Exceptional service in the national interest

Sandia National Laboratories

SWiFT Site Atmospheric Characterization

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U.S. DEPARTMENT OF ENERGY

NNSA
National Nuclear Security Administration

Presentation Outline

➢ Description of the SWiFT Site Atmospheric Facilities

➢ Data Processing of the TTU 200m Tower

➢ Findings from TTU 200m Tower historical site characterization

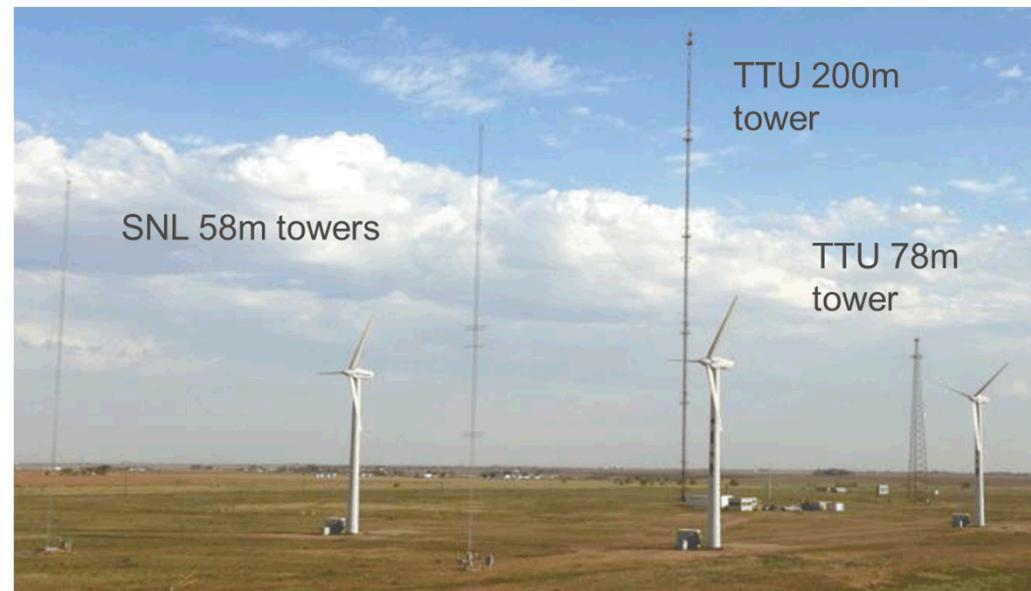➢ (time permitting) Discussion of Other Projects

SWiFT Site Atmospheric Facilities

- TTU 200m meteorological tower is 300m NNW of the SWiFT turbines

- TTU 78m tower records 10 minute logs at 78m

- Turbine-turbine interaction centerline for wind directions from:
  - 5-diameter; 180 / 0 deg.
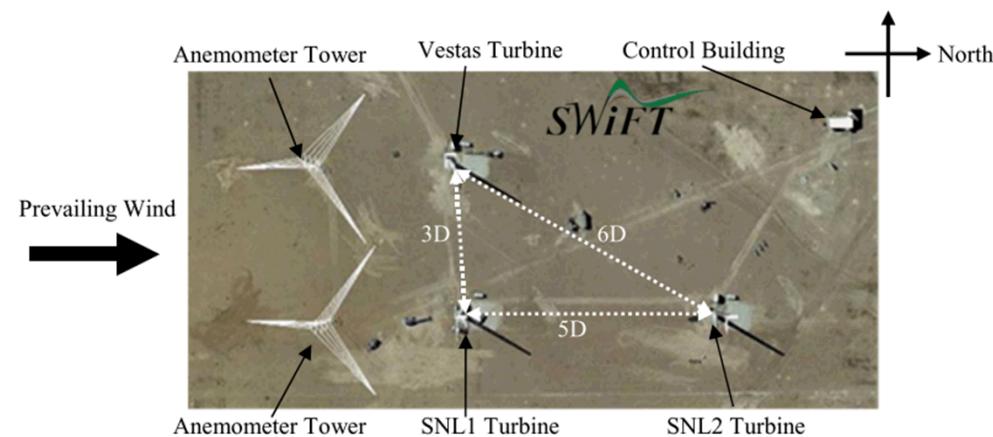 - 6-diameter; 210 / 30 deg.
  - 3-diameter; 266 / 86 deg.



Figure 3. Layout of SWiFT Facility.

TTU 200m Meteorological Tower

200m Tower Sensor Heights	
[ft]	[m]
3	0.9
8	2.4
13	4.0
33	10.1
55	16.8
155	47.3
245	74.7
382	116.5
519	158.2
656	200.0

Sensor Package
Sonic U-arm
Sonic V-arm
Sonic W-arm
Sonic Temperature
Temperature
Relative Humidity
Barometric Pressure
Propeller U-arm
Propeller V-arm
Propeller W-arm

SWiFT rotor top and bottom heights
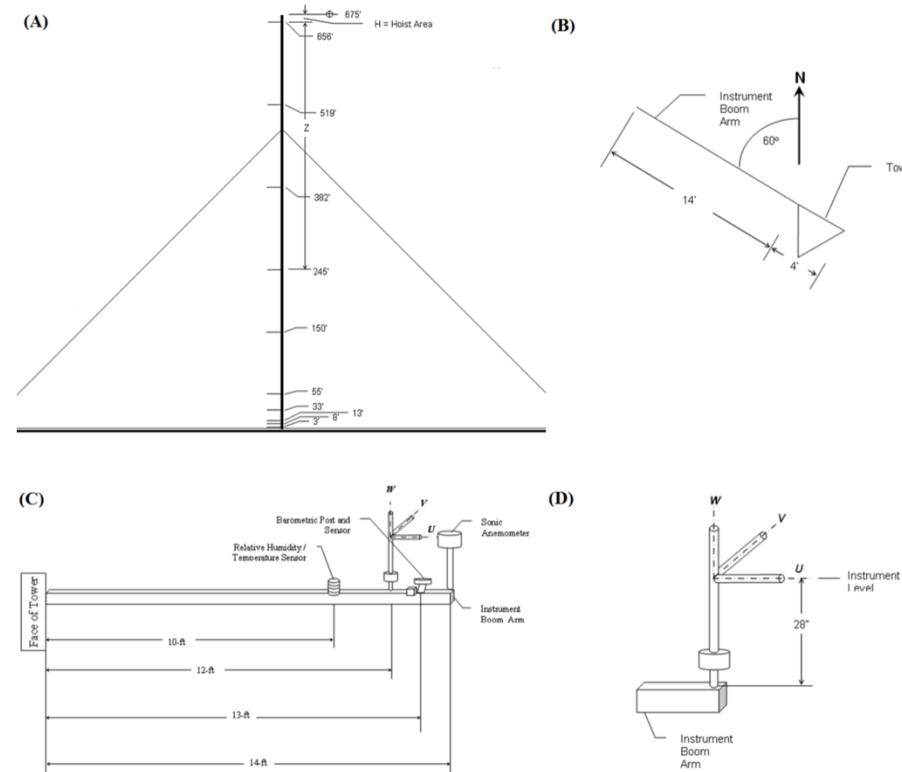
TTU 200m meteorological tower

- 3 years of historical 50-hz data beginning July 2012
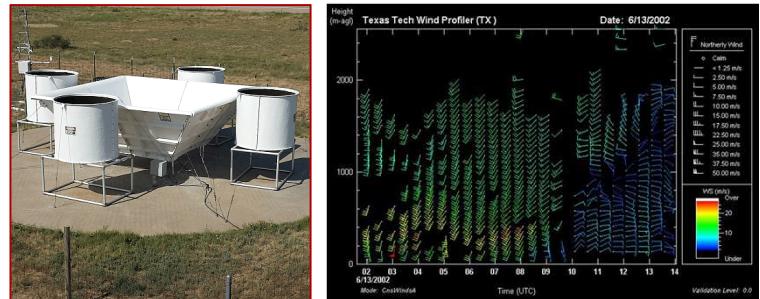- About 300m NNE of the SWiFT turbines

Vaisala LAP-3000 radar profiler

- configured to log wind speed, direction, and temperature profiles every 20-min.
- Resolution is 60m between 150-2000m AGL, 200m between 600-6000 m AGL
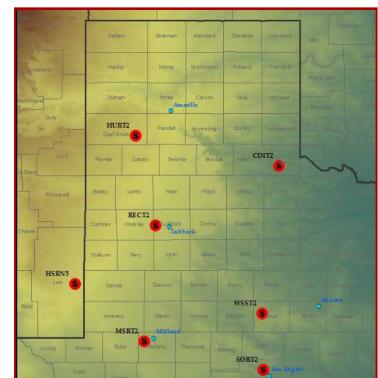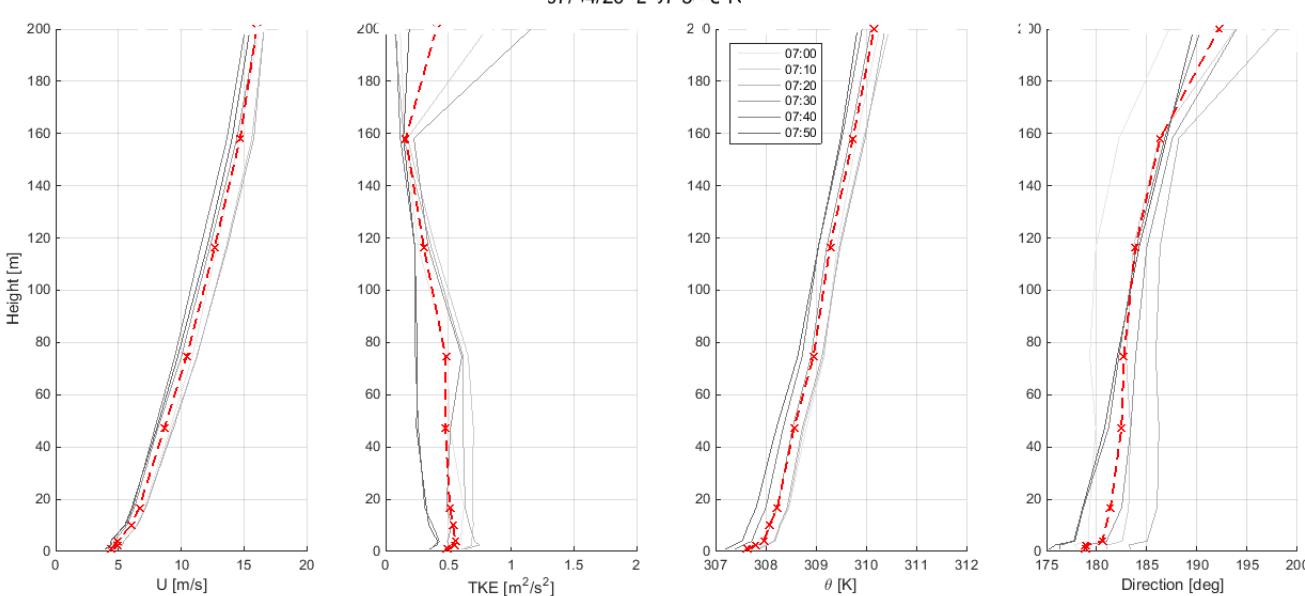- Approximately 540m to the SW of the 200m tower.

Mesonet and Sodar Networks

Historical data from weather stations in surrounding area

- 5-15 minute historical logs
- Currently unfunded and not public

200m Met Tower; 50hz historical data

Radar Profiler; 20 min data logs

West Texas Mesonet and Sodar Networks

Mesoscale-Microscale Coupling Work

Initial Benchmark Identification and MMC modeling:

- SNL Role is case identification from TTU historical data sets at the SWiFT site.
- Identification of stationary near-neutral, stable, and convective atmospheric boundary layer from 200m met tower
- Radar profiler data are used to approximate geostrophic forcing
- Low Level Jet development typical of SWiFT site
- Important phenomena to wind energy industry
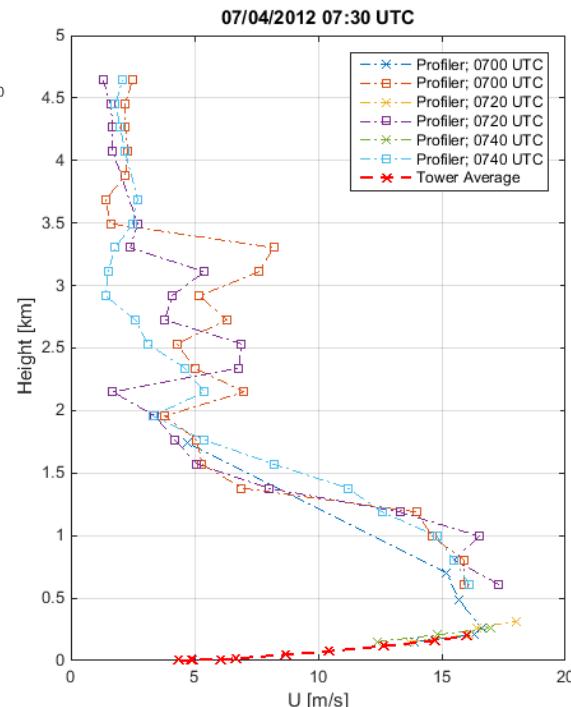
Atmospheric Facility Usage

SNL 58m Met Towers:

