Lecture 5: NYS Mesonet | Marine Atmospheric Boundary Layer and Wind Energy

<u>Announcements</u>

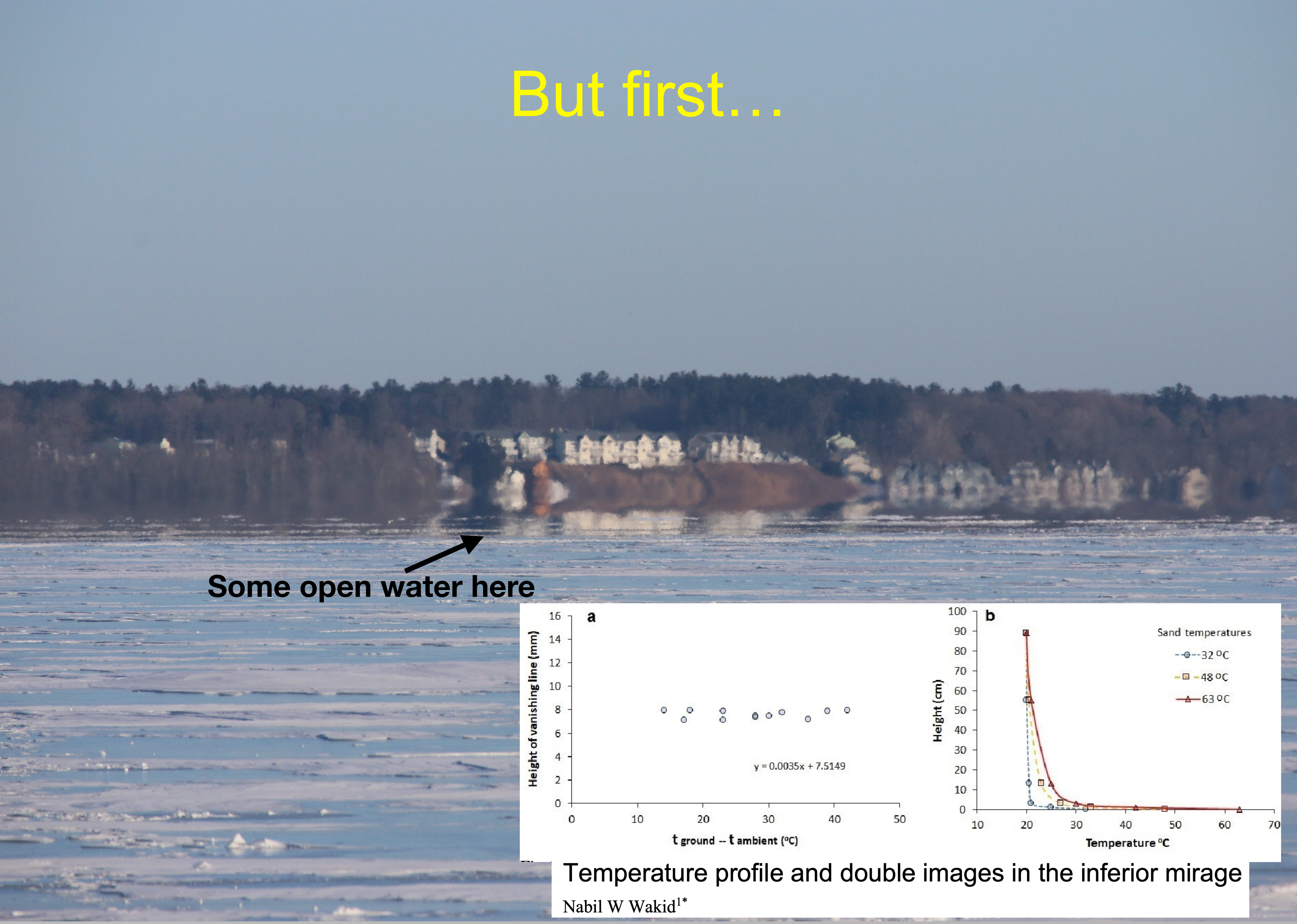
- Homework on Boundary Layer Module
  - due: Today
  - returned: Monday February 13th
  - questions on homework: by appointment
- Midterm exam: Monday March 6th

<u>Today's Lecture</u>

1. NYSM measurements—land-atmosphere exchange
2. Marine Atmospheric Boundary Layer—offshore wind

Feb 6 2023

But first…

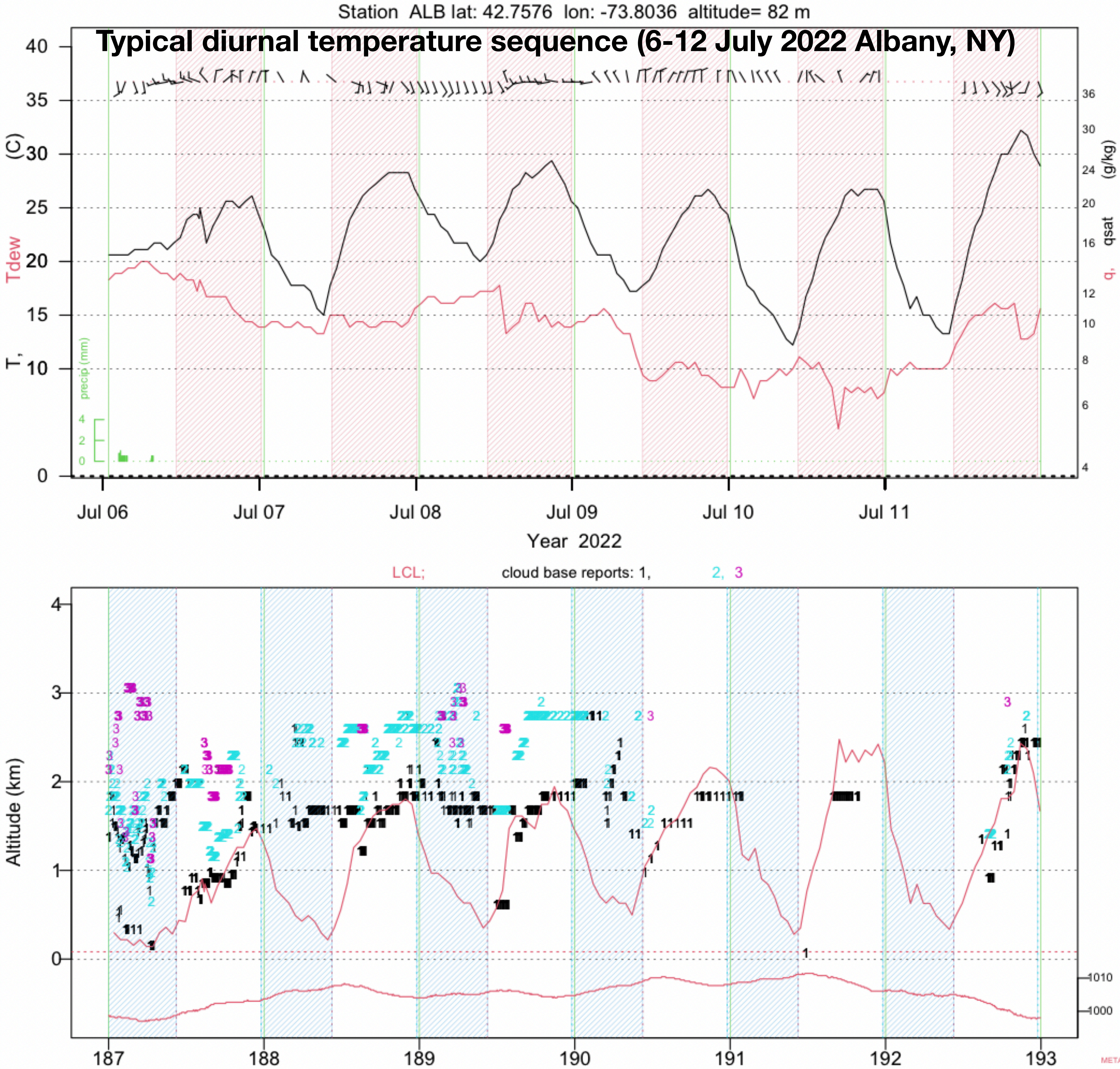


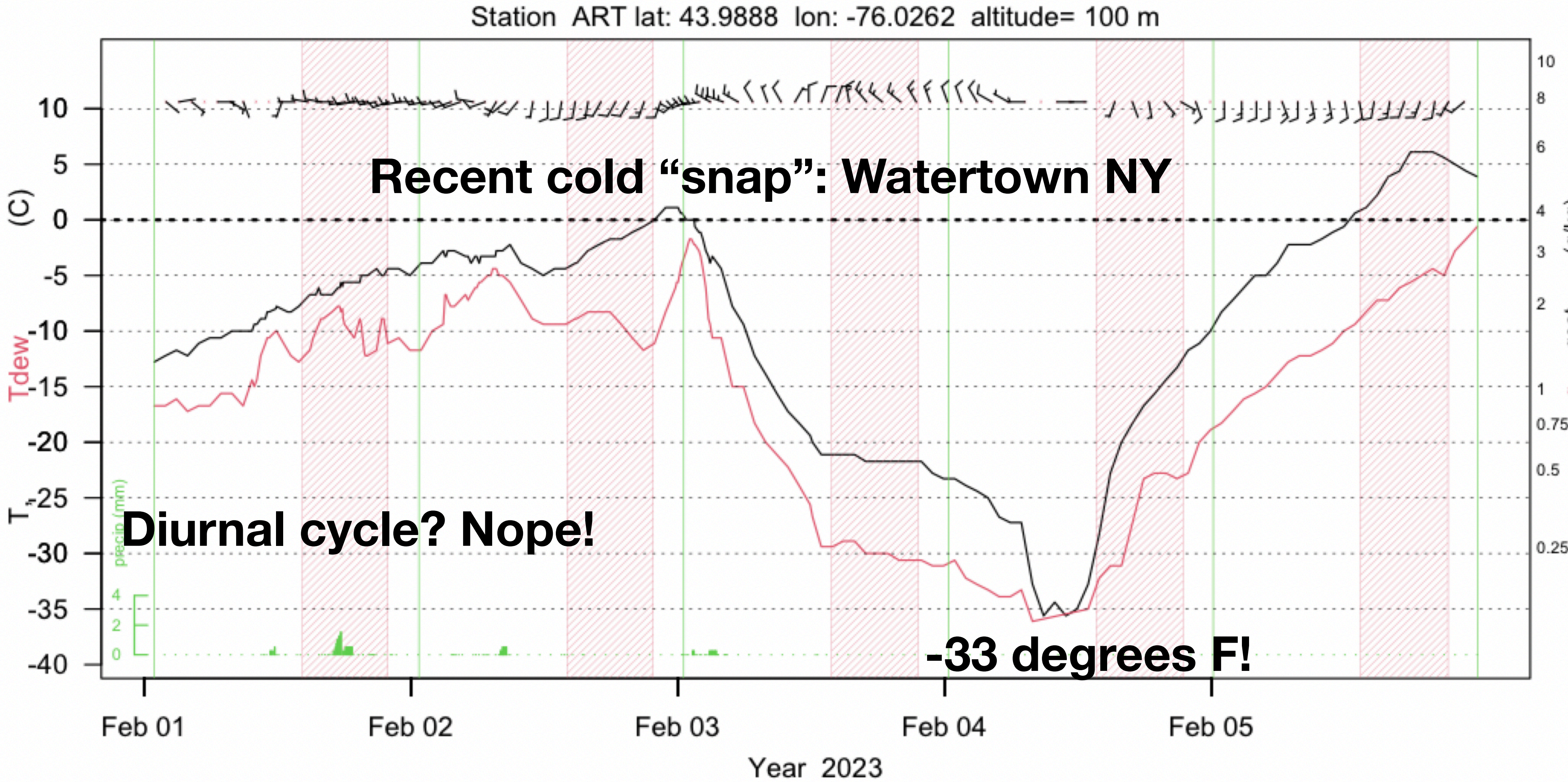
Temperature profile and double images in the inferior mirage

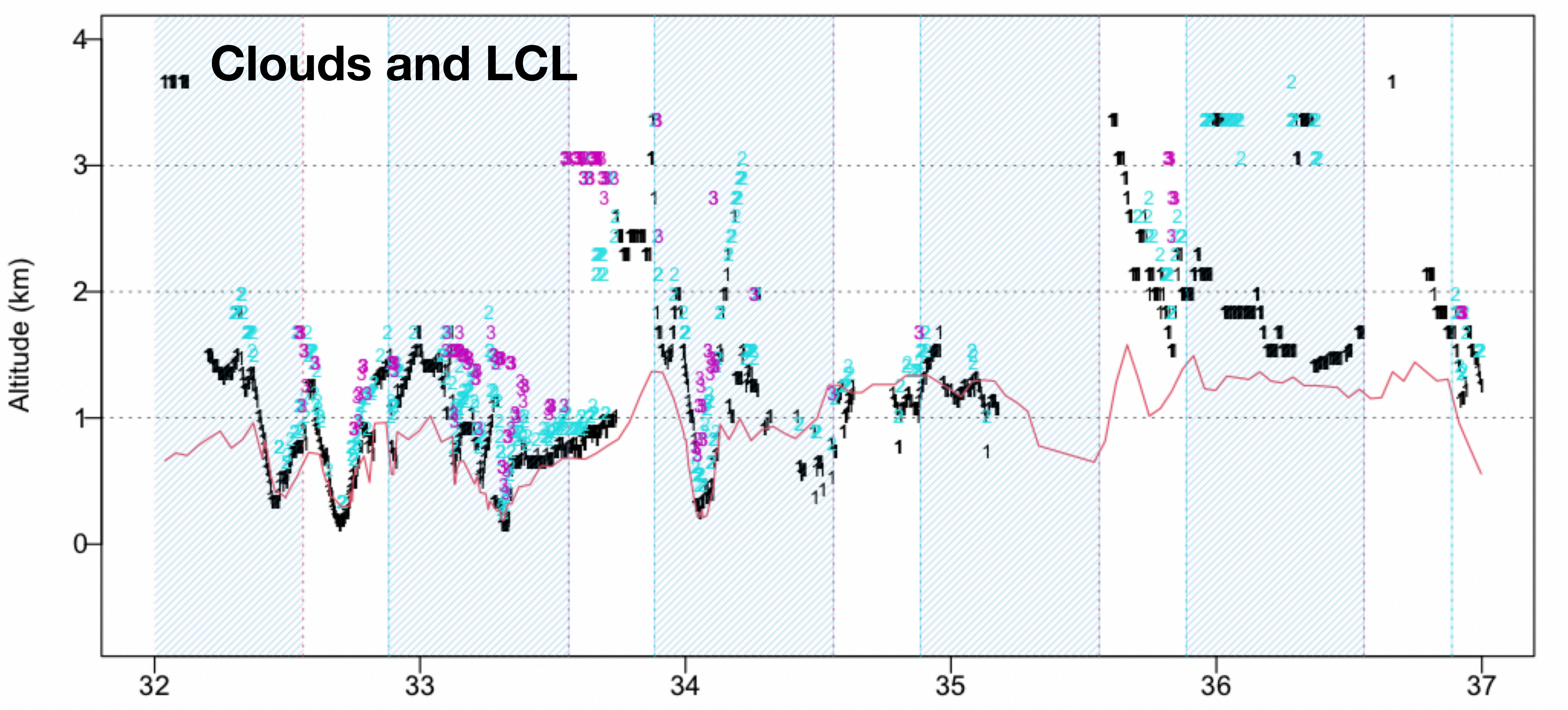
Nabil W Wakid[1*]

Saratoga Lake (4 February 2023 ~ 8 AM LT; about -13°F)

