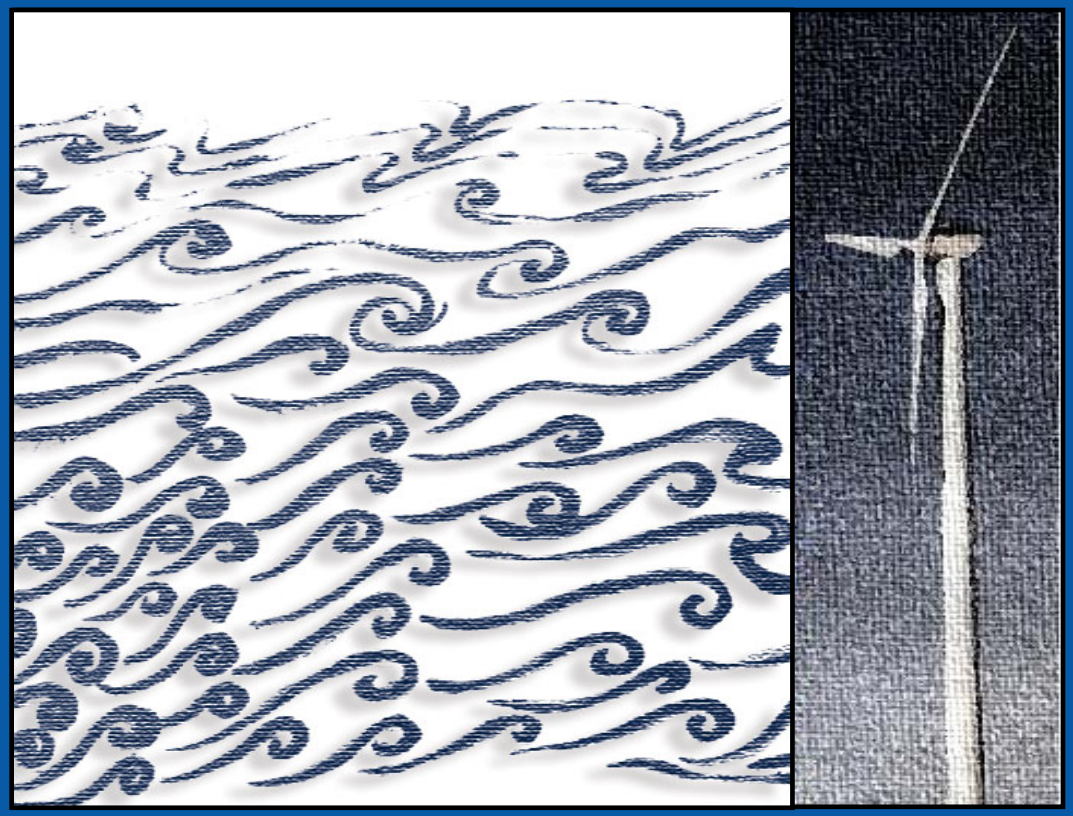
National Renewable Energy Laboratory
Innovation for Our Energy Future

TurbSim Workshop: Turbulence Characteristics that Influence the Dynamic Response of Wind Turbines



National Wind Technology Center

Neil Kelley

September 22-24, 2008

The Details of Coherent Turbulence Generation in the Stable ABL or SBL

- The weakly stable conditions that we have shown to be present for high rotor loading events indicate the possible presence of Kelvin-Helmholtz Instability or KHI.
- This type of dynamic instability is ubiquitous in the nocturnal boundary layer (NBL) and many believe it is the principal mechanism responsible for turbulent mixing in the NBL.
- Its requirements are strong vertical wind speed shear and a positive temperature gradient (a temperature inversion). A gradient Ri between 0 and +0.25 is necessary.

The Details of Coherent Turbulence Generation in the Stable ABL or SBL – cont'd

• If an air parcel (like the one in the early animated demonstration) is displaced vertically in a stably stratified boundary layer its motion is described by

$$\delta z(t) = Ae^{iNt} + Be^{-iNt} \quad where\ N = \sqrt{\frac{g}{\theta}\frac{\partial\theta}{\partial z}}$$

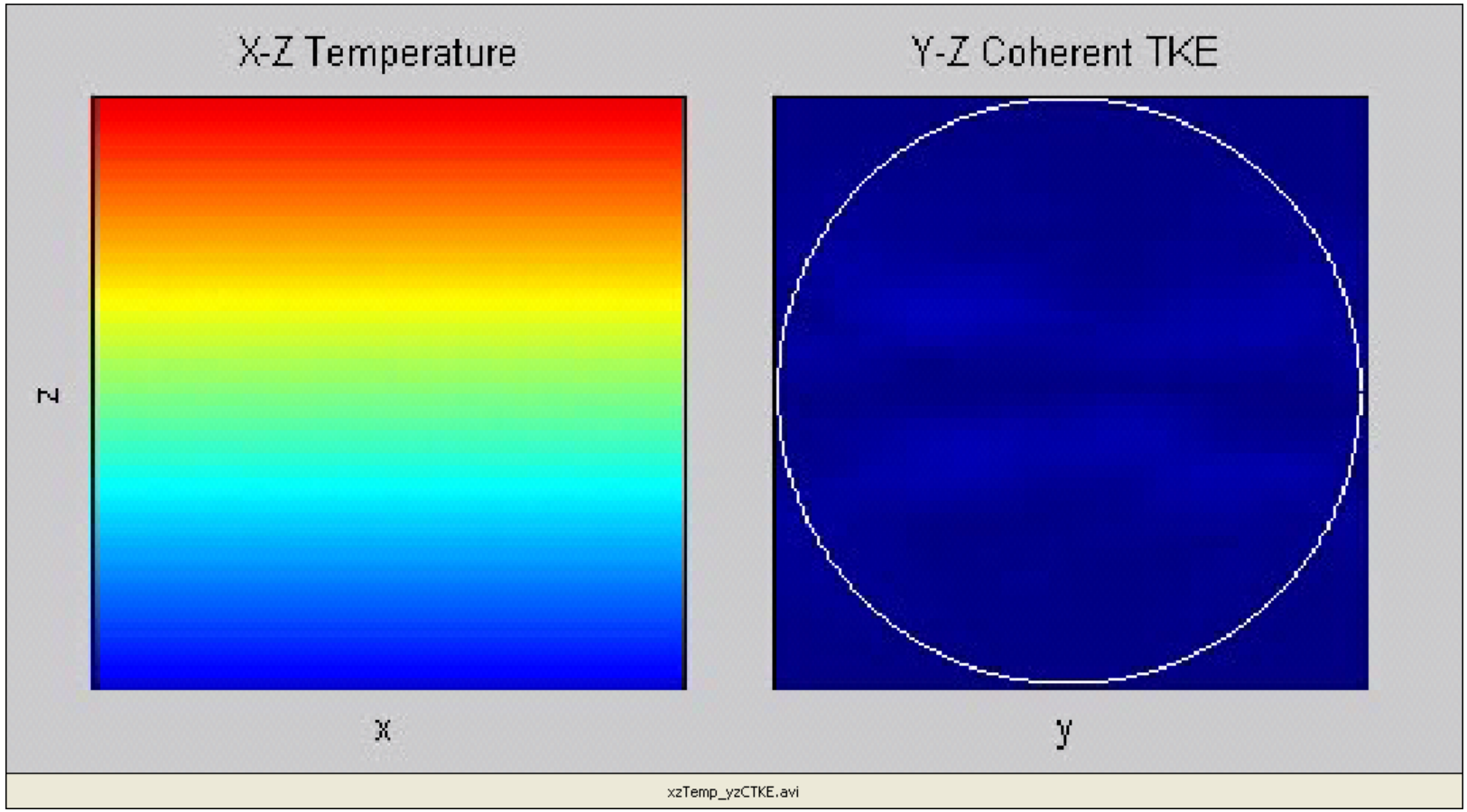
where N is the frequency at which the air parcel will oscillate. The relationship between Ri and buoyancy oscillations can be seen by

$$Ri = (g/\theta)(\partial\theta/\partial z)/(\partial U/\partial z)^2 = N^2(\partial U/\partial z)^2$$

Typically there are a range of oscillating frequencies active for a given situation.