- Accurate inflow measurement

- Atmospheric stability
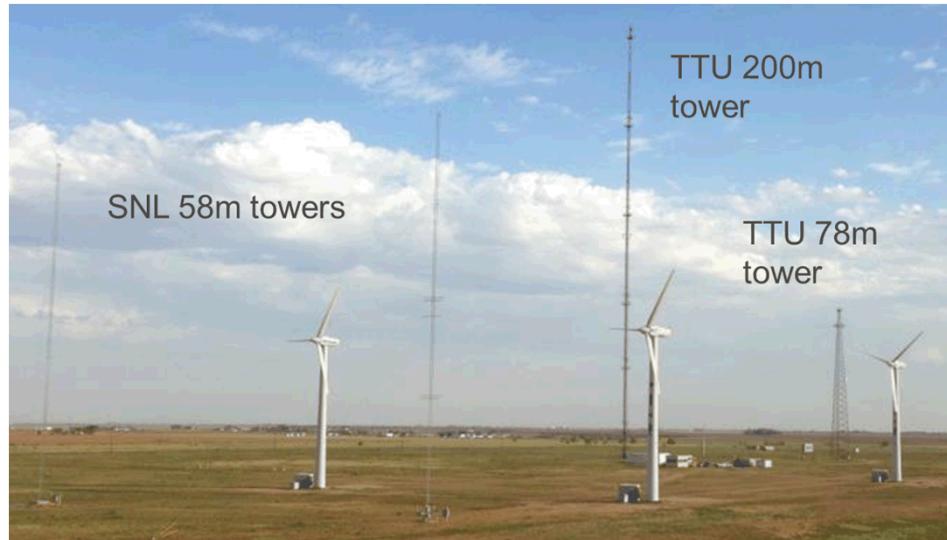
- Turbulence coherence

TTU 200m Met Tower:

- Comparison of SWiFT inflow with "full-scale" height(s)

- Turbulence coherence at an additional location

- Detailed profiles up to 200m
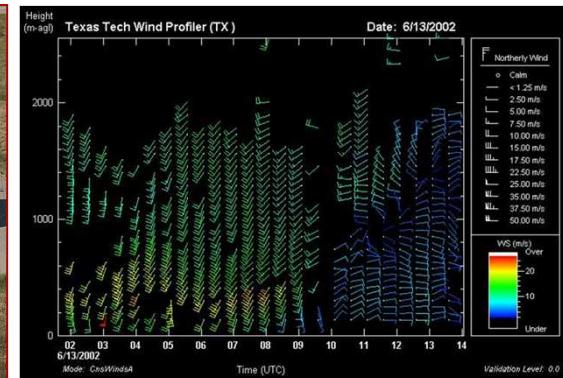
TTU 78m Met Tower:

- Point comparison of averages

TTU Radar Profiler:

- Boundary layer height / geostrophic forcing

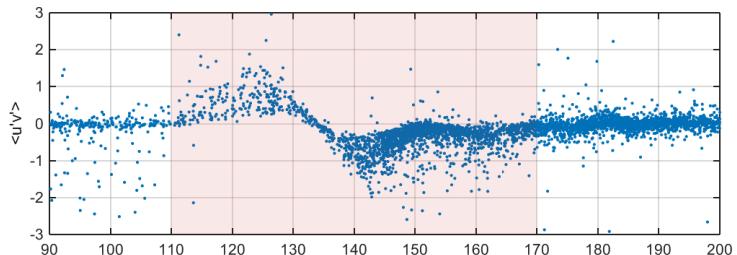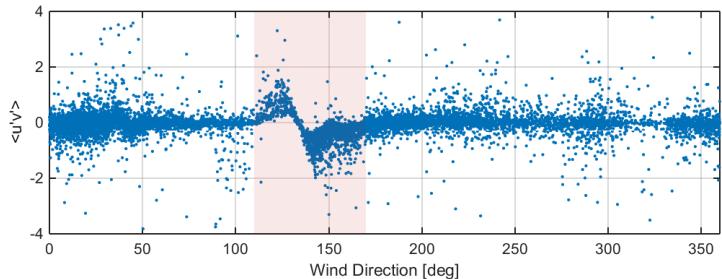Radar Profiler; 20 min data logs

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DATA PROCESSING FINDINGS

TTU 200m Tower Wake

- In a wake, velocity is decreased and turbulence is increased

- Turbulence Intensity (TI) therefore is a highly affected variable by the tower wake shadow

- Only neutral stability cases are compared, which removes effects on TI from other sources
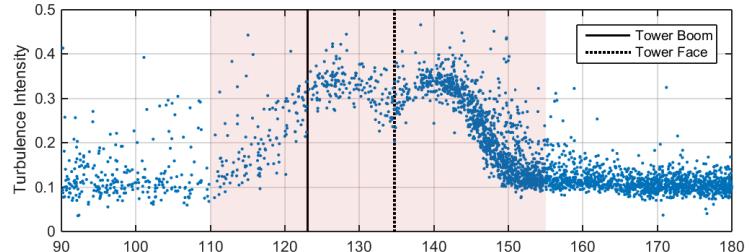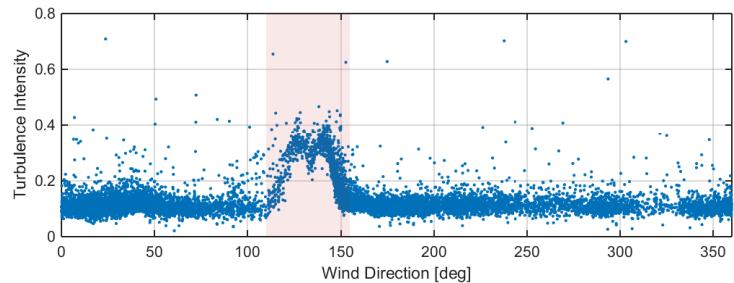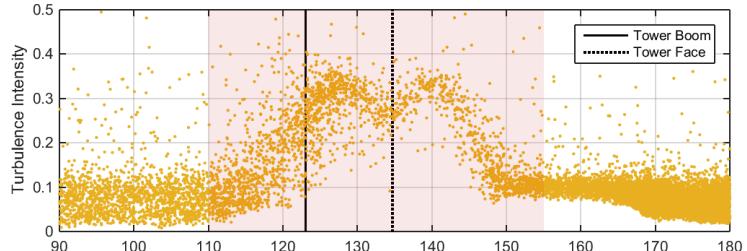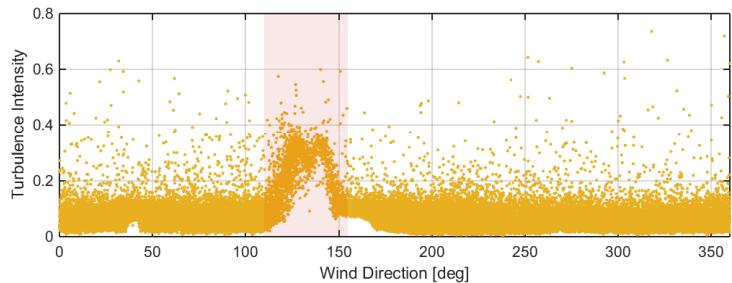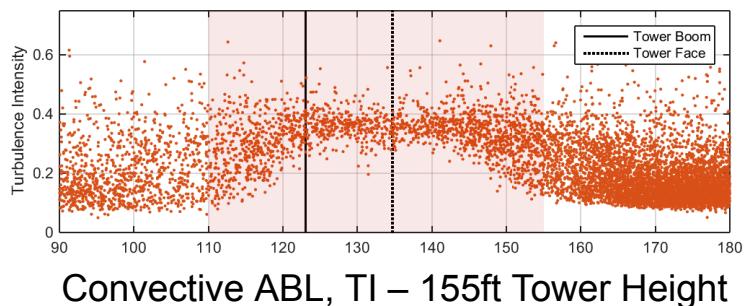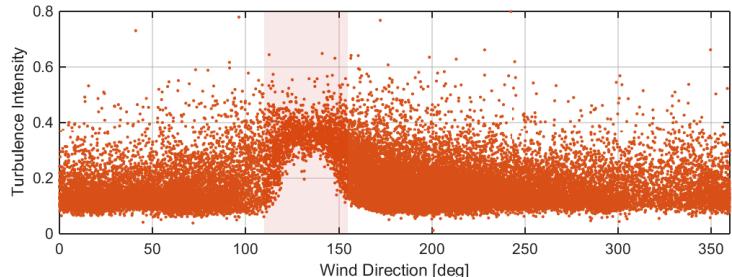

Turbulence Intensity – 155ft Tower Height

Reynold's Shear – 155ft Tower Height

TTU 200m Tower Wake

- Stable and Convective ABL cases are equally compared

- Wake effect would cover the largest directional sector for highest turbulence cases (convective)

- Tower wake sector for TTU 200m boom stations defined as [110, 155] deg.

Stable ABL, TI – 155ft Tower Height

Convective ABL, TI – 155ft Tower Height

TTU 200m Tower Wake

- Removing a directional sector of [110, 155] deg equates to 8.7 and 9.2% of the 2-year total data set.

- This directional sector is 25 deg from the 5-diameter spacing turbine-turbine interaction, 24 deg from the 3-diameter turbine-turbine interaction
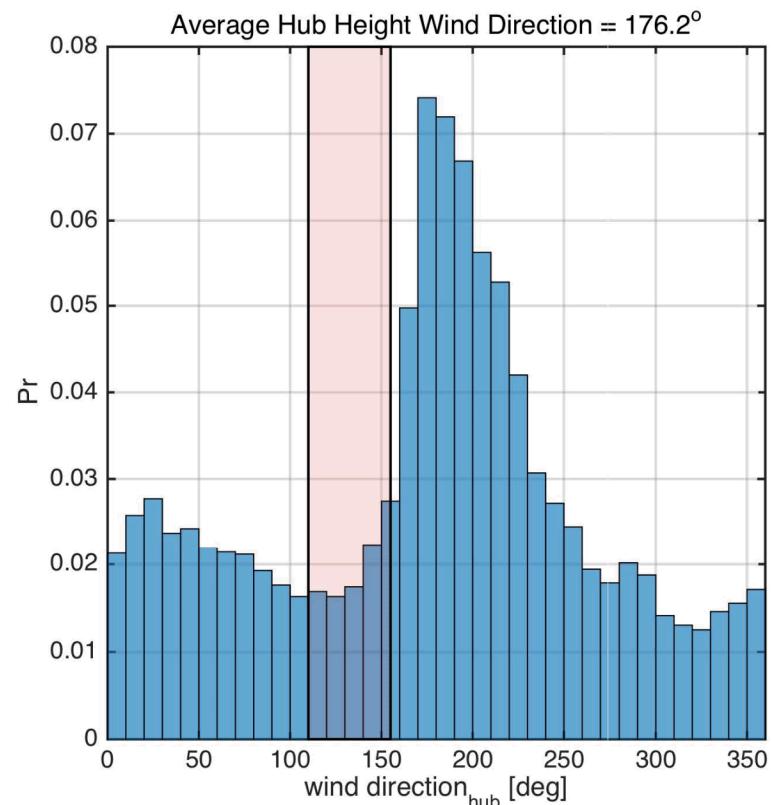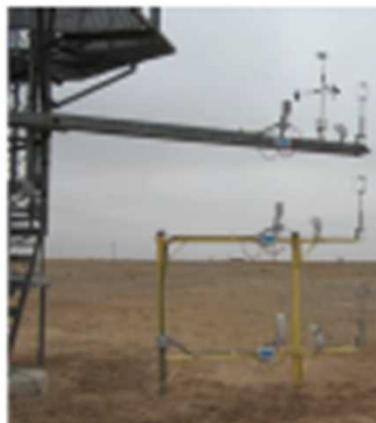
TTU 200m Tower Wake

- Sensors at 3, 8 and 13 ft stations have different obstructions

- Analysis reveals a tower wake directional sector of [110, 170] deg for these 3 measurement heights

- Affects stability measurements
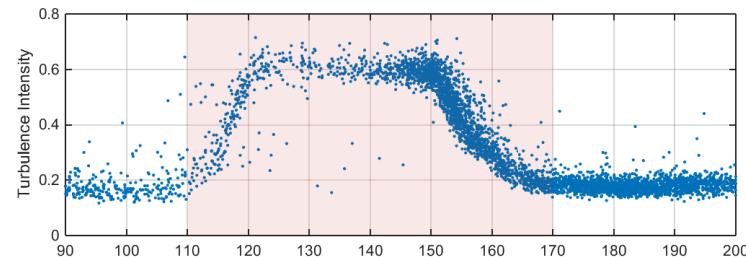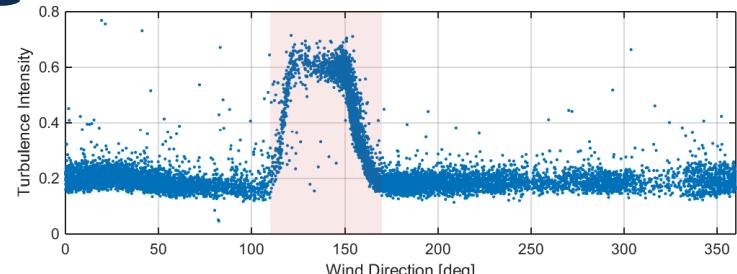
Neutral ABL, TI – 8 ft Sensors

(a) Sensor Mounting at 3, 8, and 13 ft.　(b) Tower Structure Near the Ground.　(c) Adjacent Structures to the 200 m Tower.

