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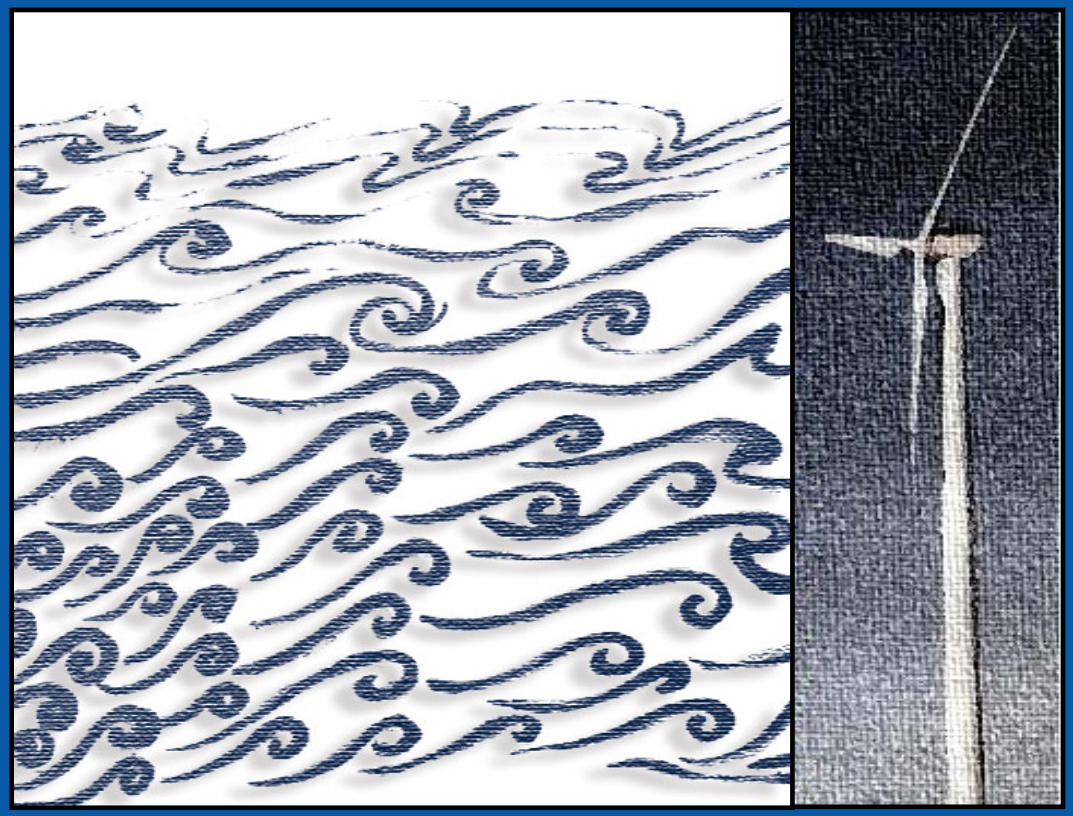
Innovation for Our Energy Future

TurbSim Workshop



National Wind Technology Center

Neil Kelley
Bonnie Jonkman

September 22-24, 2008

Meeting Purpose

- To give the wind turbine design community an opportunity to hear about the latest improvements we have made in the NREL TurbSim Stochastic Turbulence Simulator Code
- To give the community an opportunity to learn in more detail about the development of the code, its physical basis, and how to use it.
- To have the opportunity to share ideas and questions on how best to use the features of the code.

National Renewable Energy Laboratory
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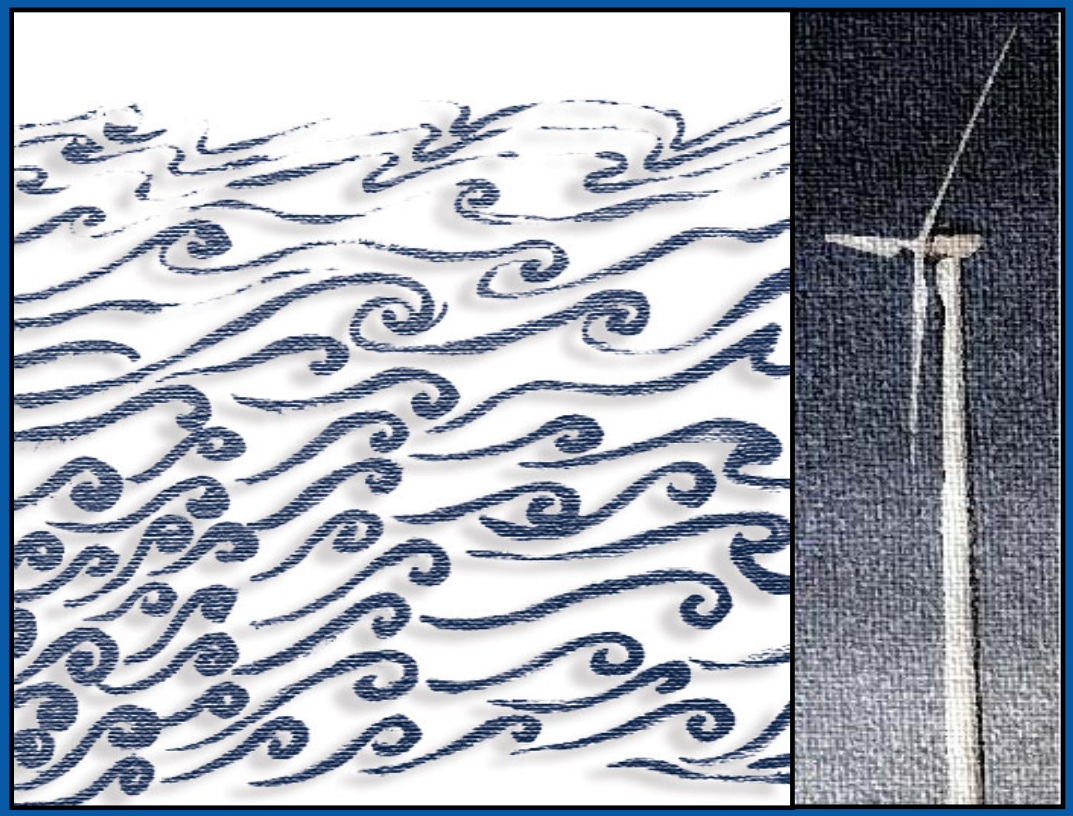
TurbSim Workshop: Boundary Layer Dynamics and Wind Turbines



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Wind Turbines and Boundary Layer Turbulence

- Wind turbines must operate in a wide range of turbulent flow conditions associated with the Atmospheric Boundary Layer (ABL)
- The ABL occupies the lowest 1-2 km of the atmosphere where surface frictional drag has an influence on the movement of the wind
- Wind turbines occupy the lowest layers of the ABL and may eventually reach heights of 200 m or more
- The vertical structure and the turbulence characteristics of the ABL vary diurnally due to the heating and cooling of the solar cycle

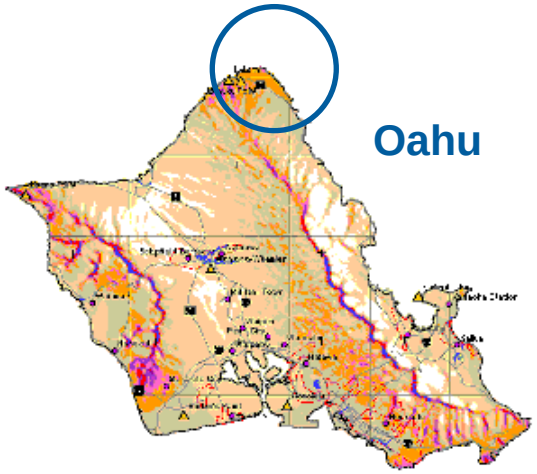
Wind Turbines and Boundary Layer Turbulence – cont'd

- It is this change in turbulence characteristics that has a significant impact on the operations of wind turbines
- Turbulence induces structural load responses in operating turbines which in turn creates wear in components from fatigue
- The purpose of the TurbSim Code is to provide the turbine designer with the ability to expose new designs to flow conditions that induce random or stochastic load responses for a range operating environments

Some real world examples

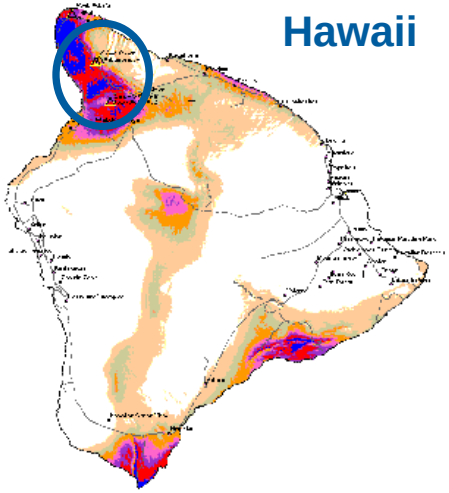
- The best way to understand the role of turbulence on the operations of wind turbine is to discuss examples who operating experiences are similar in key respects
- The greatest operating challenges were found to occur during the late afternoon and nighttime hours with the period between local sunset and midnight often the most challenging

Hawaii



- 15 Westinghouse 600 kW Turbines *(now NWTC CARTS 2 & 3)* 1985-1996
- DOE/NASA 3.2 MW Boeing MOD-5B Prototype 1987-1993
- Installed on uphill terrain at Kuhuku Point with predominantly upslope, onshore flow but occasionally experienced downslope flows (Kona Winds)
- Chronic underproduction relative to projections for both turbine designs
- Significant numbers of faults and failures occurred during the nighttime hours particularly on Westinghouse turbines. Serious loading issues with MOD-5B during Kona Winds required lock out

Hawaii – cont'd



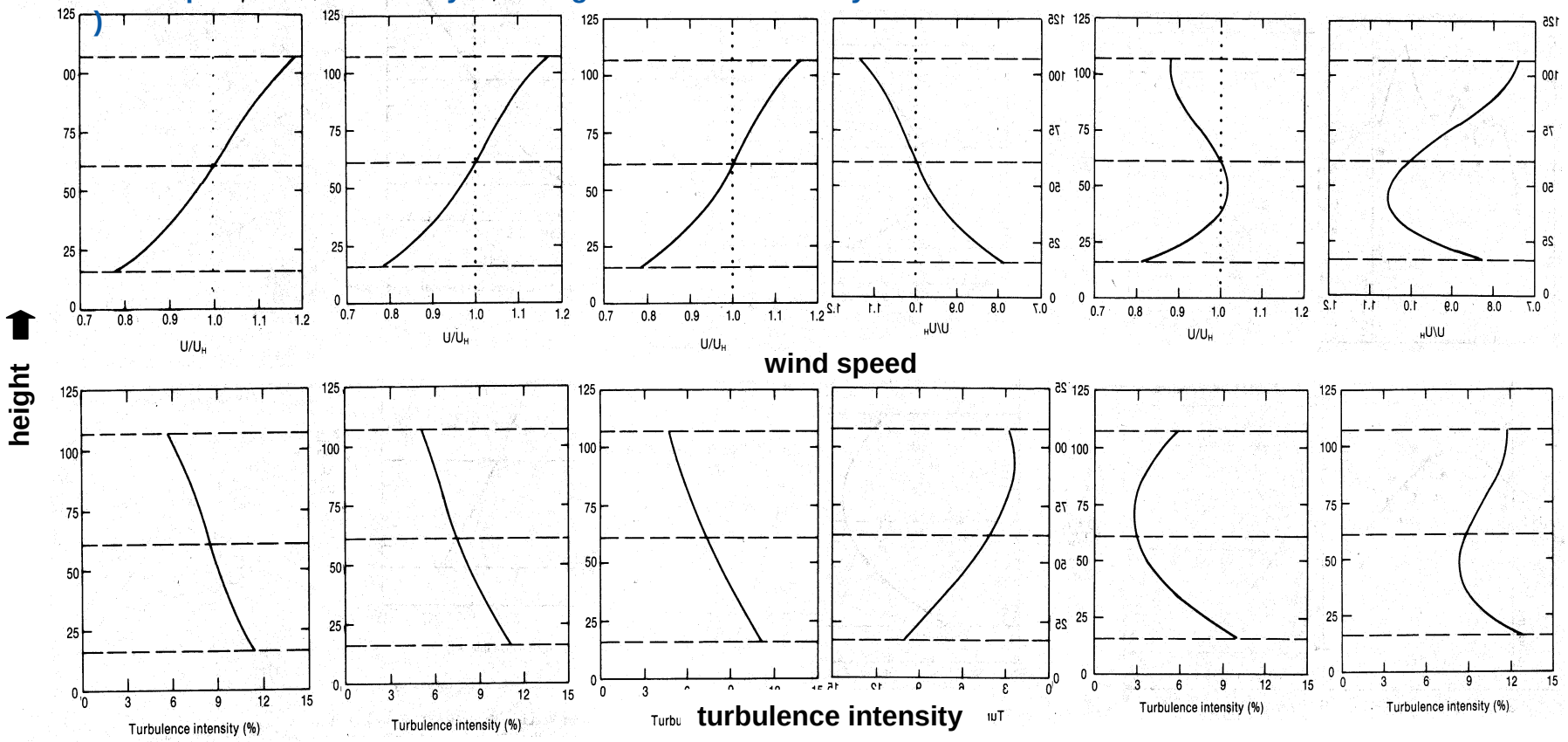
- 81 Jacobs 17.5 and 20 kW turbines installed in mountain pass on the Kahua Ranch 1985-
- Wind technicians reported in 1986 a significant number of failures that occurred exclusively at night
- At some locations turbines could not be successfully maintained downwind of local terrain features and were abandoned

2.5 MW MOD-2

- Post analysis showed loads much greater than had been predicted
- Highest loads generally to occurred during nighttime hours
- Terrain induced low-level jet structure developed during nighttime hours

Turbine Layer Vertical Wind Profile Evolution

30-minute smoothed profiles from PNL Met Tower MOD-2 Site Goldendale, Washington
MOD-2 Hub Height 61 m
Wind speeds normalized by hub-height value - Stability measured between 2 and 107 m)



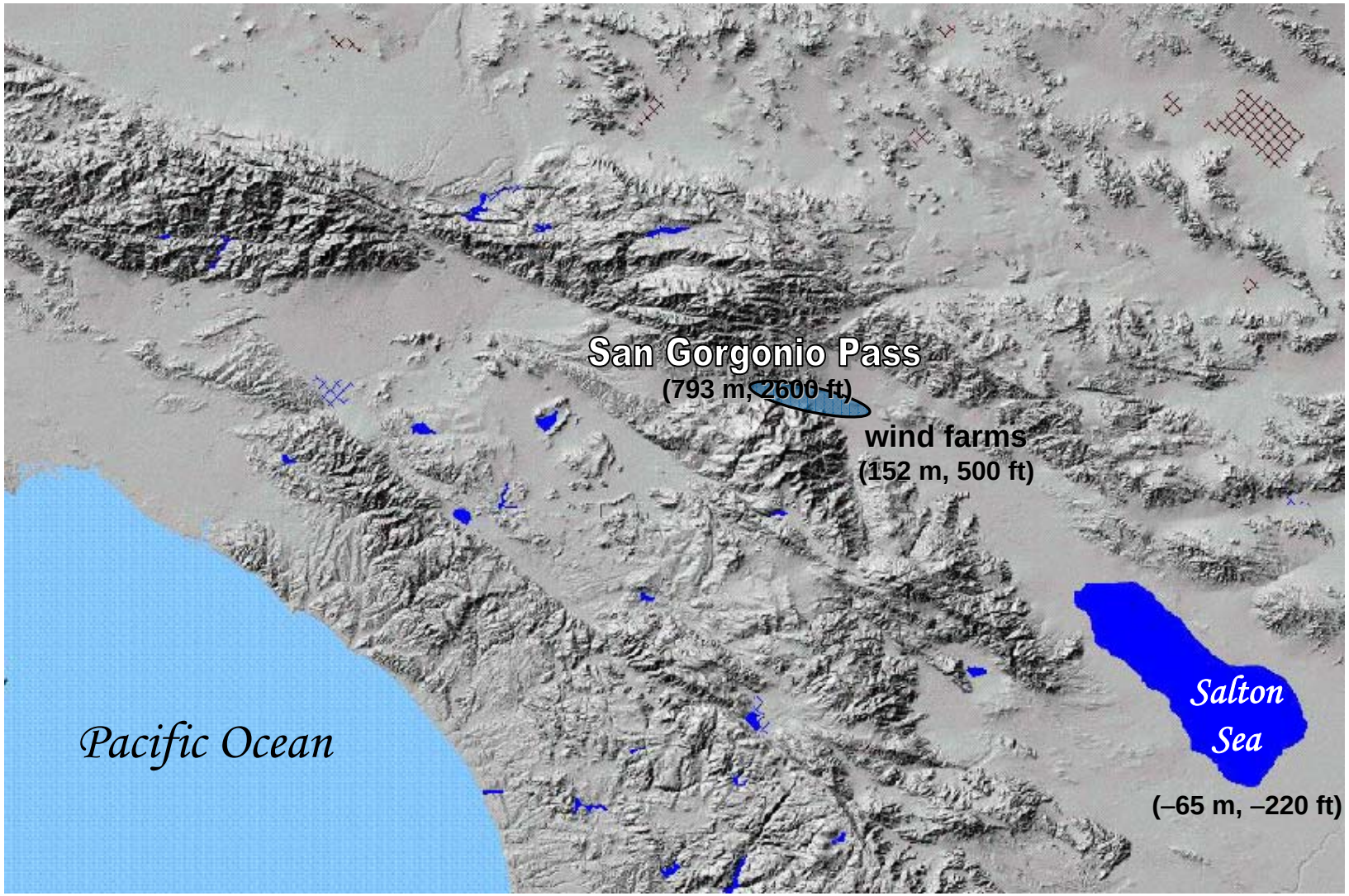
U_{hub} = 7.8 m/s	U_{hub} = 9.0 m/s	U_{hub} = 9.8 m/s	U_{hub} = 12.8 m/s	U_{hub} = 13.1 m/s	U_{hub} = 6.5 m/s
Ri = – 0.12	Ri = + 0.13	Ri = + 0.26	Ri = + 0.72	Ri = + 6.68	Ri = + 11.7

16:00 ***Time (LST)*** → **02:00**

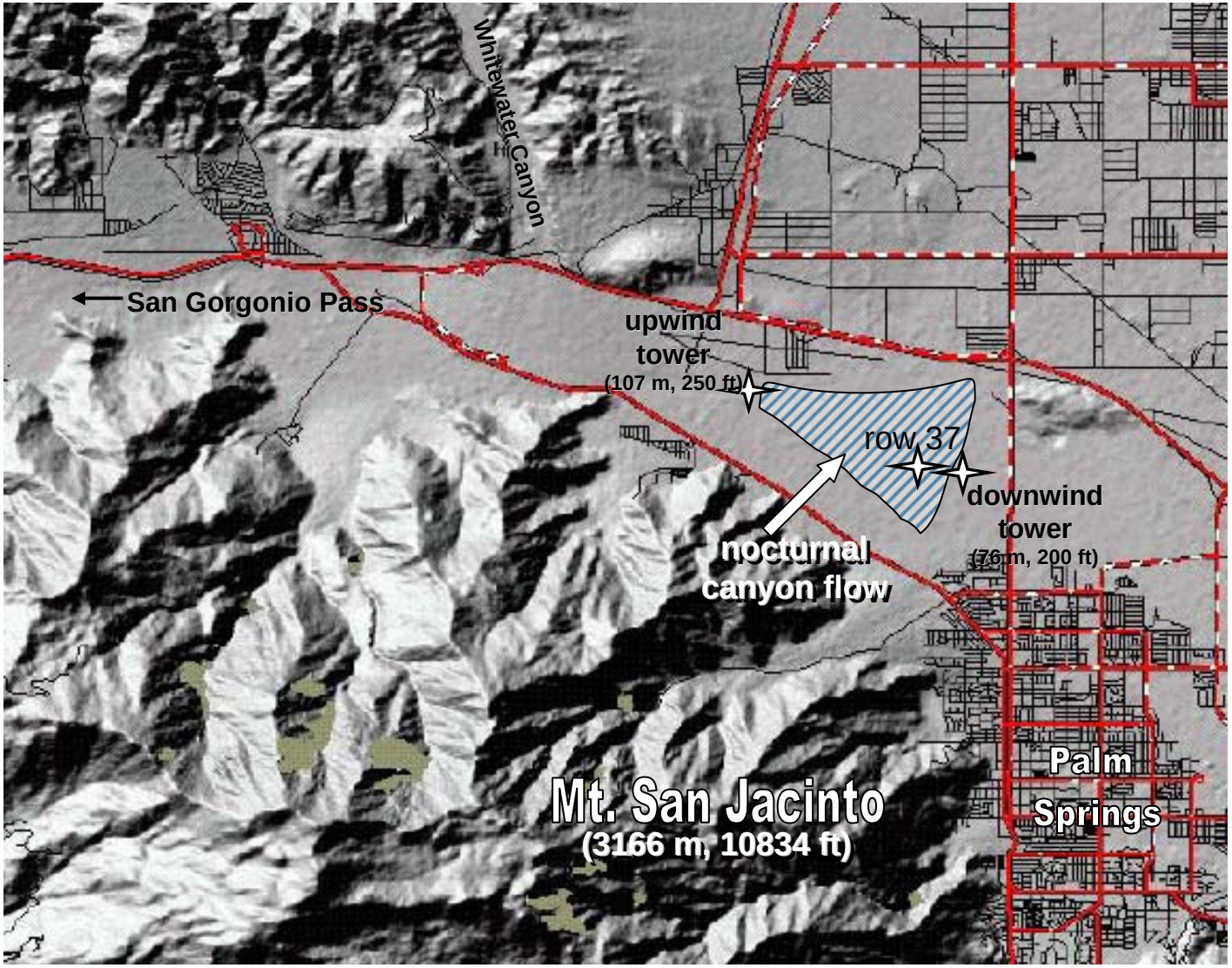
San Gorgonio Pass California

- Large, 41-row wind farm located downwind of the San Gorgonio Pass near Palm Springs
- Wind farm had good production on the upwind (west) side and along the boundaries but degraded steadily with each increasing row downstream as the cost of turbine maintenance increased
- Frequent turbine faults occurred during period from near local sunset to midnight

San Gorgonio Regional Terrain



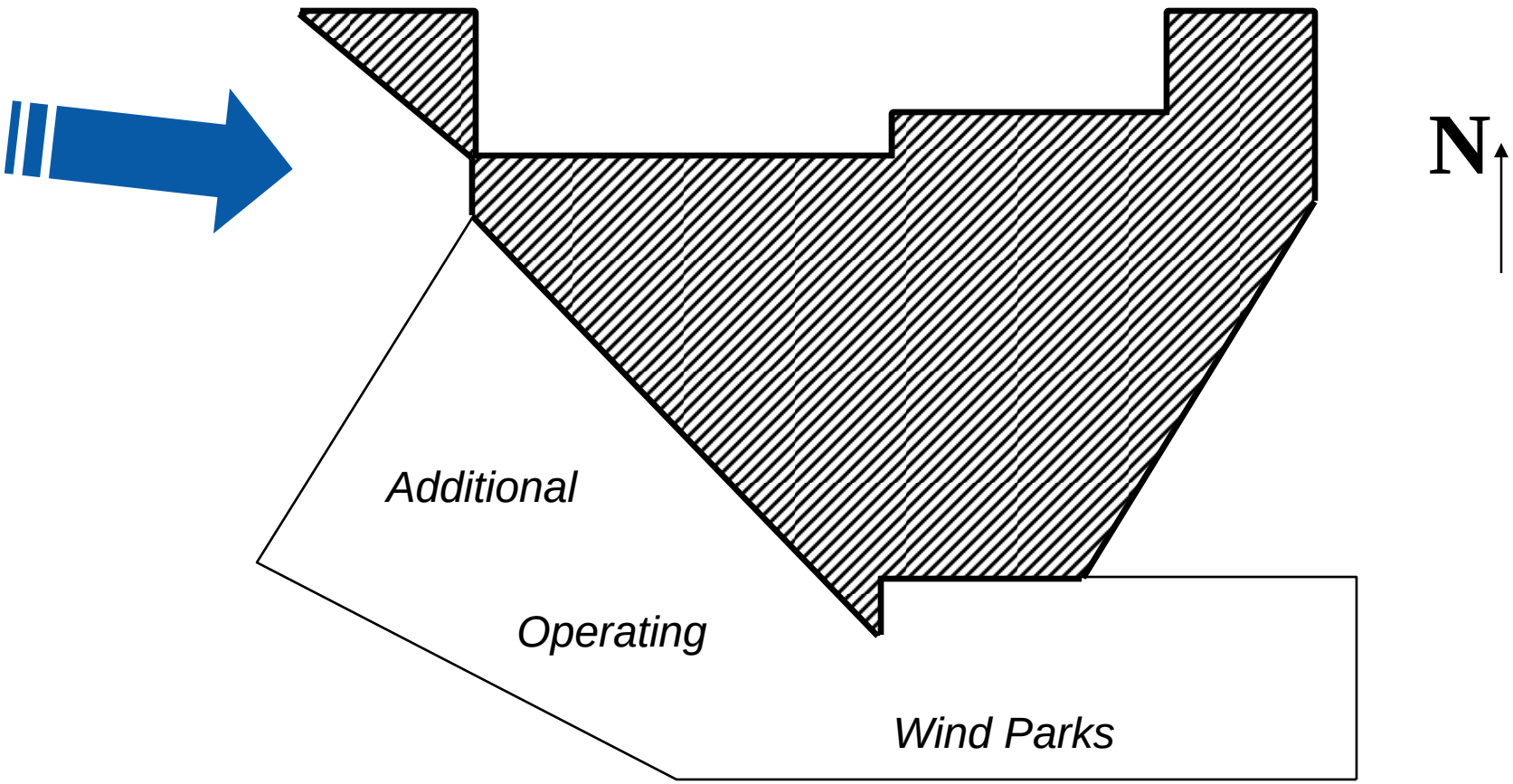
Wind Farm Nearby Topography



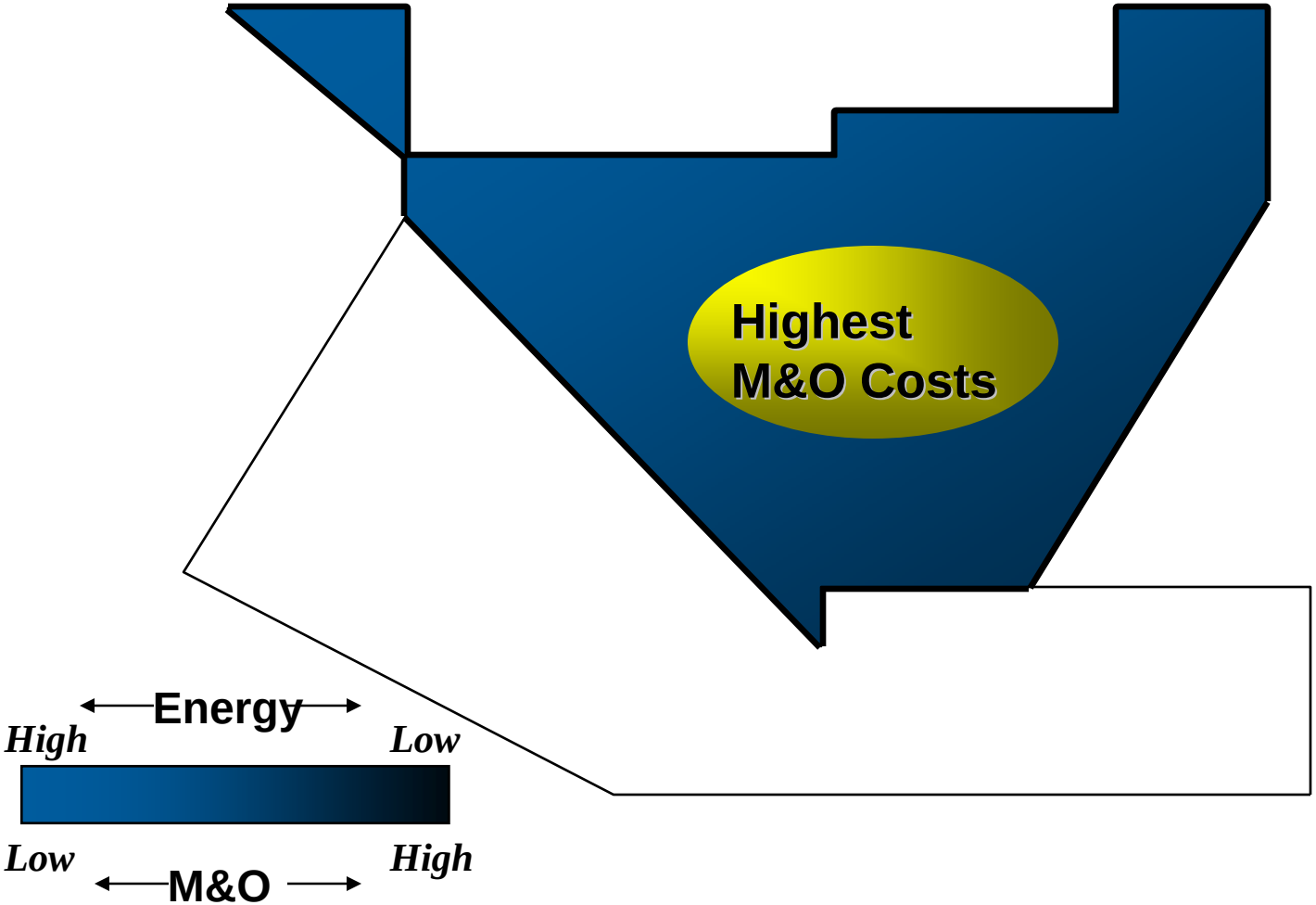
SeaWest Wind Farm San Gorgonio Pass

- 1000 unit wind farm of 44, 65, 108 kW wind turbines (1989-90)
- Significant turbine faulting occurred during late evening hours
- Yaw drive slew rings required repositioning every 3 months and replacement once a year

