Lecture 4: Surface Parameterizations

Announcements

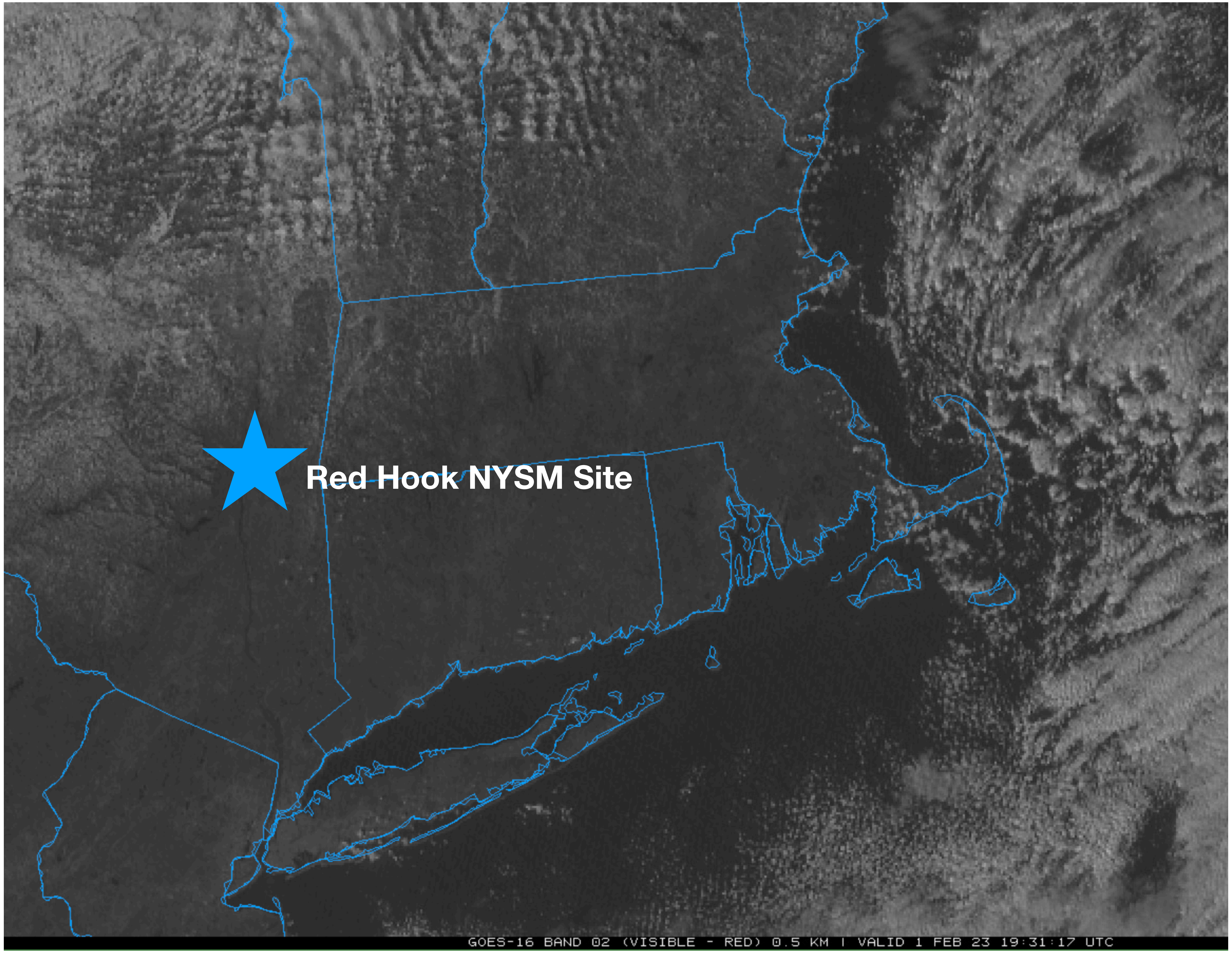
- Homework on Boundary Layer Module
  - due: Monday Feb 6th
  - returned: Monday Feb 13th
  - questions on homework: by appointment
  - Readings: Stull Chapter 7
- Midterm exam: Monday March 6th

Today's Lecture

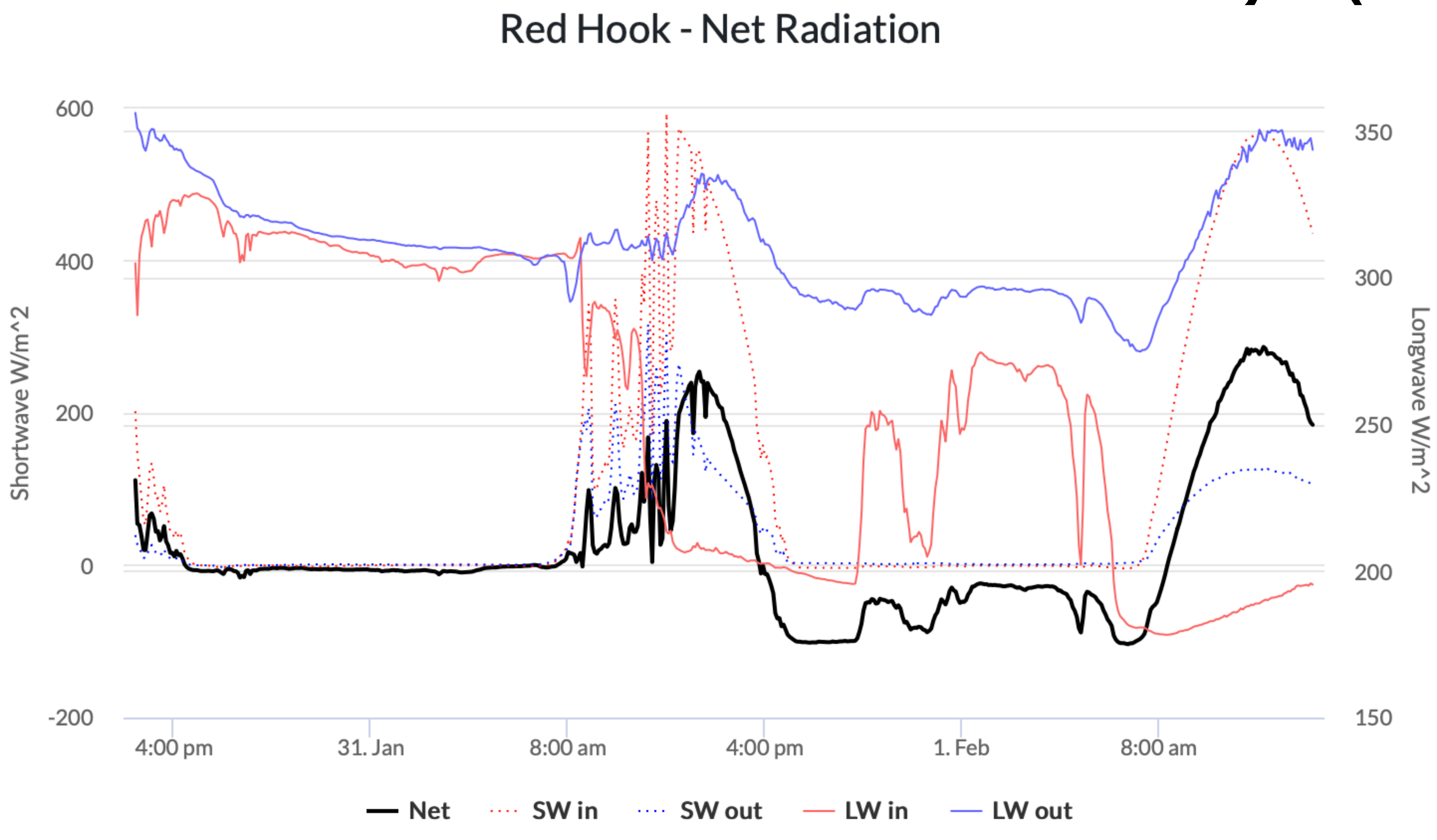
1. Bulk aerodynamic formulas
2. Drag coefficients, surface roughness
3. Energy Balance
4. NYS Mesonet—wind profiles

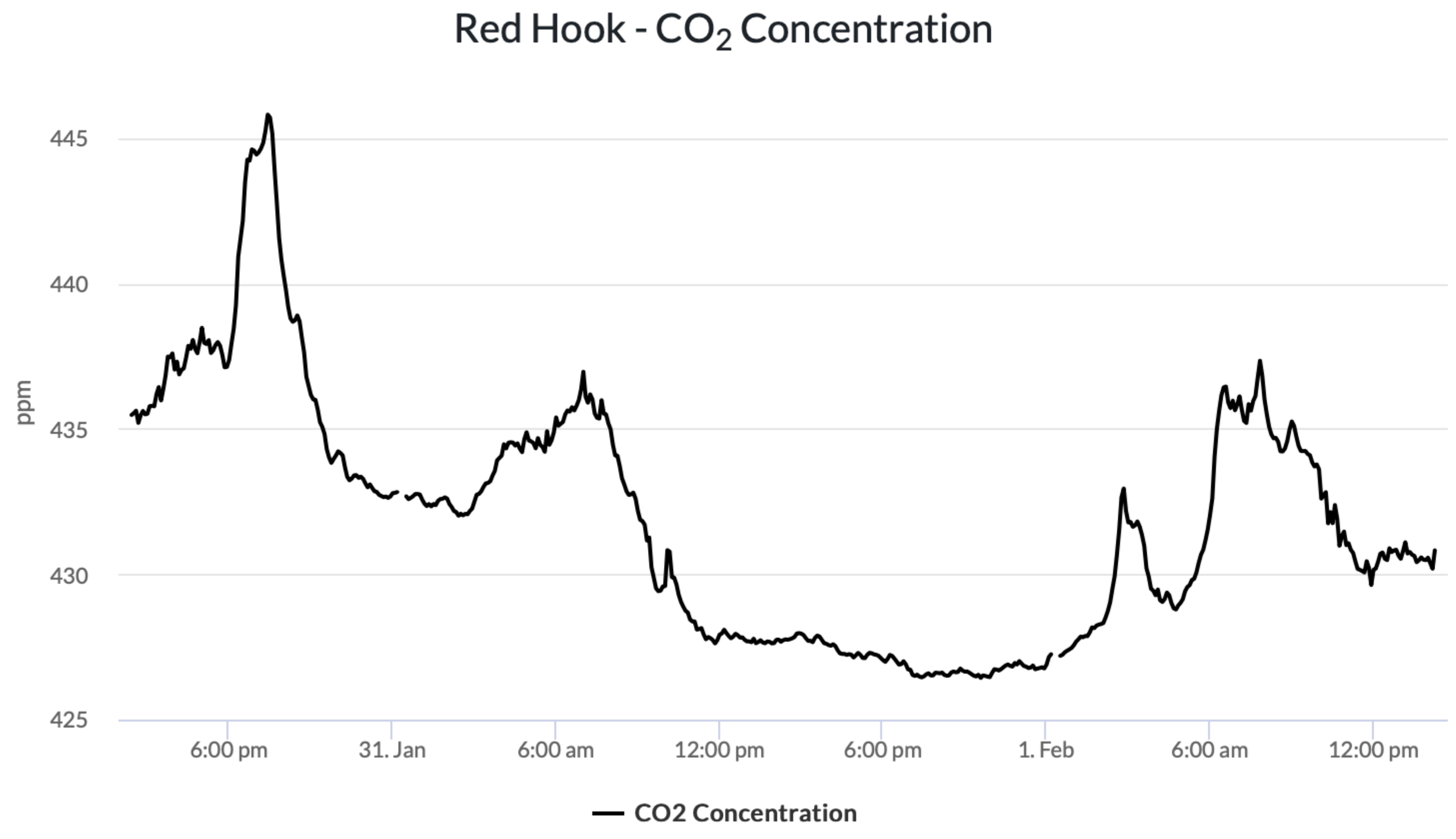
1 February 2023

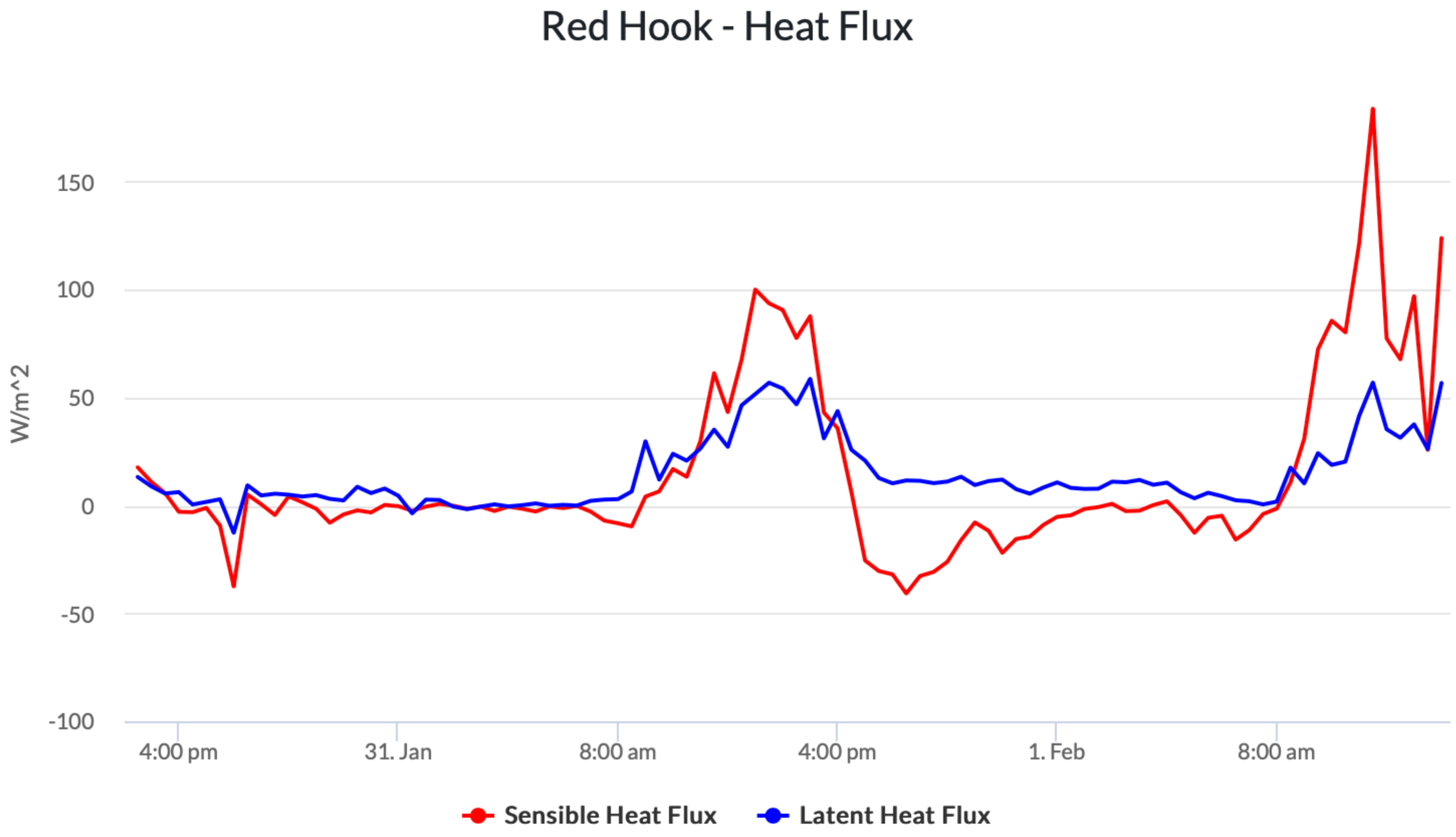
Today!

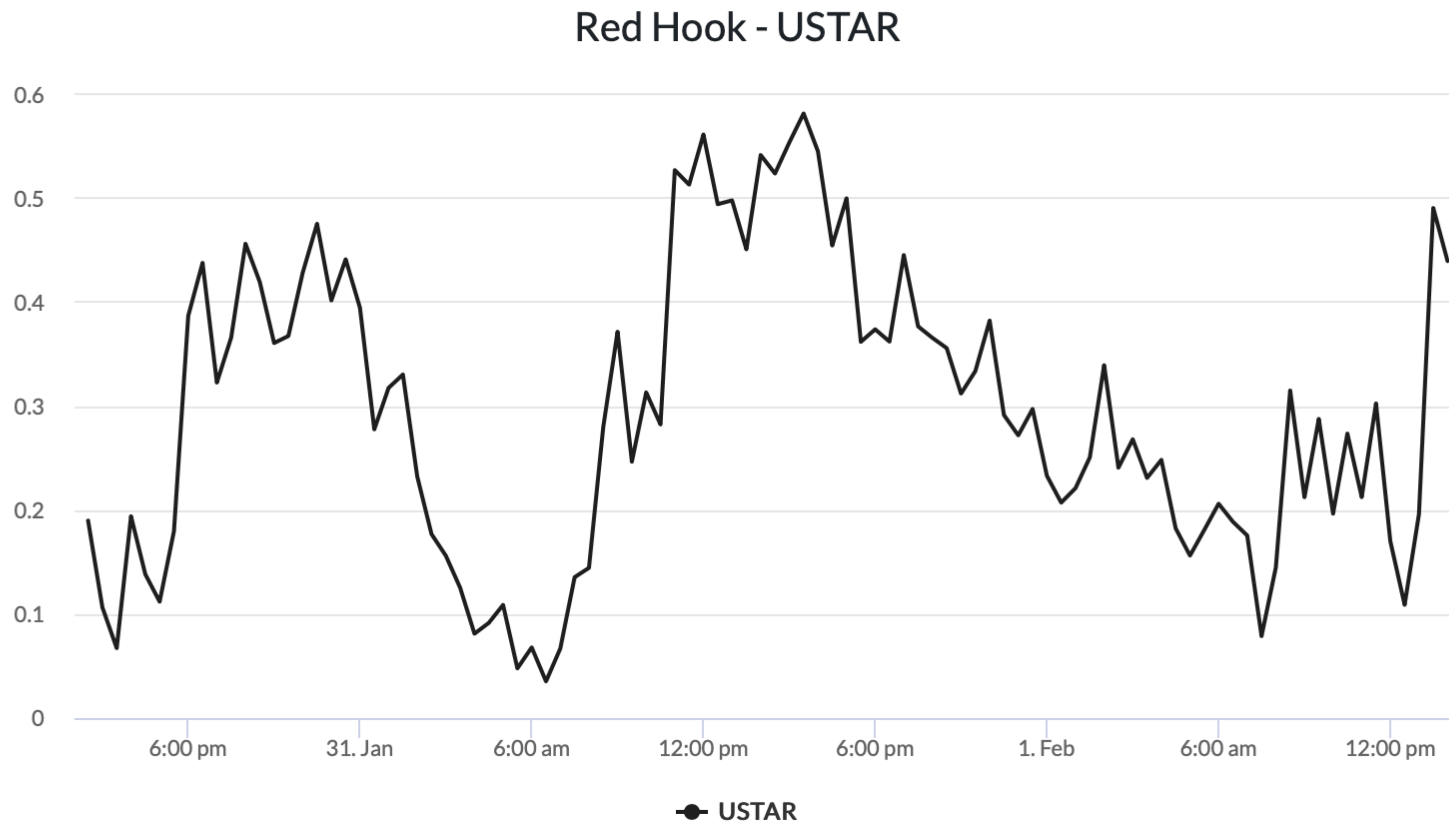

Red Hook NYSM Site
GOES-16 BAND 02 (VISIBLE - RED) 0.5 KM | VALID 1 FEB 23 19:31:17 UTC

Today (and yesterday)!







