NAWEA 2015 Symposium
11 June 2015
Virginia Tech, Blacksburg, VA

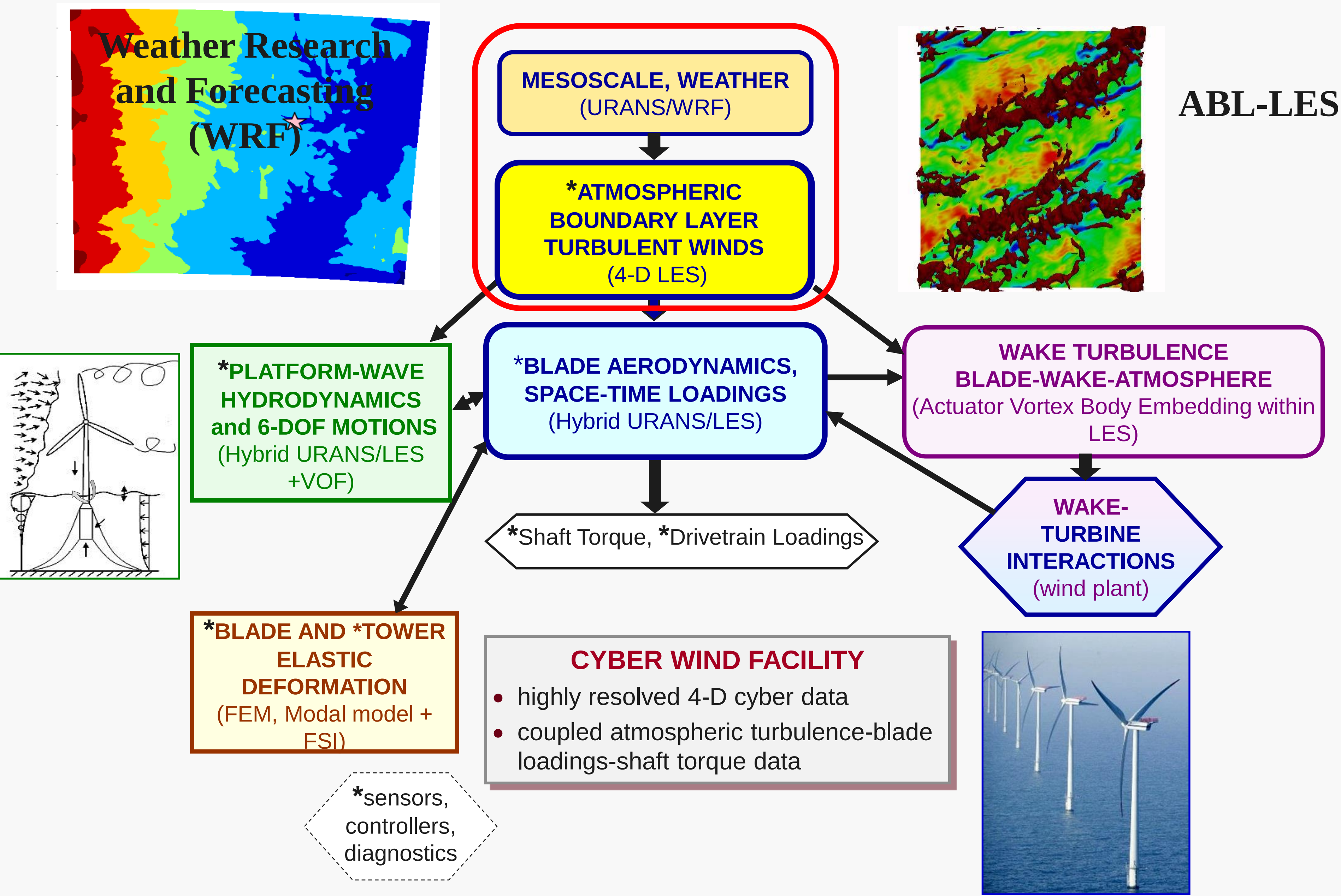
The Forcing of Wind Turbine Rotors by True Weather Events as a Function of Atmospheric Stability State*

Balaji Jayaraman[1] and James G. Brasseur[1]
Collaborators: Jared Lee[2], Tyler McCandless[2] and Sue Haupt[2]

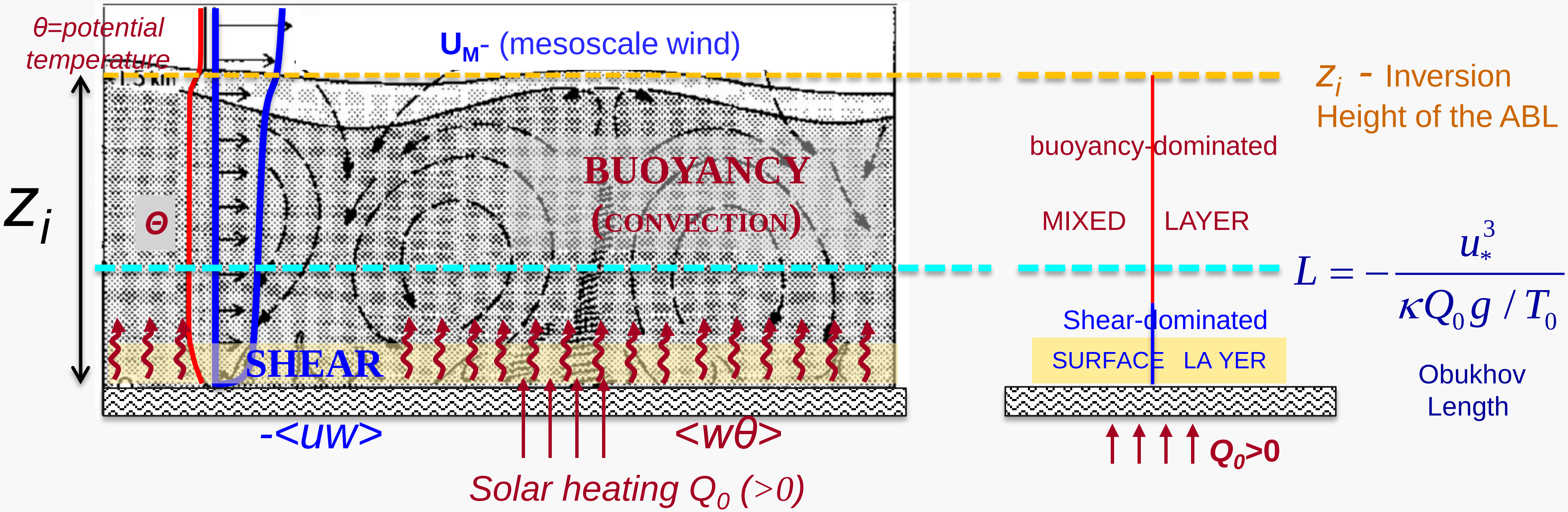
[1]Department of Mechanical Engineering, The Pennsylvania State University, USA
[2]National Center for Atmospheric Research (NCAR), USA

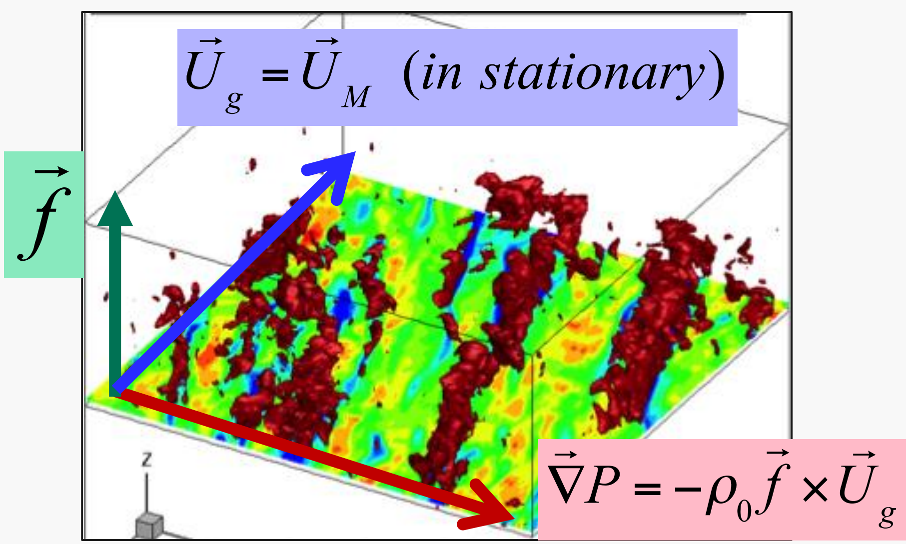
*Supported by:
- DOE (EERE) Offshore Wind Technology Development Program
- Computer Resources: NSF XSEDE program; Penn State University Institute of Cyber Science