Summary:

- 200m tower has an observed tower wake effect from [110, 155] deg at turbine heights
- This corresponds to between 9-10% of the time series
- 8ft sensor has a tower wake shadow from [110, 170] deg
- There is not a SWiFT hub height sensor package on the TTU tower

Next steps:

- TTU 200m analysis and report being reviewed at SNL and NREL – published by 12/24/15
- Sue Haupt and Branko Kosovic have the tower wake sections and will provide feedback
- Package conclusions and recommendations for the TTU 200m facility's support of the SWiFT site to provide to DOE
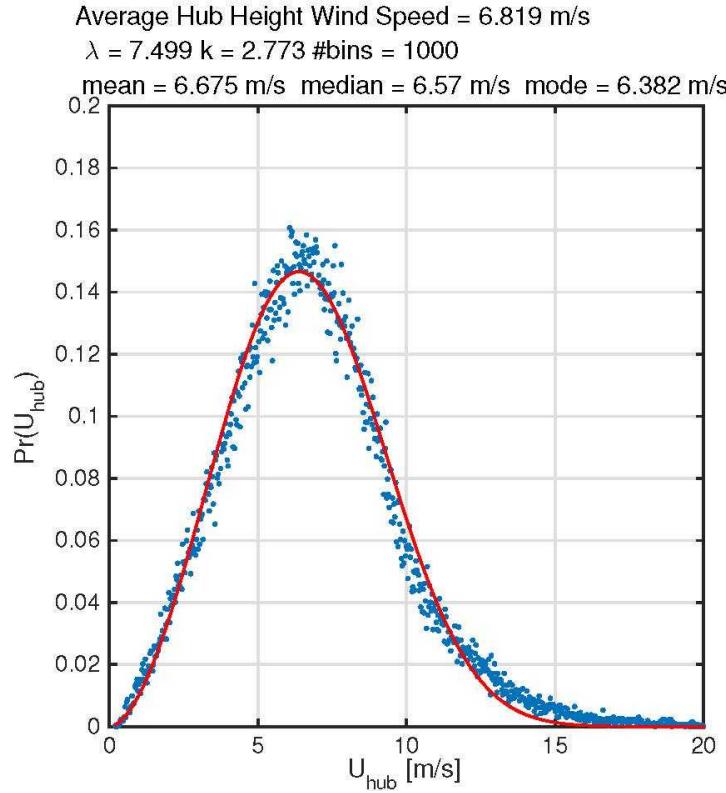
# HISTORICAL ANALYSIS RESULTS

Historical Analysis Purpose

- Inform Experimental Campaign Planning
  - How long does a campaign need to be run, over what timeframe to statistically produce a representative amount of data covering the atmospheric conditions of interest?
  - What are the specific pairings/values of atmospheric conditions that are statistically achievable at the SWiFT site?

- Determine Model Simulation Inputs
  - What are common values of turbulence intensity, velocity profile shear exponent, degrees of veer?
  - What atmospheric values should be used as design inputs for the site?

- To provide a benchmark for comparison to other sites for scaled testing at SWiFT

Average Conditions at SWiFT

- Average hub height wind speed is 6.8 m/s
- Weibull distribution

- Two year average of wind speed velocity profile
- Average TI for SWiFT rotor is 12.9%

Average Hub Height Wind Speed = 6.819 m/s
λ = 7.499 k = 2.773 #bins = 1000
mean = 6.675 m/s median = 6.57 m/s mode = 6.382 m/s
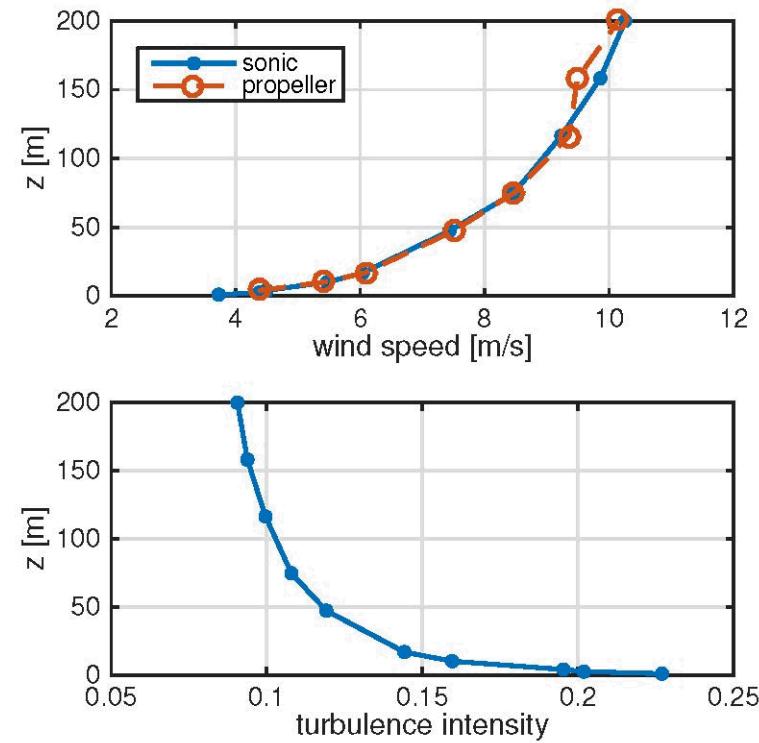
IEC Classification of SWiFT Turbines

- Classification defined in terms of wind speed and turbulence intensity

Wind Turbine Class	I	II	III
V_{avg} (m/s):	10	8.5	7.5
A	$I_{ref @ 15 m/s}$: 0.16		
B	$I_{ref @ 15 m/s}$: 0.14		
C	$I_{ref @ 15 m/s}$: 0.12		

- Using 2-years of historical TTU 200m tower data at 32m hub height (SWiFT Turbines)

  - SWiFT site determined to be **III-C**
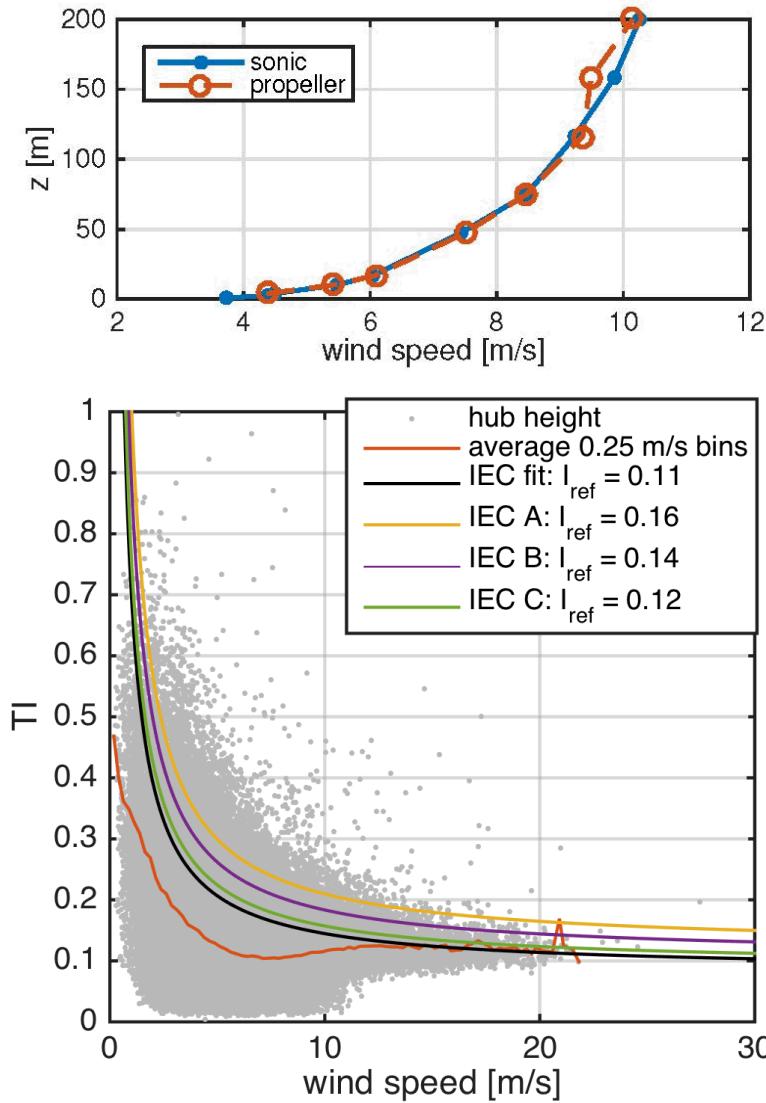
Average Conditions at SWiFT

Two-year distributions of SWiFT site atmospheric conditions

TI average is 12.9%

- Common occurrences of 5-20%.
- Important for test campaigns

Density average is 1.08 kg/m³

- NOT constant, total of about 20% spread

Velocity profile shear exponent average is 0.208

- Typically assumed as a constant 0.15 in design
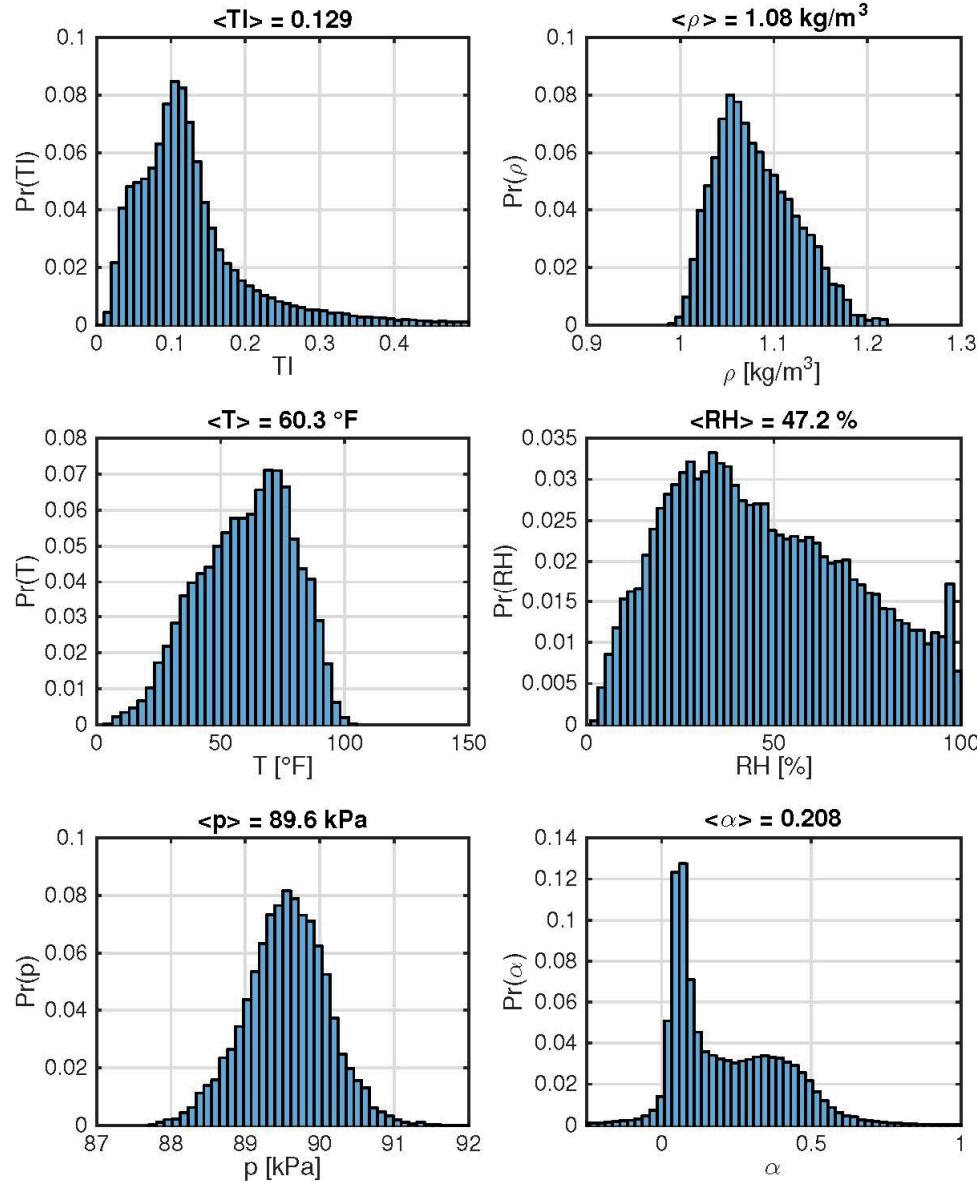
Air Density Fluctuation at SWiFT

- Air density averaged per month

- Summer months have an average air density of about 10% less than winter months

- Air density is directly proportional to the amount of power available in the wind

$$P_{wind} = \frac{1}{2}\rho V^3 A$$
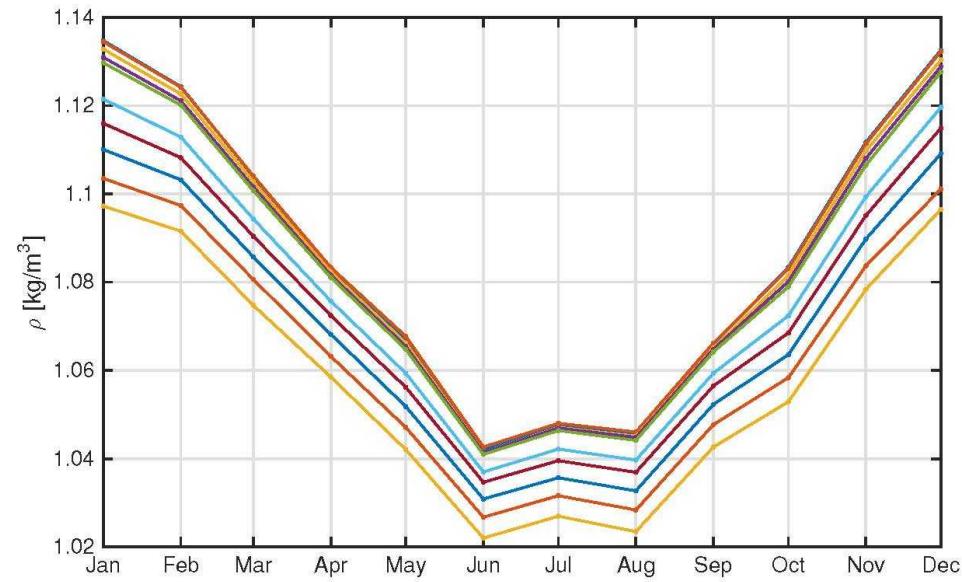
Average Conditions at SWiFT