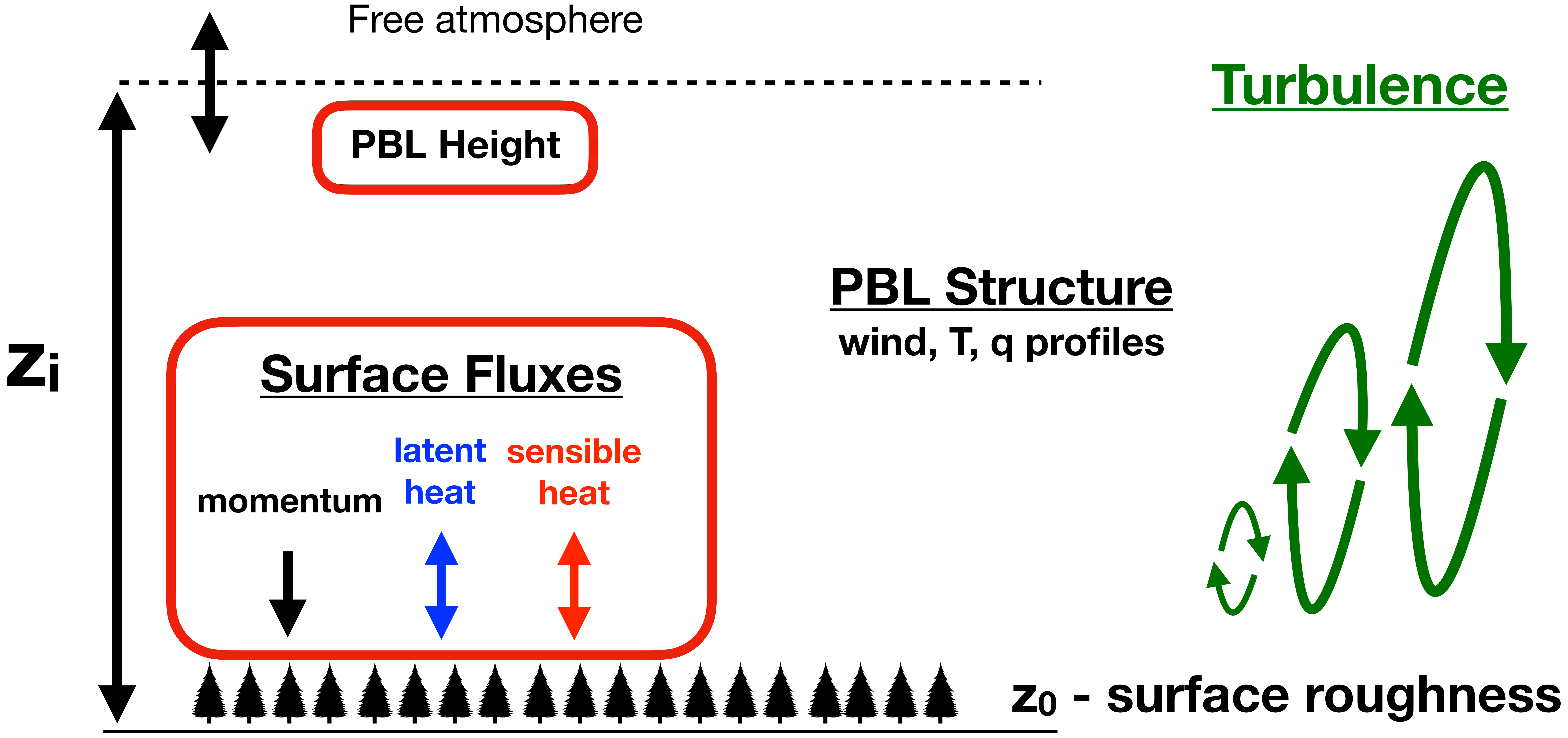


About that Problem Number 4….

Make sure you convert flux units (W m^{-2}) given in the time series to kinematic units (ms^{-1} K)

Hint: see Stull pages 47 -50!

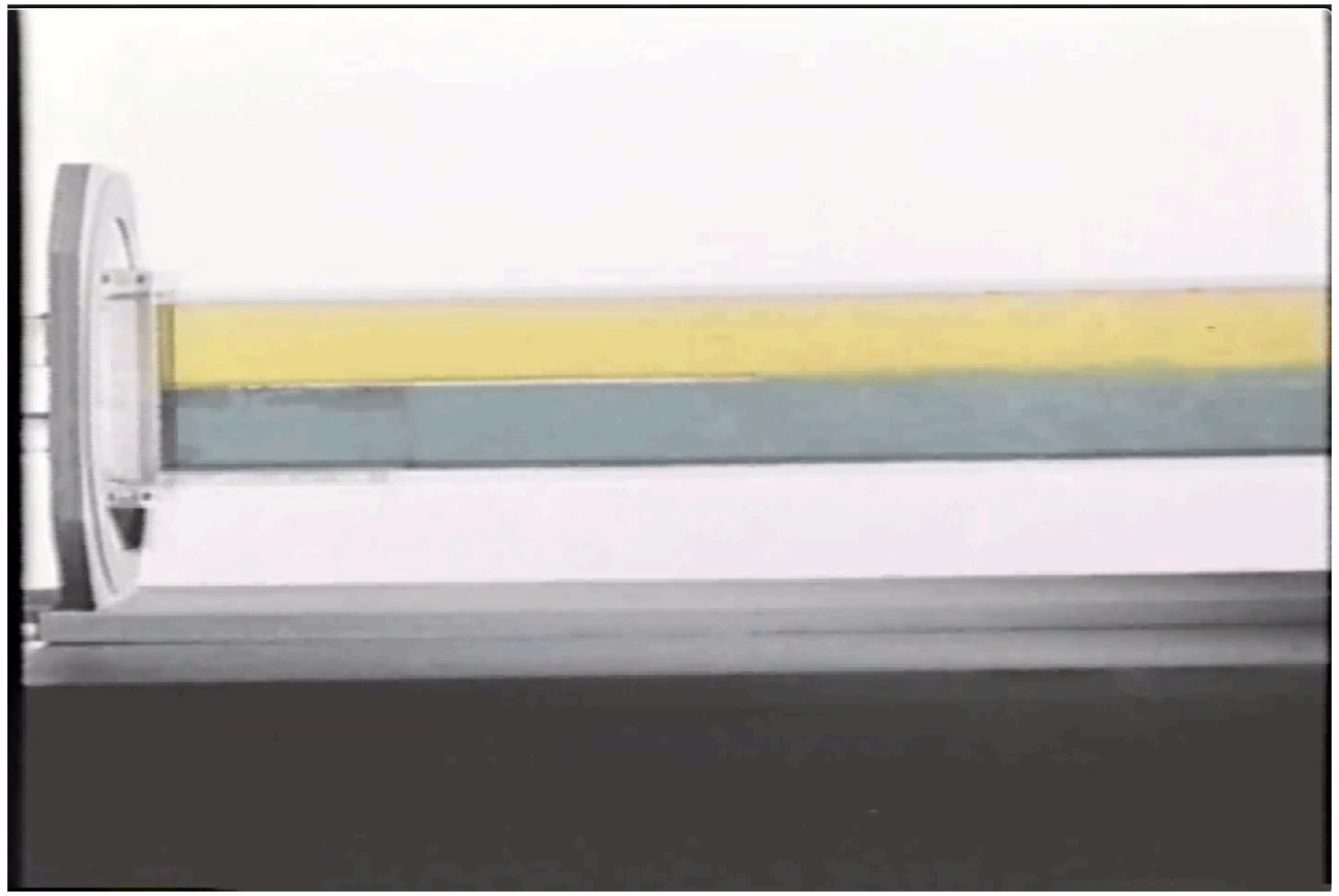
Conceptual Model of the ABL



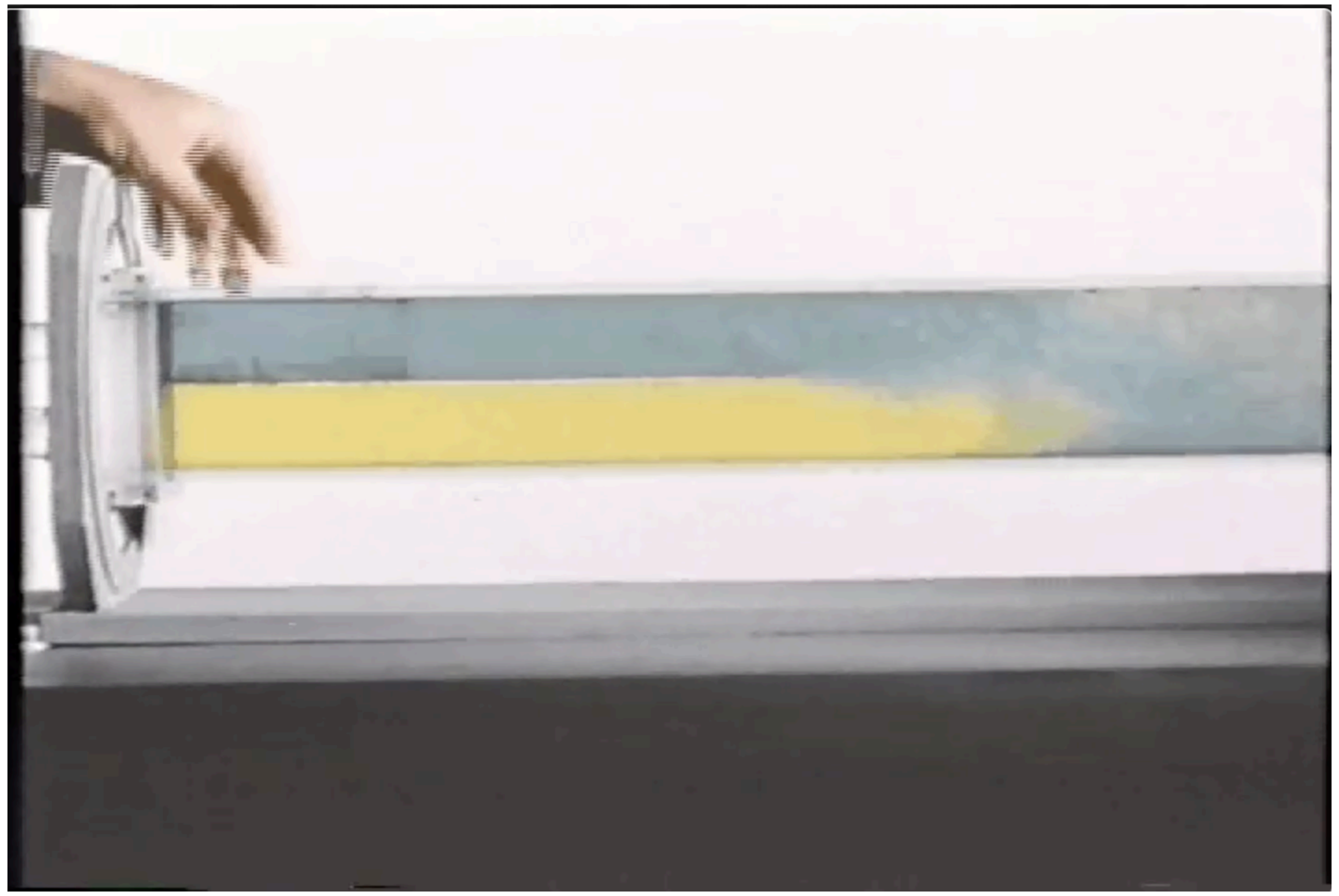
horizontally homogeneous

Stability enhances or supresses turbulence (and fluxes)

Stable



Unstable

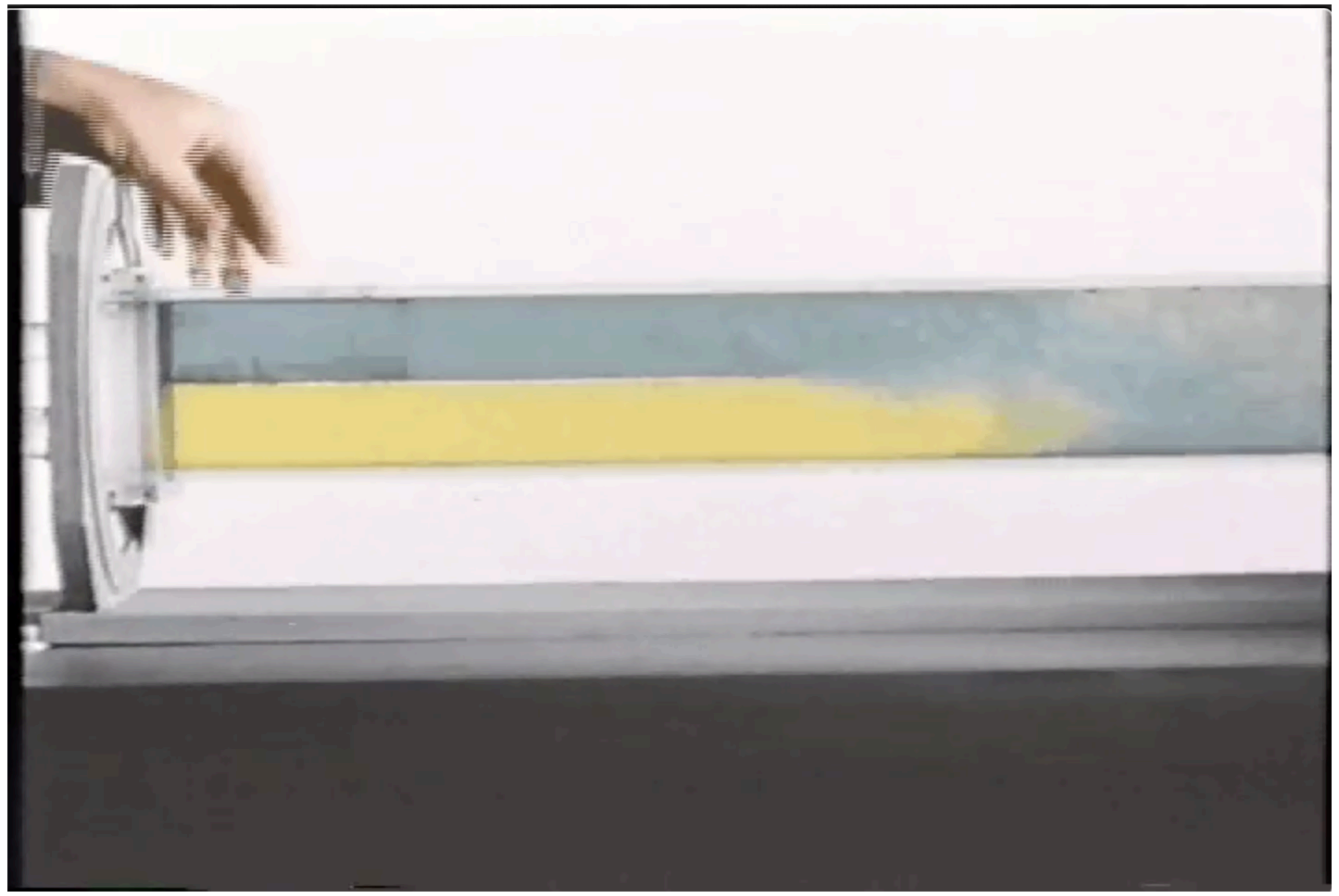


Turbulence, R.W. Stewart (1968)
Photos: J. Freedman

Stability enhances or supresses turbulence (and fluxes)

Stable

Unstable



<u>Turbulence,</u> R.W. Stewart (1968)
Photos: J. Freedman

Stability enhances or supresses turbulence (and fluxes)

Stable

Unstable

Turbulence, *R.W. Stewart (1968)*
Photos: J. Freedman

Stability Parameters

Gradient Ri

$$Ri = \frac{(g/\overline{\theta_v})\, \partial\overline{\theta_v}/\partial z}{(\partial\overline{U}/\partial z)^2}$$

$$Ri \approx \frac{\text{buoyancy forcing}}{\text{shear forcing}}$$

- predicts turbulent/laminar flow
- applies any height in PBL

Obukhov Length

$$L = -\frac{\theta_v\, u_*^3}{g\kappa\, (\overline{w'\theta_v'})_s}$$

$$L \approx -\frac{\text{shear forcing}}{\text{buoyancy forcing}}$$

- requires turbulence
- applies near-surface layer

Monin-Obukhov Similarity, z/L

- MO Similarity accounts for relative importance of shear (mechanical turbulence) and buoyancy in the generation of turbulence and their effects on surface fluxes and surface layer profiles
- z= height above the surface
- ratio z/L is dimensionless
- can be described as a surface layer scaling parameter
- when z/L is small, buoyancy is less important
- as z increases, buoyancy increasingly important

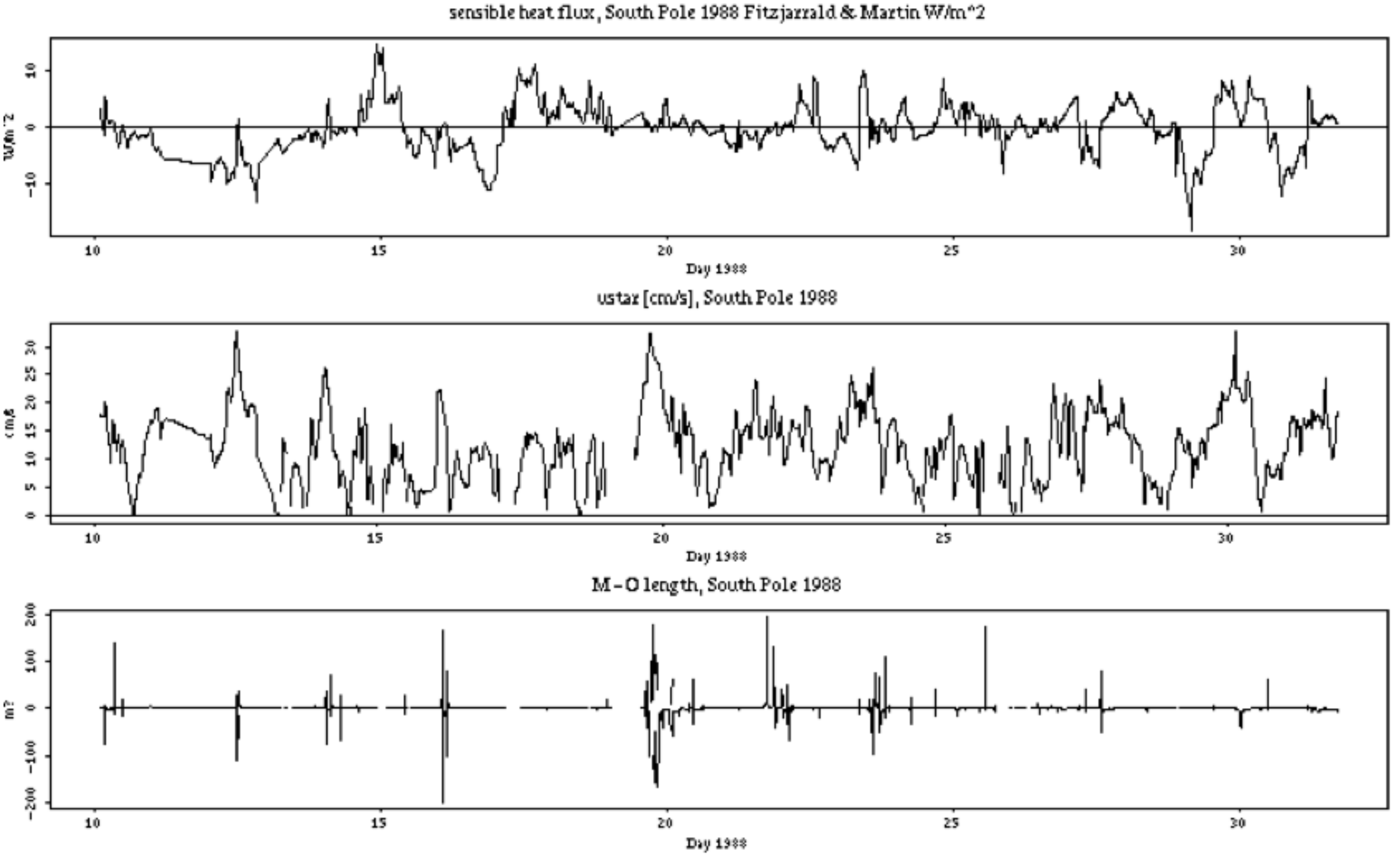
Free Convection at the South Pole!