The DOE Penn State Cyber Wind Facility Program



Daytime Atmospheric Boundary Layer (ABL) and Stability





ABL Stability parameter: $-z_i/L$

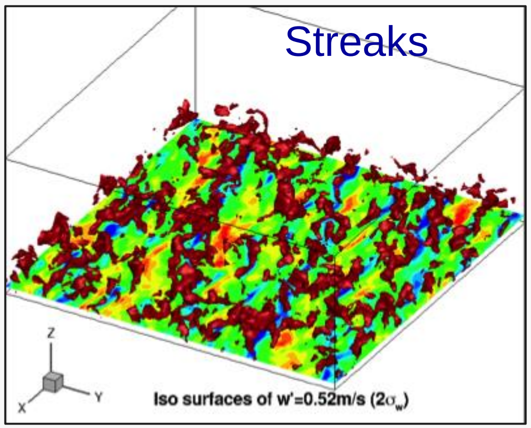
$-z_i/L \ll 1$	→ 'near' neutral ABL (purely shear-driven)
$-z_i/L \sim 1\text{-}10$	→ Moderately convective (shear & buoyancy)
$-z_i/L \gg 1$	→ Convective (purely buoyancy-driven)

Canonical Equilibrium ABL Turbulence

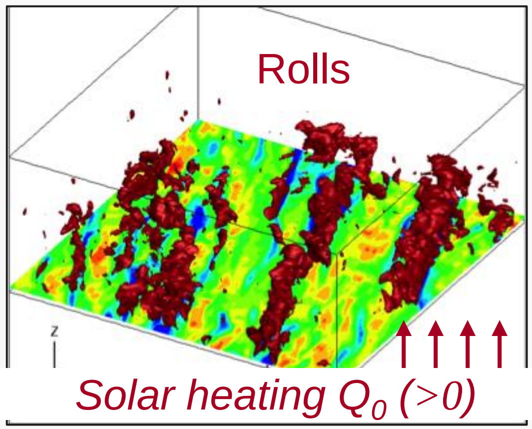
Equilibrium ABL is well understood

Large Eddy Simulation (LES)

NEUTRAL (NBL)

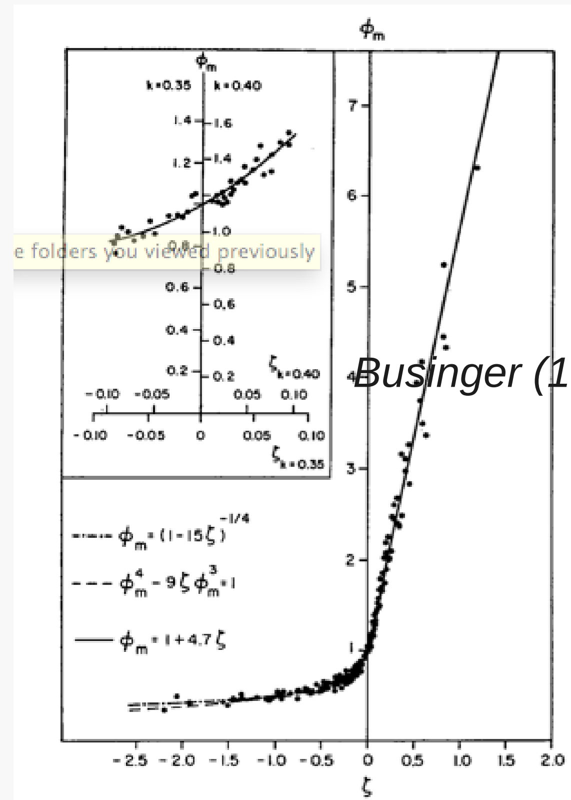


MODERATELY CONVECTIVE (MCBL)



Khanna & Brasseur, 1998; Moeng & Sullivan,1994, Jayaraman & Brasseur (in preparation)

Field Experiments



Businger (1971)

<u>Canonical Equilibrium ABL</u>:

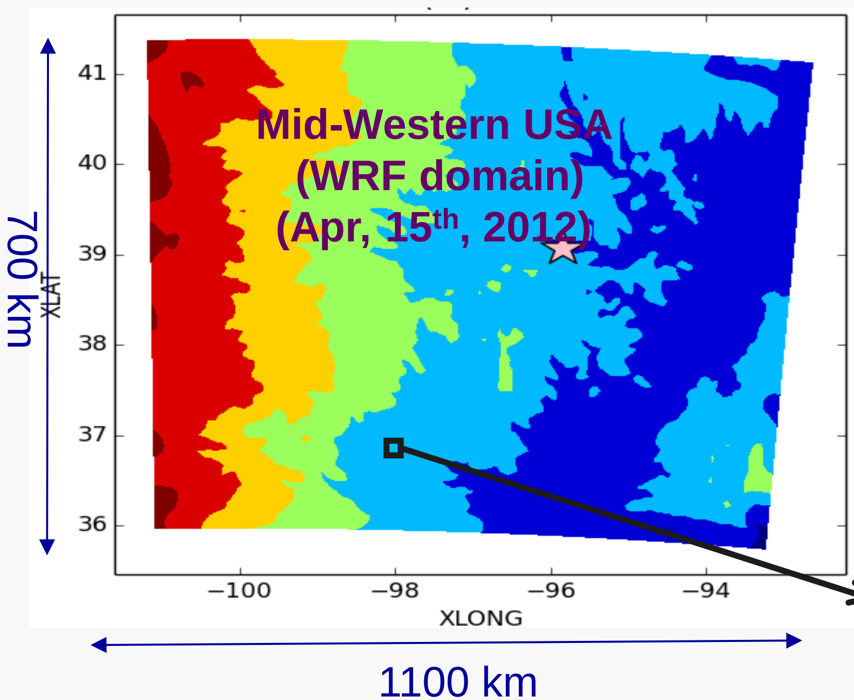
(a) Horizontal homogeneity (roughness, Q_0,$U_{M....}$)

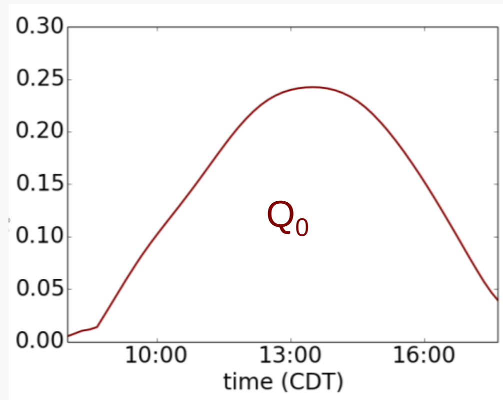
(b) Quasi-stationarity

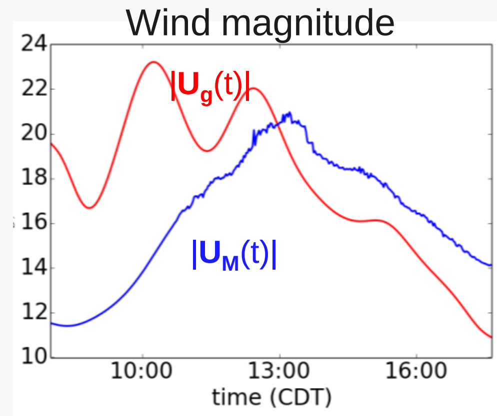
How non-stationarity in Q_0 and U_M impact ABL structure?