• The National Center for Atmospheric Research (NCAR) developed an LES numerical simulation of the life cycle of a stationary KHI-induced billow flow formation for NREL. We have used this simulation as a mechanism to insert coherent turbulent structures in the TurbSim Code.

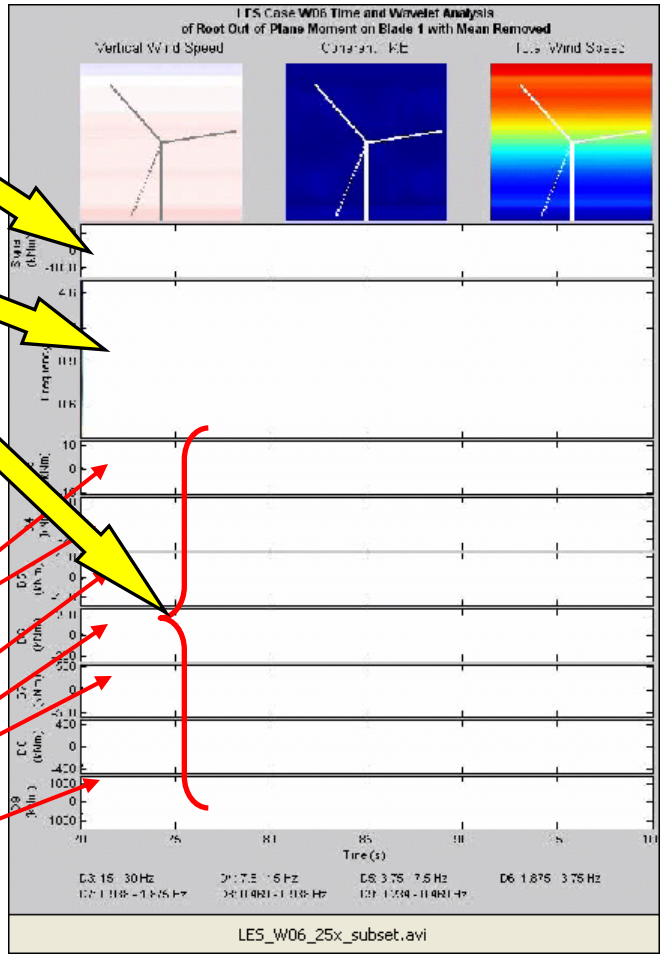
The NCAR KH Billow Simulation

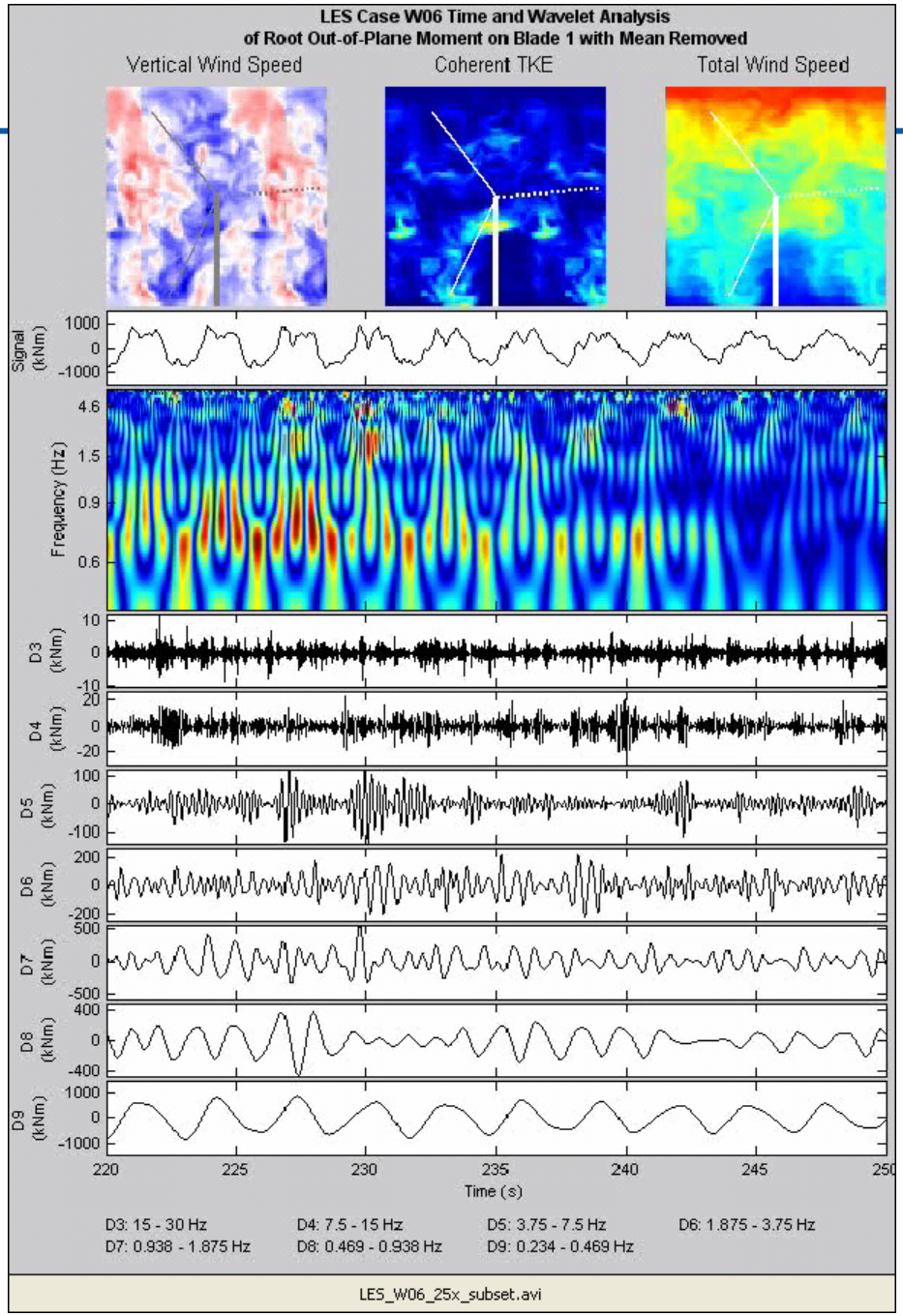


Using Wavelet Analysis to Observe a Time-Frequency Variation of Blade Root Loads Induced by Coherent Turbulence from a Simulated KH Billow Breakdown

Using Wavelet Analysis to Observed Turbulence Rotor Interaction

- Blade root flapwise load time series
- Scalogram showing dynamic stress levels as a function of time and frequency
- Time series of root loads in 7 frequency (detail) bands using the discrete wavelet transform
  - Detail band frequency ranges roughly correspond to groups of modal frequencies including . . .
    - D3 (15.00 – 30.00 Hz) = blade bending/torsion/tower
    - D4 (7.500 – 15.00 Hz) = blade/tower interactions
    - D5 (3.750 – 7.500 Hz) = blade bending/torsion/tower
    - D6 (1.875 – 3.750 Hz) = blade, tower bending modes
    - D7 (0.936 – 1.875 Hz) = blade 1st bending modes
    - D9 (0.234 – 0.468 Hz) = 1-P, tower 1st bending mode




