Atmospheric Boundary Layer & Wind Turbine Interactions

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Acknowledgement: NSF and Dr. Matt Churchfield (NREL)

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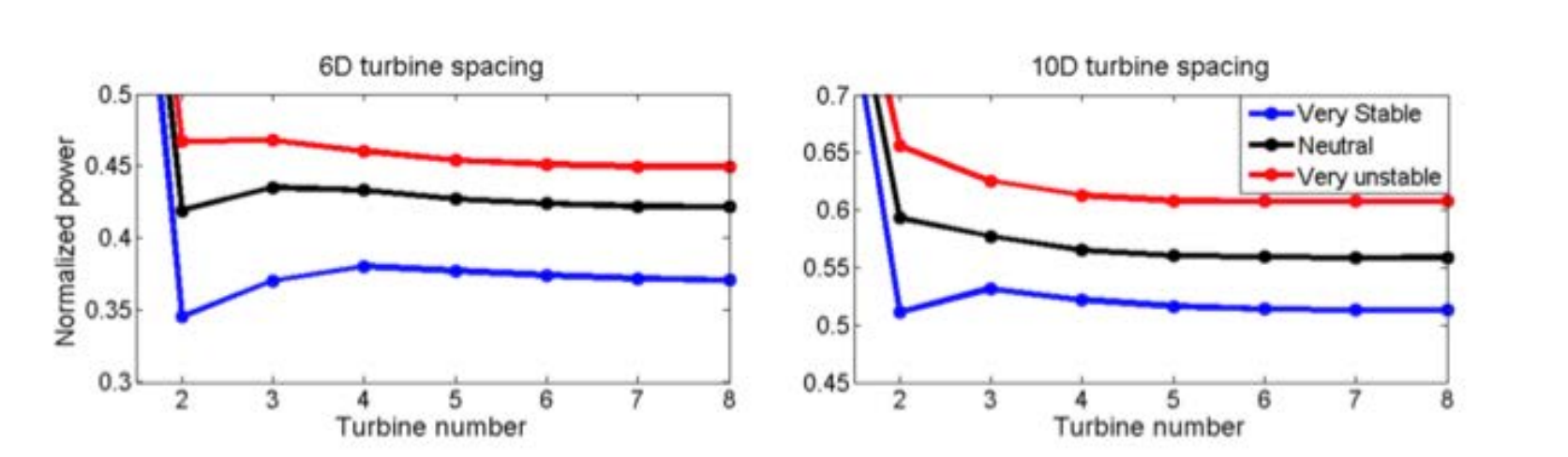
Department of Mechanical Engineering

Motivation: What are the imminent issues?



Motivation: What are the imminent issues?

Stability class	Boundary layer properties	Hub-height wind speed	Wind shear	Turbulence
Strongly stable	Highest shear in swept-area, nocturnal LLJ may be present, little turbulence except just below the LLJ	Strong, especially at night	Highest: $\alpha > 0.3$	Lowest: $I_U < 8\%$; $I_w < 4\%$; TKE < 0.4 m^2 s^{-2}
Stable	High wind shear in swept-area, low amount of turbulence unless a nocturnal LLJ is present	Strong, especially at night	High: $0.2 < \alpha < 0.3$	Low: $8\% < I_U < 10\%$; $4\% < I_w < 6\%$; $0.4 <$ TKE < 0.7 m^2 s^{-2}
Near-neutral	Logarithmic wind profile	Generally strongest	Moderate: $0.1 < \alpha < 0.2$	Moderate: $10\% < I_U < 13\%$; $6\% < I_w < 9\%$ $0.7 <$ TKE < 1.0 m^2 s^{-2}
Convective	Lower wind speeds, low shear in swept-area, high amount of turbulence	Low	Low: $0.0 < \alpha < 0.1$	High: $13\% < I_U < 20\%$; $9\% < I_w < 17\%$ $1.0 <$ TKE < 1.4 m^2 s^{-2}.
Strongly convective	Lowest wind speeds, very little wind shear in swept-area, highly turbulent	Lowest	Lowest: $\alpha < 0.0$	Highest: $I_U > 20\%$; $I_w > 17\%$; TKE > 1.4 m^2 s^{-2}.

S. Wharton and J. K Lundquist (2012)

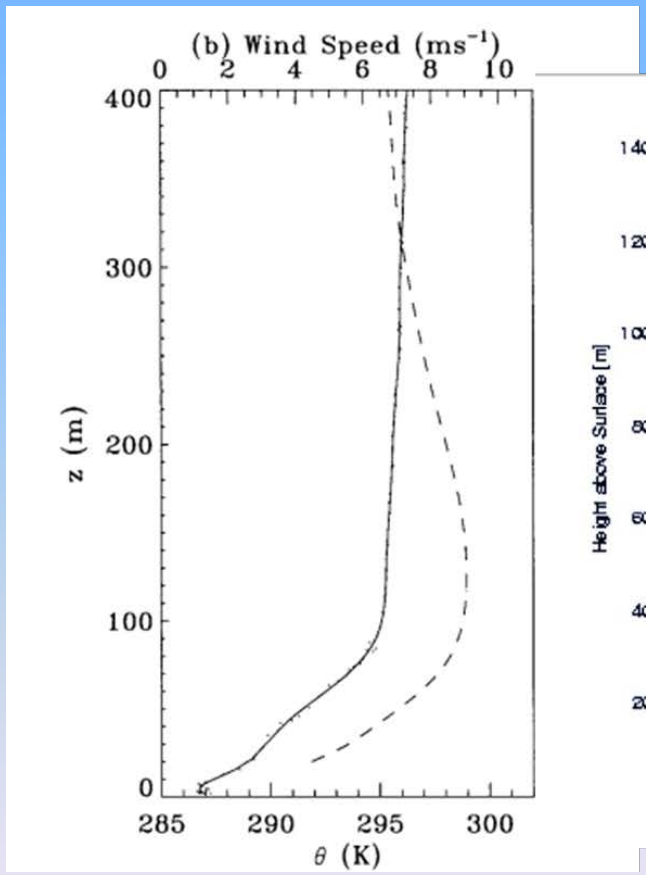
Motivation (Cntd)

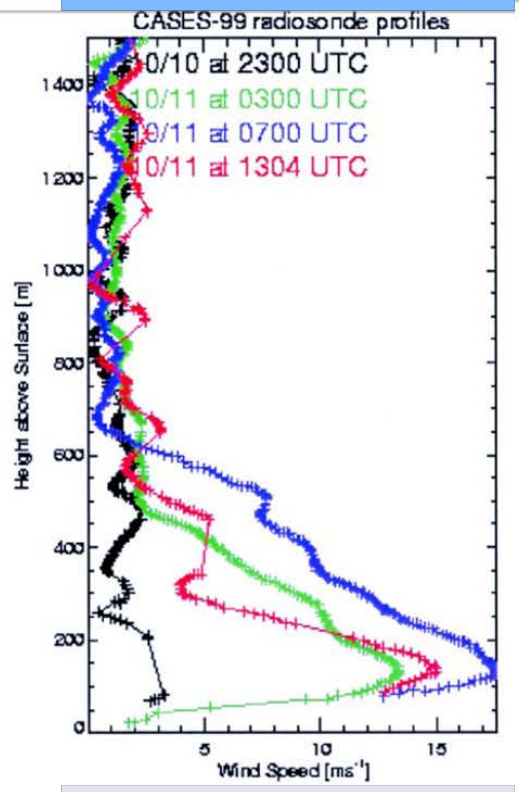
- Why is night-time (Stable) ABL so complicated?

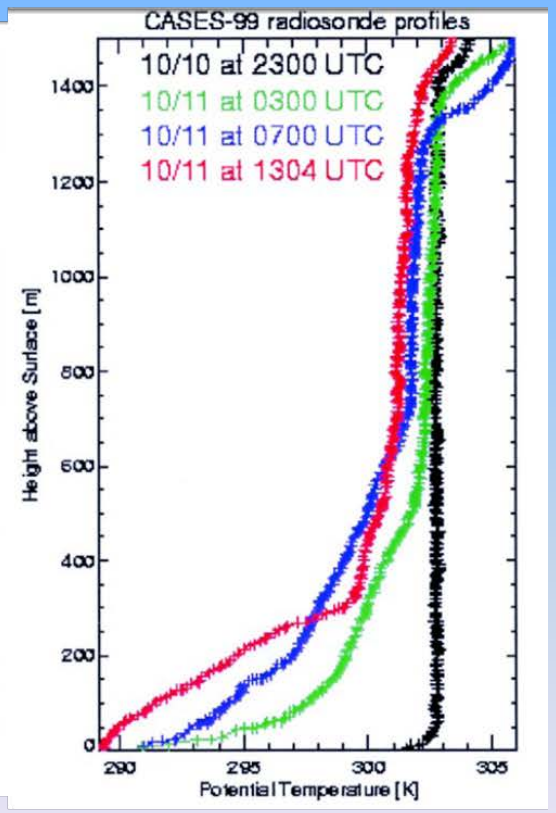
CASES-99 and GABLES Study

- LLJ
- Non-uniform shear
- Temperature gradient profile
- Wind angle
- Intermittency of turbulence in atmosphere

Motivation (Cntd)







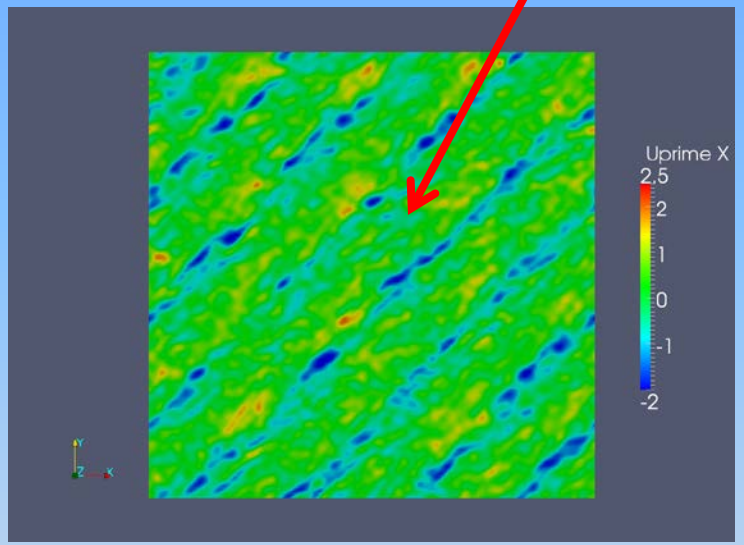
Outline of talk

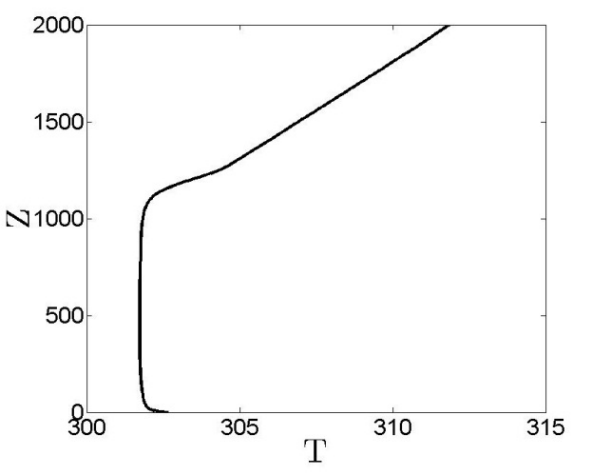
- Significance of stable ABL with different stratifications wrt WT
- Application of stable ABL with wind turbine
- Analysis of WT wake
- Different inlet condition for multiple WT

Atmospheric Boundary Layer

Convective

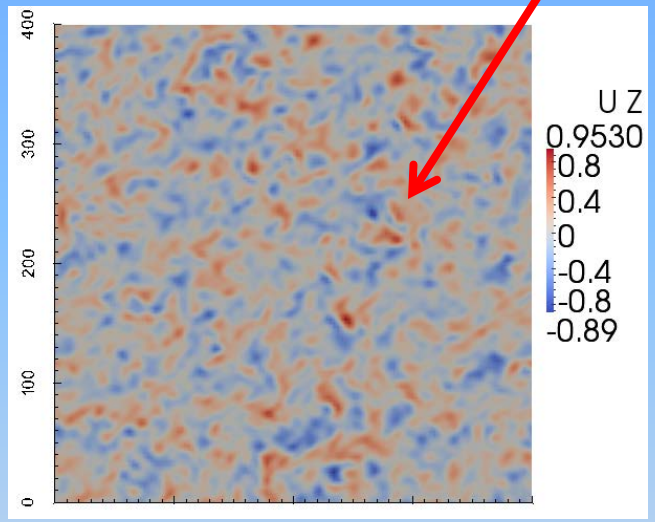
Long streaks represents large vertical structure and movement

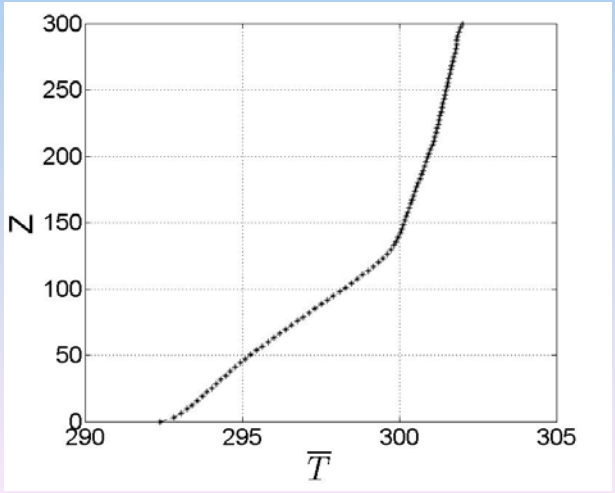




Stable

Small Structures





Methodology

- SOWFA LES code (Dr. Churchfield,NREL)
- Rigorously validated stable ABL with GABLES study (2006), classical experiments of Kosovic and Curry (2000).
- Established optimal grid spacing vs. LES model parameters (static model) as function of atmospheric stability.
- Compared static and dynamic model