Mesoscale-driven Non-Stationary ABL

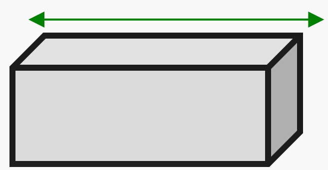
WRF: Weather Research and Forecasting

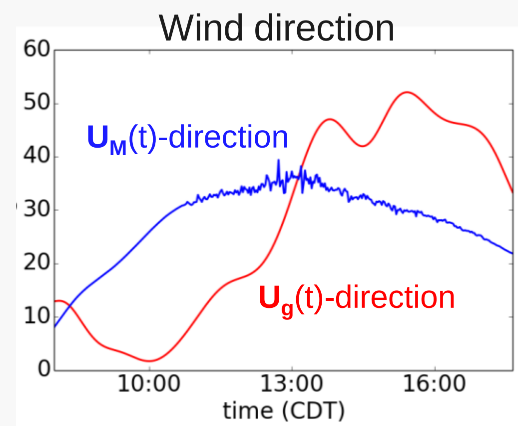






1 WRF cell (5km) = size of LES domain for ABL





Define $-\frac{1}{\rho_0}\vec{\nabla}P(t) \equiv \vec{f}\times\vec{U}_g(t)$

Dynamical relationship between $\vec{\nabla}P(t)$ and $\vec{U}_M(t)$ is :

$$-\frac{1}{\rho_0}\nabla P(t) - \vec{f}\times\vec{U}_M(t) = \vec{f}\times\left[\vec{U}_g(t) - \vec{U}_M(t)\right] = \frac{\partial \vec{U}_M(t)}{\partial t}$$

Non-stationary ABL

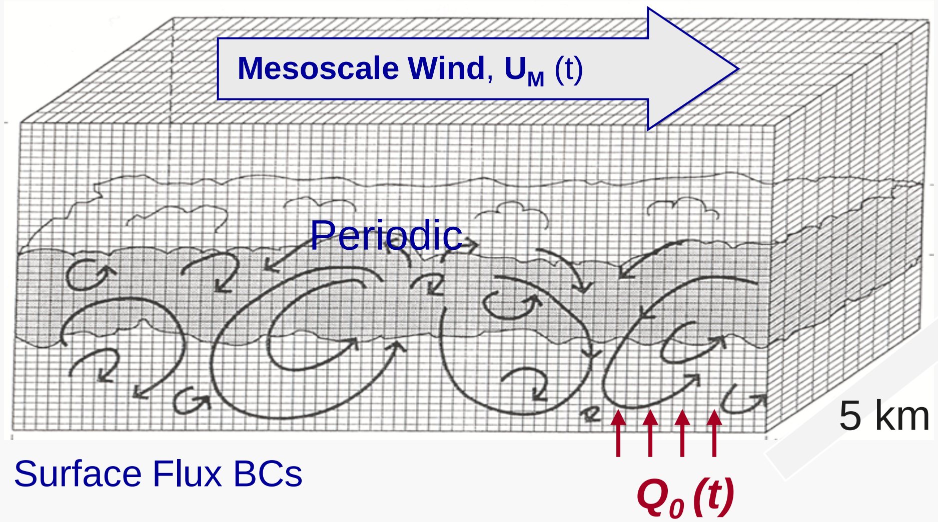
In the stationary limit, $\frac{\partial \vec{U}_M(t)}{\partial t} = 0 \Rightarrow$ $\boxed{\vec{U}_g(t) = \vec{U}_M(t)}$

Stationary/ Equilibrium ABL

Non-stationarity in U_M → Deviation of U_g from U_M → Non-equilibrium ABL ?

LES of Non-stationary ABL

Pseudo-spectral algorithm



Grid: 324x324x144 before dealiasing.

SFS model: 1-eq. eddy viscosity.

Non-stationarity:

- $U_M(t)$ and $Q_0(t)$ from WRF data.
- **Series of academic 'Dissection' cases for fundamental analysis**

Dynamical Relationship between $U_M(t)$ and $U_g(t)$: $\vec{f} \times \left[\vec{U}_g(t) - \vec{U}_M(t) \right] = \dfrac{\partial \vec{U}_M(t)}{\partial t}$

Continuity: $$\nabla \cdot \tilde{\mathbf{u}} = 0$$

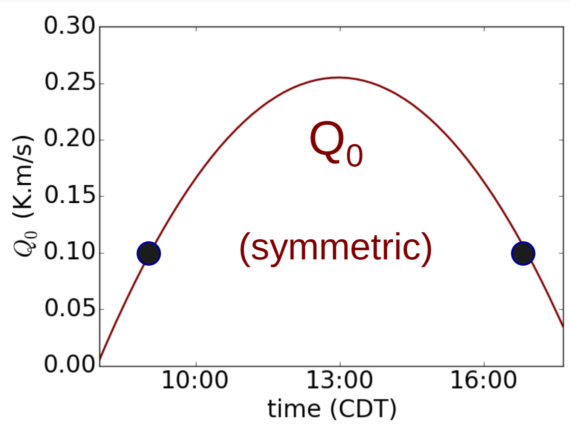
Momentum: $$\frac{\partial \tilde{\mathbf{u}}}{\partial t} + \nabla \cdot \left(\widehat{\tilde{\mathbf{u}}\tilde{\mathbf{u}}} \right) = -\frac{1}{\rho_0} \nabla p^* - \nabla \cdot \boldsymbol{\tau}_u^{SFS} + \frac{\mathbf{g}}{\theta_0} \left(\tilde{\theta} - \theta_0 \right) + \mathbf{f} \times \left(\mathbf{U}_g - \tilde{\mathbf{u}} \right)$$

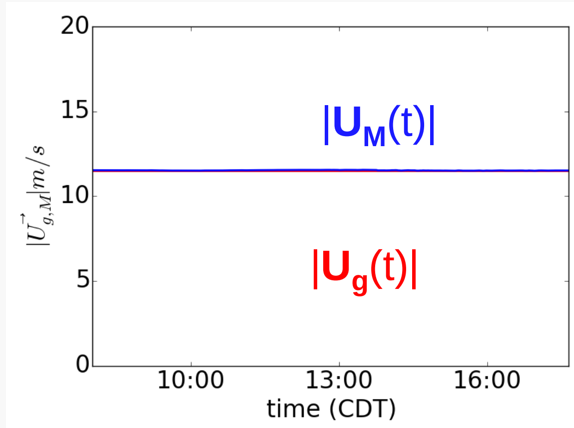
Potential Temperature: $$\frac{\partial \tilde{\theta}}{\partial t} + \nabla \cdot \left(\widehat{\tilde{\theta}\tilde{\mathbf{u}}} \right) = -\nabla \cdot \boldsymbol{\tau}_\theta^{SFS}$$

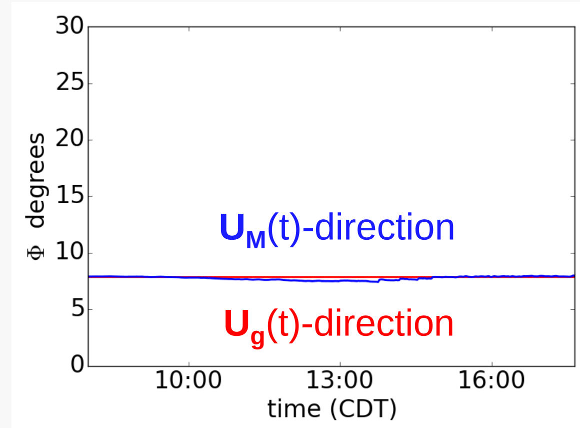
Bousinesq   Coriolis

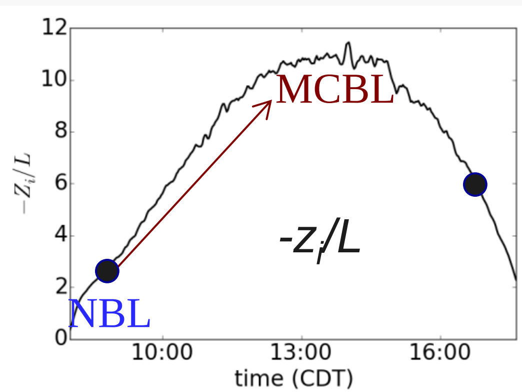
$$-\vec{\nabla} P(t) = \vec{f} \times \vec{U}_g(t)$$

Non-equilibrium Effects: From Nonstationarity in Surface Heat Flux (Diurnal Changes)