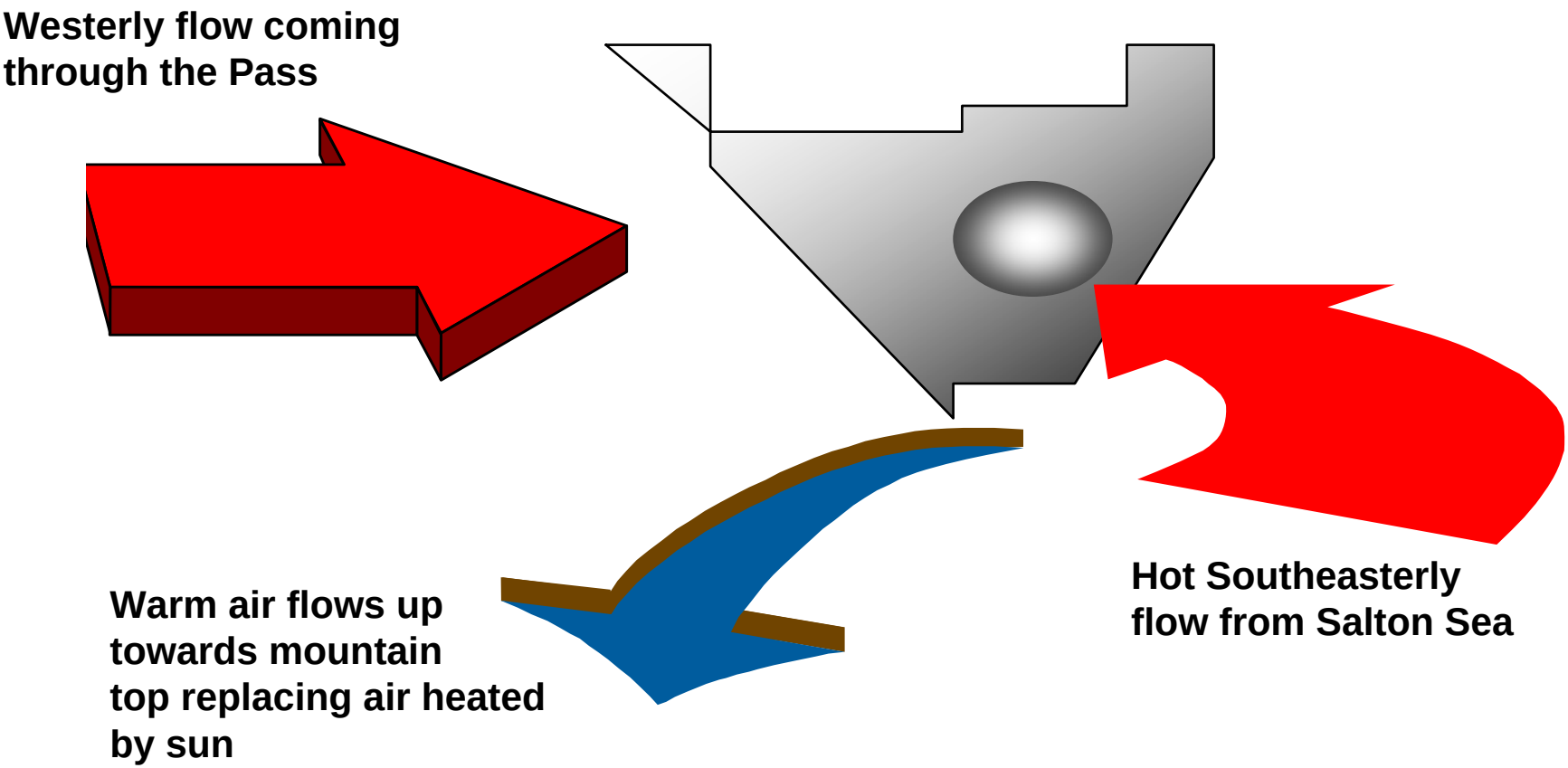
Schematic of SeaWest San Gorgonio Wind Park



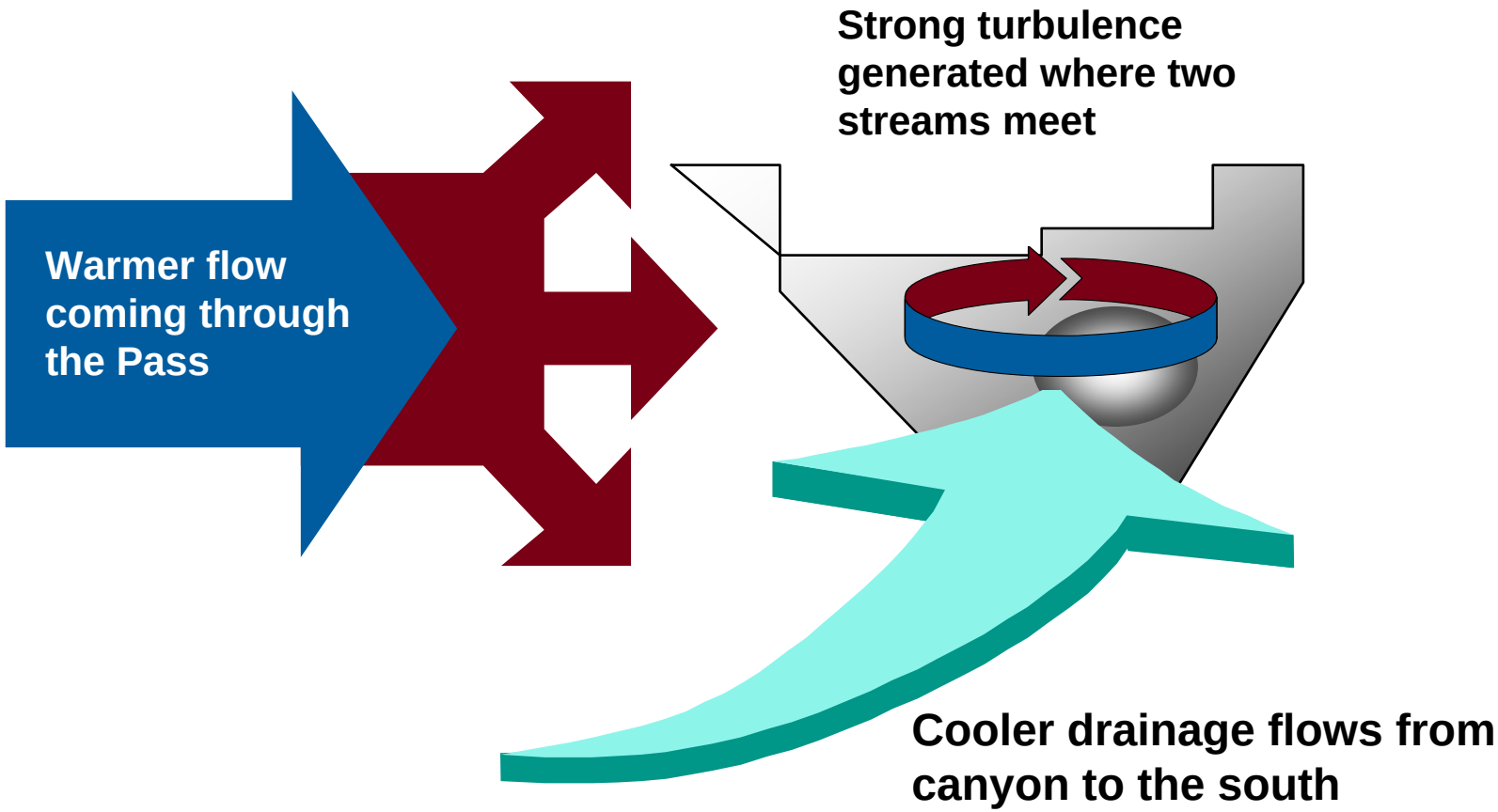
Park Energy Production and Maintenance & Operations Costs



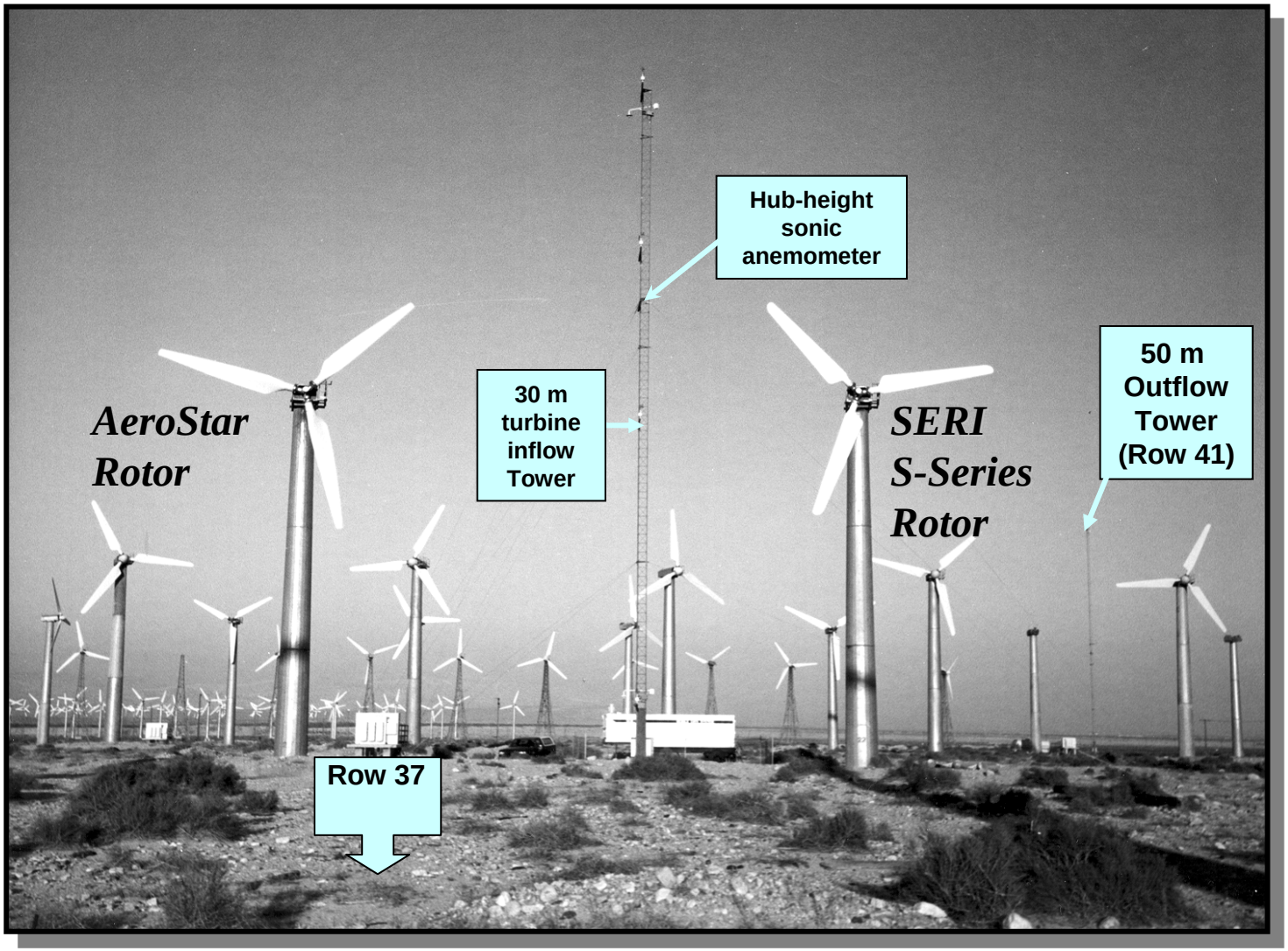
Daytime Flow Patterns Affecting the Wind Park



Nighttime Flow Patterns Affecting the Wind Park

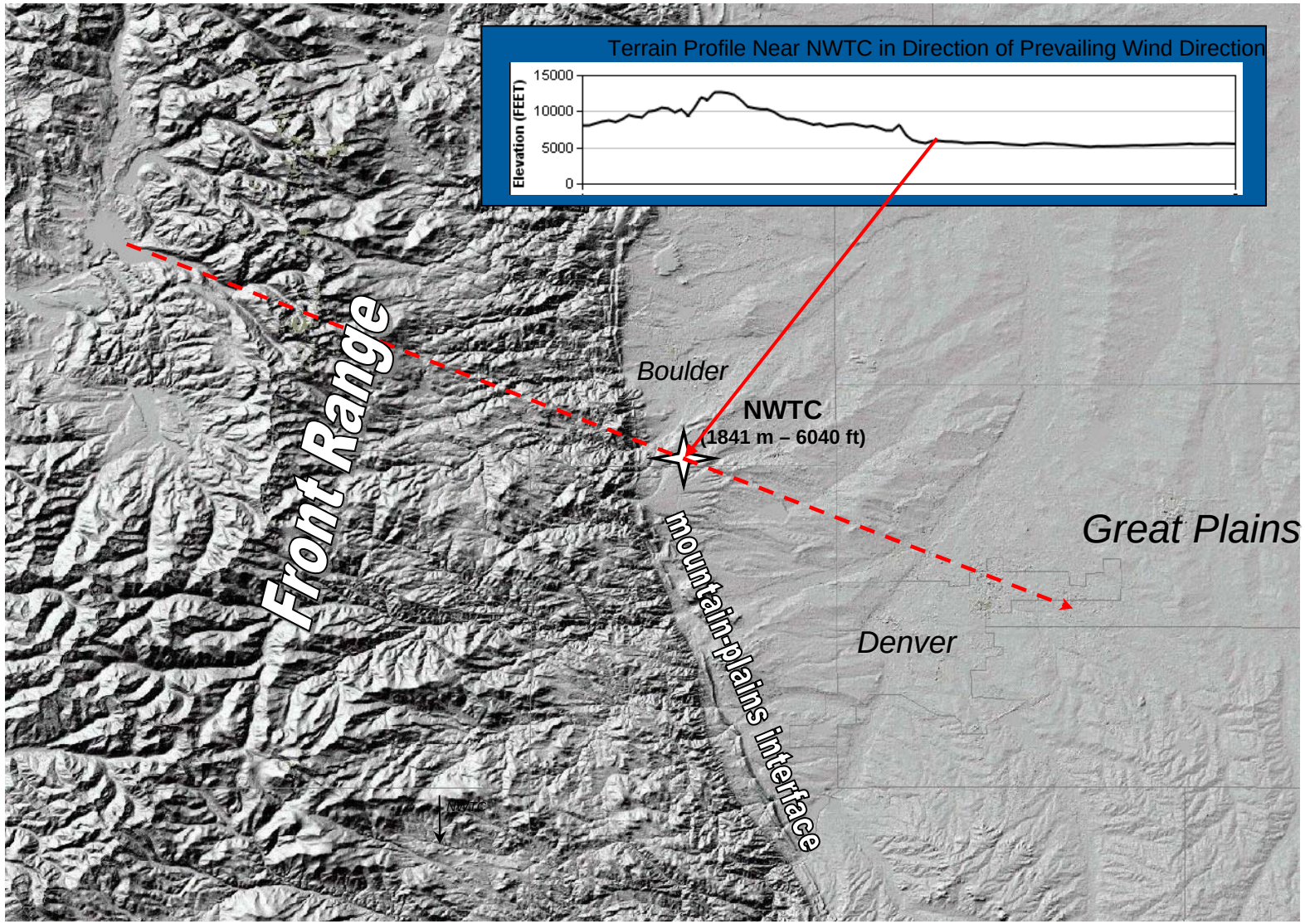


Micon 65 kW Turbine Inflow/Structural Response Testing

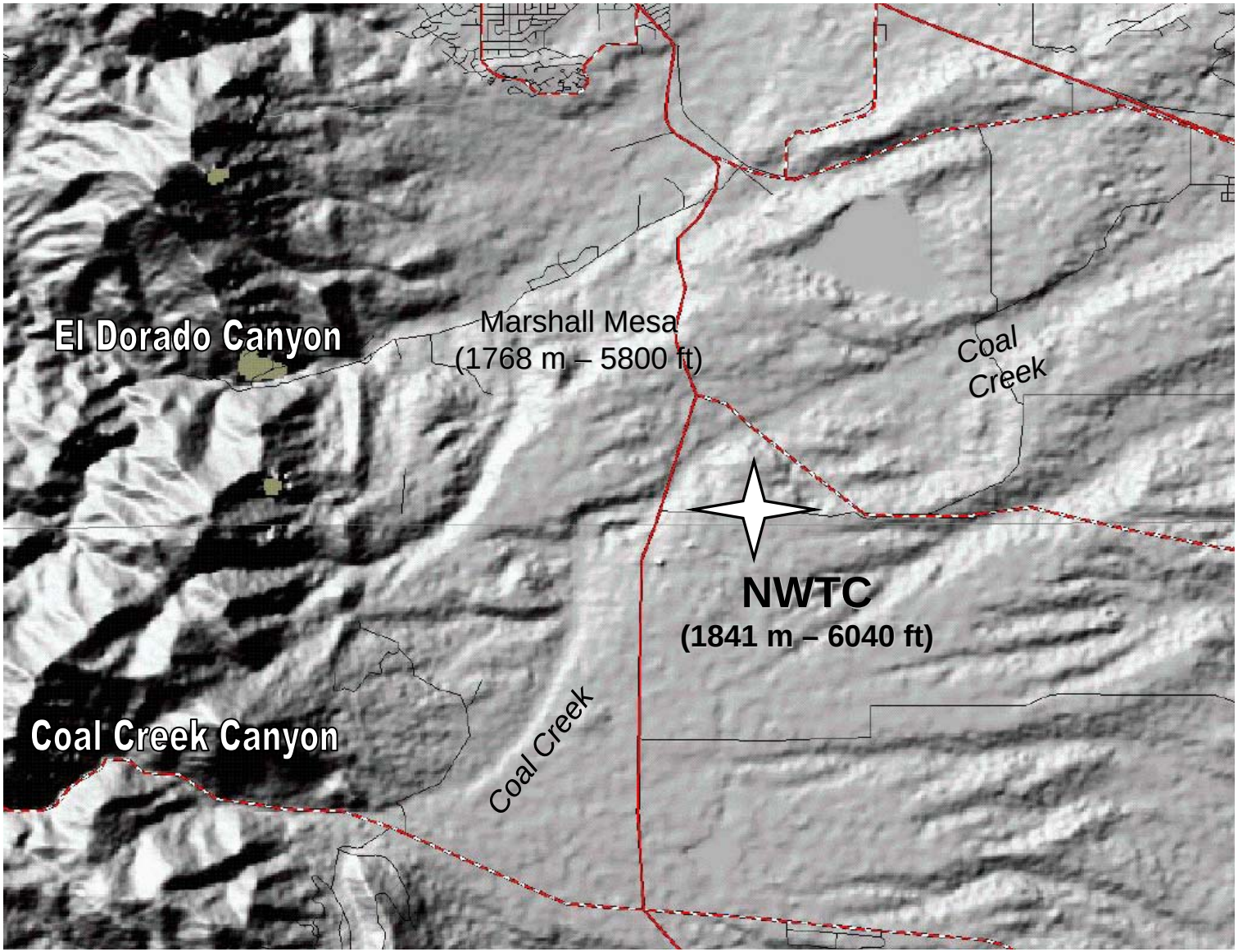


NWTC ART Turbine

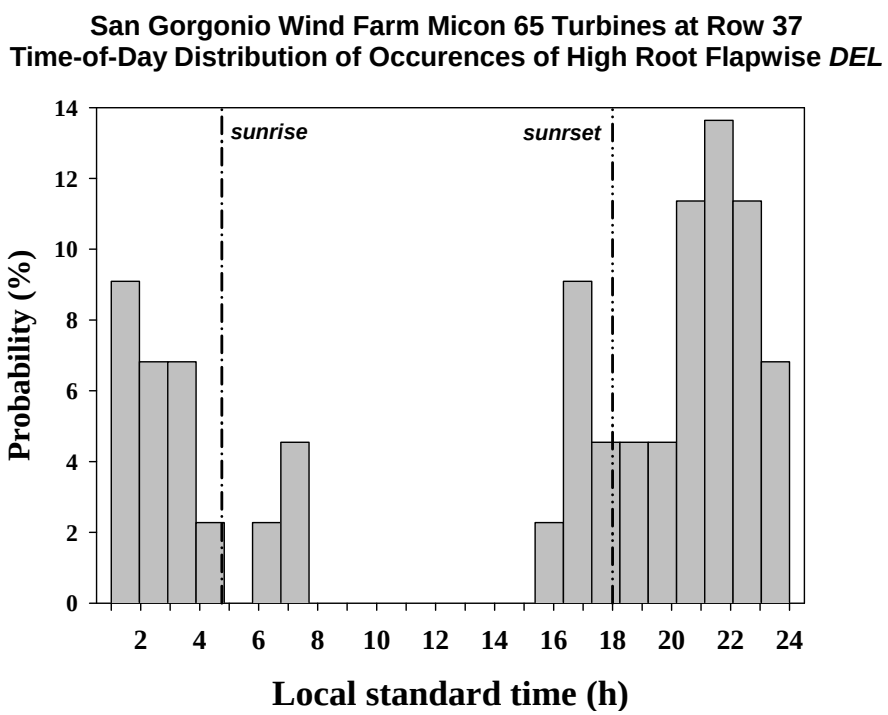
NWTC Regional Topography

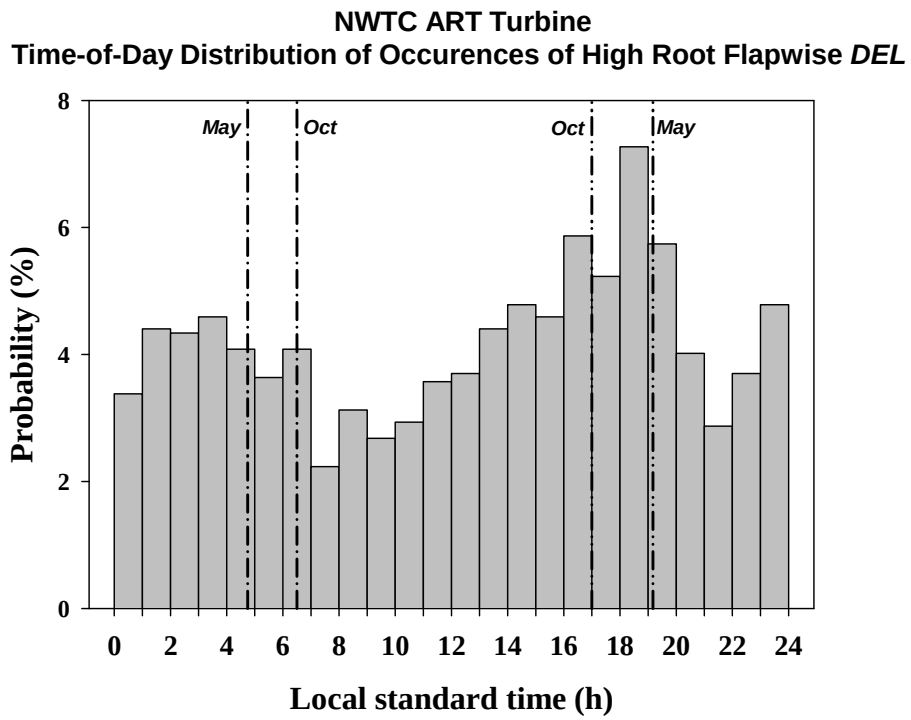


NWTC Local Topography

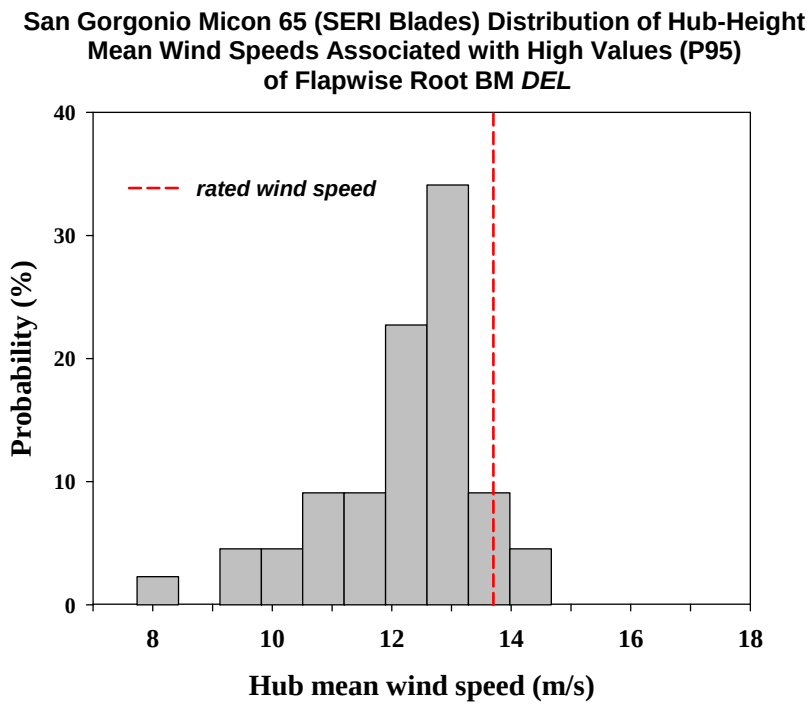


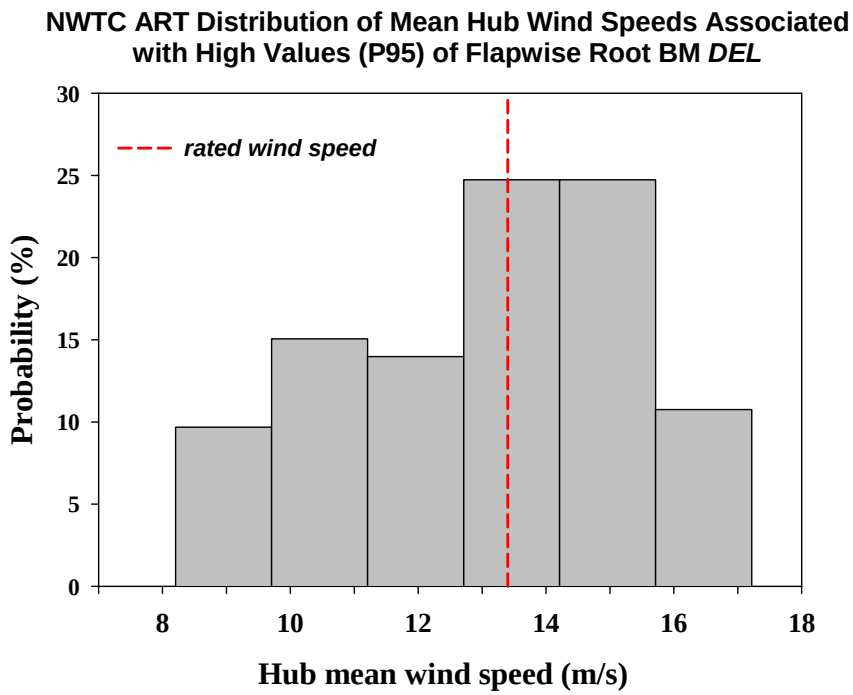
Diurnal Variations in High Blade Loads





Wind speeds at High Loads





Before we can proceed . . .