LES methodology

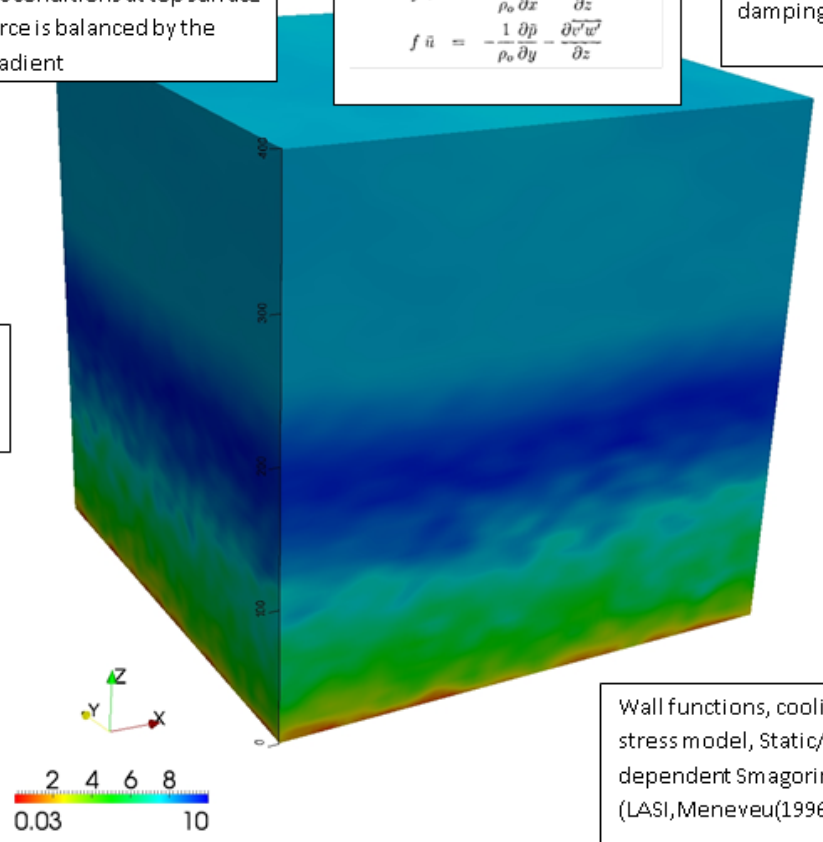
Geostrophic conditions at top surface : Coriolis force is balanced by the pressure gradient

$$-f\,\bar{v} = -\frac{1}{\rho_o}\frac{\partial \bar{p}}{\partial x} - \frac{\partial \overline{u'w'}}{\partial z}$$

$$f\,\bar{u} = -\frac{1}{\rho_o}\frac{\partial \bar{p}}{\partial y} - \frac{\partial \overline{v'w'}}{\partial z}$$

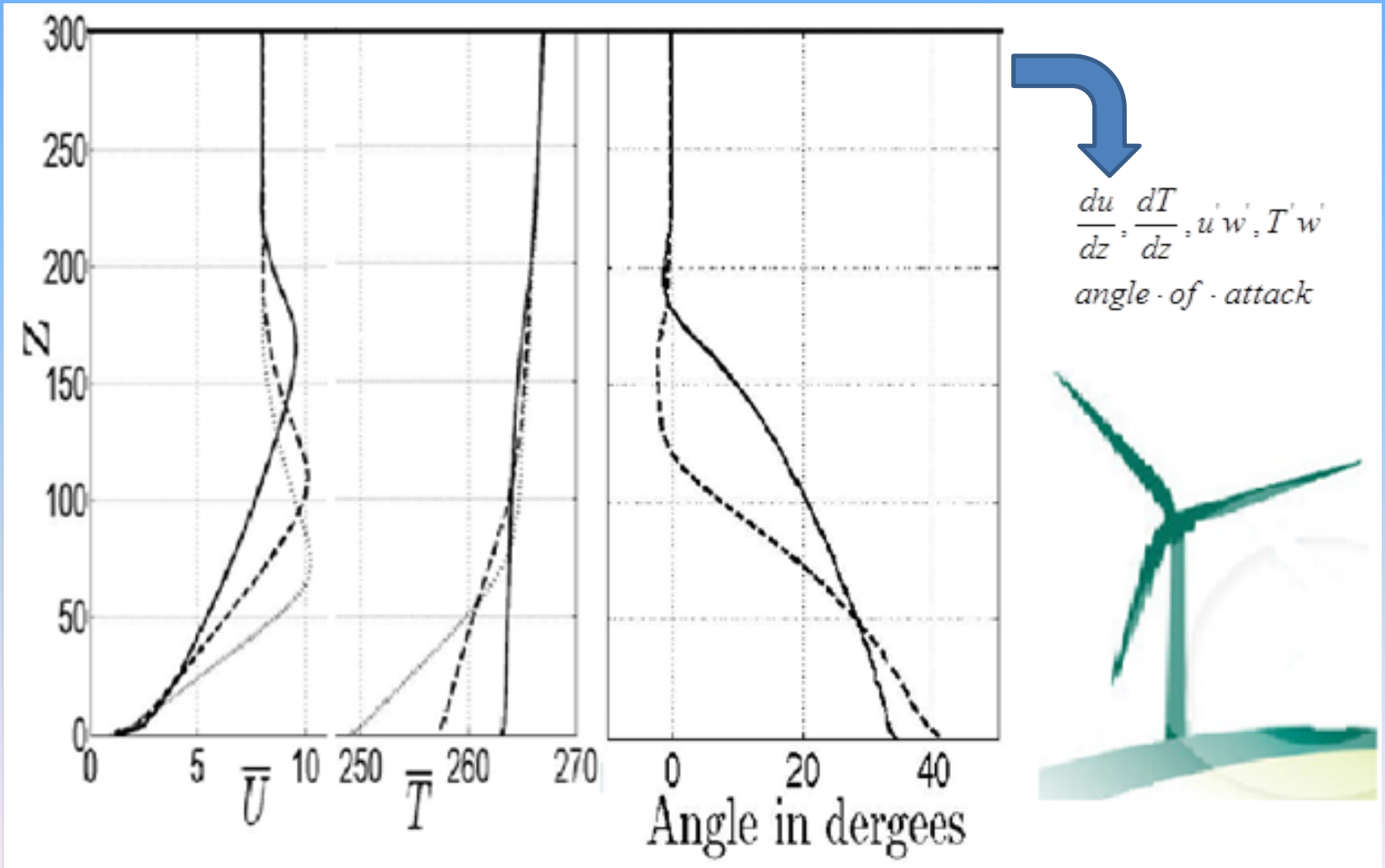
Stress free top surface. No damping function is used

Periodic boundary condition for all the sides

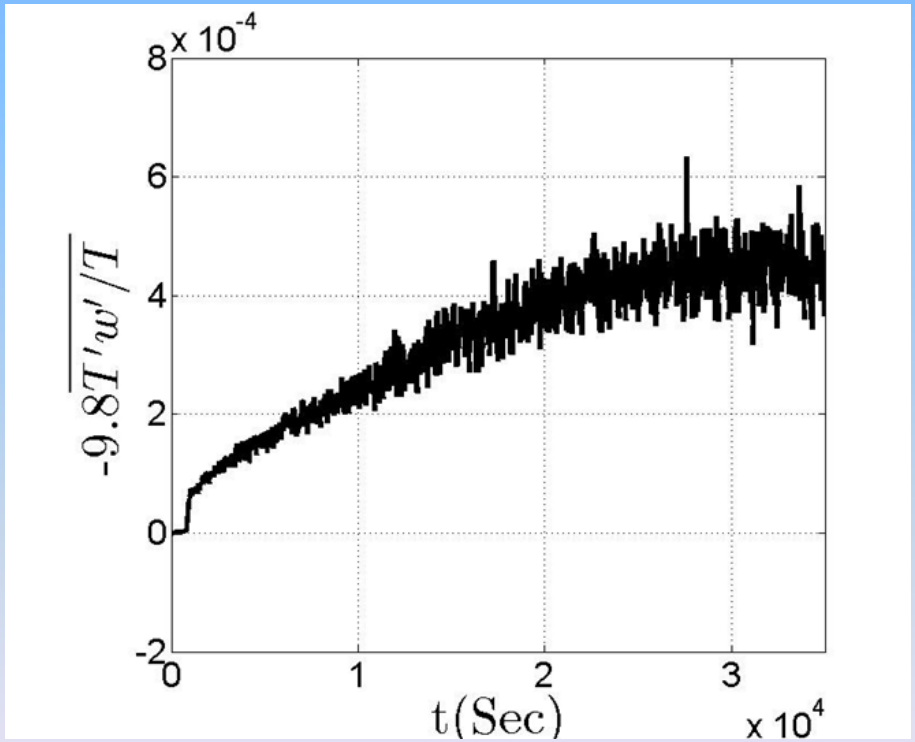


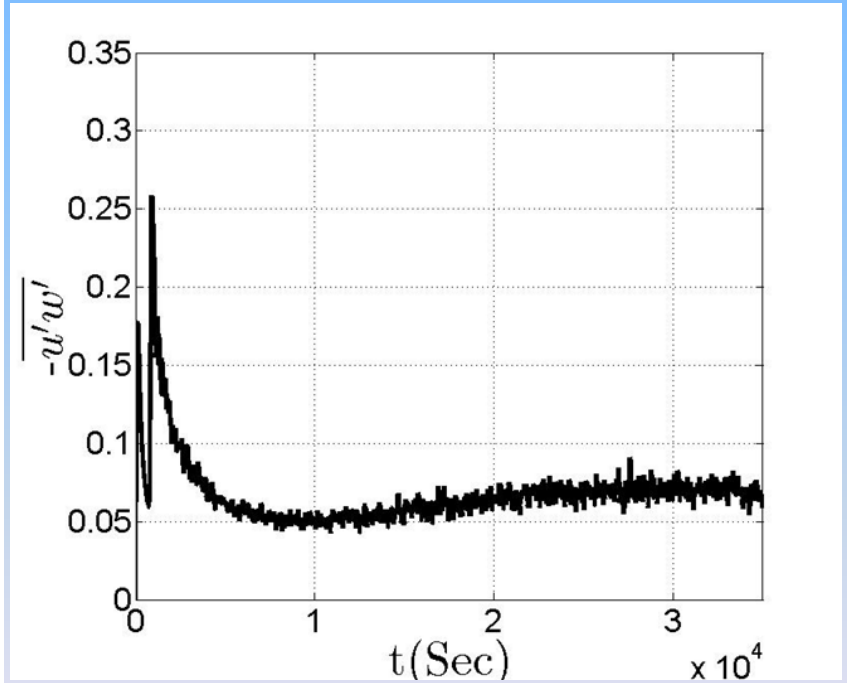
Wall functions, cooling rate, Schumann stress model, Static/dynamic scale dependent Smagorinsky model (LASI, Meneveu(1996)) for the wall

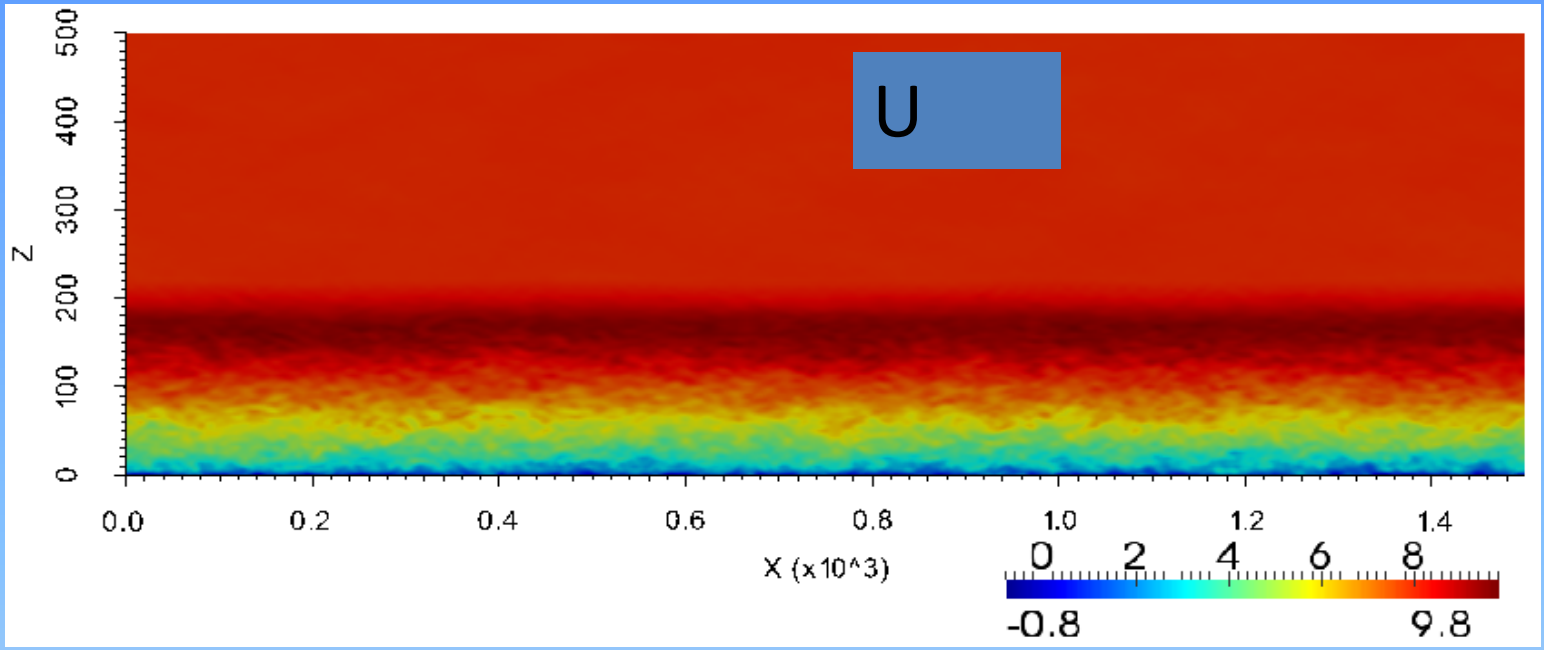
ABL metrics with different stratification: Wind Shear, Wind Angle, dT/dz, Turbulence Distribution