- Turbulent daytime conditions result in low shear profiles

- Green and adjacent blue curves show SWiFT shear

- SWiFT height good for achieving large/low shear

- Turbulence Intensity averages vary on the day on the order of 100%

- SWiFT height averages vary on the day from 10-20%; which is good for experimental campaigns
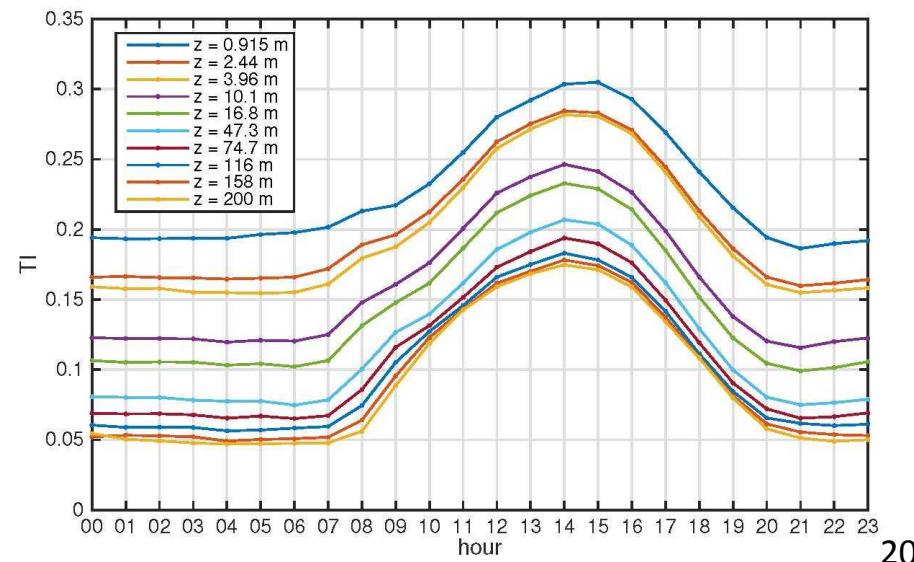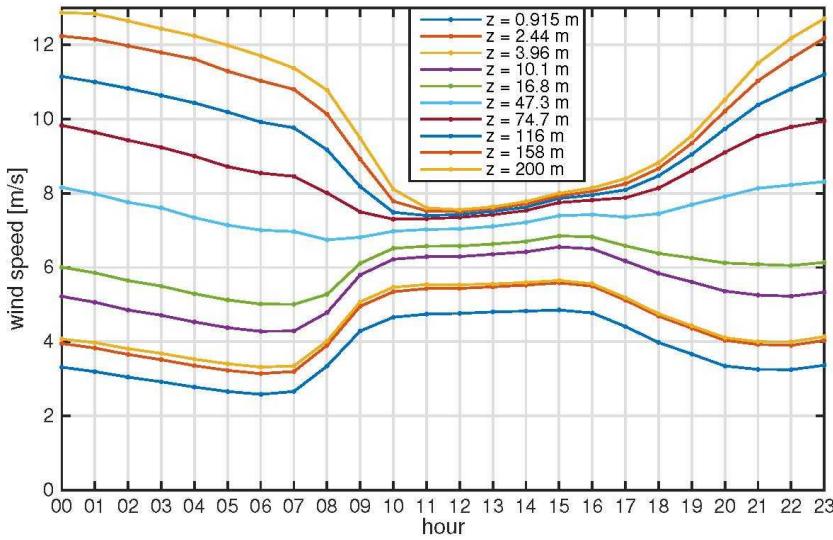
Atmospheric Stability at SWiFT

- Represented by the Bulk Richardson number formulation

- Ratio of turbulence production due to buoyancy forces to mechanical/shear production

- **At the SWiFT site, neutral conditions occur 5-10% of the time**

- Most CFD modelers simulate only neutral ABL conditions.

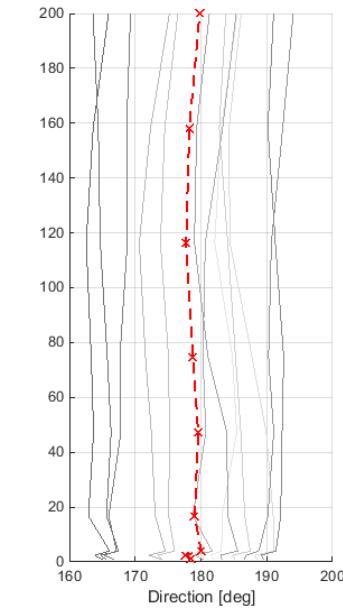$$Ri_B = \frac{g\Delta\theta_v\Delta z}{\theta_v(\Delta U_\infty)^2}$$

21
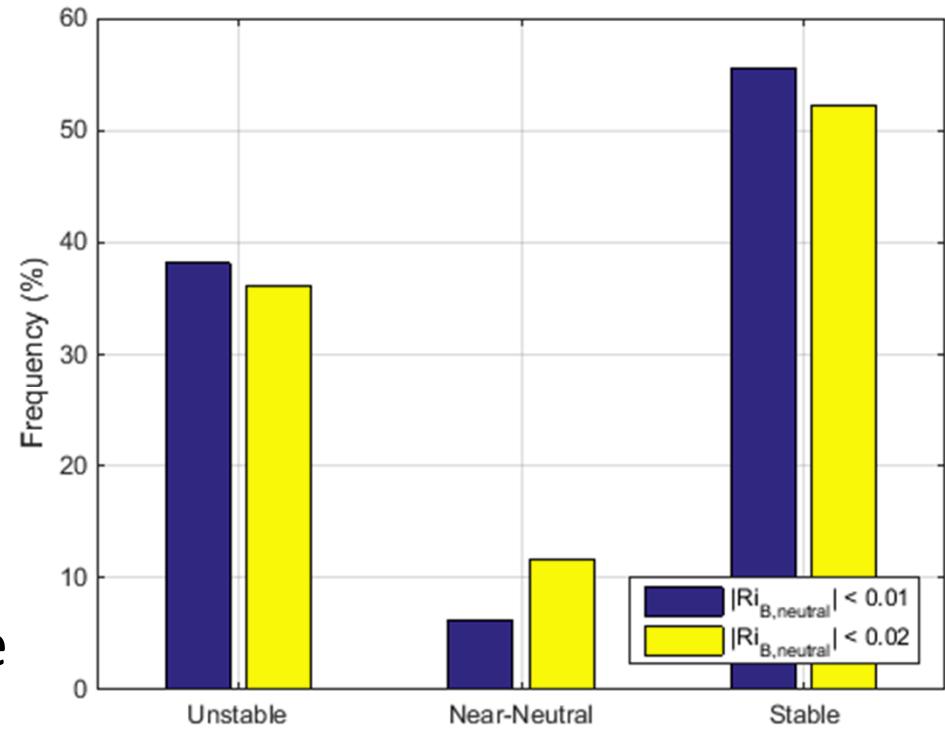
Stable ABL:

- Positive potential virtual temperature gradient
- Downward buoyant momentum flux
- Turbulence is suppressed
- Strong velocity profiles / shear
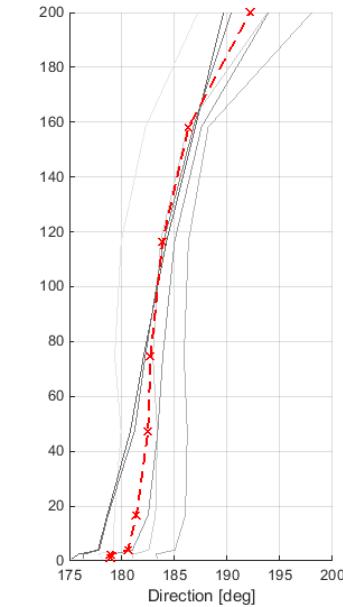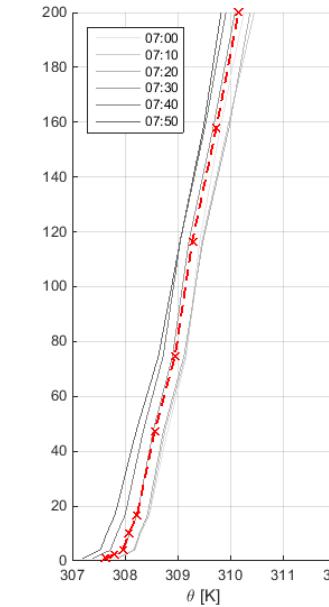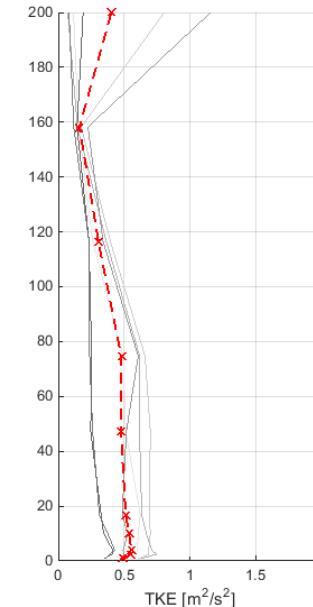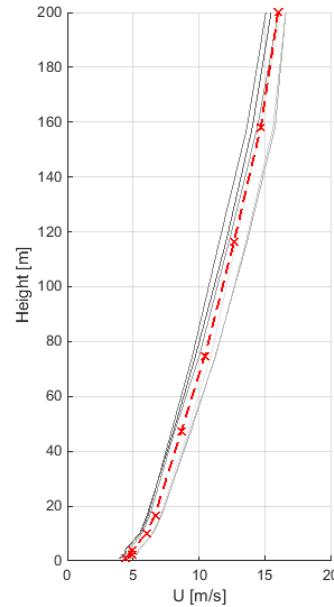
Convective ABL:

- Ground surface heating
- Positive buoyant momentum flux
- Turbulence is generated and convected upward
- Minimal velocity profiles / shear
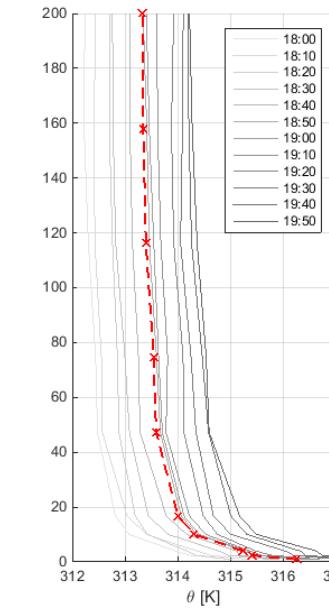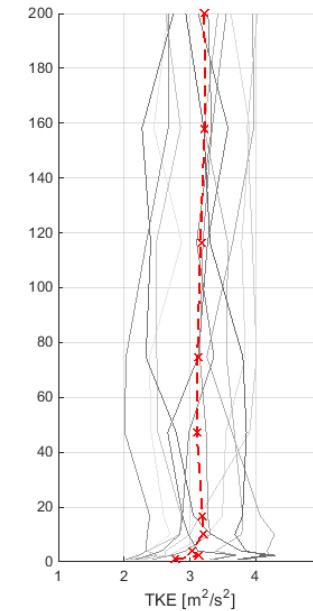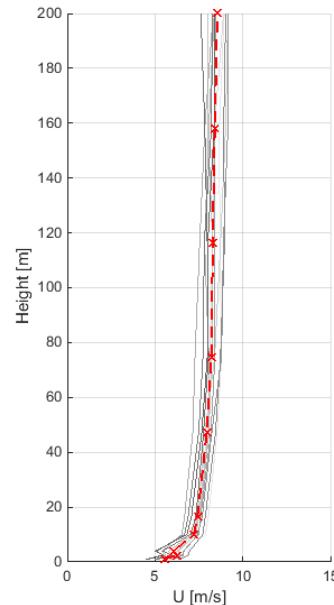

07/04/2012 07:30 UTC

07/04/2012 19:00 UTC

Atmospheric Stability Trends

- Neutral cases have a higher average wind speed than stable and convective cases