LES Case W06 Time and Wavelet Analysis
of Root Out-of-Plane Moment on Blade 1 with Mean Removed
Vertical Wind Speed
Coherent TKE
Total Wind Speed
Signal (kNm)
Frequency (Hz)
D3 (kNm)
D4 (kNm)
D5 (kNm)
D6 (kNm)
D7 (kNm)
D8 (kNm)
D9 (kNm)
Time (s)
D3: 15 - 30 Hz
D4: 7.5 - 15 Hz
D5: 3.75 - 7.5 Hz
D6: 1.875 - 3.75 Hz
D7: 0.938 - 1.875 Hz
D8: 0.469 - 0.938 Hz
D9: 0.234 - 0.469 Hz
LES_W06_25x_subset.avi

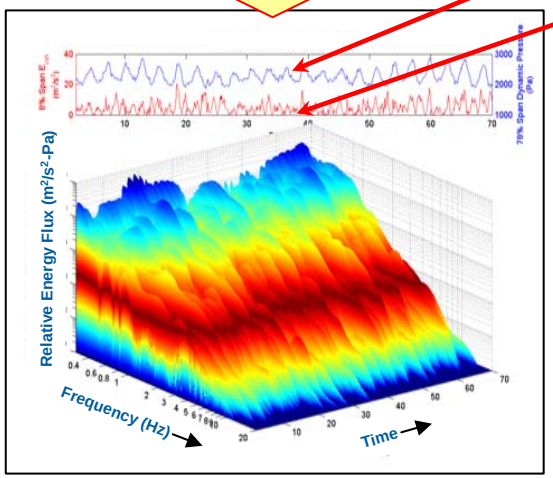
Coherent structures produce higher frequency loading

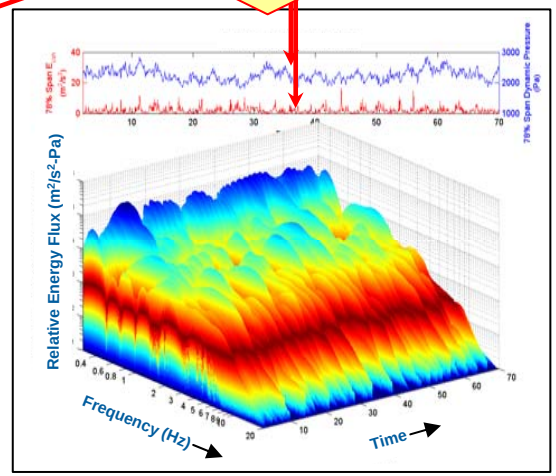
Energy Flux from Coherent Turbulence (CTKE) to Blade Dynamic Pressure at 78% Span Under Three Inflow Conditions

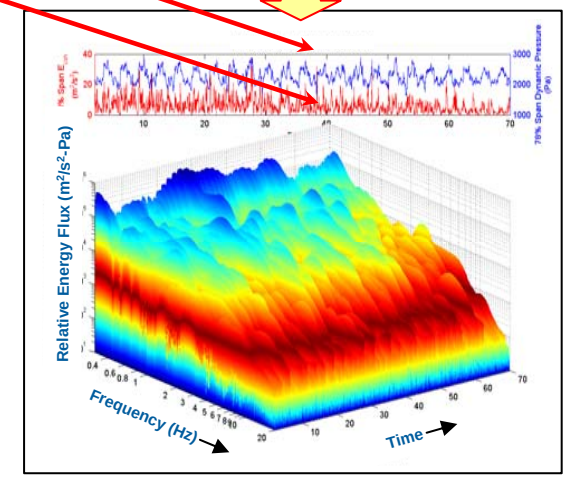
Wavelet Continuous Transform Co-Scalograms of CTKE and q_c

Dynamic Pressure, q_c Time Series

CTKE Time Series







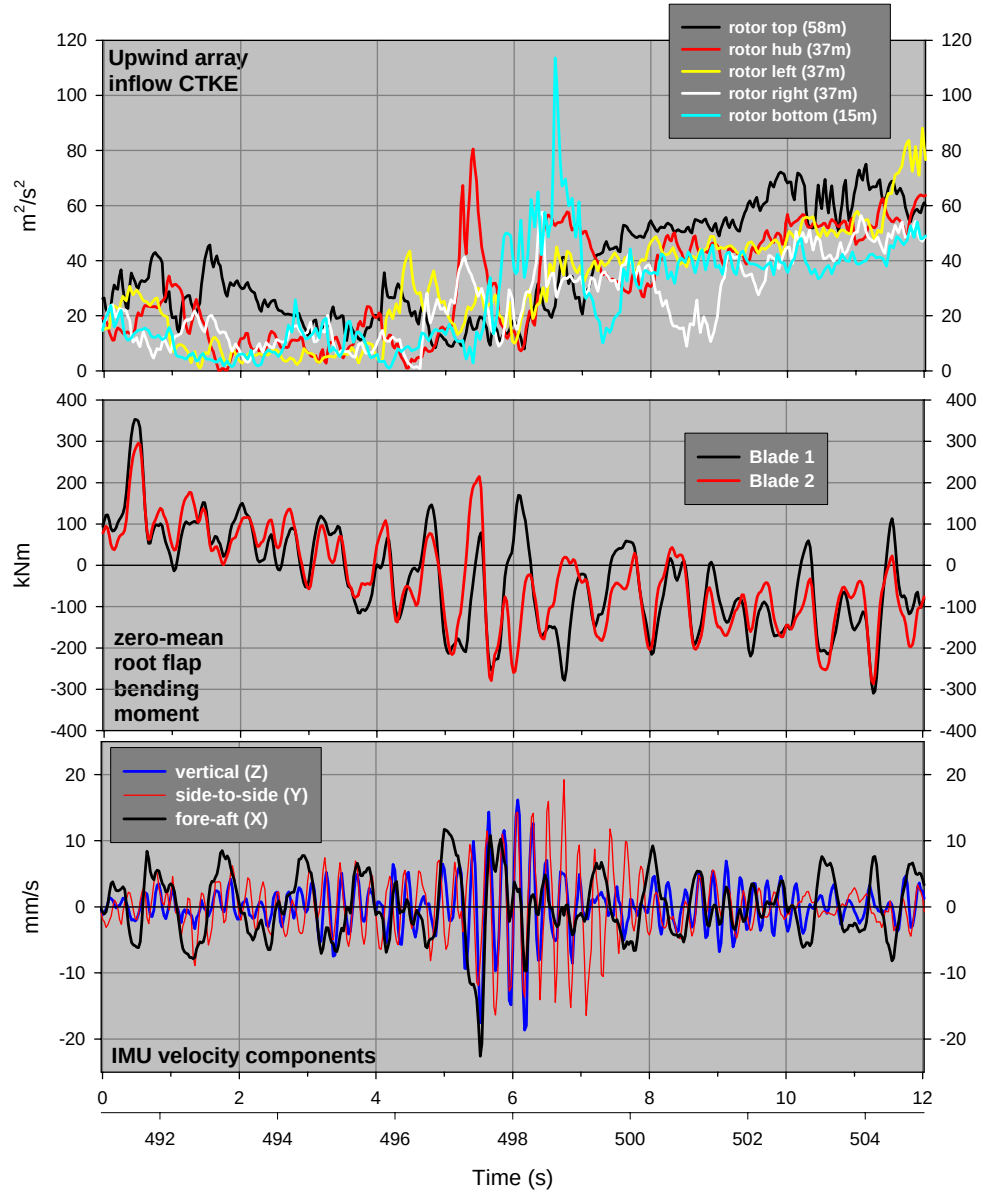
- Steady, High Shear (α = 1.825)
- Slightly stable (*Ri* = + 0.05)
- Steady, equilibrium flow conditions