- We need to define a range of tools that we can employ to describe both the motions and thermodynamics of the ABL, its vertical structures, and the turbulence characteristics associated with those structures
- We will then be in a position to interpret the observed turbine aeroelastic response seen over a diurnal period
- First some ***atmospheric thermodynamics*** . . .

Adiabatic Temperature Changes

- Air parcels moving vertically (lower pressure) in the atmosphere expand when rising and contract when descending (higher pressure)
- With this expansion/contraction their temperature changes in accordance with the 1st Law of Thermodynamics
- The following discussion assumes that the air we are tracking is dry and not saturated with water vapor

Adiabatic Lapse Rate

It can be shown that for dry air changing height from z_1 (p_1) and temperature T_1 to z_2 (p_2) its temperature will be T_2 as a result of an adiabatic expansion/contraction (assuming no heat is gained or lost in the process)

$$\ln\left[\left(p_2/p_1\right)^{R_d/c_p}\right] = \ln\left(T_2/T_1\right)$$

And after taking the anti-logs of both sides

$$\left(p_2/p_1\right)^{R_d/c_p} = T_2/T_1$$

This result allows us to define an adiabatic change in air temperature with a change in height (pressure)

The rate of (heating/cooling) is 1° C per 100 m height change

Potential Temperature

Using the definition of the adiabatic lapse rate we can define the **potential** (or thermodynamic) temperature as . . .

$$\theta = T(z)\left[\frac{p_o}{p(z)}\right]^{R_d/c_p}$$

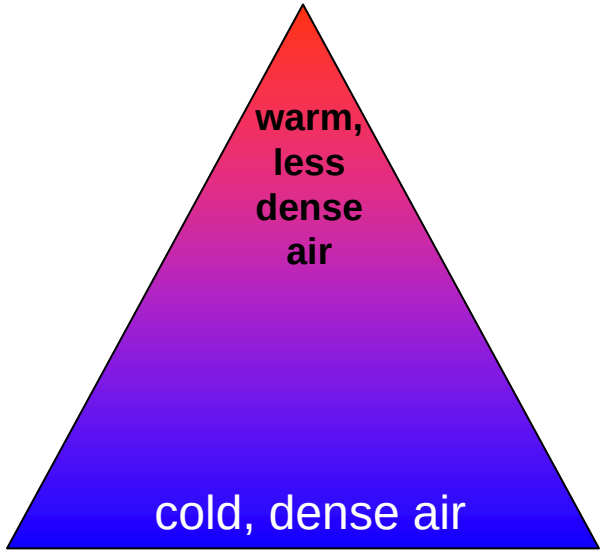
where

z is in meters
T is in °K
p and p_o are in equivalent units of pressure (mb, kPa, etc)
p_o is a reference pressure = 1000 mb or 100 kPa
R_d/c_p = 0.286

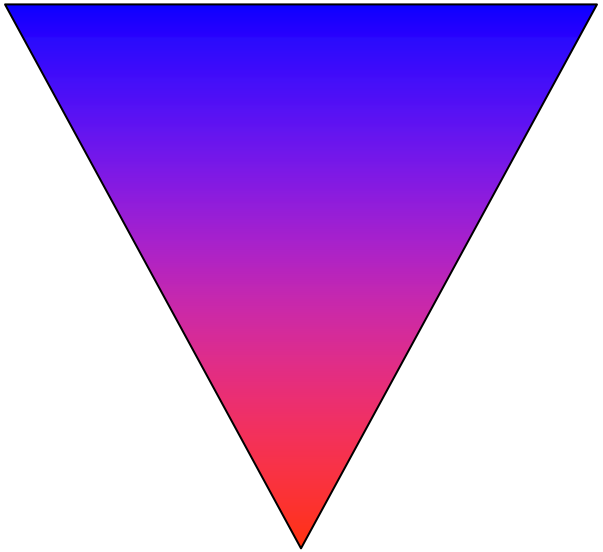
Concept of Atmospheric Stability

- Static Stability
- Dynamic Stability

Schematically



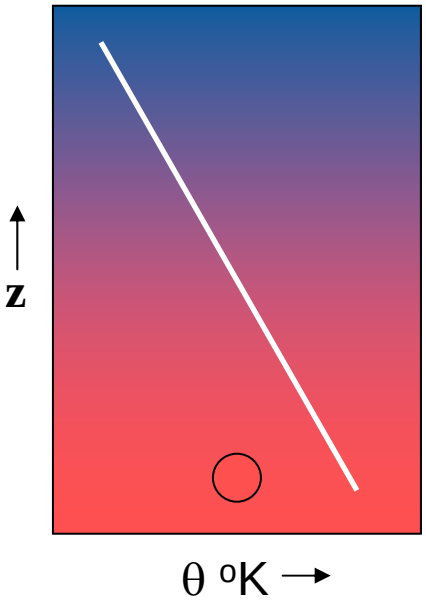
IT IS **STABLE**



IT IS **UNSTABLE**

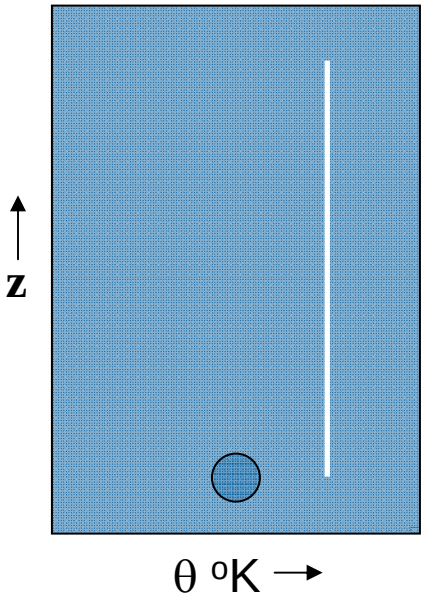
Static Stability

If we vertically displace the air parcels below .. .



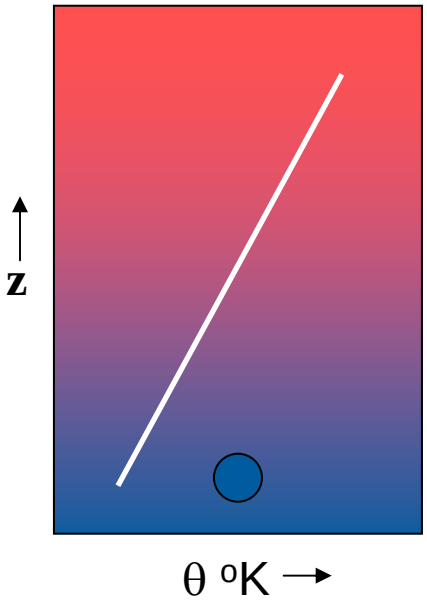
Parcel has positive buoyancy and will continue to rise

It is **Unstable**



Parcel has no net buoyancy and will remain at this height

It is **Neutral**

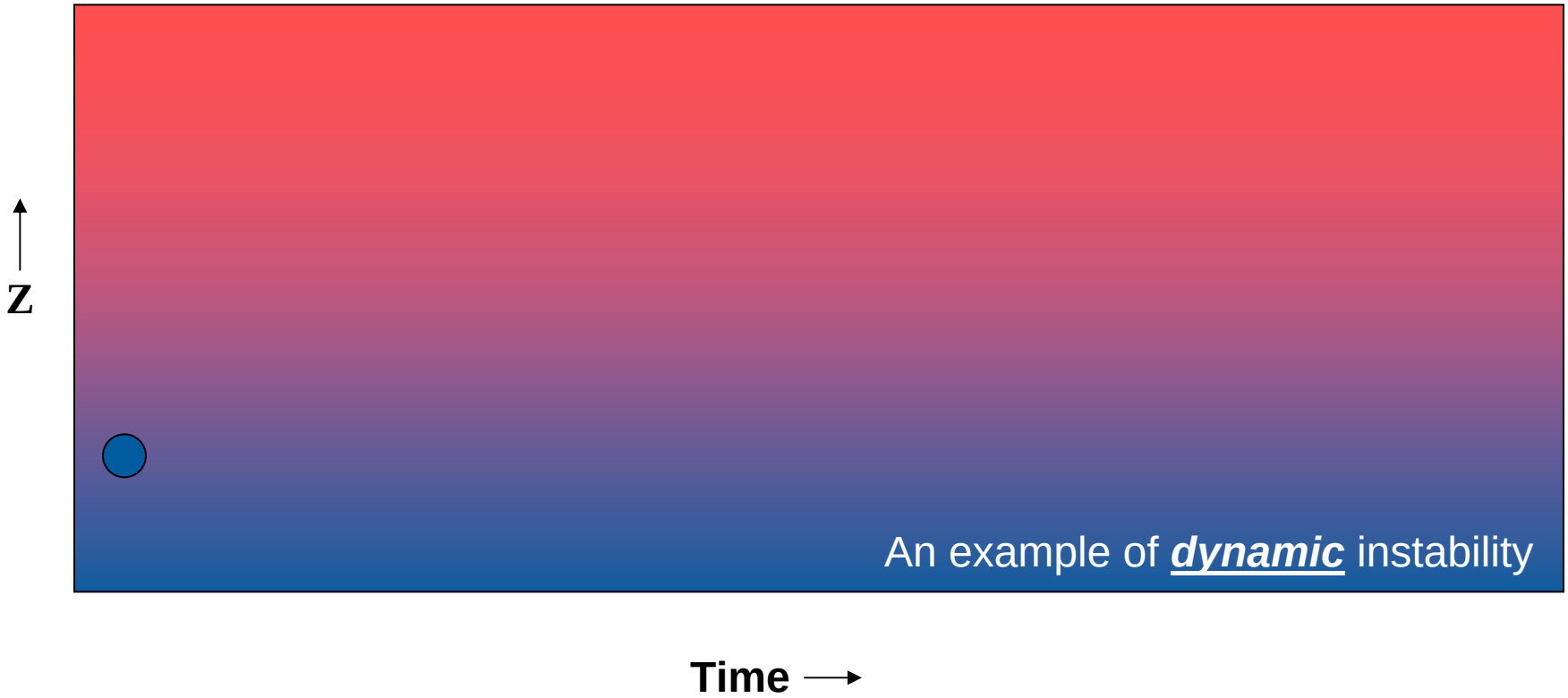


Parcel has negative buoyancy and will return to its original level

It is **Stable**

Dynamic Stability or Instability

The right combination of vertical temperature and wind speed stratification can produce an oscillatory or resonant response in the wind field particularly in vertical motions



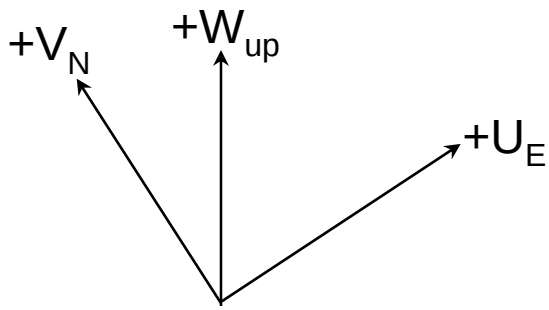
Stability is Important

- The vertical stability exerts a significant influence over the nature of turbulence in the atmospheric boundary layer
- We will show that under certain narrow ranges of atmospheric stability, wind turbines can experience significant structural loading and fatigue damage

Next . . .

- Now lets more on to describing atmospheric motions and their chaotic behavior --- turbulence!
- This is the stuff that wind turbine blades must ride through 24/7 year and year out
- ABL turbulence, while stochastic in nature, does exhibit spatial and temporal organizational structures and that have an impact on wind turbines and we will see
- First some basic definitions and turbulence scaling concepts . . .

Flow Coordinate Systems

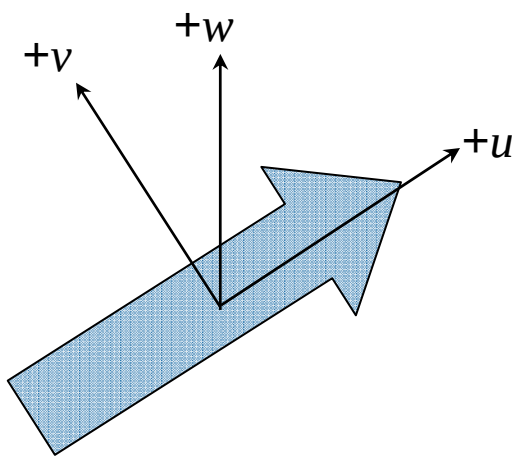


Meteorological Coordinates

U = E-W flow component

V = N-S flow component

W = vertical component



Aligned with the local flow vector

$\pm u$ = streamwise component (*parallel to the mean streamline*)

$\pm v$ = lateral or cross-wind component

$\pm w$ = vertical component

Definition of Turbulent Wind Components

Decompose orthogonal flow velocity components and temperature into **mean** $(\bar{\ })$ and fluctuating (**eddy**) components $(')$

$$u = \bar{u} + u'$$

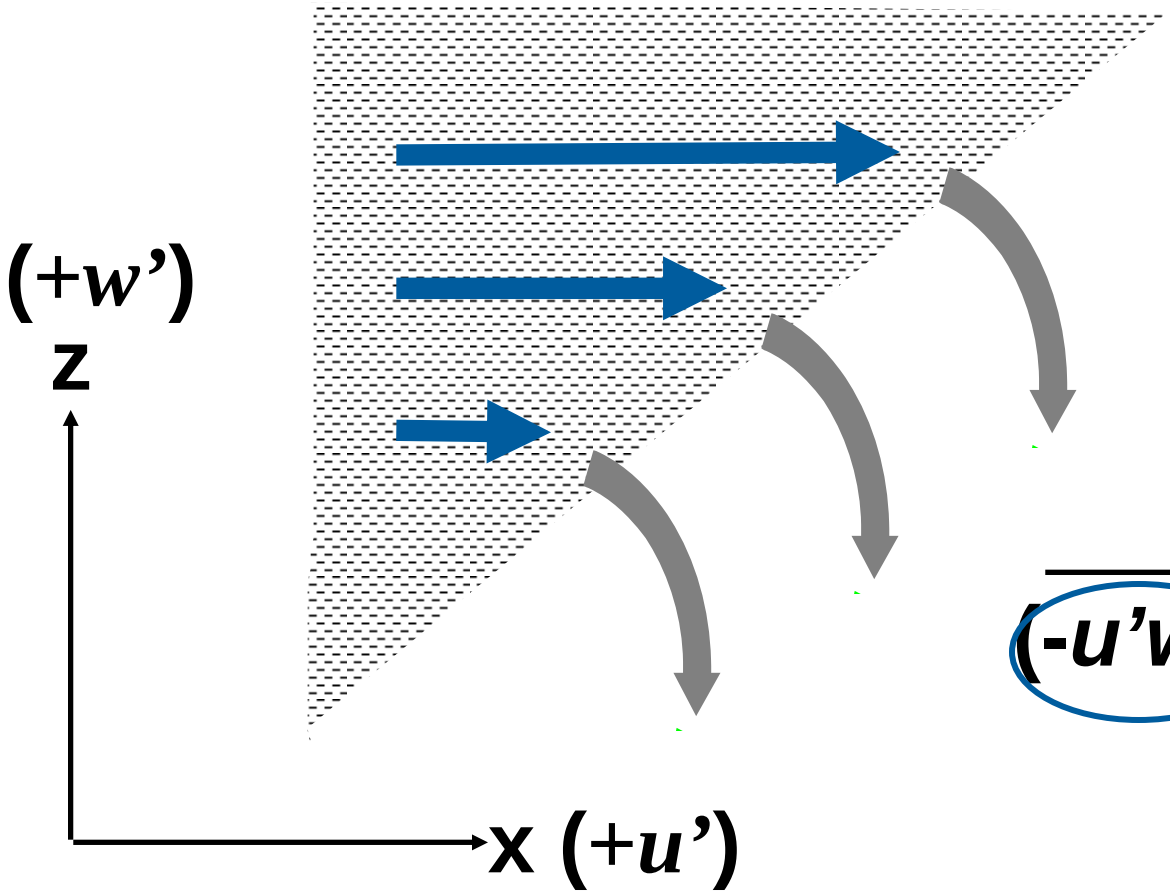
$$v = \bar{v} + v'$$

$$w = \bar{w} + w'$$

$$\theta = \bar{\theta} + \theta'$$

where $\overline{u'} = \overline{v'} = \overline{w'} = \overline{\theta'} = 0$

The Role of Friction -- Vertical Shearing Stress



Downward flux or transport of horizontal momentum

$$\left(-\overline{u'w'}\right)^{1/2} \equiv u_*$$

friction or shear velocity

Shearing Stress ⇨ The Log Wind Profile

- **Has a physical basis**
- **Assumes that the <u>shearing stress in the wind is constant with height</u> and that the influence of the earth's rotation can be ignored**
- **The height of this "constant stress" layer can extend up to 200 m under neutral stability conditions**
- **This is called the "<u>surface layer</u>" of the atmospheric boundary layer**

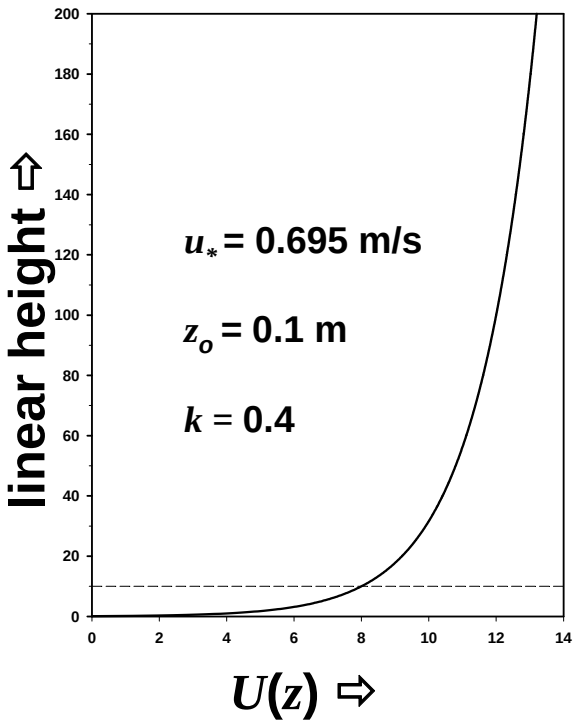
The Log Wind Profile

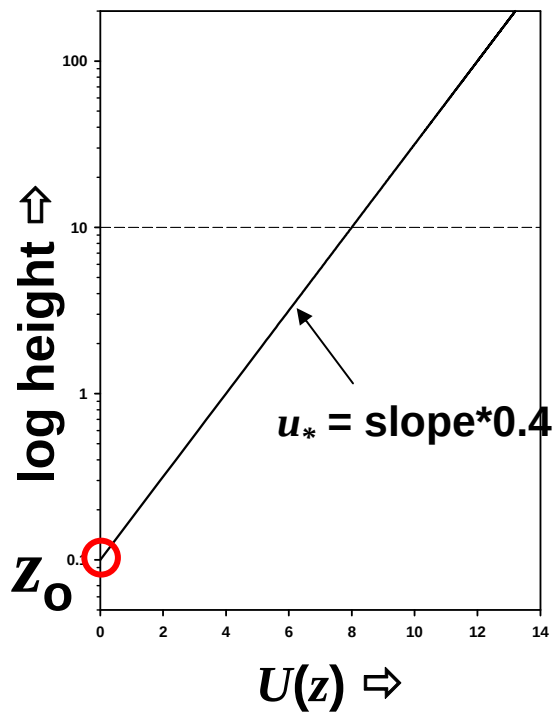
Under these assumptions for a <u>statically neutral</u> boundary layer . . .

The "log" wind speed profile can be written

$$U(z) = \frac{u_*}{k} \ln\left[\frac{z}{z_o}\right]$$

where z_o is the surface aerodynamic roughness length





Surface Layer (SL) Characteristics

- Assumes horizontal homogeneity
- The value of u_* is approximately constant (> ±10%) throughout its depth ≅ constant shear stress
- The logarithmic wind profile applies
- The effect of the earth's rotation can be ignored (insensitive to Coriolis accelerations)

How Turbulence Scales in the Surface Layer

Monin & Obukhov developed <u>Similarity Theory</u> using advanced dimensional analysis techniques

If the vertical fluxes of heat, moisture, and momentum are "constant" with height (<u>everything is in a more or less steady state or balance</u>), then the following velocity, temperature, and length scales can be used to scale turbulence in the surface layer:

Velocity: $u_* = \sqrt{\tau_o / \rho}$ ***where τ_o is the shear stress at the surface and ρ is the air density***

Temperature: $T_* = -F_{H_o} / u_*$

Length: $L = -\dfrac{u_*^3 \theta}{kgF_{H_o}}$

Often referred to as the M-O or Obukhov length

where F_{Ho} is the vertical heat flux at the earth's surface

Measures of SL Dynamic Stability

Gradient Richardson number, *Ri*

$$Ri = \frac{\left(g/\overline{\theta}\right)\left(\partial\overline{\theta}/\partial z\right)}{\left(\partial\overline{u}/\partial z\right)^2} = \frac{\text{turbulence generation by buoyancy}}{\text{turbulence generation by shear}}$$

Monin-Obukhov (M-O) stability parameter, *z/L*

$$\frac{z}{L} = -\frac{(g/\overline{\theta})(\overline{w'\theta'})_o}{u_*^3/kz}$$

where $(\overline{w'\theta'})_o =$ **temperature flux at ground surface**

***k* = 0.4**

g = gravity acceleration

Ri, *z/L* < 0 = unstable; *Ri*, *z/L* = 0, neutral; *Ri*, *z/L* > 0, stable

Important Turbulence Fluid Dynamics Parameters

Turbulent Reynolds Stresses, Fluxes, & Kinetic Energy

Need to be reasonably matched for proper modeling

$$\left.\begin{matrix} \overline{u'u'} & \overline{u'v'} & \overline{u'w'} \\ \overline{v'u'} & \overline{v'v'} & \overline{v'w'} \\ \overline{w'u'} & \overline{w'v'} & \overline{w'w'} \end{matrix}\right\} \text{Reynolds stress tensor}$$

assume $\overline{u'w'} = \overline{w'u'}, \overline{u'v'} = \overline{v'u}\ , \overline{v'w'} = \overline{w'v'}$

$\sigma_u^2 = \overline{u'u'}, \sigma_v^2 = \overline{v'v'}, \sigma_w^2 = \overline{w'w'}$