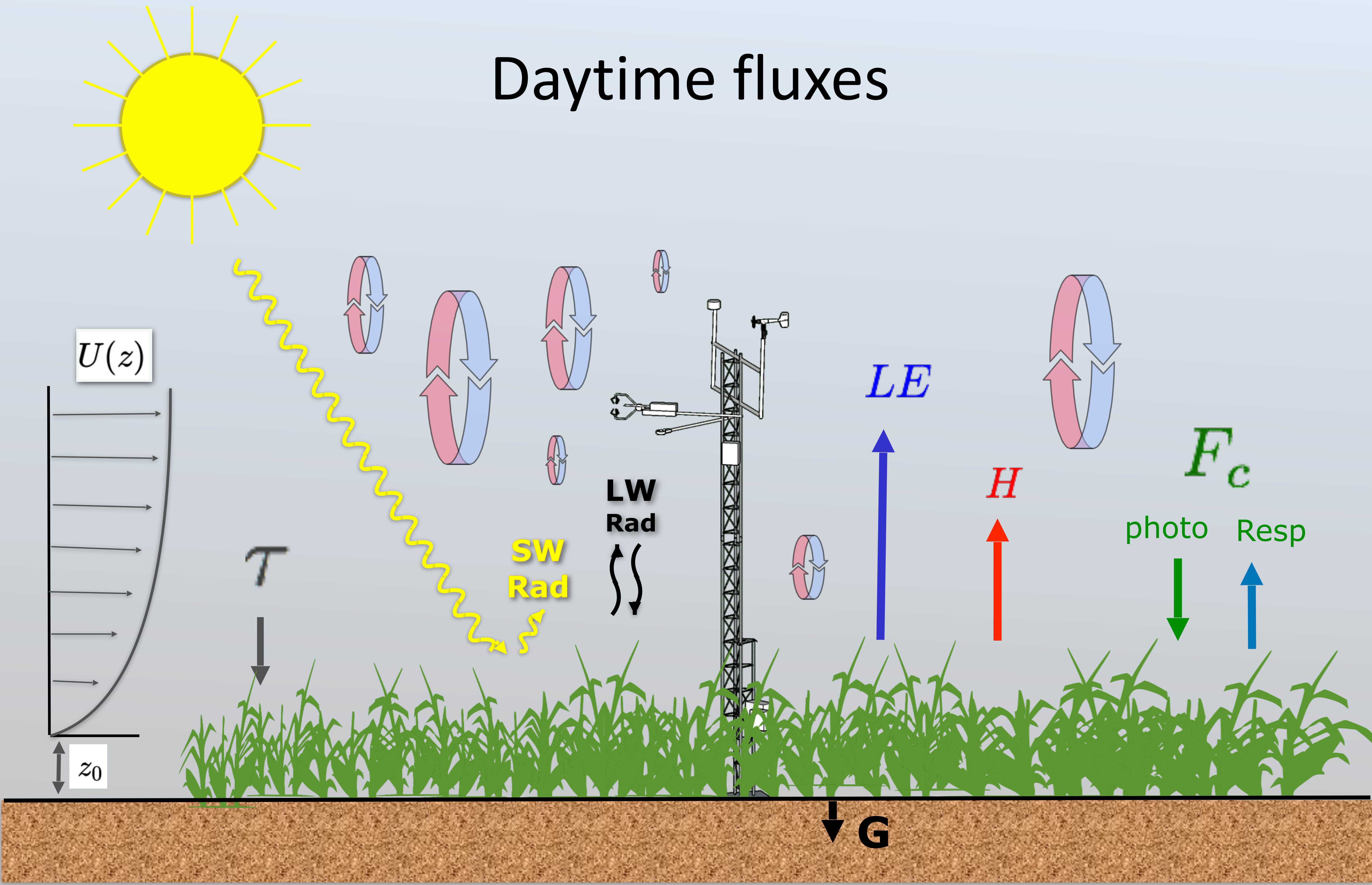

Because of how close boiling water is to evaporating. Because the tiny droplets are so hot, they start to vaporize. Since cold air can't hold as much water vapor as warmer air, the water condenses.


Station ALB lat: 42.7576 lon: -73.8036 altitude= 82 m
Typical diurnal temperature sequence (6-12 July 2022 Albany, NY)
T, Tdew (C)
q, qsat (g/kg)
precip (mm)
Jul 06
Jul 07
Jul 08
Jul 09
Jul 10
Jul 11
Year 2022
LCL; cloud base reports: 1, 2, 3
Altitude (km)
187
188
189
190
191
192
193
META


Station ART lat: 43.9888 lon: -76.0262 altitude= 100 m
Recent cold "snap": Watertown NY
Diurnal cycle? Nope!
-33 degrees F!
Tdew
T
(C)
precip (mm)
qsat
q
(g/kg)
Feb 01
Feb 02
Feb 03
Feb 04
Feb 05
Year 2023

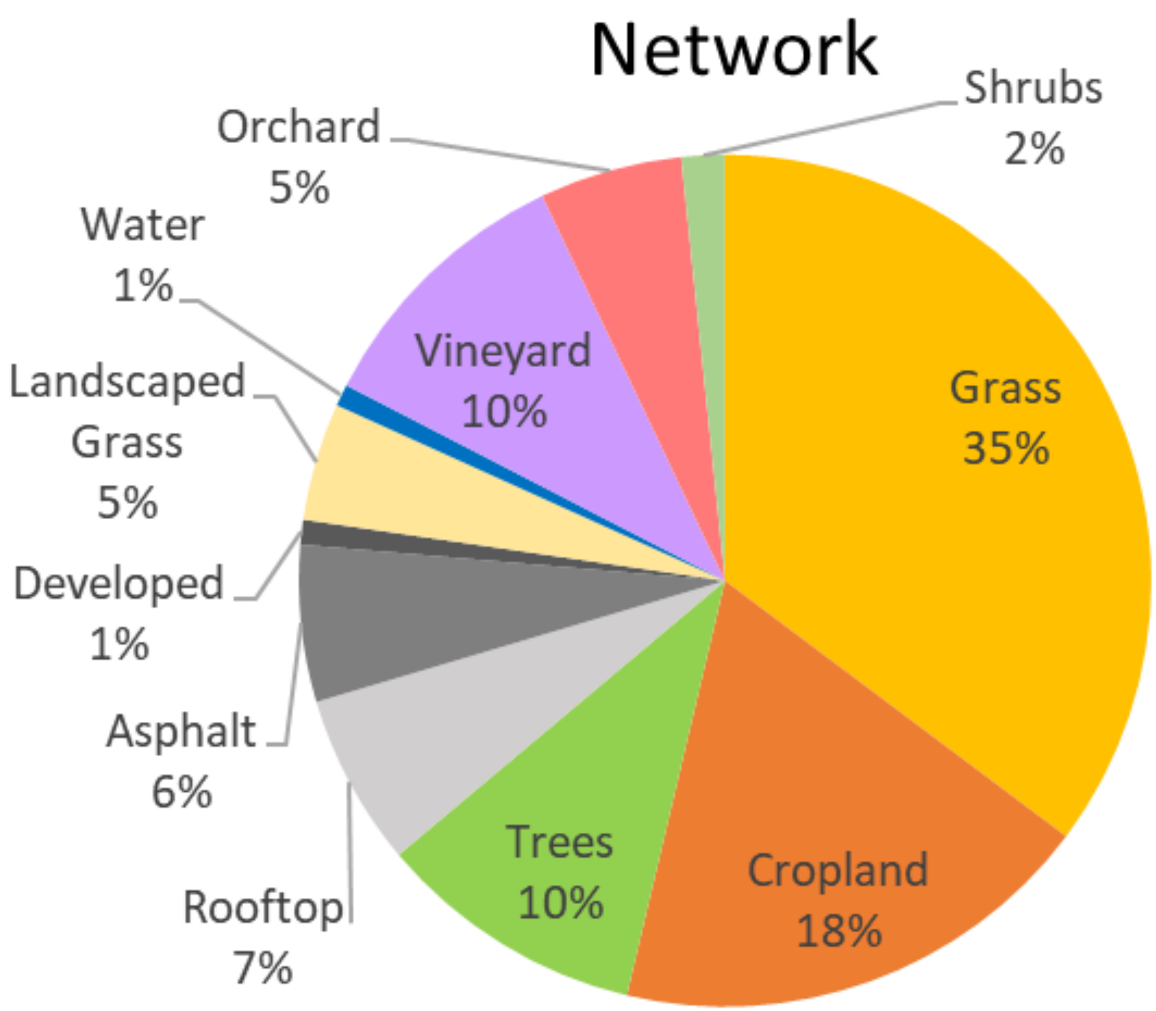

Clouds and LCL
Altitude (km)