Courtesy of D. Fitzjarrald

Heat Flux

u*

M-O length (L)



Law of the Wall

<u>Neutral</u>

$$\frac{k}{u_*}\frac{d\overline{U}}{d\ln z} = 1$$

$$\overline{U}(z) = \frac{u_*}{k}\ln\frac{z}{z_0}$$

<u>Diabatic</u>

$$\frac{k}{u_*}\frac{d\overline{U}}{d\ln z} = \phi_m(\frac{z}{L})$$

$$\overline{U}(z) = \frac{u_*}{k}\left(\ln\frac{z}{z_0} + \psi_m(\frac{z}{L})\right)$$

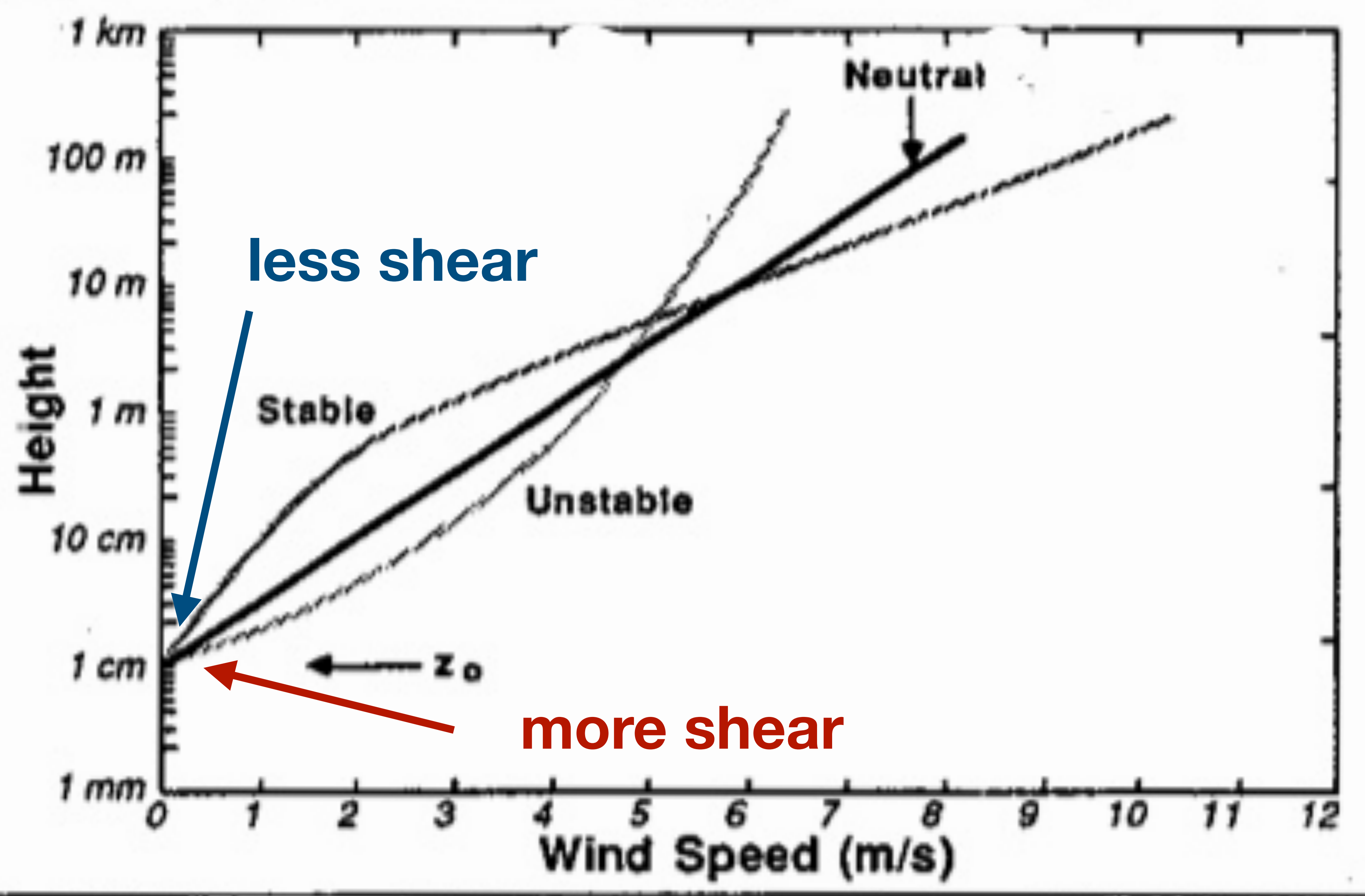
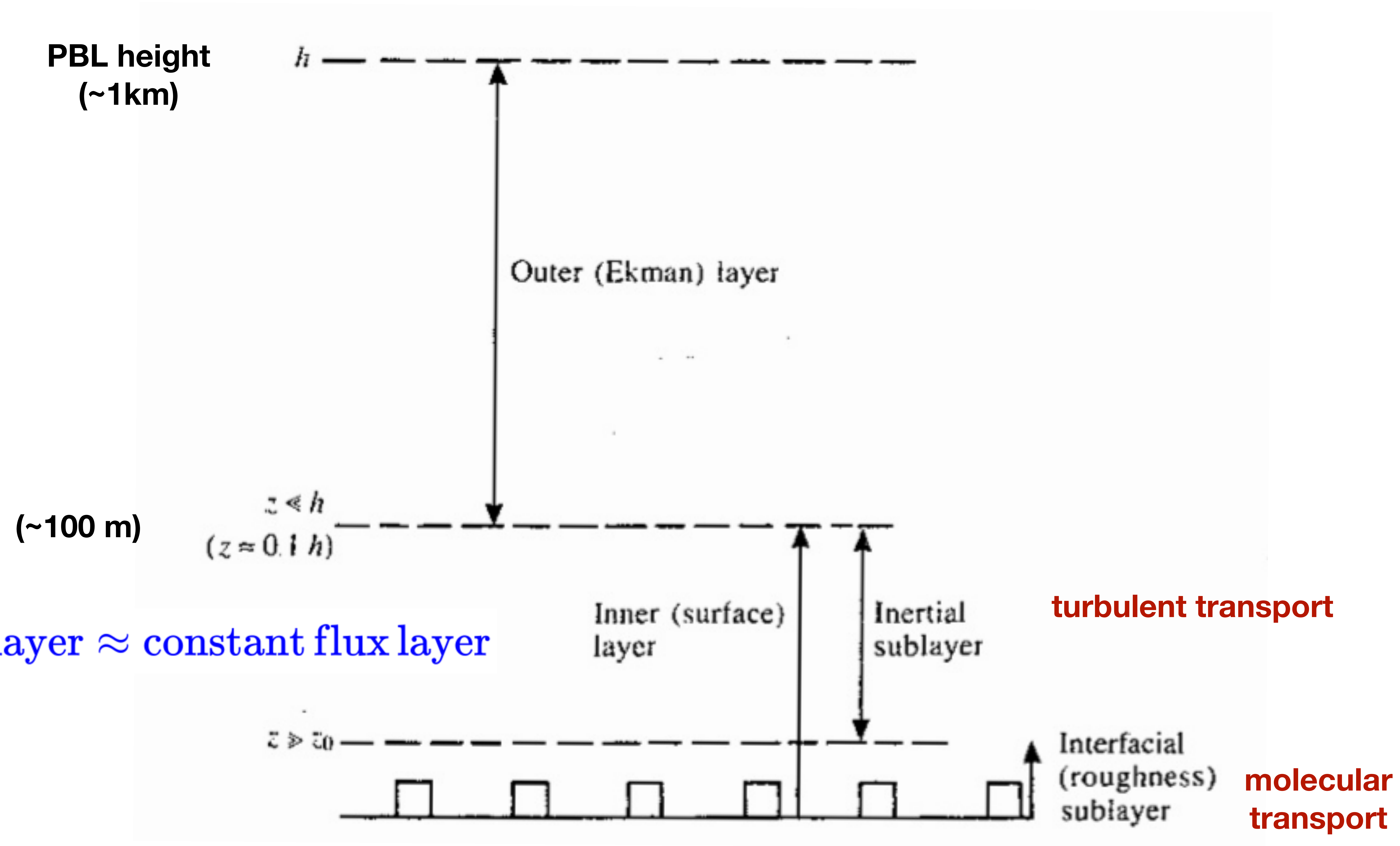


Fig. 9.5 Typical wind speed profiles vs. static stability in the surface layer

Stull 1988

Bulk Flux Parameterizations



surface layer ≈ constant flux layer

Garratt (1994)

Bulk Flux Parameterizations

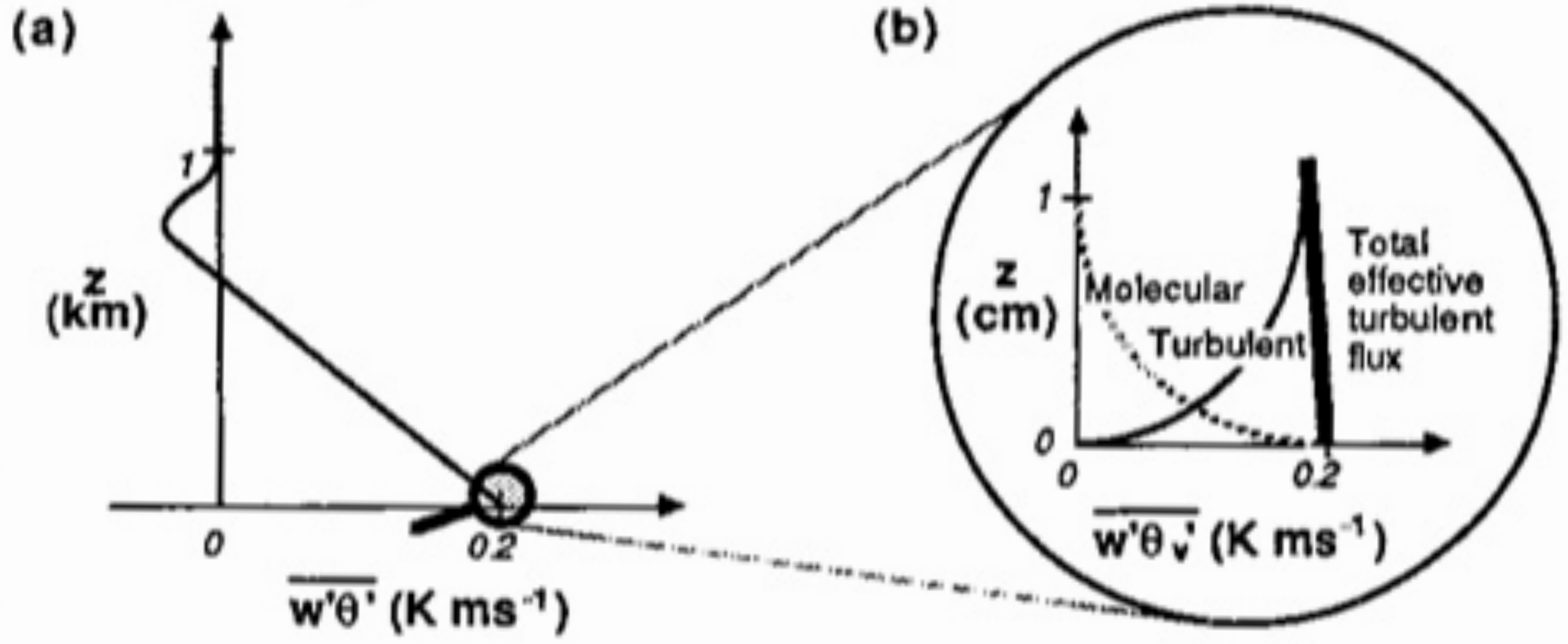
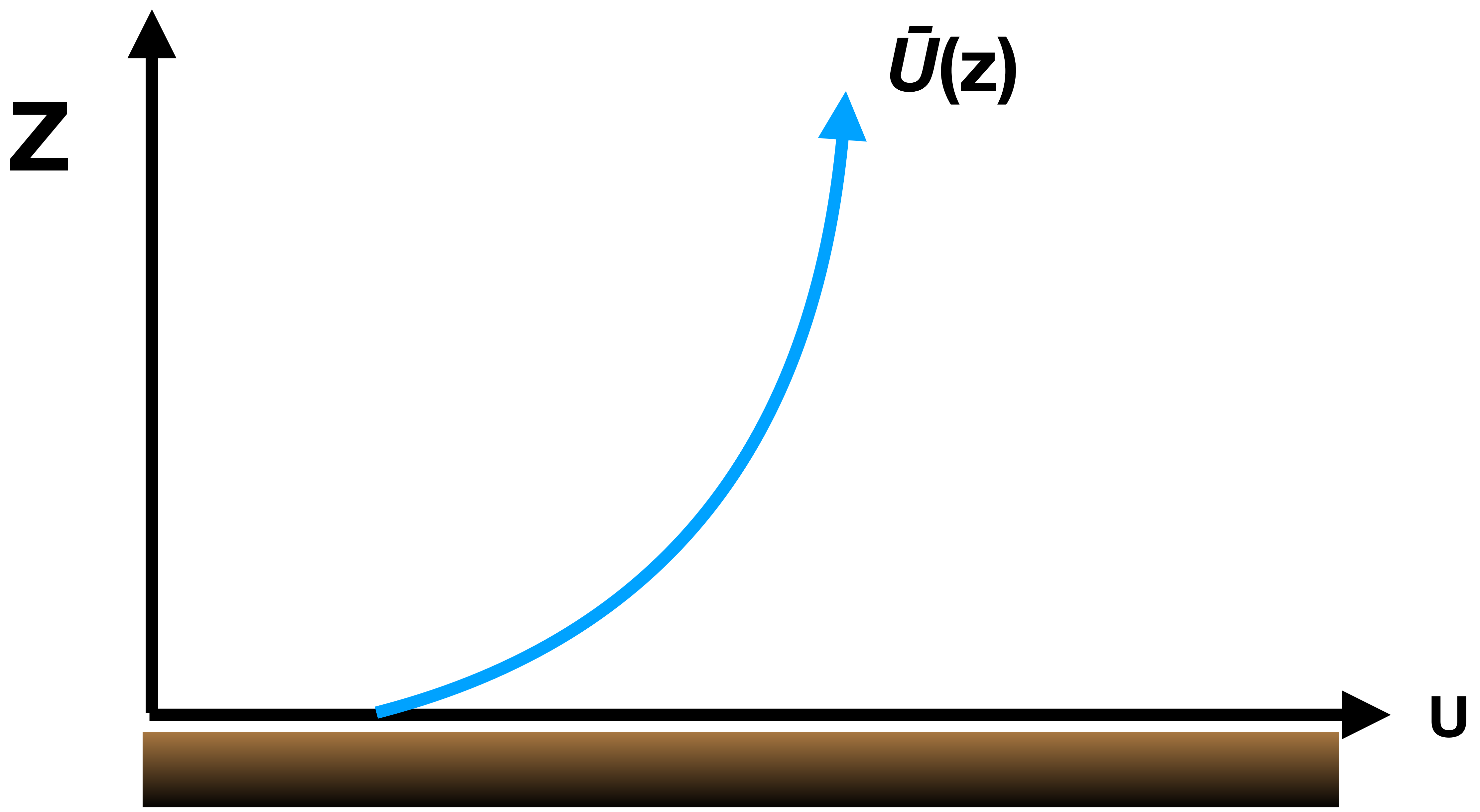


Fig. 7.1 (a) The effective turbulent heat flux using daytime convective conditions as an example, may be nonzero at the surface. (b) This effective flux, however, is the sum of the actual turbulent flux and the molecular flux.

- total flux is constant with height in surface layer
- at surface (“wall”), turbulence vanishes (no slip condition)
- away from surface (wall), molecular diffusion relatively small
- bulk methods attempt to avoid these complexities

Stull 1988

Bulk Fluid—away from interface —encompasses all processes



ρū ≡ horizontal momentum

ū·ρū ≡ horizontal advection of horizontal momentum

$\tau = C_D \cdot [\bar{u} \cdot \rho \bar{u}]$

C_D ≡ fraction of horizontal momentum "lost" to surface

Typically, $C_D \sim 0.001 - 0.005$

Bulk Flux Parameterizations

- τ constant with height
- C_D, ū vary with height
- select ref height, say 10 m

$$\frac{\tau}{\rho} = u_*^2 = C_{D10}\, U_{10}^2$$

Bulk Heat Flux Parameterization

$$\frac{H}{\rho\, C_p} = \overline{w'T'} = -C_{H10} \cdot \overline{U}_{10}(T_{10} - T_0)$$

vertical turbulent heat flux

mean horizontal advection of heat at 10 m height

$$C_{H10} = \frac{\text{vertical turbulent flux}}{\text{bulk horizontal advection}}$$

- fraction of horizontal heat flux transferred to surface
- efficiency of transport to surface

Drag coefficient vs stability

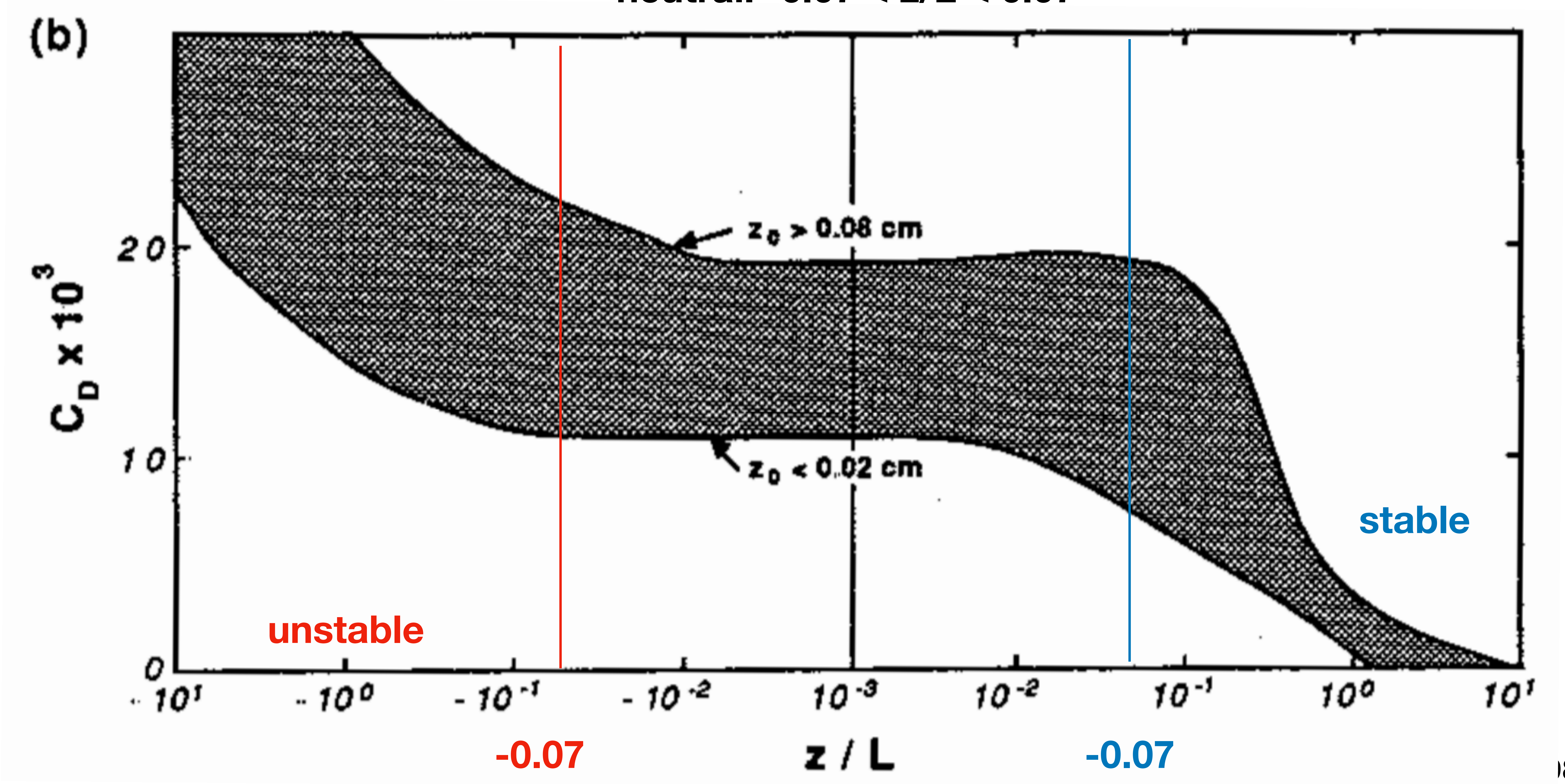
non-neutral (diabatic)

$$C_D = k^2\left[\ln\left(\frac{z}{z_0}\right) - \psi_m\left(\frac{z}{L}\right)\right]^{-2}$$