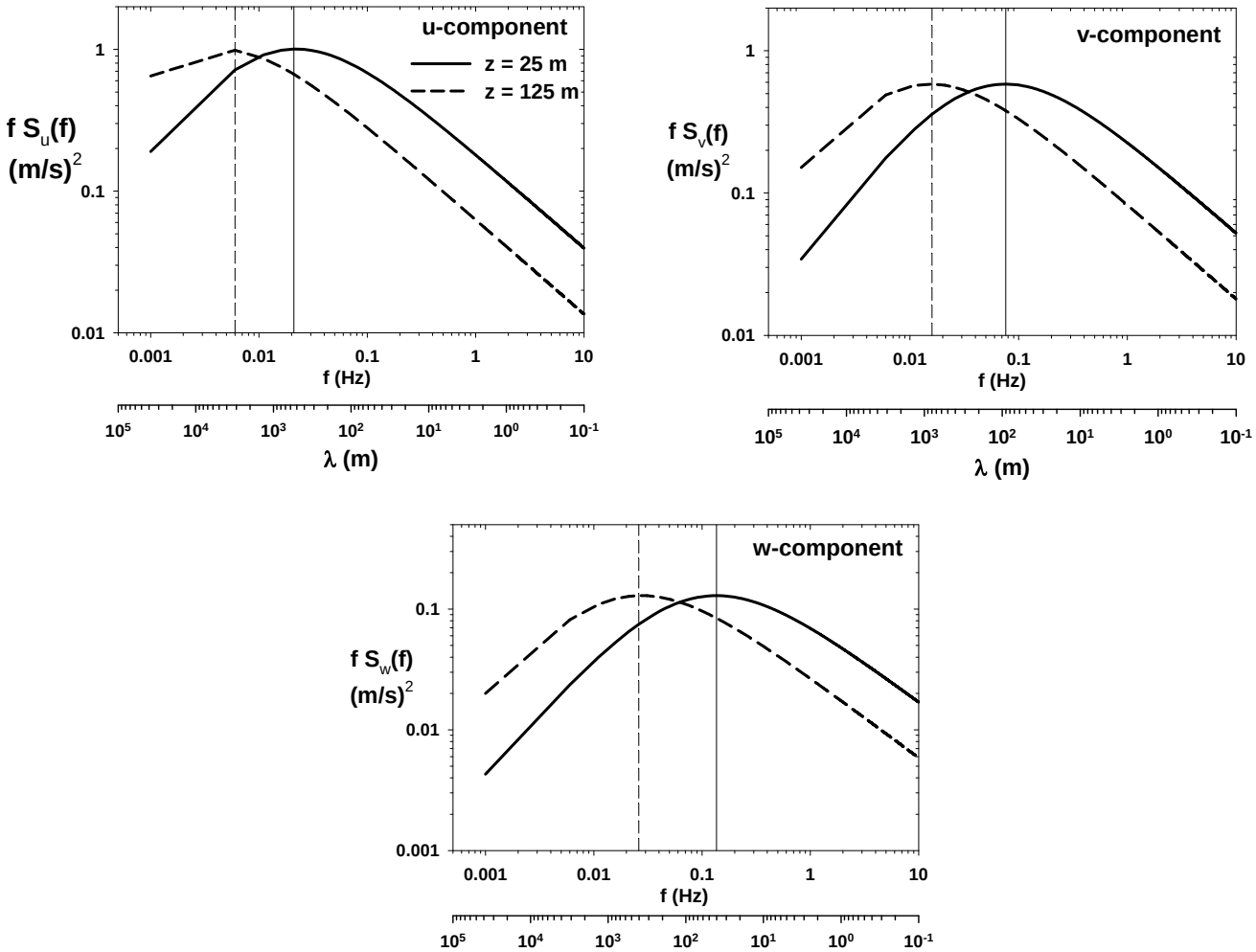
➡ Reynolds stress components ***(turbulence component covariances)***

Turbulent Kinetic Energy (TKE) $= 1/2(u'^2 + v'^2 + w'^2)$

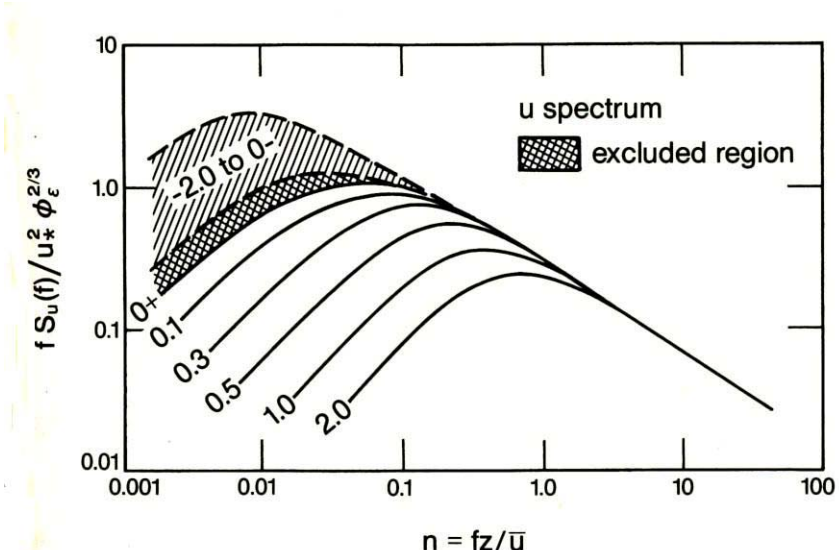
Coherent Turbulent Kinetic Energy (CTKE) $= 1/2[(u'w')^2 + (u'v')^2 + (v'w')^2)]^{1/2}$

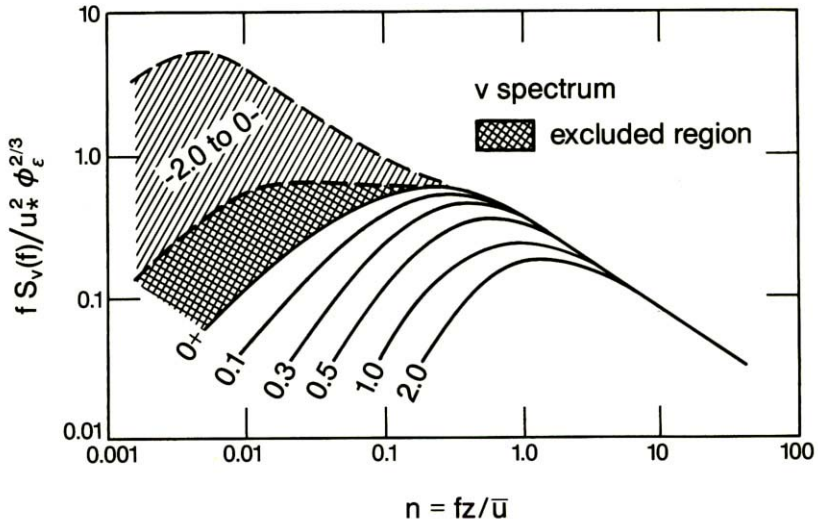
$u_{*_o} = \left[-(\overline{u'w'})_0\right]^{1/2}$ **= momentum flux at ground surface**

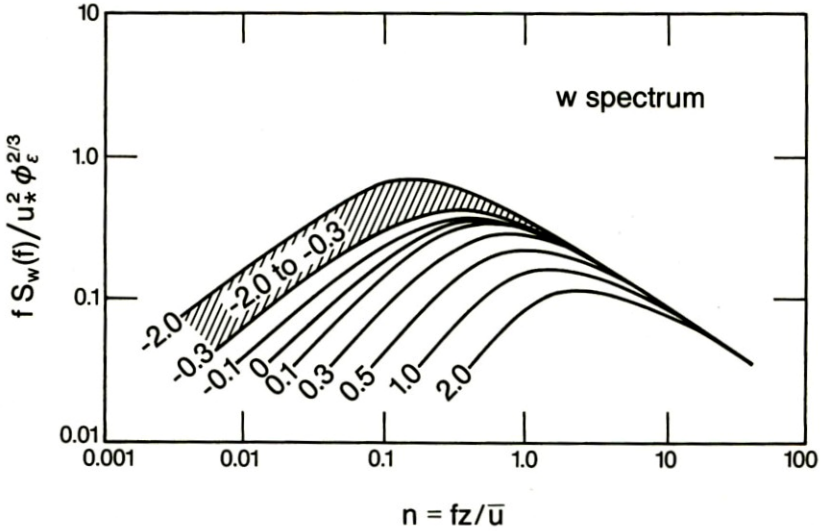
Surface Layer Turbulence Spectra Scales with Height Above Ground



Turbulence Spectra Also Scaled by Stability (*z/L*)







f = cyclic frequency (Hz)

n = non-dimensional or reduced frequency

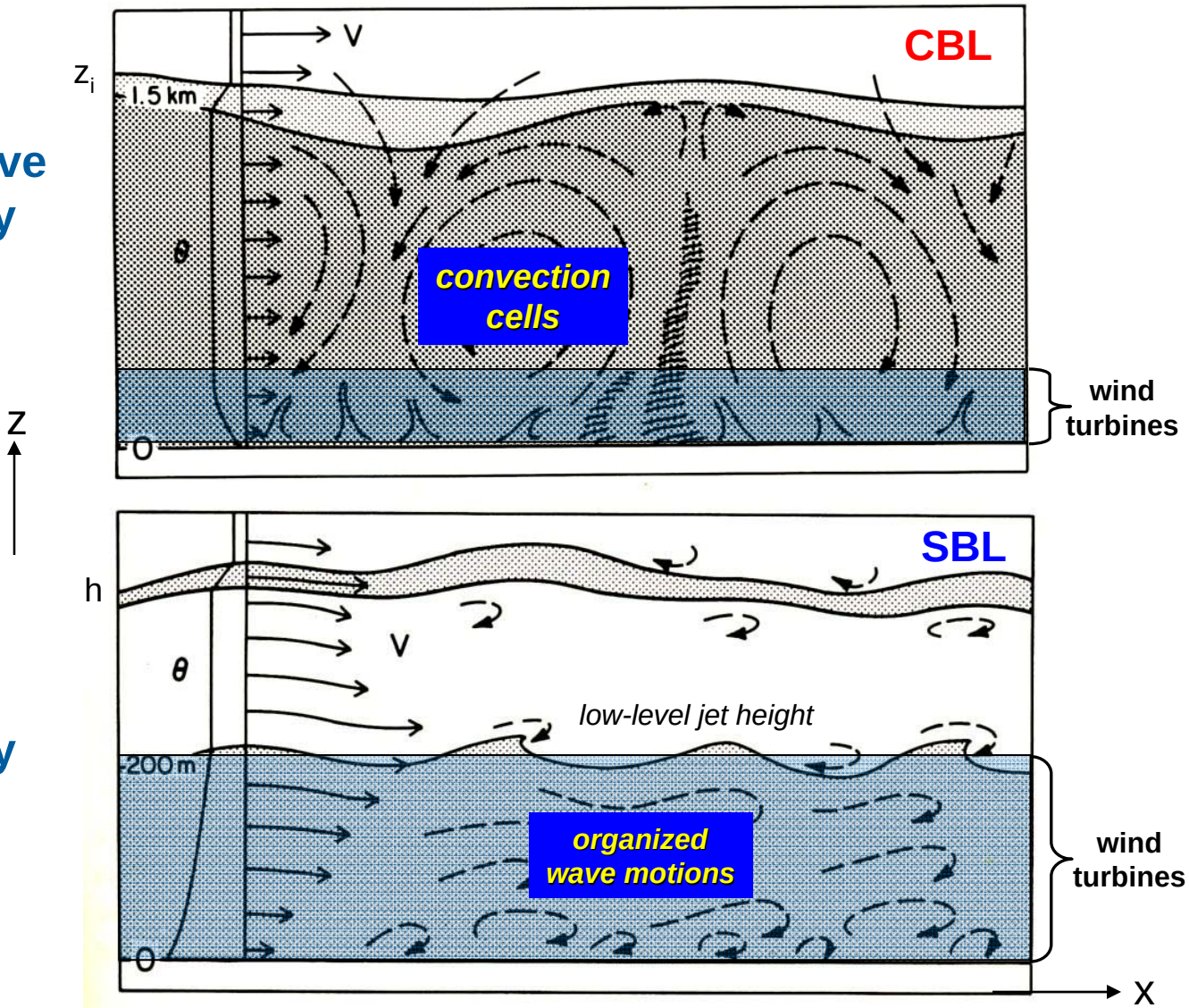
S(f) = power spectral density (m/s)^2/Hz

$$\varphi_\varepsilon = \frac{kz\varepsilon}{u_*^3}$$ **scales dissipation of TKE**

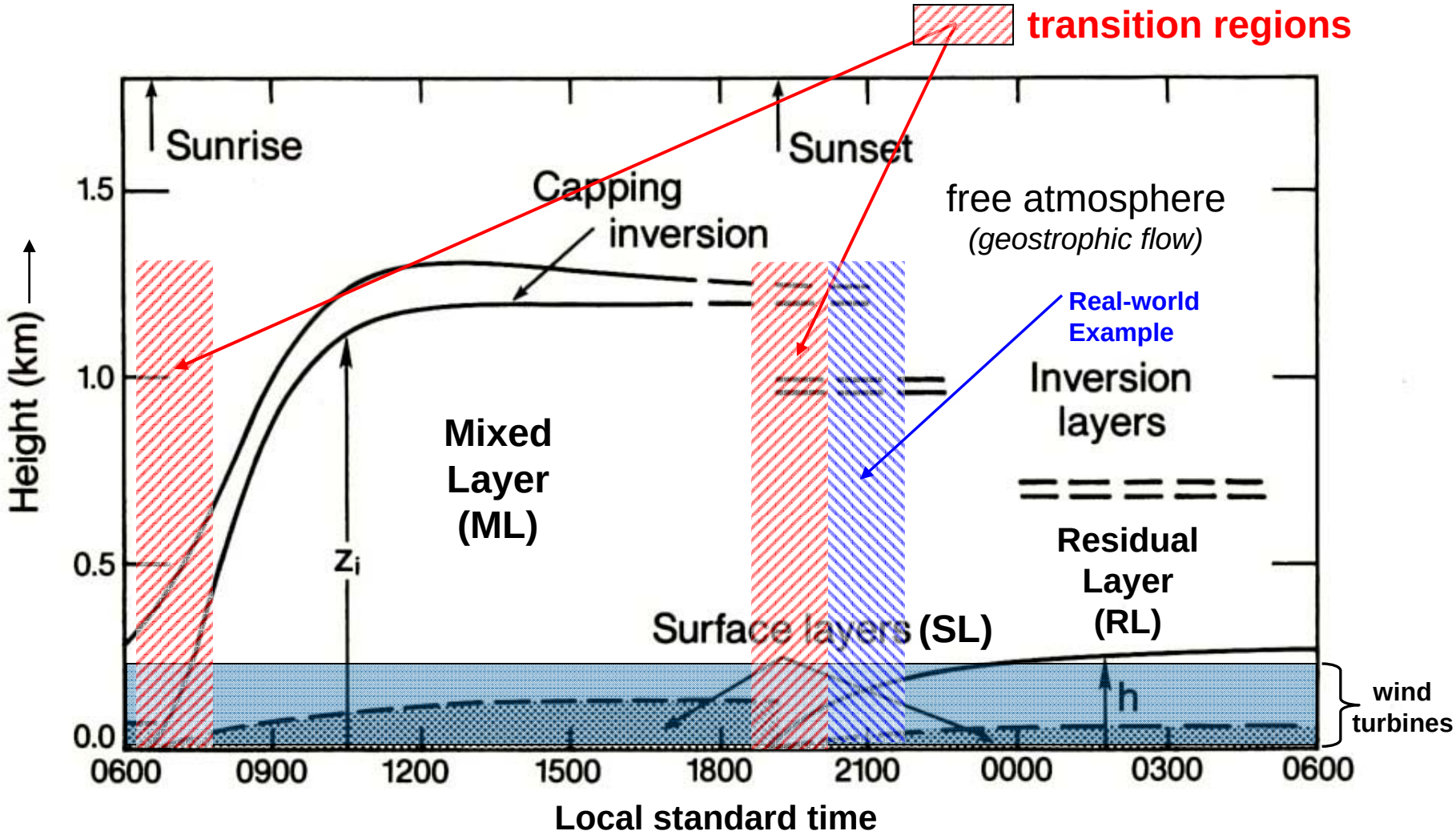
ABL Vertical Structural Characteristics

Convective Boundary Layer

Stable Boundary Layer



ABL Diurnal Evolution



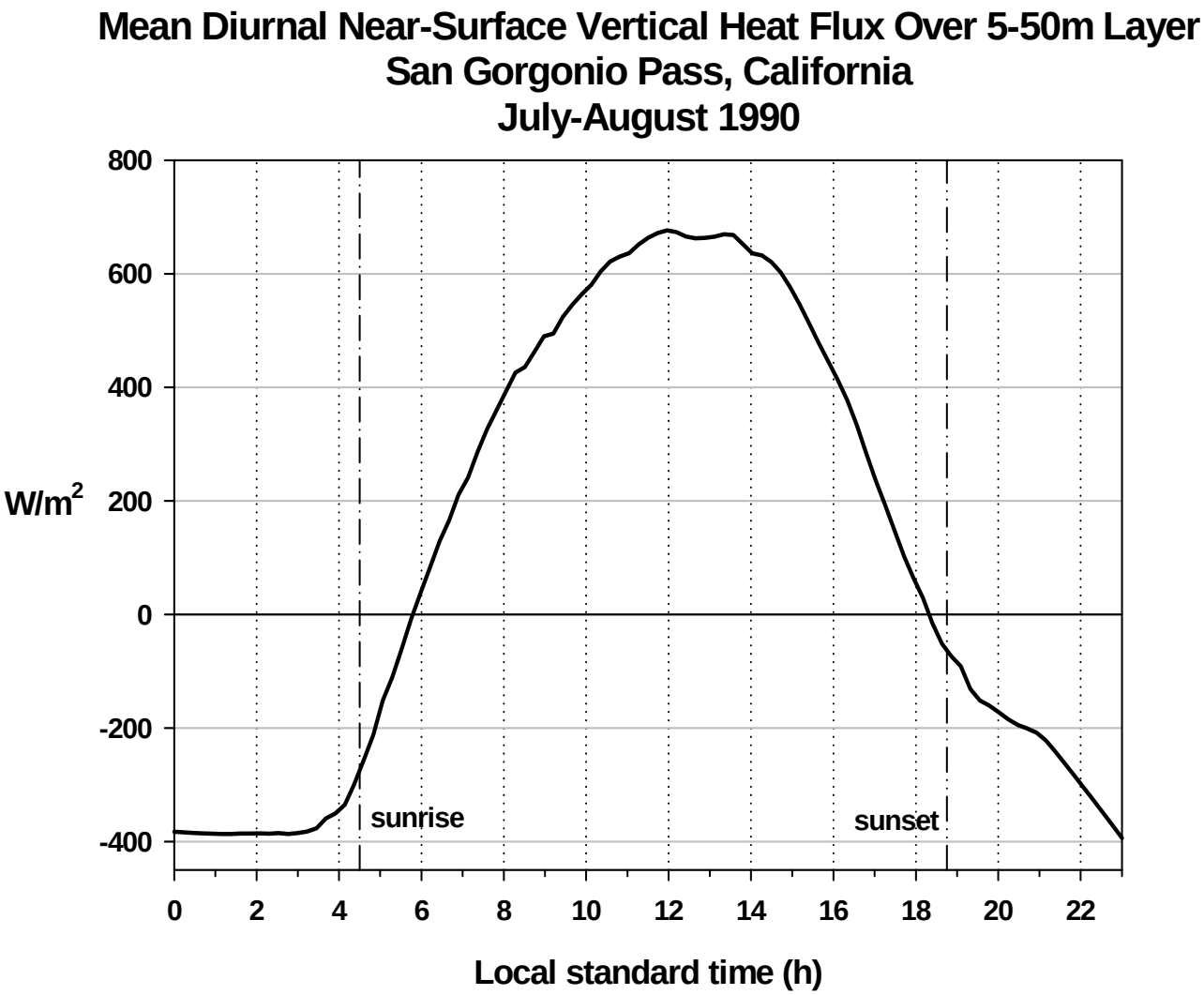
A Real World Example . . .

- Let's look at the typical diurnal variation in many of the surface layer parameters we just discussed
- The data was derived from measurements at the SeaWest Wind Farm in San Gorgonio Pass California

- We start with what drives the whole shmear

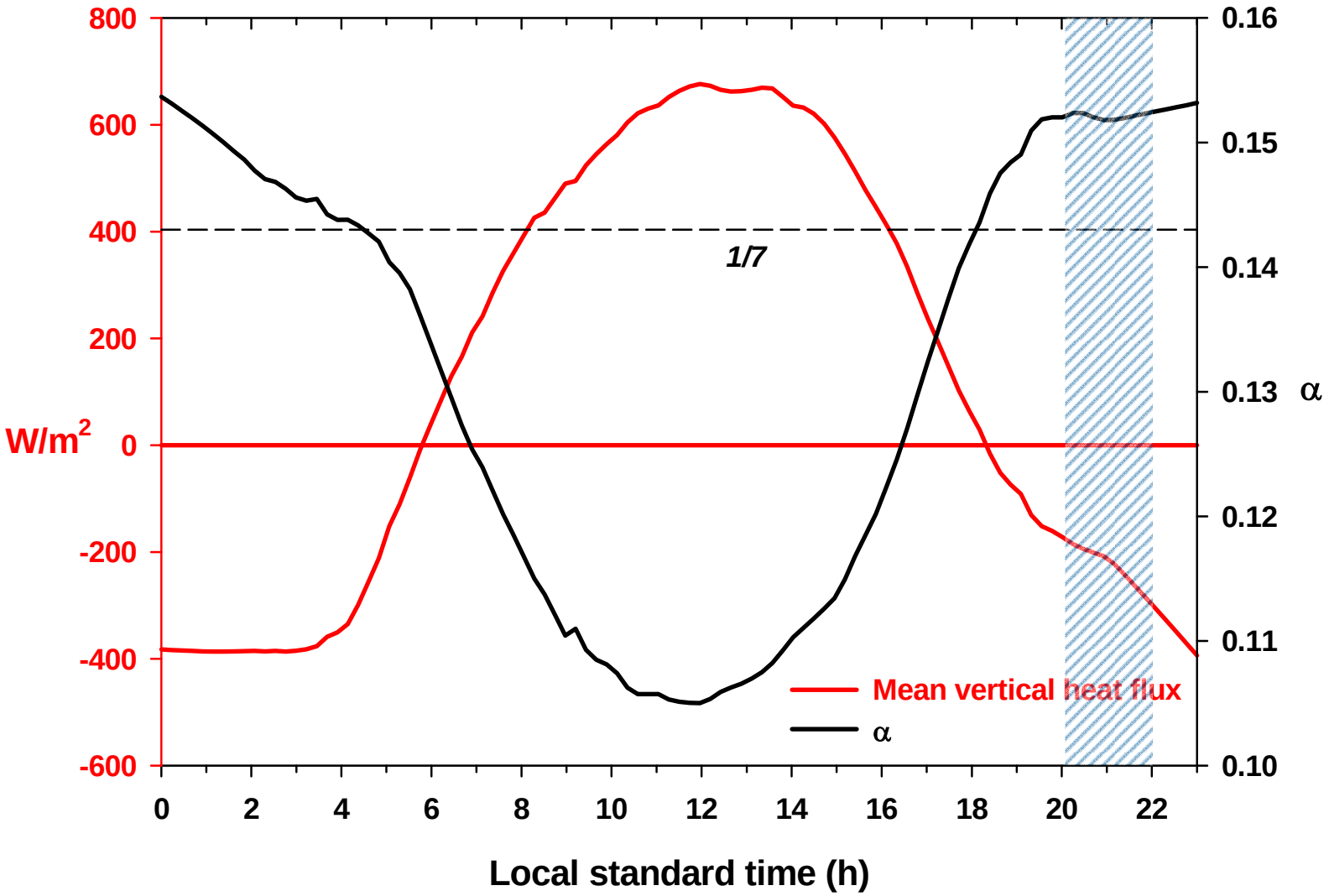
The diurnal variation in incoming solar heat energy . . .

Diurnal Variation of Vertical Heat Flux F_H

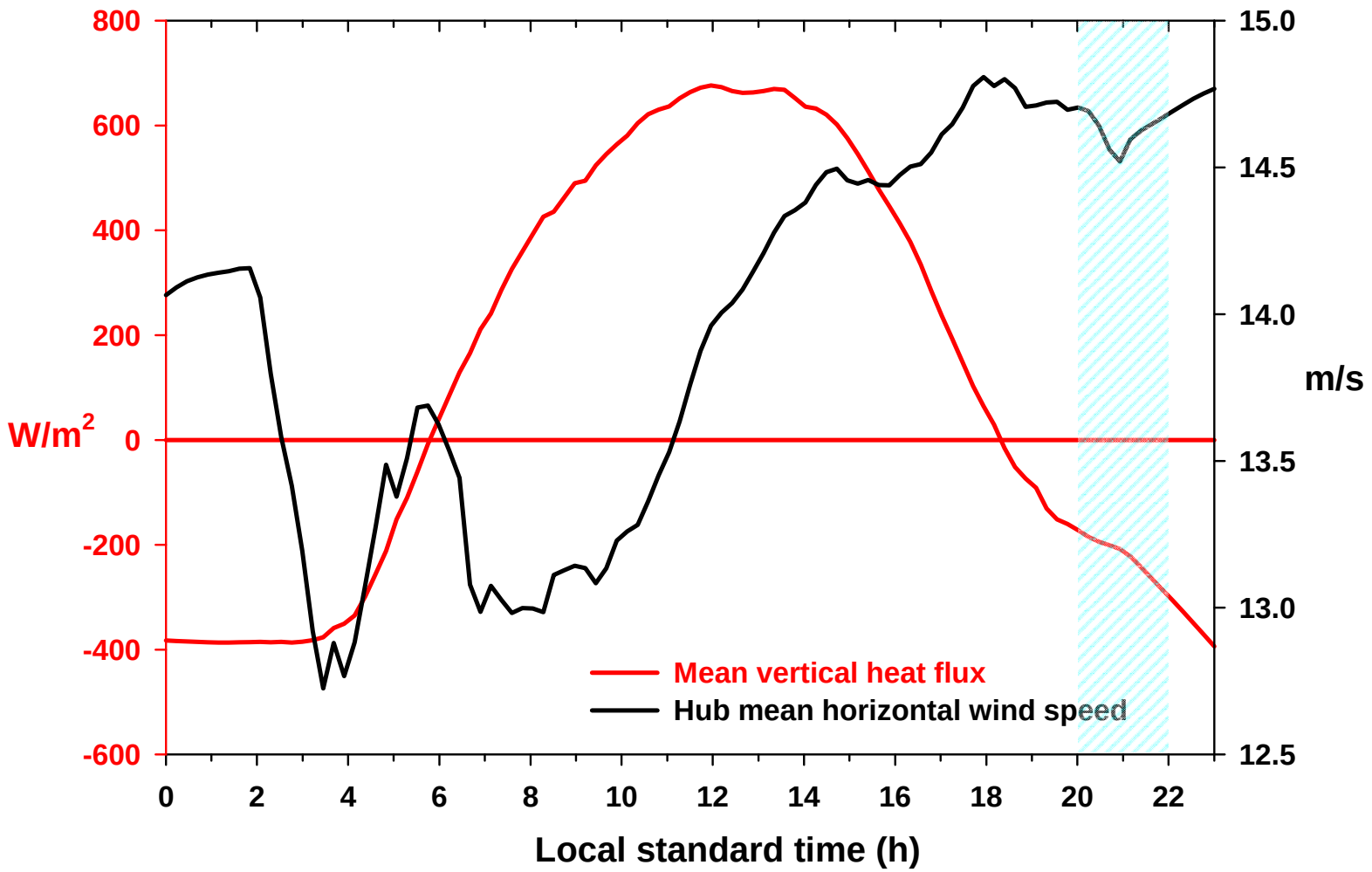


Measured upwind of the wind farm's first row of turbines

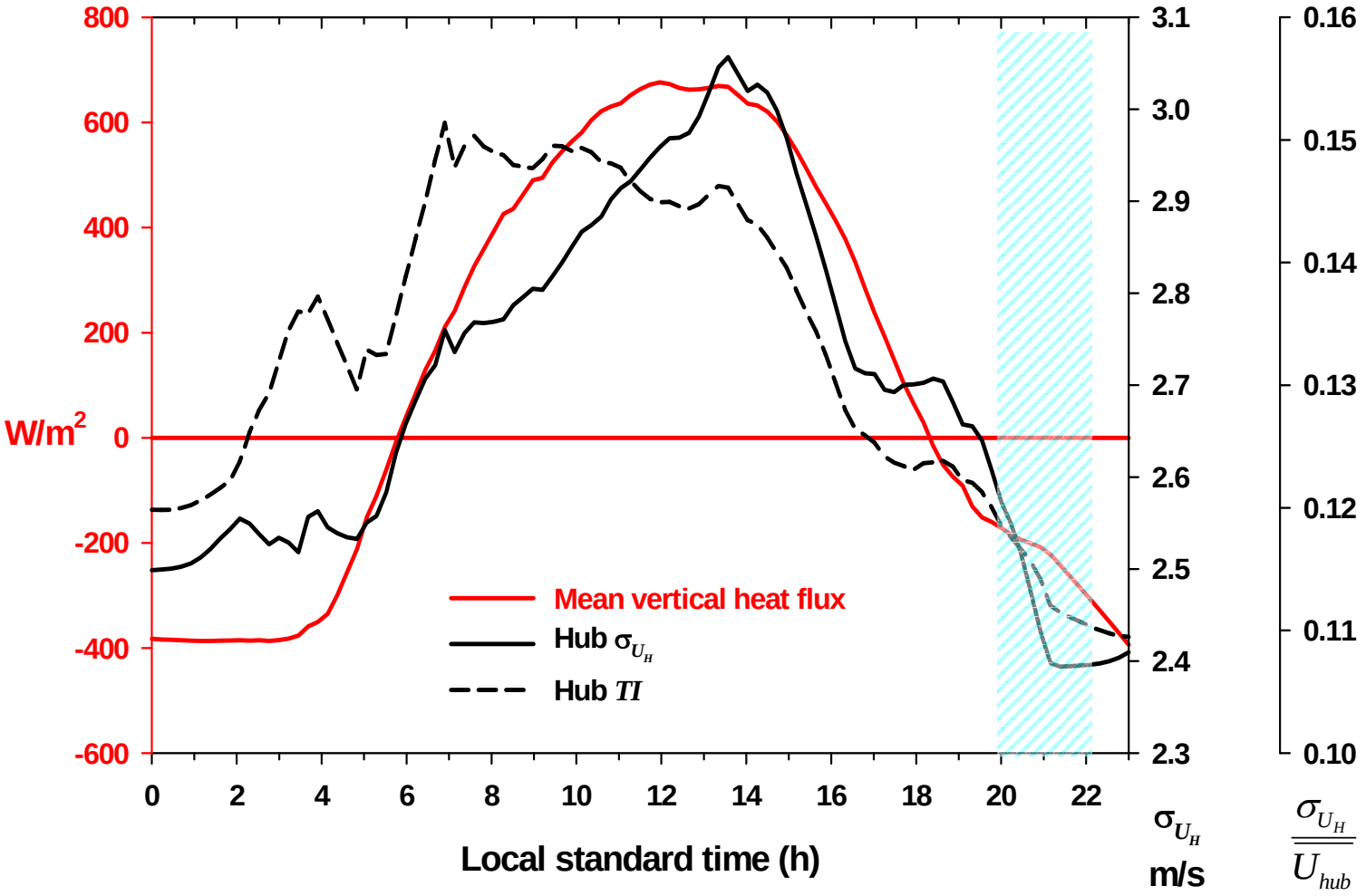
Variation of Heat Flux and Power Law Wind Shear Across Rotors, α