- IEC Kaimal NTM (α = 0.2)
- Neutral stability (*Ri* = 0)
- Steady, equilibrium flow conditions

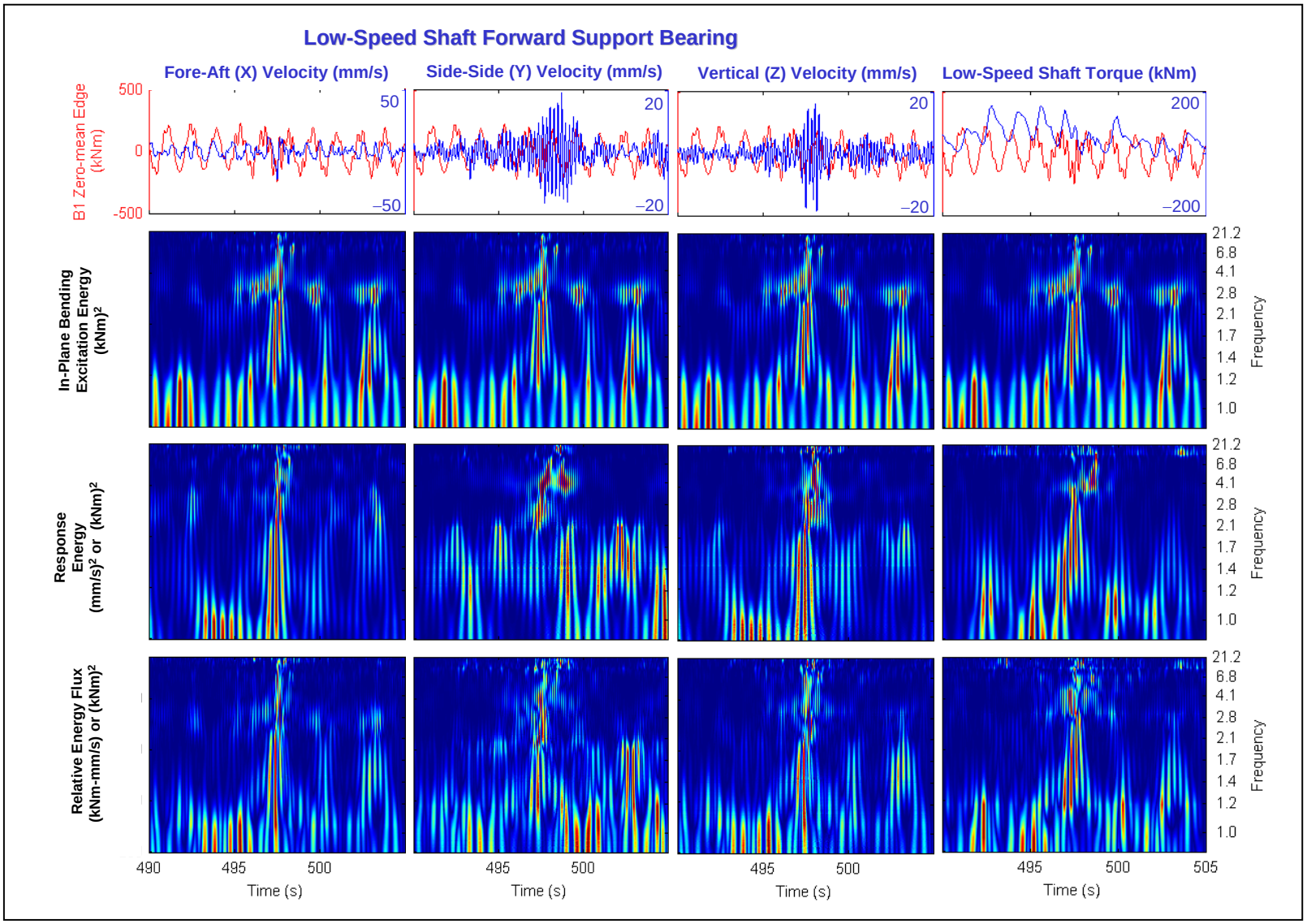
- Breaking KH Billow (α_o = 1.825)
- Slightly stable (*Ri* = +0.05)
- Unsteady, <u>non-equilibrium</u>, flow conditions

Actual Measurement of Coherent Structure and ART Turbine Interaction

- ***CTKE*** measurements from five sonic anemometers on upwind array
- Flapwise root bending measurements
- X-Y-Z velocity measurements from Inertial Measure Unit mounted on low-speed shaft forward billow block immediately behind turbine rotor