unstable: $\psi_m > 0$, $C_D \uparrow$

stable: $\psi_m < 0$, $C_D \downarrow$

neutral: -0.07 < z/L < 0.07



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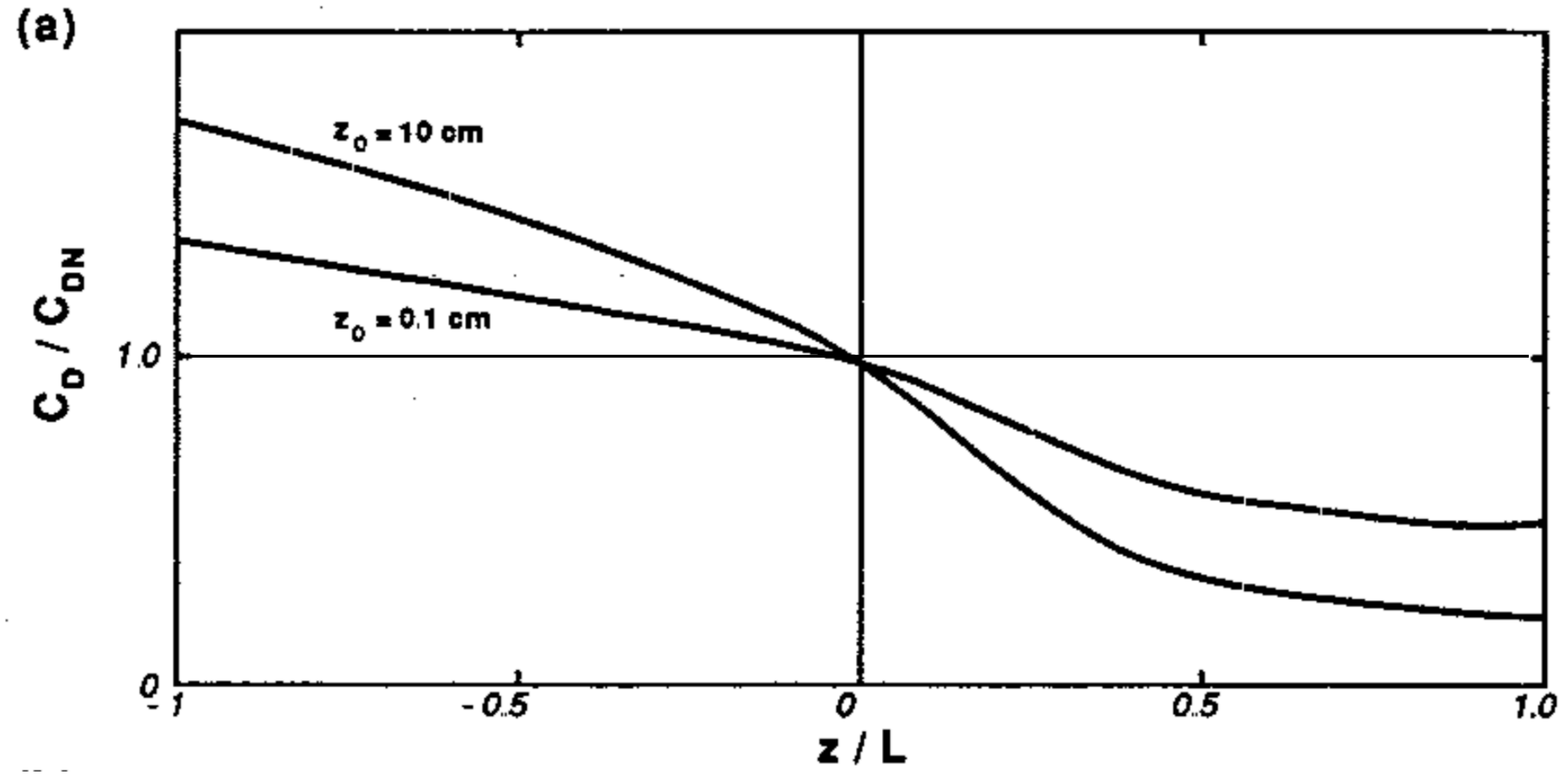
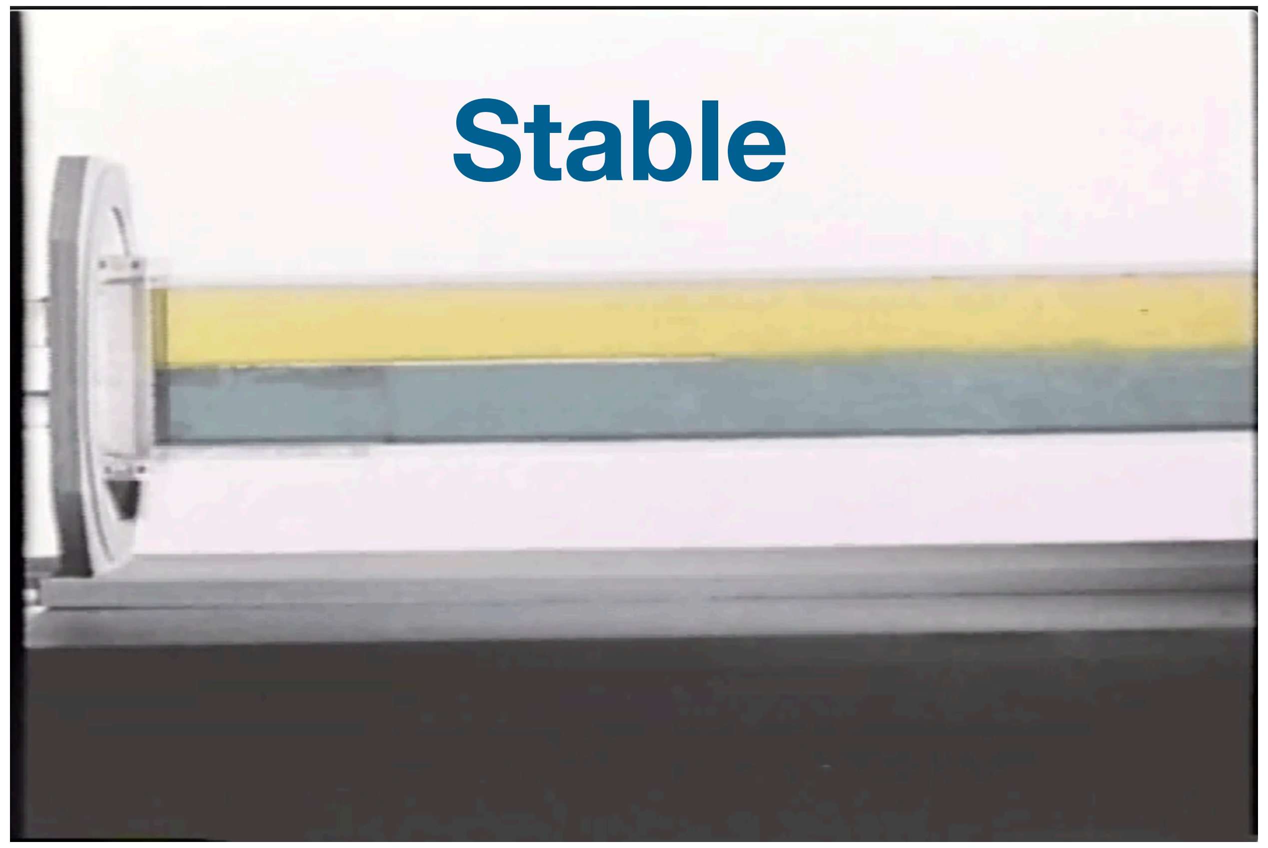
Drag Coefficient (C_D) versus Stability

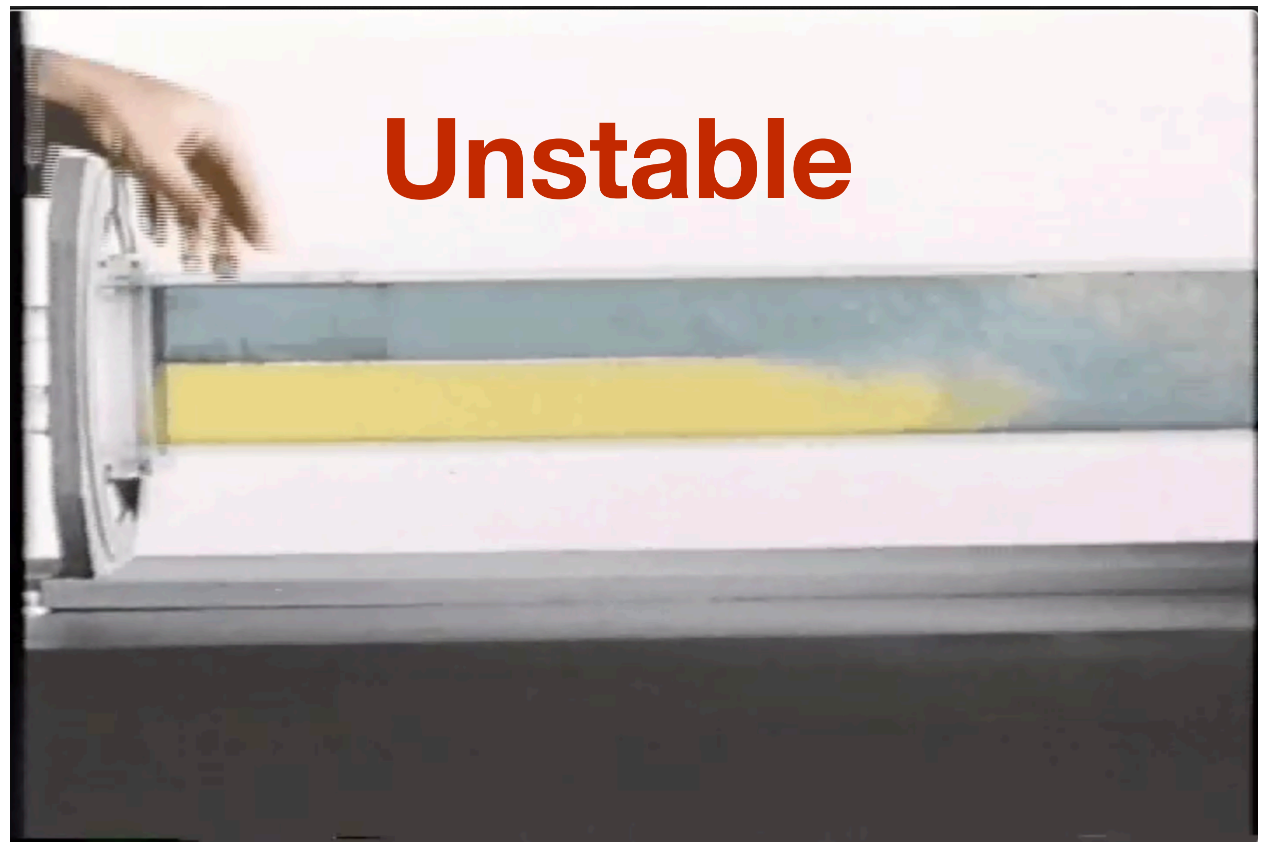
$$C_{D10} = \frac{\text{vertical turbulent momentum flux}}{\text{bulk horizontal advection of momentum}}$$



unstab neutr stabl

Stull





~0.001 (efficiency 0.1%)

Bulk Flux Parameterizations

$$\text{vertical flux} = \text{Coeff} \cdot [\text{horizontal advective flux}]$$

momentum: $$\tau = \mathrm{C_{D10}} \cdot \left[U_{10} \cdot \rho_a U_{10} \right]$$

heat: $$H = \mathrm{C_{H10}} \cdot \left[U_{10} \cdot \rho_a \mathrm{c_p} (\theta_s - \theta_{10}) \right]$$

moisture: $$H_L = \mathrm{C_{E10}} \cdot \left[U_{10} \cdot \rho_a \mathrm{L_v} (q_s - q_{10}) \right]$$

$\mathrm{C_D},\ \mathrm{C_H},\ \mathrm{C_E}$ depend on z_0, z/L, …

Example drag coefficients

Table 7-3. Sample drag and bulk-transfer coefficients. After Garratt (1977), Anthes and Keyser (1979), Gadd and Keers (1970), Deardorff (1968), Verma, et al (1986), and Kondo and Yamazawa (1986a).

Coefficient	Conditions
$C_{DN} = 1.4 \times 10^{-3}$	10 m winds over plains, daytime
$C_D = 16.0 \times 10^{-3}$	10 m winds over deciduous forest
$C_D = 40.0$ to 160.0×10^{-3}	10 m winds over coniferous forest
$C_{DN} = [0.75 + 0.067 \cdot M] \times 10^{-3}$	10 m winds over water

Roughly 0.1% to 4% of horizontal momentum advecting over surface is transferred down to the surface

Stull 1988

Drag and Roughness, z_0

$$\frac{\tau}{\rho} = u_*^2 = C_D U^2$$

$$C_D = \frac{u_*^2}{U^2}$$

Intuitively, the more rough the surface ➠ more drag

Recall, for neutral conditions: $\bar{U}(z) = \frac{u_*}{k} ln \frac{z}{z_0}$ (↑z_0, ↓U)

Rewrite as $\frac{u_*}{U(z)} = k[ln \frac{z}{z_0}]^{-1}$

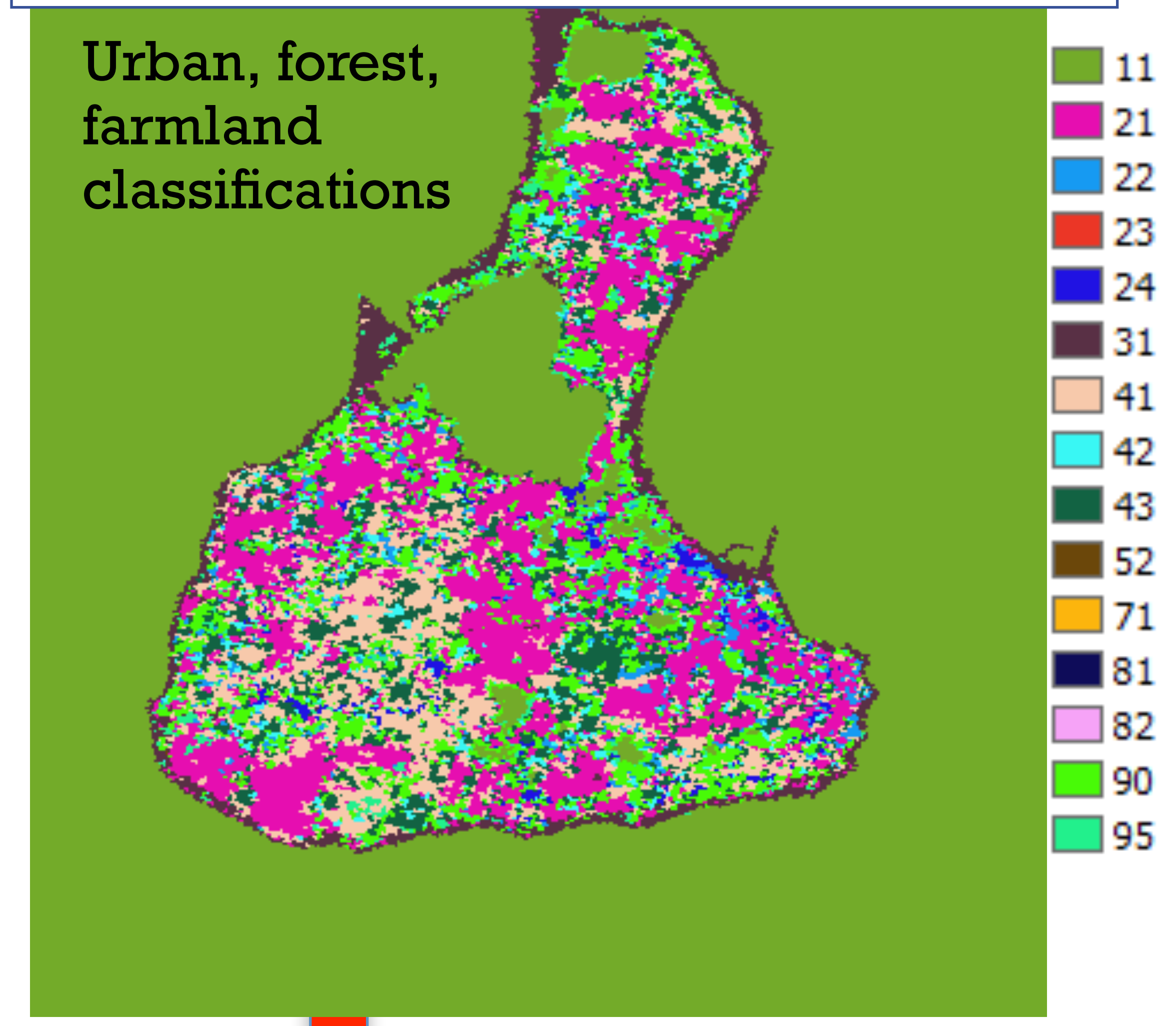
$C_D = \frac{u_*^2}{U(z)^2} = k^2 [ln \frac{z}{z_0}]^{-2}$ (↑z_0, ↑C_D)

Surface Roughness

Getting it right crucial to accurate wind resource assessment

While working on the Deepwater Offshore Wind Project off of Block Island, RI….