Variation of Heat Flux and Hub-Height (23m) Mean Wind Speed

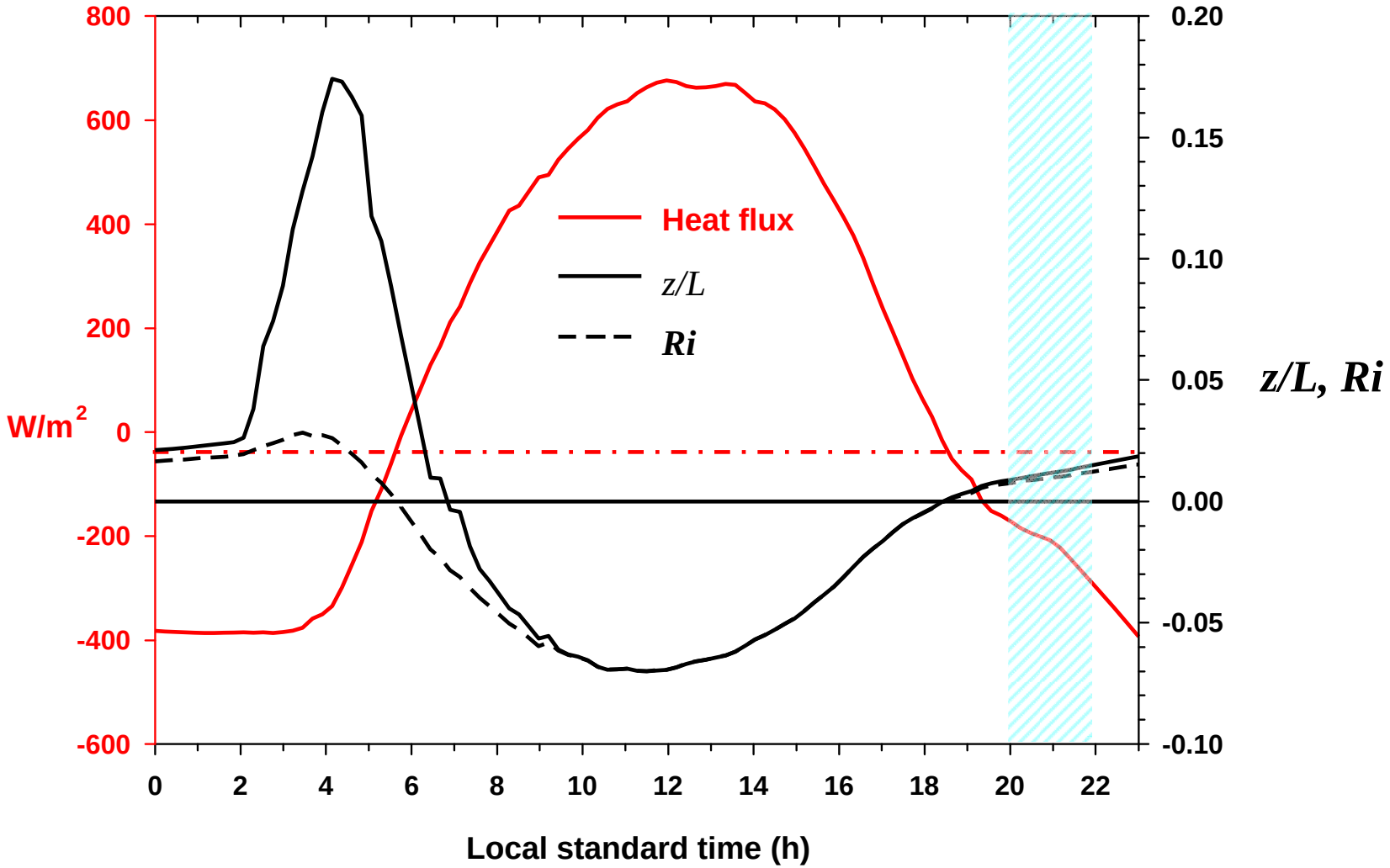


Diurnal Variation of Mean Heat Flux, Hub Wind Speed, and Turbulence Level

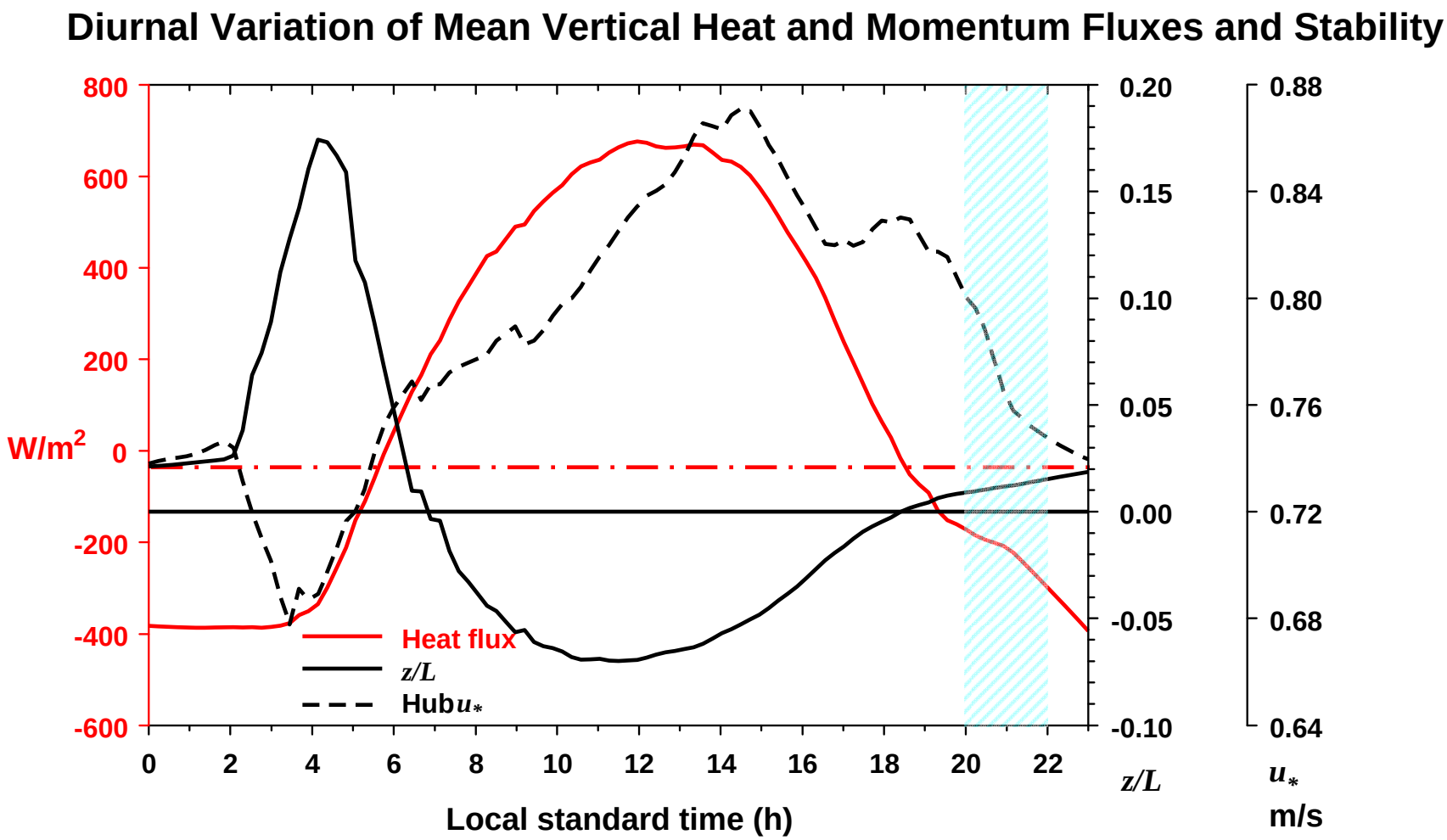


Variation of Heat Flux and Stability

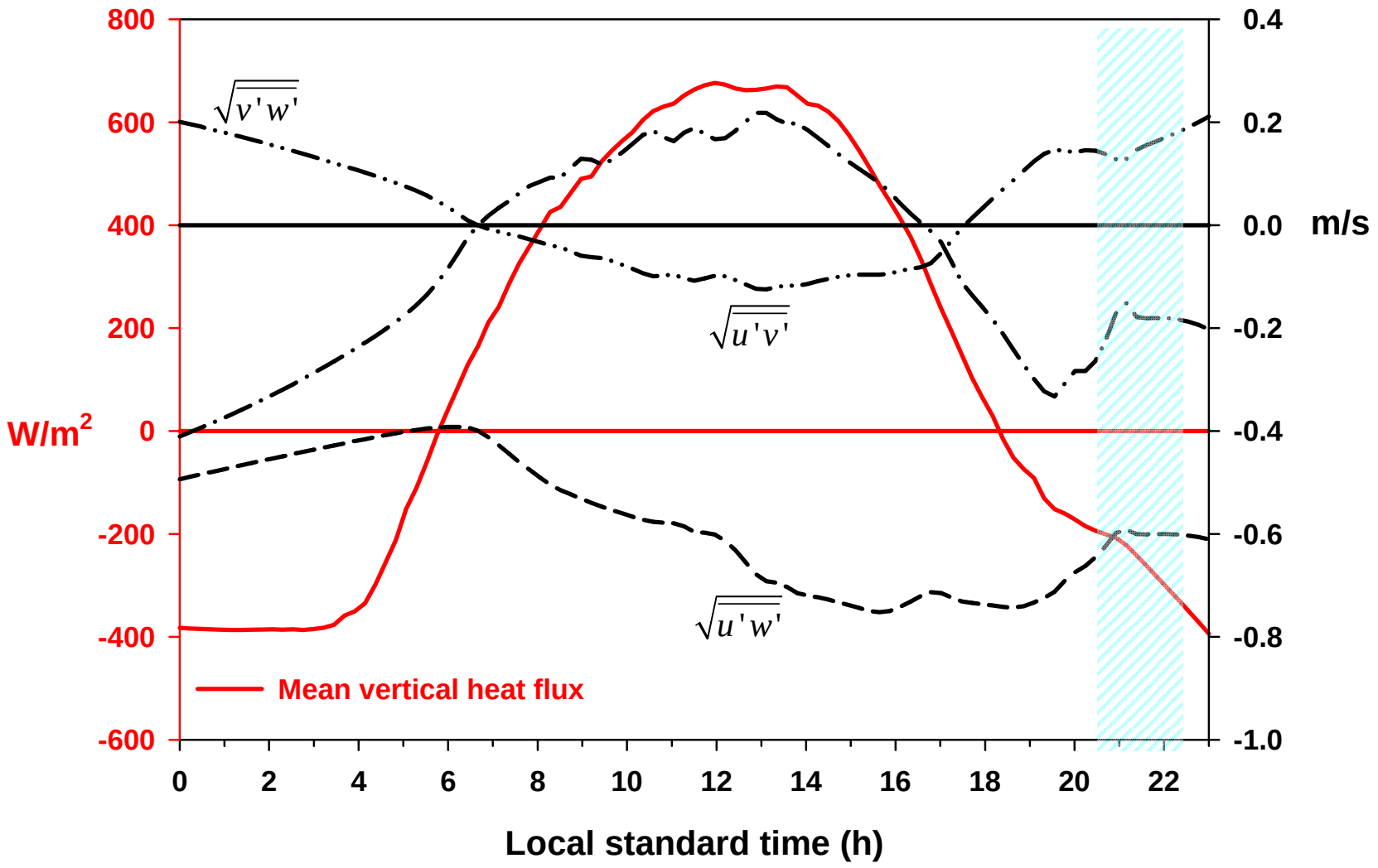
Diurnal Variation of Mean Vertical Heat Flux and Stability Over 5-50m Layer



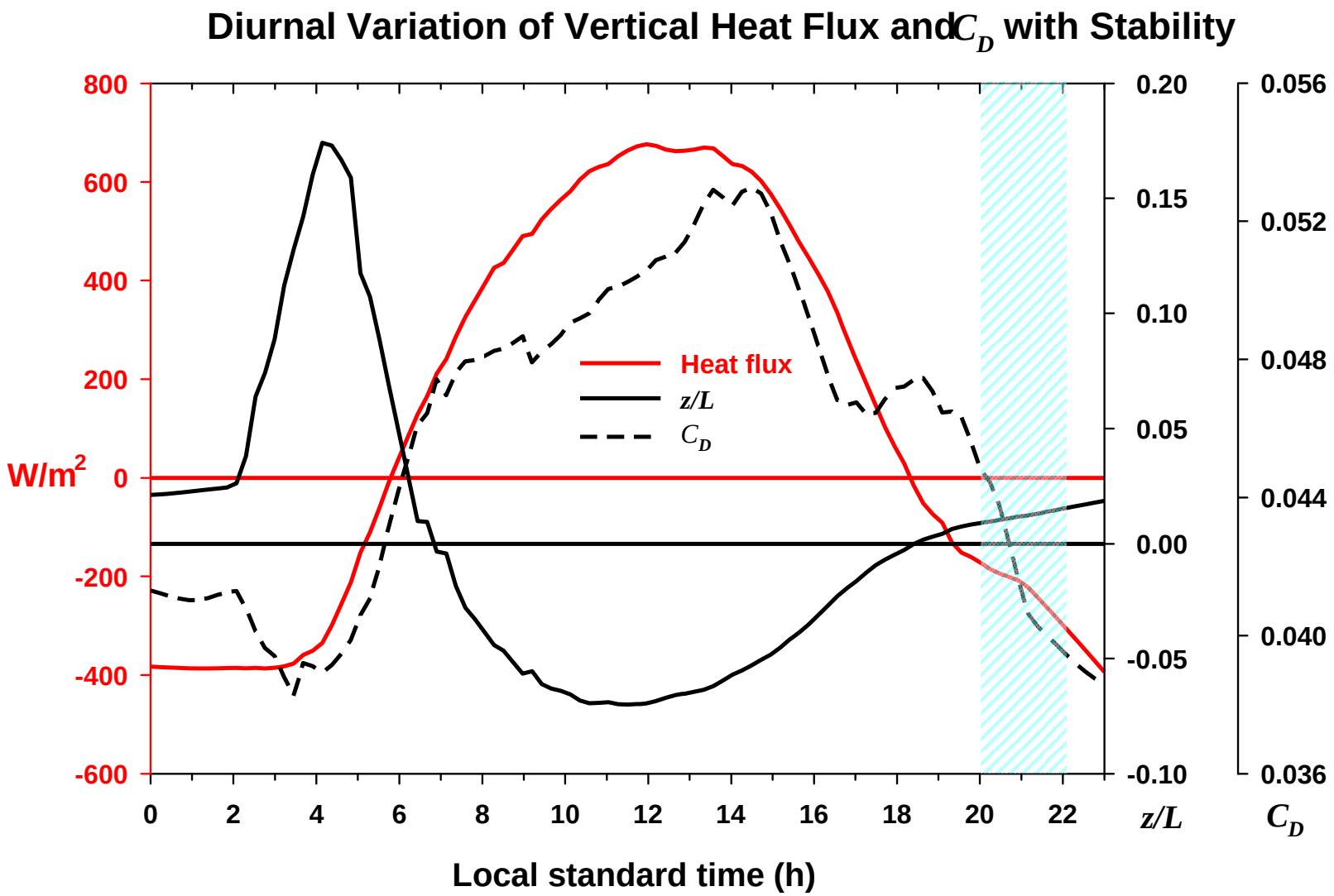
Variation of Heat Flux and Mean Shearing Stress, u_*



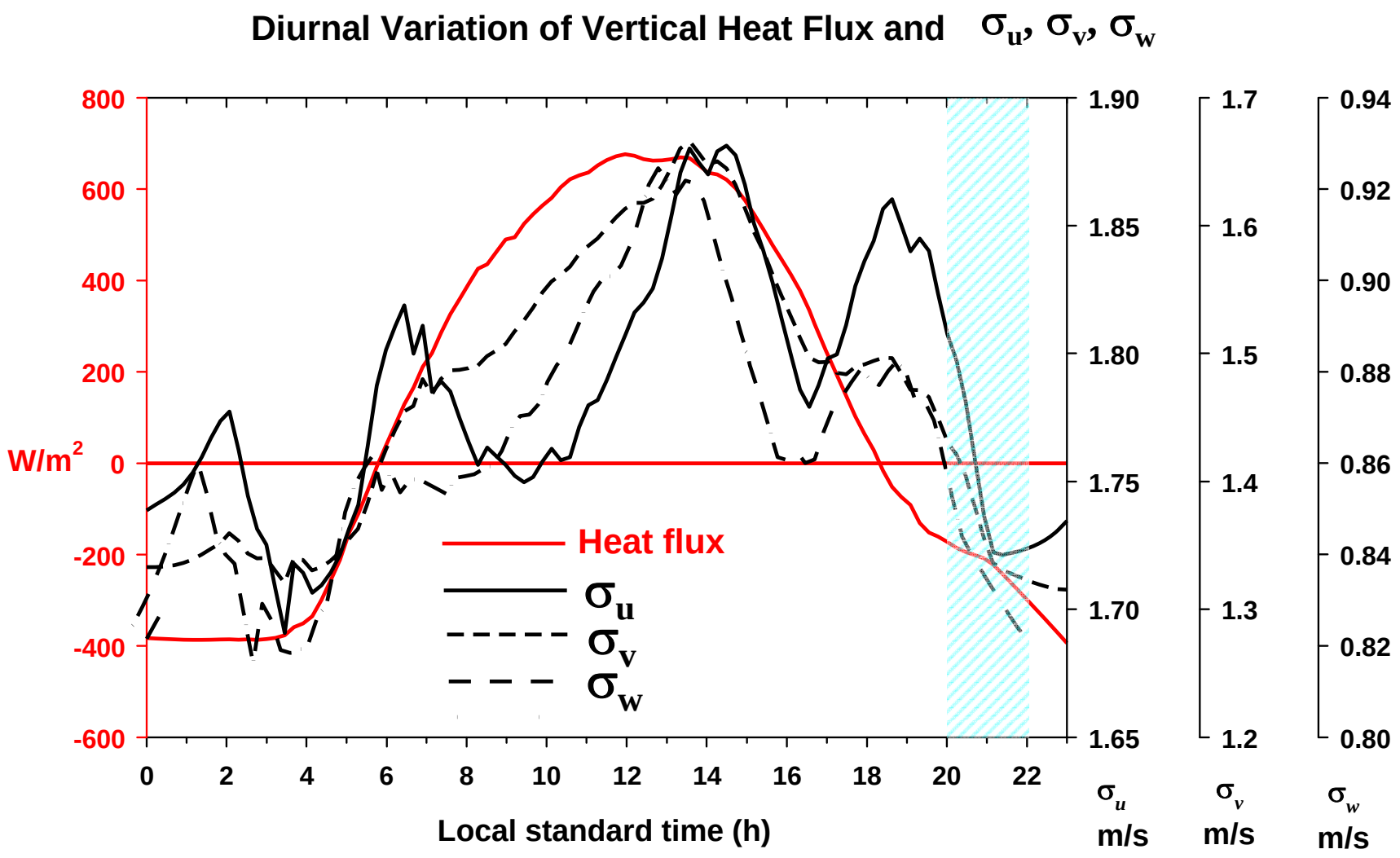
Variation of Heat Flux and Mean Reynolds Stresses



Variation of Heat Flux, Stability, and Surface Drag Coefficient C_D



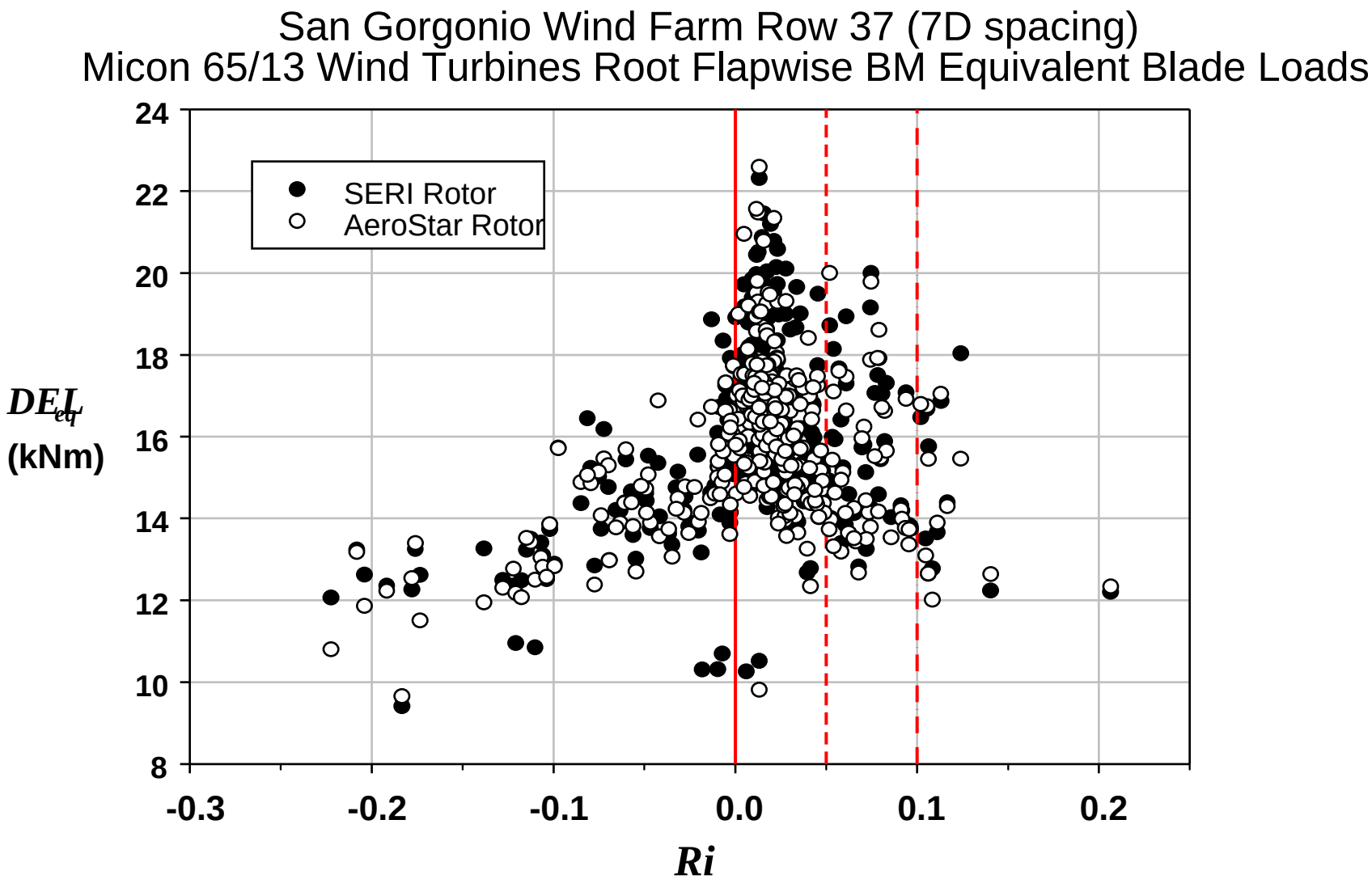
Variation of Heat Flux and Turbulent Component Std Devs



Back to the Micon 65 Loads Data …

- Let’s now take a look at the distribution of blade root damage equivalent blade loads as a function of other turbulence scaling parameters
- First vertical dynamic stability, Ri