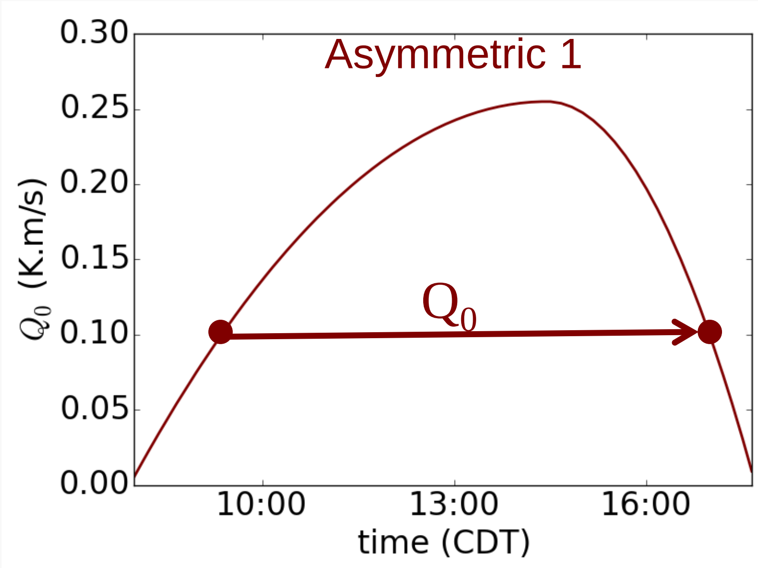
$$\vec{f} \times \left(\vec{U}_g(t) - \vec{U}_M(t) \right) = \frac{\partial \vec{U}_M(t)}{\partial t}$$

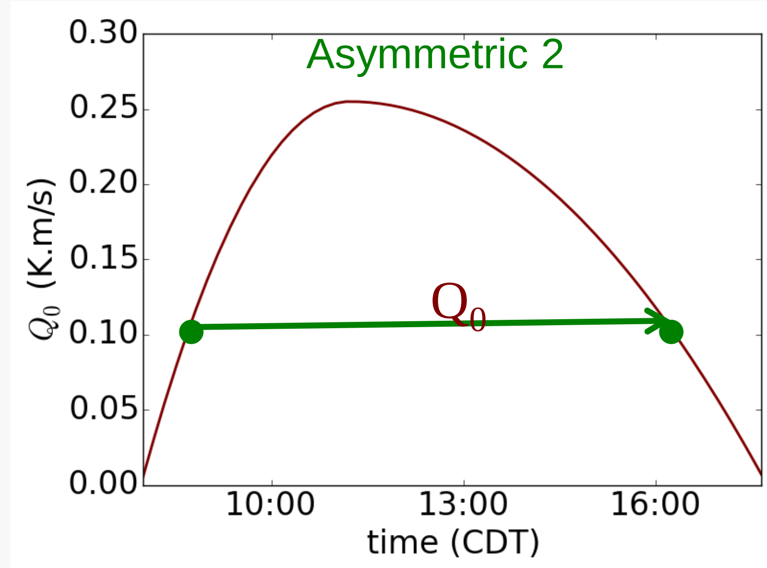
$$-\vec{\nabla} P(t) = \vec{f} \times \vec{U}_g(t)$$

Time	***Q_0 (K.m/s)***	***$-z_i/L$***	***$\|U_M(t)\|$ (m/s)***
0900	0.1	**2.7**	**11.5**
1700	0.1	**6**	**11.5**

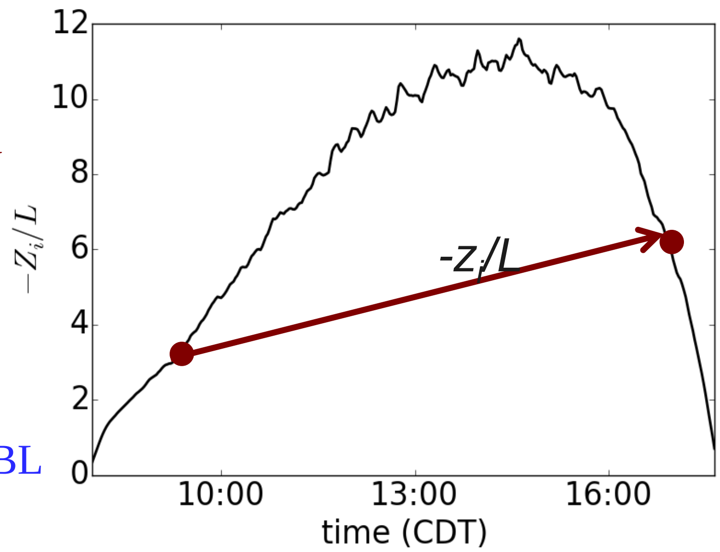
Non-stationarity (diurnal) in Q_0 → Deviation from equilibrium of ABL Turbulence.