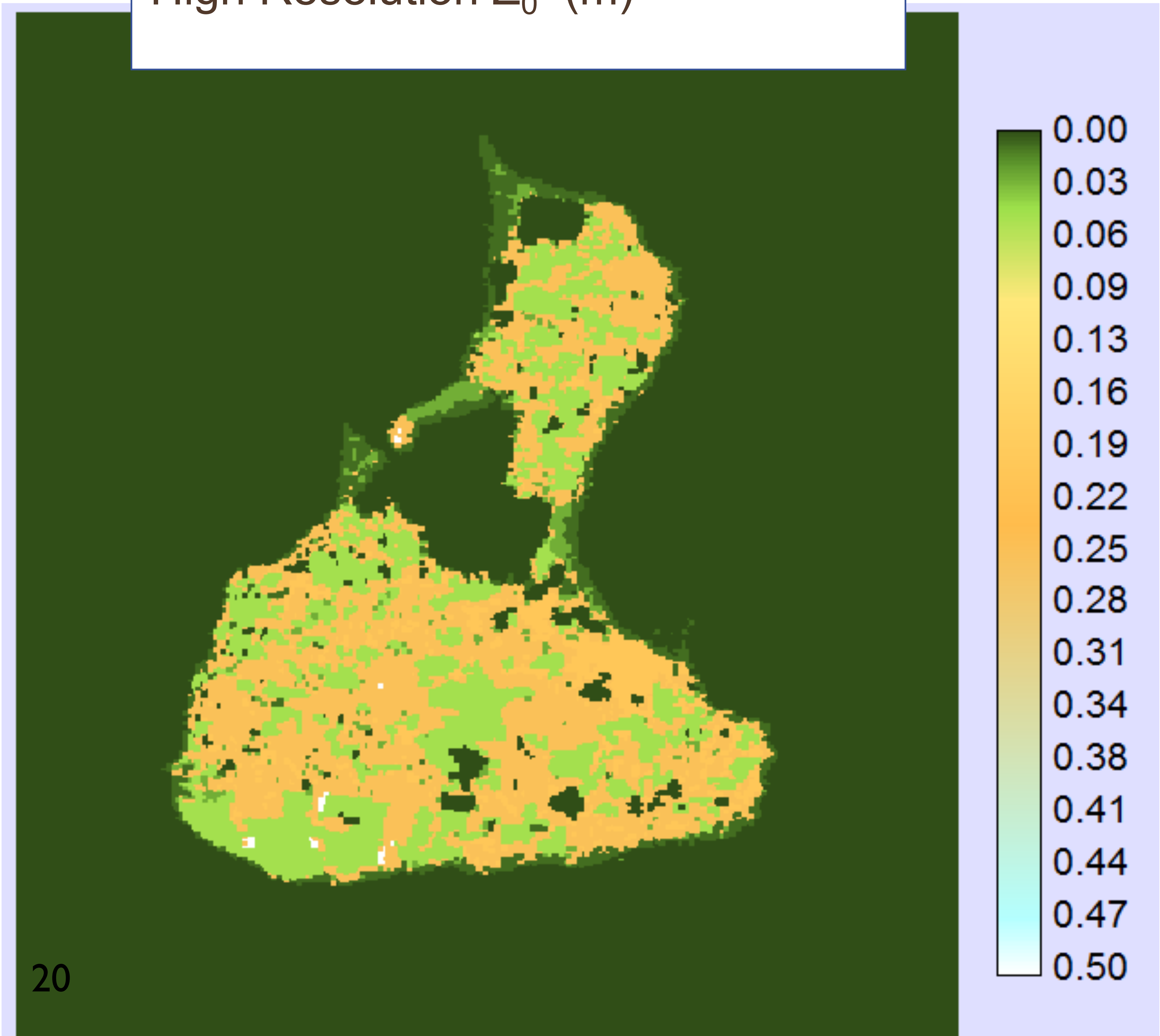
Existing: NLCD/Landsat



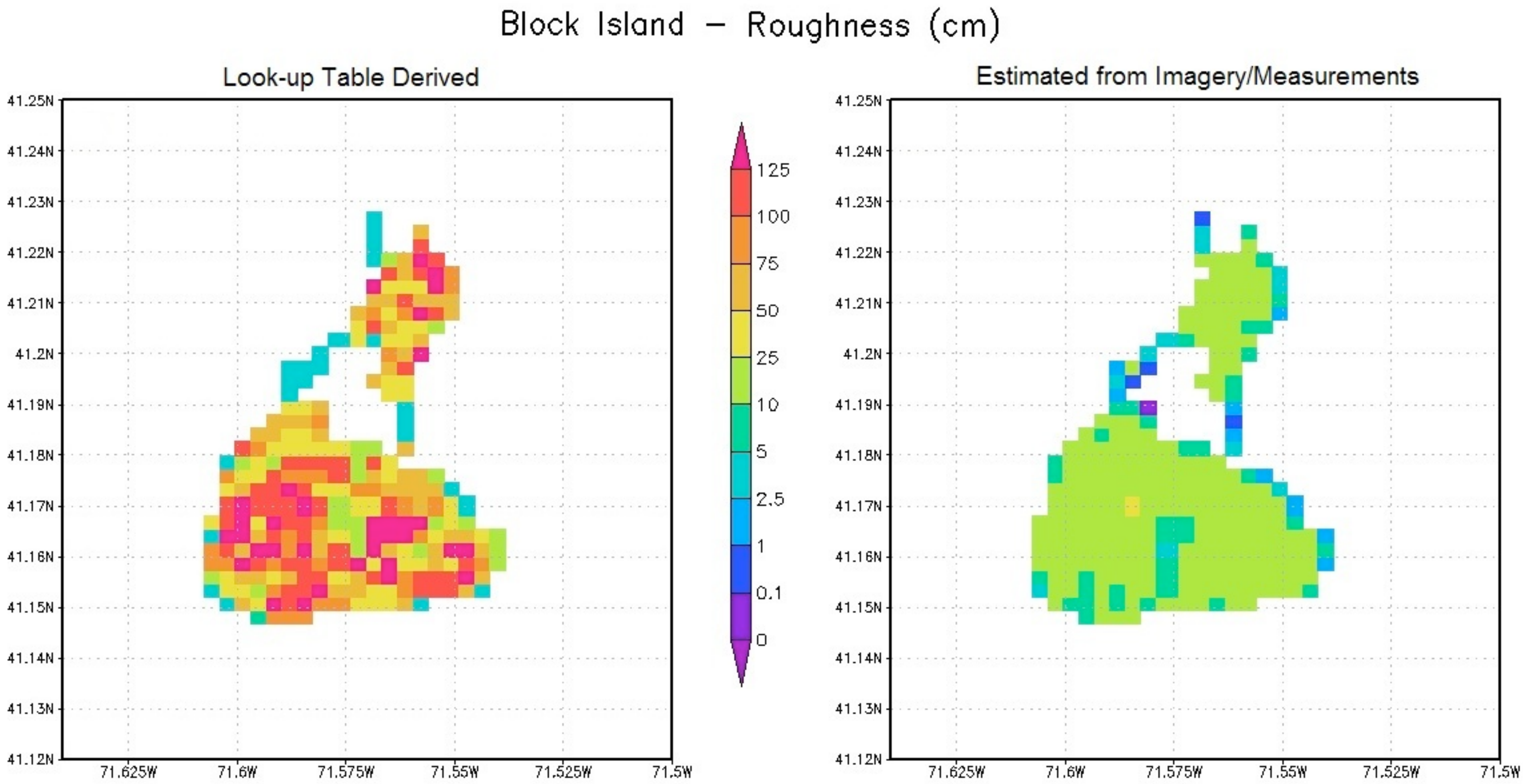
Site Photography

Aerial Photography

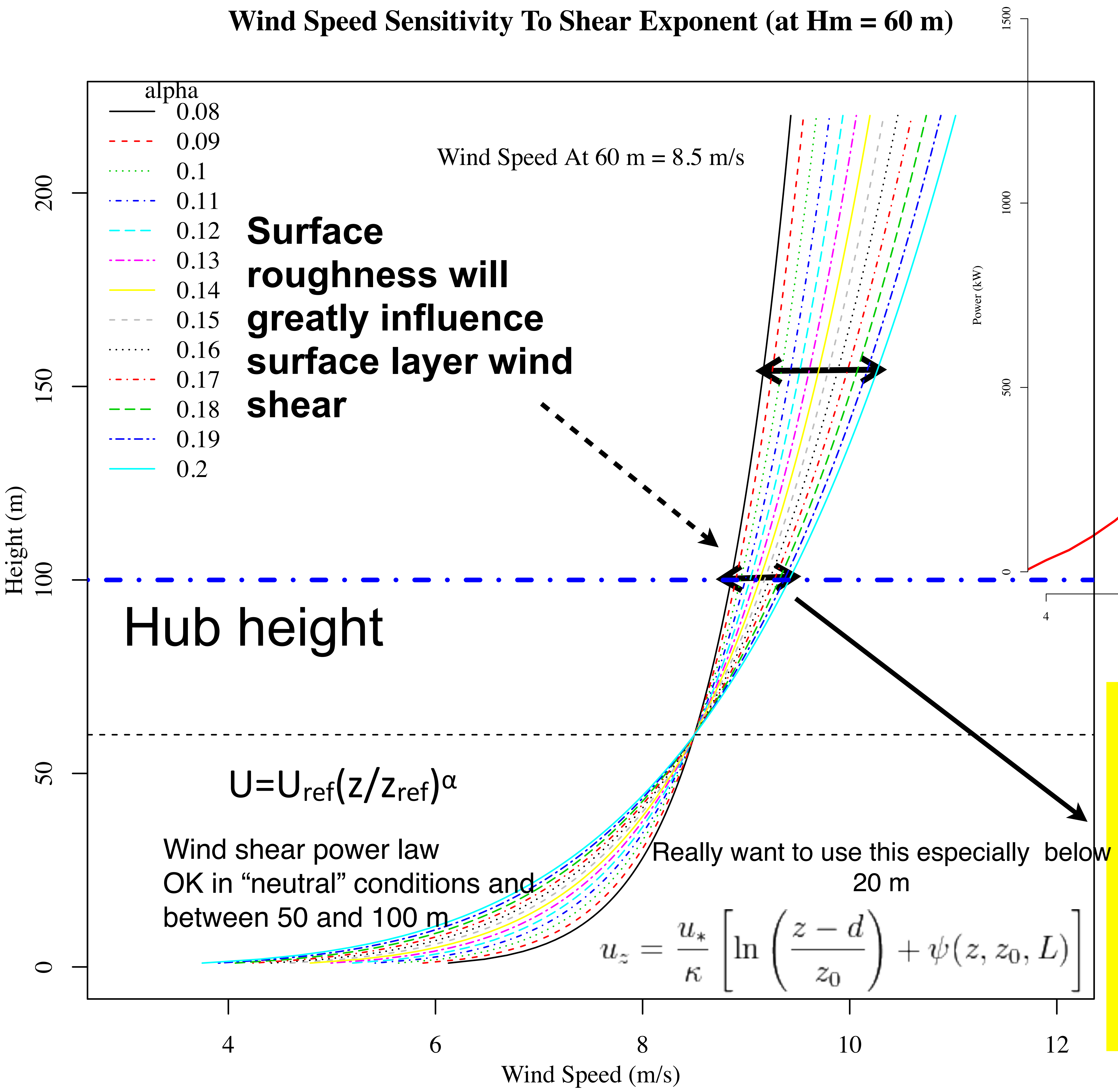
High Resolution Z_0 (m)

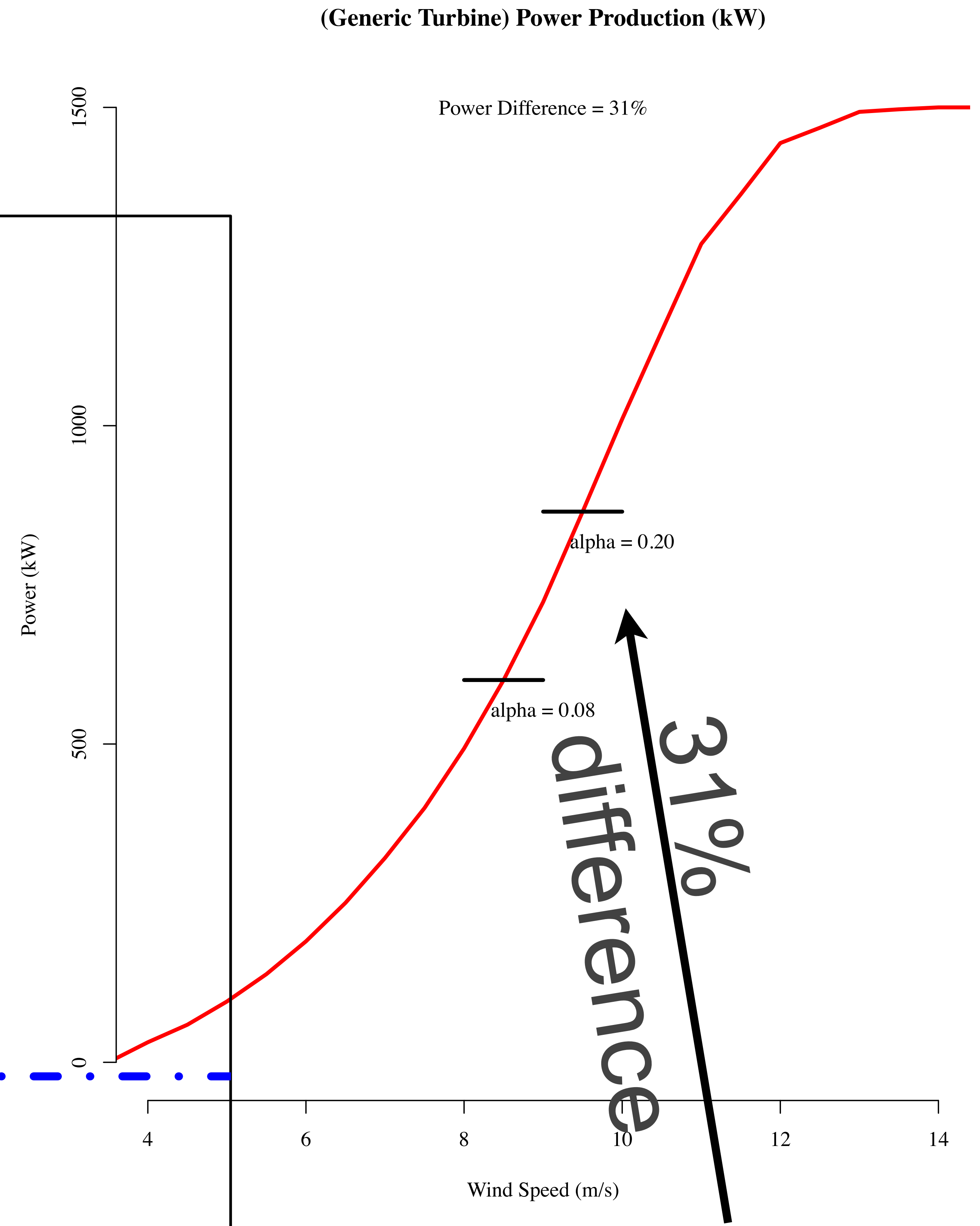


Comparison of Model Roughness Fields—from WRF



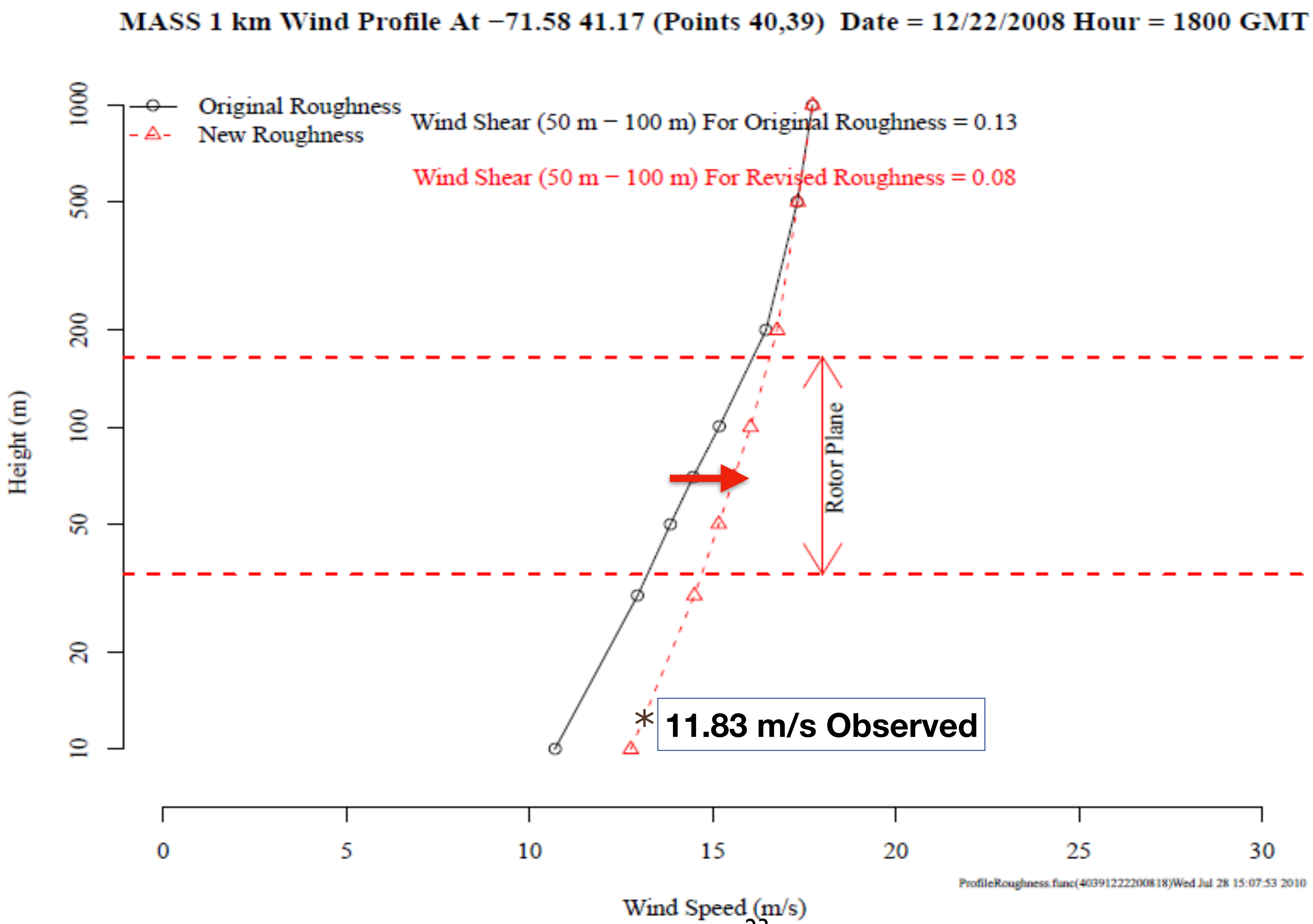
~1 m difference in model roughness fields – Variability within land cover classes





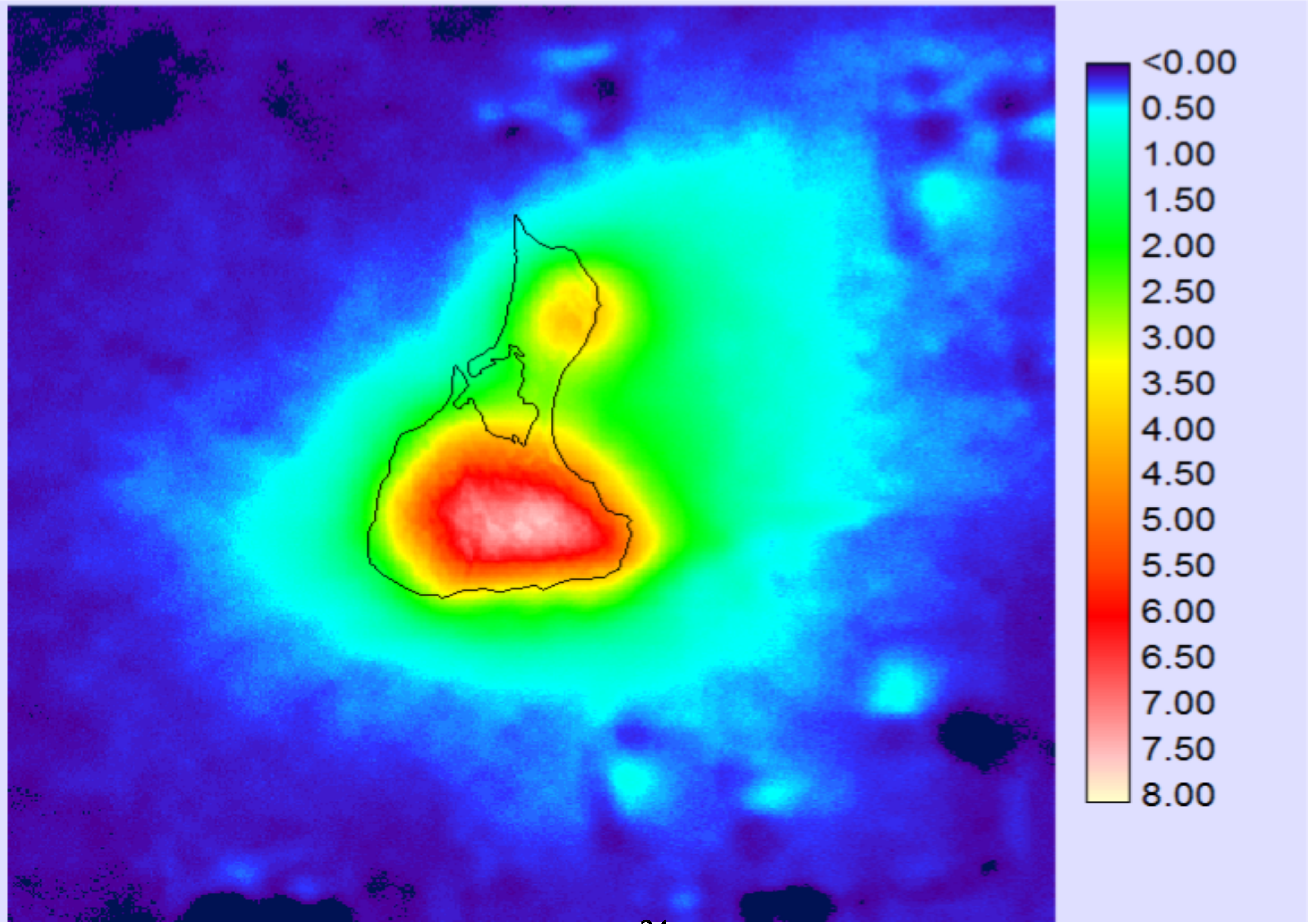
This can certainly affect power production estimates as surface roughness has great influence over the wind profile (shear) in the lowest 100s of meters

Results – Wind Speed Profile (KBLI)



Energy Production Estimates

Use of new roughness map increased capacity factor over 8% in southern sections of Block Island



Surface Energy Balance

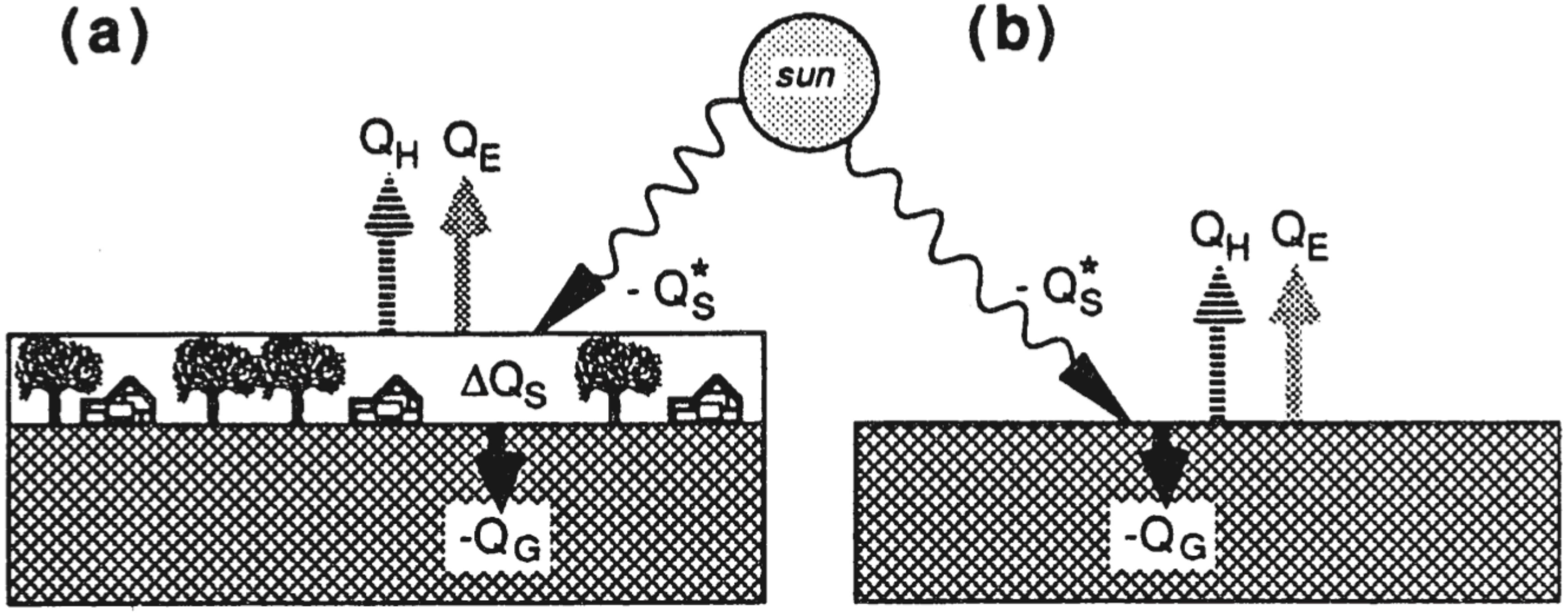


Fig. 7.2 Contributions to the surface energy balance (a) for a finite thickness box and (b) for an infinitesimally thin layer. $-Q_S^*$ is the net radiative contribution, Q_H is turbulent sensible heat flux, Q_E is turbulent latent heat flux, $-Q_G$ is molecular flux into the ground, and ΔQ_S is storage.

Stull 1988

$$-Q_s^* = Q_H + Q_E - Q_G + \Delta Q_S \qquad (7.2b)$$

Q^*_s = net upward radiation at the surface
Q_H = represents the upward sensible heat flux out of the top
Q_E = represents the upward latent heat flux out of the top
Q_G = represents the upward molecular heat flux into the bottom
ΔQ_S = denotes the storage or intake of internal energy (positive for warming and for chemical storage by photosynthesis).