Time evolution of buoyancy and momentum flux



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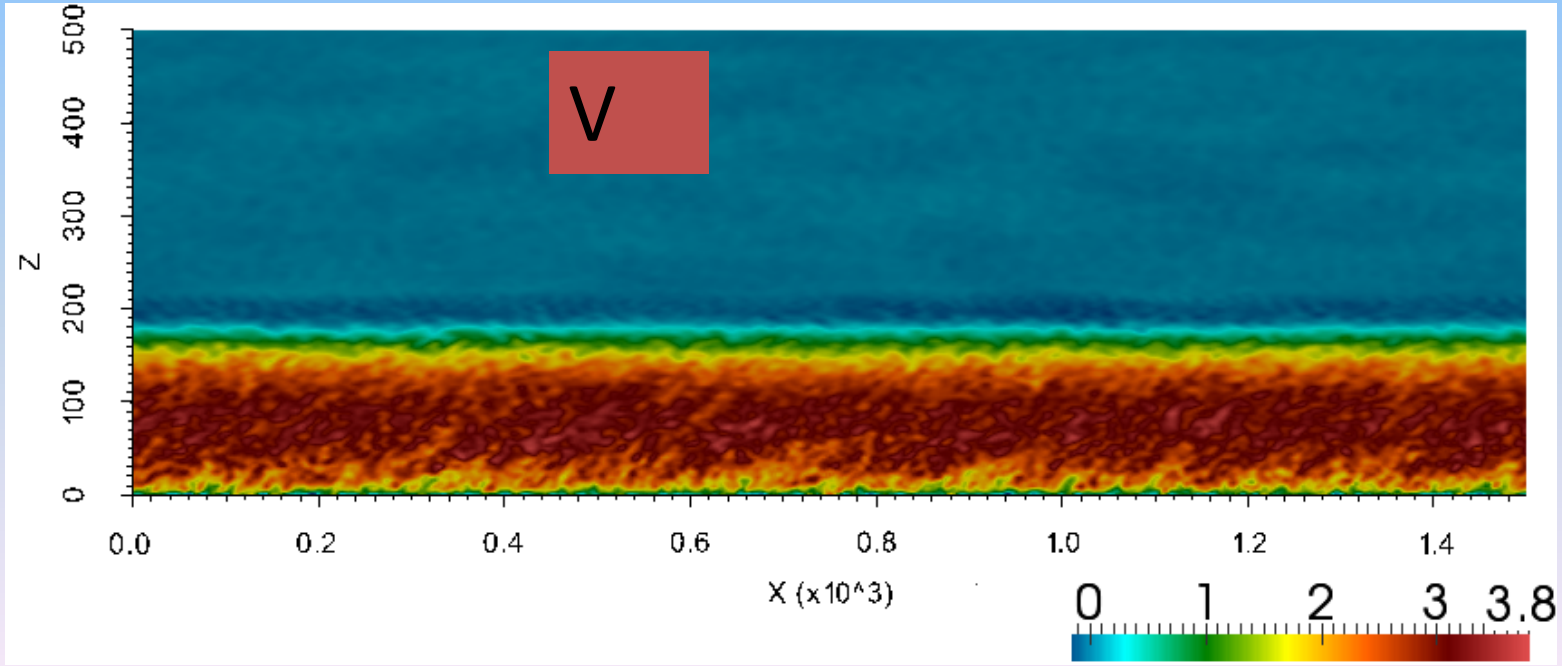
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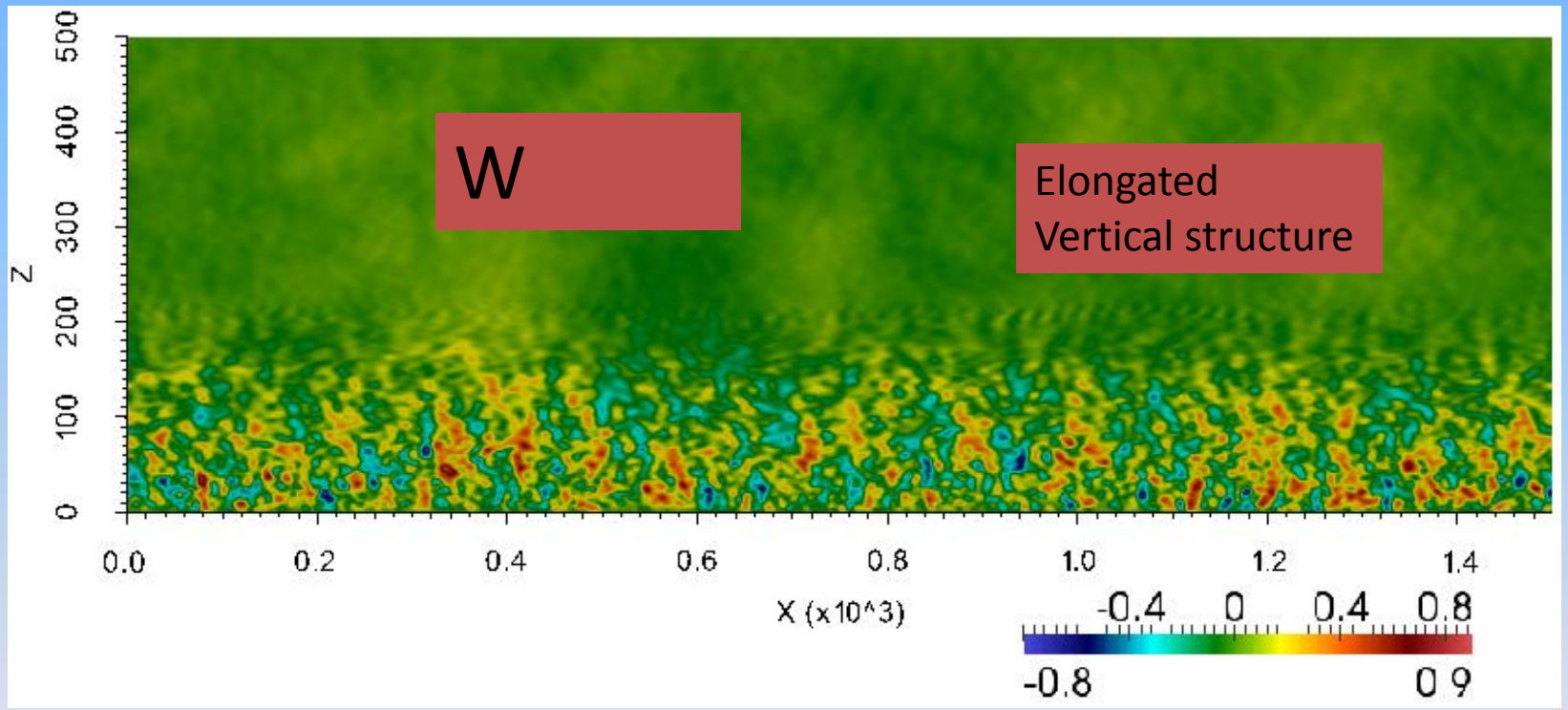
Vertical Structure



Conclusion on mean structure

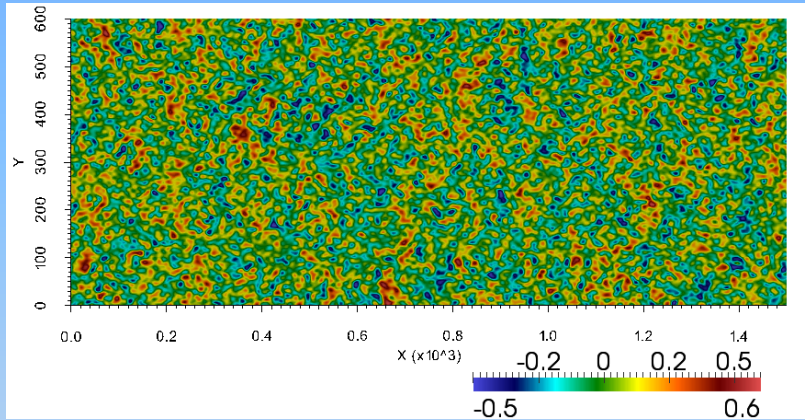
ABL metrics relevant to WT wake turbulence

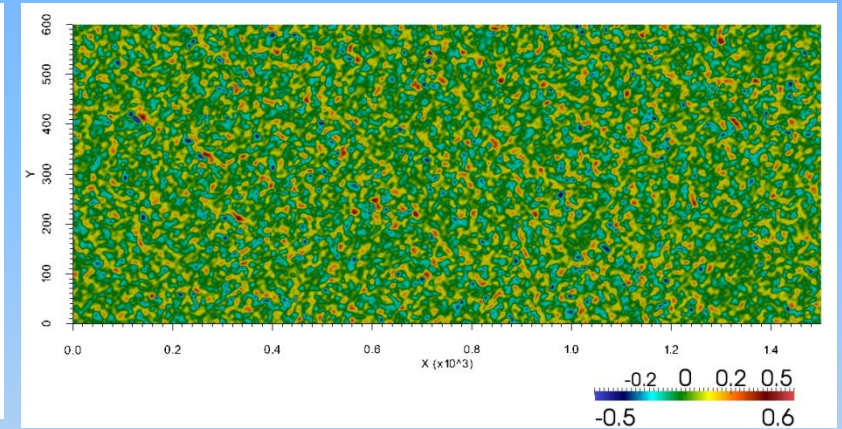
1. Location and Strength of LLJ
   (Wind shear, temperature gradient)
2. Wind angle
3. Turbulence distribution (Shear production, buoyancy dissipation)

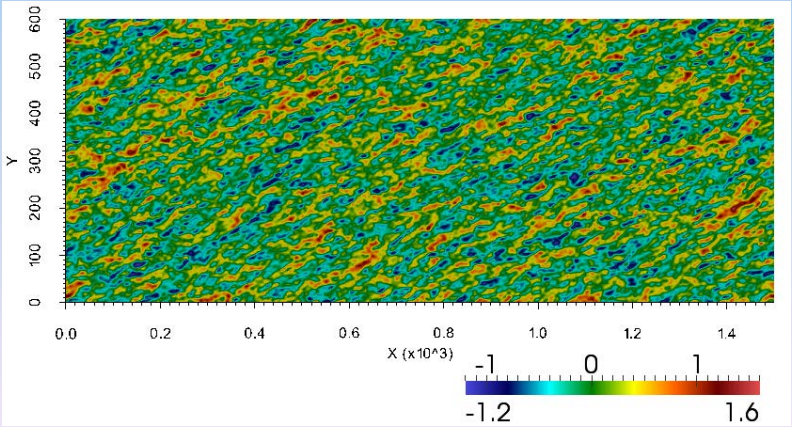
Higher Stratification Causes Smaller Scale Vertical and Horizontal Structures.

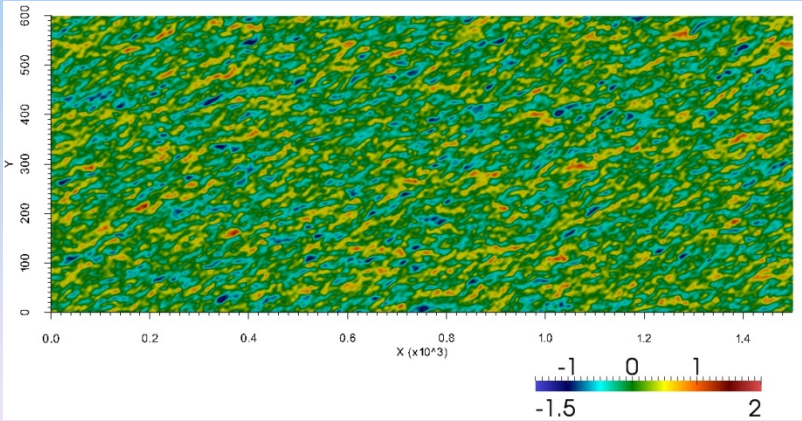
LOW STRATIFICATION

HIGH STRATIFICATION



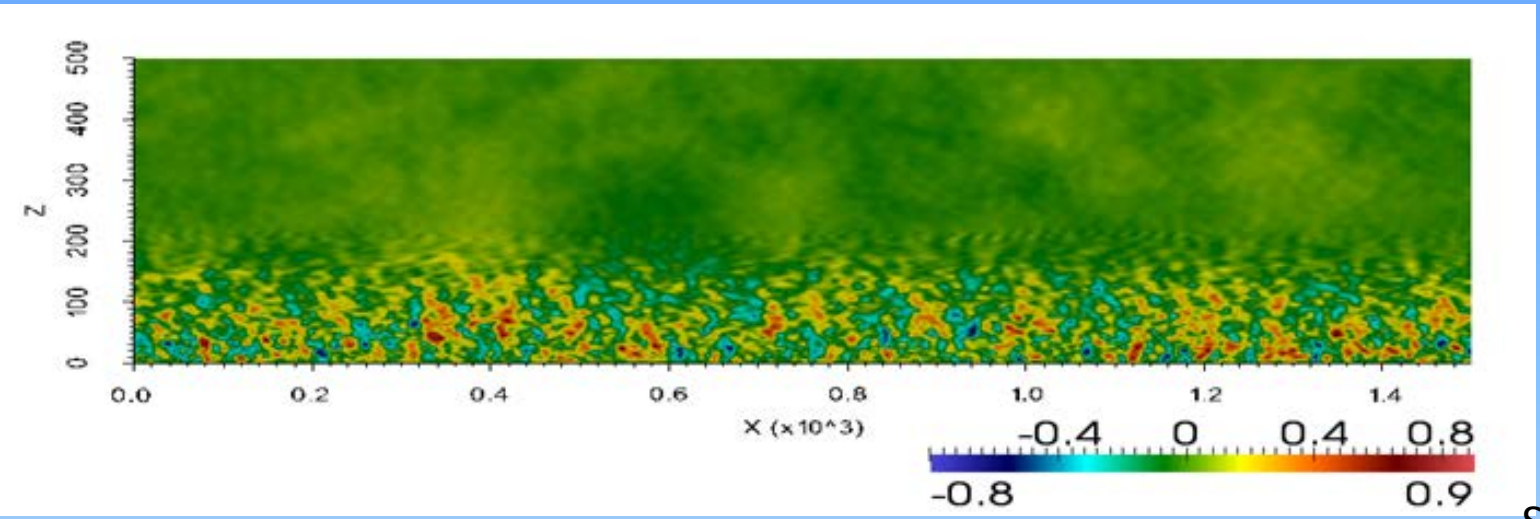




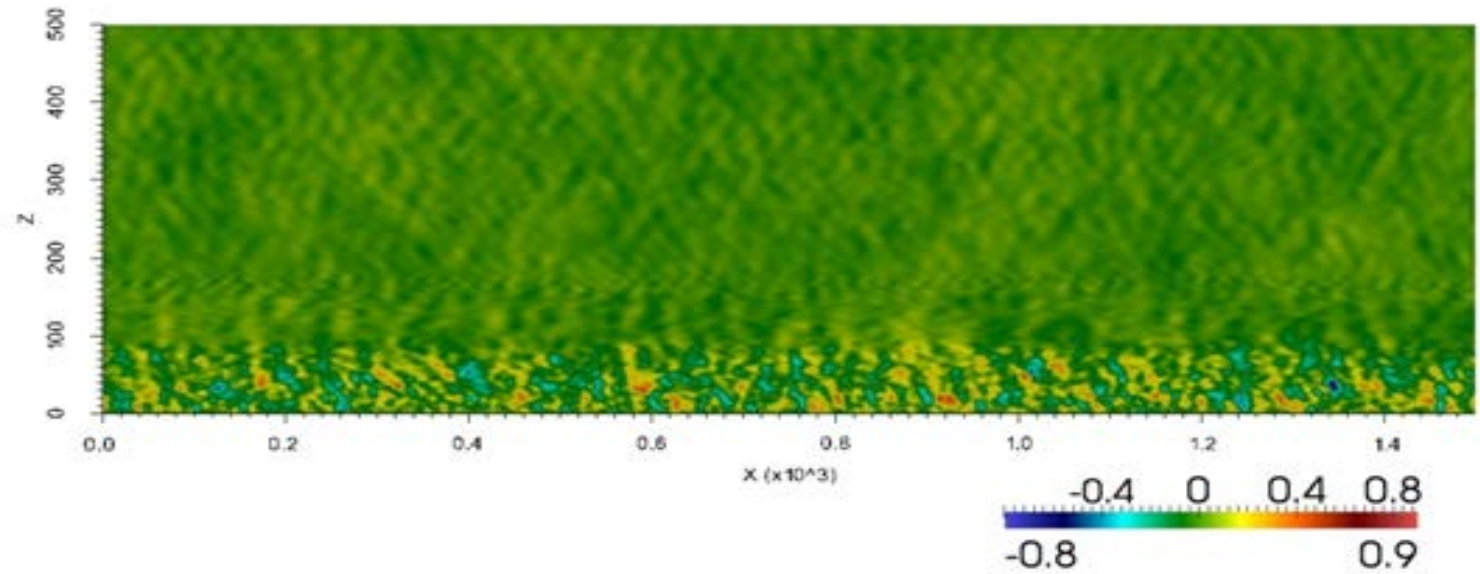


Vertical Structures: Low and High Stratification

LOW STRATIFICATION



HIGH STRATIFICATION



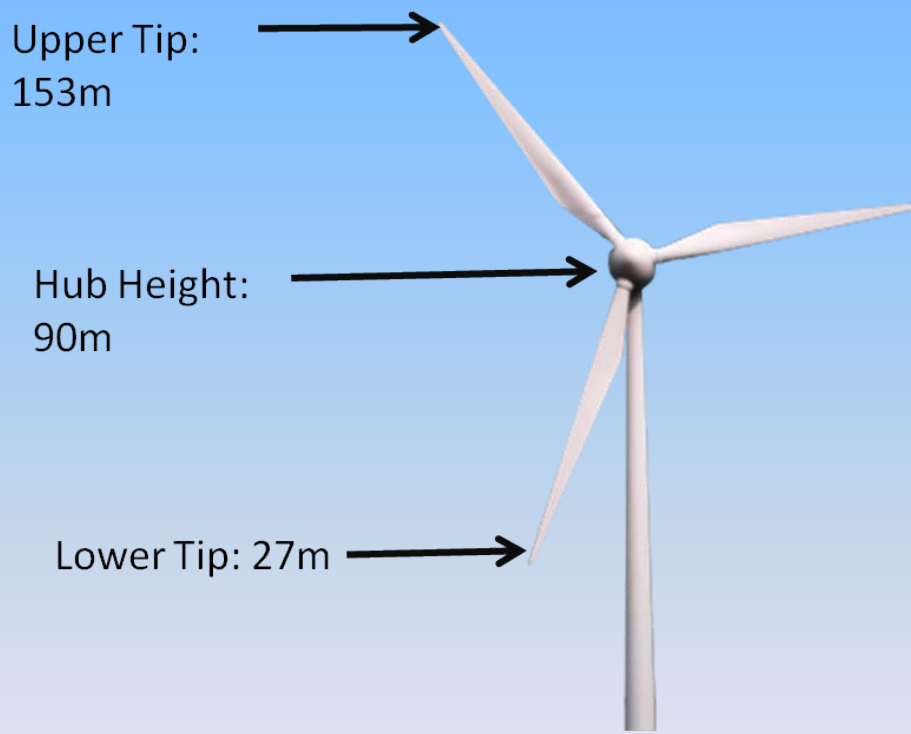
-Size and magnitude decreases with higher stratification