Non-equilibrium Effects: Q_0 time history on ABL Stability

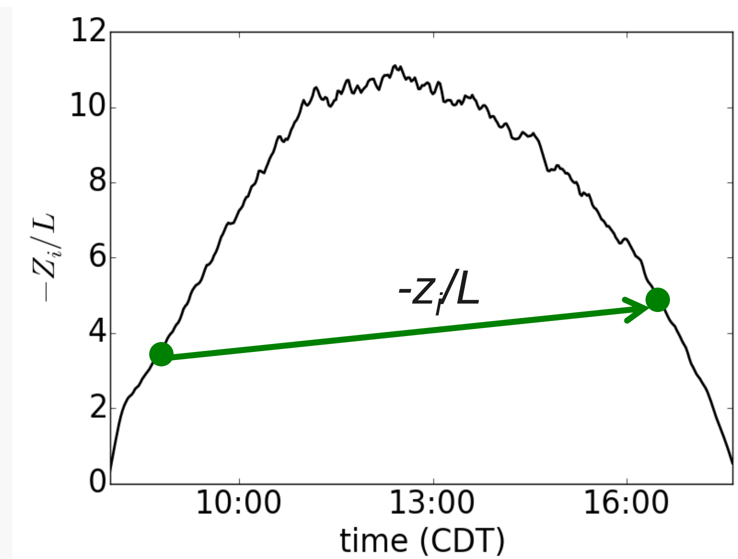




Moderately convective ABL



Neutral ABL

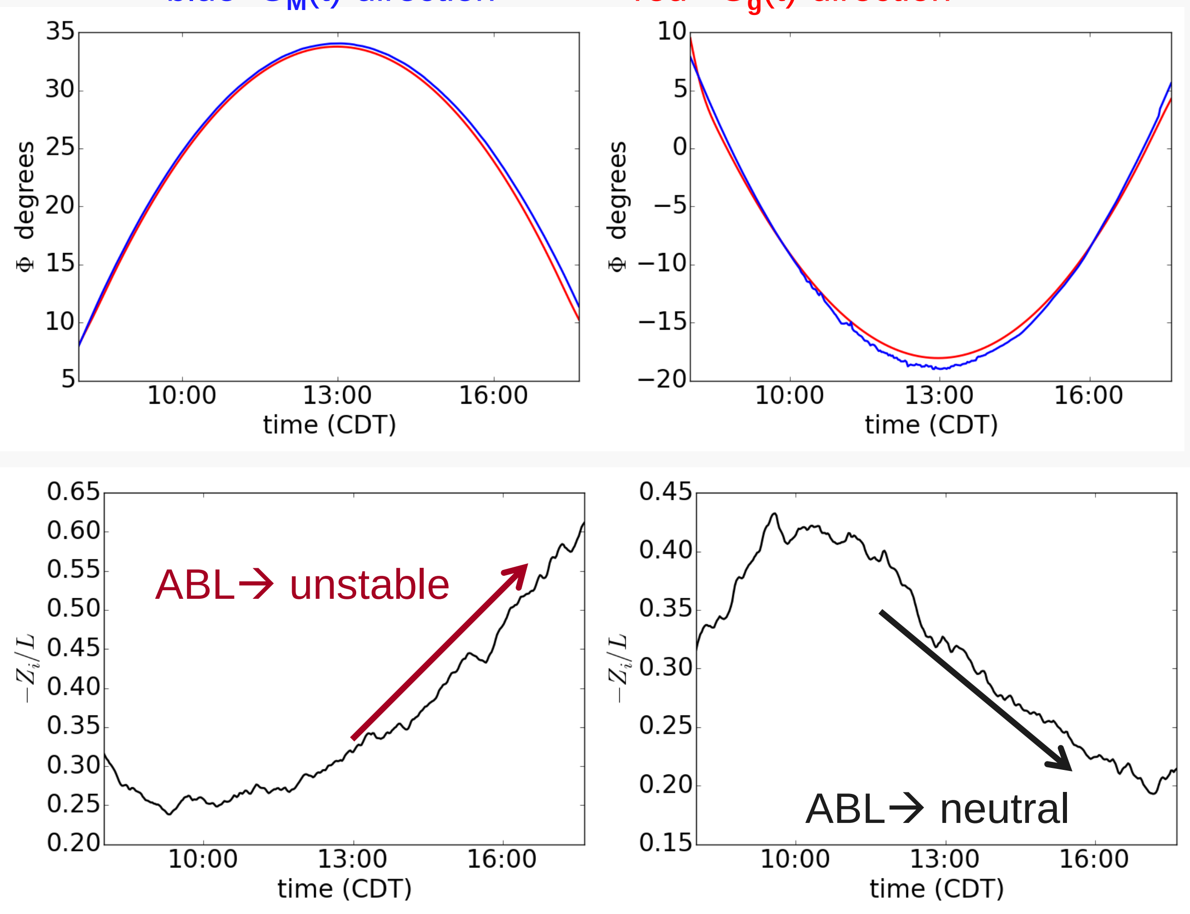


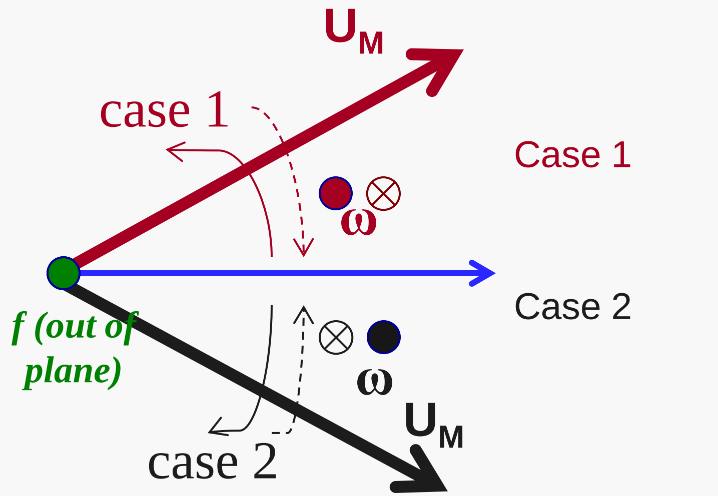
Structure of ABL turbulence depends not-only on non-stationarity, but also on time-history → deviation from equilibrium

Change in ABL Stability from Changing Wind Direction

Case 1 (f ↑ and ω ↑↓)   Case 2 (f ↑ and ω ↓↑)

blue- $\mathbf{U}_M$(t)-direction   red - $\mathbf{U}_g$(t)-direction





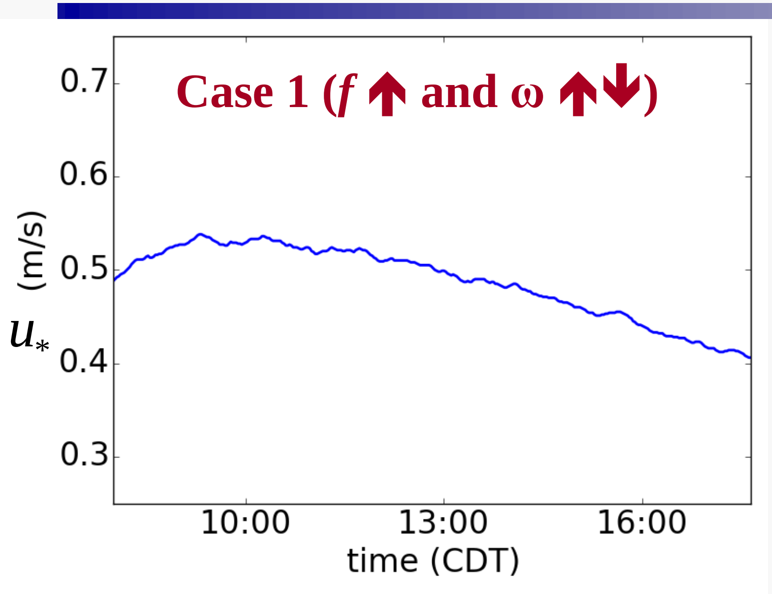
- Q_0 is invariant and non-zero.
- $|U_M|$ is constant with time

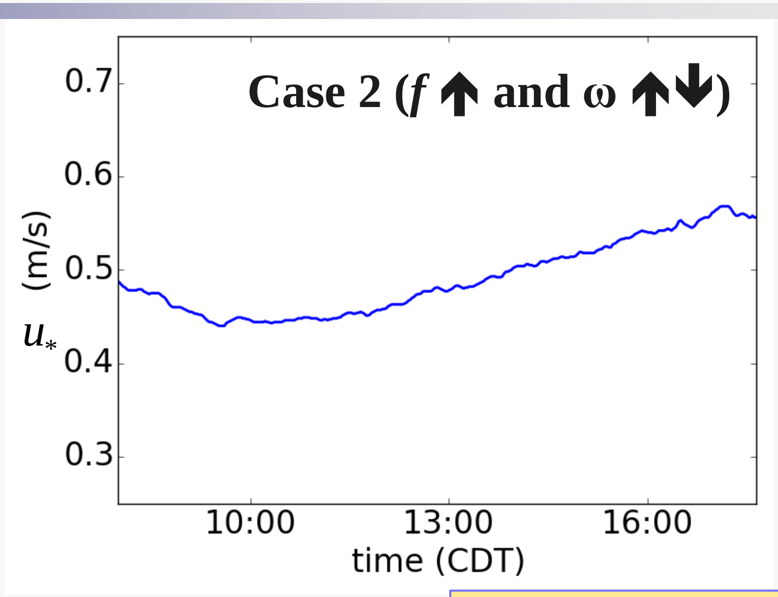
$$\frac{\partial \vec{U}_M(t)}{\partial t} = \vec{f} \times \left[\vec{U}_g(t) - \vec{U}_M(t)\right]$$

$$-\vec{\nabla} P(t) = \vec{f} \times \vec{U}_g(t)$$

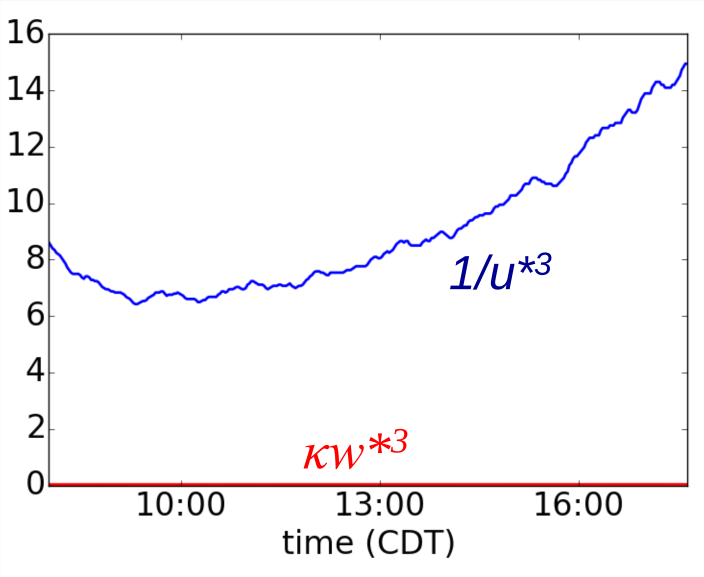
Change in direction of $\mathbf{U}_M$ alone → modifies $-z_i/L$.

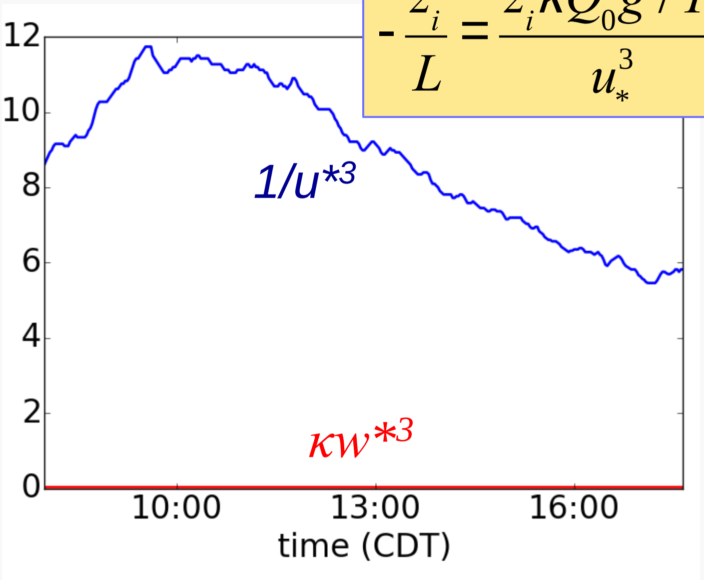
Why does ABL stability state change with no change in Q_0?