- Wind direction has a minor trend with stability
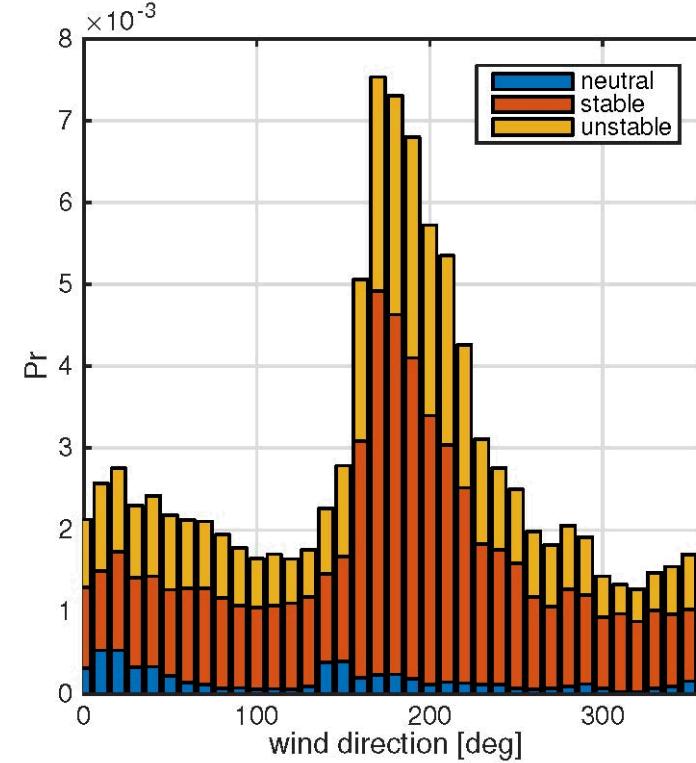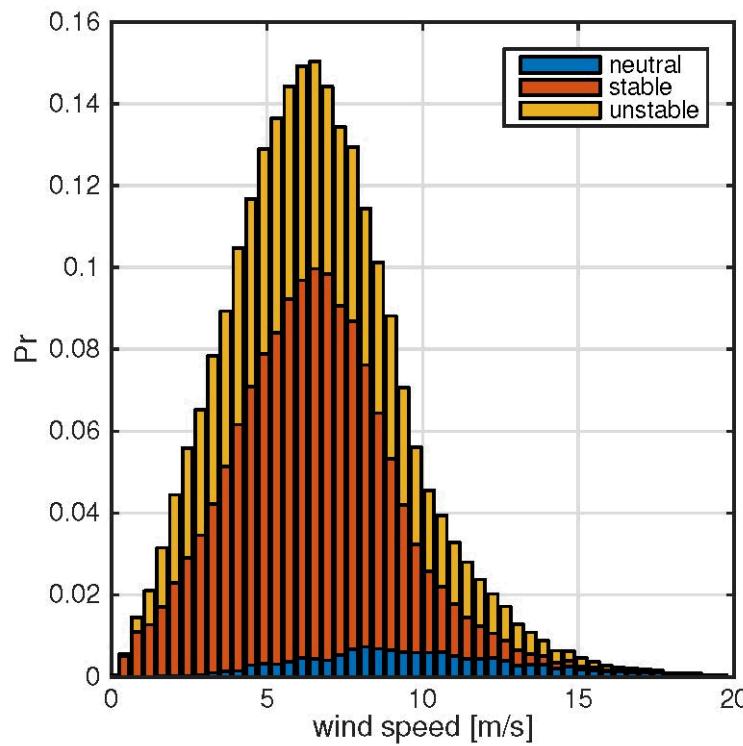
Atmospheric Stability Trends

- Neutral cases have a higher average wind speed than stable and convective cases

- TI is strongly dependent on atmospheric stability

- Finding very low TI unstable case would be challenging
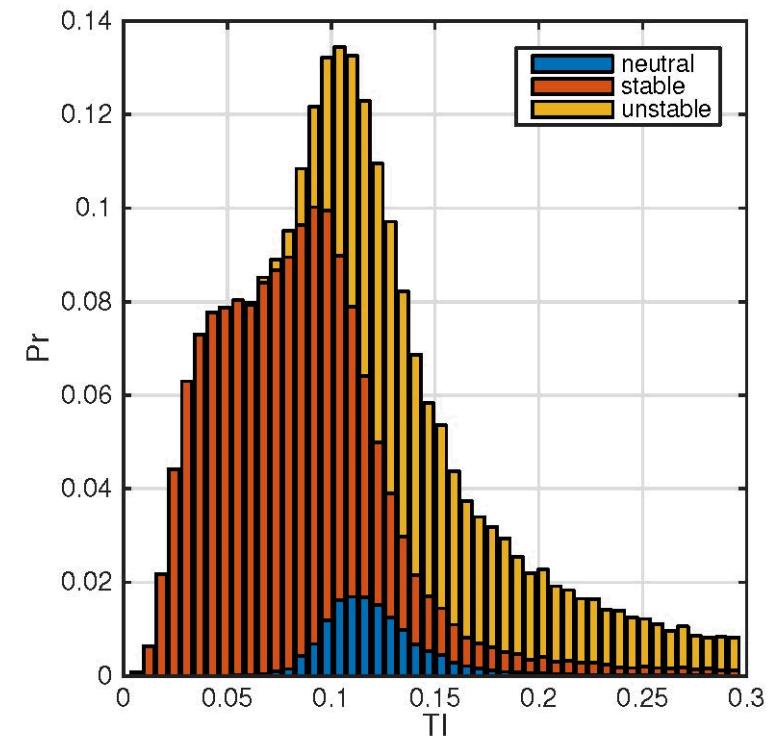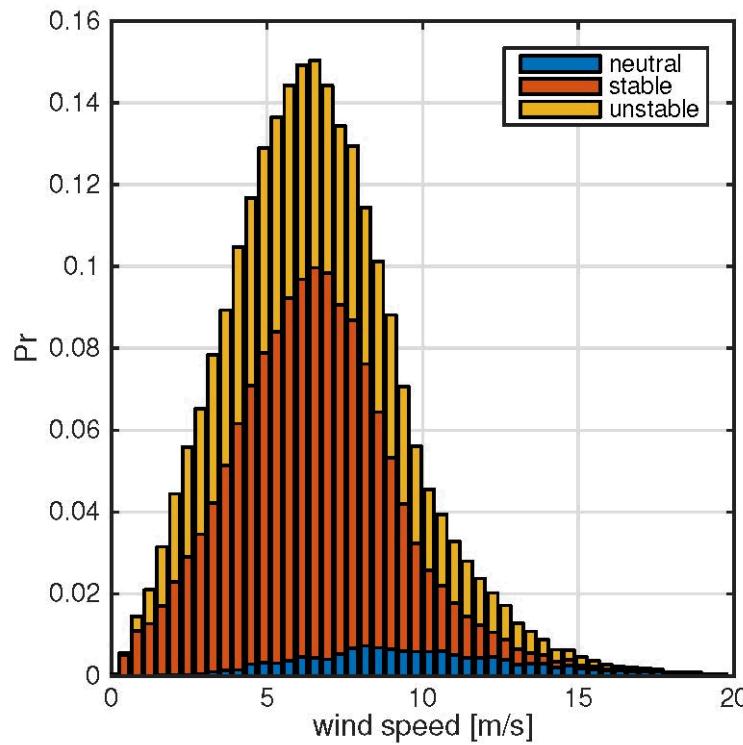
Atmospheric Stability Trends

- Percentage of neutral cases is consistent on the year; Unstable cases increase surrounding summer

- Affects experiment planning

- Convective daytimes transition to stable nights

- ABL transition between around 8-9am and 6-8pm
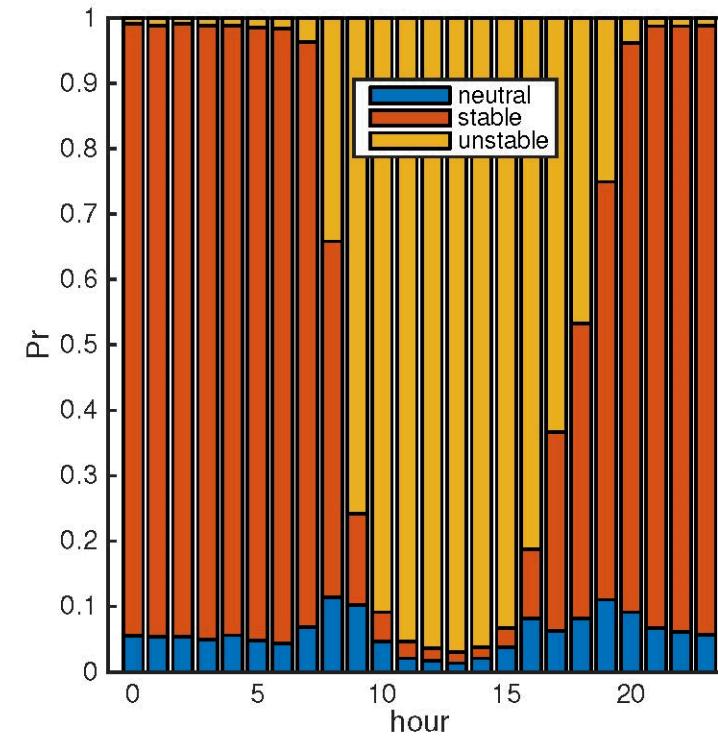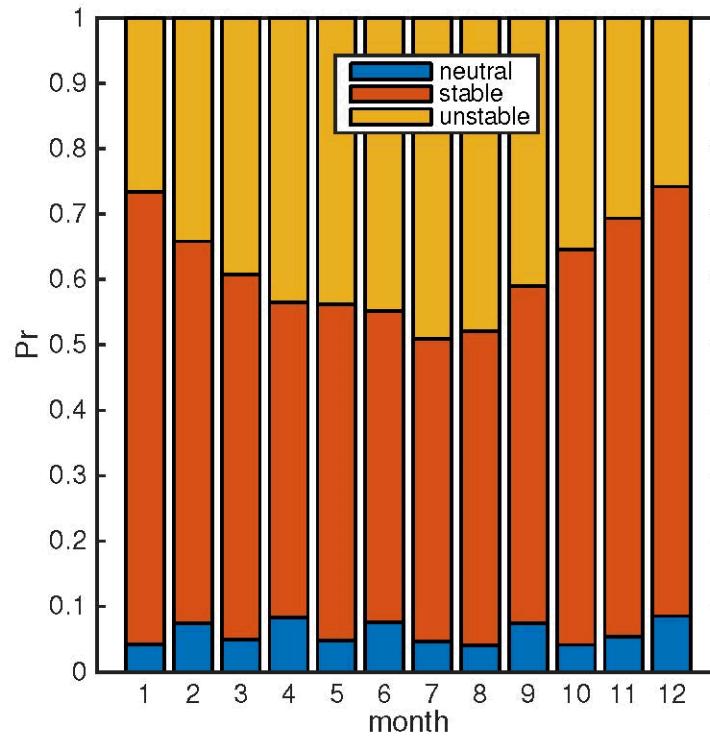
Atmospheric Stability Trends