Surface energy balance

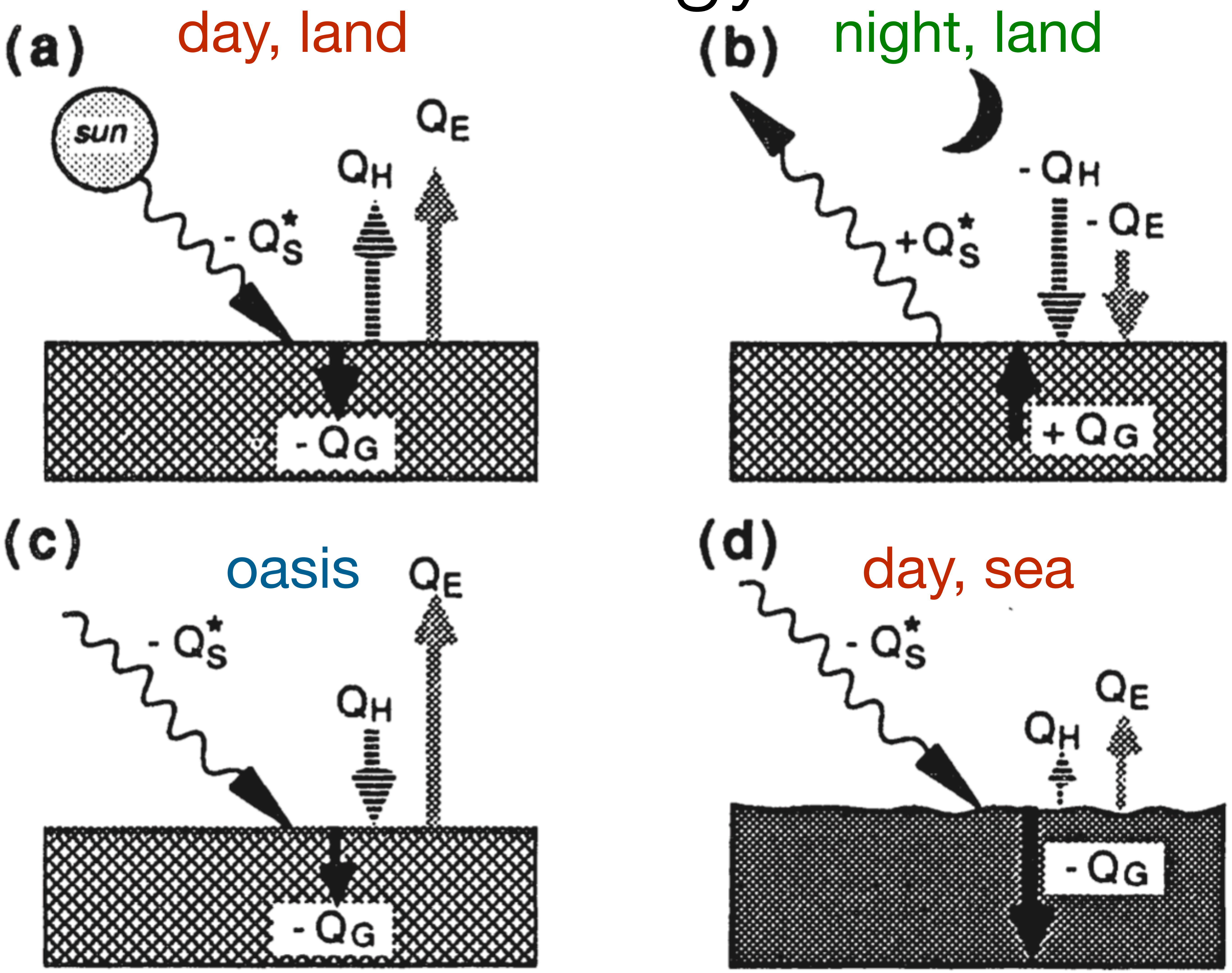


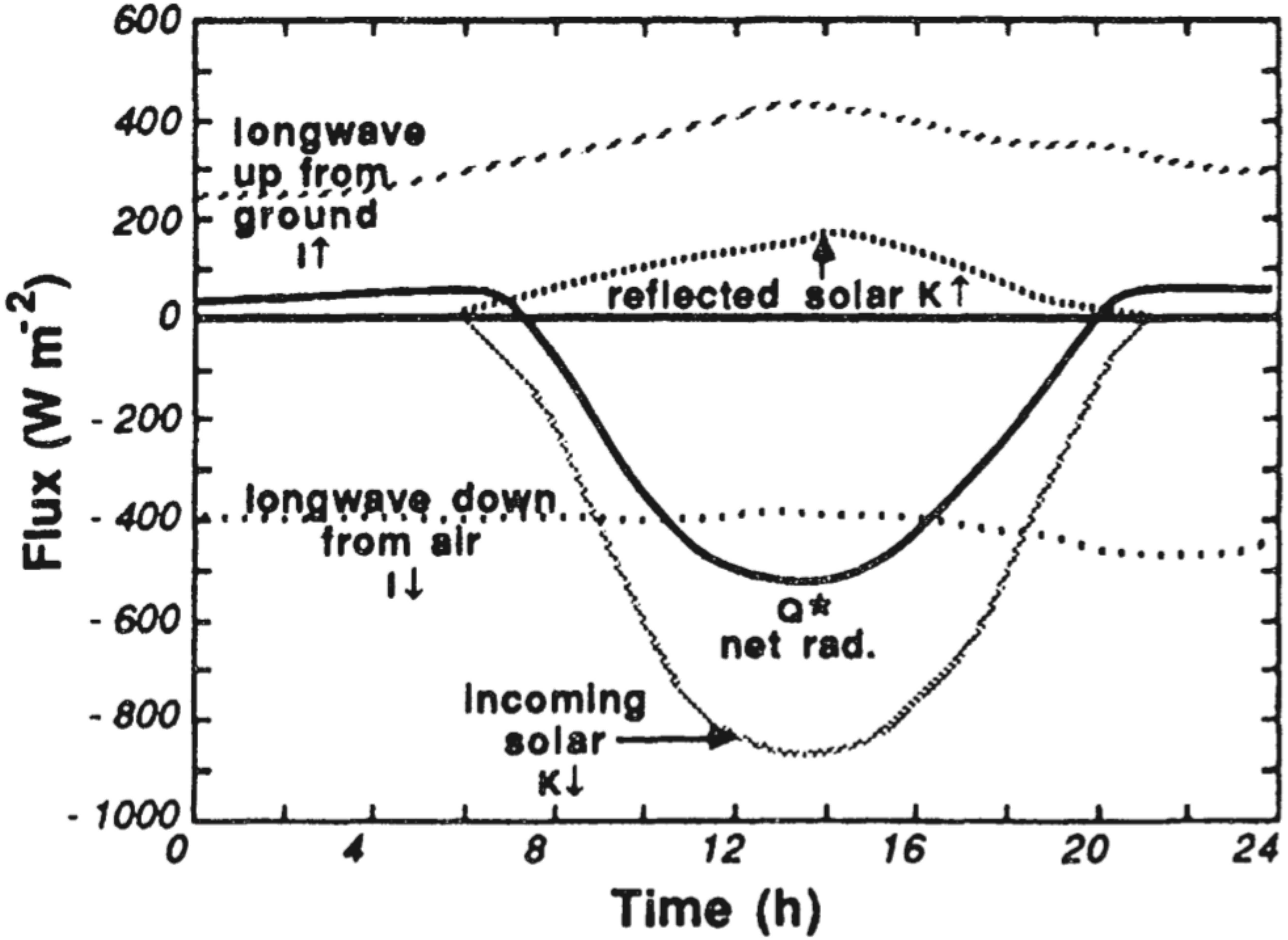
Fig. 7.3 Typical variation of terms of the surface energy balance for (a) daytime over land; (b) nighttime over land; (c) oasis effect of warm dry air advection over a moist surface; and (d) daytime over the sea with no advection. Arrow size indicates relative magnitude.

Stull 1988

Surface Energy Balance—Radiation Components

Fig. 7.5 **Stull 1988**

Surface radiation budget components for 30 July 1971, at Matador, Saskatchewan (50°N) over a 0.2 m stand of native grass. Cloudless skies in the morning, increasing clouds in the late afternoon and evening (after Ripley and Redmann, 1976).

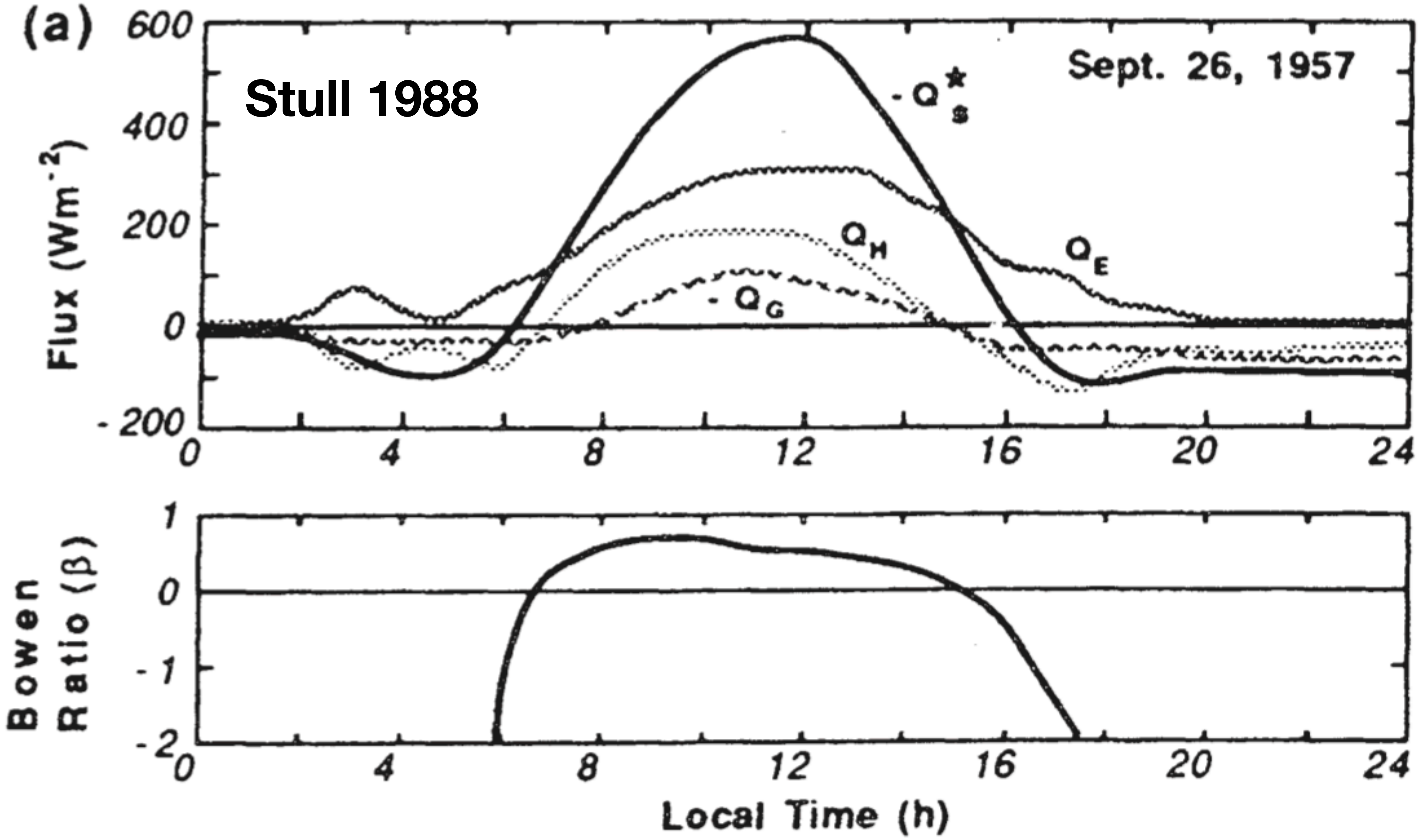


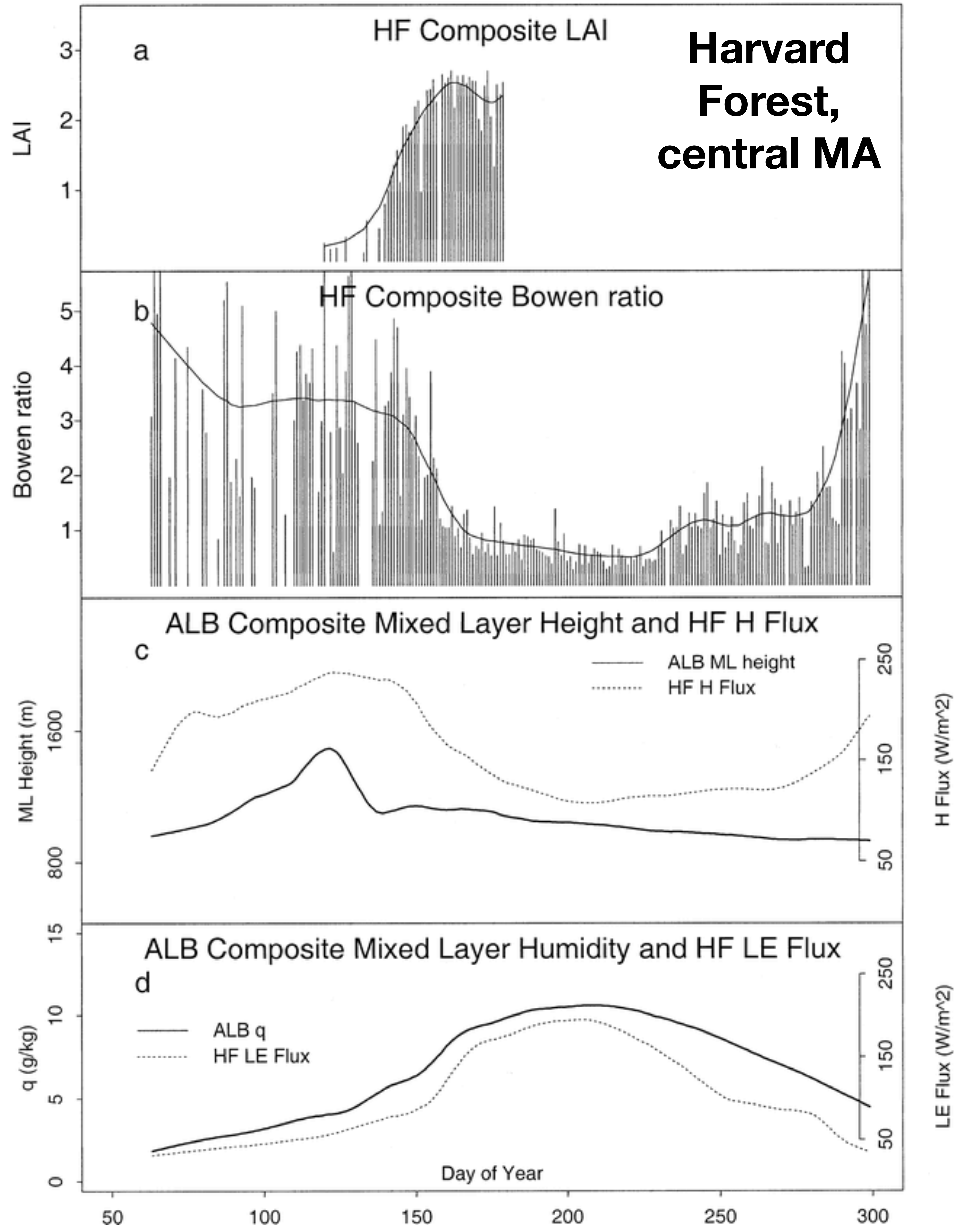
126 NYSM standard sites measure incoming solar
18 NYSM flux sites measure all 4 components (radiation)

Surface Energy Balance—Fluxes, Bowen Ratio

$$\beta = \frac{Q_H}{Q_E} = \frac{\text{sensible heat}}{\text{latent heat}}$$

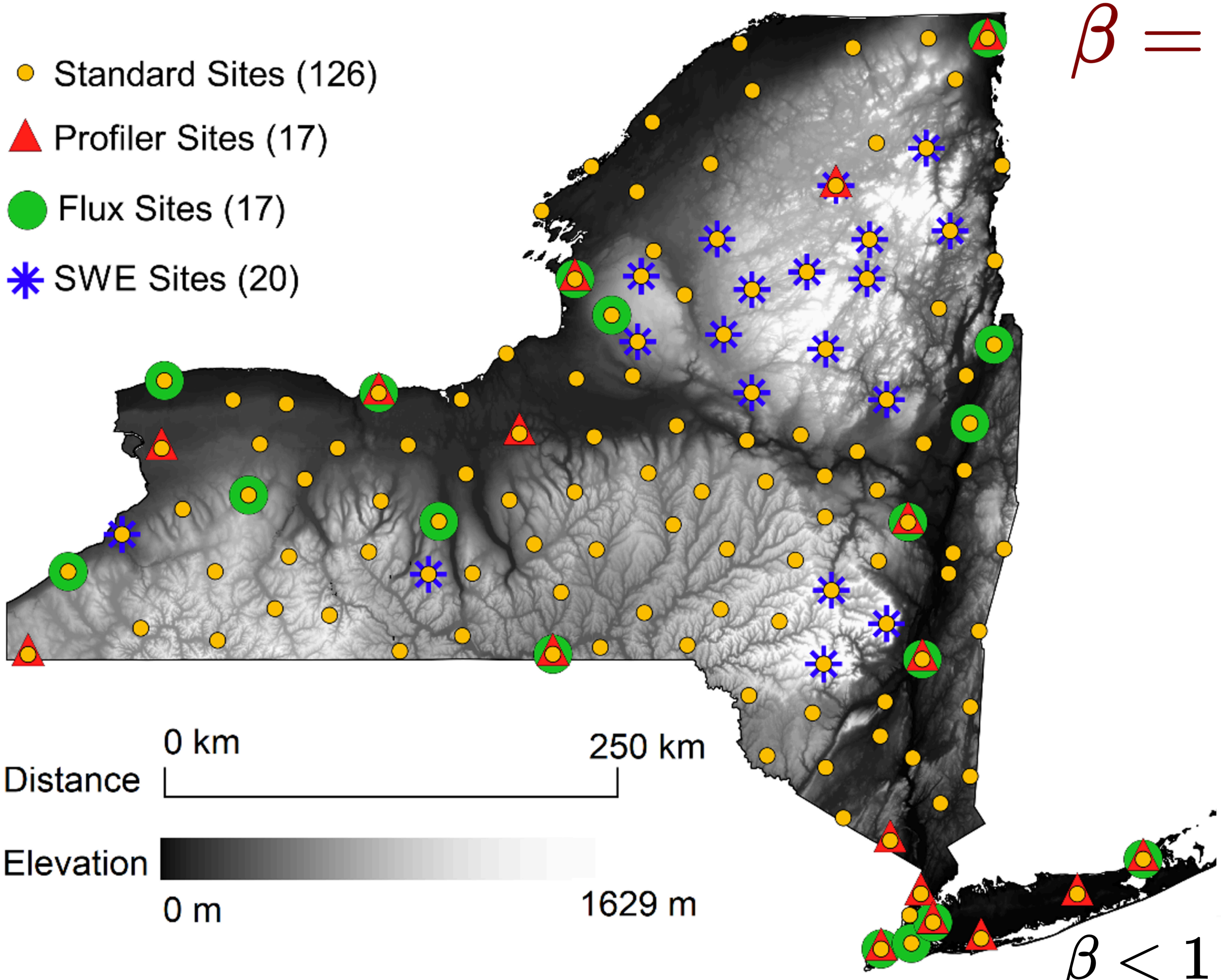
irrigated crop field





$\beta < 1$ for moist surface $\beta > 1$ for dry surface

Surface Energy Balance—NYSM Leafout



$$\beta = \frac{Q_H}{Q_E} = \frac{\text{sensible heat}}{\text{latent heat}}$$

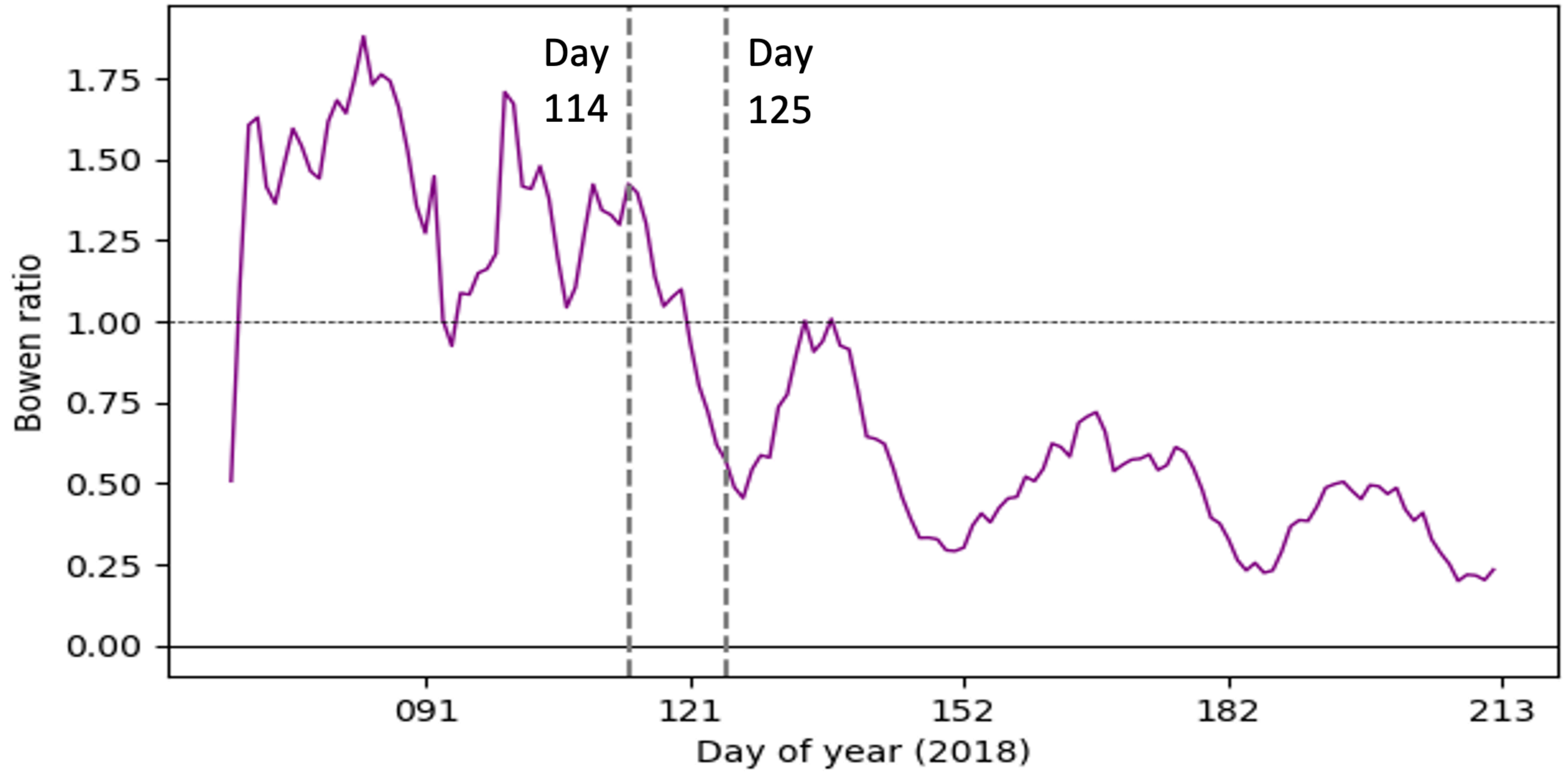


Figure 8. New York State Mesonet Flux Network average noontime (11–13 hrs) Bowen Ratio for all flux sites excluding New York City sites (BKLN, QUEE, STAT). The first vertical dotted line to the left indicates the state-wide average day of first visible grass growth (114), and the second vertical line represents the average day of first visible leaf emergence (125). Data with quality control grades 1-3 between Mar 10-Aug 1 2018 were used. Running mean …