The effect of buoyancy dissipation

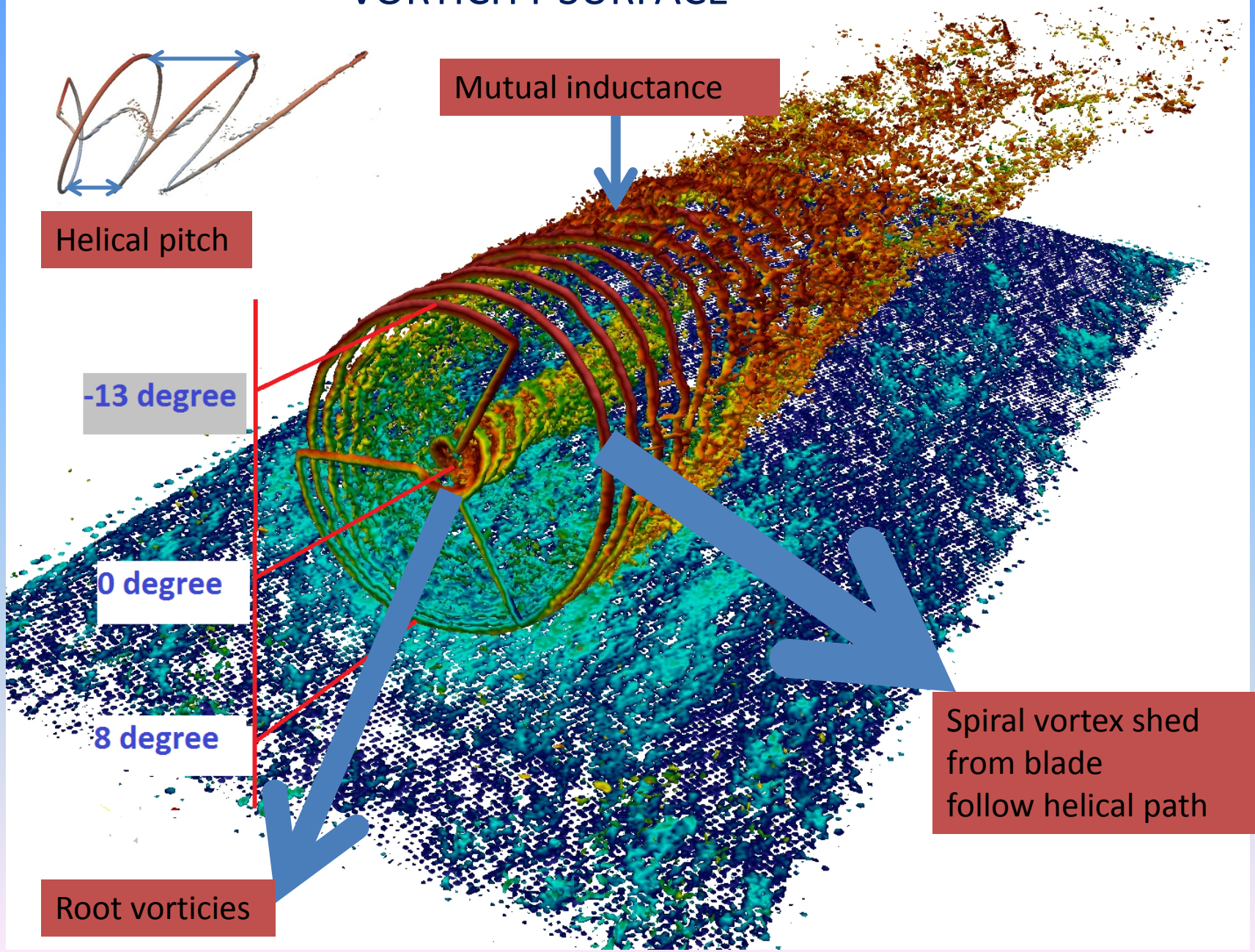
- Precursor ABL simulated for 50000s
- Atmospheric stability cases (Low an High stratification with continuous turbulence(Ri <0.25))
- WT simulation for 250sec

Low Stratification

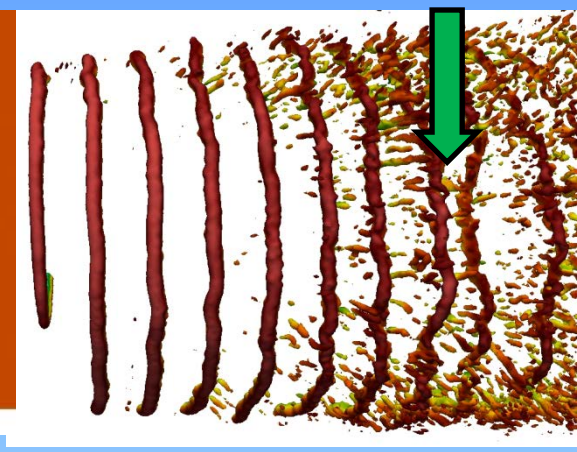
- Cooling rate = 0.25K/hr
- ABL height = 165m
- LLJ = 175m (peak velocity 10m/s)
- (above WT height)
- Surface temperature=263K
- Geostrophic wind=8m/s
- Wind angle varies 35 degrees (surface), 31 (lower blade tip), 23 (hub), 0 (183m above the LLJ height)



VORTICITY SURFACE

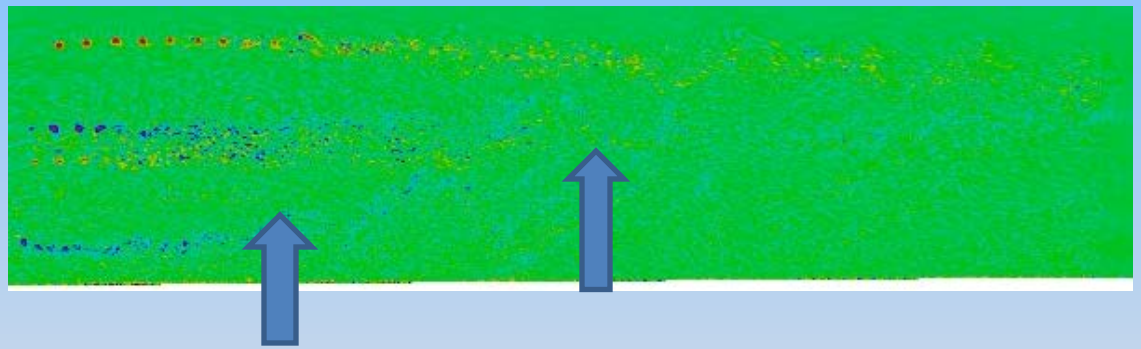


Mutual inductance mode of instability



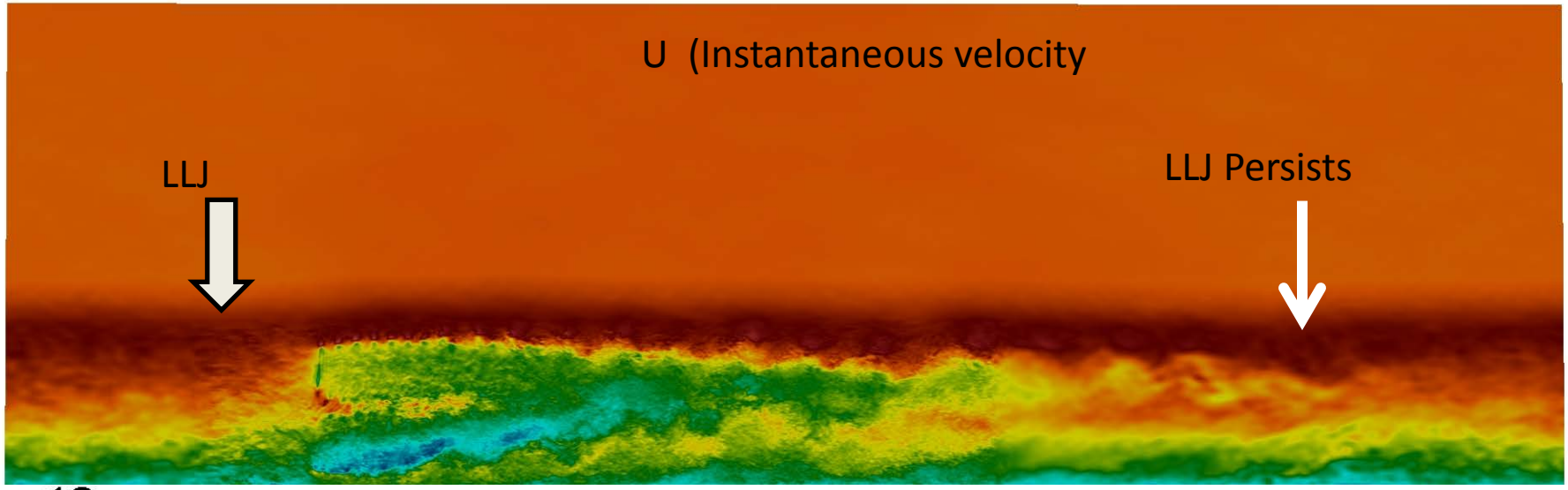
Upper-tip of spiral vortex

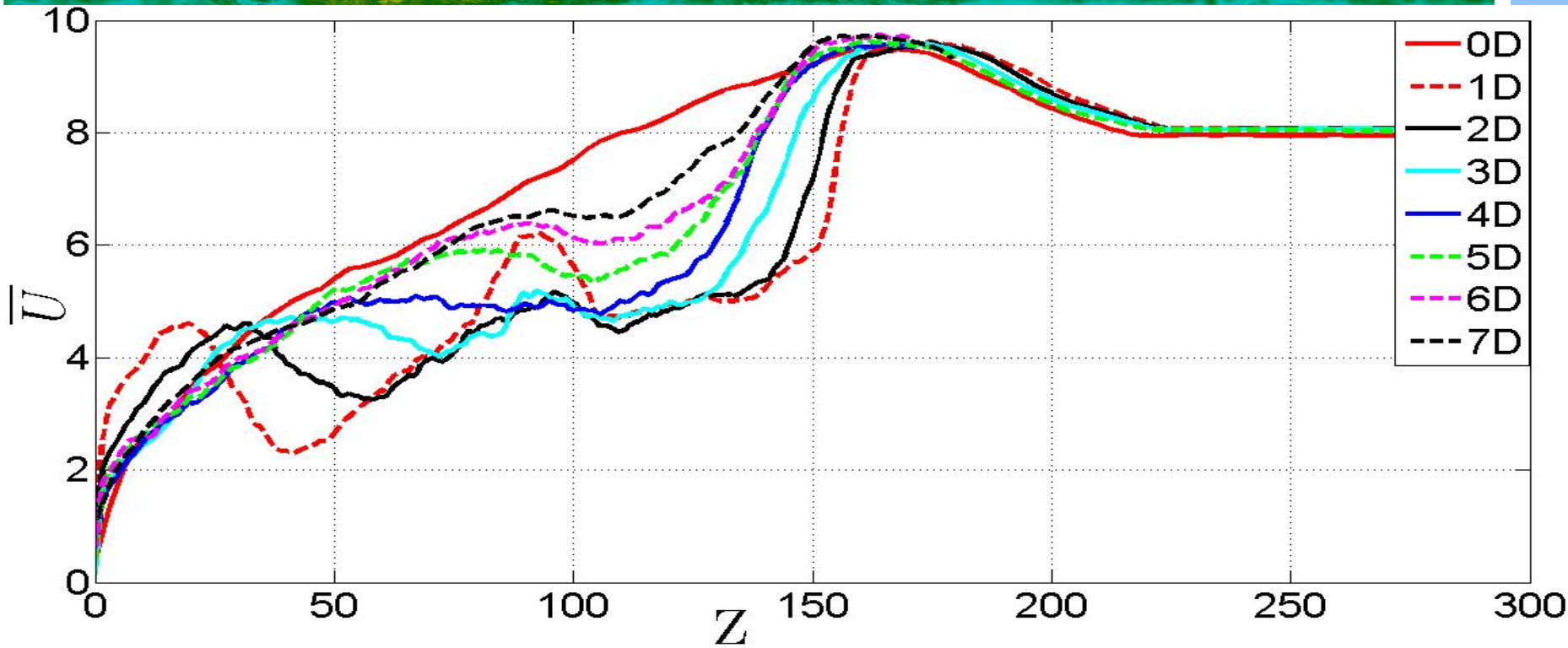
Lower-tip of spiral vortex



Mode of instability: Mutual inductance

- Vortex merging is detected: Mutual inductance between neighboring helical spirals caused the merging with the resultant merged vortices moving as a blob.
- Higher tip speed ratio with shear creates shear layer
- Wake meandering: Striking of the lower tip vortex with hub causes the meandering of both tip and hub vortex.