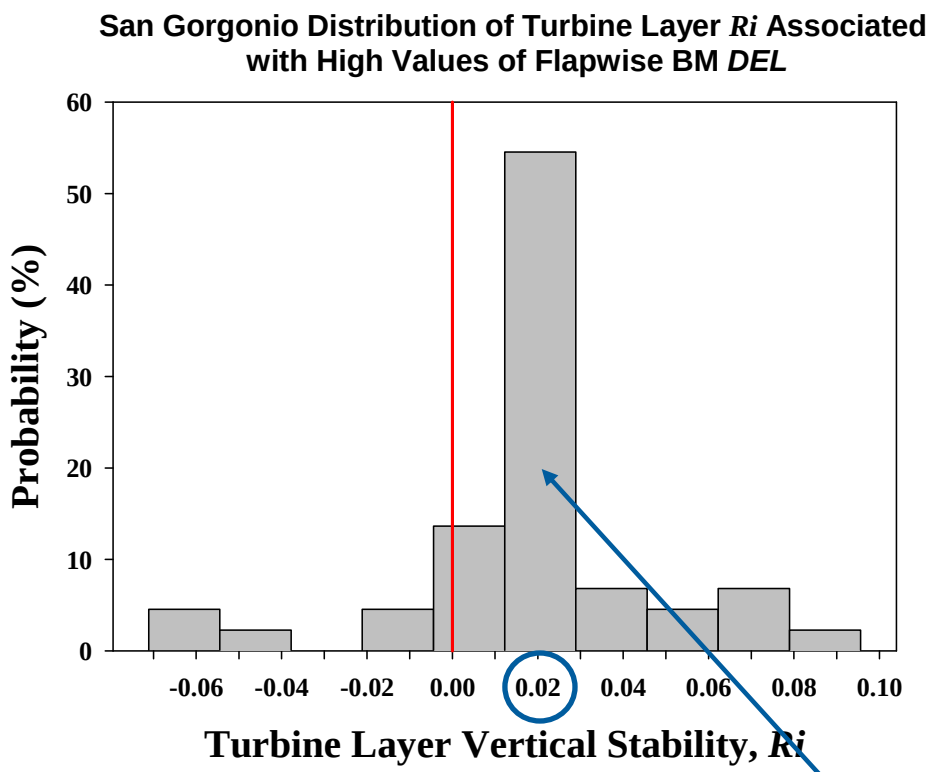
Comparison of Measured Turbine Loads as Function of Stability, *Ri*

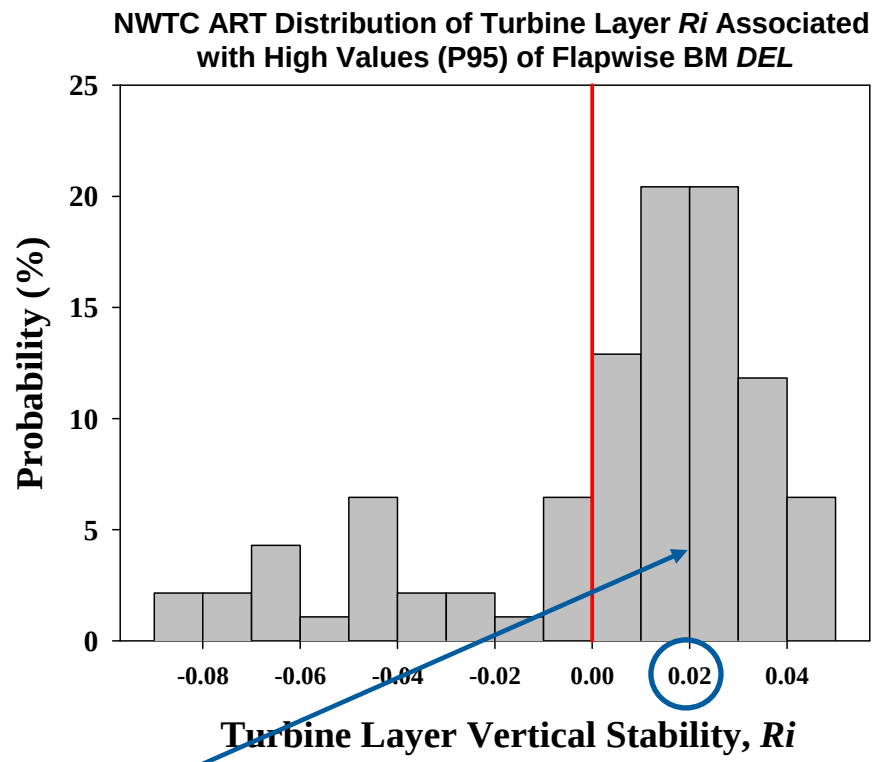


Hmmm . . .

How do these compare with our blade root load measurements at on the NWTC ART Turbine?

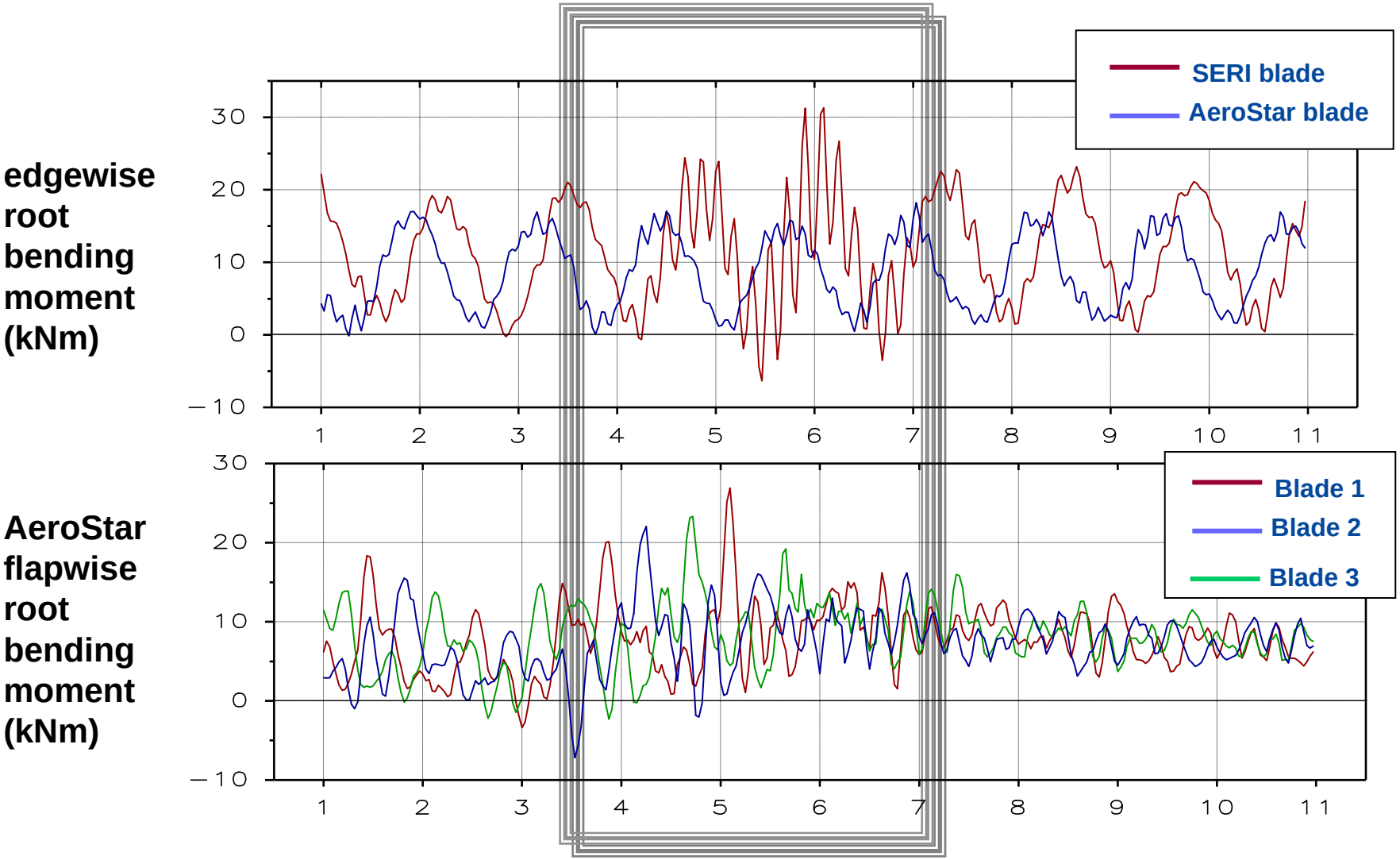
Ri Values Associated with High Blade Root Fatigue Loads for the San Gorgonio Wind Farm and the NWTC





Both peaks occur in weakly or slightly stable conditions!

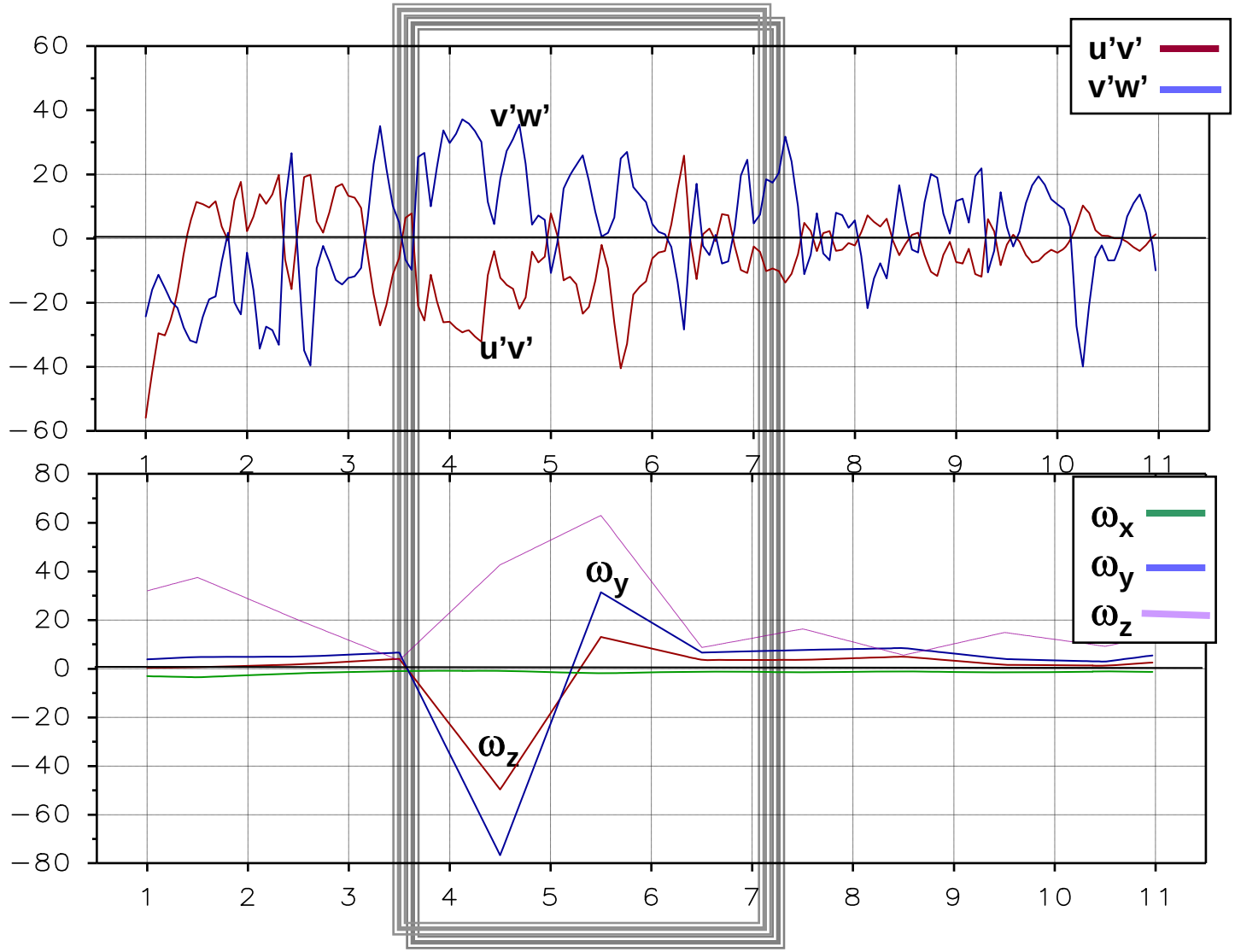
Example of Rotor Encountering a Coherent Turbulent Structure – Aeroelastic Response



3-D Coherent Turbulent Structure at Hub Height Responsible for AeroStar Rotor Response

Instantaneous local Reynolds stresses $(m/s)^2$

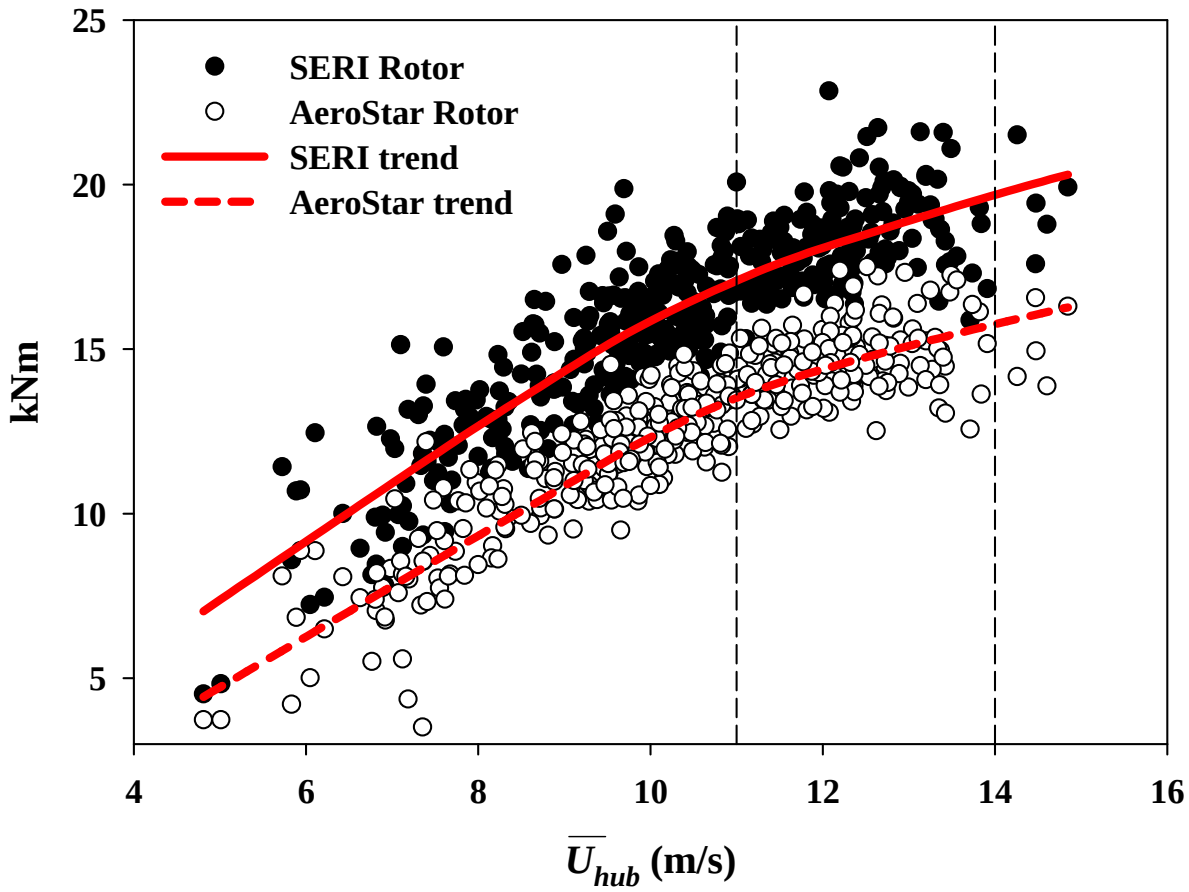
Estimated local vorticity components (rad/sec)



Correlation with Other Turbulence Parameters

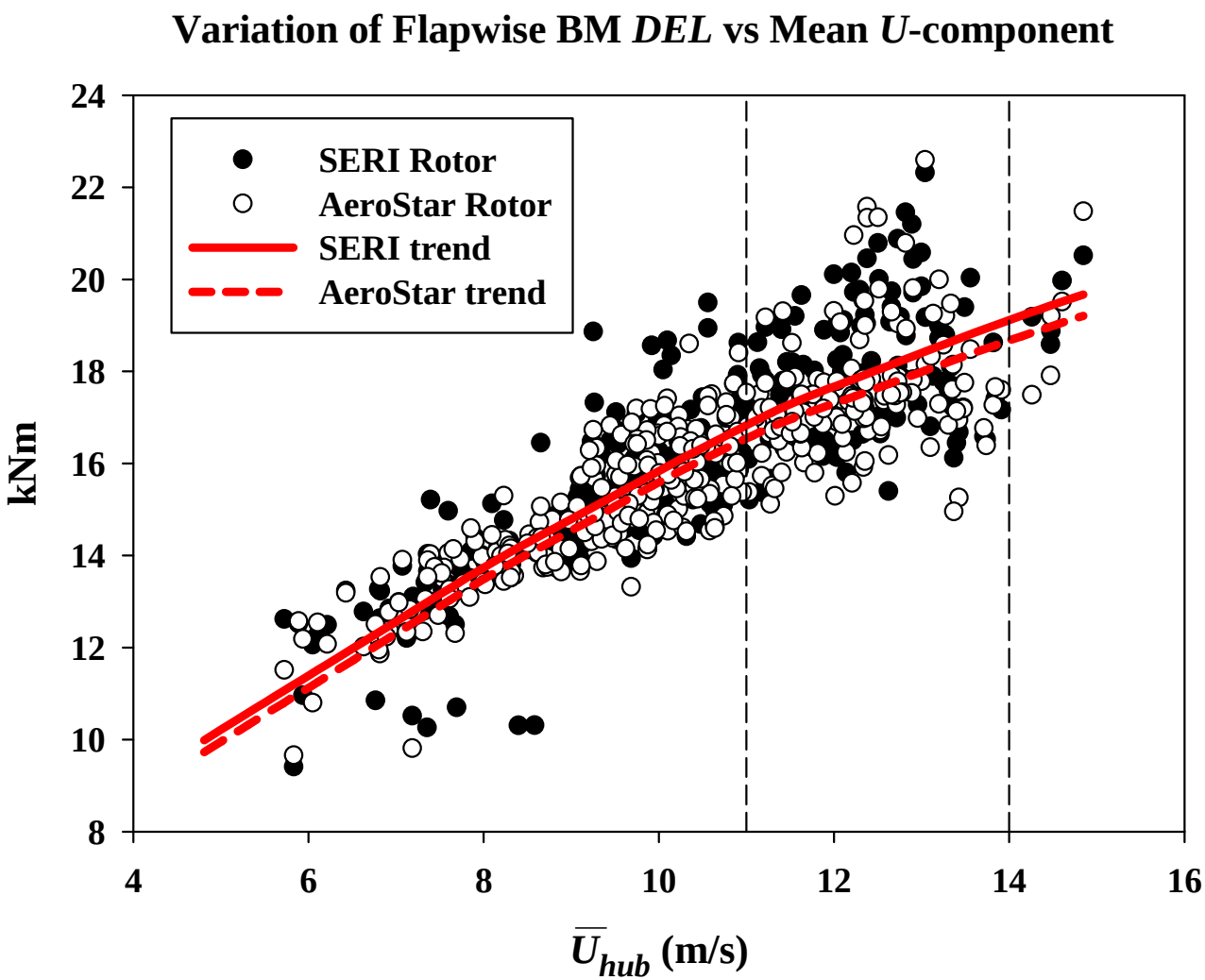
- Correlation analysis of root flapwise bending equivalent loads with a range of turbulence parameters found strong correlations with the following:
  - The mean hub-height wind speed (as would be expected)
  - The hub measurement of $-\boldsymbol{u'w'}$ or its equivalent, u_{*hub}
  - This suggests that large, transient blade loads are often associated with strong downward bursts of organized turbulence
  - A new fluid dynamics parameter is needed that represents the intensity of coherent or organized turbulence that can be correlated with load parameters such as DEL

Variation of 3-Blade Mean Flapwise BM with Hub Mean *U*-component



- Reflects the larger swept area of the SERI rotor
- Underlying response is nearly identical

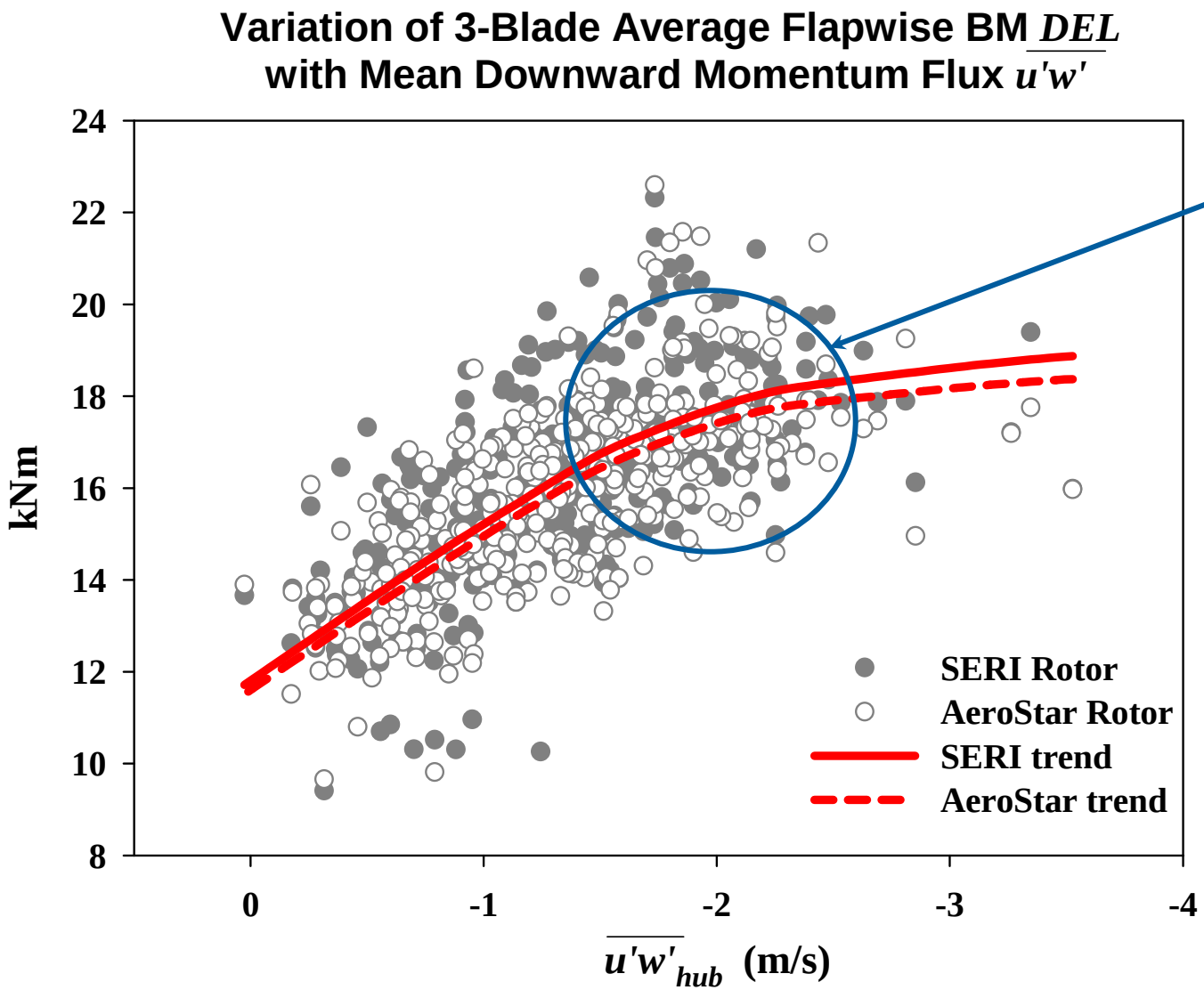
Correlation of Flap *DEL* with U_{hub}



The fatigue response of both rotors is nearly identical except at the highest wind speeds

The slightly lower fatigue of the AeroStar rotor is probably due to its rated wind speed is slightly higher

Correlation of Flap *DEL* with $\overline{u'w'}$



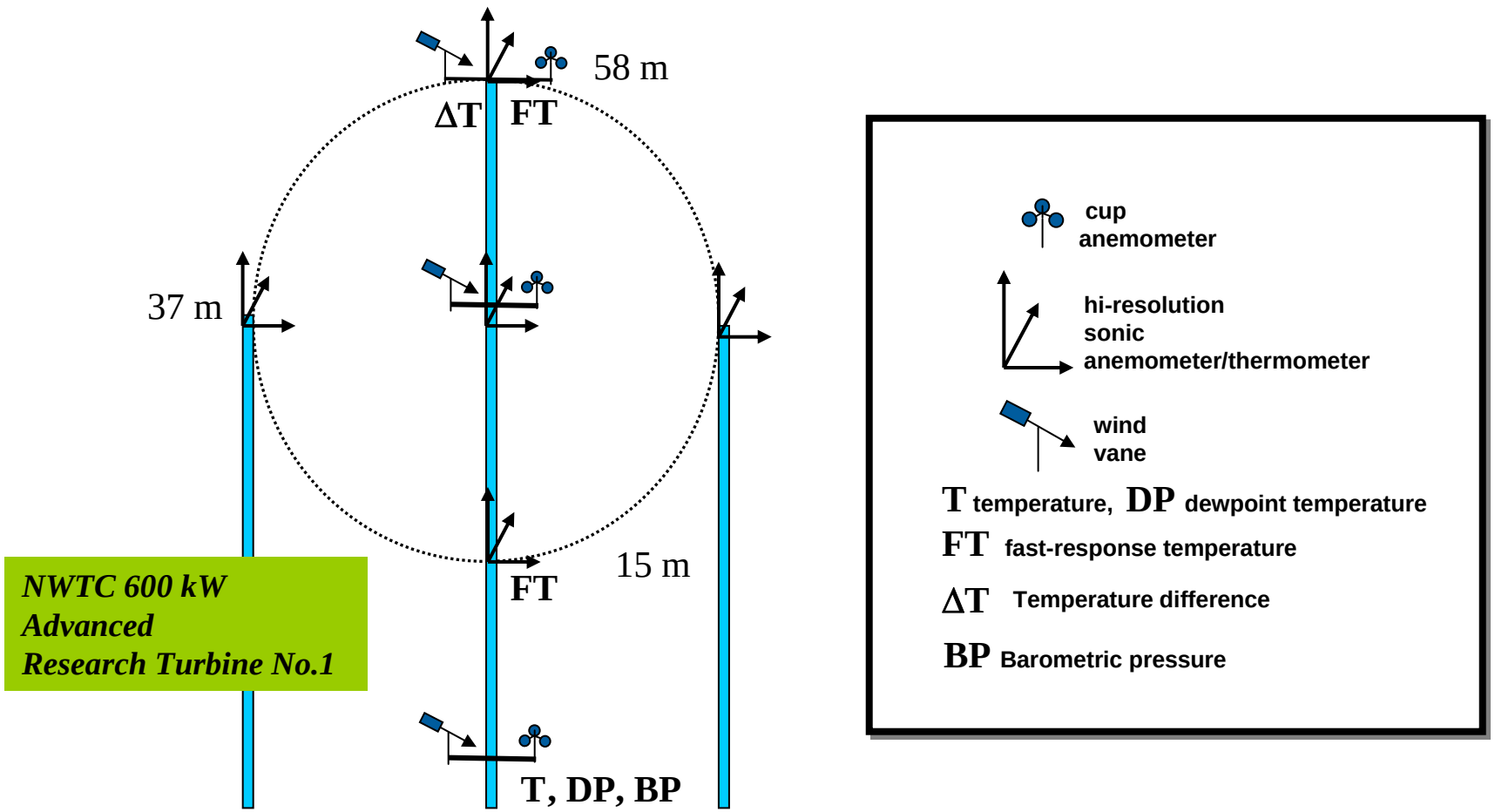
Reflects stall characteristics of rotor blades