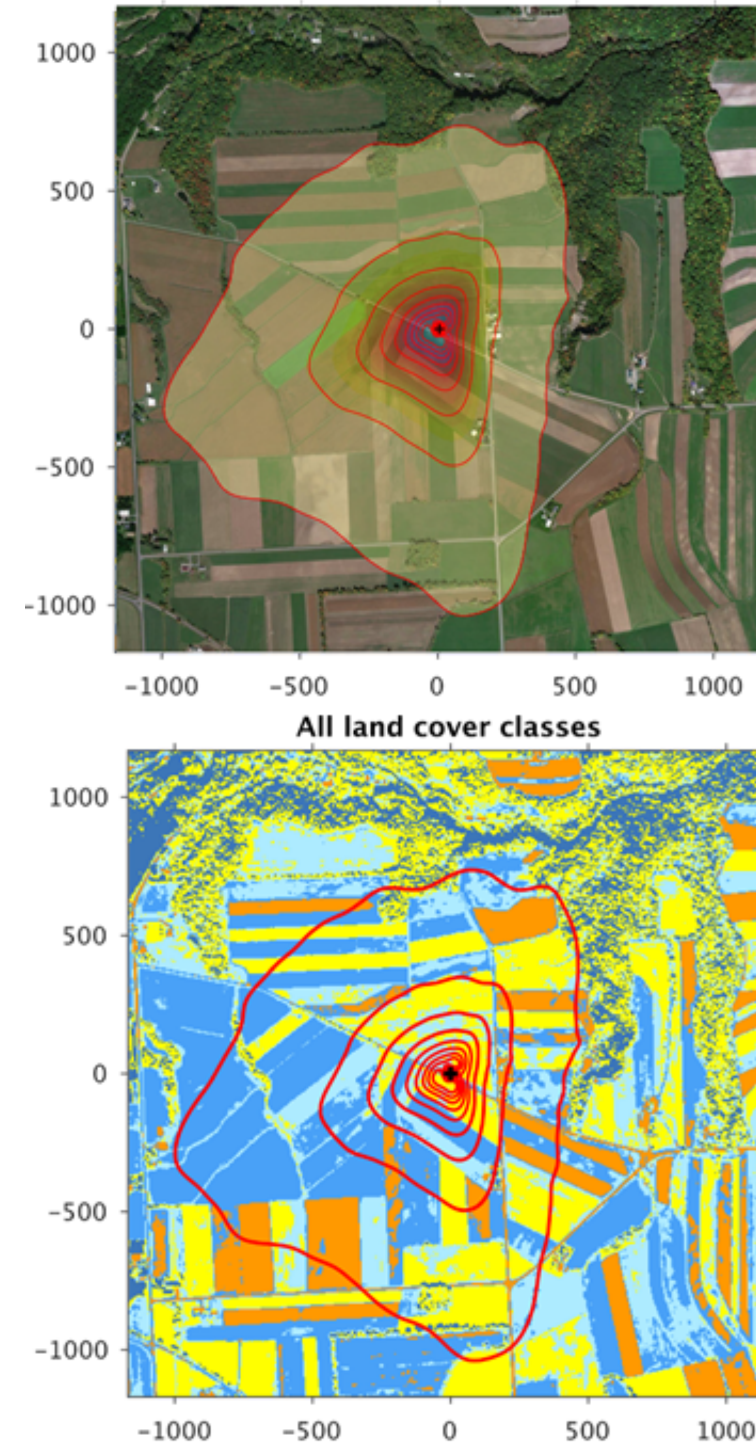
Daytime fluxes



Energy Balance: $R_n - G = H + LE$

Footprint-based Land Cover Representation

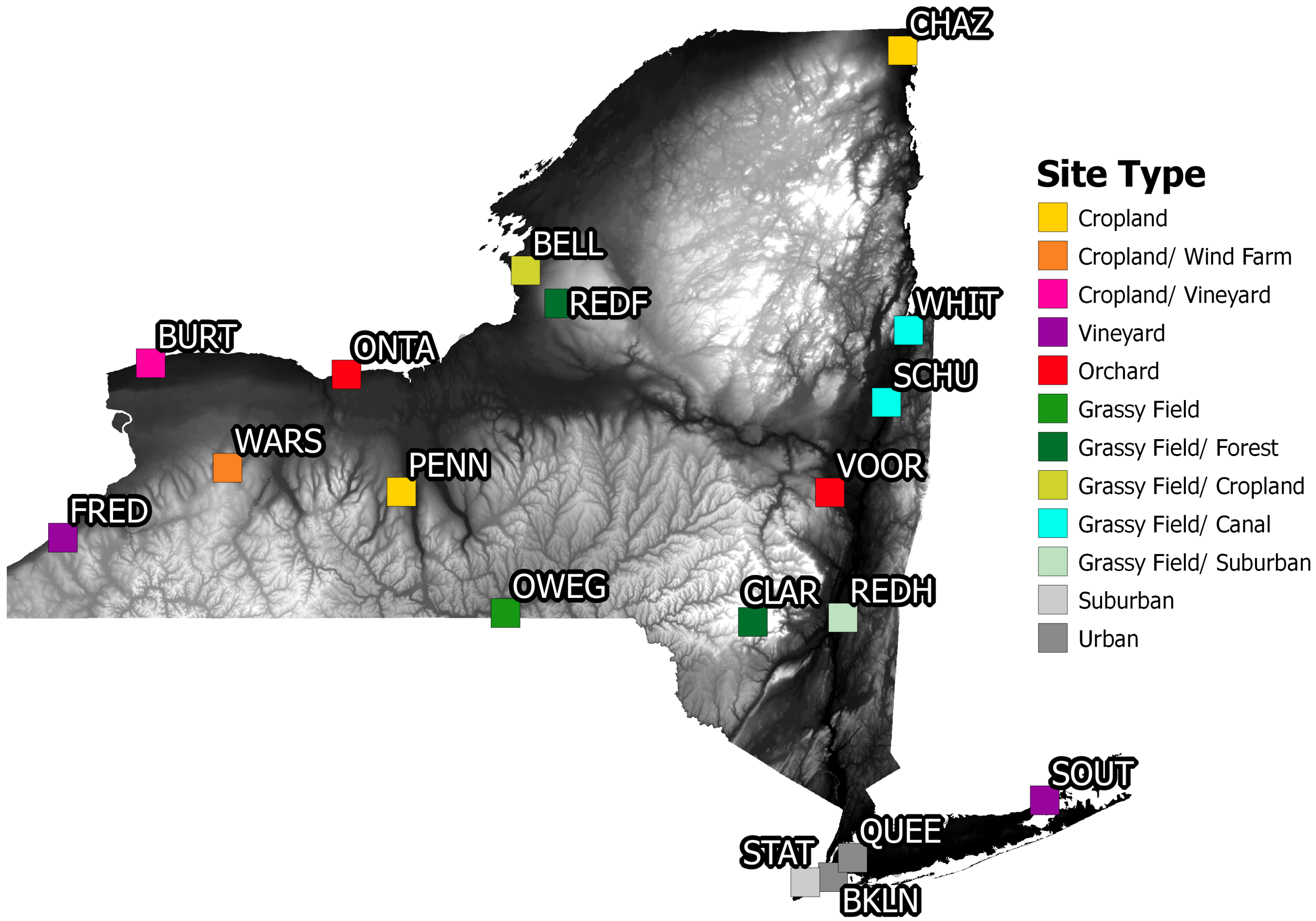


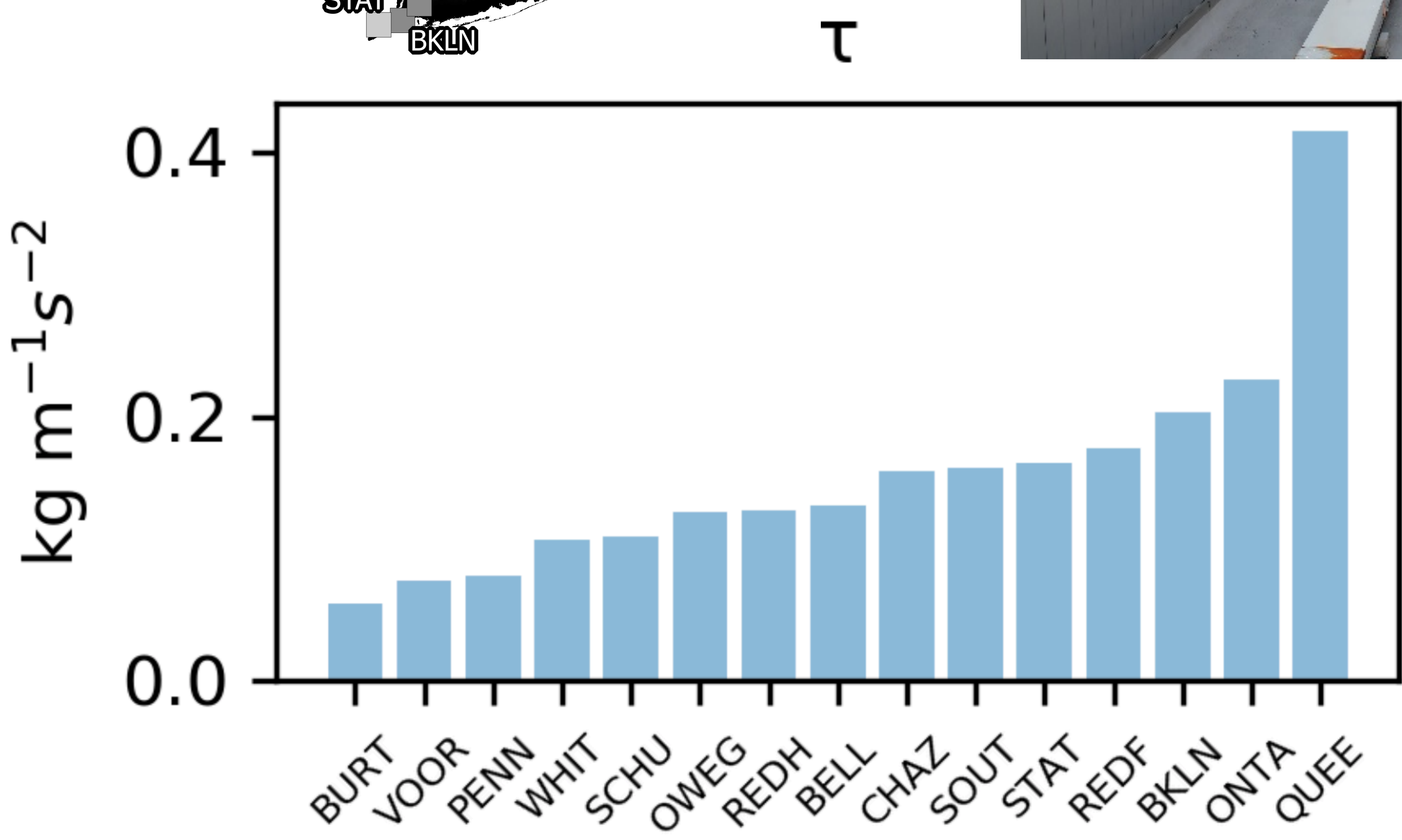


PENN

Footprint depends on z_0, z/L,…

Momentum Flux

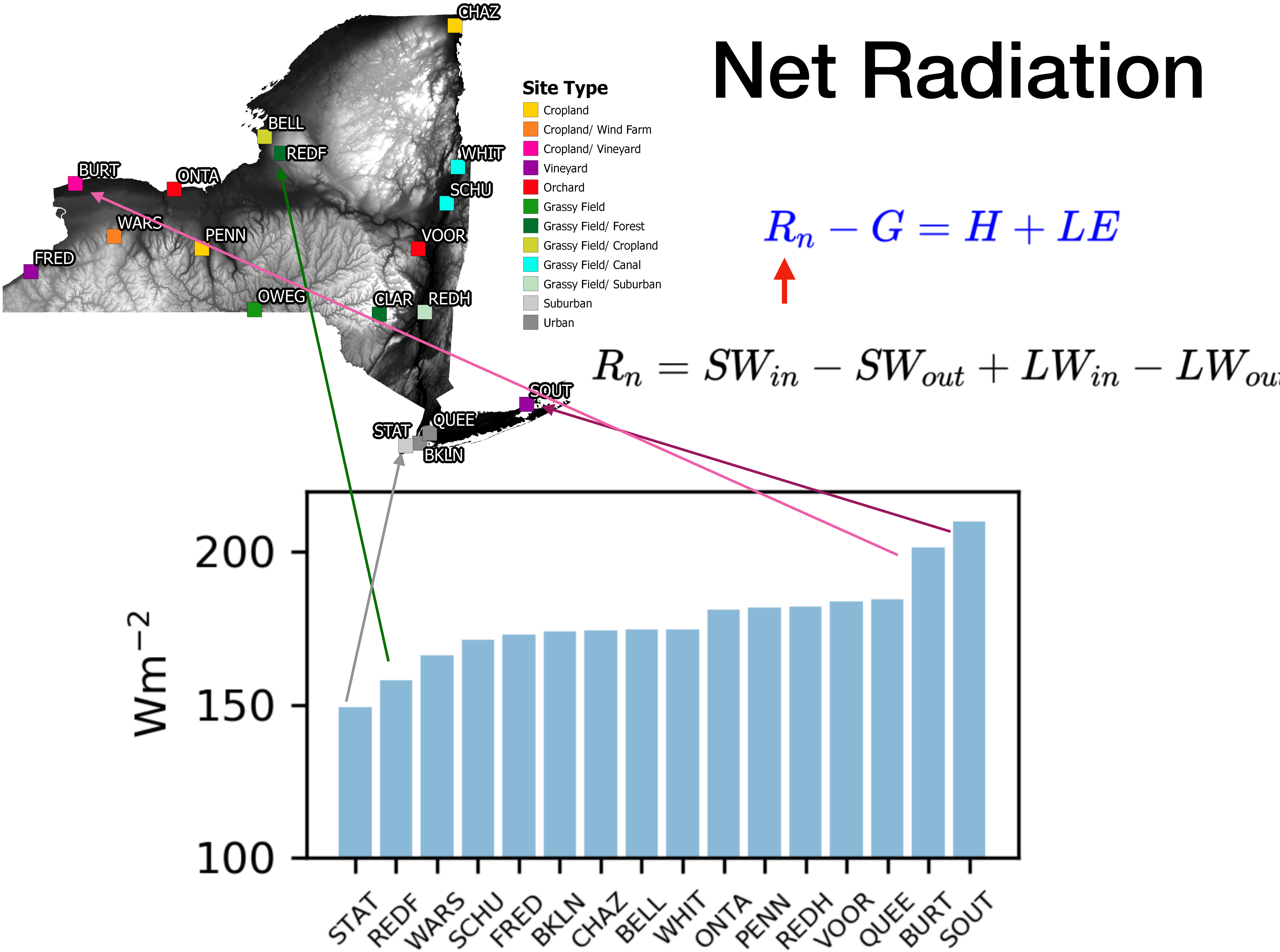


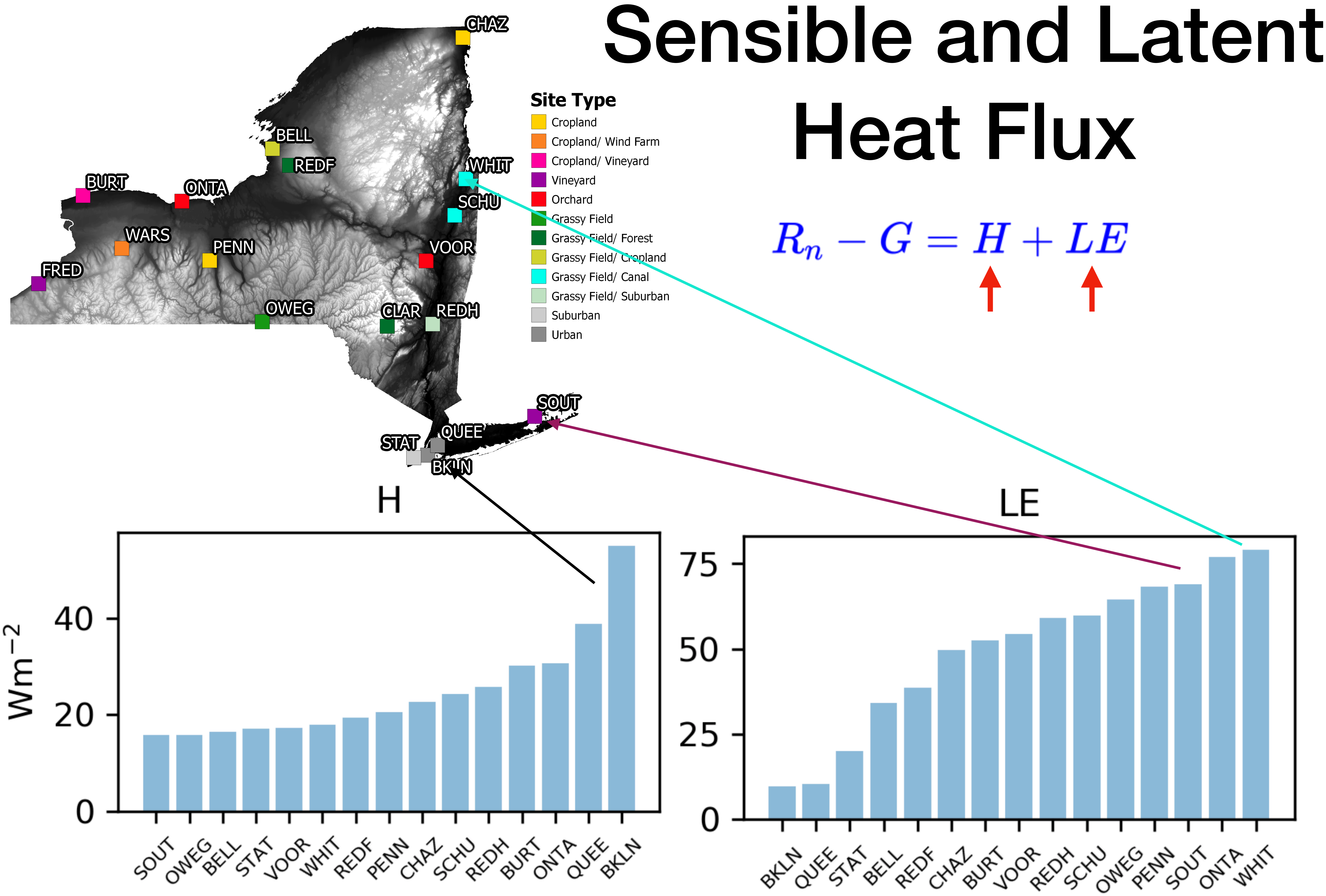


Net Radiation

$$R_n - G = H + LE$$

$$R_n = SW_{in} - SW_{out} + LW_{in} - LW_{out}$$

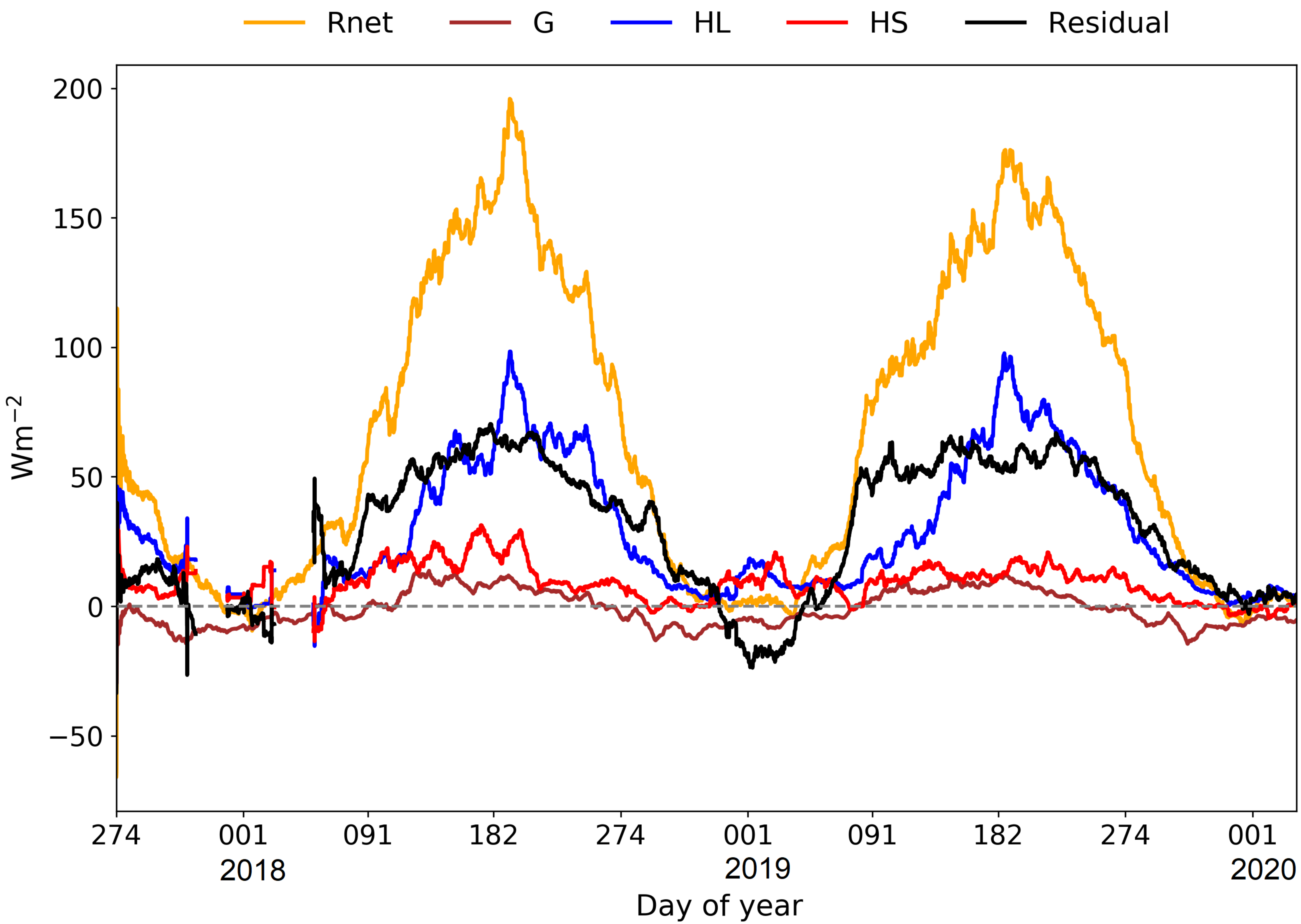




Sensible and Latent Heat Flux
$R_n - G = H + LE$
Site Type
Cropland
Cropland/ Wind Farm
Cropland/ Vineyard
Vineyard
Orchard
Grassy Field
Grassy Field/ Forest
Grassy Field/ Cropland
Grassy Field/ Canal
Grassy Field/ Suburban
Suburban
Urban
CHAZ
BELL
REDF
WHIT
BURT
ONTA
SCHU
WARS
PENN
VOOR
FRED
OWEG
CLAR
REDH
SOUT
QUEE
STAT
BKLN
H
Wm^{-2}
0
20
40
SOUT OWEG BELL STAT VOOR WHIT REDF PENN CHAZ SCHU REDH BURT ONTA QUEE BKLN
LE
0
25
50
75
BKLN QUEE STAT BELL REDF CHAZ BURT VOOR REDH SCHU OWEG PENN SOUT ONTA WHIT