U (Instantaneous velocity
LLJ
LLJ Persists


0D
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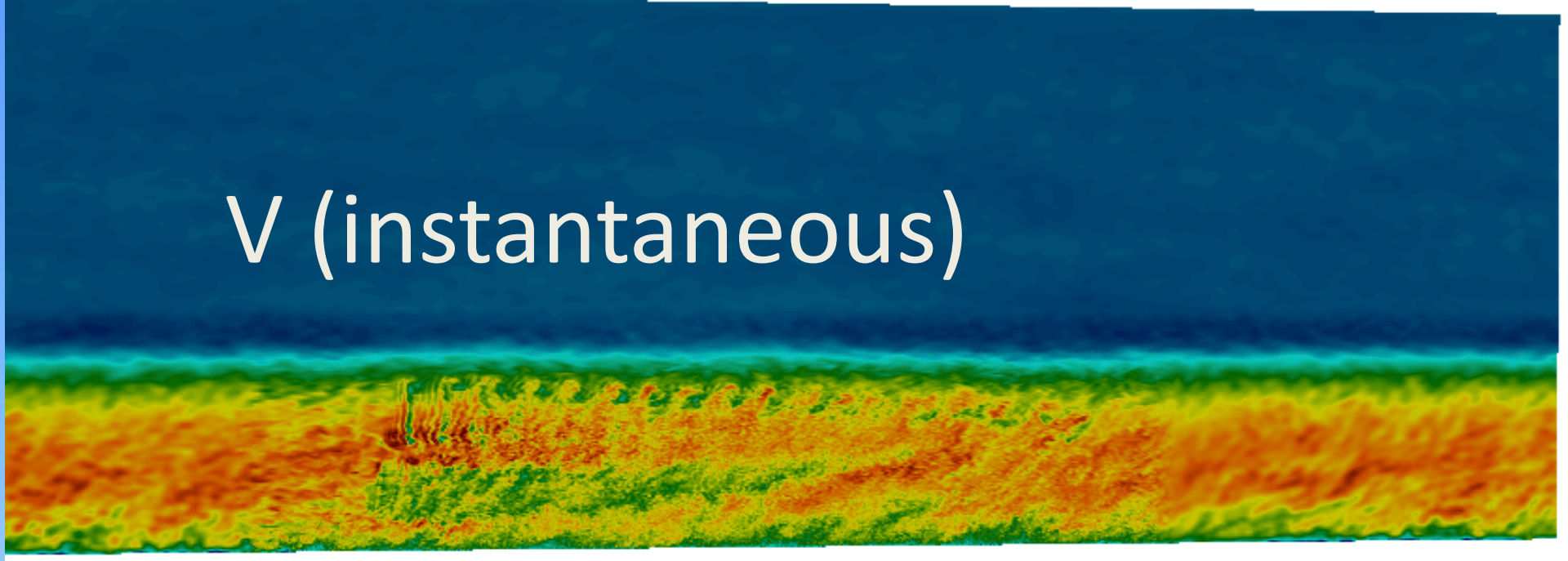
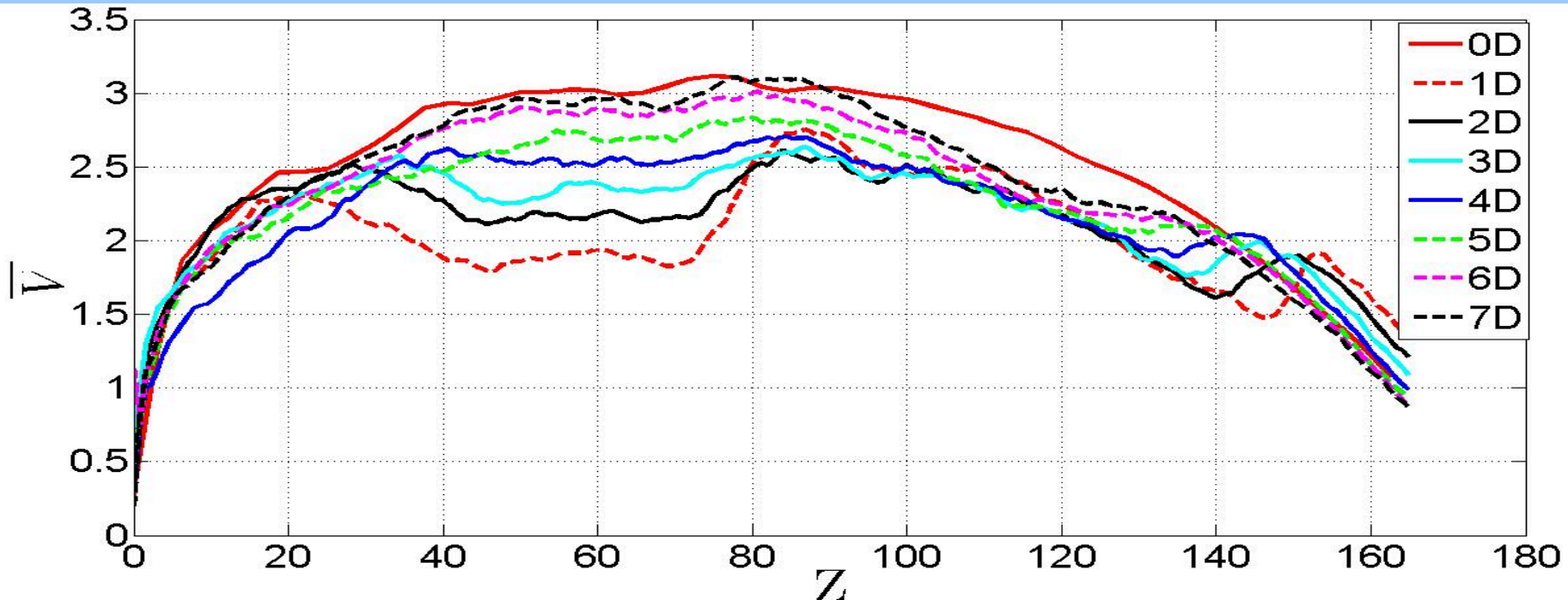
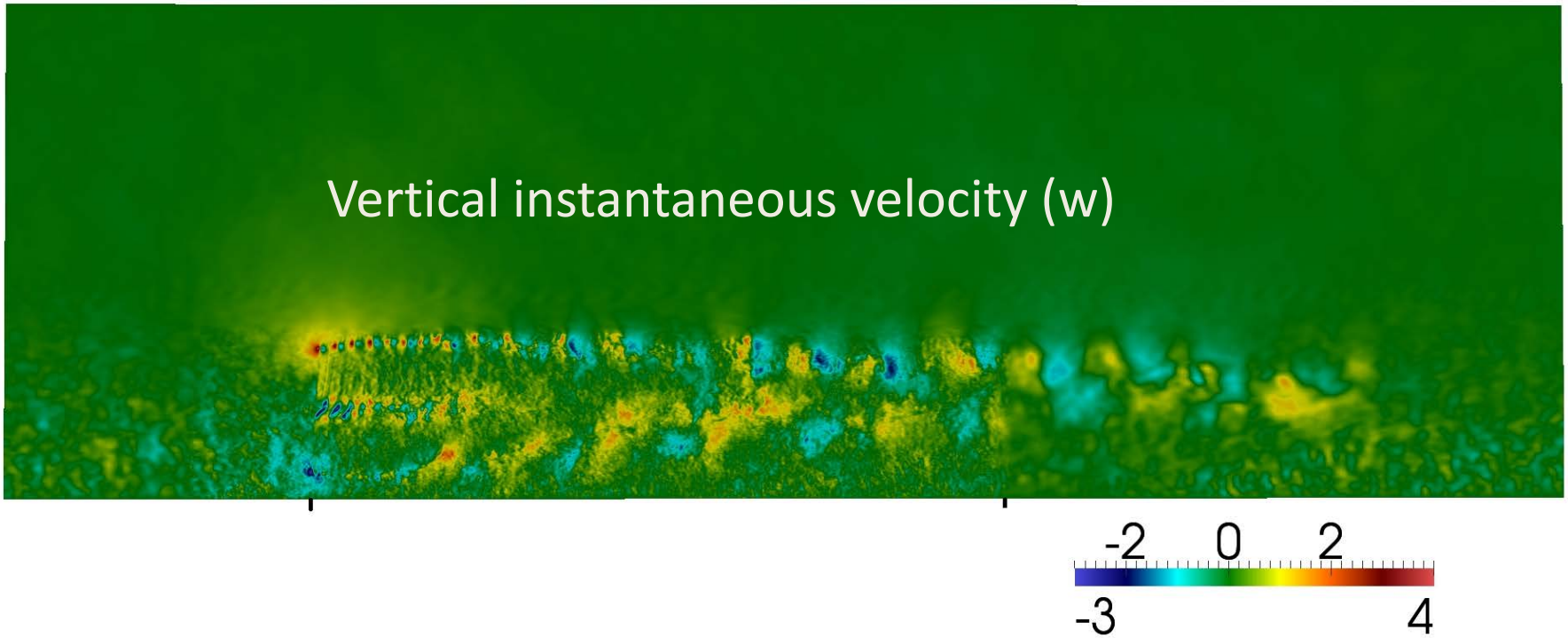
V (instantaneous)





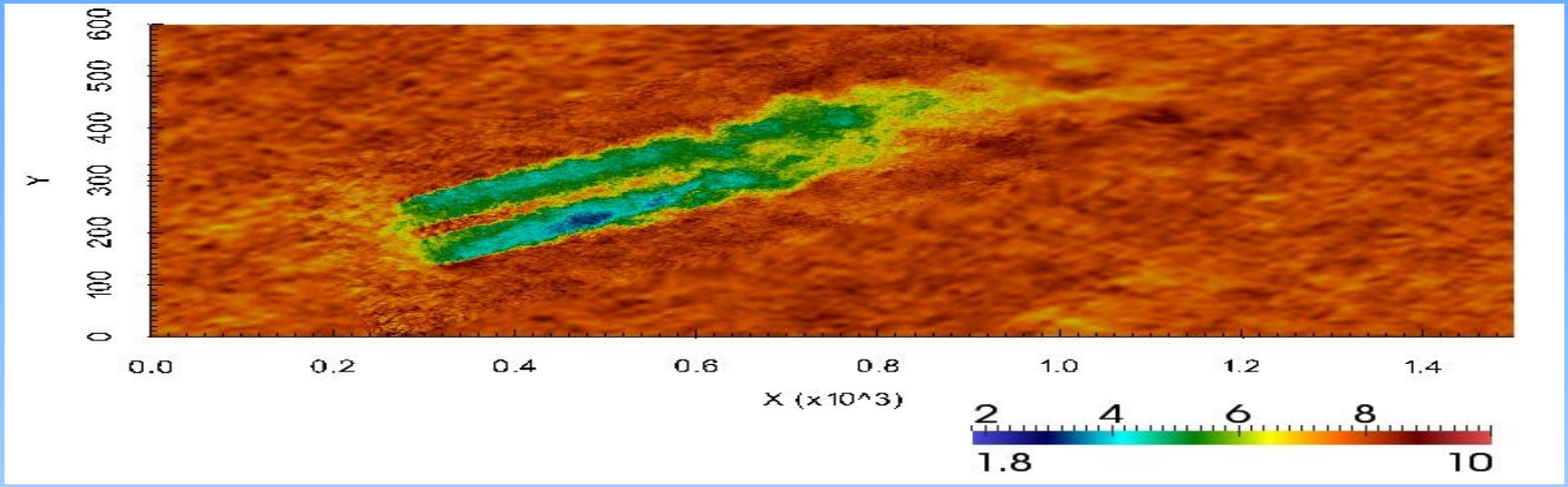


Summary:

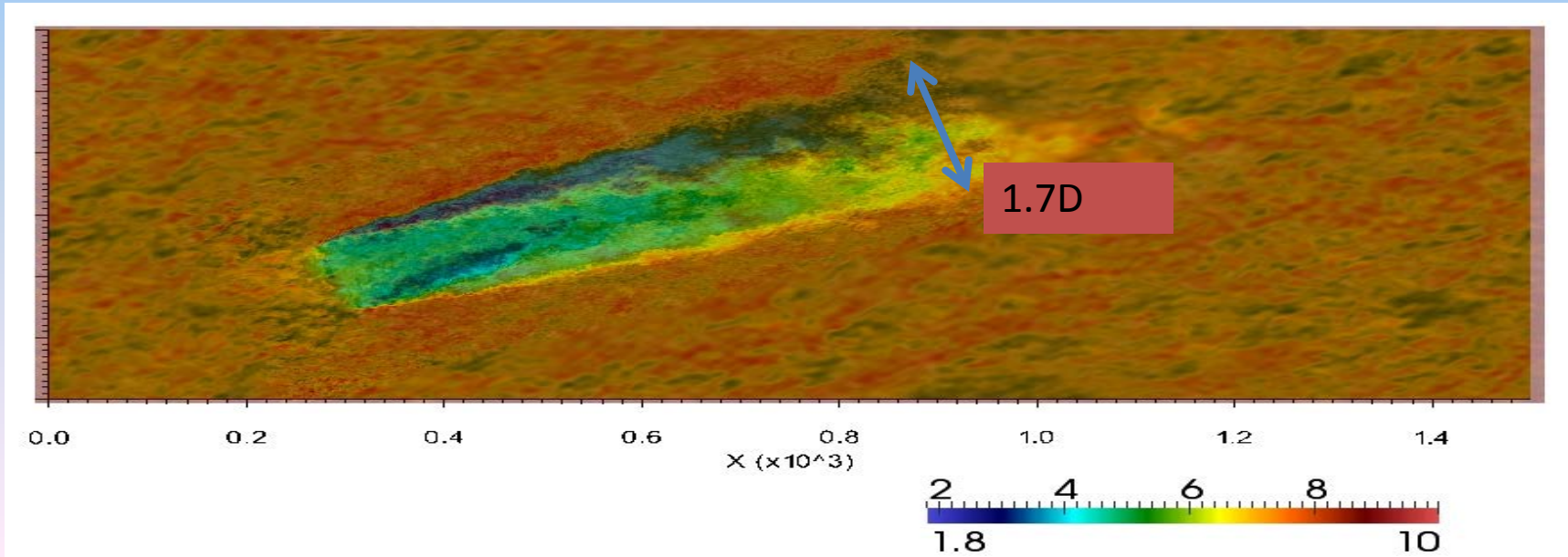
1. Shear layer at lower blade tip interacts with the shear layer at hub resulting in mixing.
2. Due to these interactions the shear at upper blade tip undergoes instabilities(Advection)
3. The spanwise structures oriented in vertical direction in contrast to inclined nature in ABL
4. In near-wake region WT rotation bring in entrained air from air into the domain. Strong vertical motion are in the mixed regions.