- Due to turbulent mixing, unstable ABL's have the lowest shear

- Shear exponent peak = 0.05

- Highest veer conditions occur during the overnight stable boundary layer development
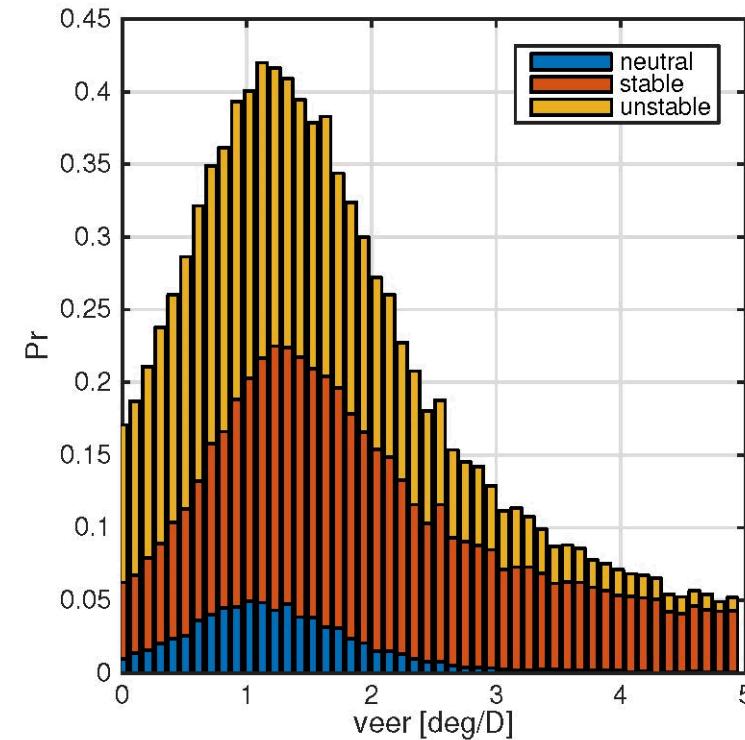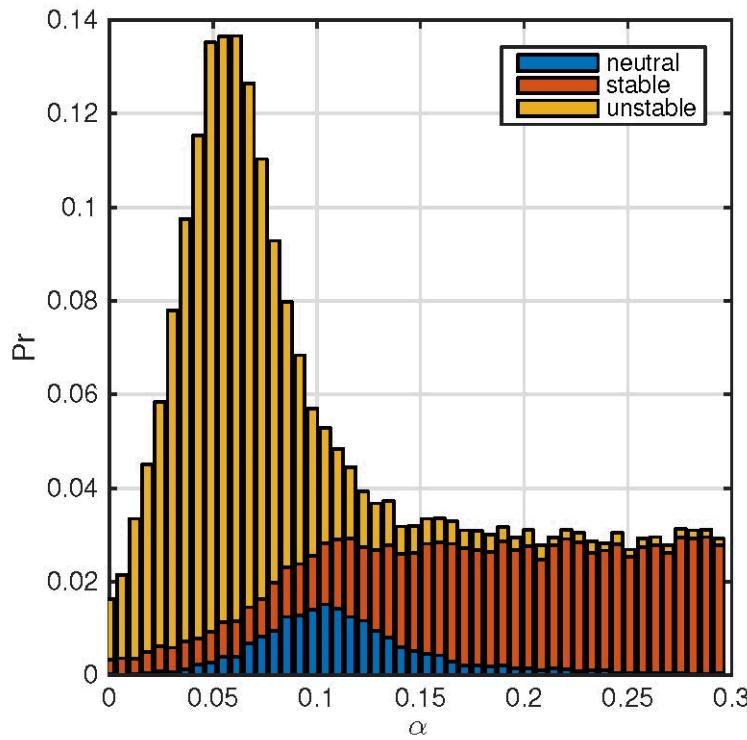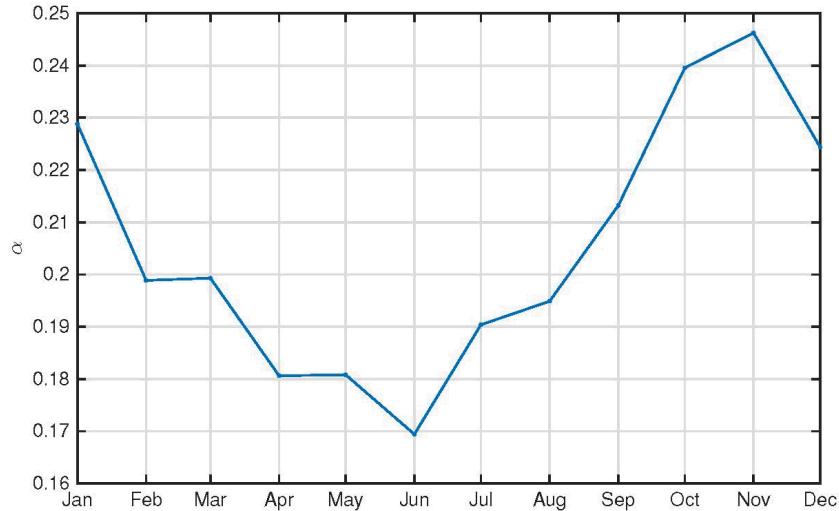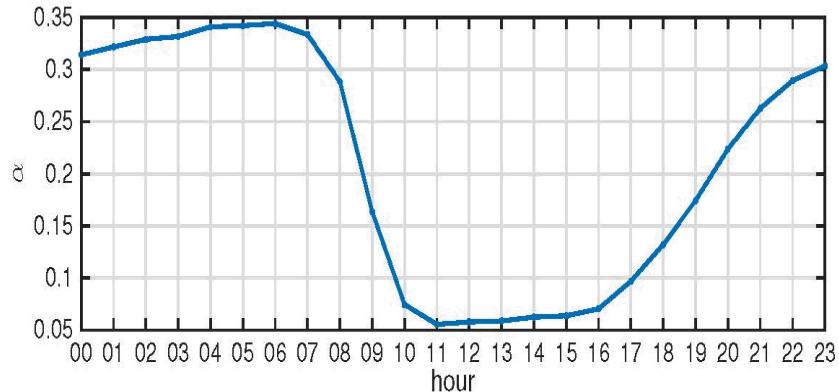
Velocity Profile Shear Trends

- Due to turbulent mixing, unstable ABL's have the lowest shear

- Shear exponent peak = 0.05

- Correlation between turbulence intensity and the velocity profile is observed
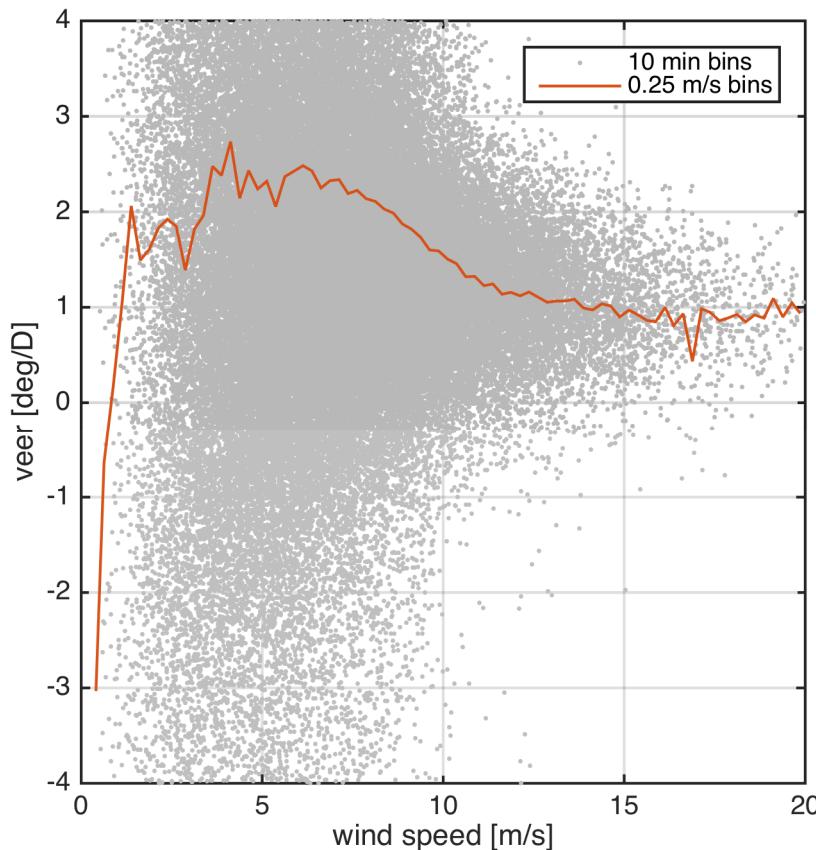
- Low TI typically has high shear

27
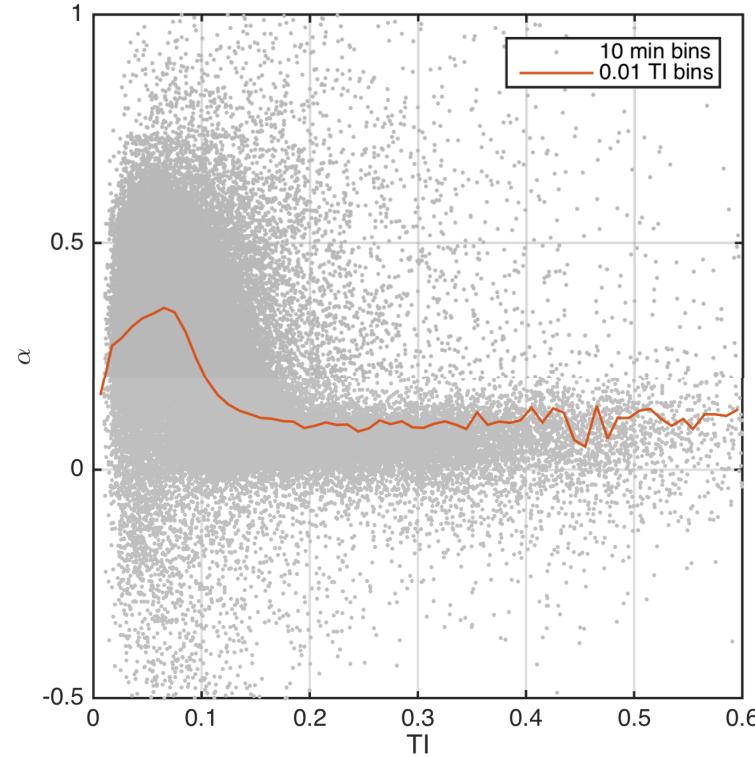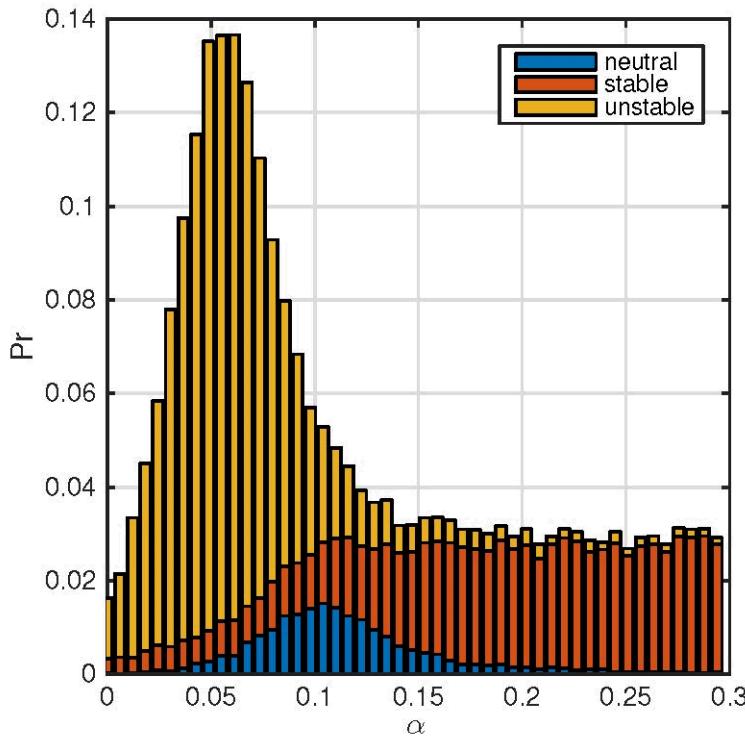
Velocity Profile Shear Trends

- In the average day, the shear exponent varies from about 0.35 to 0.05

- For a statistically significant amount of high shear cases testing should be performed at night or early morning

- The highest shear cases occur in late Fall where there is less turbulence


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Velocity Profile Veer Trends

- Highest values of veer occur most commonly at lower wind speeds (up to about 10 m/s)

- Due to the correlation between stable cases and wind speed

- Veer averages of 2 degrees are seen, with 10 min average data points exceeding 4 deg of veer

Velocity Profile Veer Trends

- High values of veer are mostly seen with high values of shear

- But, veer with low shear happens – less frequently

- Correlation between turbulence intensity and the velocity profile is observed

- Low TI typically has high shear
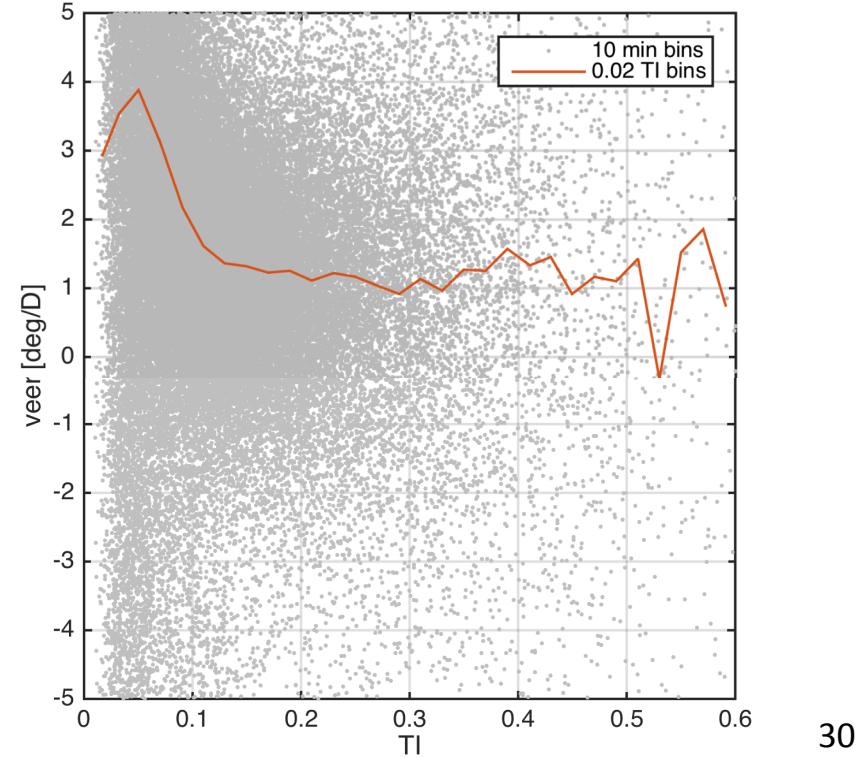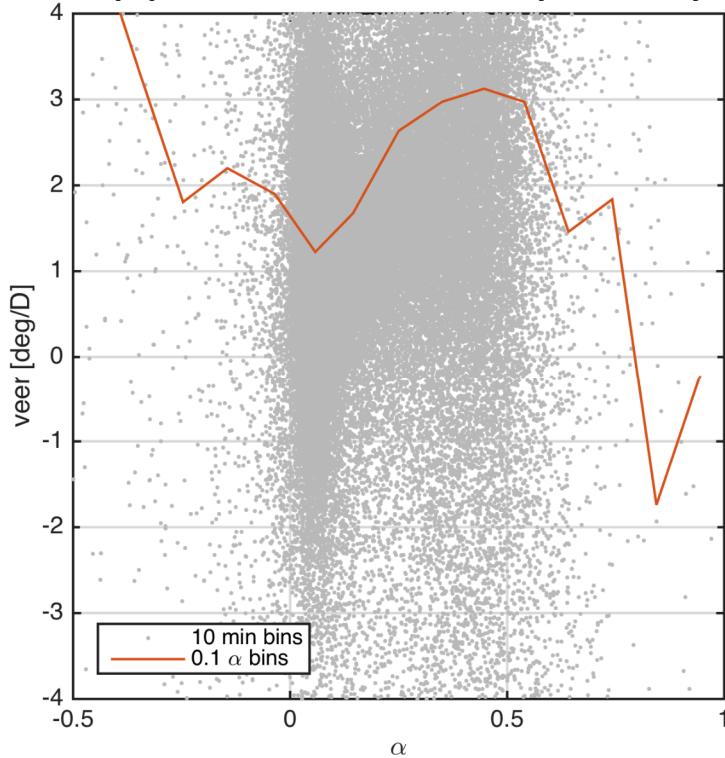
Potential Future Work