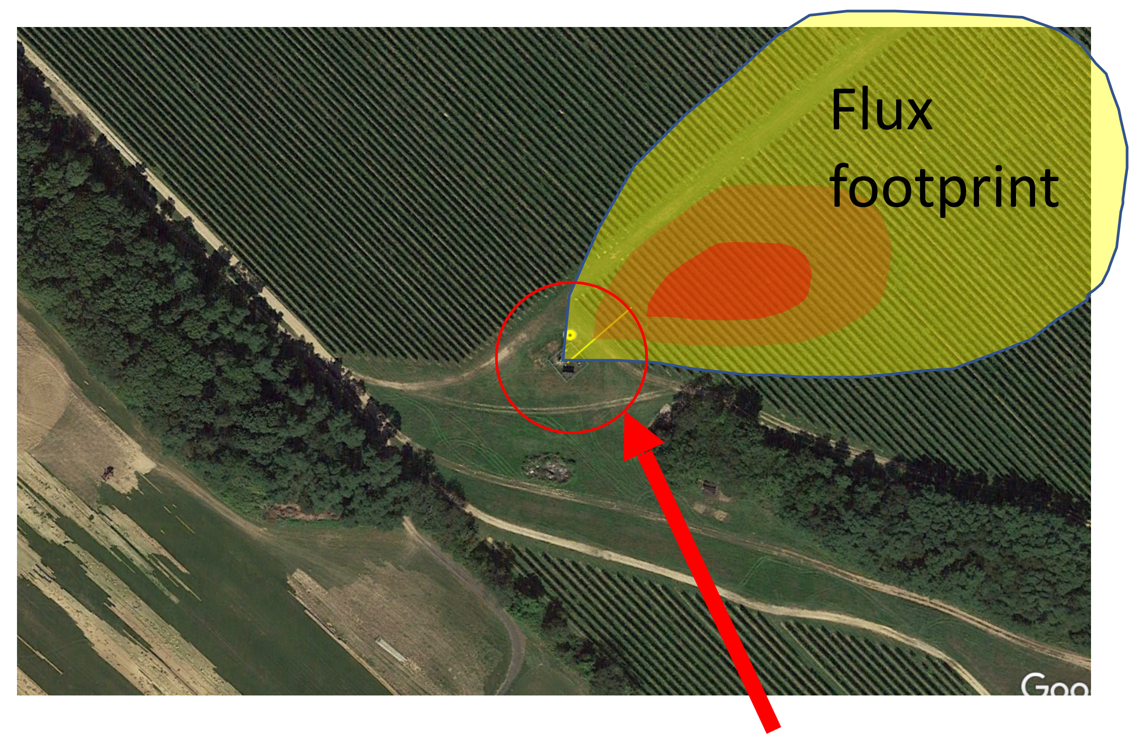
Energy Balance

$$\text{Residual} = R_n - G - H - LE$$



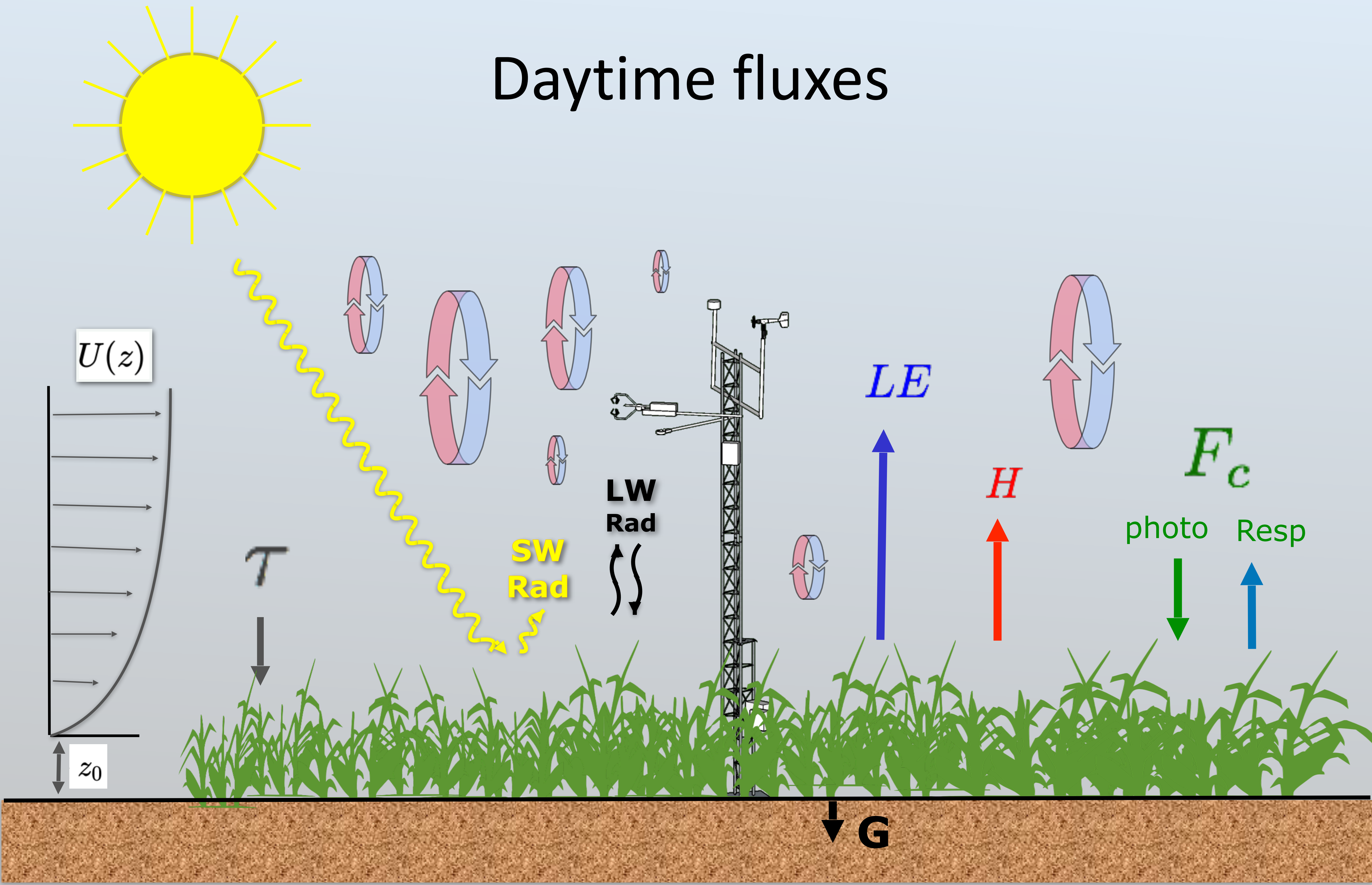
Why doesn’t the budget close?

- Instrument/computational error
- footprint mismatch
- siting
- missing low or high freq turbulent flux



Foken, 2008, Wilson et al., 2002

Daytime fluxes



Bowen Ratio

$$B = \frac{H}{LE}$$

Bowen Ratio (*B*)

B* = *H*/*LE

$$H = \rho c_p \overline{w'T'}$$
$$LE = \rho L_v \overline{w'q'}$$

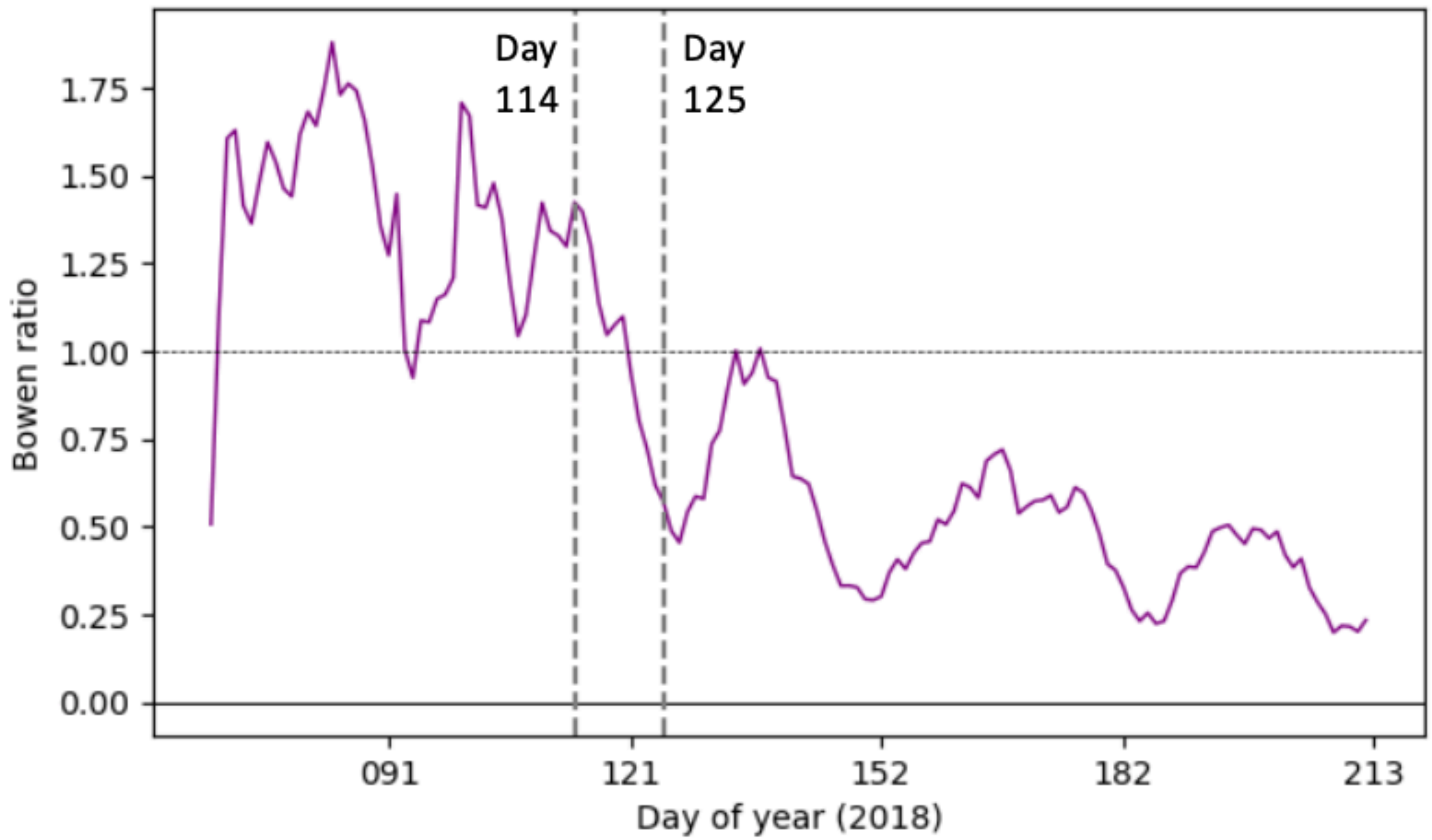


Figure 4.2. Composite average of noontime (11–13 hrs) Bowen ratio for all flux sites excluding BKLN, QUEE, and STAT. The first vertical dotted line to the left indicates the state-wide average day of first visible grass growth (114). The second vertical line represents the average day of first visible leaf emergence (125). Data are valid between March 10, 2018 and August 1, 2018. QC grade: 1–3.

From J. Covert

Common Values of *B*

Type of surface	Range of Bowen ratios
Deserts	>10.0
Semi-arid landscapes	2.0-6.0
Temperate forests and grasslands	0.4-0.8
Tropical rainforests	0.1-0.3
Tropical oceans	<0.1

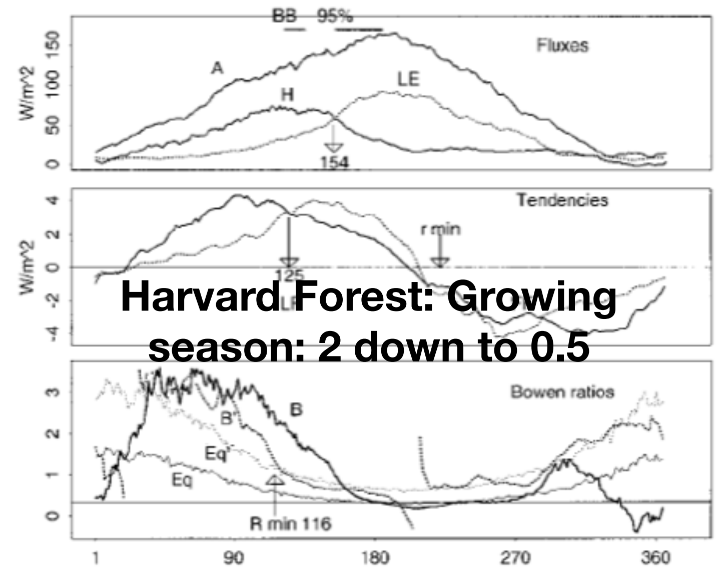
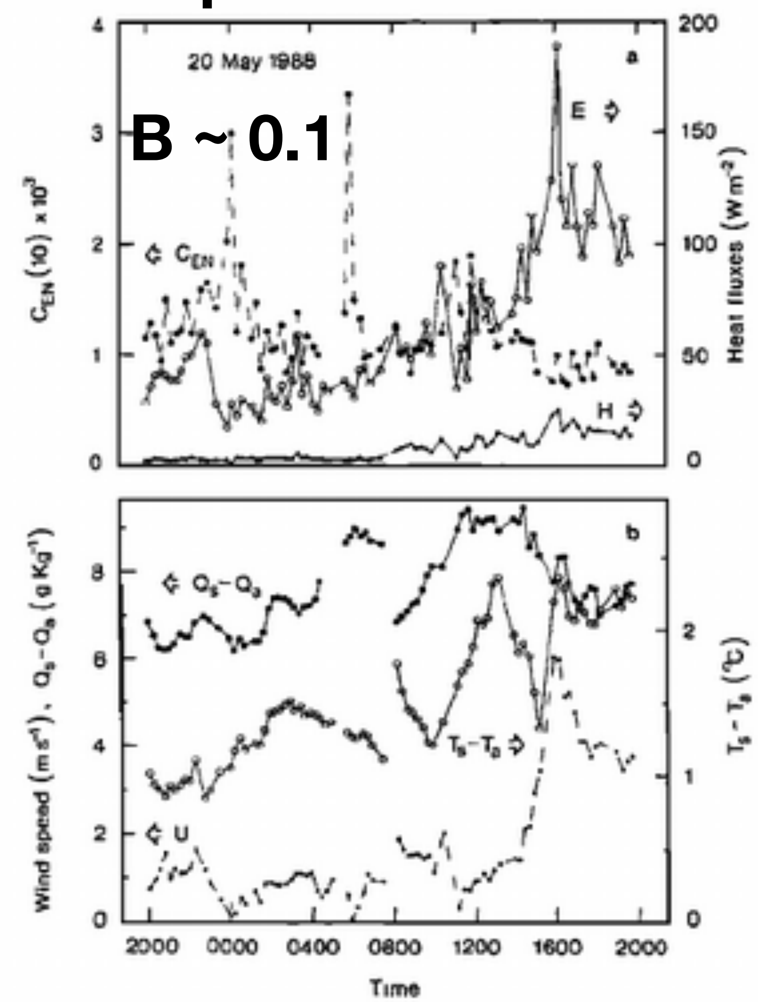


FIG. 2. (top) Daily averaged fluxes above the canopy at Harvard Forest for 1991–98. Available energy $A = (-Q^* - Q_g)$, sensible heat flux H, and latent heat flux LE (dotted). Here "BB" and "95%" are as indicated in Fig. 1, and H = LE at day 154. (center) 1946–94 daily averaged and smoothed temperature tendency ($C_p \partial T/\partial t$, solid) and humidity tendency ($L\partial q/\partial t$, dotted). Tendencies are equal at day 125. Here "r min" represents the average date of the annual minimum canopy resistance at Harvard Forest (Sakai et al. 1997). Here "LF" and "FF" represent climatological last and first 0°C freeze dates. (bottom) Bowen ratios B and B' and equilibrium Bowen ratios Eq' and Eq as described in the text. Date of average annual minimum relative humidity "R min 116" indicated.

Equatorial Pacific



...ture and humidity differences, sensible ...ent heat flux, and the neutral exchange ...ient for moisture during May 20, 1988.