Wake in horizontal plane at different heights: Spanwise wake spread (wind angle)

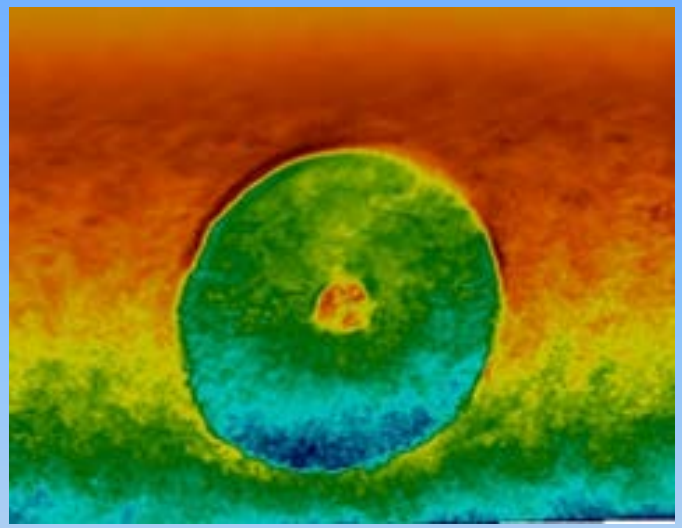
Z=90m

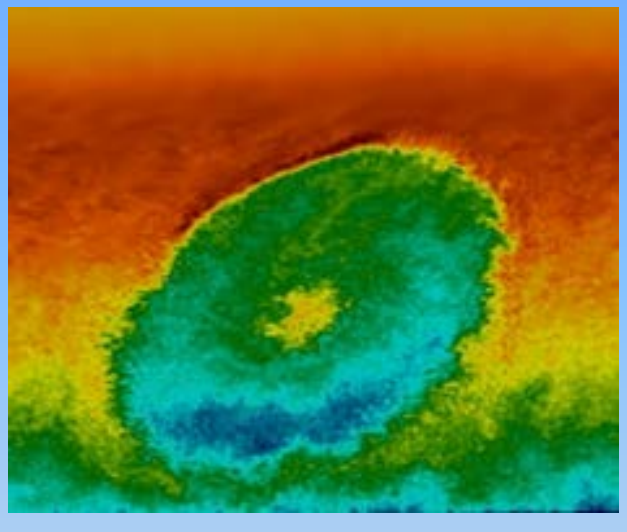


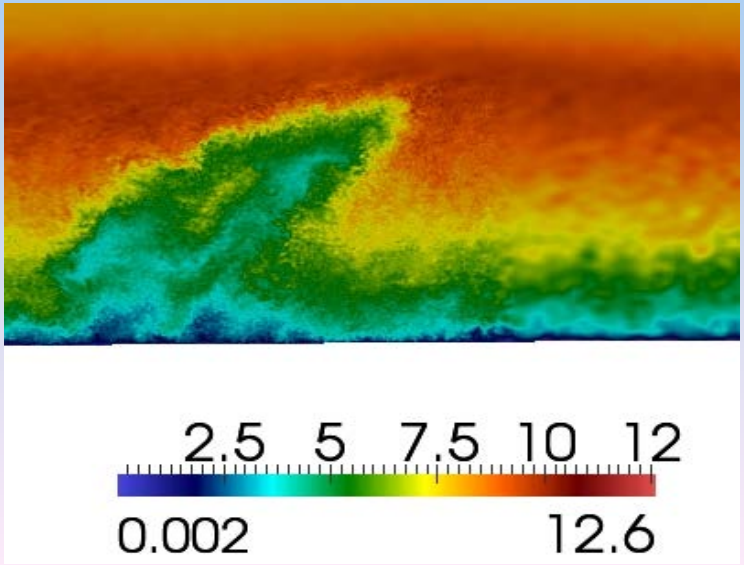
Overlay at z = 60m (blue) & 120m (green)



1D, 3D, 6D from WT : U

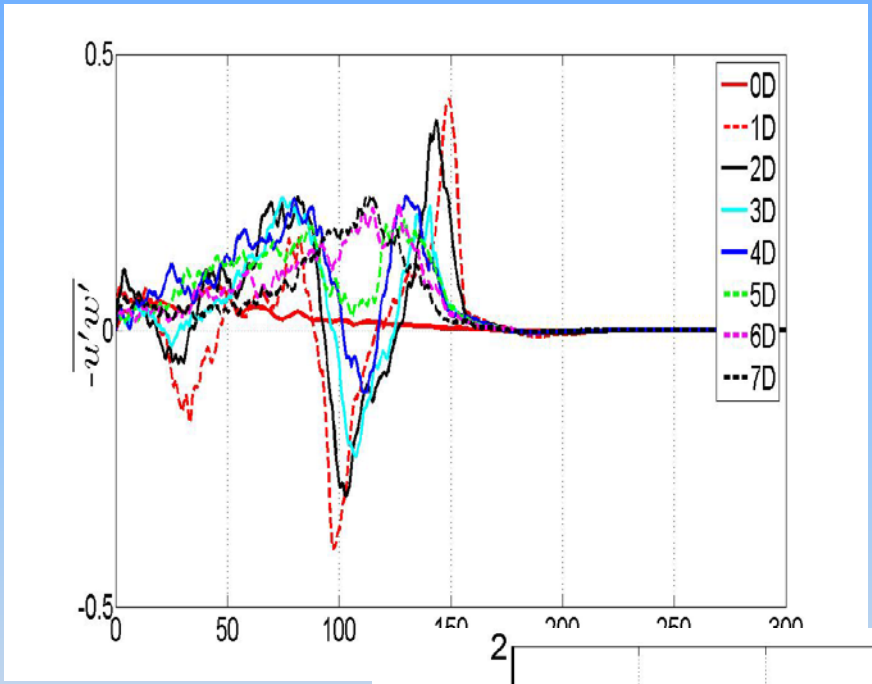


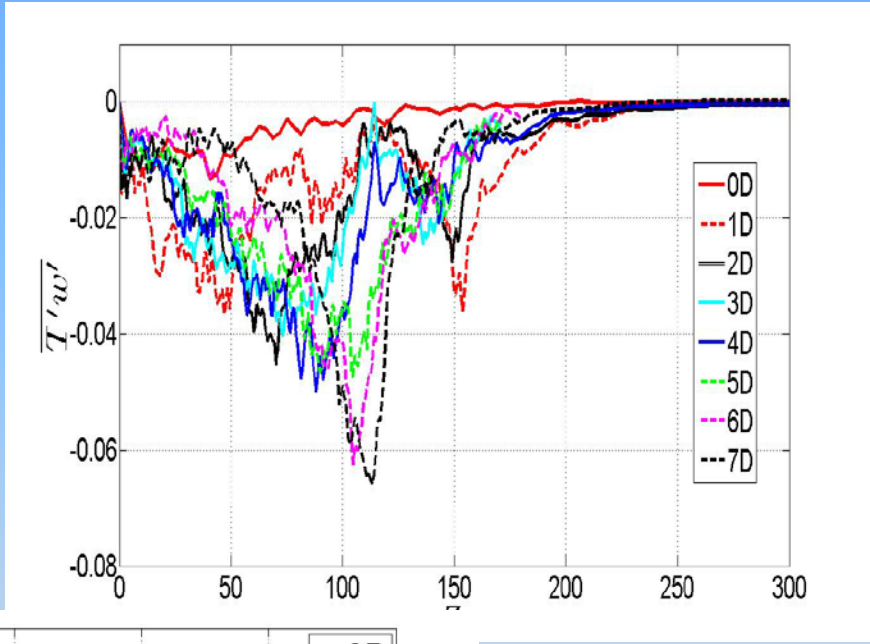


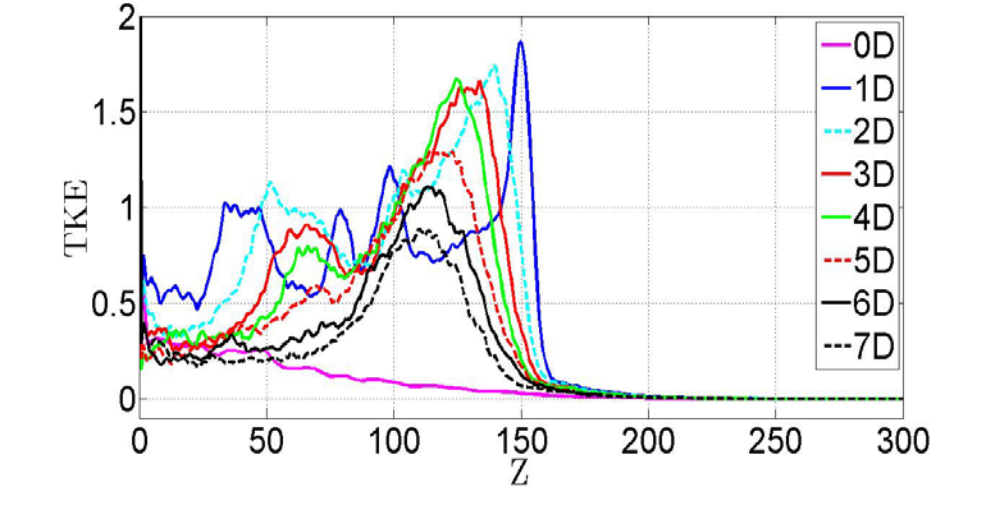


Consequence effect of pressure gradient, velocity component, and wind angle

Turbulence: TKE balance of shear production and buoyancy dissipation







Summary of Low-Stratification case

- We classify it as Regime- I : Due to the atmospheric stability LLJ is above WT
- The wind shear is almost uniform between the lower and upper-blade tips.
- TKE is balance of Shear production and buoyancy damping is present throughout WT height due to turbulence transport. Hence uniform mixing between the blade tips. The peak production occurs near the LLJ.
- Mutual inductance mode of instability causes vortex merging and results in wake meandering.

High Stratification

Cooling rate 1K/hr

ABL height = 95m

LLJ = 110m (peak velocity 11 m/s)

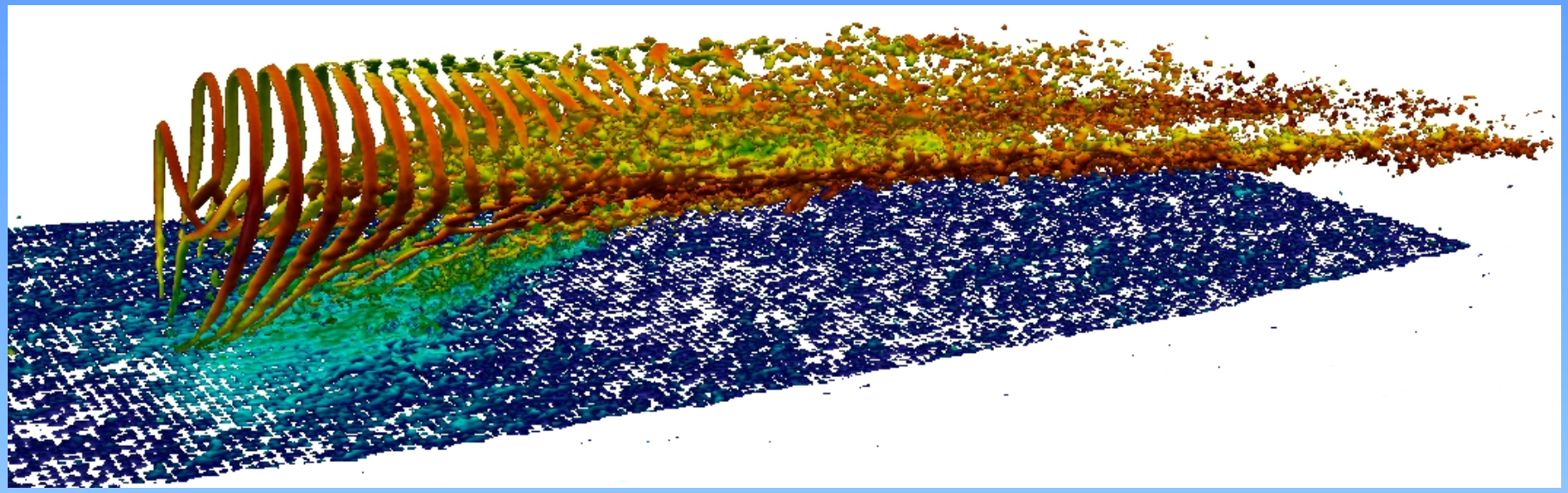
Surface temperature=257K

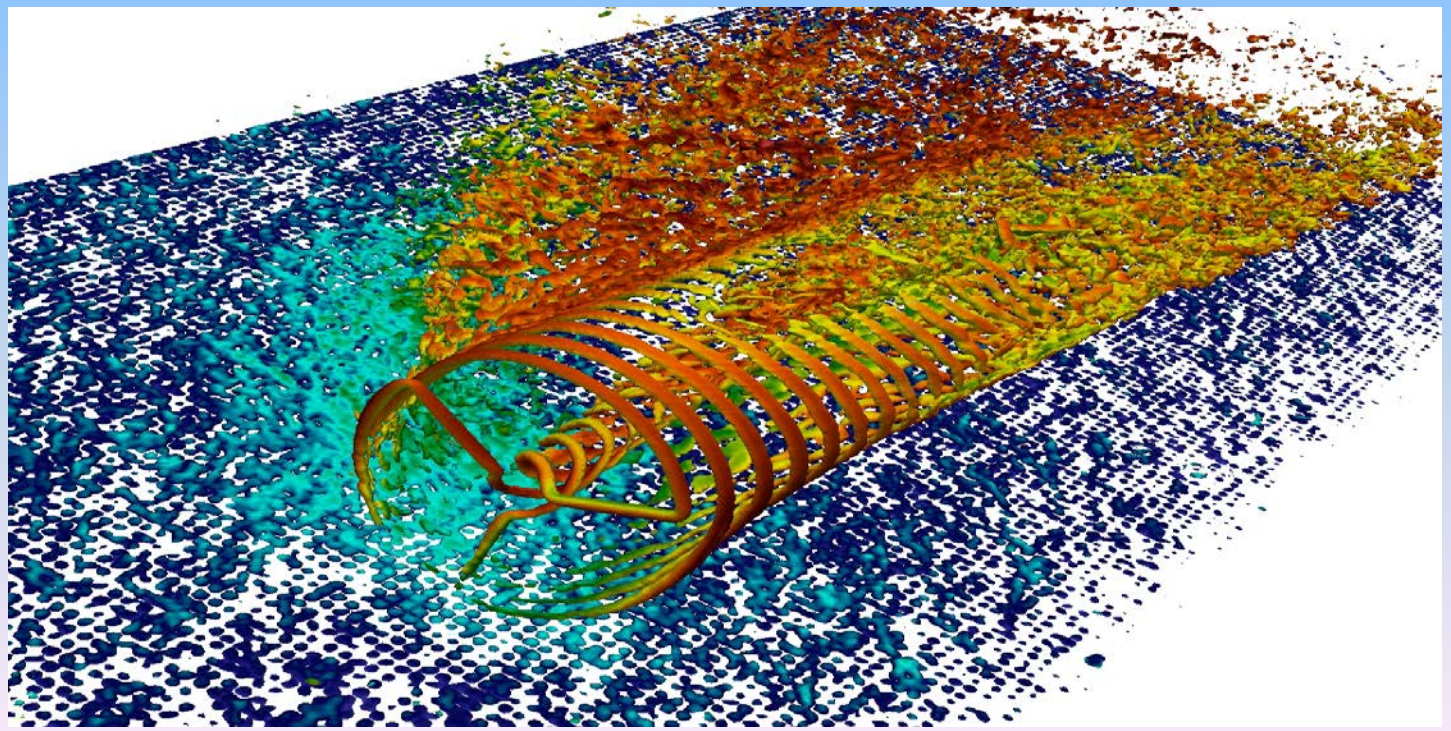
Geostrophic wind=8m/s

Wind angle 42° (surface), 34° (lower blade tip), 13° (hub height), 0 (upper-blade tip)

High Stratification

- LLJ moves closer to surface as stability increases.
- In this case: lower and upper tips are in completely different condition. i.e. lower faces high shear, turbulence. Whereas upper is in ambient atmosphere (outside the boundary layer).

