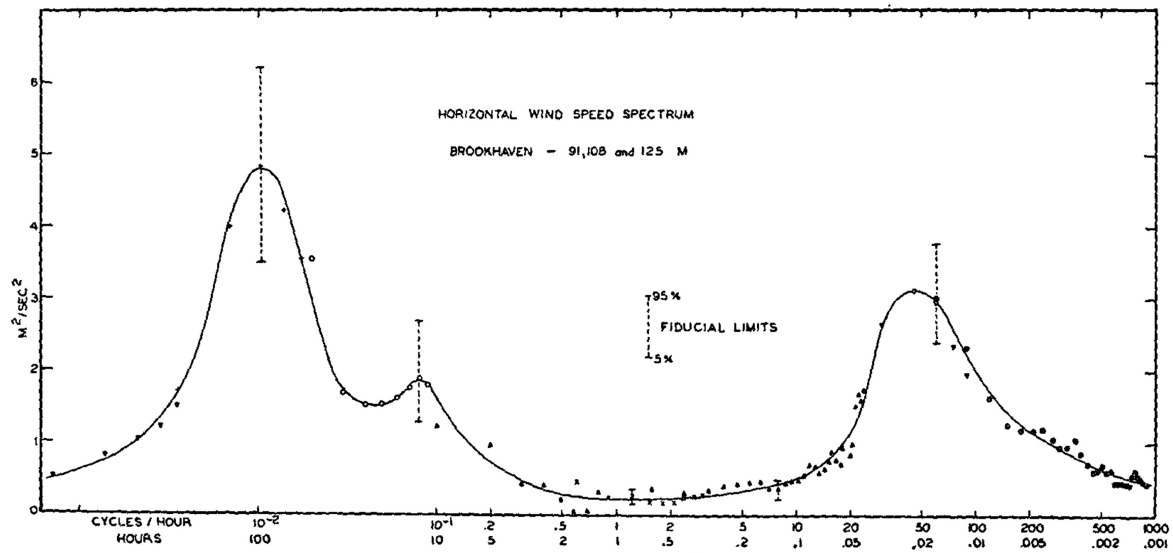

Figure: Frequency-weighted power spectral density for Brookhaven NY, van der Hoven

Spectral individuality: what spectral gap?