$\beta < 1$ for moist surface $\beta > 1$ for dry surface

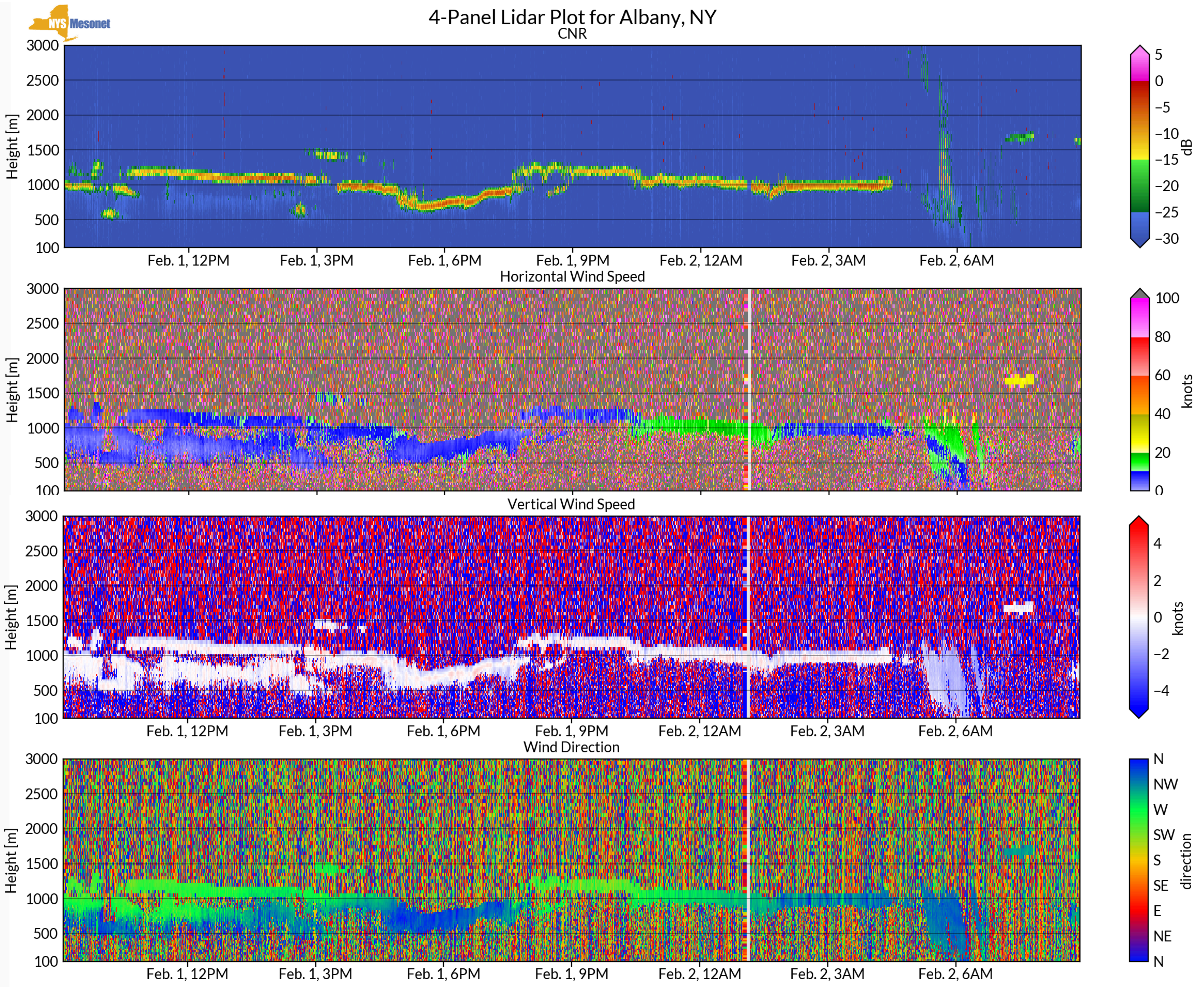
Observing the ABL: vertical structure

remote: lidar, microwave radiometer

vertical wind profiles to ~3-5 km

temperature/moisture profiles to ~10 km

Feb 1-2 2020



NYS Mesonet
4-Panel Lidar Plot for Albany, NY
CNR
Horizontal Wind Speed
Vertical Wind Speed
Wind Direction
Height [m]
3000
2500
2000
1500
1000
500
100
Feb. 1, 12PM
Feb. 1, 3PM
Feb. 1, 6PM
Feb. 1, 9PM
Feb. 2, 12AM
Feb. 2, 3AM
Feb. 2, 6AM
dB
5
0
−5
−10
−15
−20
−25
−30
knots
100
80
60
40
20
0
knots
4
2
0
−2
−4
direction
N
NW
W
SW
S
SE
E
NE
N

Diurnal Profile evolution

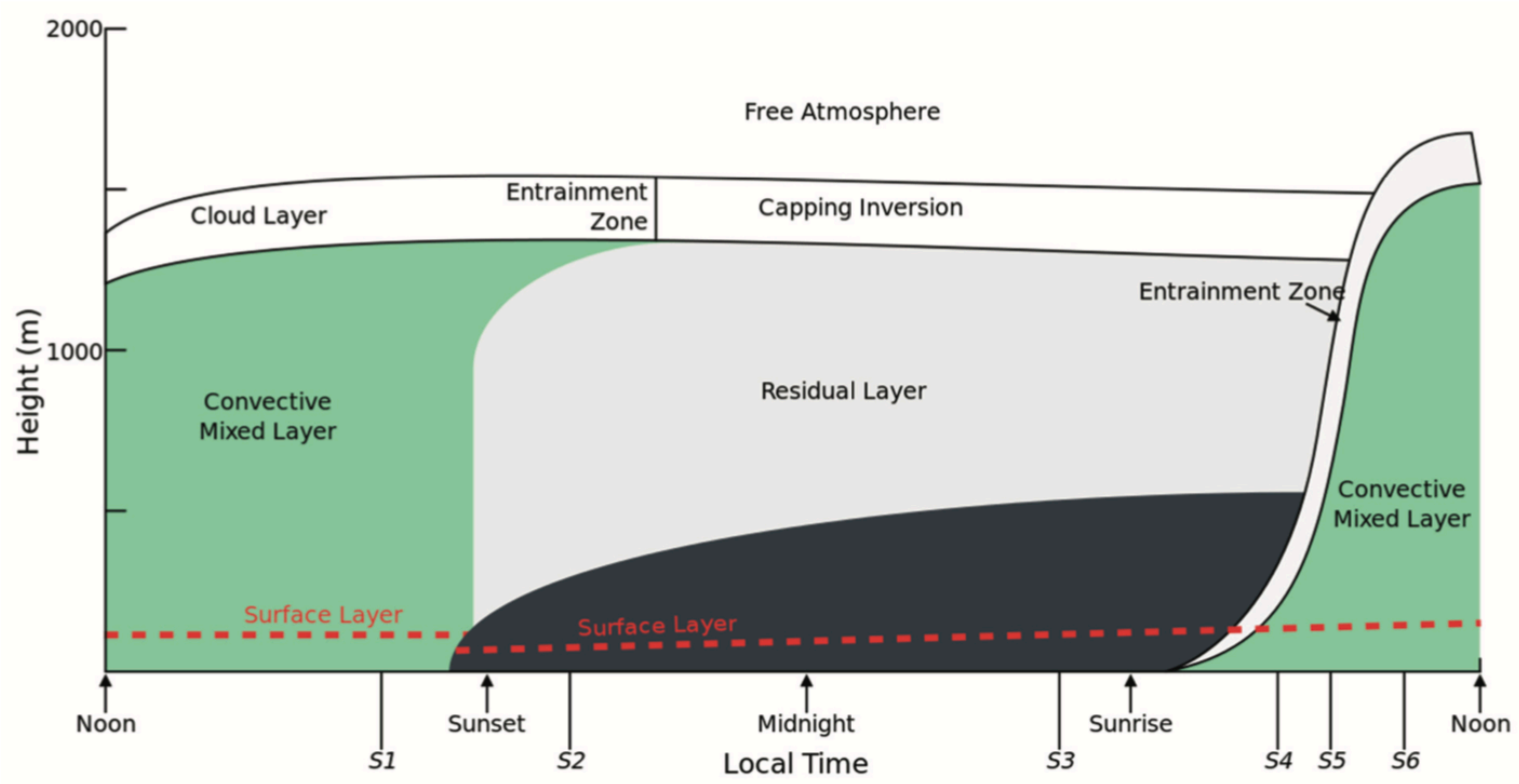


FIGURE 1. Schematic of the structure of the atmospheric boundary layer in high pressure regions over land, showing daily variations. SOURCE: Wikimedia Commons.

Stull 1998

Boundary Layer Evolution

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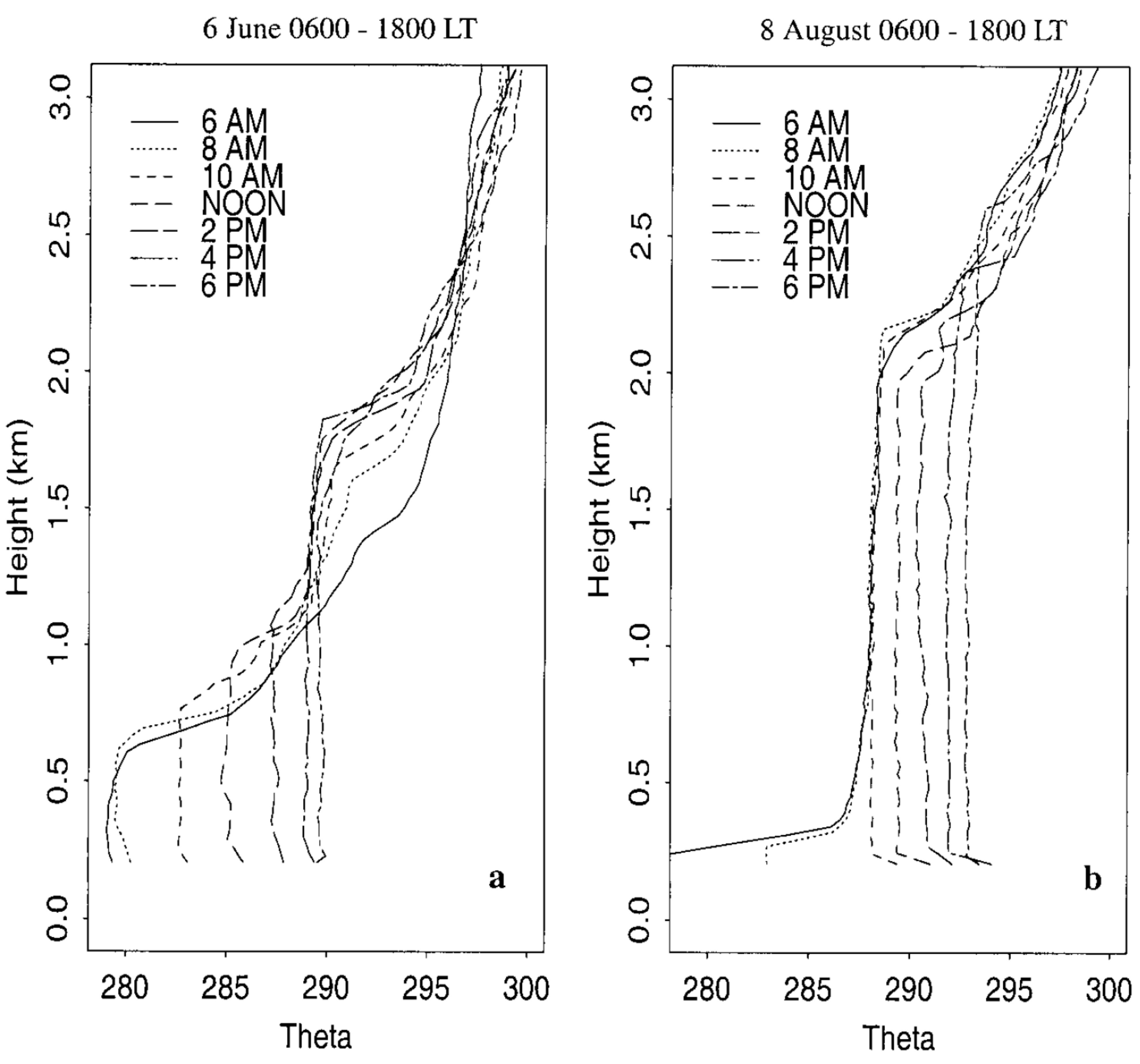
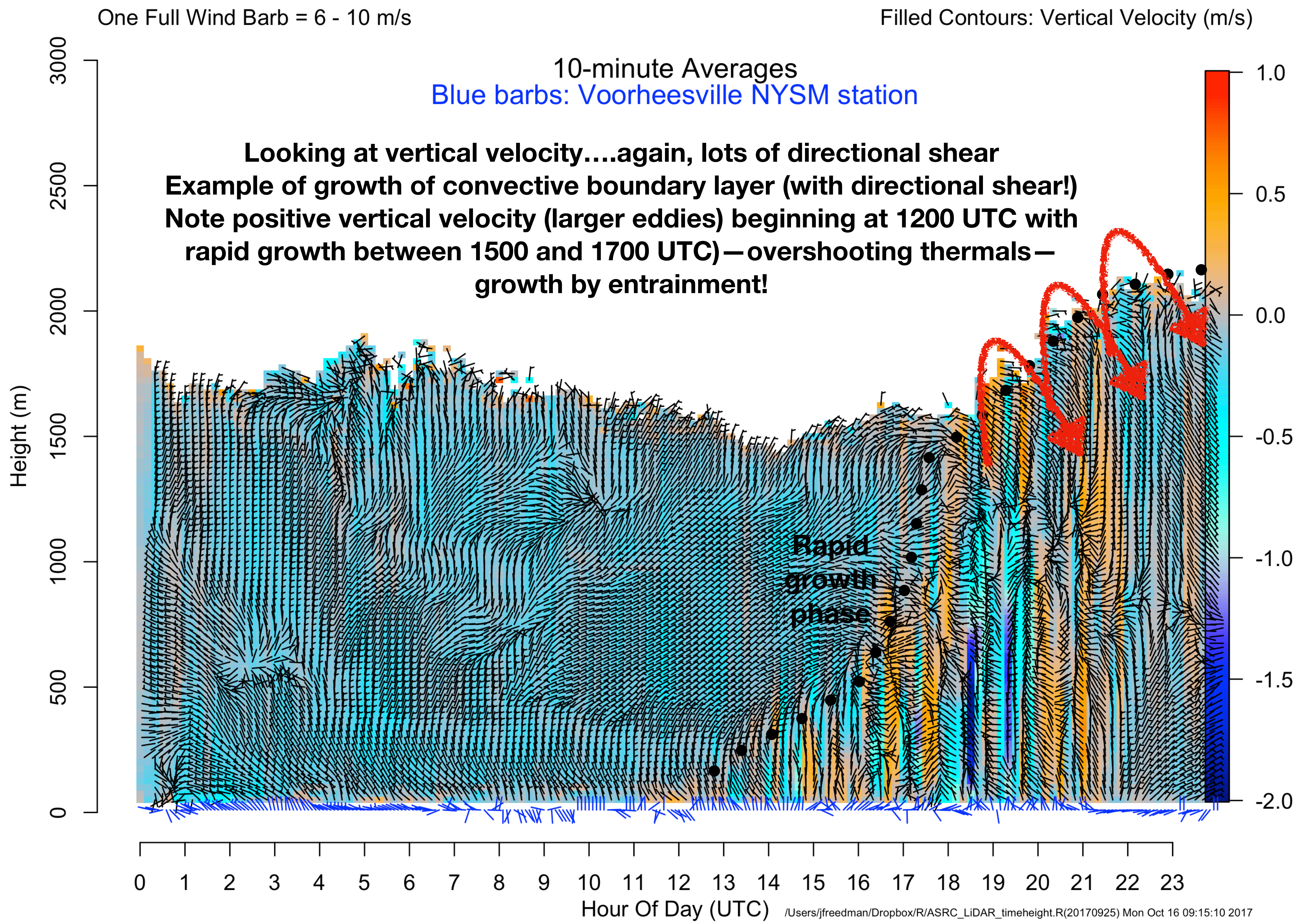


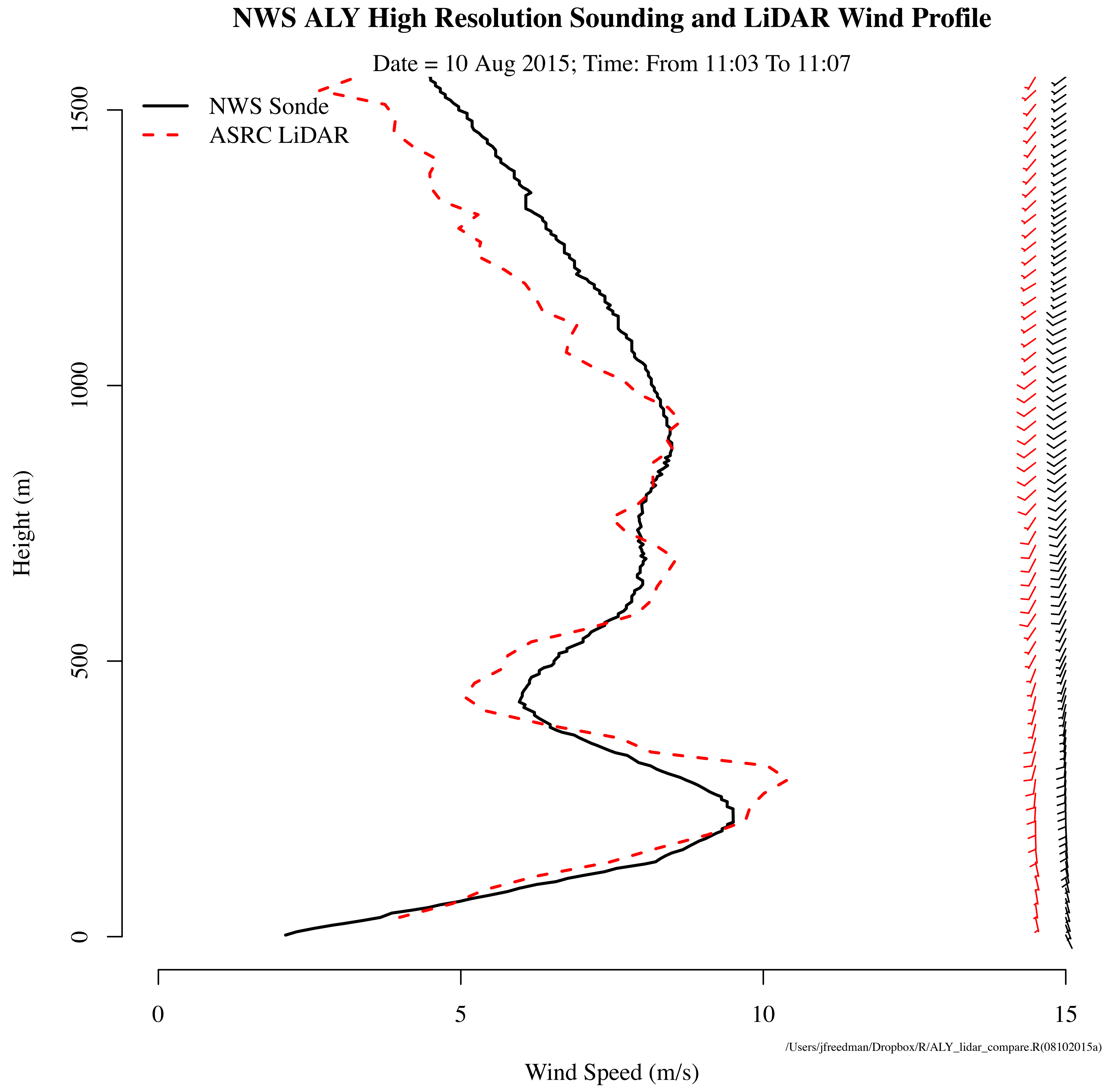
FIG. 4. BOREAS soundings from Thompson, MB, Canada, for (a) 6 Jun 1994, first day after a frontal passage, and (b) 8 Aug 1994, second day after a frontal passage.