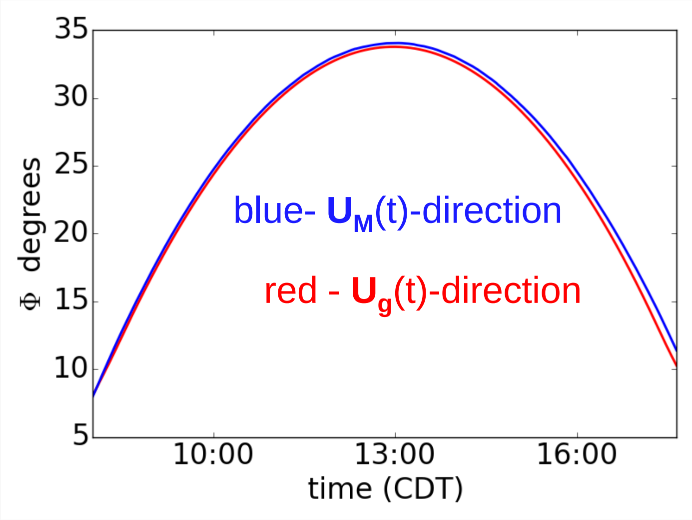


$$-\frac{z_i}{L} = \frac{z_i k Q_0 g / T_0}{u_*^3} = k\frac{w_*^3}{u_*^3}$$

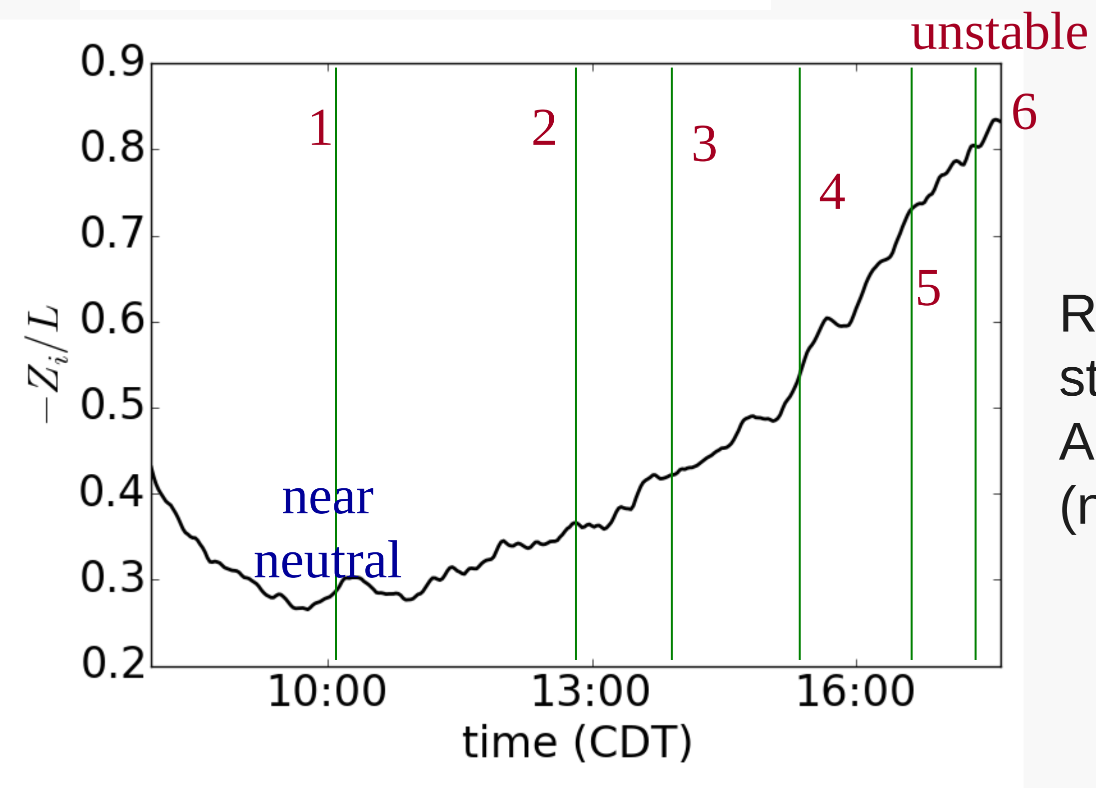




Change in Wind Direction can alter ABL Structure



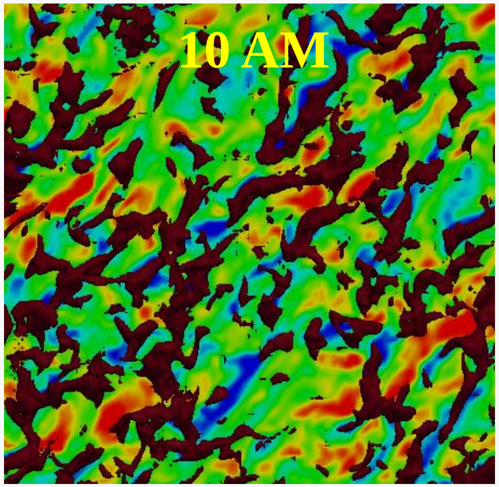
- Q_0 is invariant and non-zero.
- Initial $-z_i/L = 0.41$
- $|\mathbf{U_M}|$ is constant with time



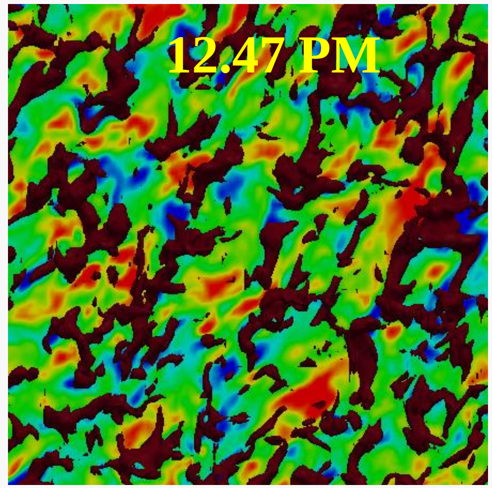
Relationship between stability state, $-z_i/L$ and ABL turbulence structure (next slide)