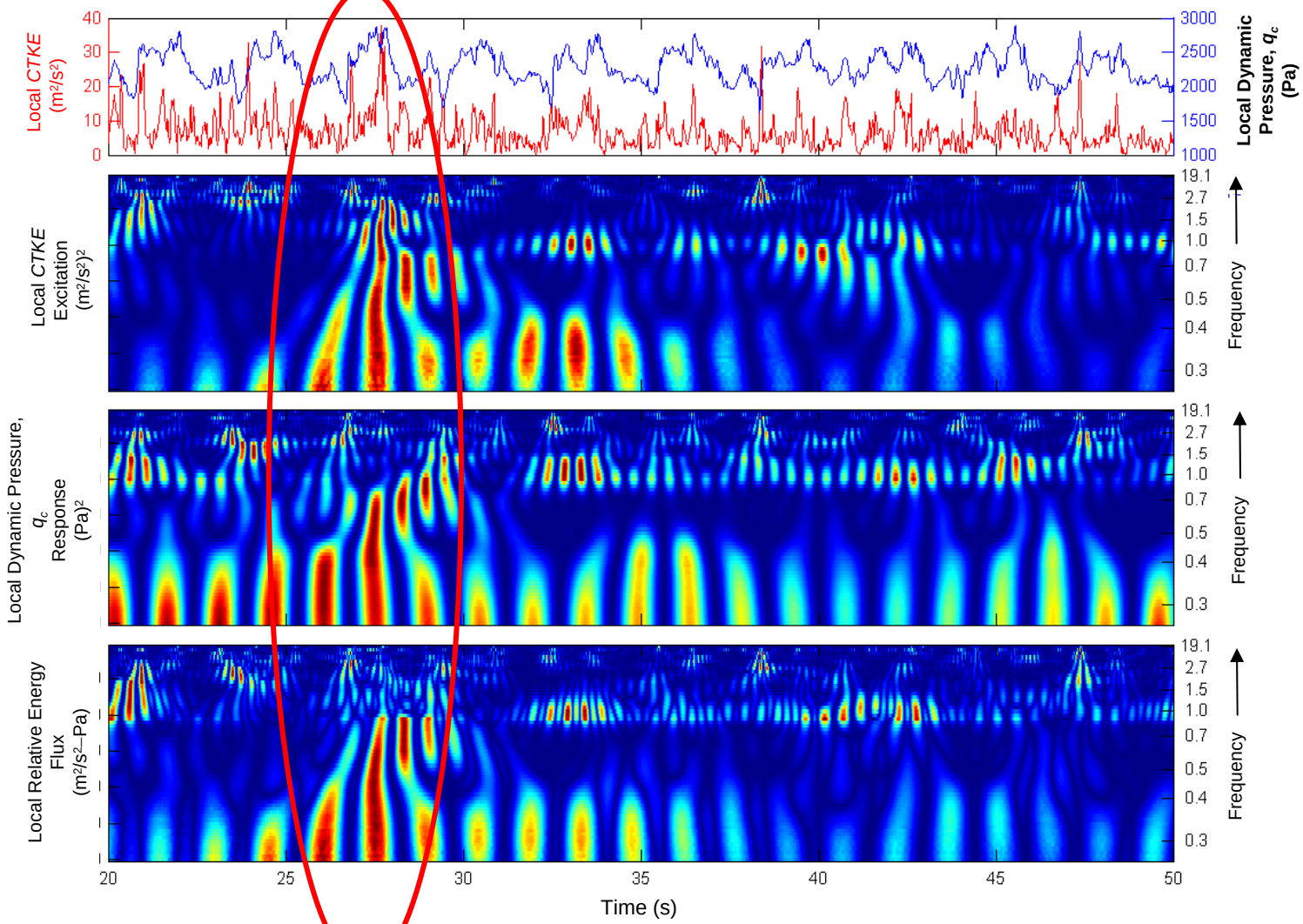


Energy Flux from Coherent Structure to ART Drivetrain



TurbSim Coherent Structure Interaction Simulation

WindPact 1.5 MW Virtual Turbine



Energy flux from turbulence to 78% span blade q_c

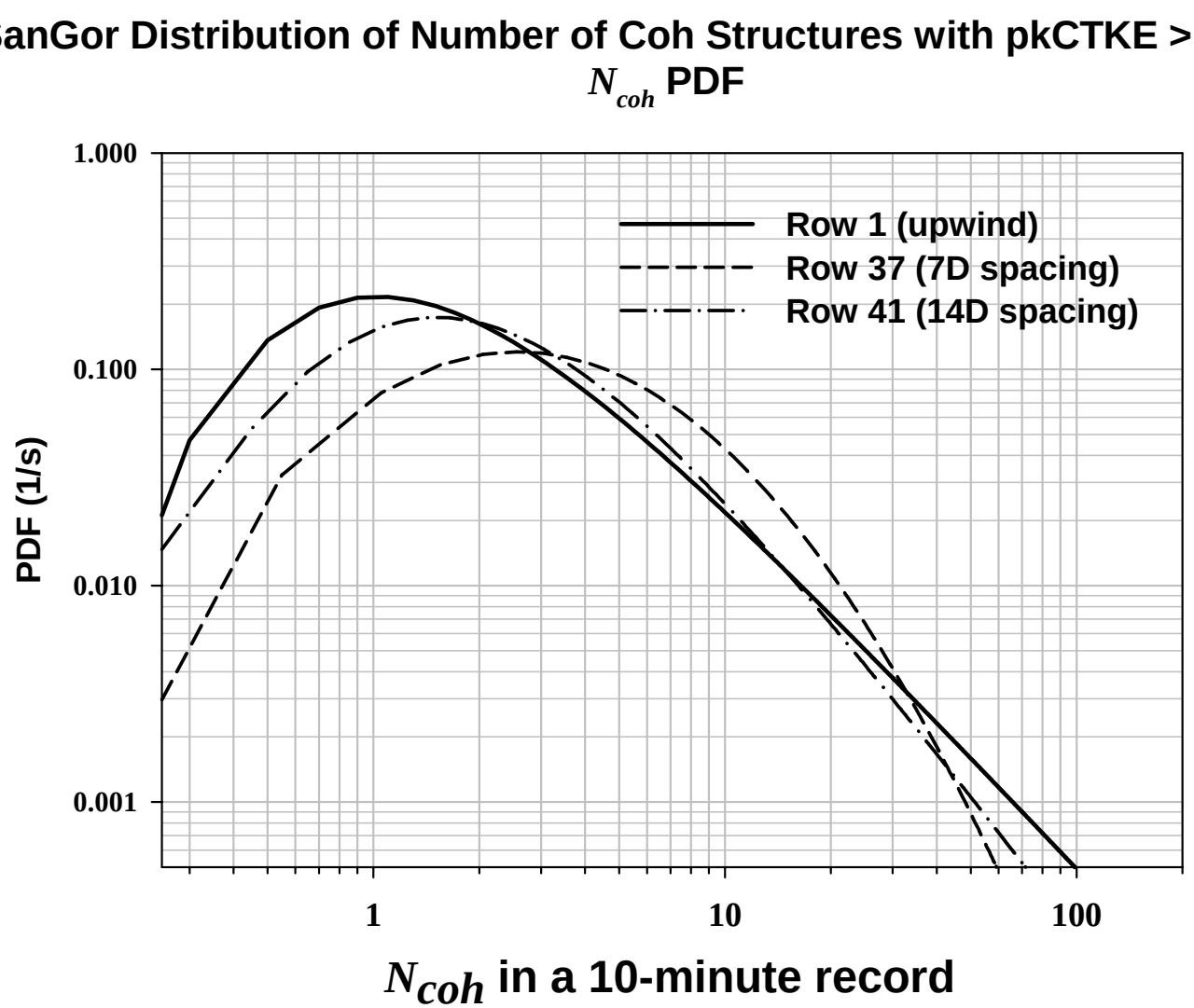
Measuring and Simulating Coherent Structures

- Coherent structures were determined from the available measurements (San Gorgonio, the NWTC, and the tower in SE Colorado)
- The process identifies the intensity (peak $CTKE$), the total number of structures and their length in a 10-minute record from measured data.
- We found that the number of coherent events and the intensity or rate of occurrence in a record could be modeled by a inhomogeneous Poisson Process; i.e.,

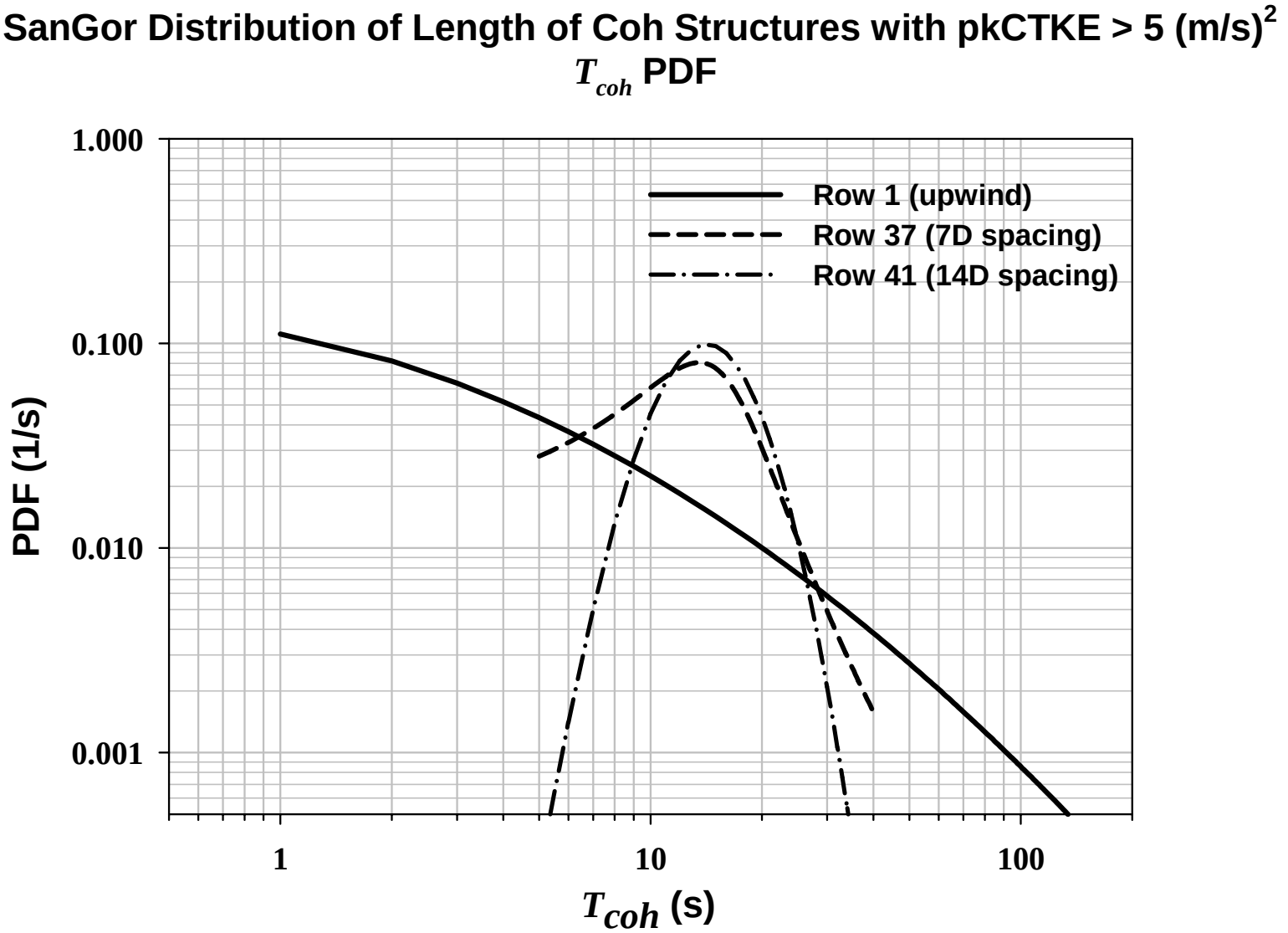
$$P\left\{N(t)=n\right\}=e^{-\lambda t}\frac{(\lambda t)^n}{n!}$$