Freedman and Fitzjarrald 2001

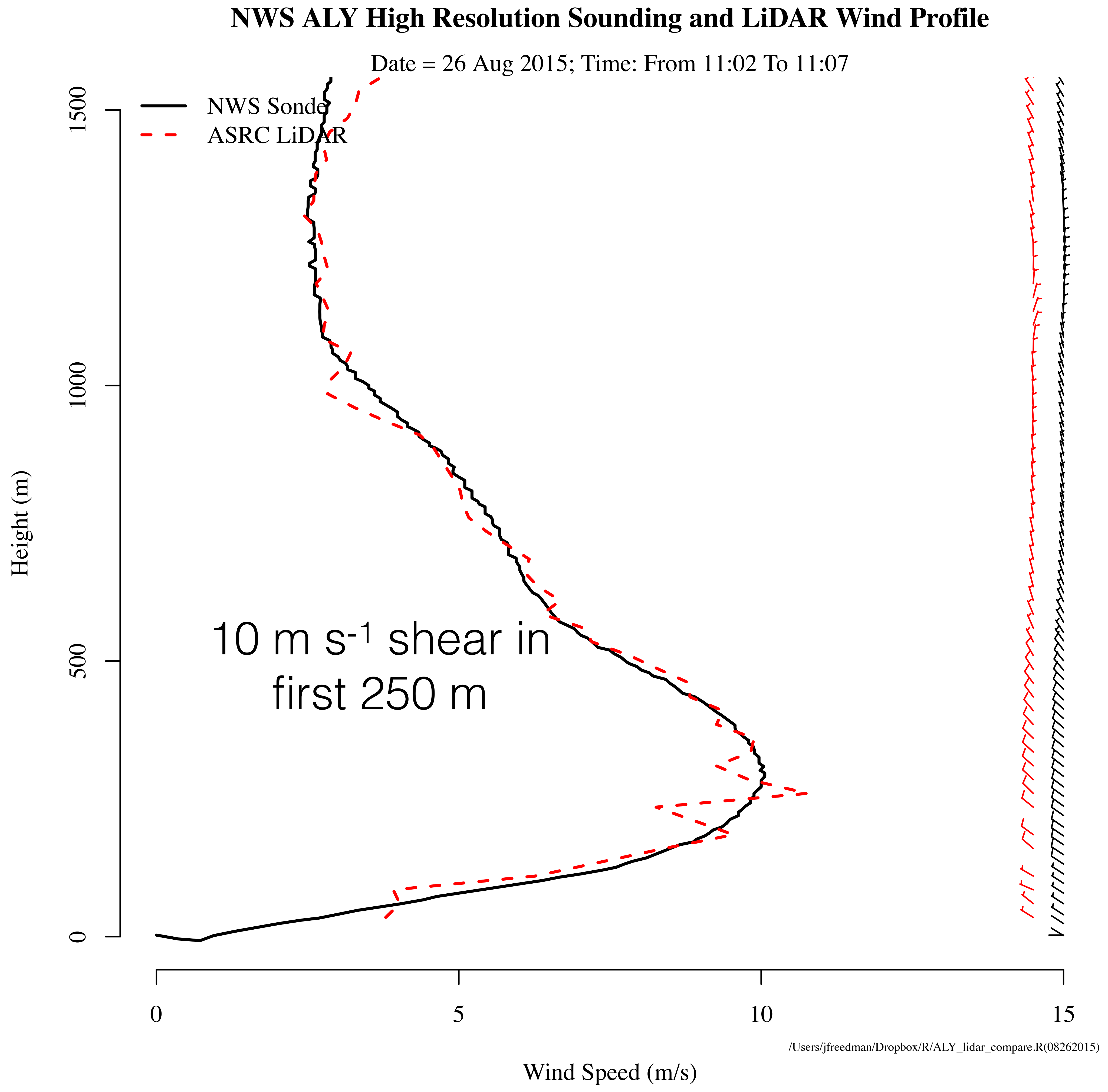
LiDAR Wind and Vertical Velocity Time-height Cross Section at ASRC Roof, 09/25/2017



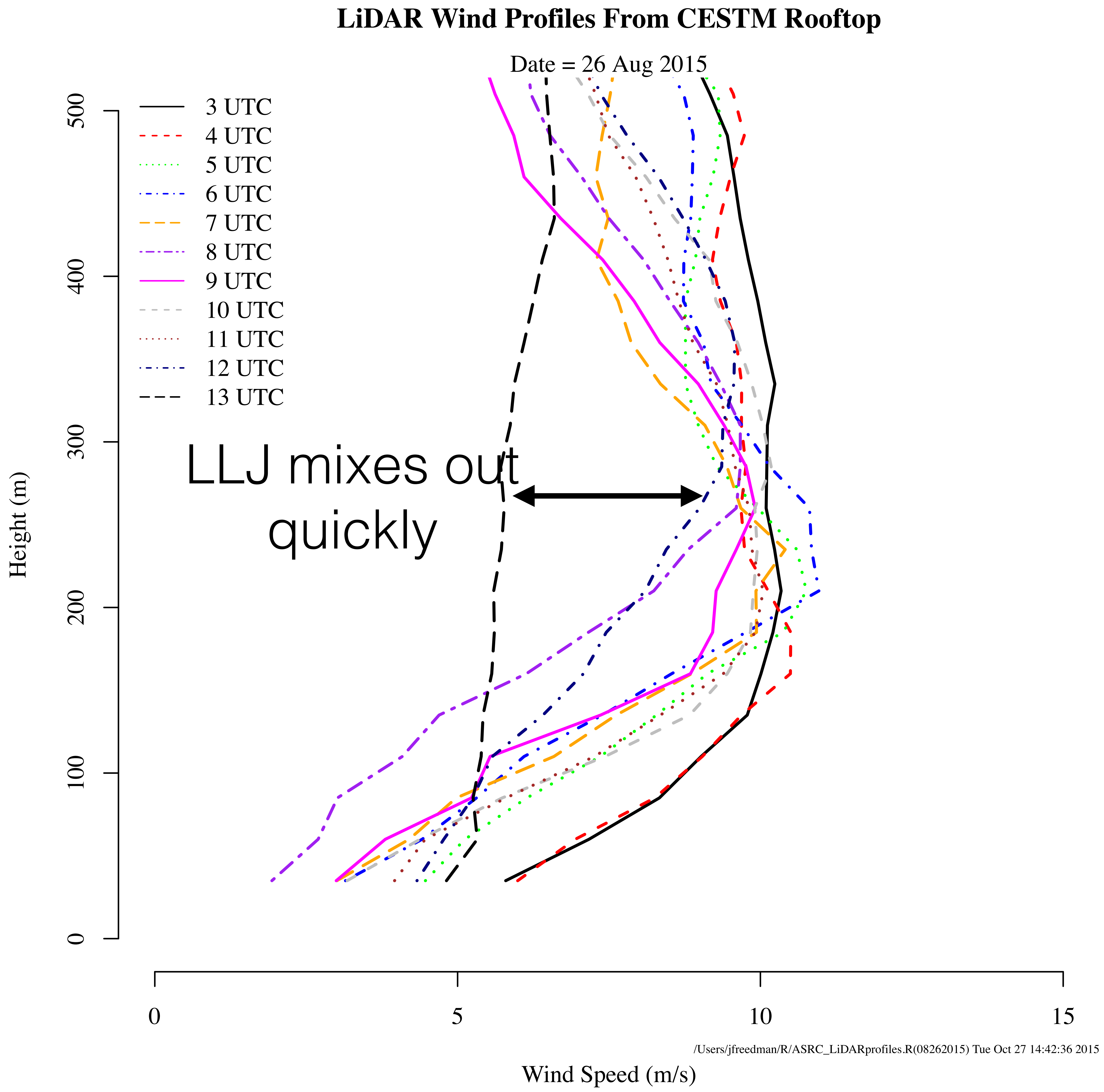
Early morning `channeled LLJ



Southerly—Hudson Valley

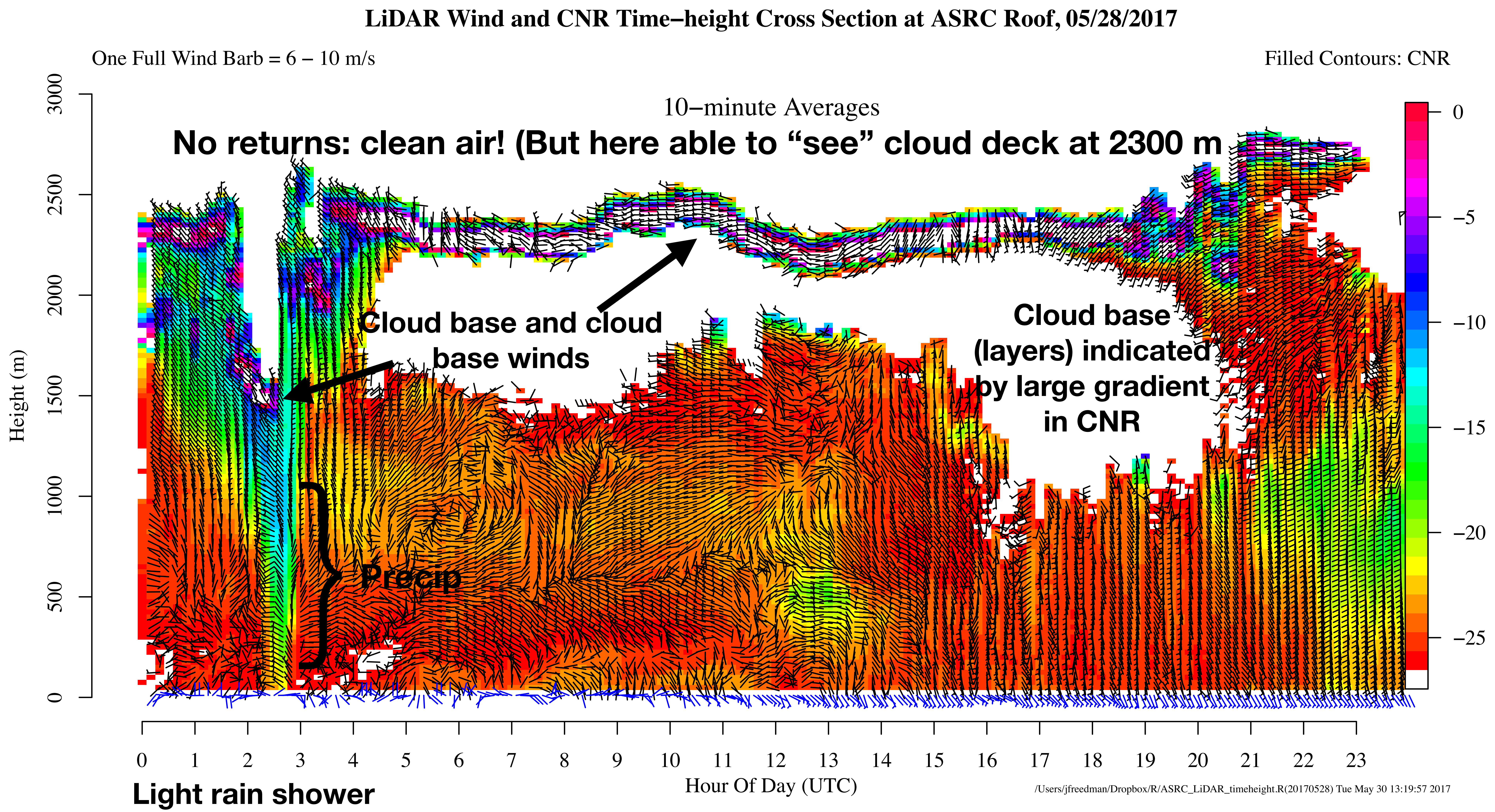


WNW—Mohawk Valley



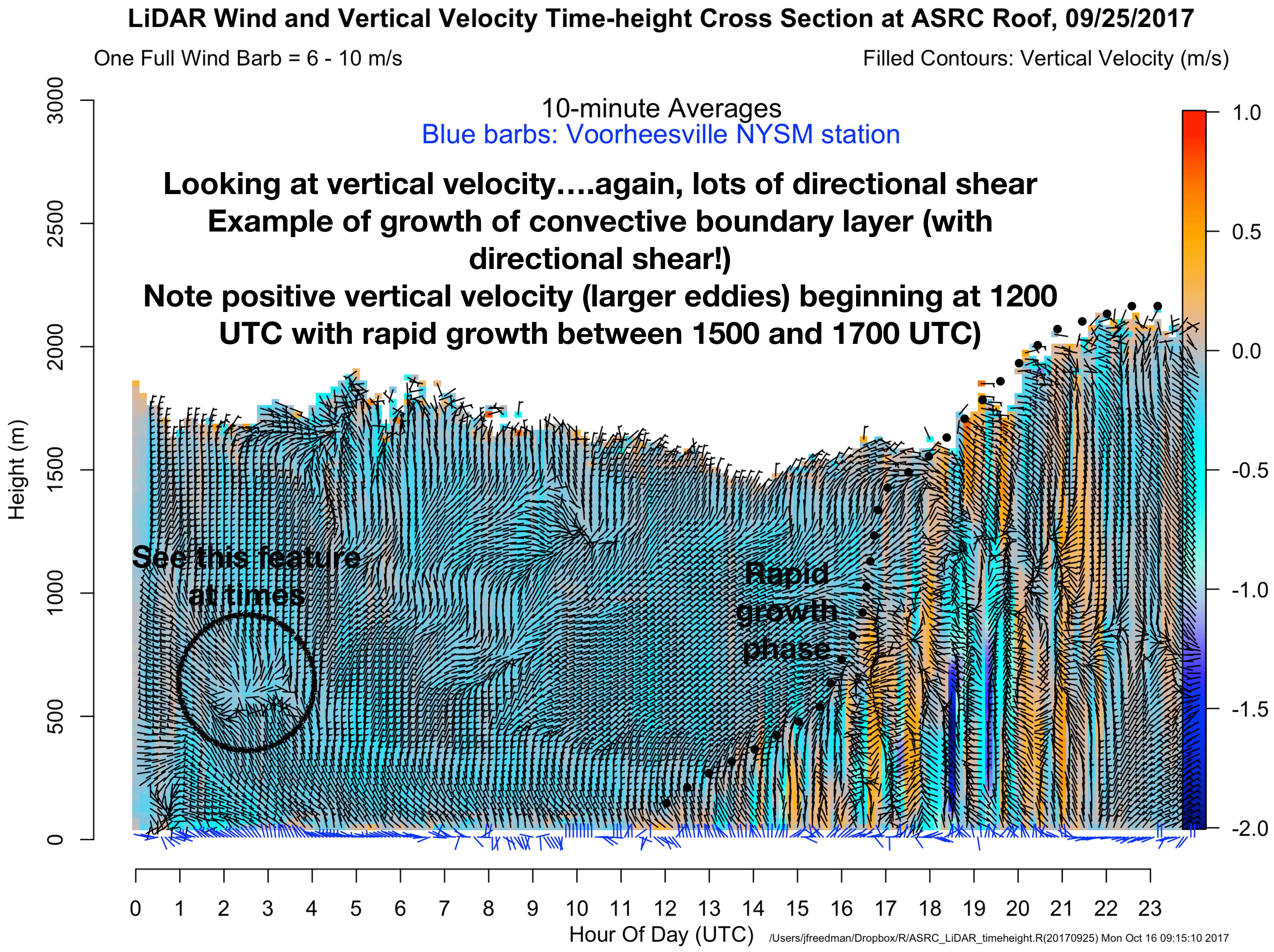
LiDAR Wind Profiles From CESTM Rooftop
Date = 26 Aug 2015
3 UTC
4 UTC
5 UTC
6 UTC
7 UTC
8 UTC
9 UTC
10 UTC
11 UTC
12 UTC
13 UTC
LLJ mixes out quickly
Height (m)
0
100
200
300
400
500
Wind Speed (m/s)
0
5
10
15
/Users/jfreedman/R/ASRC_LiDARprofiles.R(08262015) Tue Oct 27 14:42:36 2015

A lot going on here….



Light rain shower between 0200 and 0300 UTC

CNR: carrier to noise ration (similar to SNR)

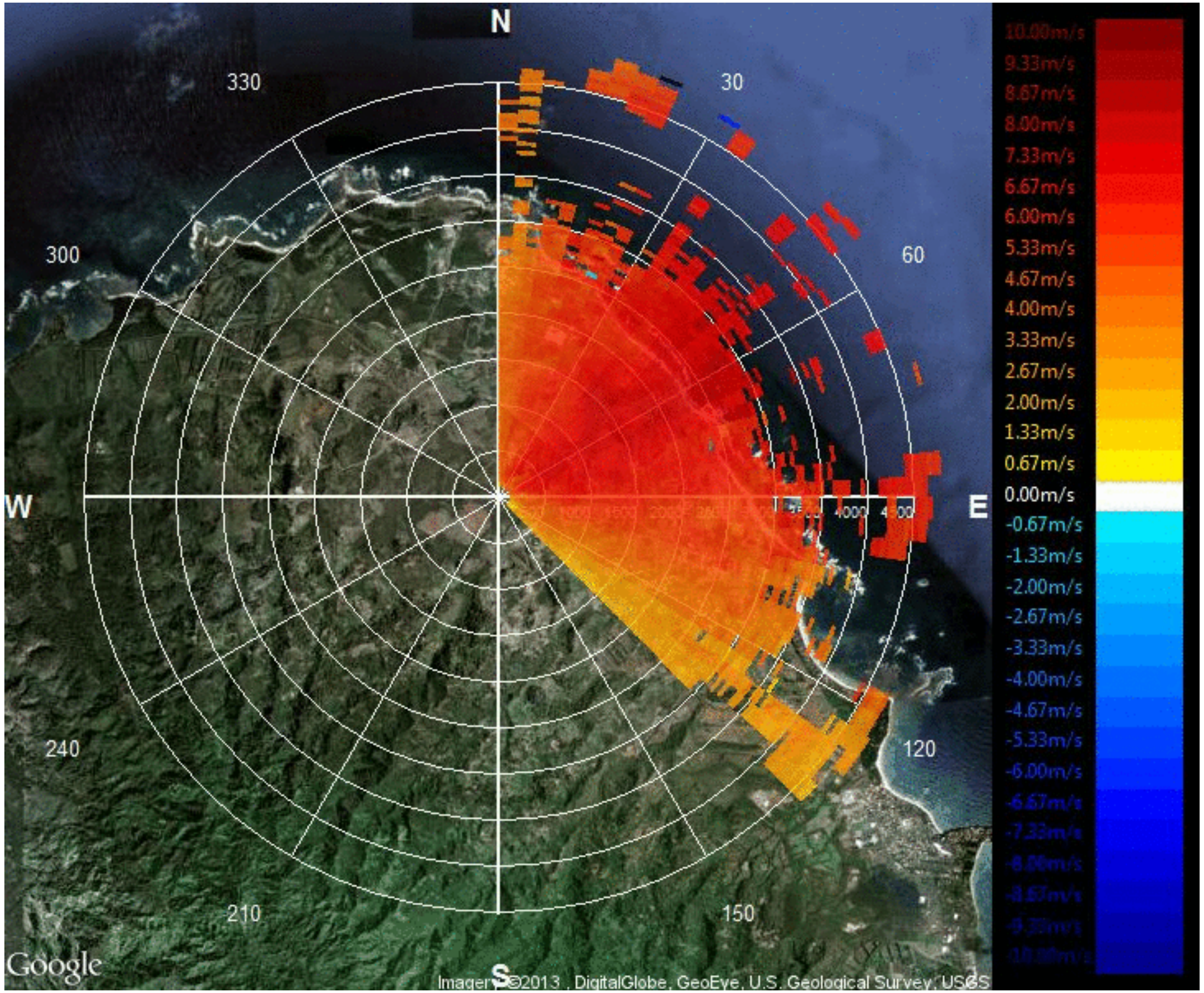

LiDAR Wind and Vertical Velocity Time-height Cross Section at ASRC Roof, 09/25/2017
One Full Wind Barb = 6 - 10 m/s
Filled Contours: Vertical Velocity (m/s)
10-minute Averages
Blue barbs: Voorheesville NYSM station
Looking at vertical velocity….again, lots of directional shear
Example of growth of convective boundary layer (with directional shear!)
Note positive vertical velocity (larger eddies) beginning at 1200 UTC with rapid growth between 1500 and 1700 UTC)
See this feature at times
Rapid growth phase
Height (m)
0
500
1000
1500
2000
2500
3000
Hour Of Day (UTC)
0 1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 20 21 22 23
1.0
0.5
0.0
-0.5
-1.0
-1.5
-2.0
/Users/jfreedman/Dropbox/R/ASRC_LiDAR_timeheight.R(20170925) Mon Oct 16 09:15:10 2017

Leosphere Windcube 100S at Kahuku, Oahu
28 August 2013 0900 - 1500 UTC
Elevation angle = 10°

Disruption of Trade Winds

Persistent ENE winds (towards LiDAR—warmer shading)

Become more N, NW flow (away from LiDAR—cooler colors)



Courtesy K. Rojowsky, AWS Truepower

Next Class (Monday 2/6—Lecture 5)

Offshore Wind and the Marine Atmospheric Boundary Layer (air-sea interactions)

Homework #1 DUE!!!

Zoom office hours (10 - 11:30 AM Monday)