Measurements of wind speed, air-sea

GTE/ABLE 2A MARTIN ET AL.: AMAZONIAN MIXING LAYER CHARACTERISTICS 1367

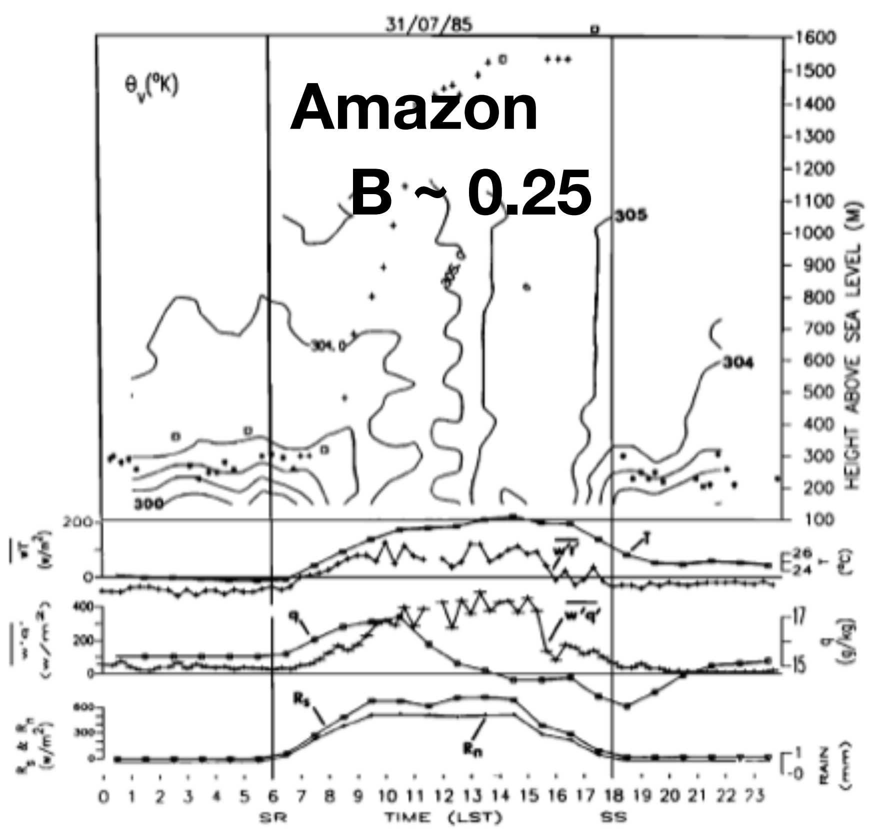
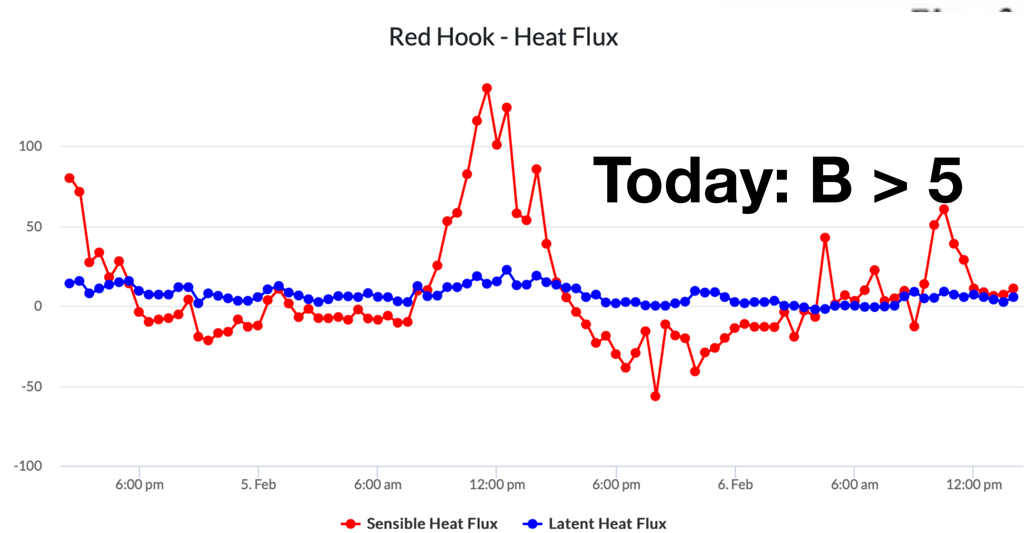
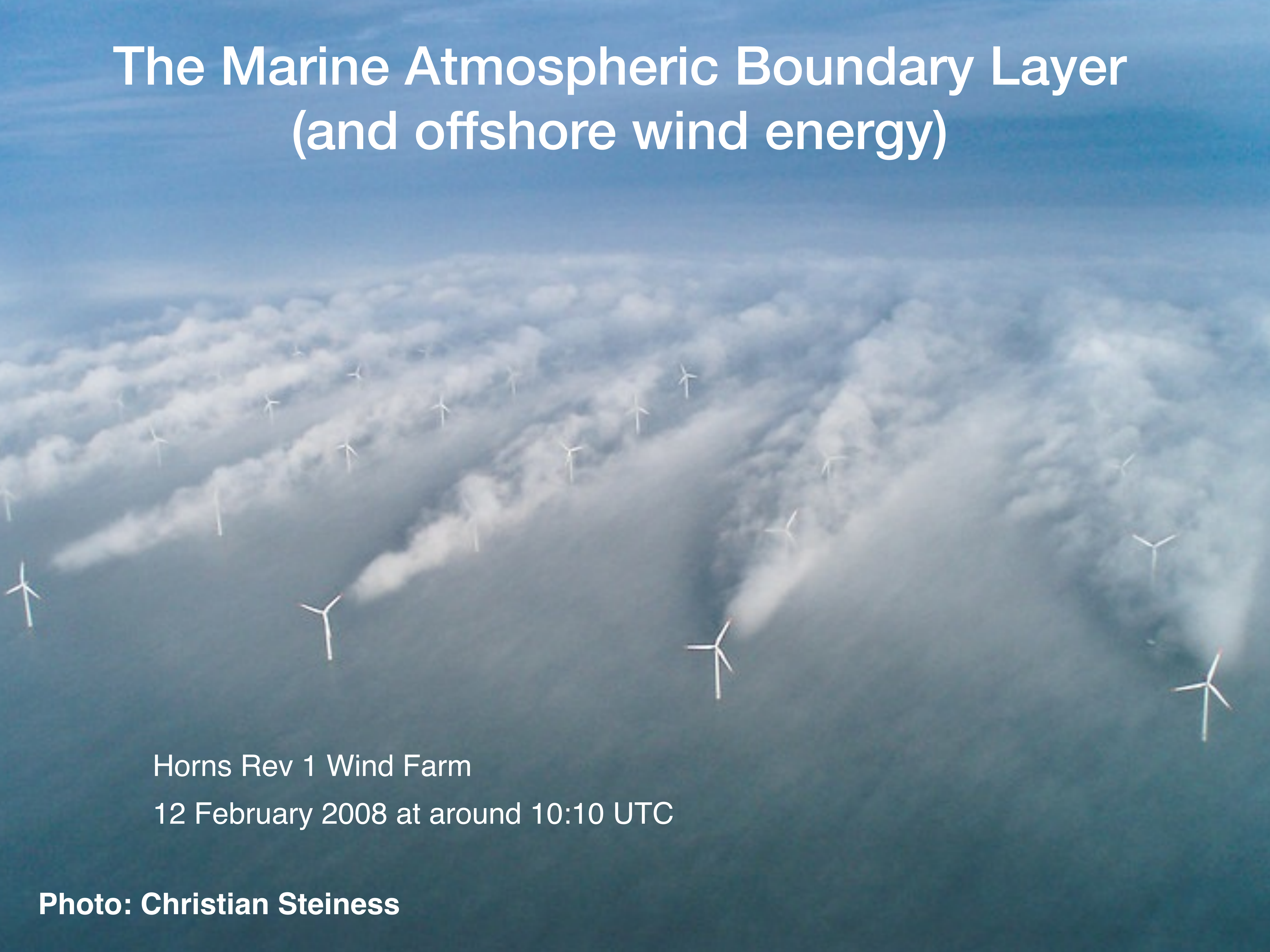


Fig. 4. As in Figure 3, but for July 31 (undisturbed day).



The Marine Atmospheric Boundary Layer (and offshore wind energy)

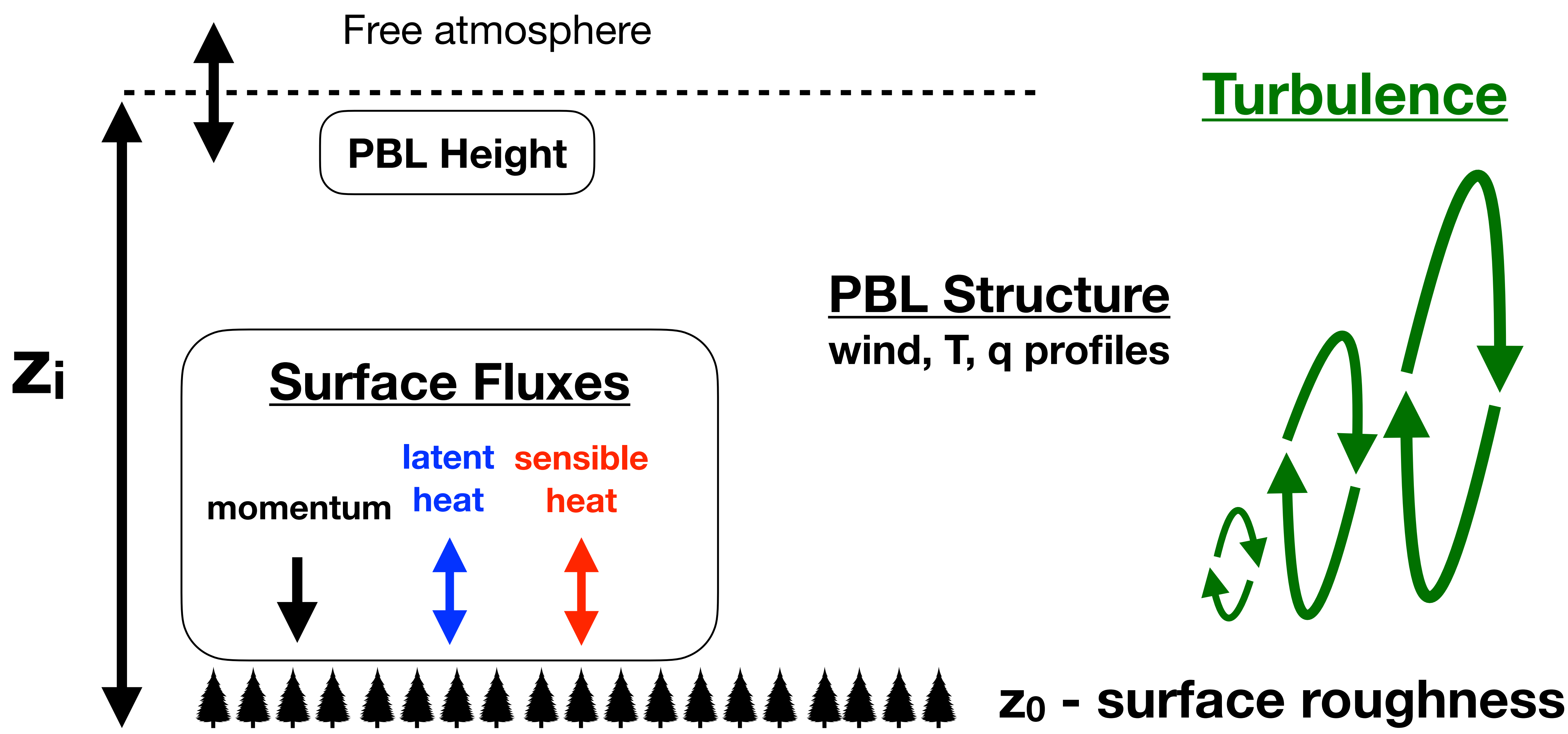


Horns Rev 1 Wind Farm

12 February 2008 at around 10:10 UTC

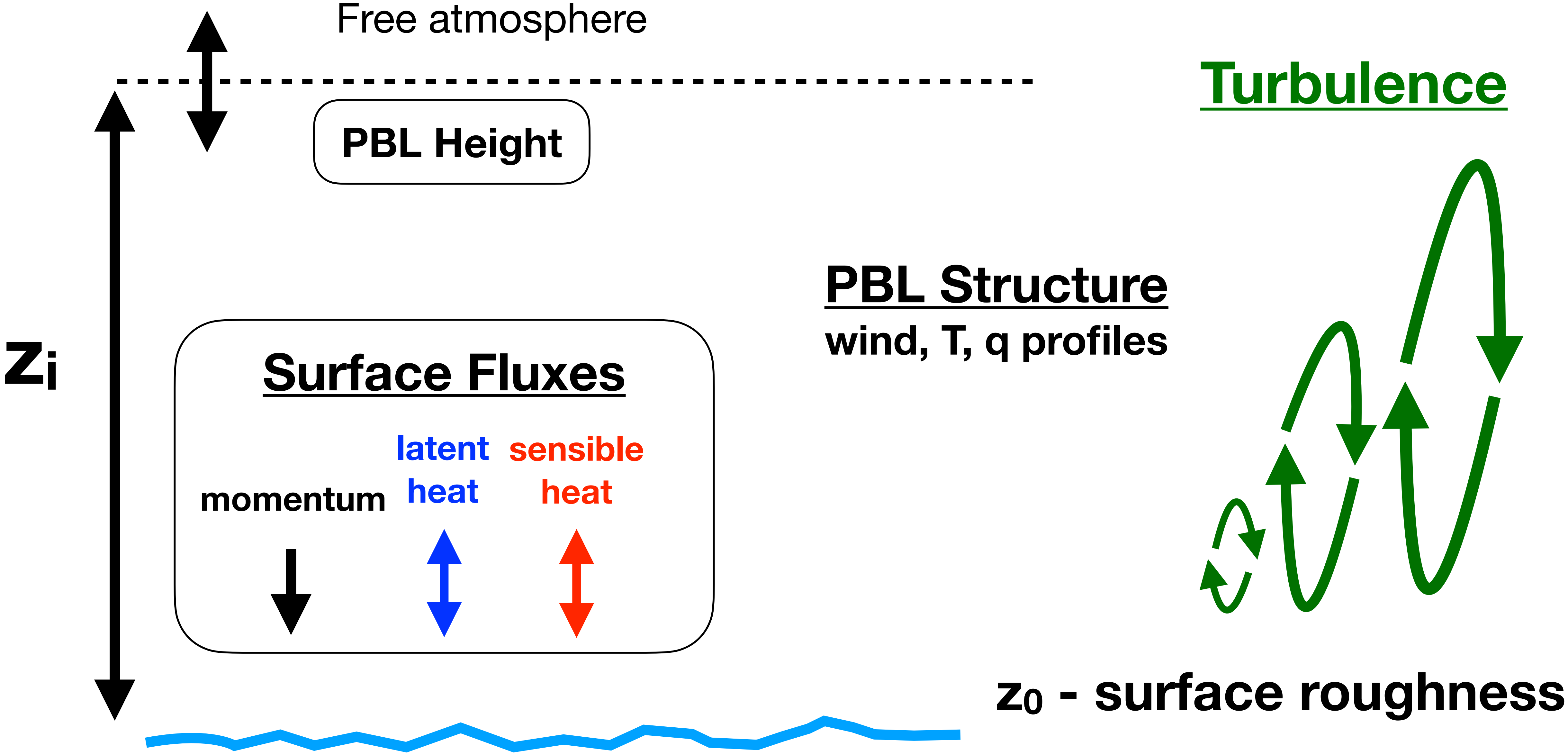
Photo: Christian Steiness

Conceptual Model of the ABL
But what about over the ocean?