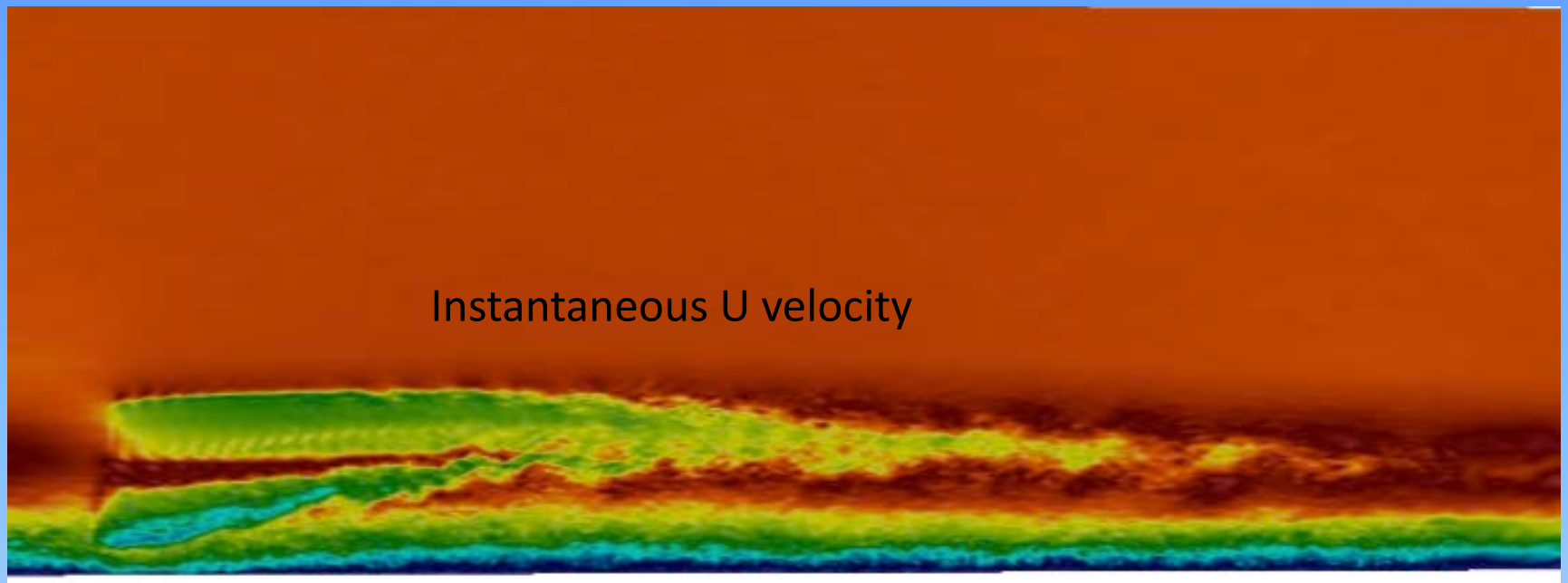


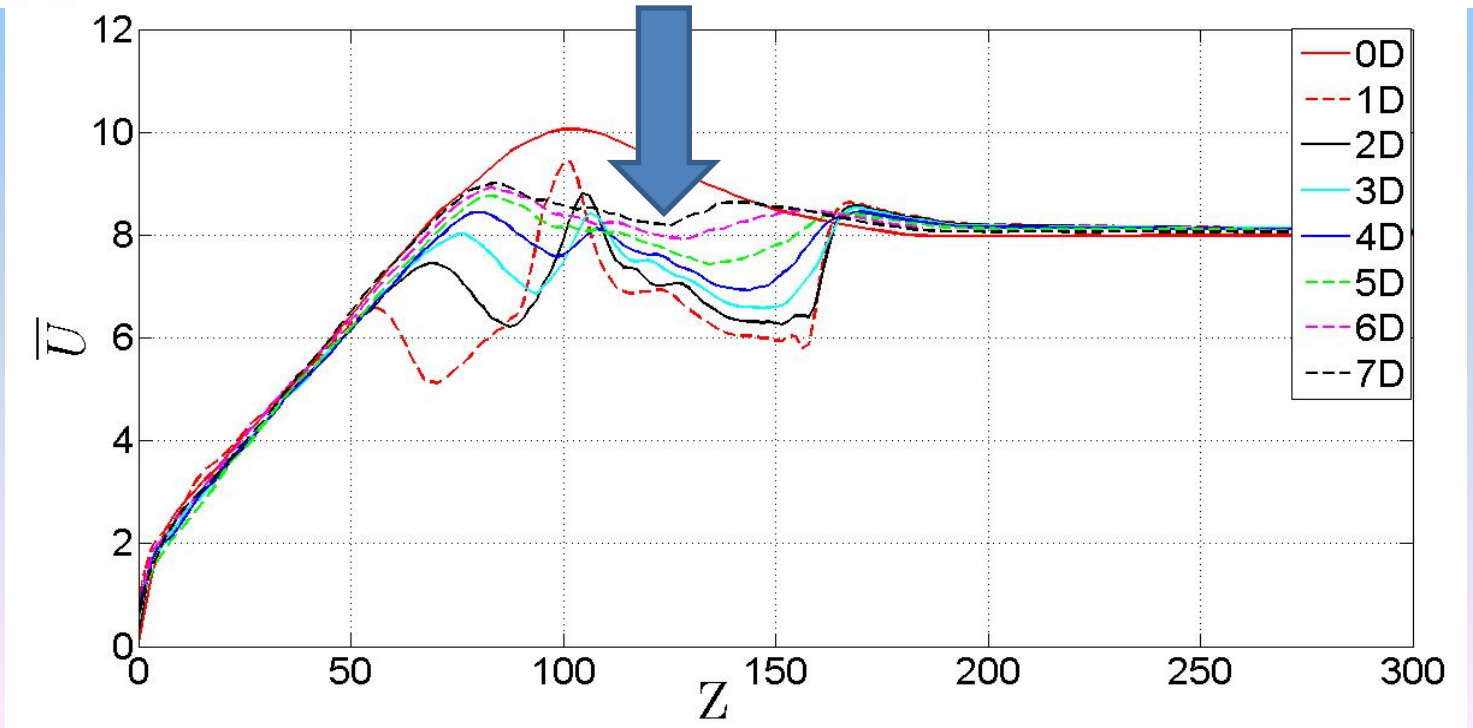


Strong shear and wind angle varies within hub .

Top tip is outside of BL.

Different gradient along the blade


Instantaneous U velocity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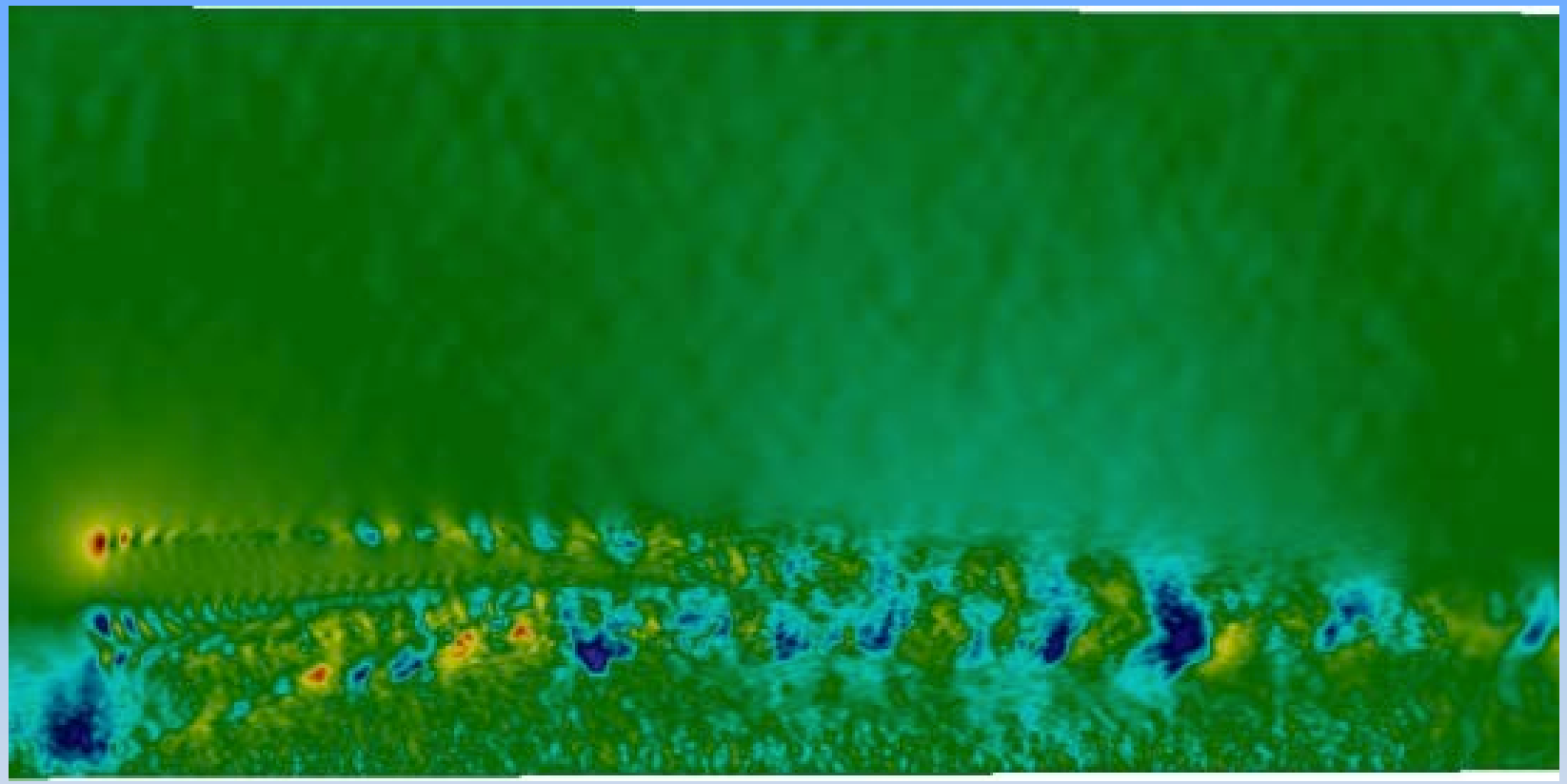
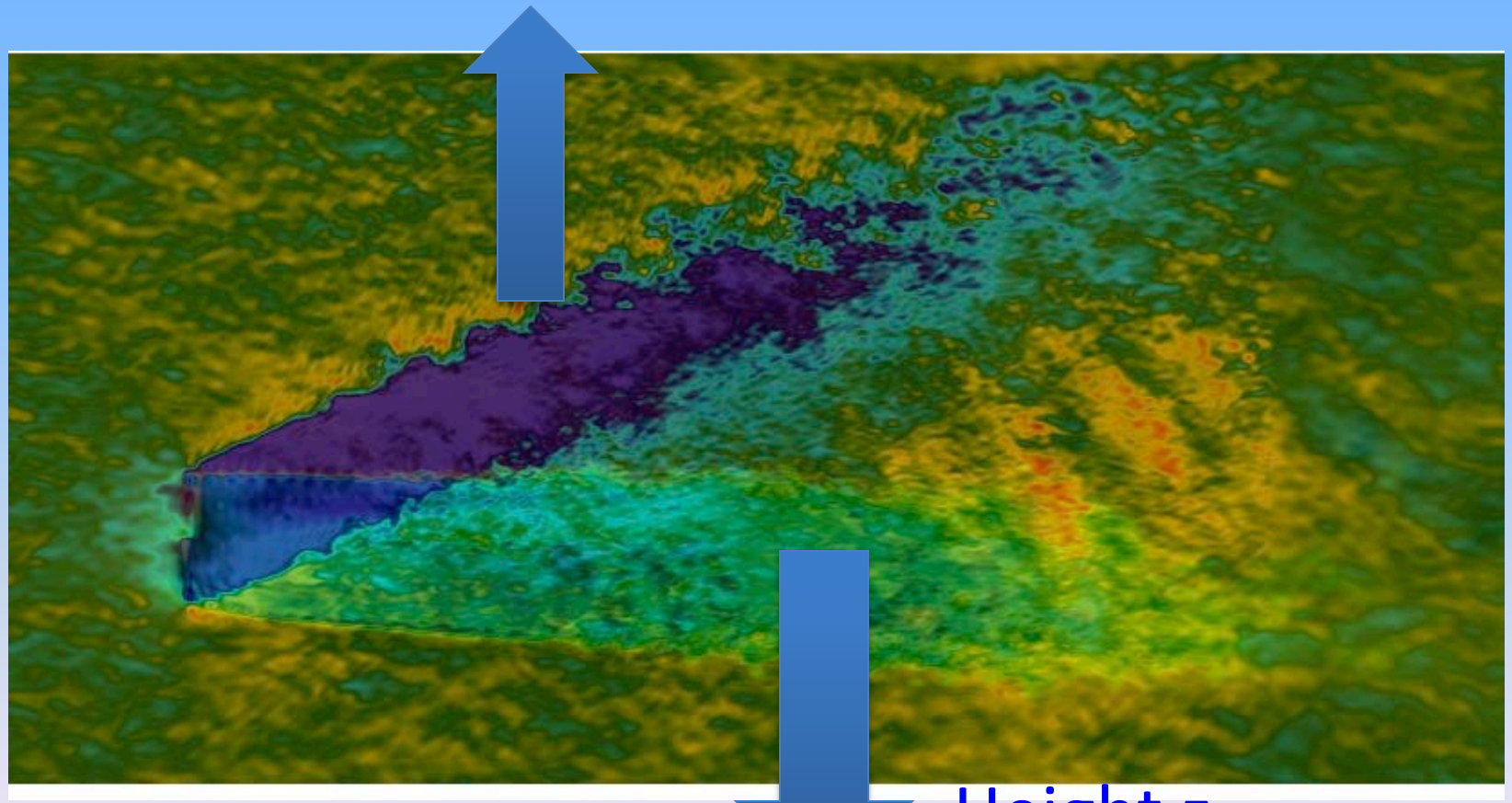
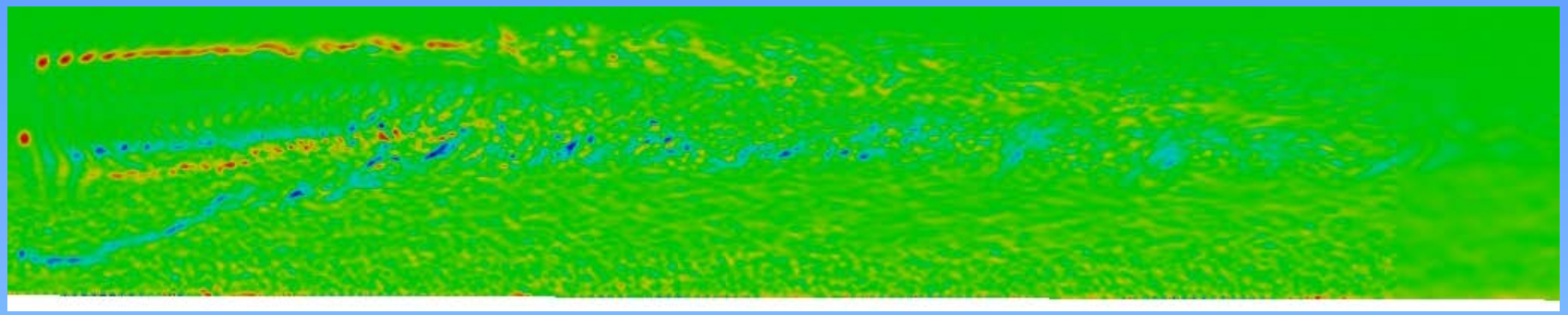
Vertical velocity (W) structures