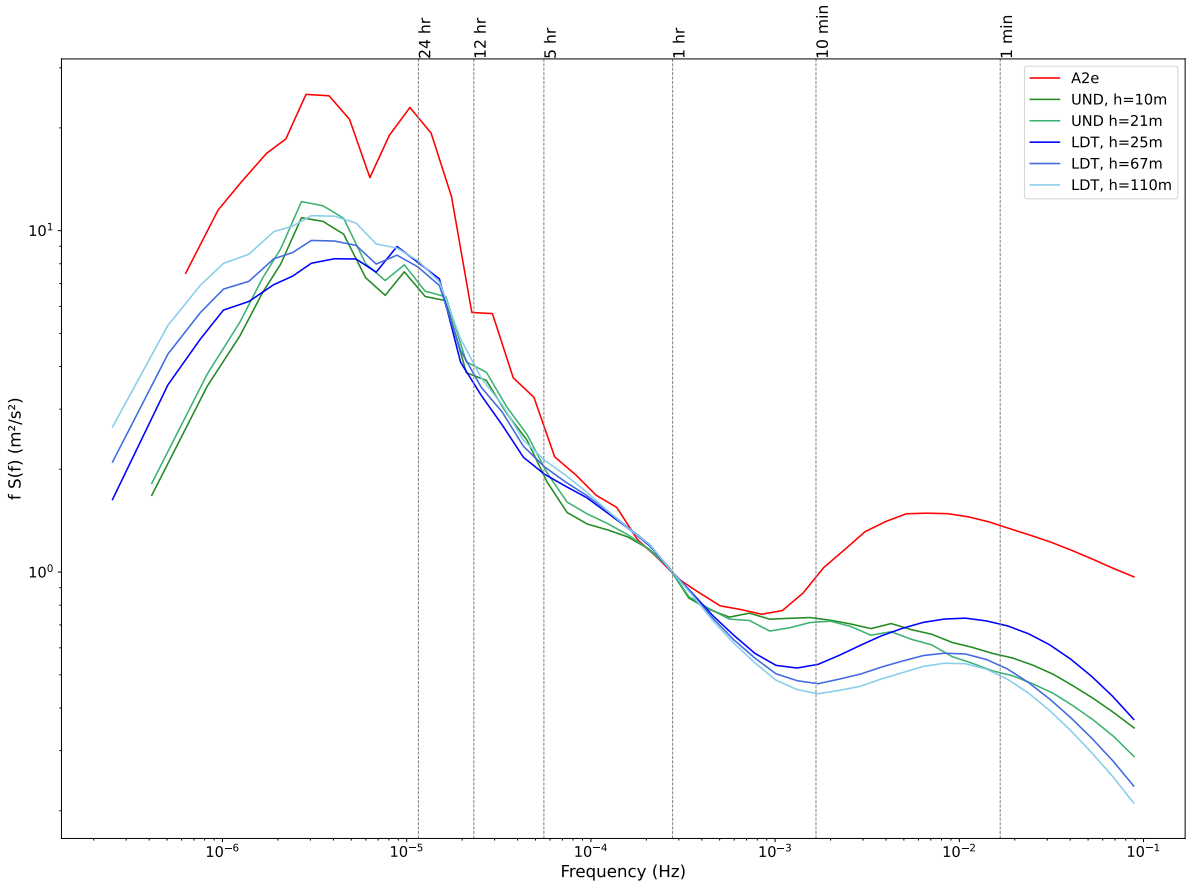

Figure: Frequency-weighted power spectral density for three different sites

Spectral seasonality

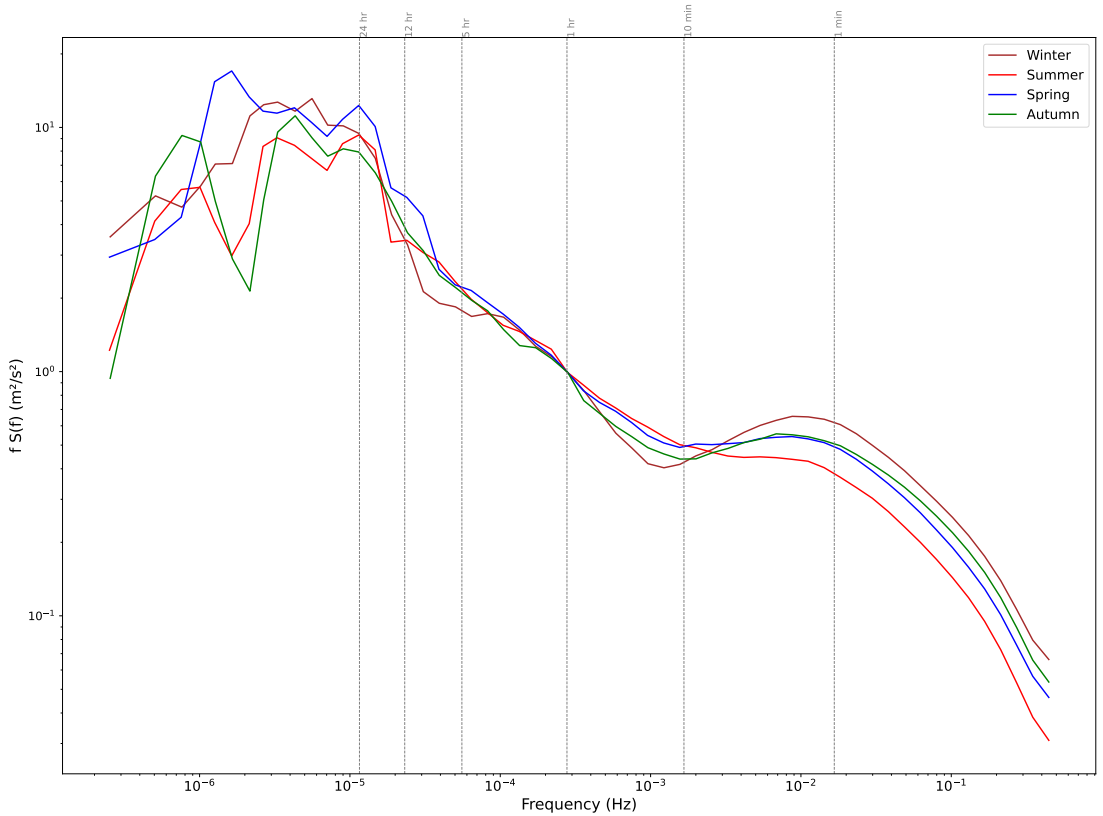

Figure: Frequency-weighted power spectral density for each season. LDT dataset ($h = 67\,\mathrm{m}$) Spectra normalised by their value at $t = 1\,\mathrm{hr}$