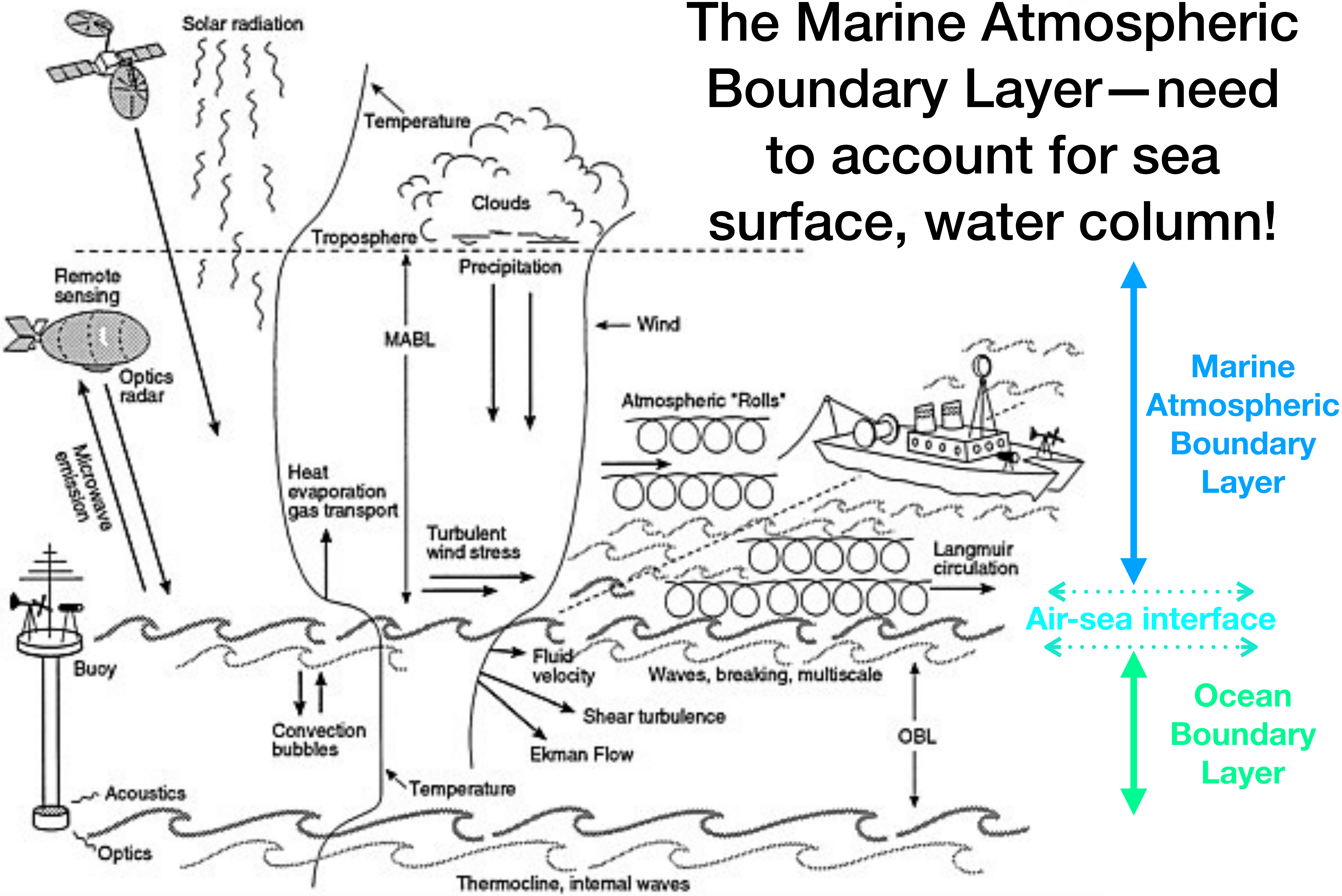
horizontally homogeneous

Conceptual Model of the ABL
But what about over the ocean?



horizontally homogeneous(?)

The Marine Atmospheric Boundary Layer—need to account for sea surface, water column!



Sea Breeze Circulation

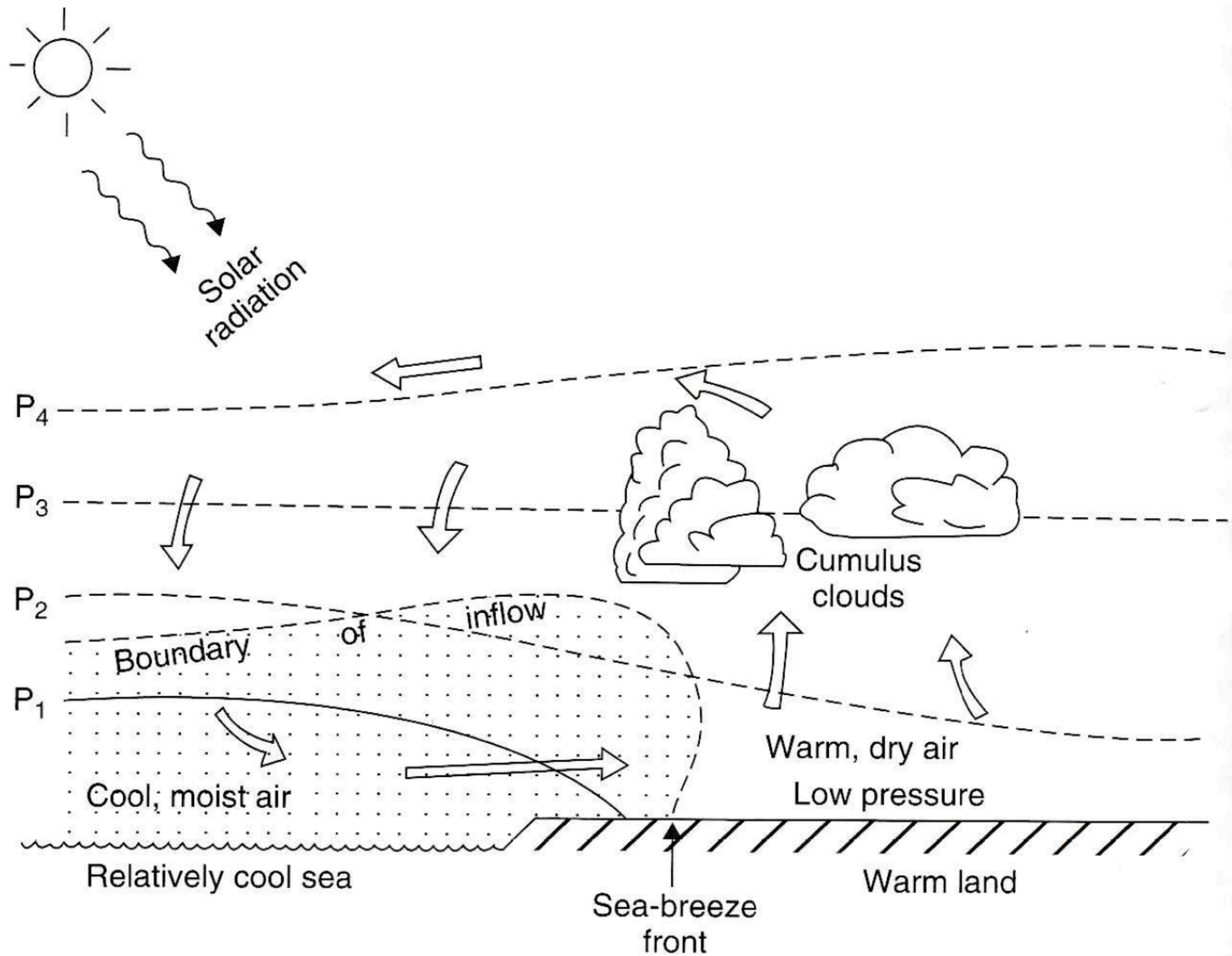


Figure 14-4. A schematic representation of a sea breeze circulation. As the sun heats the land the air above it warms and rises (right). This produces a drop in pressure, which draws cool air from over the water. *Source:* Royal Meteorological Society.

Offshore flow—wind profile modification

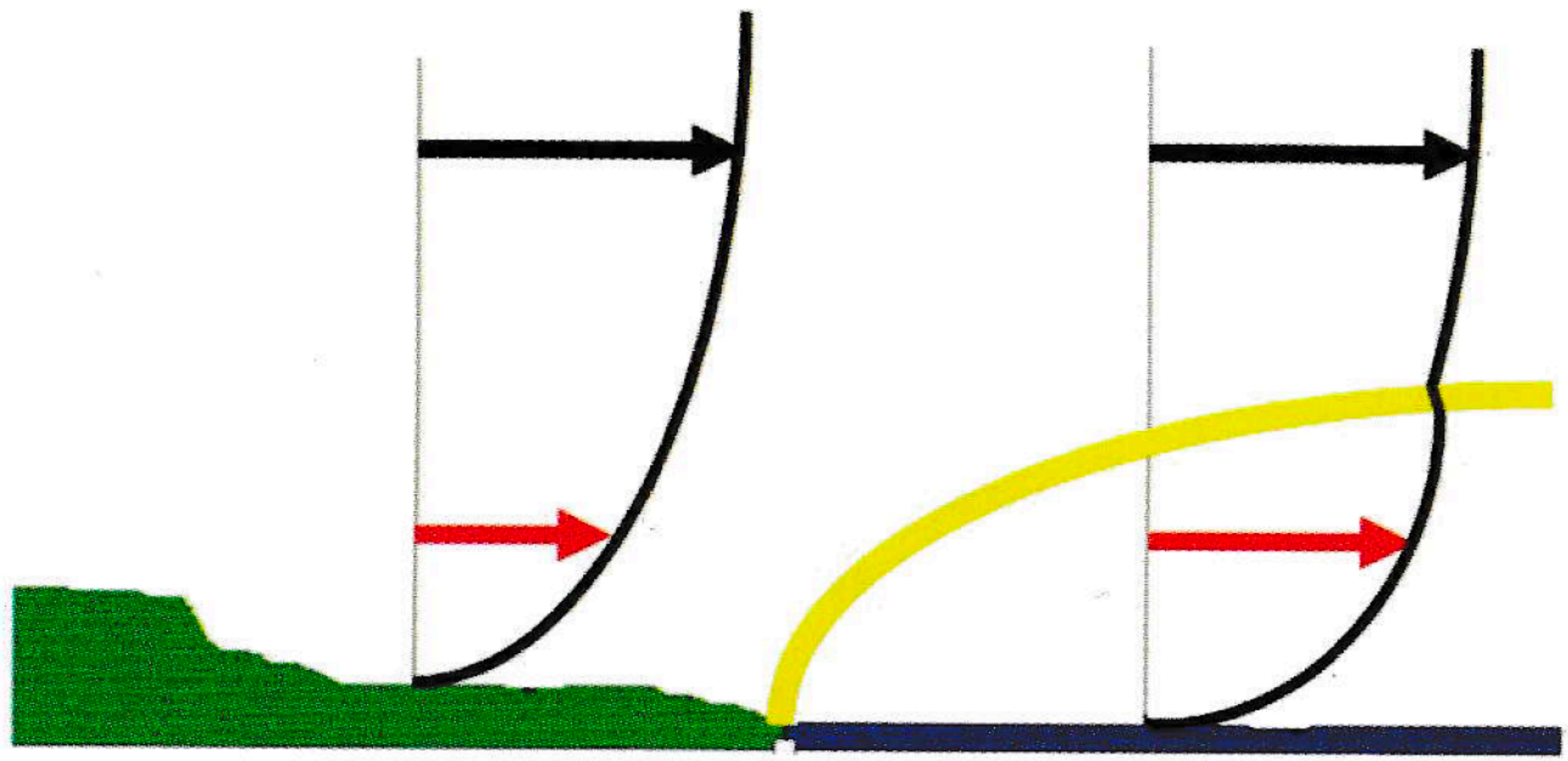


Figure 14-3. Schematic representation of the evolution of a wind speed profile as the wind moves off the land over water (from left to right). The initial profile reflects the land surface roughness. As the air moves over the much smoother water, an IBL (yellow line) develops and grows with distance from shore. Within the IBL, the wind speed increases, and the wind profile assumes an offshore shear pattern. *Source:* AWS Truepower.