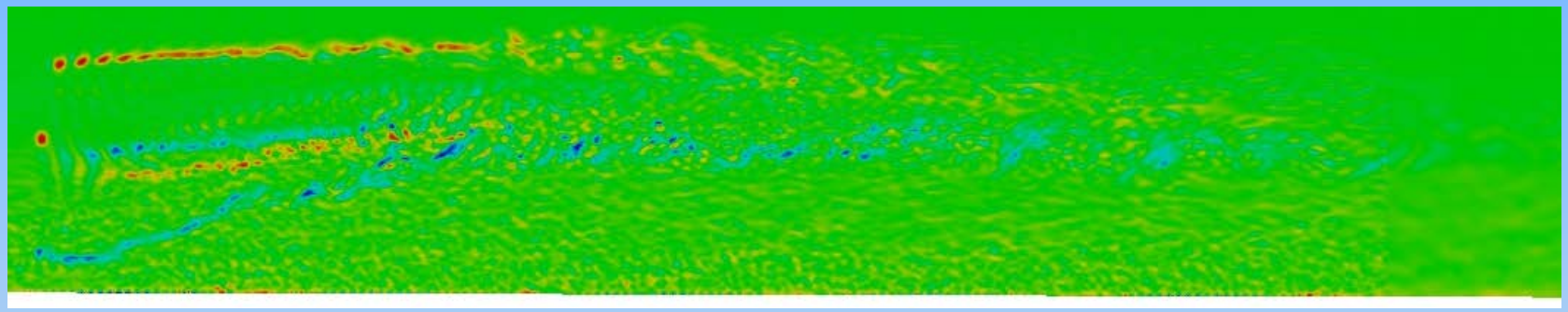


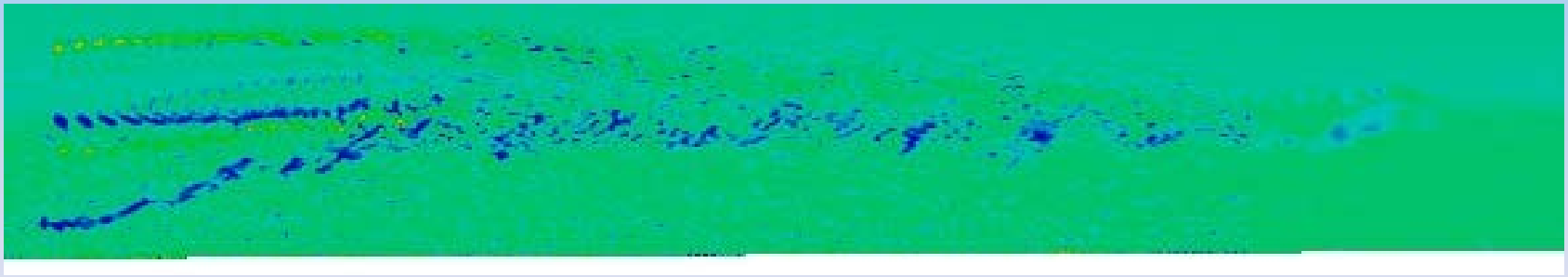
Height z = 60 (m)



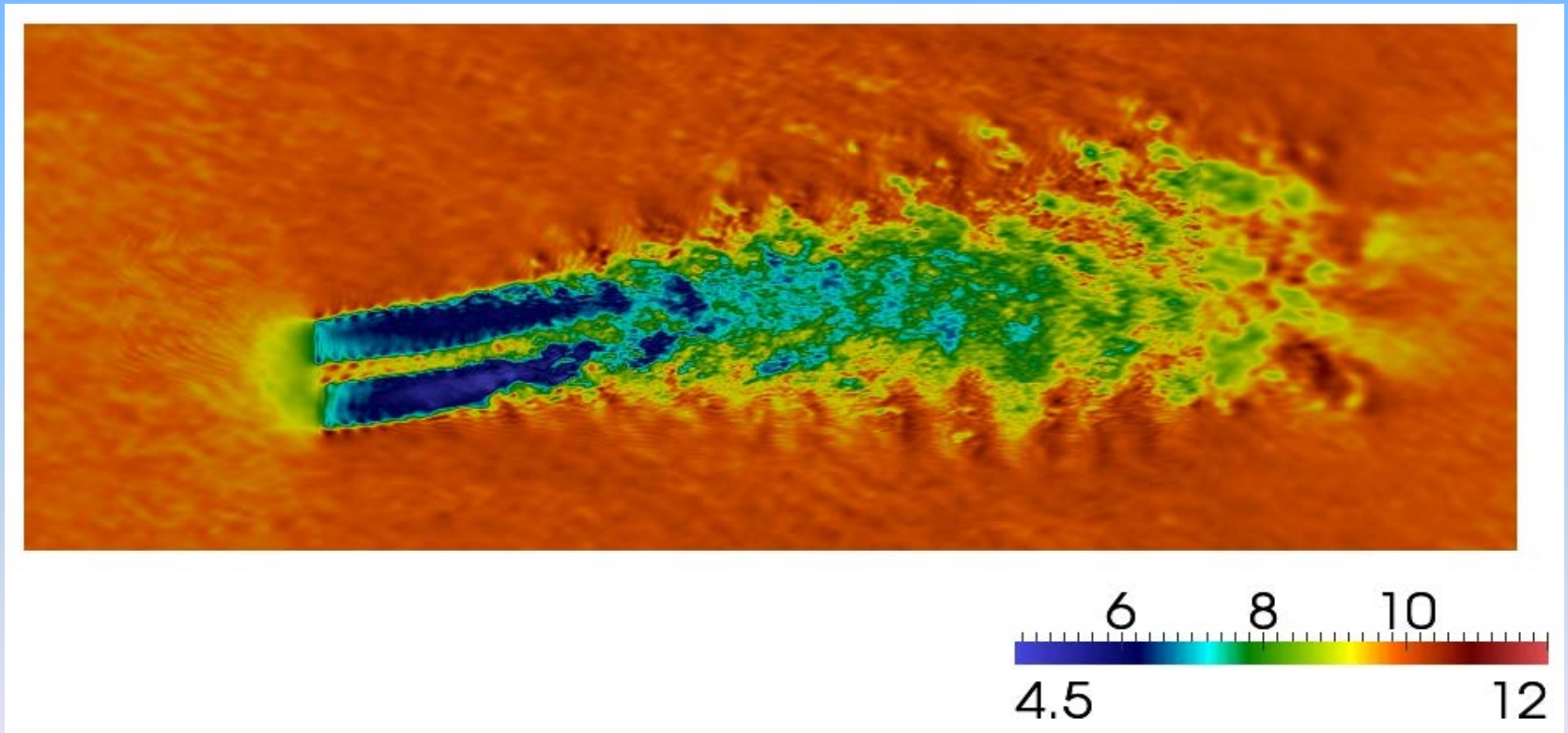
Height z= 120 (m)



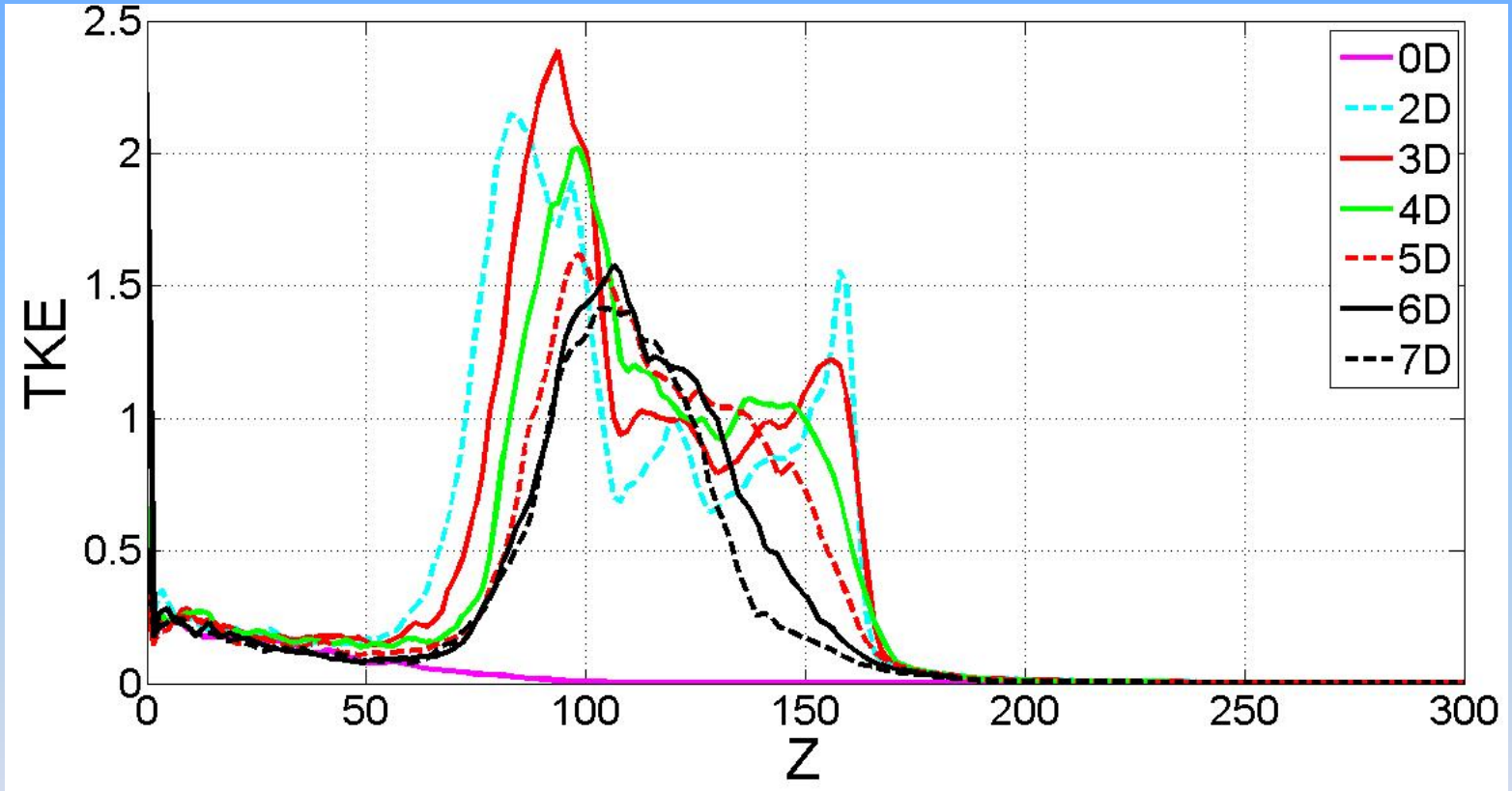


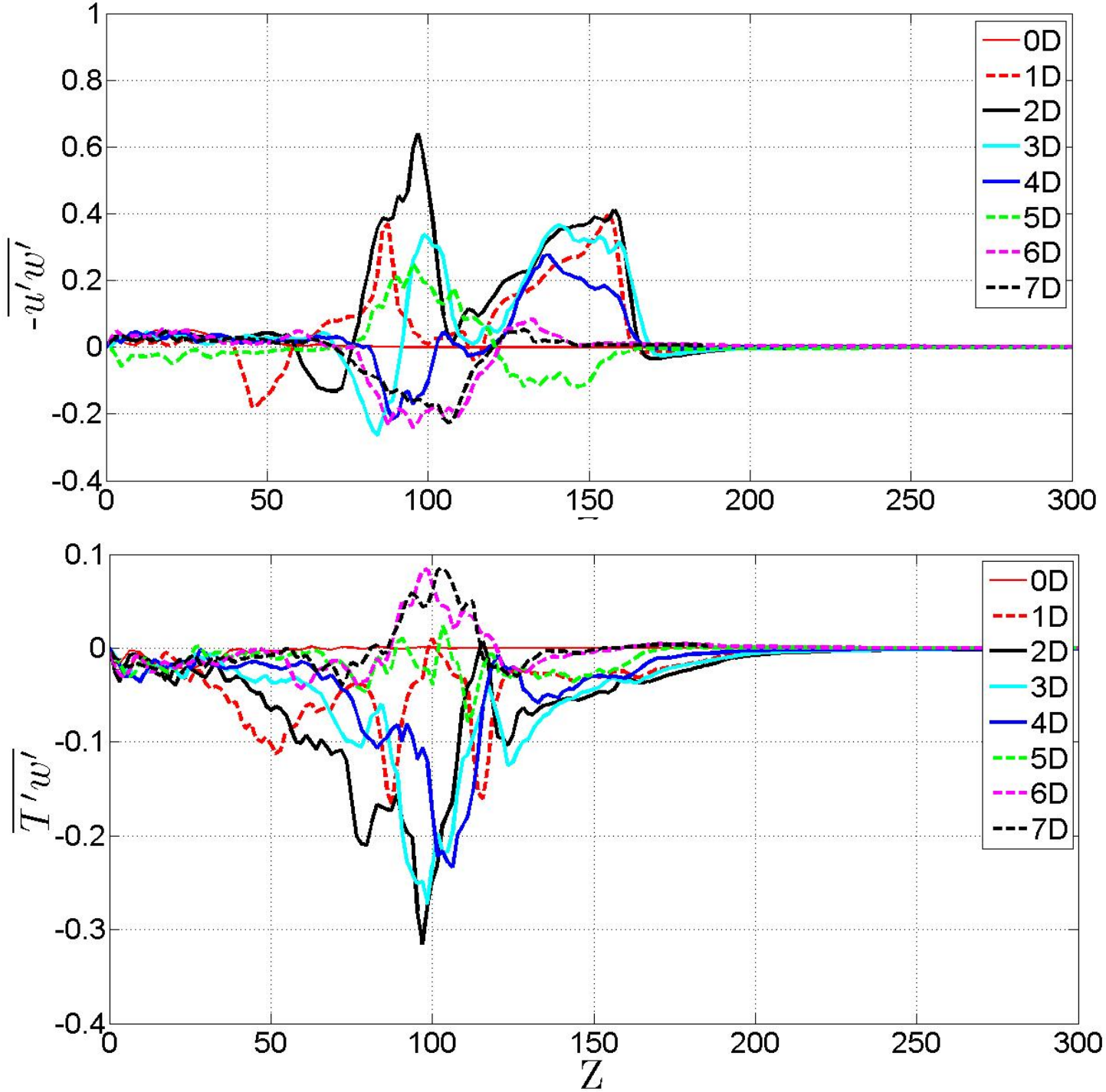


Structures showing turbulent jet behavior: 90 m height



High Stratification: Statistics




$-\overline{u'w'}$
$\overline{T'w'}$
Z
0D
1D
2D
3D
4D
5D
6D
7D

Conclusion on high stratification

- In this regime the LLJ is near to the hub height.
- LLJ acts like a jet surrounded by low momentum region. When shear layer interacts it behaves like a turbulent mixing jet
- Strong gradient of velocity and temperature
- Different sign of gradient along the blade

Moving Forward

- Inflow changes the shape of the and characteristics of the wake.
- Continue looking at different inflows such as adding intermittency.