- SAND report to be released by 12/24/15 – *SWiFT Site Atmospheric Characterization*

- Dataset can be used to compare atmospheric trends for utility size turbine and SWiFT scale
  - Trends must be scaled by relevant rotor parameters
  - Atmospheric scale comparison

- Future updates to the analysis and document revisions when additional data become available from TTU – potentially annual updates
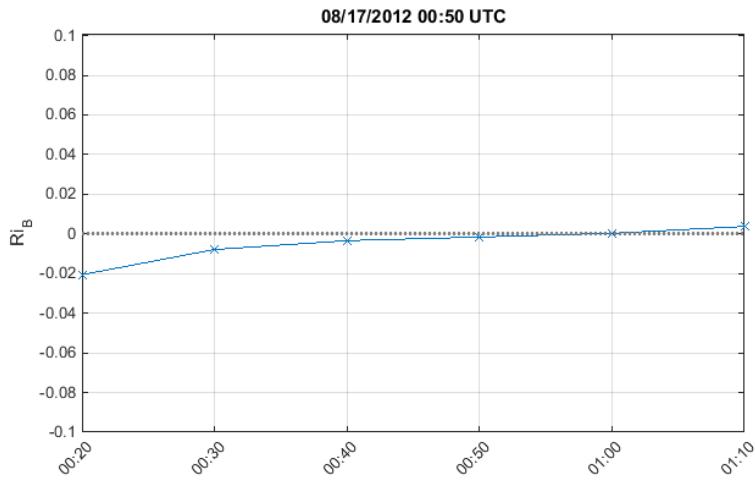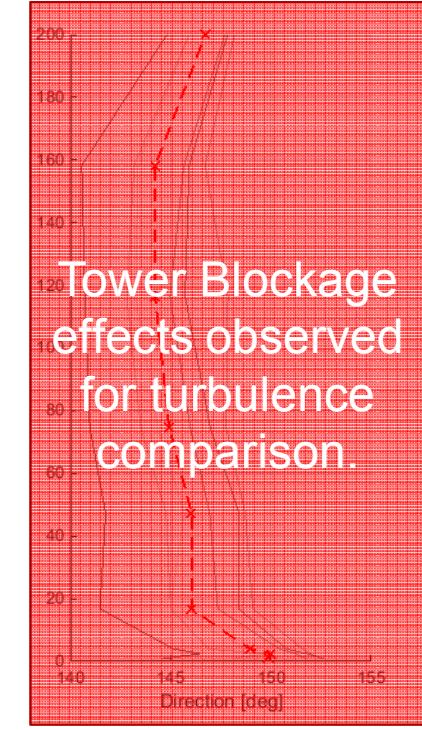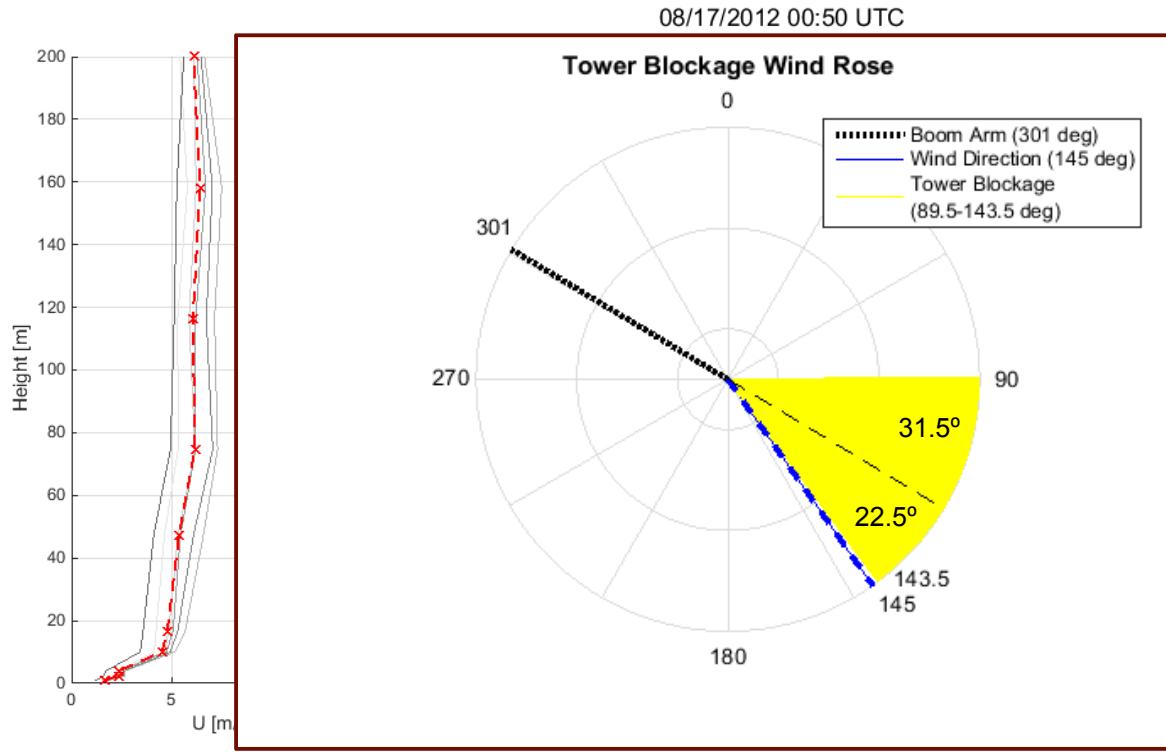
Acknowledgments

Thanks to **DOE EERE** for funding this work package to characterize the SWiFT site.

Thanks to **Texas Tech University** for providing this high-quality historical dataset and support.

BACKUP SLIDES

Neutral Case – 08/17/12

08/17/2012 00:50 UTC

Tower Blockage Wind Rose

- Boom Arm (301 deg)
- Wind Direction (145 deg)
- Tower Blockage (89.5-143.5 deg)

31.5°

22.5°

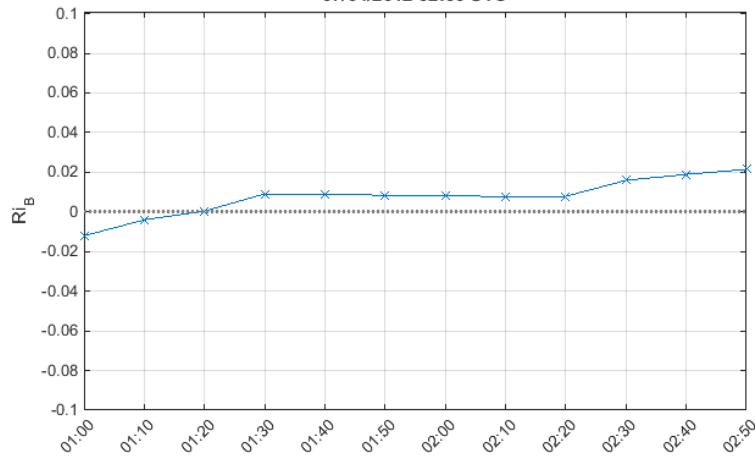Tower Blockage effects observed for turbulence comparison.

08/17/2012 00:50 UTC

- Tower Blockage direction sector determined from a comparison of the tower and Sodar by Deola in 2009 (SAND2009-7895)

- Sector should be increased to account for the turbulence effects from the tower wake

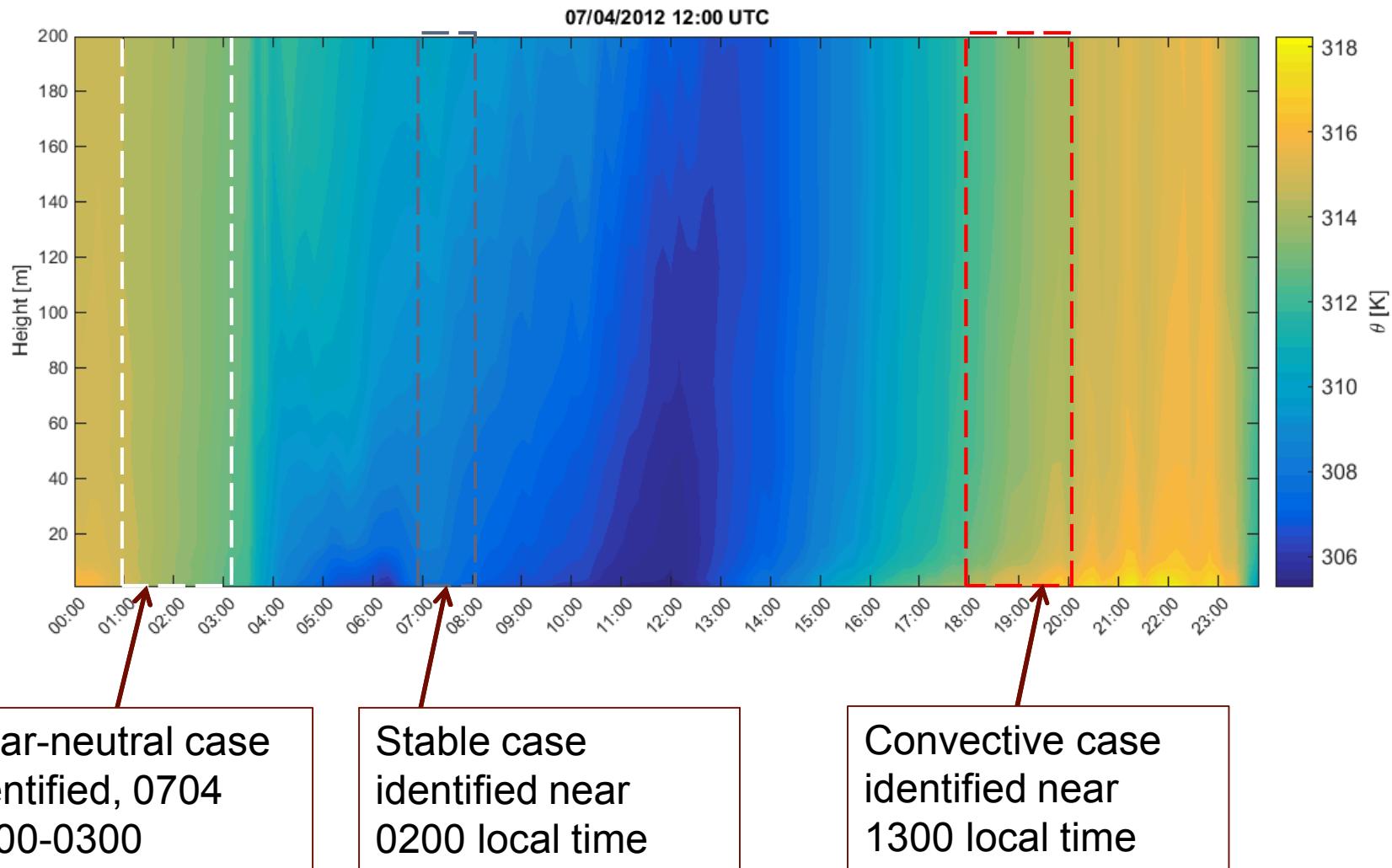# Neutral Case – 07/04/12 – *future case*
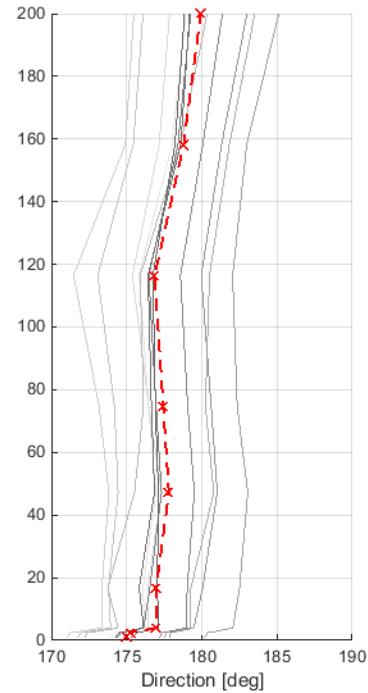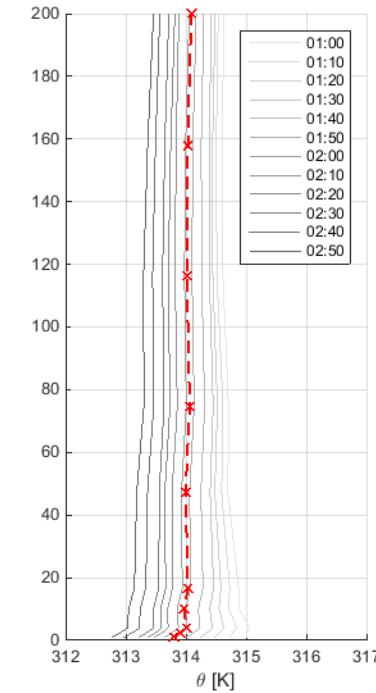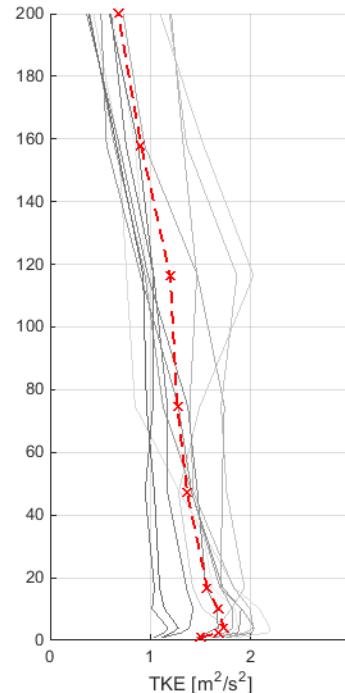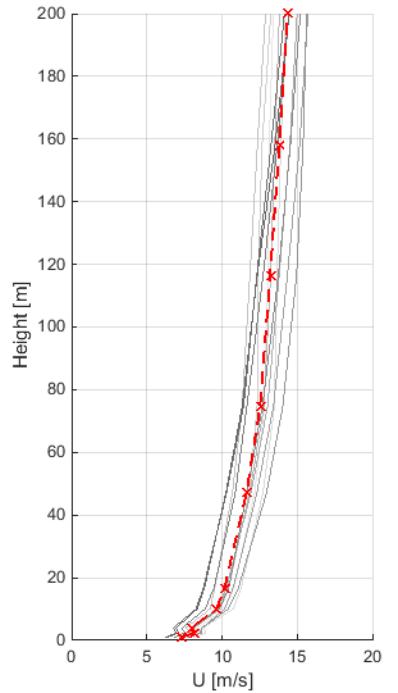
07/04/2012 02:00 UTC