Wind direction

Effect on power

- Power, where γ angle between the wind velocity vector and the rotor normal,

$$P = \frac{1}{2}\rho C_P A u^3 (\cos\gamma)^p \tag{2}$$

- Assuming $p = 3$, performing Reynolds decomposition $u = \overline{u} + u'$, $\gamma = \overline{\gamma} + \gamma'$, taking Taylor 1st order and averaging, we obtain

$$\overline{P} = \frac{1}{2}\rho C_P A \overline{u}^3 \left[1 + 3I_u^2\right] \left[1 - \frac{\sigma_\gamma^2}{2}\right]^3 \tag{3}$$

(Choukulkar et al 2016, Wind Energy, 19, 1439, DOI: 10.1002/we)

Effect on loads

- Effect on loads more complicated, especially for passive yawing (gyroscopic forces, nonlinear response)
- Requires aero-elastic modelling

Statistics of wind direction

- Circular variable: jumps around 0/360 degrees
  - Angular differences

$$\Delta\theta = ((\theta_2 - \theta_1 + 180) \bmod 360) - 180 \tag{4}$$

Wind direction changes

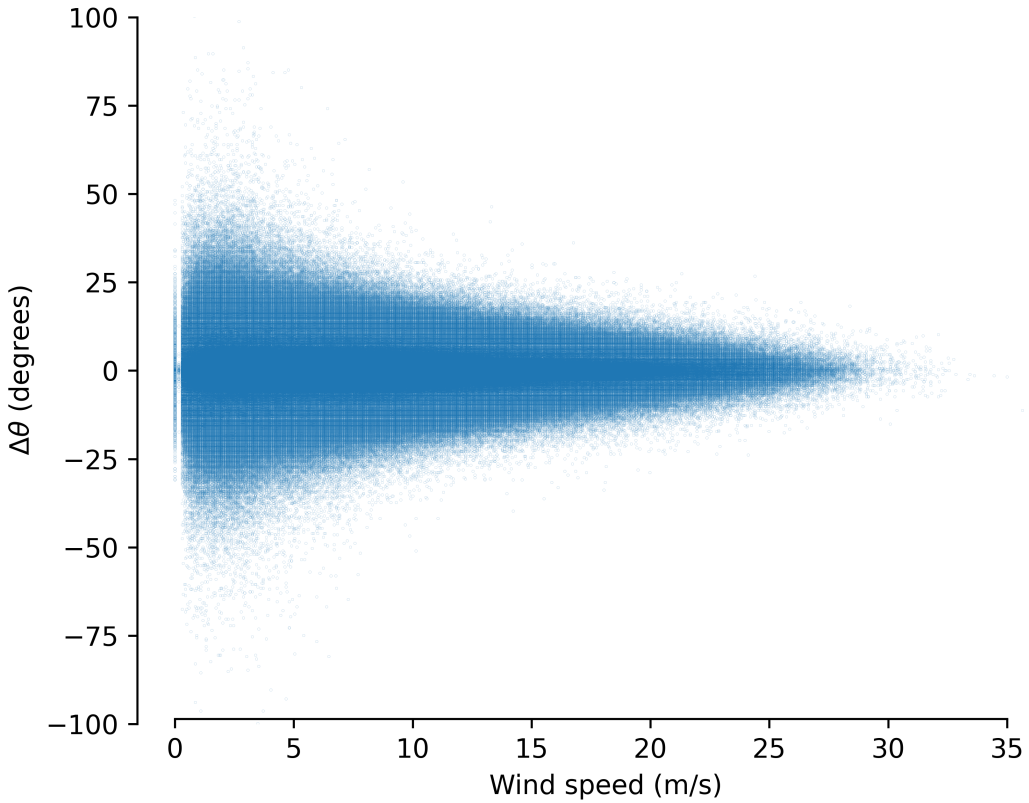