where the rate parameter λ is a function of a combination of the scaling variables in TurbSim including U_{hub}, Ri, σ_w, u_*, and height.

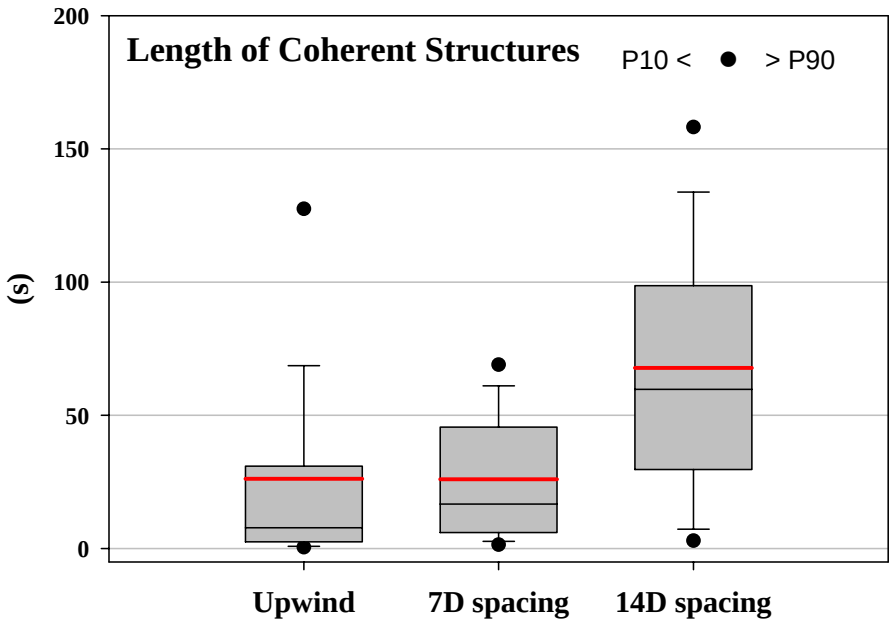
San Gorgonio Example for Probability Distribution of the Number of Coherent Structures Contained in a 10-minute Record, N_{coh}

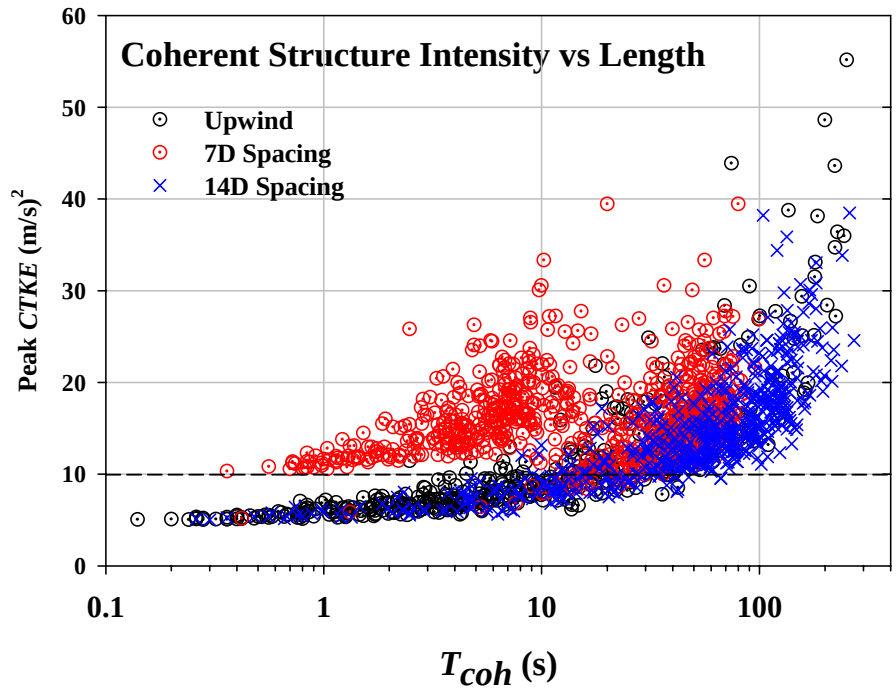


San Gorgonio Example for the Probability Distribution of the Total Length of Coherent Structures in a 10-minute Record, T_{coh}



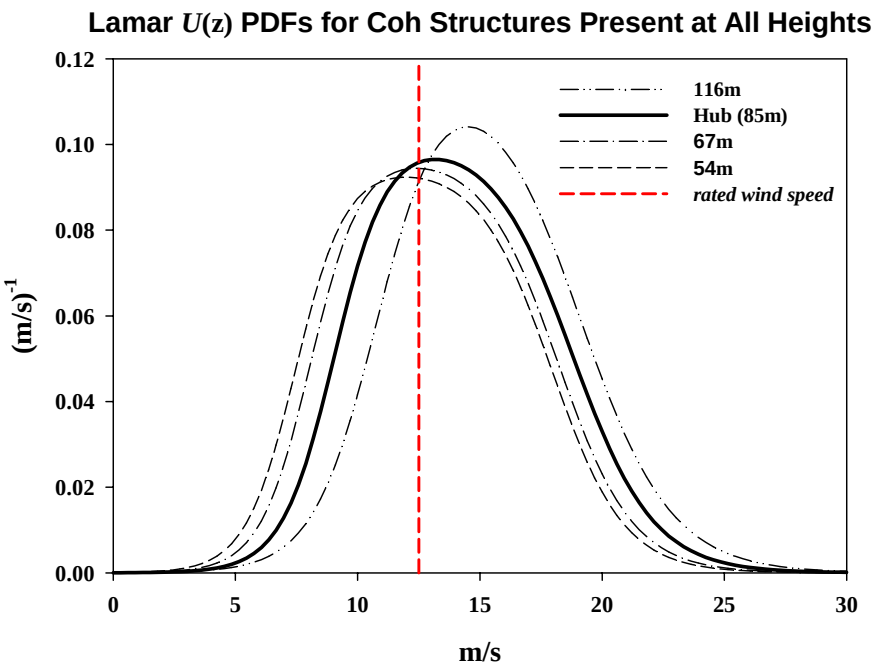
Coherent Structure Properties in San Gorgonio Wind Farm