Both rotors are responding similarly to downward bursts of organized turbulence

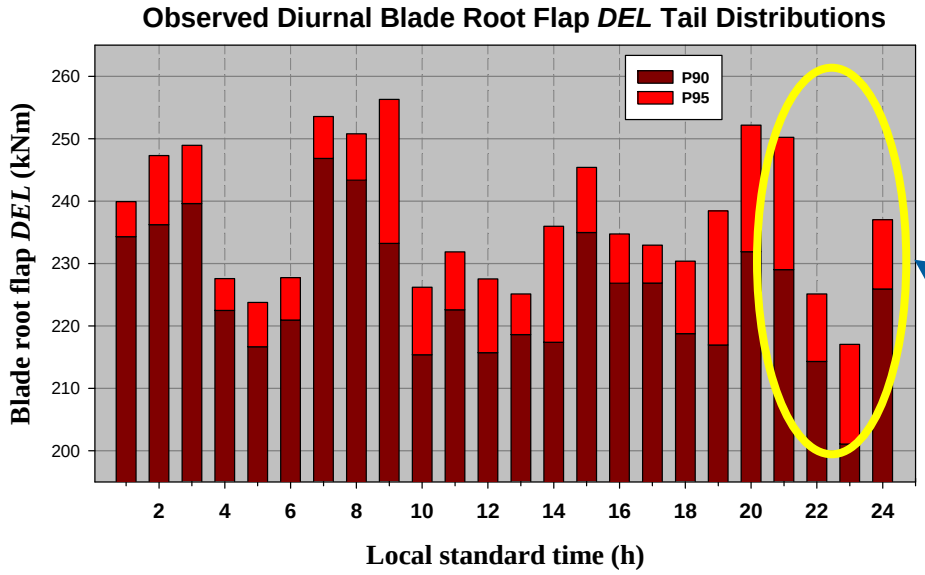
NWTC ART Turbulence-Aeroelastic Response Correlations

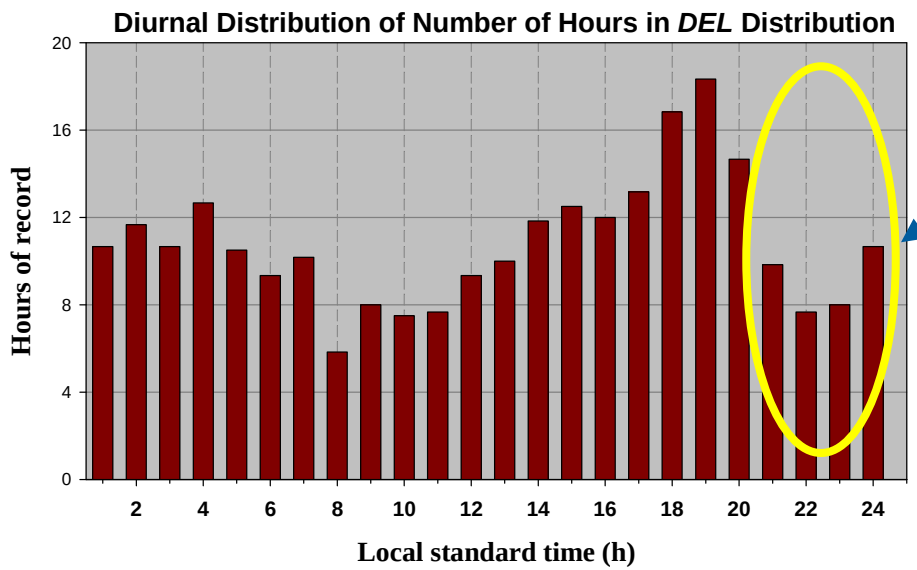
- The ART dataset encompasses a much larger record of inflow conditions that occurred over an entire wind season
- There were no large turbines operating upstream so the response was due to the natural turbulence experienced at the NWTC and not enhanced by the presence of multiple rows of upwind turbines
- Five sonic anemometers were employed in an array upstream of the rotor
- We cross-correlated the root flapwise BM DEL with several inflow parameters

NWTC 43-m Inflow Array



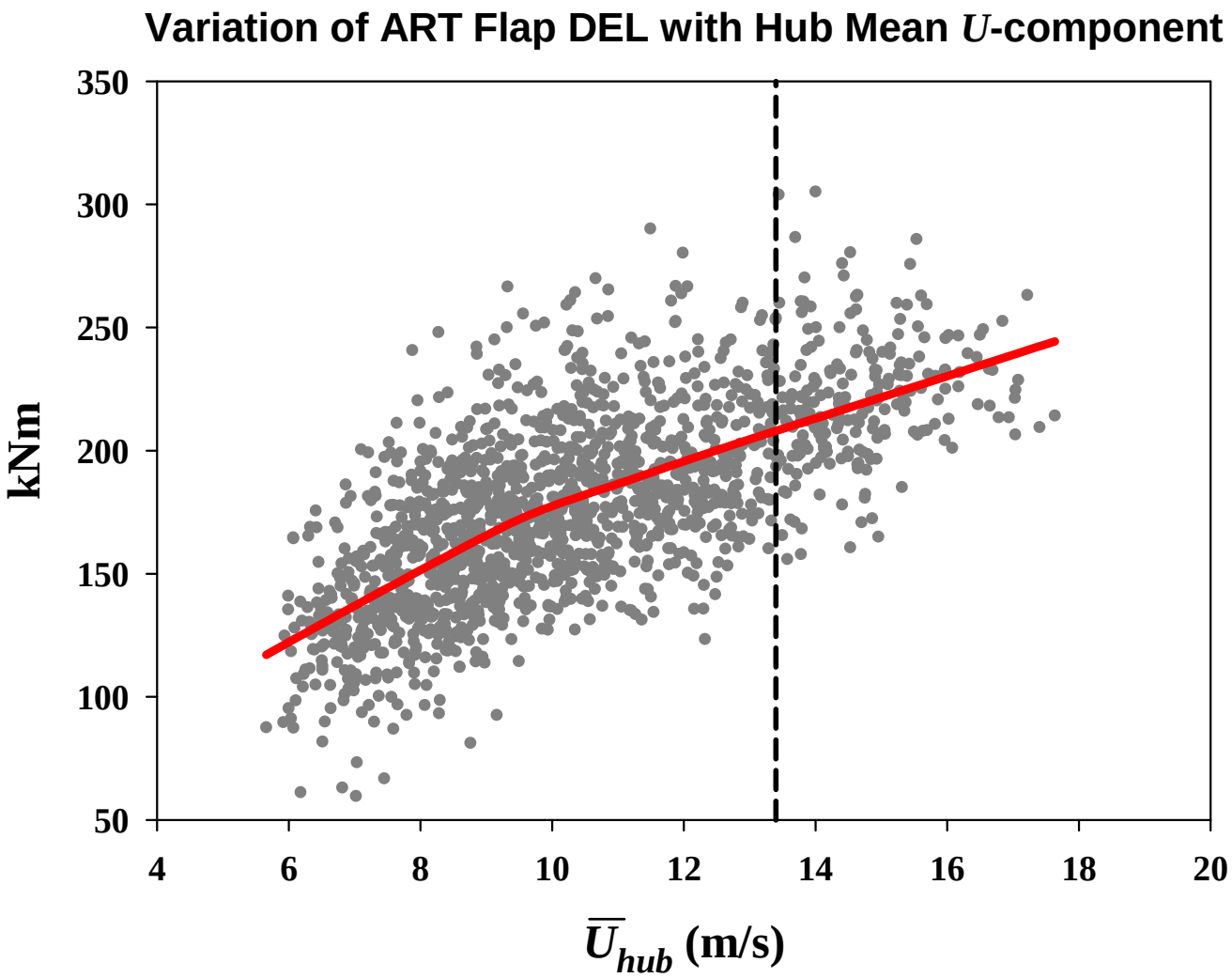
Diurnal Variation of ART High Flap *DELs*



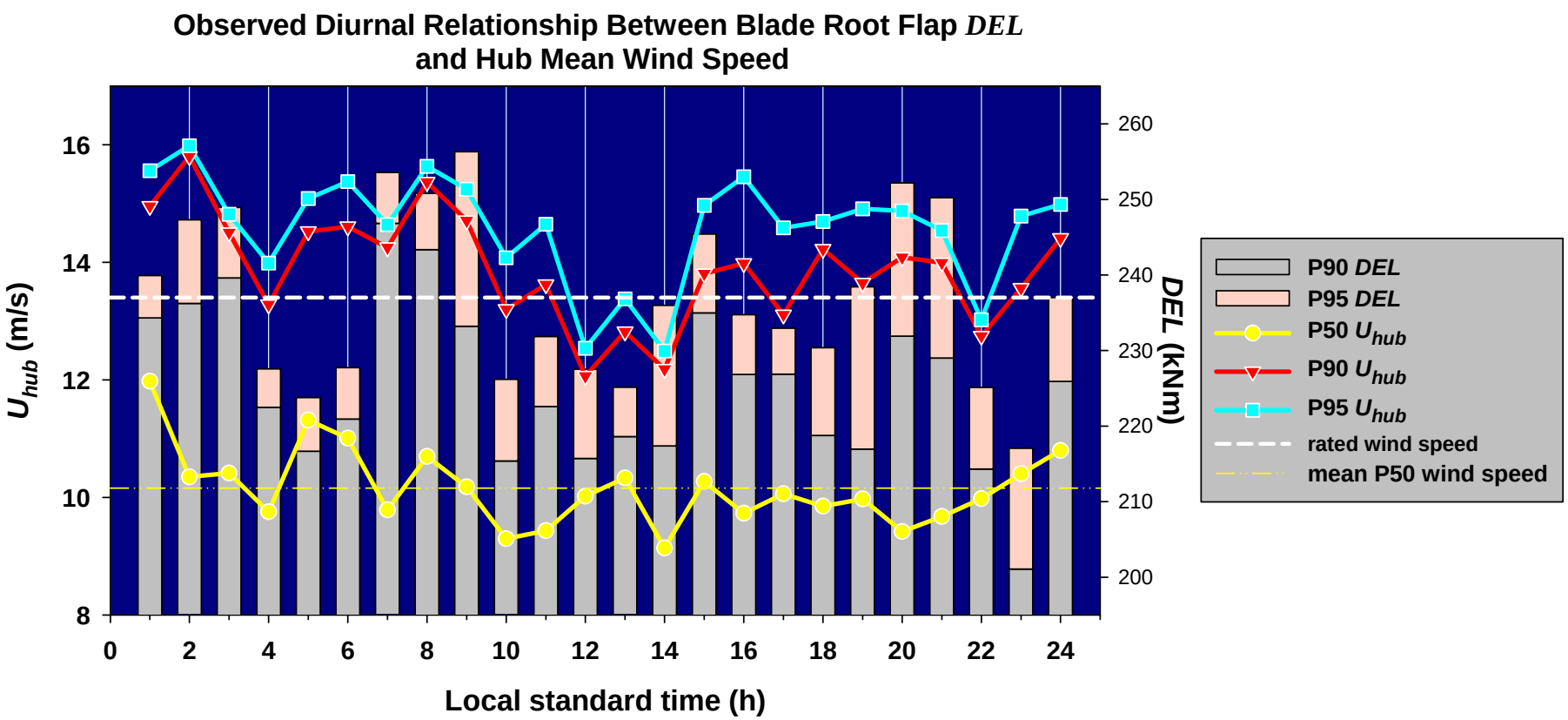


Data loss due to frequent wind speeds above turbine cutout

Correlation of ART Hub *U*-component with Flapwise BM *DEL*

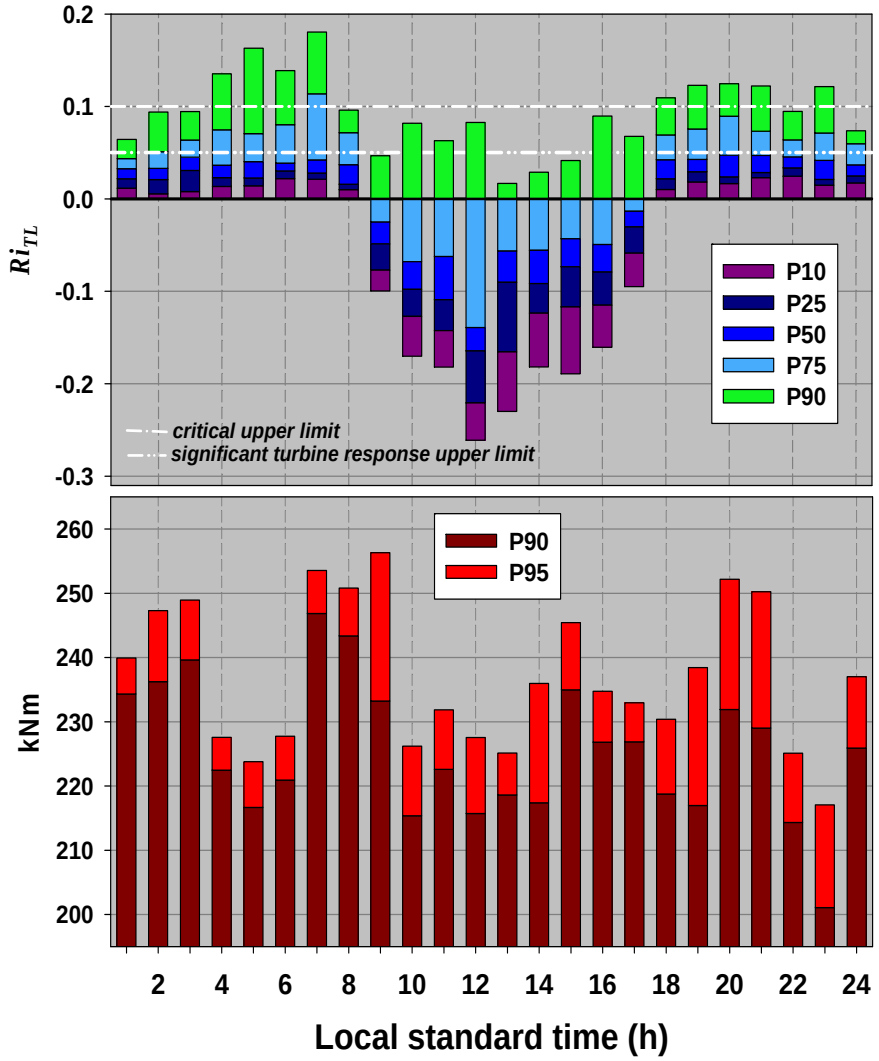


Diurnal Variation of Flap *DEL* and Hub Mean Wind Speed

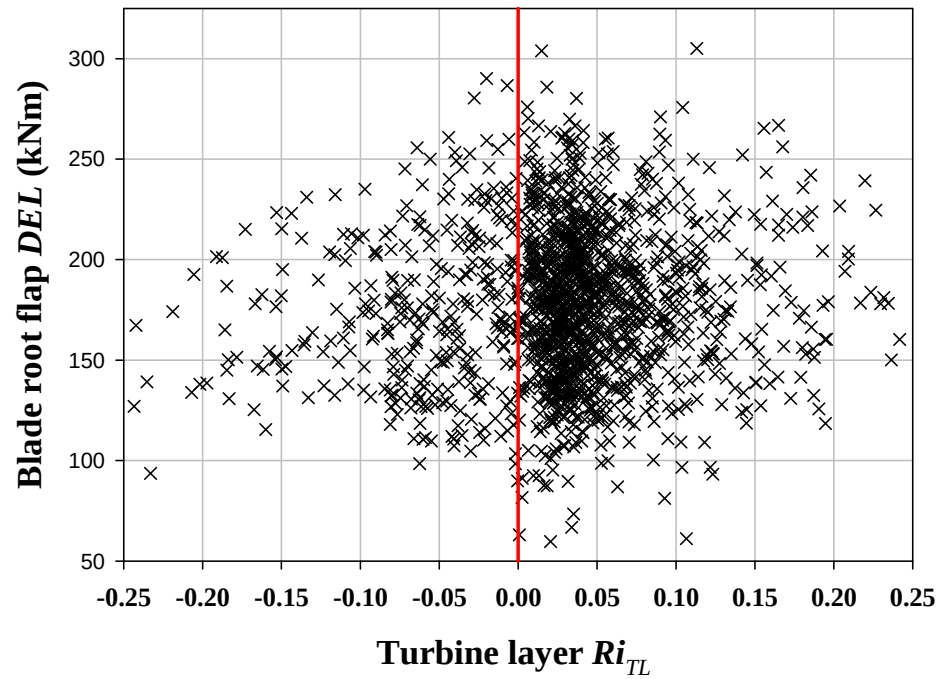


Variation of Root Flap *DEL* with *Ri*

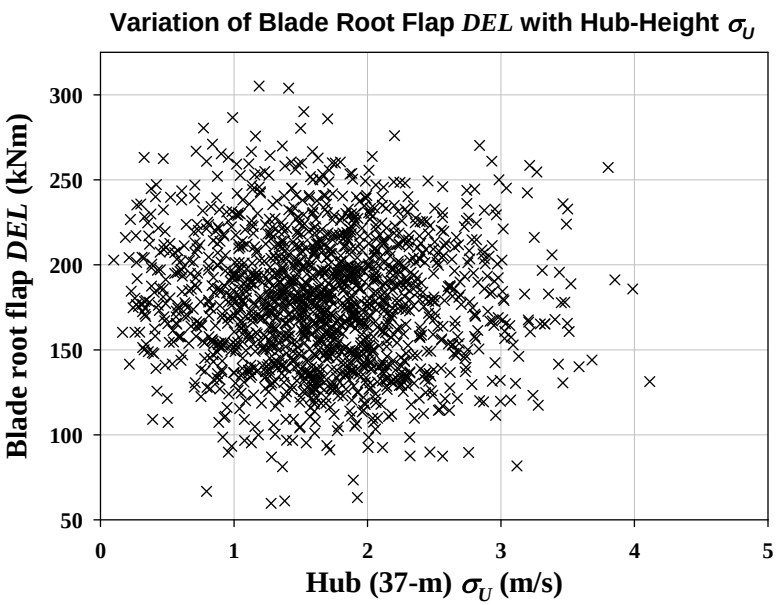
Observed Diurnal Variation of Turbine Layer Ri_{TL} and Corresponding Flapwise Root BM *DEL* Distributions

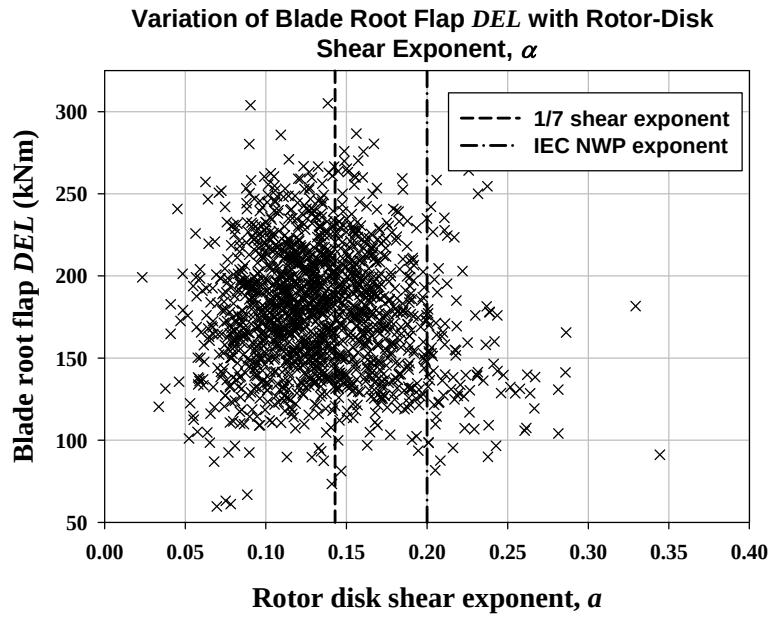


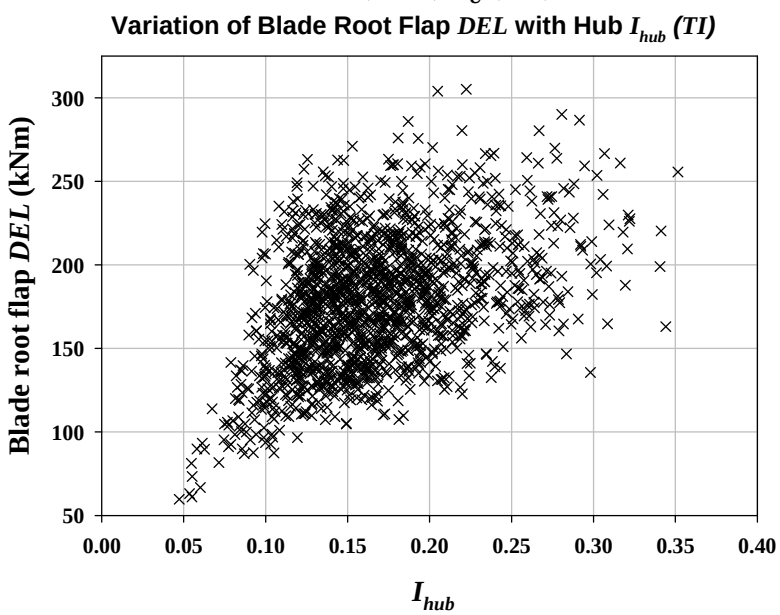
Variation of Blade Root Flap *DEL* with Turbine Layer Ri_{TL}