Effect of Change in Wind Direction : ABL Turbulence 3D Structure

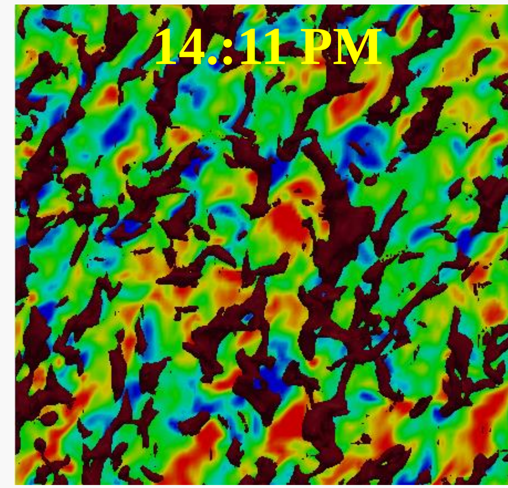
1: $-z_i/L = 0.27$



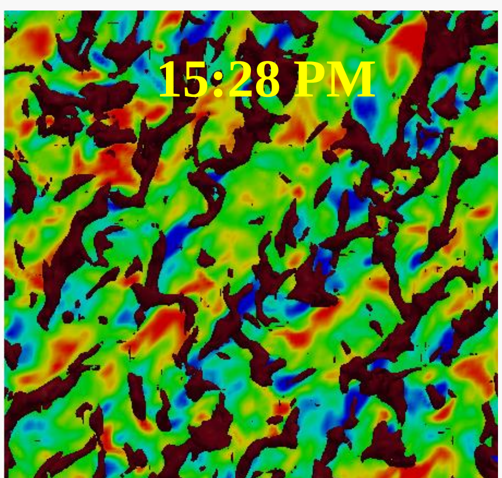
2 : $-z_i/L = 0.36$



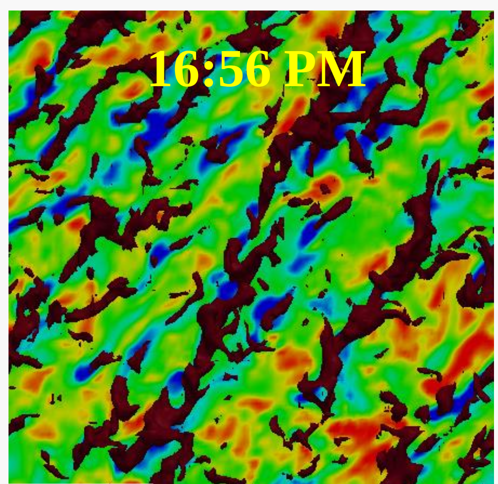
3 : $-z_i/L = 0.41$



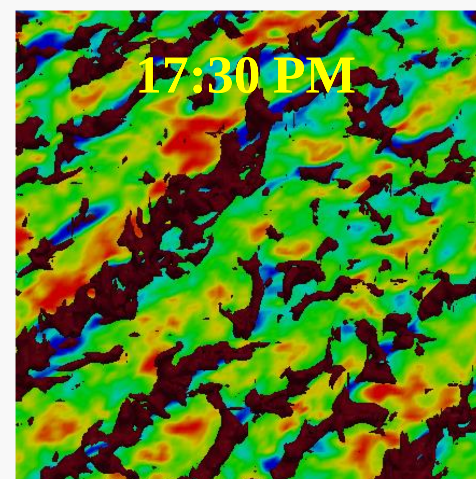
4 : $-z_i/L = 0.57$



5 : $-z_i/L = 0.75$



6 : $-z_i/L = 0.82$



u'-isocontours ($-2\sigma_u$ to $+2\sigma_u$) at 10% ABL height

Forcing of Wind Turbine Rotors by ABL Turbulence

Rotor in daytime ABL Turbulence

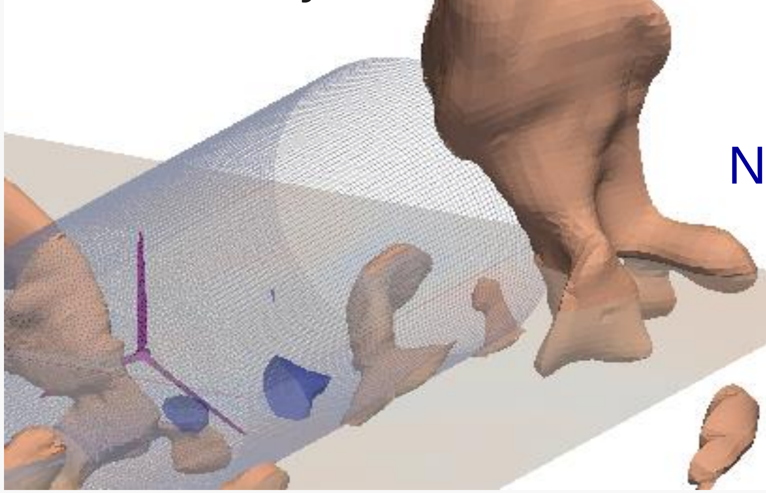


Image made by Adam Lavely at Penn State CWF

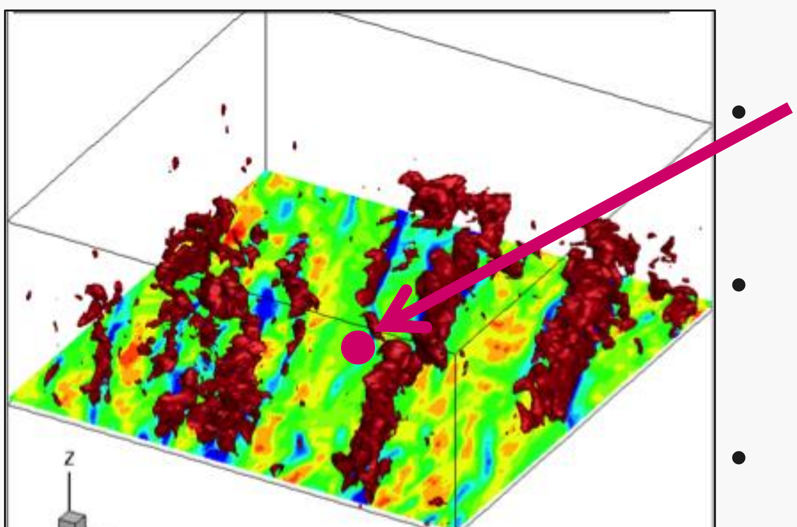
Blade cuts through eddies

↓

Non-steady changes in sectional *flow angles*

↓

3D non-steady separation dynamics and *transient loadings*



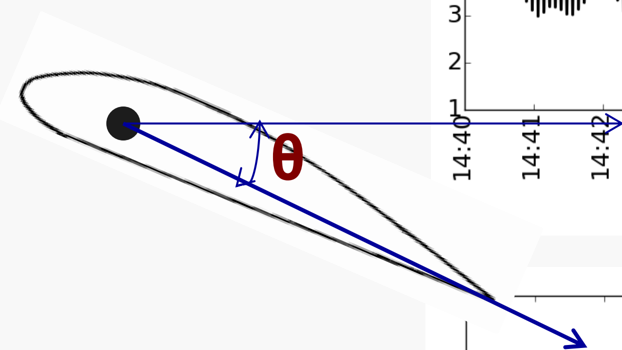
Passive Wind Turbine Analysis

- Imagine a hypothetical wind turbine in ABL flow
- Effect of wind turbine on ABL flow is not modeled
- Estimate temporal variations in ‘Flow Angles’ relative to blade sections

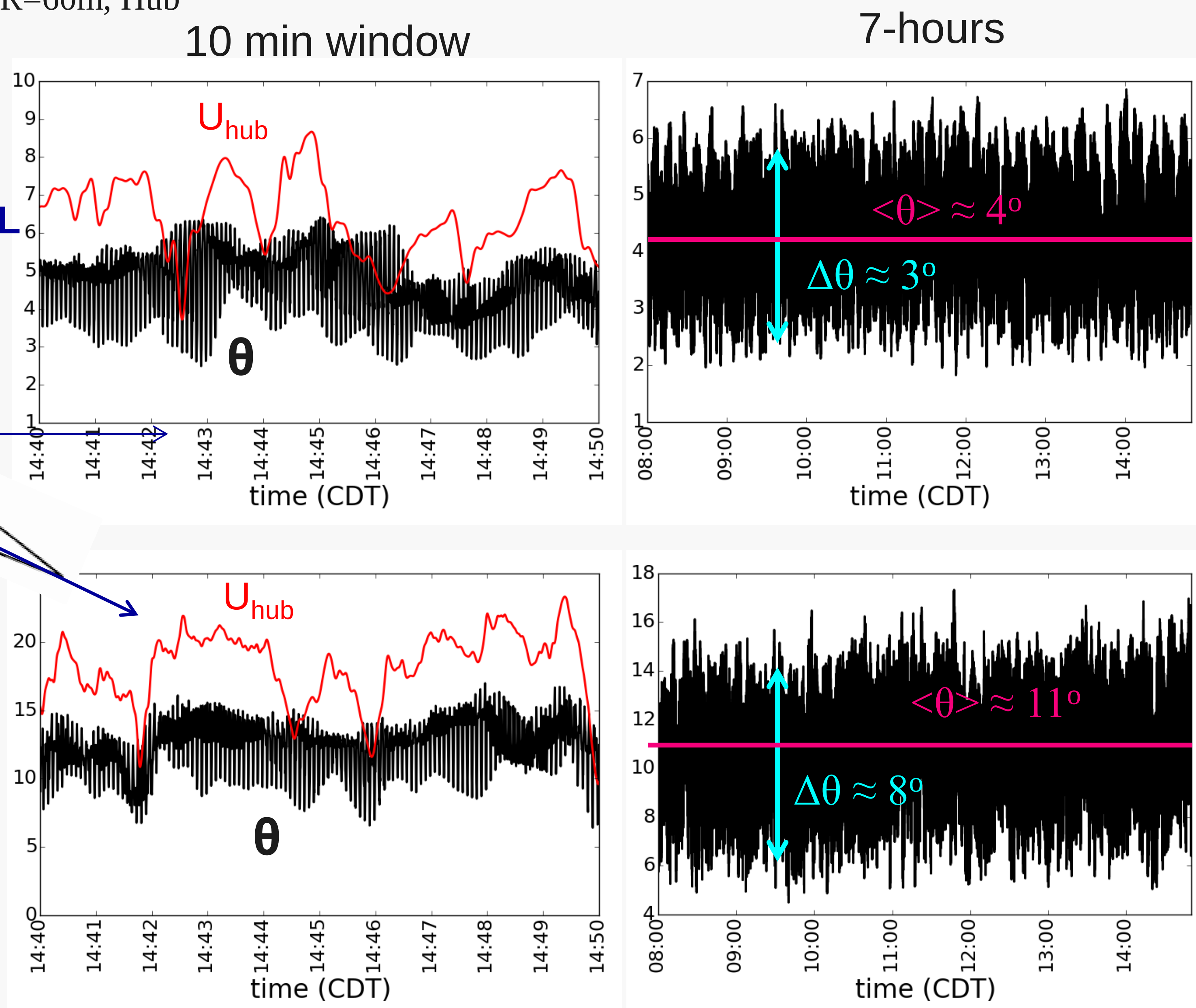
Forcing of WT Rotors by Equilibrium ABL Turbulence