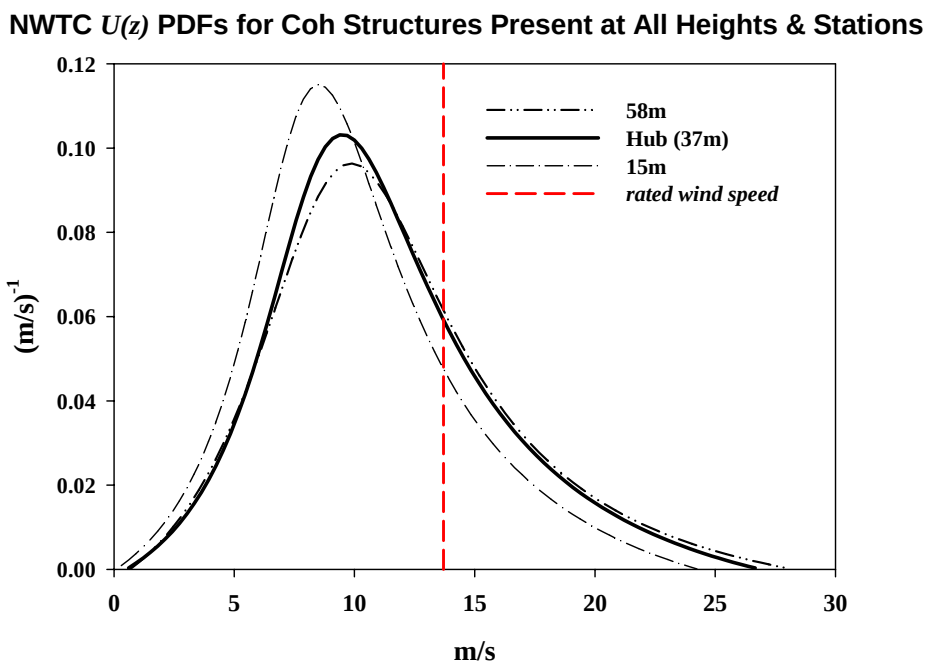




Comparing Lamar and NWTC

Probability Distributions for Wind Speeds
at Which Coherent Structures Are Present
at All Heights and Measurement Stations





Spatial Coherence

- The spatial coherence was calculated from the available measurements for the three sites: San Gorgonio, the NWTC, and Lamar.
- The Davenport and the IEC (Thresher-Holley) coherence models were compared with the two parameter IEC model providing the best performance.
- Coherence models were determined for all three wind components and at all available measurement stations at each location.

Spatial Coherence – cont'd

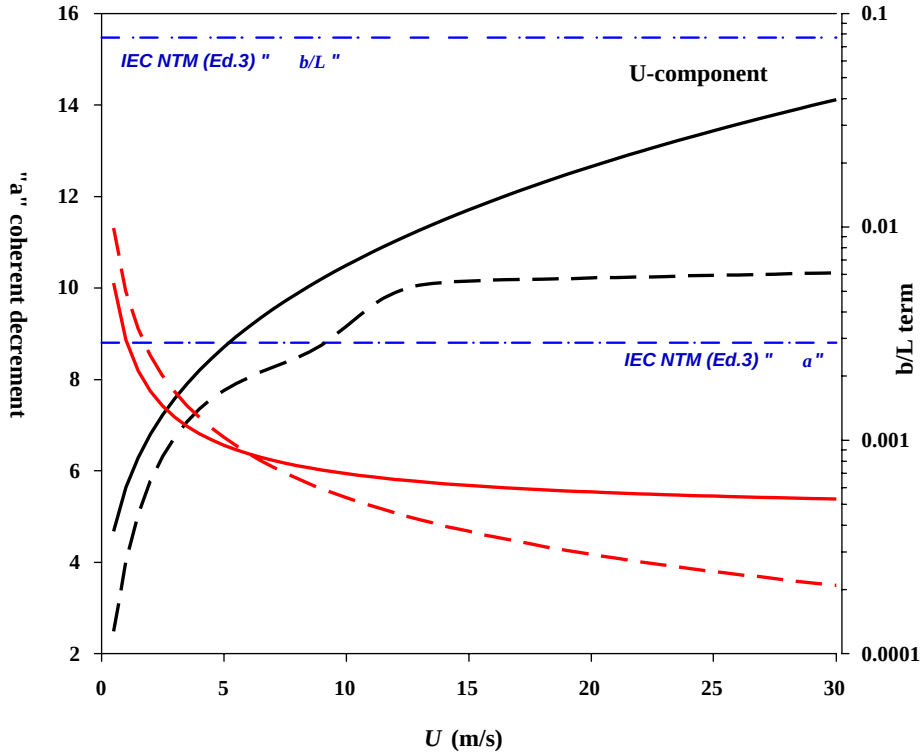
- The IEC Coherence Model is

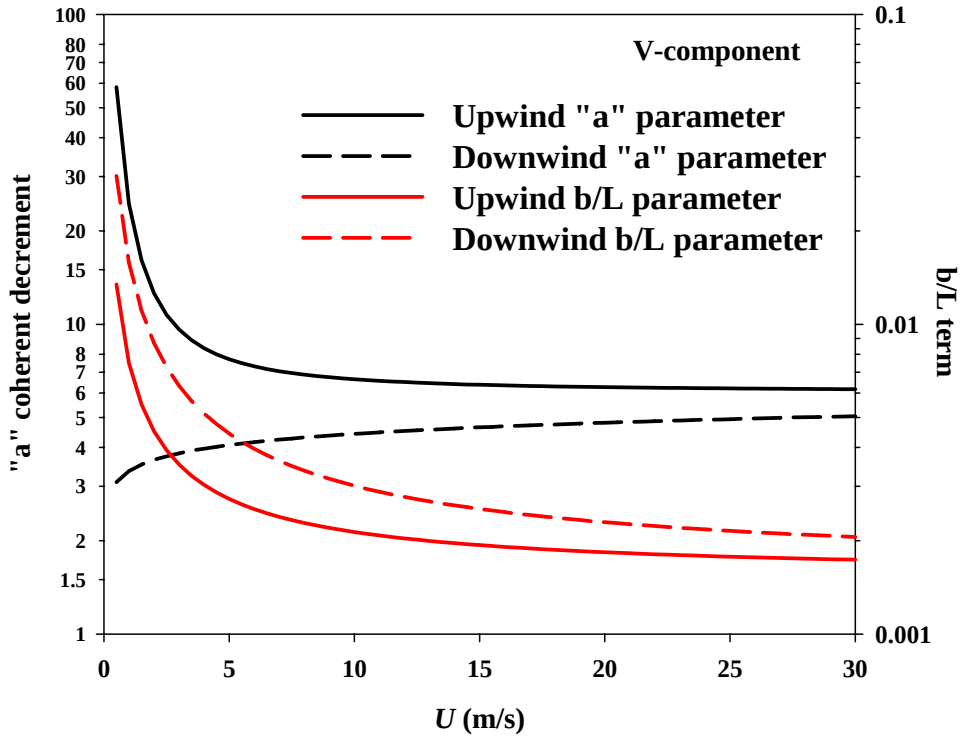
$$Coh(r, f) = \mathbf{exp}\left[-a\left(\left(f \cdot r / V_{hub}\right)^2 + (r(b / L_c)^2\right)^{0.5}\right]$$

where the decrement $\boldsymbol{a}$ and $\boldsymbol{b/L_c}$ term are the two free variables fitted to the data. The IEC values for Ed.3 are 12 and 0.12 respectively.