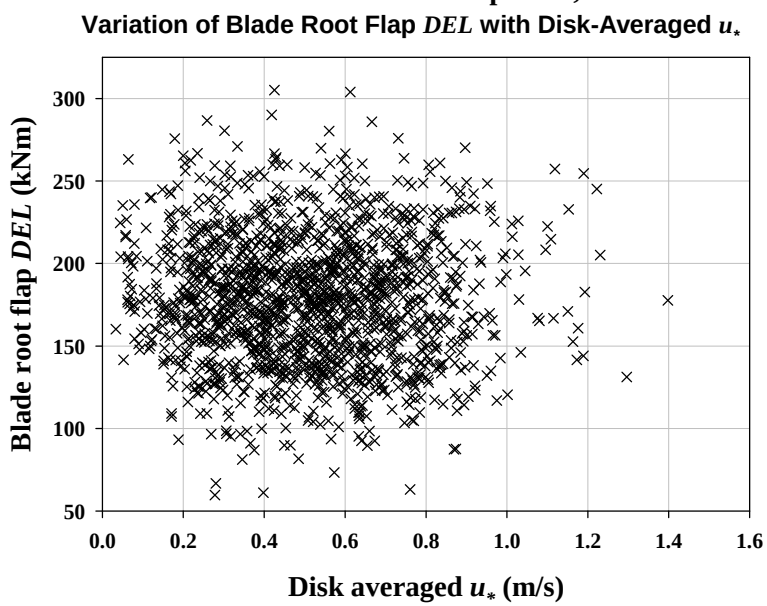


Little or no correlation with the usual suspects

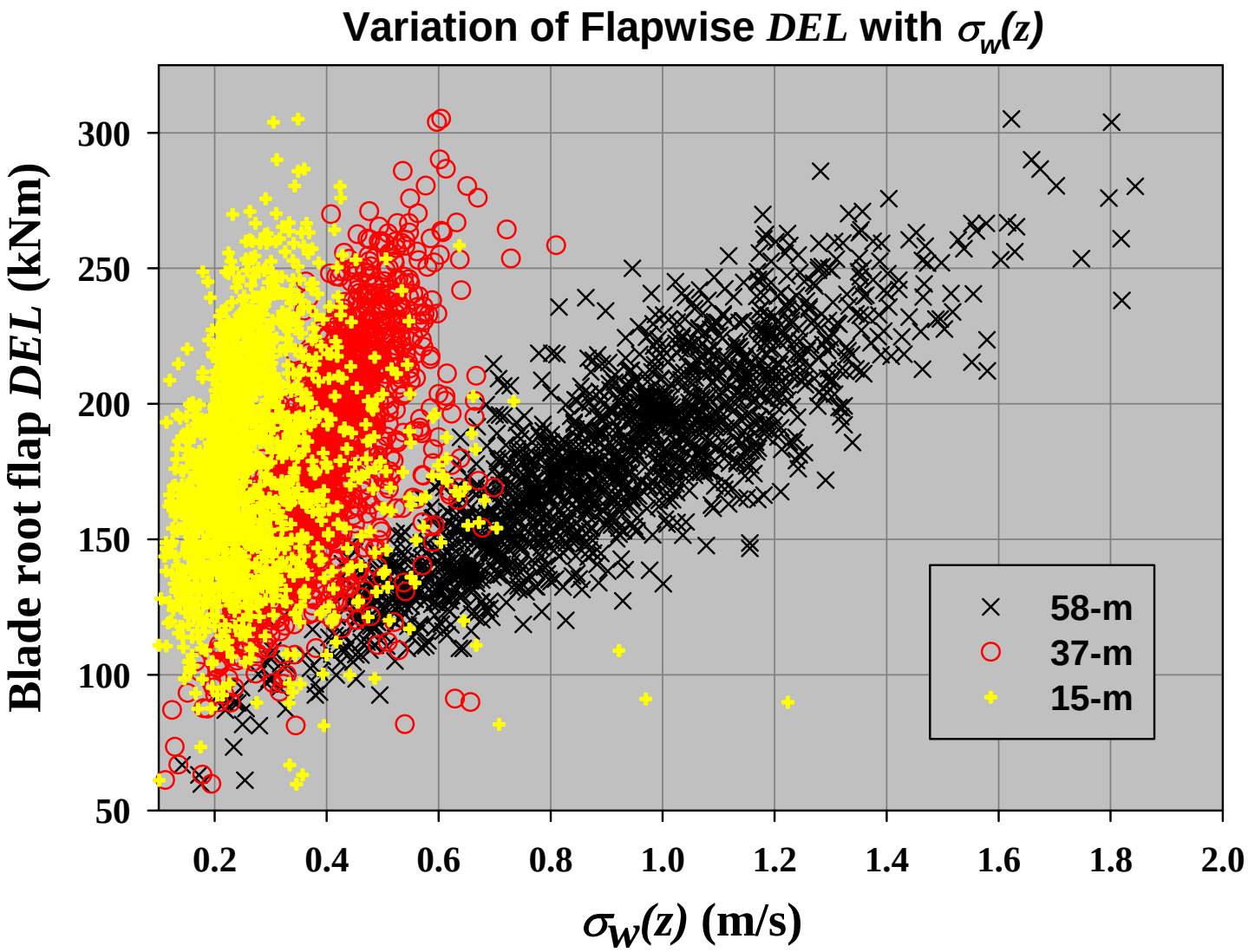




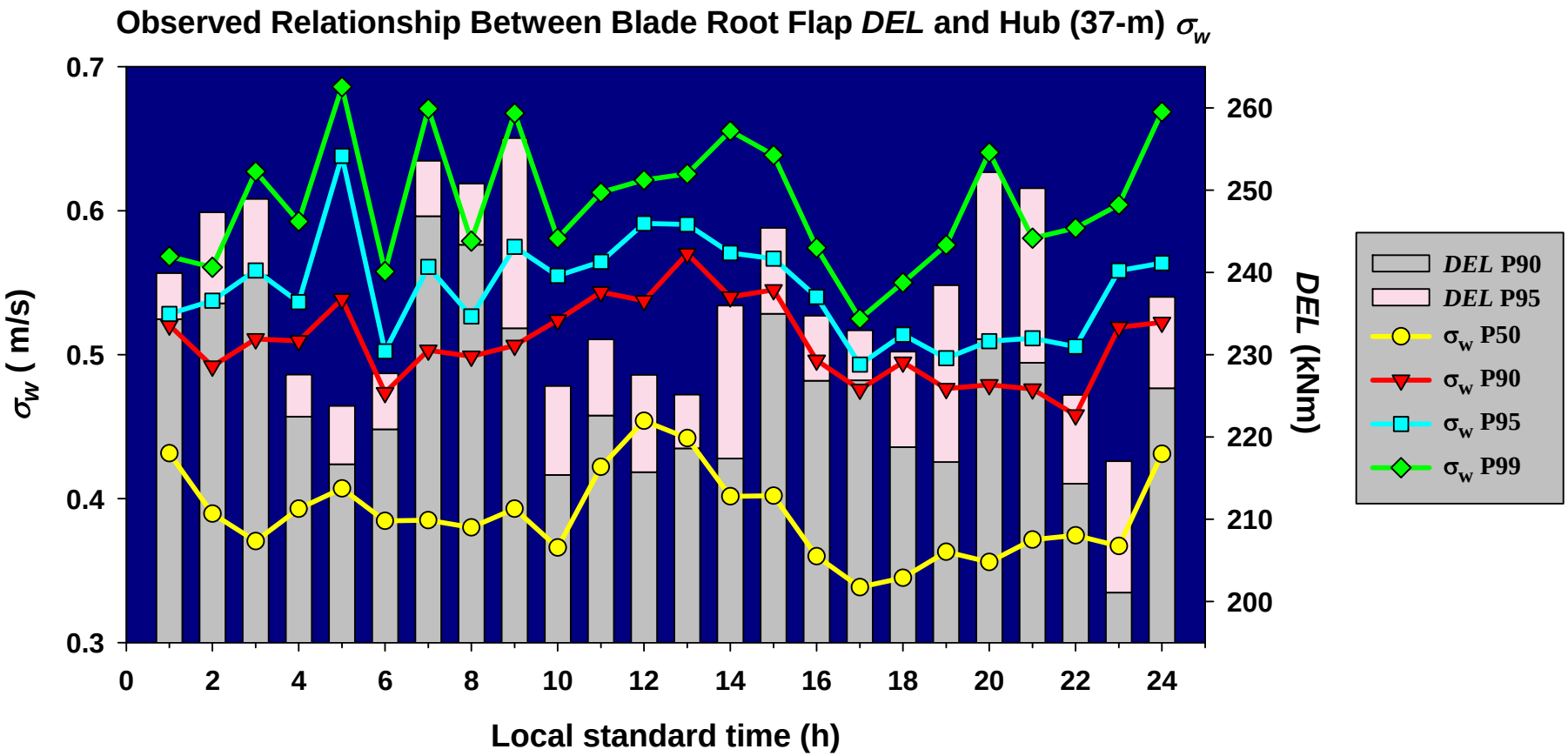




However with the local value of σ_w …



And Diurnally with the Hub value of σ_w . . .



Some Hints

- The strong correlation with the flap DEL and σ_w as a <u>function of height</u> suggests a strong downward transport mechanism is a work at the NWTC.
- The question is what is being transported?
- A detailed examination revealed the existence of intense coherent turbulent structures entering the rotor disk and its upwind measurement array from above.
- Clearly we needed to define a turbulence parameter that reflected the spatial and temporal organization of these structures and their intensity.

Coherent Turbulence Kinetic Energy (*CTKE*)

- Turbulent kinetic energy is defined as

$$TKE = \tfrac{1}{2}\,(\sigma_u^2 + \sigma_v^2 + \sigma_w^2)$$

it says nothing about the correlations between u, v,& w

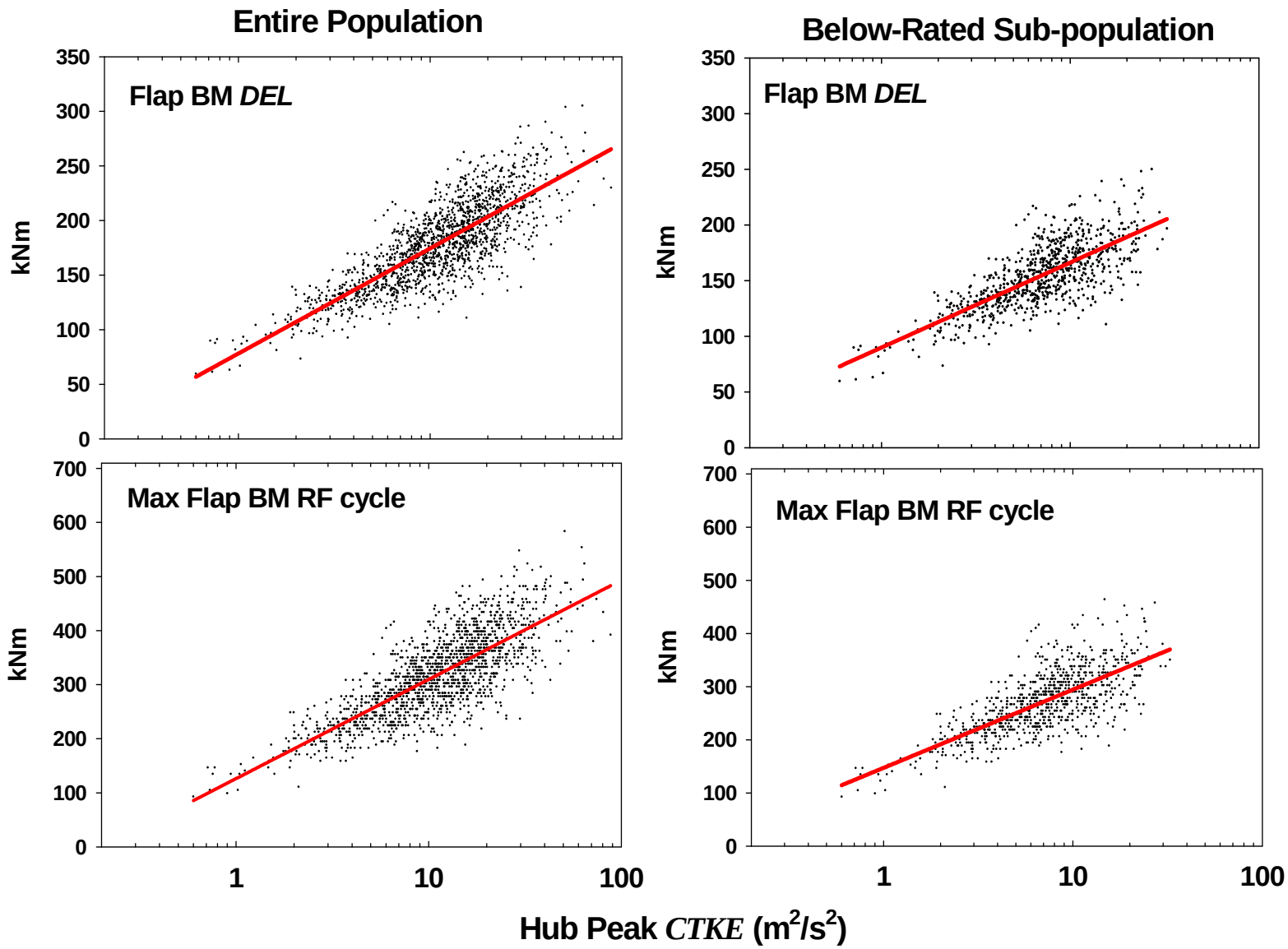
- However the off-axis Reynolds stress components represent the covariance and cross-correlation between these three orthogonal components – $u'w'$, $u'v'$, *and* $v'w'$

- Extending the TKE concept, we define a <u>coherent</u> kinetic energy parameter as

$$CTKE = \tfrac{1}{2}\,[(u'w')^2 + (u'v')^2 + (v'w')^2)]^{1/2}$$

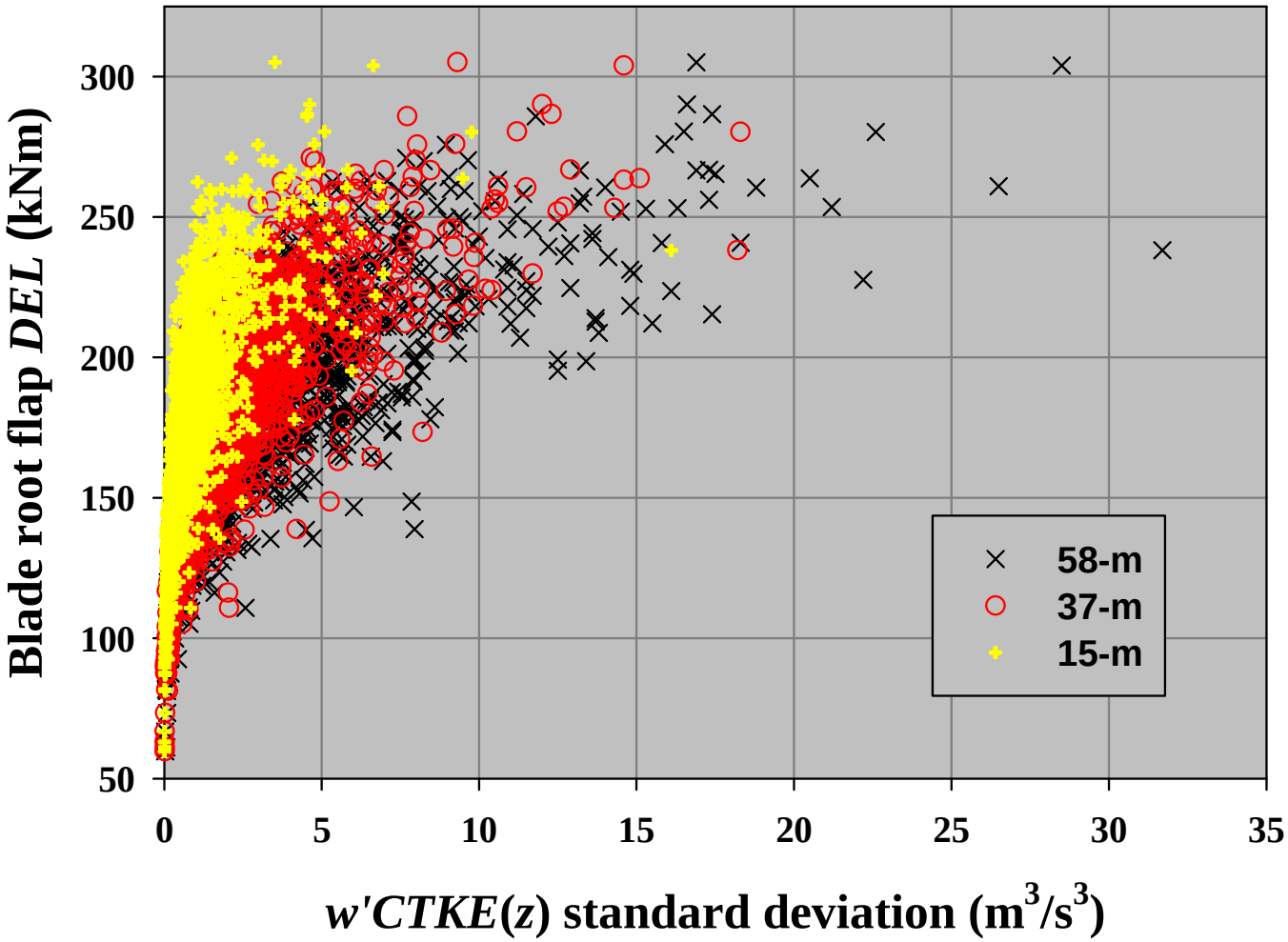
where $CTKE$ is always $\leq TKE$ and is 0 in isotropic flow

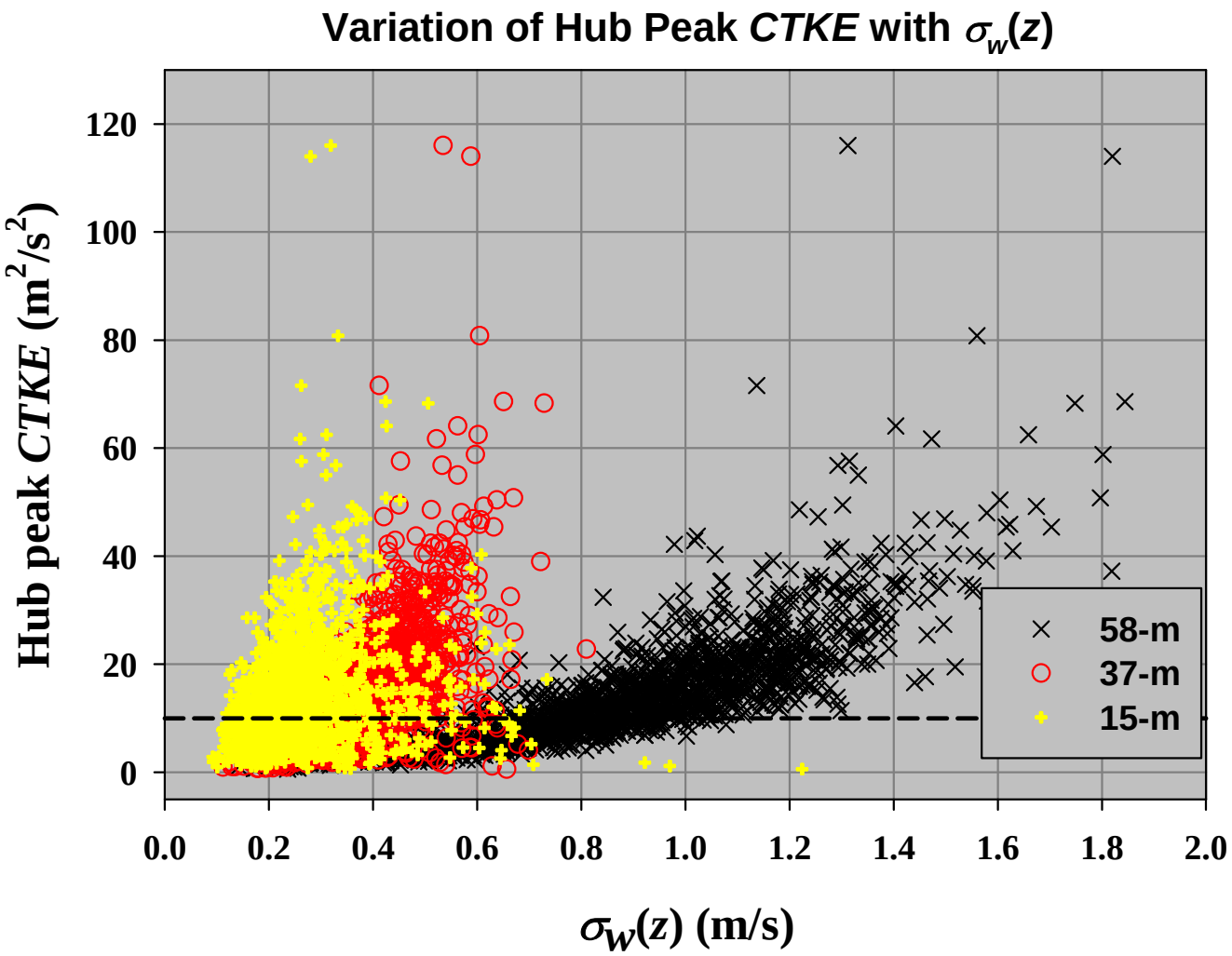
NWTC ART Flap DEL vs pk *CTKE*



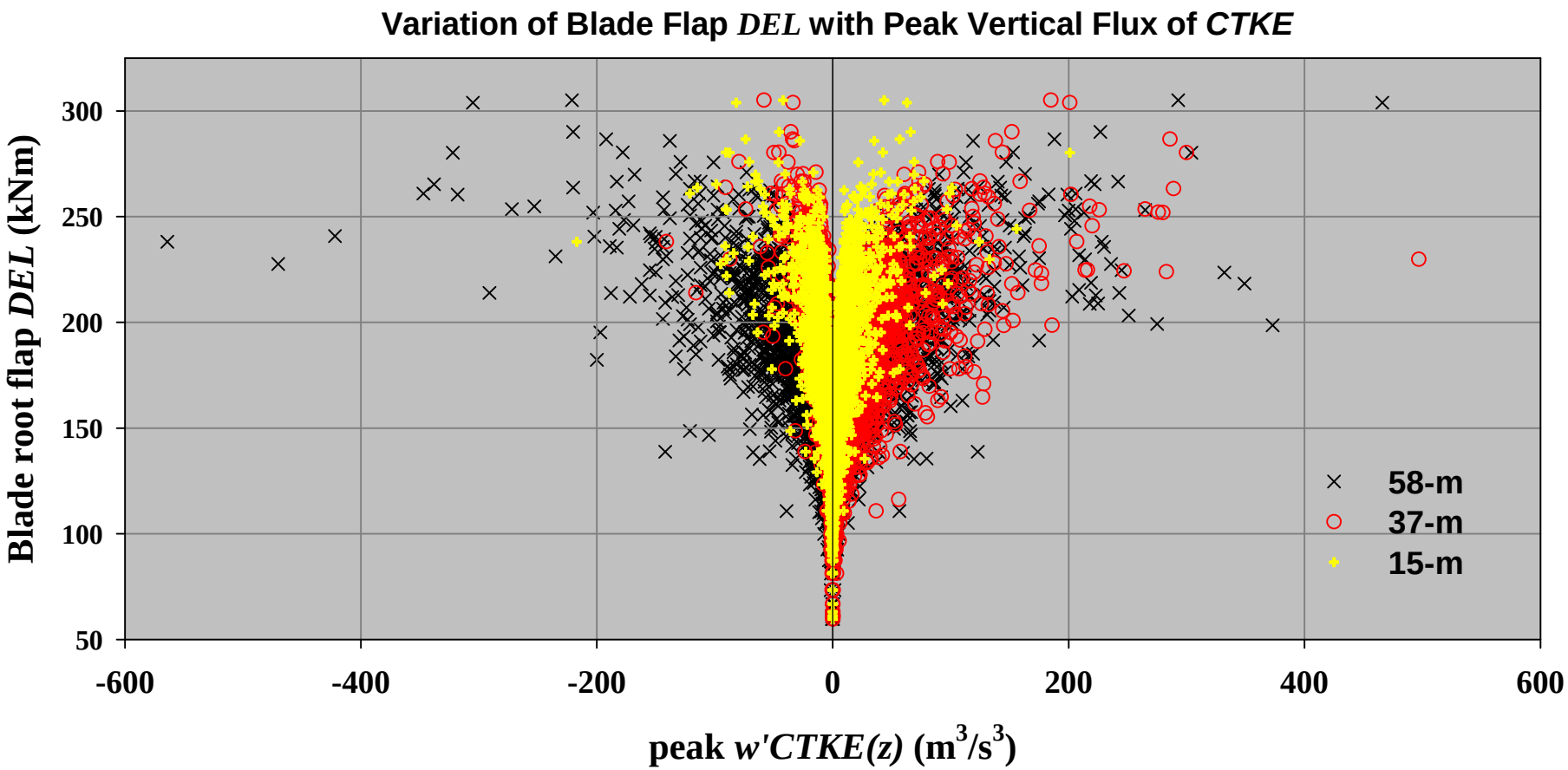
High Blade Fatigue Loads are Induced by Intense, Fluctuating Vertical Transport of *CTKE*

Variation of Flapwise *DEL* with Standard Deviation of Vertical Flux of *CTKE*



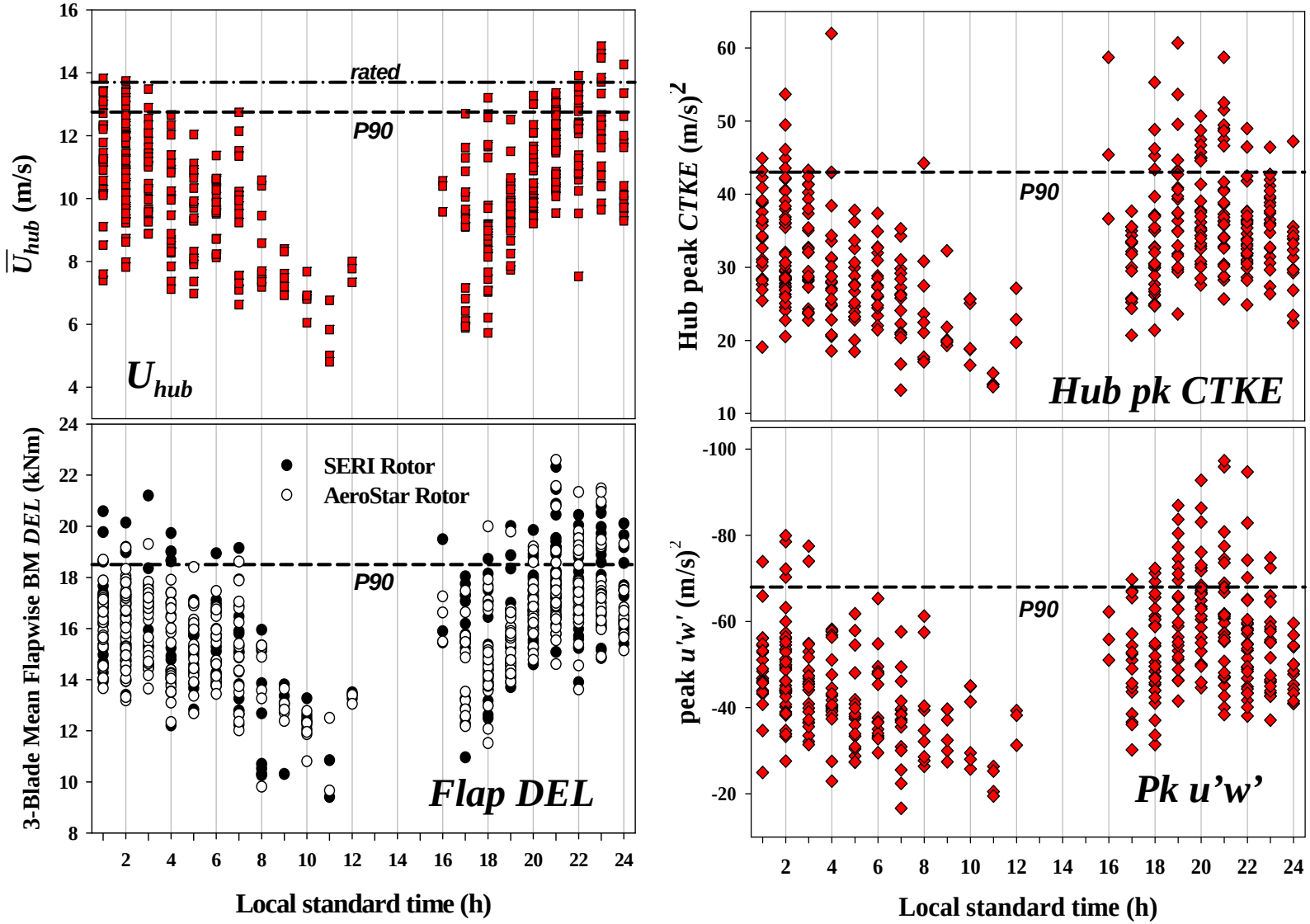

Variation of Hub Peak CTKE with σw(z)
Hub peak CTKE (m2/s2)
120
100
80
60
40
20
0
0.0
0.2
0.4
0.6
0.8
1.0
1.2
1.4
1.6
1.8
2.0
σw(z) (m/s)
58-m
37-m
15-m

Vertical Flux of pk *CTKE* by Height



Indicates strong vertical transport of coherent turbulence is taking place at NWTC

San Gorgonio Diurnal Variations of Flap *DEL* and Inflow Parameters



CTKE – cont'd

- *CTKE* is easy to measure with the three-axis sonic anemometers we have used to measure the turbulent properties of the inflows to the San Gorgonio Micon 65 turbines and the NWTC ART.
- On the average, the ratio of *CTKE*/*TKE* is about 0.4 but it can range from 0.2 to 0.9.
- *CTKE* represents the intensity of turbulent coherent elements in the flow as they pass through the measurement volume of a sonic anemometer.

Our Conclusions Are …

- The largest turbine fatigue loads are primarily associated with ***slightly stable conditions*** within a narrow range of the turbine-layer gradient ***Ri*** stability parameter
- They are often not associated with the high values of σ_U or turbulence intensity ($\sigma_U/\overline{U}$)
- The vertical transport of coherent turbulence energy from above and within the wind farm rotor disk layer is a major contributor to high fatigue loads.
- It is important when simulating turbine inflow turbulence to include the ability to (1) model a range of stability conditions and (2) develop a method to include organized, turbulent structures.

Problem:

- Modern multi-megawatt turbines often operate their rotors simultaneously in both the surface and mixed layers
- No consensus on the best way to scale turbulence in this layer. Some form of a combination of SL and local scaling is generally used
- We have found that the average height of the SL is the order of 50-60 m and higher during the day and lower at night
- We have scaled it in our TurbSim code from actual measurements taken at two locations: the NWTC Test Site and Lamar, Colorado

Defining Additional Flow Variables for Coherent Turbulence

- We would like a single variable that reflects the intensity of highly correlated turbulent structures seen in the three cross-axis Reynolds stresses