Single blade section at R=60m, Hub height = 90 m
RPM = 12
Pitch = twist = 0°

Near-Neutral ABL
$-z_i/L=0.41$

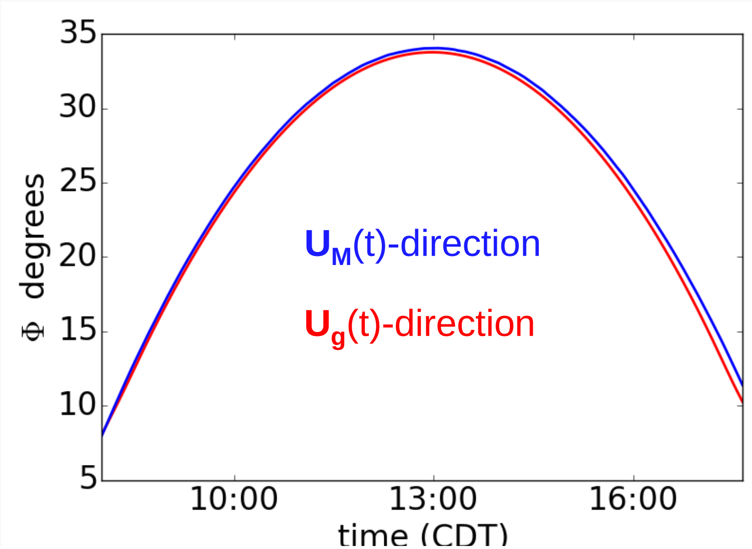


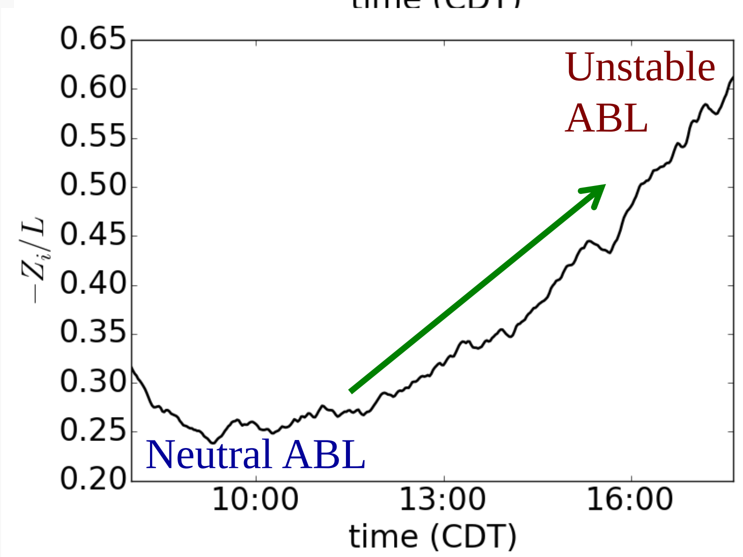
Moderately Convective BL
$-z_i/L=2.4$



Forcing of WT Rotors by ABL Turbulence : Non-equilibrium ABL

Q_0, $|\mathbf{U_M}|$ are invariant

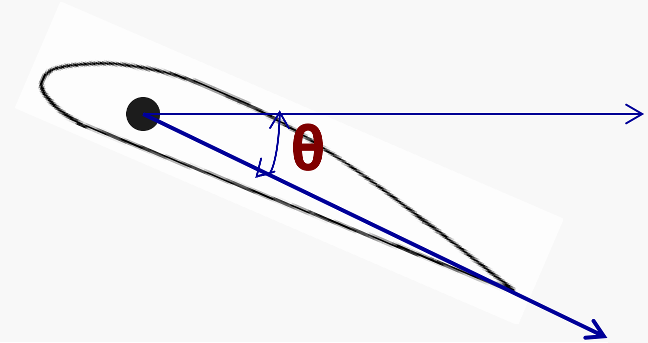


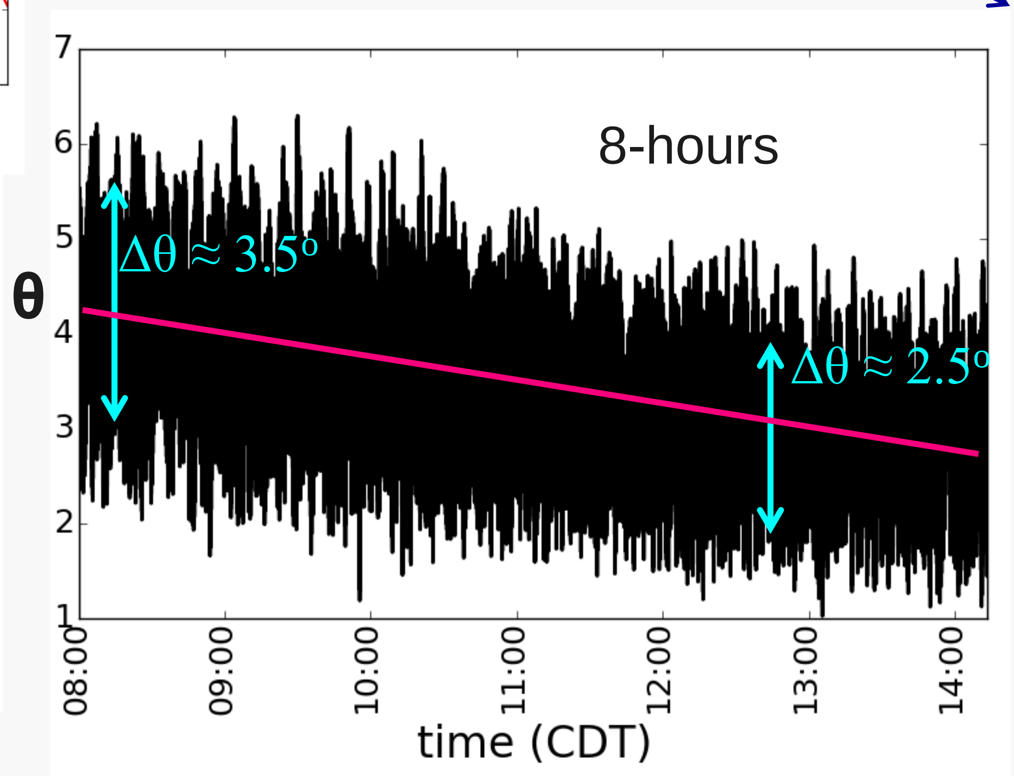


Single blade section at R=60m, Hub height = 90 m

RPM = 12

Pitch = twist = 0°





Summary

- Performed LES studies of non-stationary mesoscale forcing of ABL

- *Non-stationarity* in mesoscale occurs from two sources (a) $\mathbf{U_M(t)}$ and (b) $\mathbf{Q_o(t)}$ → diurnal cycle

- *Non-stationarity* causes the mesoscale wind vector, $\mathbf{U_M(t)}$ to deviate from the geostrophic wind vector, $\mathbf{U_g(t)}$.

- *Non-stationarity* → *Non-equilibrium* ABL turbulence

  - With a non-zero steady surface heat flux, $\mathbf{Q_o}$, change in direction of mesoscale wind vector, $\mathbf{U_M(t)}$ can modify ABL stability state.

  - Time history of diurnal variation of Q_0 causes deviation of the ABL from equilibrium.

- Preliminary experiments indicate change in $-z_i/L$ changes the mean and small-scale variability of the flow angles differently in equilibrium and non-equilibrium forcing.