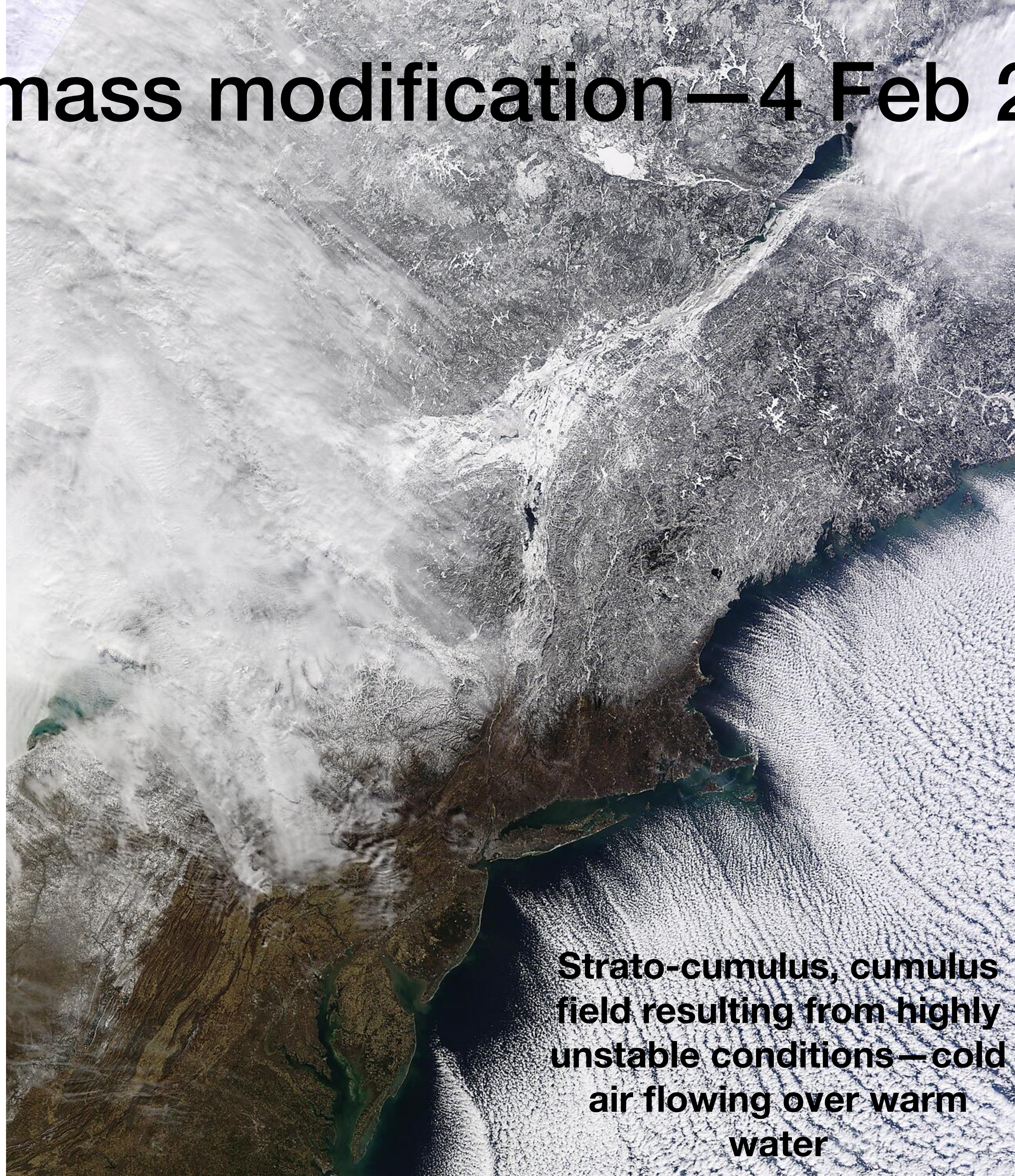
Estimating H and LE over the ocean

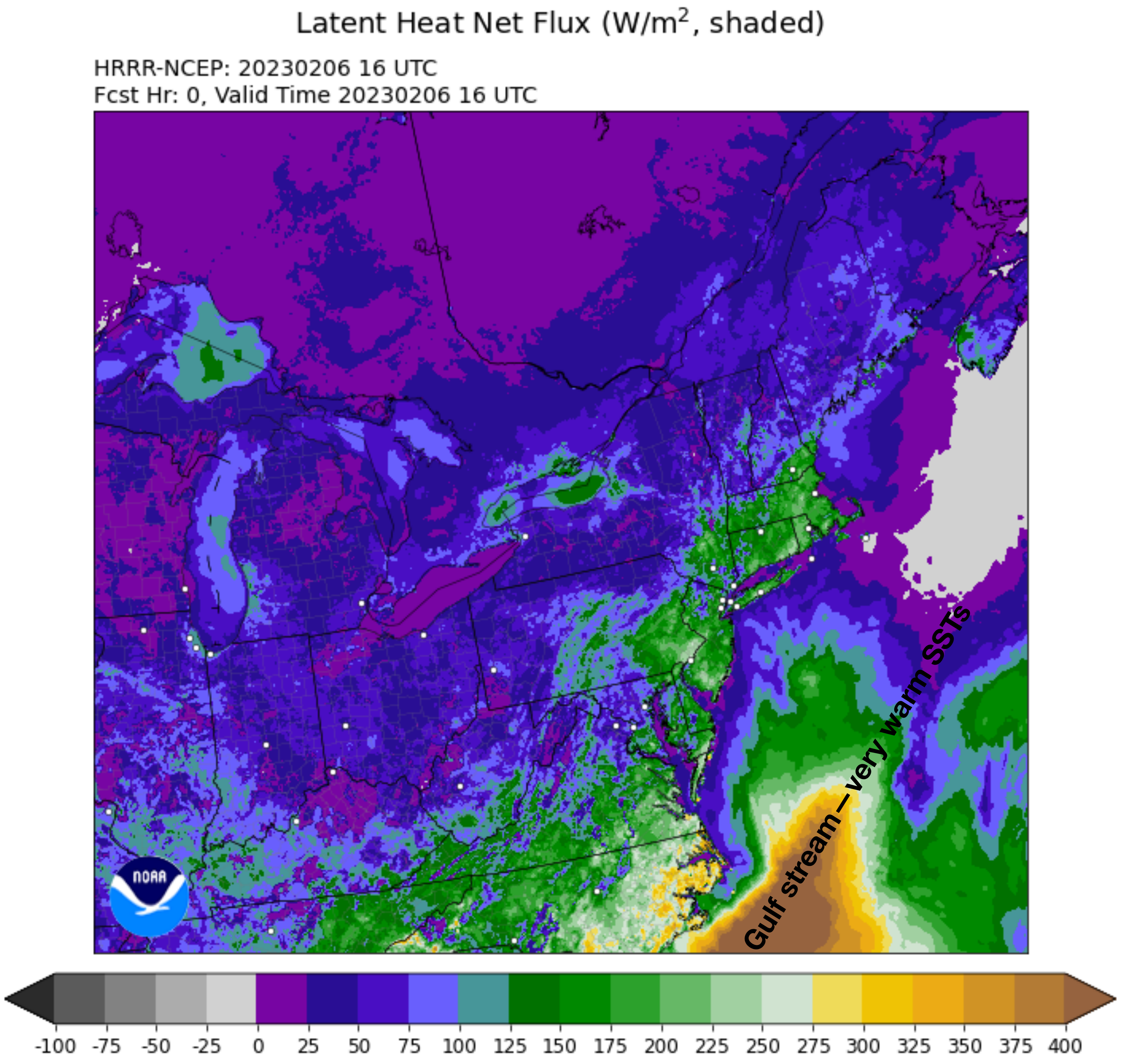
$$Q_H = \rho c_p C_h u (T_s - (T_a + \gamma z))$$

$$Q_E = \rho L C_e u (q_s - q_a)$$

where ρ is the density of air; c_p, the specific heat capacity of air at constant pressure; L, the latent heat of vaporization; C_h and C_e, the stability and height dependent transfer coefficients for sensible and latent heat respectively; u, the wind speed; T_s , the sea surface temperature; T_a, the surface air temperature with a correction for the adiabatic lapse rate, γ; z, the height at which the air temperature was measured; q_s, 98% of the saturation specific humidity at the sea surface temperature to allow for the salinity of sea water, and q_a, the atmospheric specific humidity.

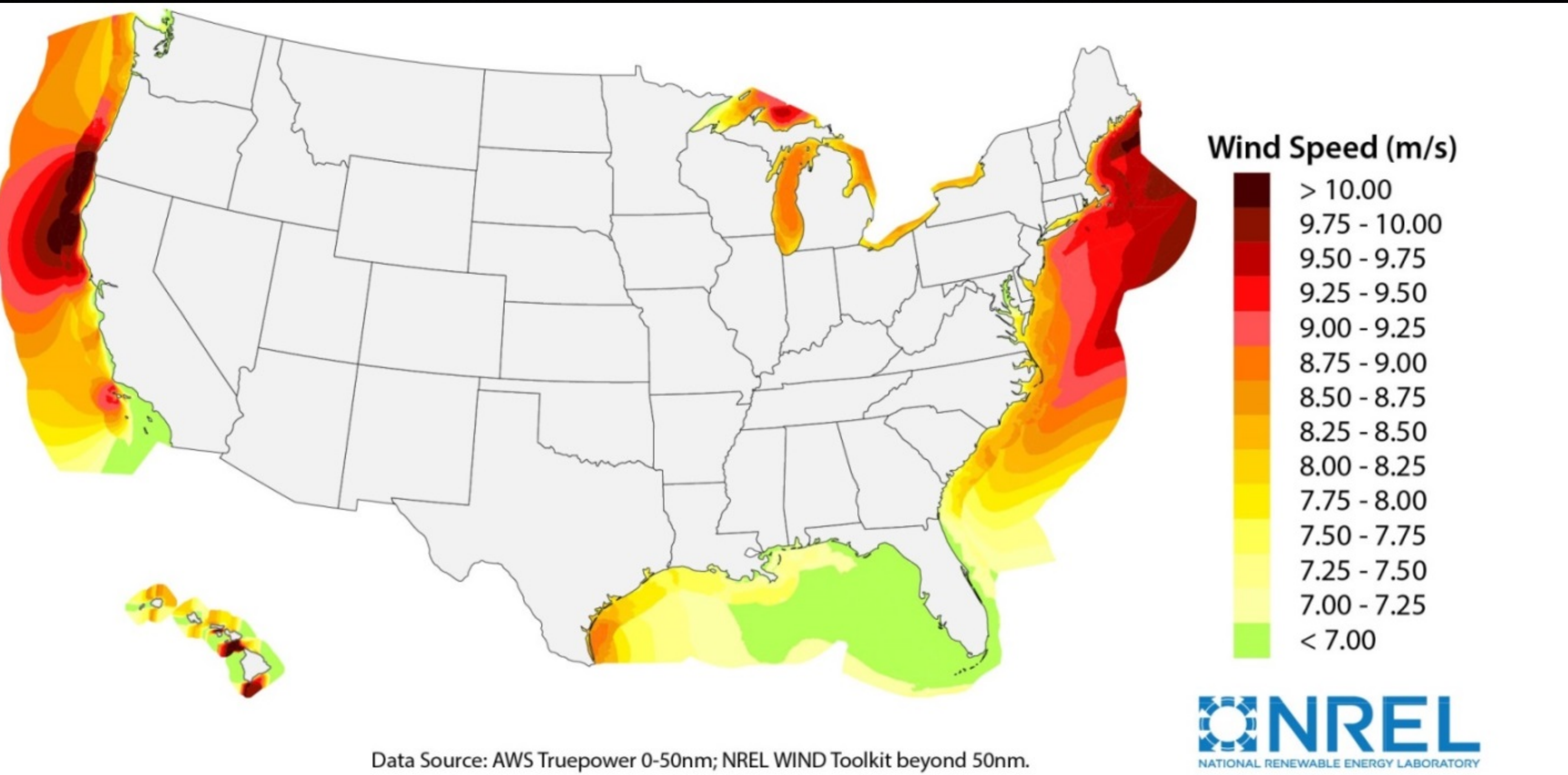
Air mass modification—4 Feb 2023



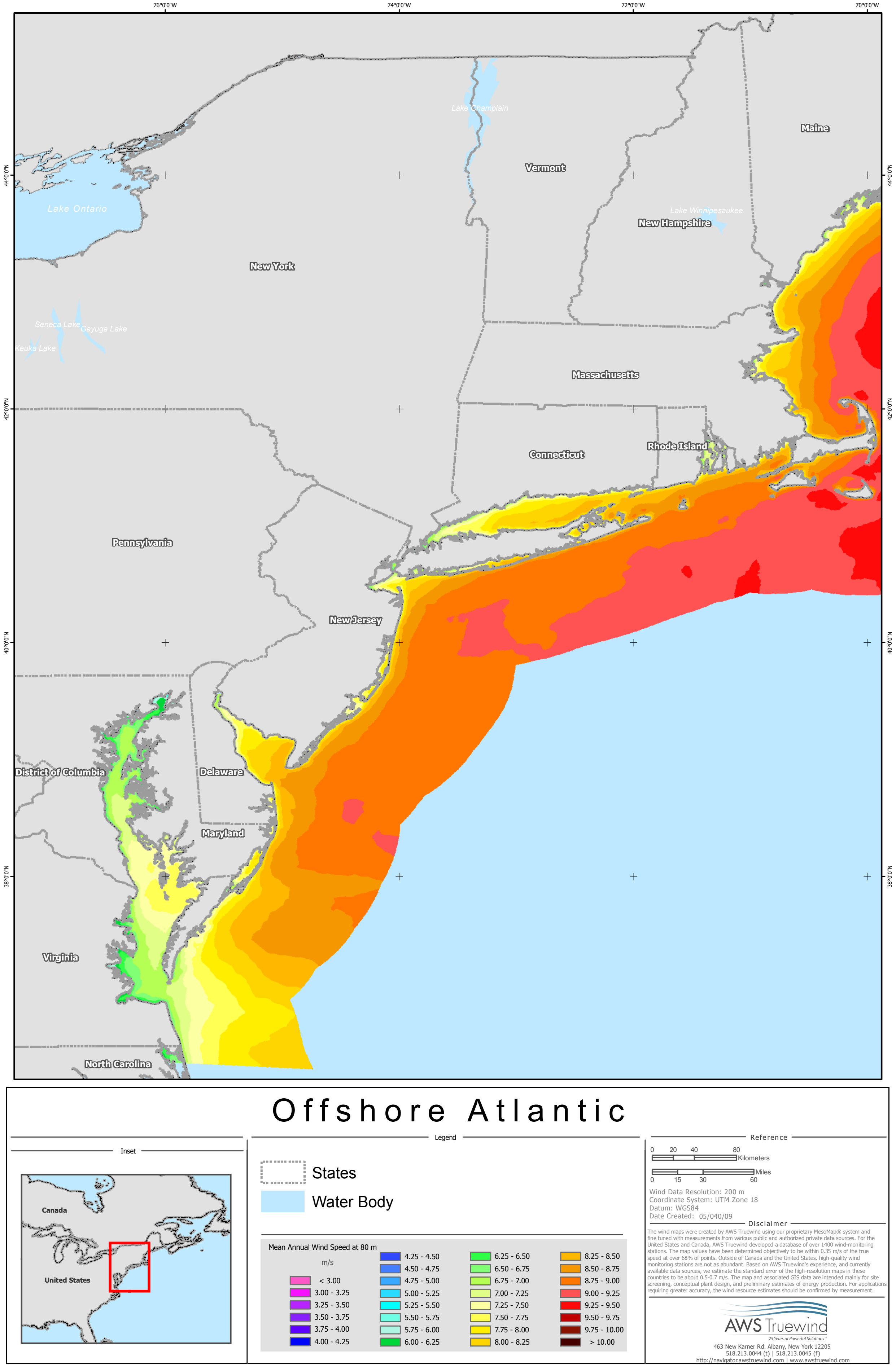

Latent Heat Net Flux (W/m², shaded)
HRRR-NCEP: 20230206 16 UTC
Fcst Hr: 0, Valid Time 20230206 16 UTC
NOAA
Gulf stream—very warm SSTs
-100 -75 -50 -25 0 25 50 75 100 125 150 175 200 225 250 275 300 325 350 375 400

Meteorological-Oceanographic Challenges Faced by Offshore Wind Development Along the Northeast Coast of the US

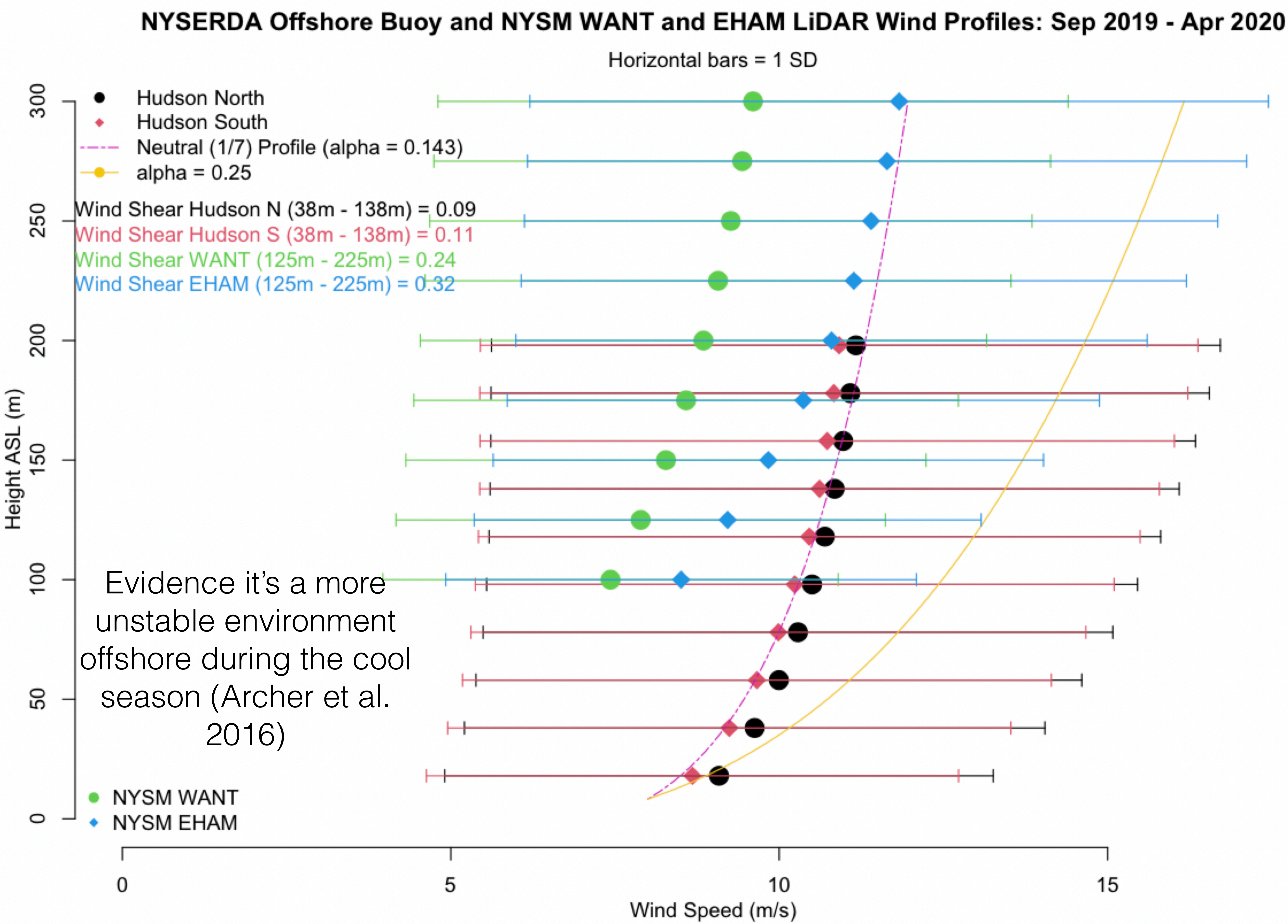
The Resource—US



Offshore wind resource data (100 m ASL) used for the 2016 offshore wind resource assessment. Map provided by NREL, AWS Truepower, and Vaisala/3TIER