Figure: Changes of wind direction, over 1-sec. LDT dataset, $h = 67$ m

Relation between turbulence and changes in wind direction

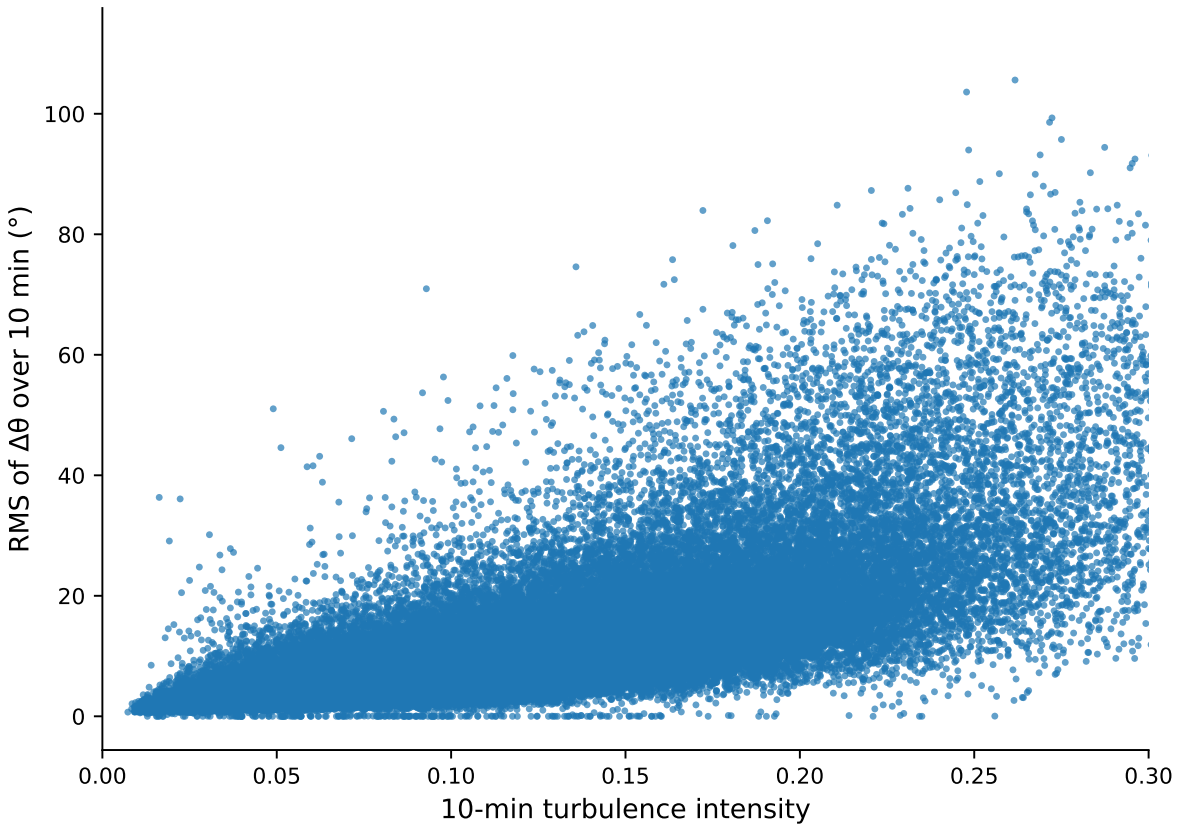

Figure: RMS wind direction changes as a function of TI. M2 dataset (NREL)

Findings

- TI should be reported for 10-min averages, even when 1-min intervals are used for duration testing
- Even though 15 m/s is an impractical reference wind speed to report TI for distributed wind energy, there is no clear site-independent trend of TI as a function of wind. Normal turbulence model cannot be used for this purpose, so adopting a different value may be confusing
- Care should be taken when drawing conclusions from a single site
- A user-documented data-base of wind data would be valuable

Future work

- Extend analysis to wider dataset
- Better understand relation between atmospheric turbulence and wind direction
- Work towards a user-documented data-base of wind data
- Combine this work with synthetic data generators