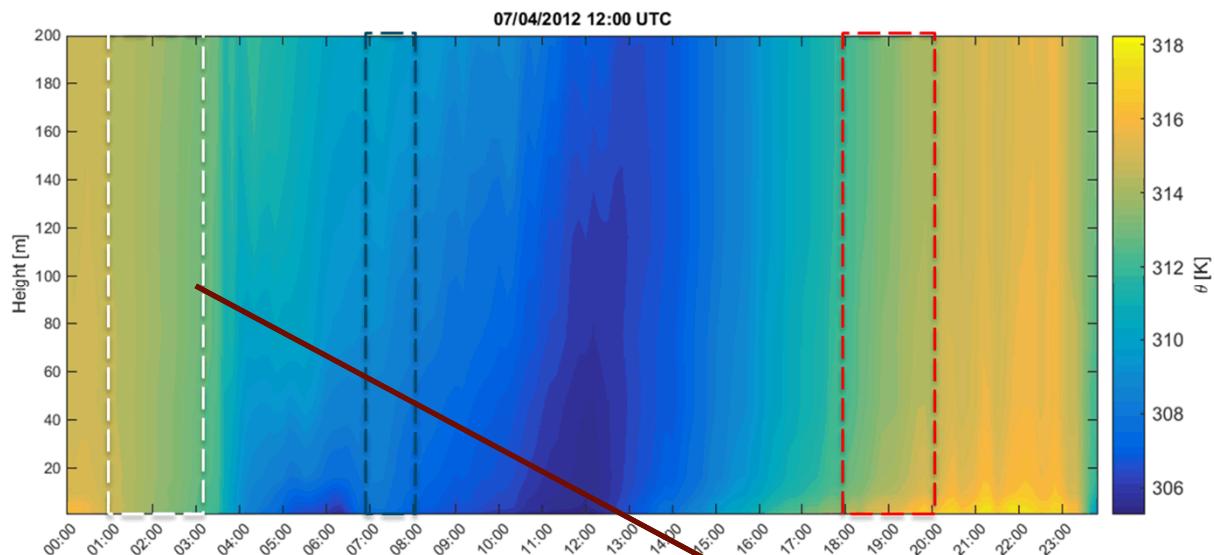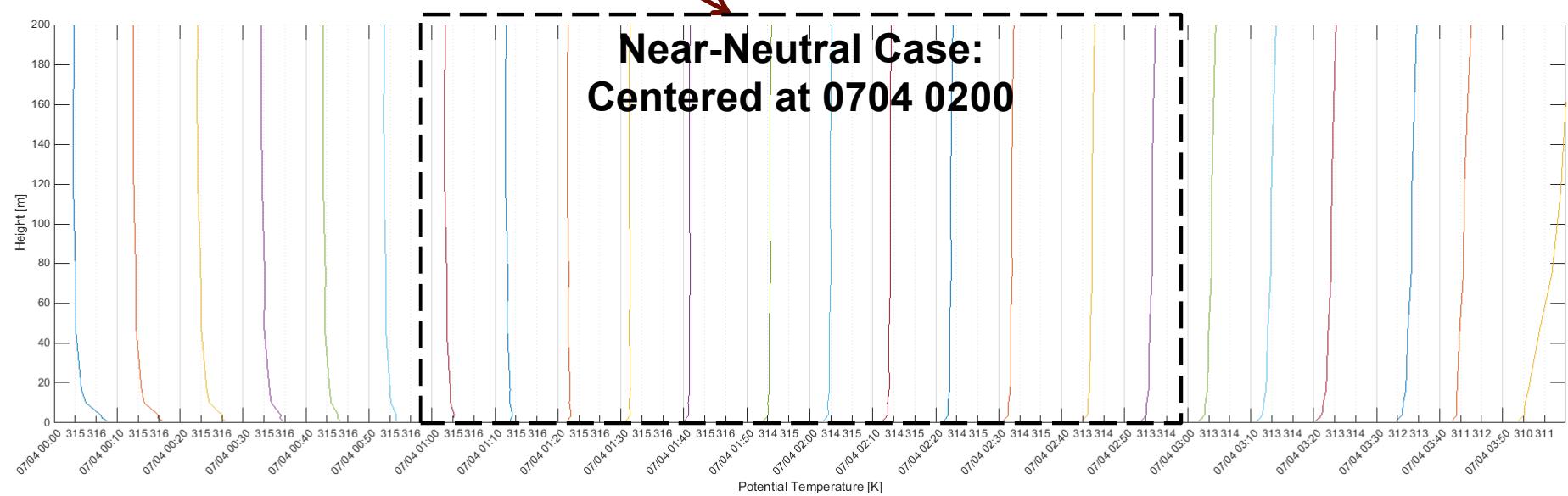# Case Identification – Stable and Convective

Potential Temperature Evolution (1-day)

Near-neutral case identified, 0704 0100-0300

Stable case identified near 0200 local time
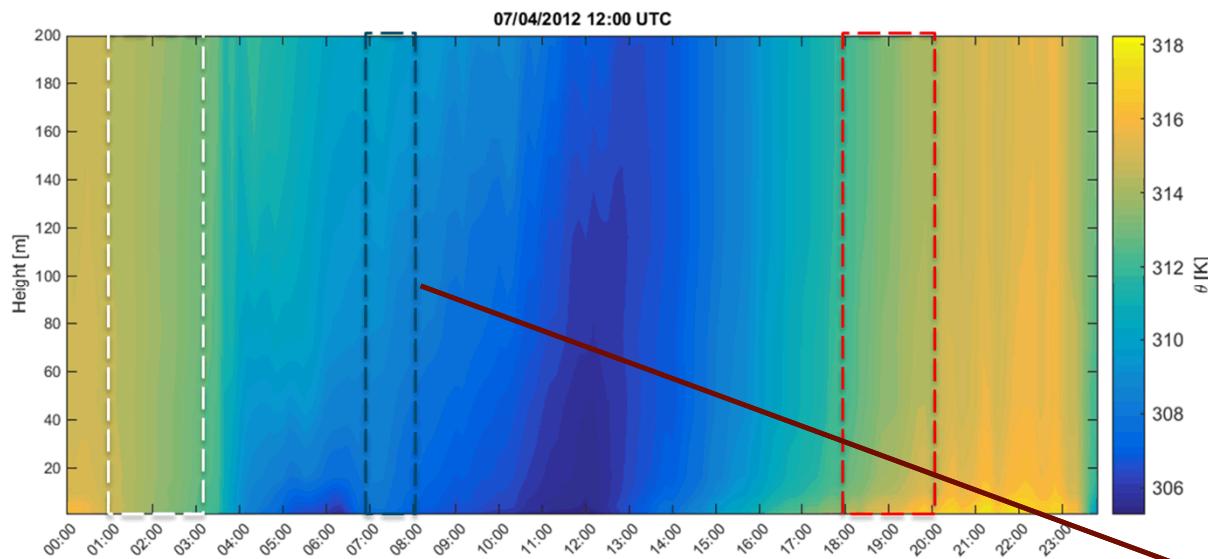
Convective case identified near 1300 local time

Case Identification – Stable and Convective

Evening Transition from convective to stable at 8pm local time

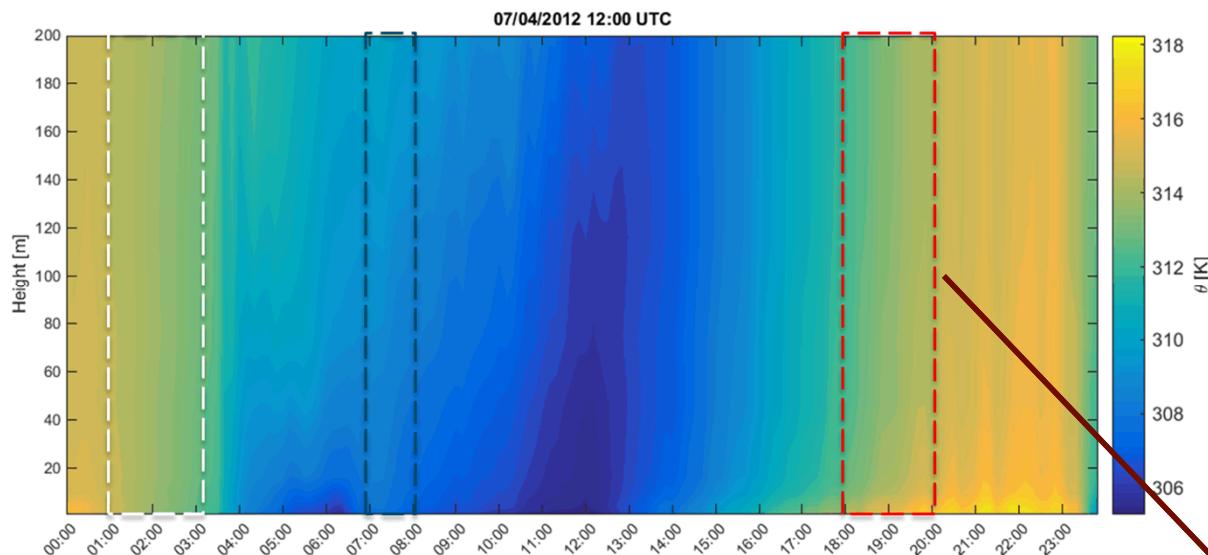Near-Neutral Case: Centered at 0704 0200

Case Identification – Stable and Convective

Stable case chosen through data comparison to WRF simulations
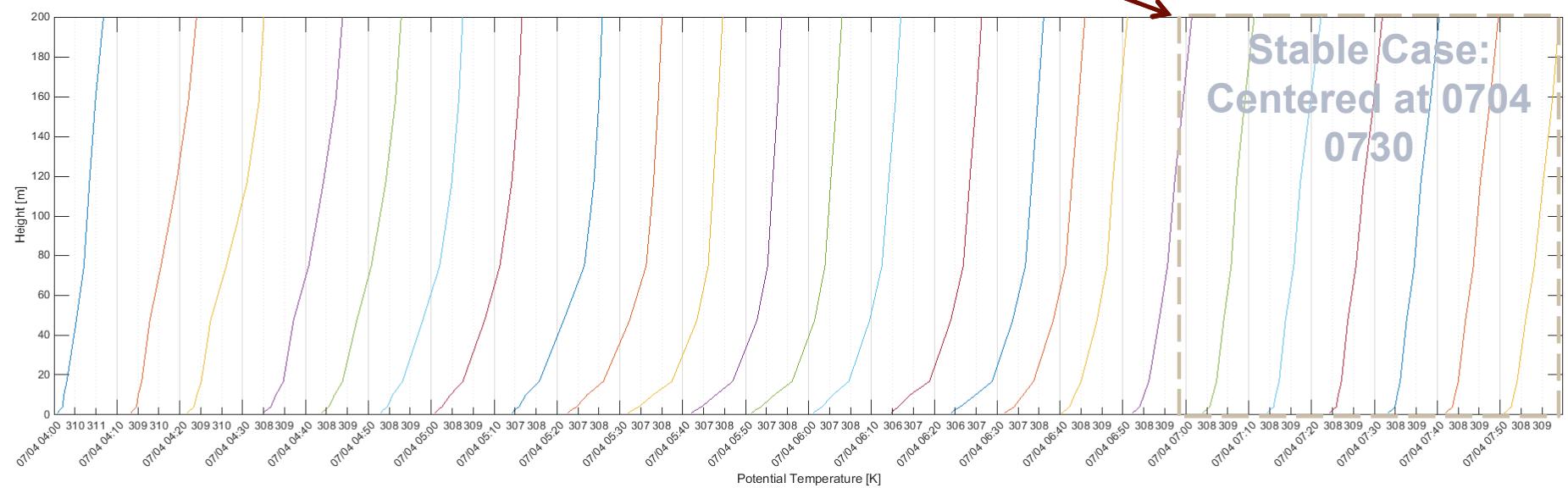
Case Identification – Stable and Convective

Convective case chosen through data comparison to WRF simulations

Convective Case:
Centered at 0704 1900