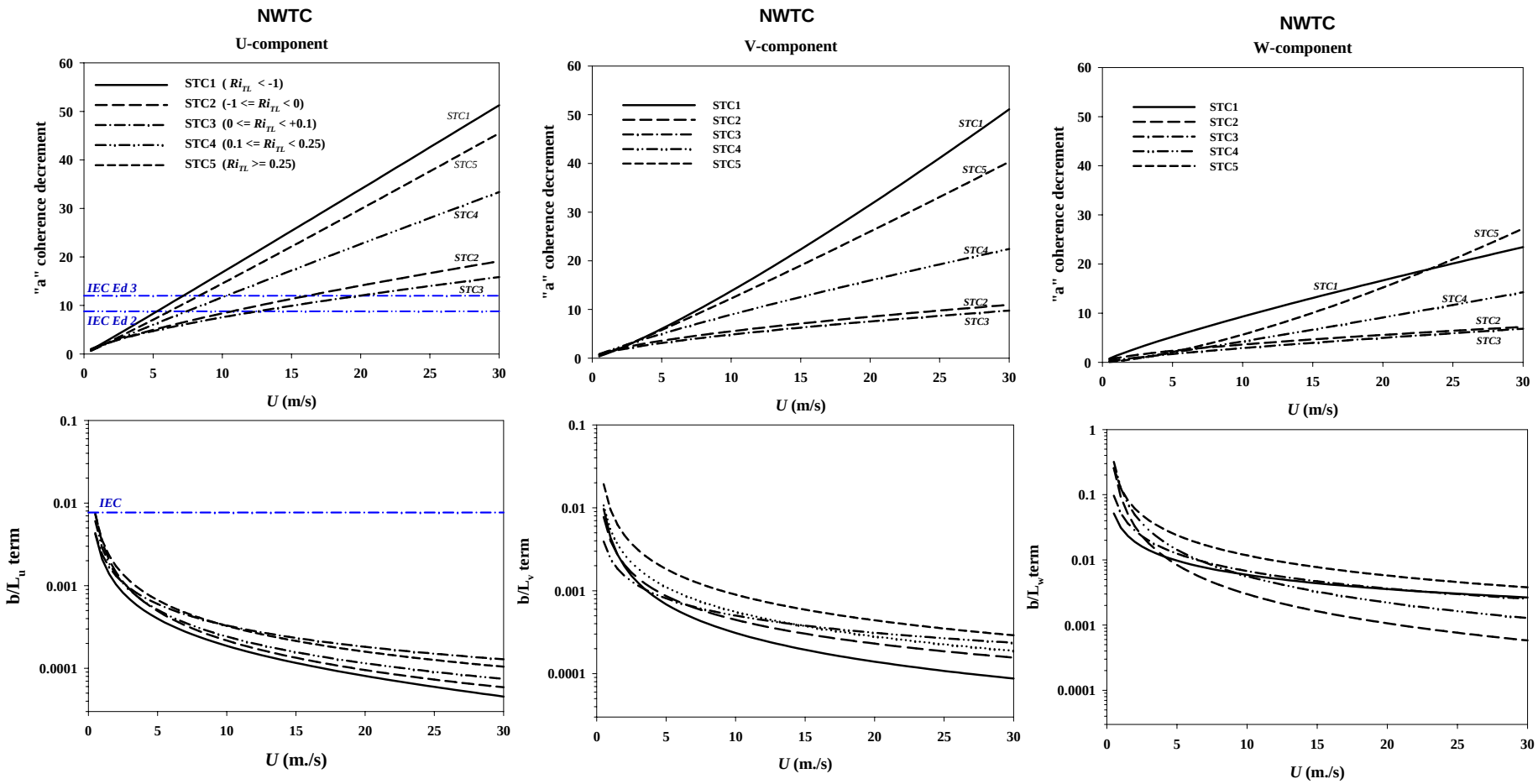
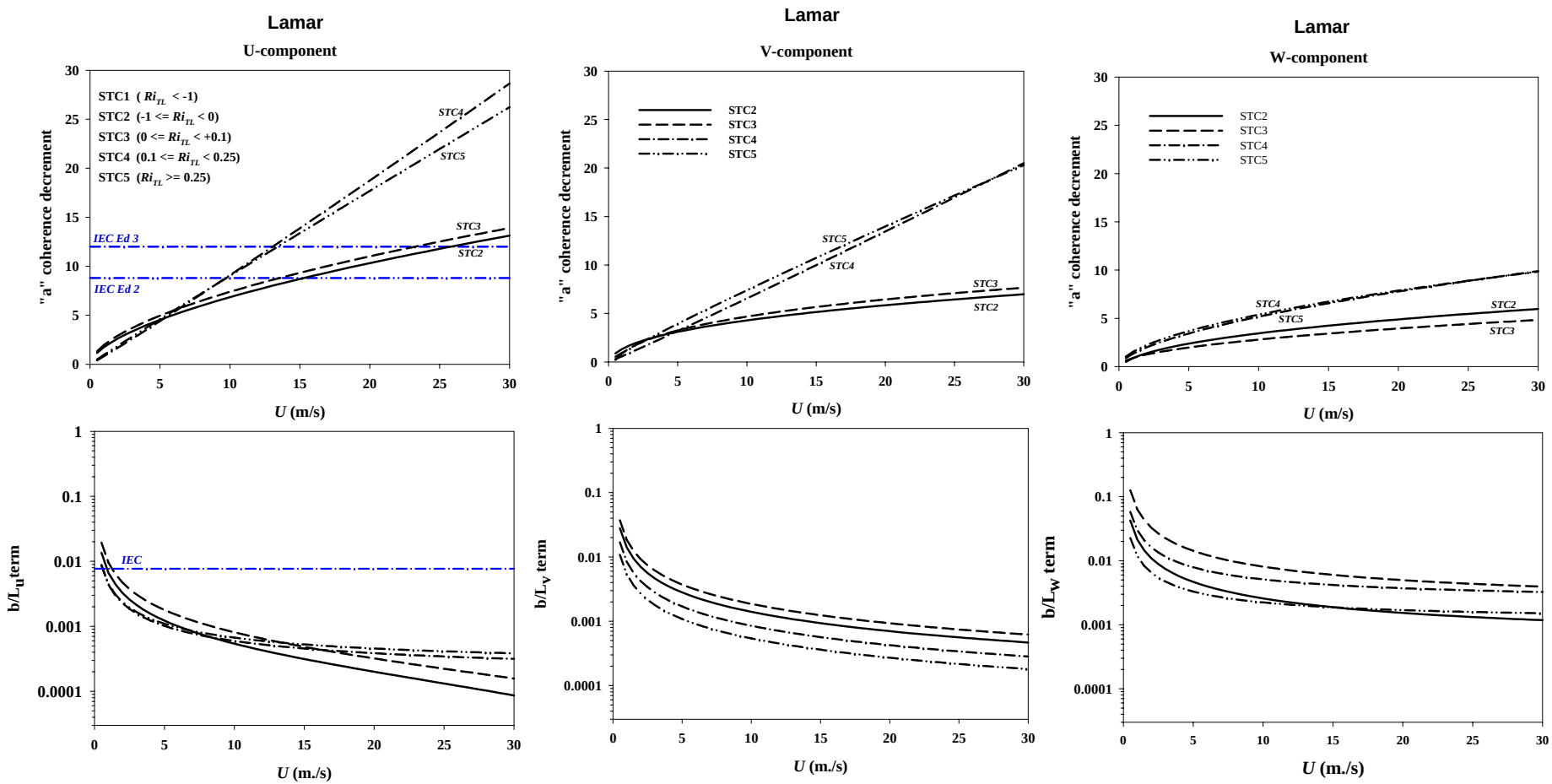
- Both parameters were found to be functions of wind speed and stability (Ri) and, in some cases, height as well.
- Only the U and V components are available for San Gorgonio

San Gorgonio Spatial Coherence





NWTC Spatial Coherence



Lamar Spatial Coherence