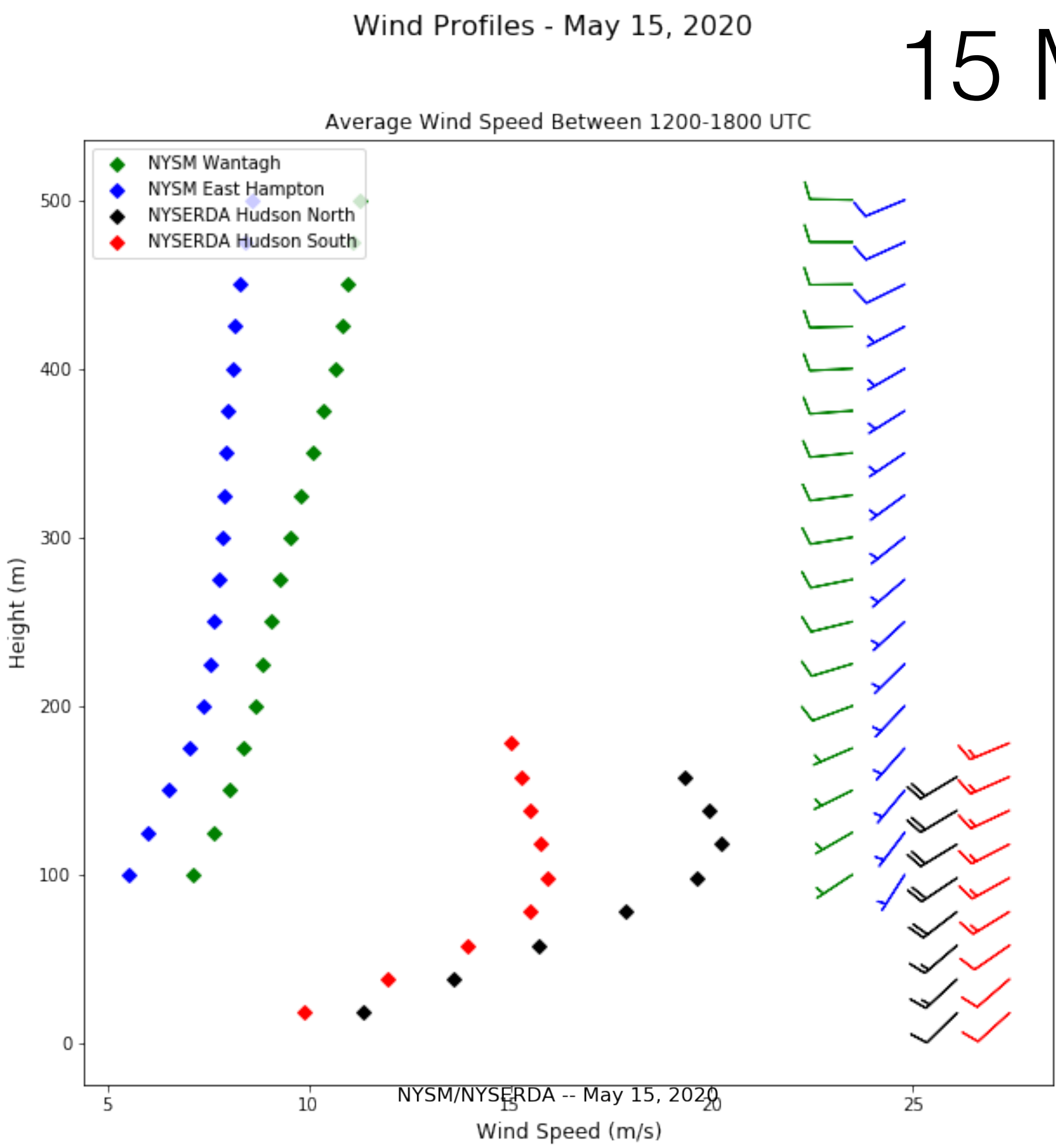
Generally, greatest wind speeds are found as we go further offshore. But, under enhanced sea breeze/LLJ conditions...

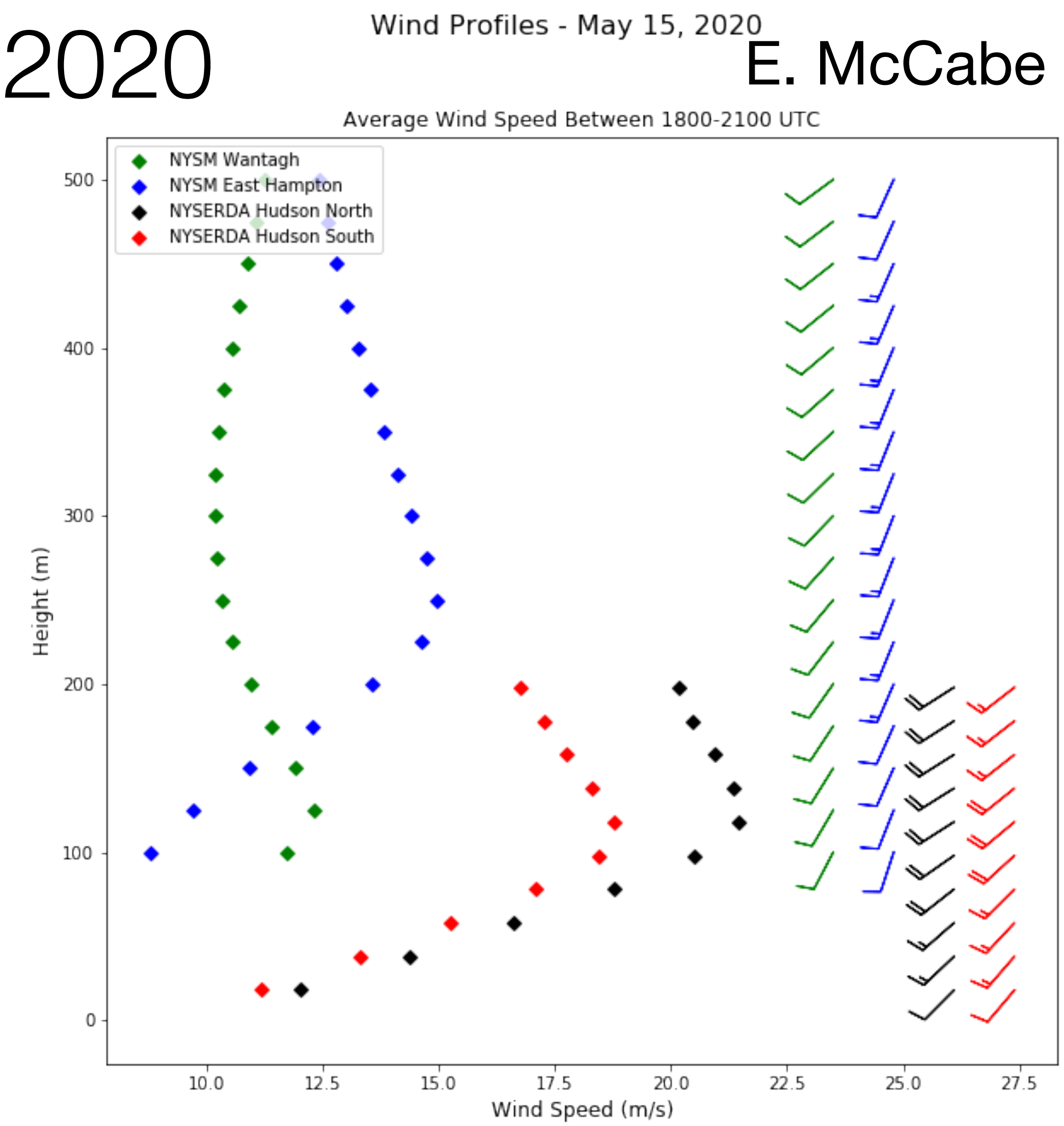


Evidence it's a more unstable environment offshore during the cool season (Archer et al. 2016)

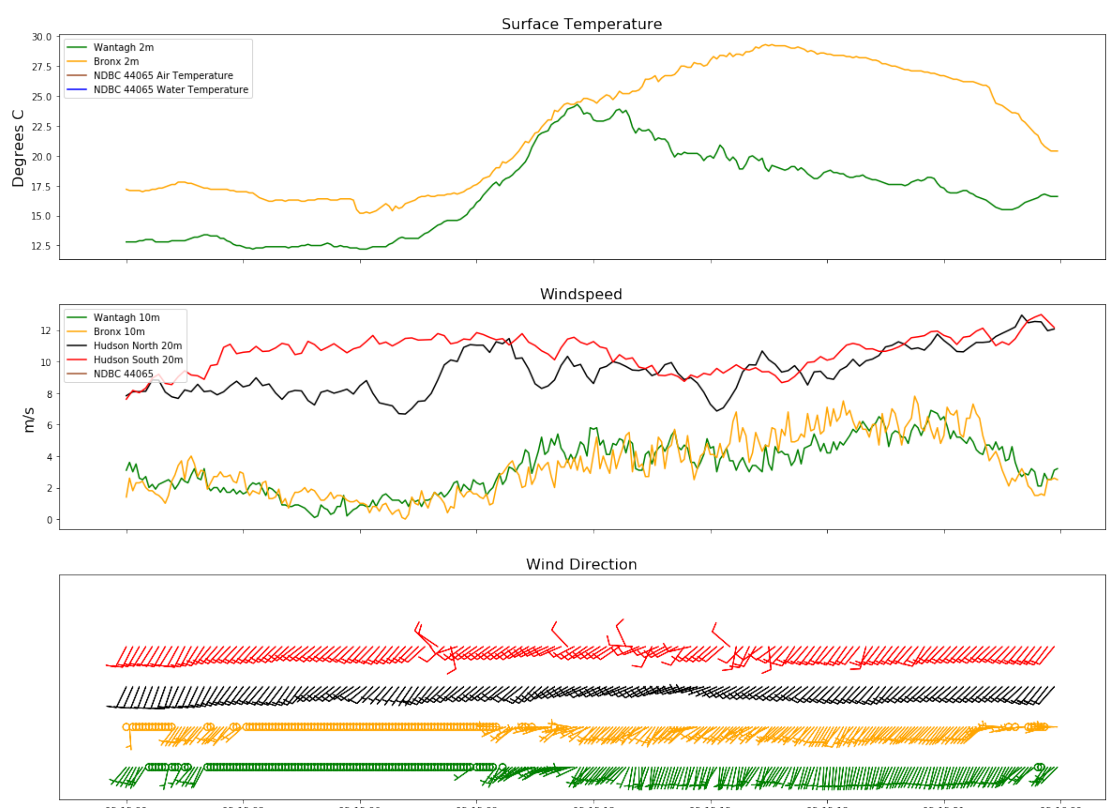
15 May 2020

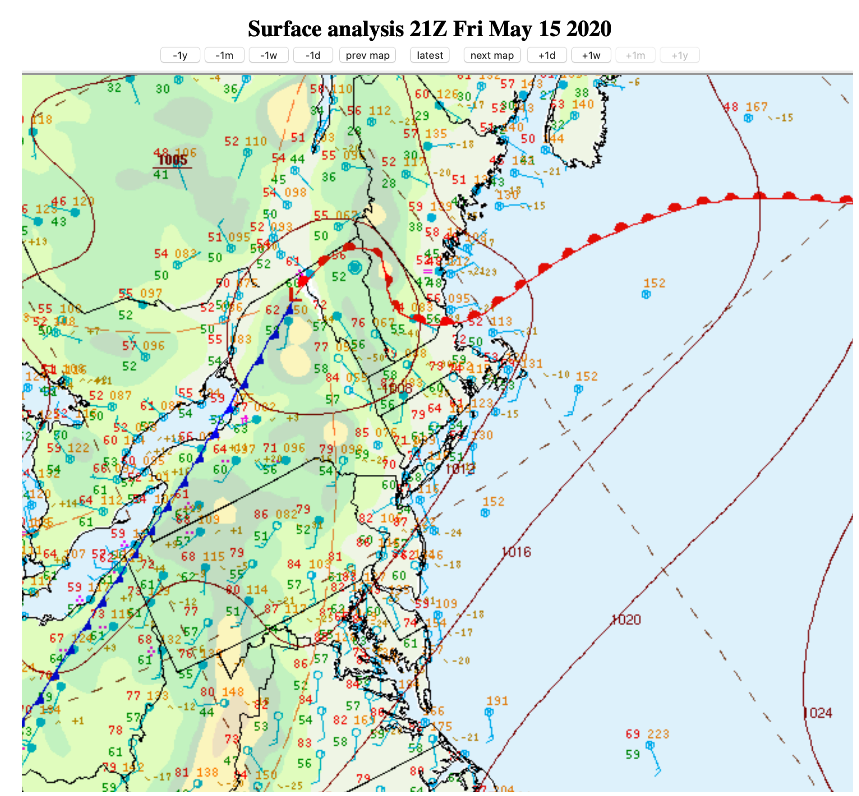
E. McCabe





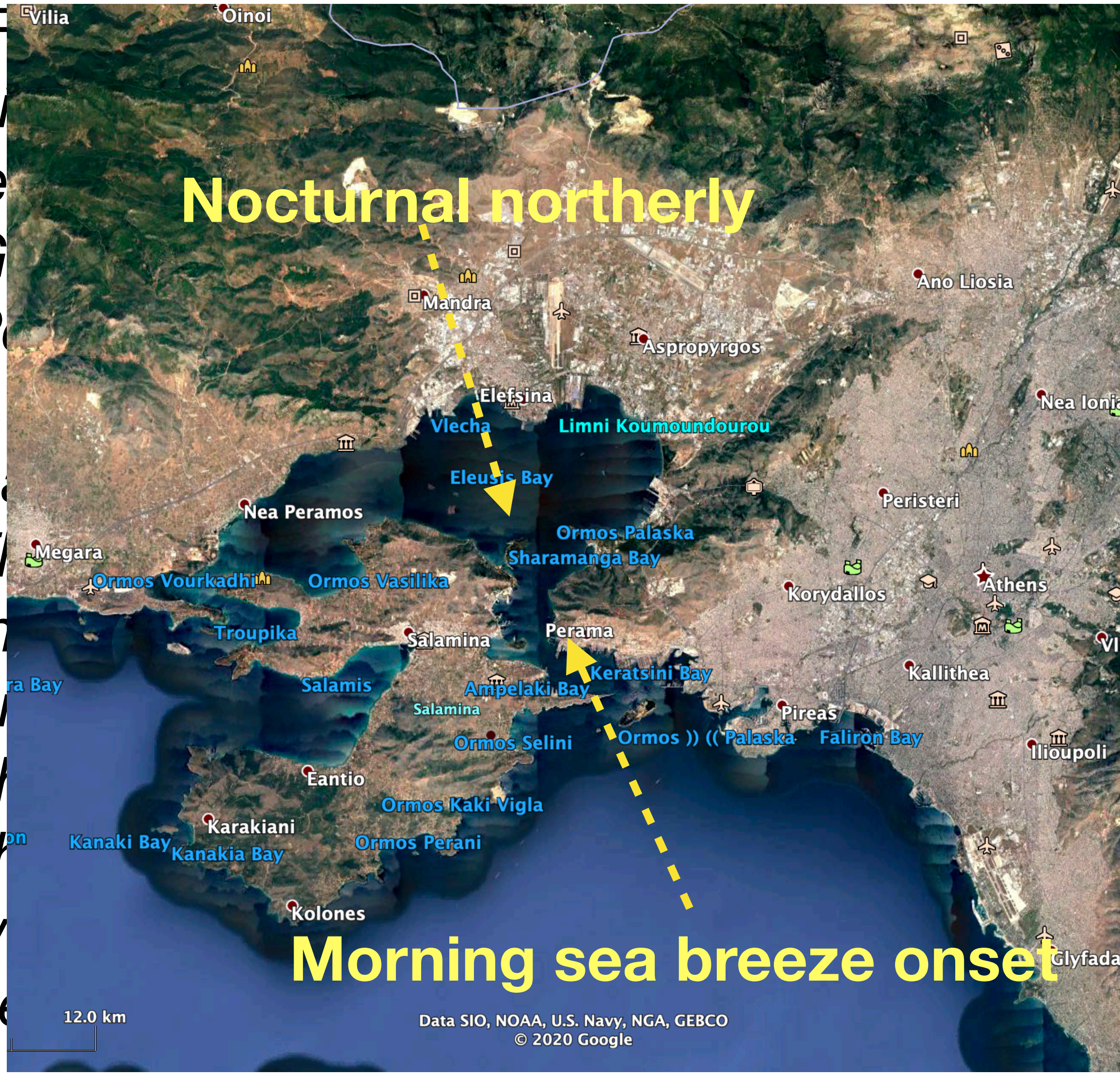
NYSM/NYSERDA -- May 15, 2020

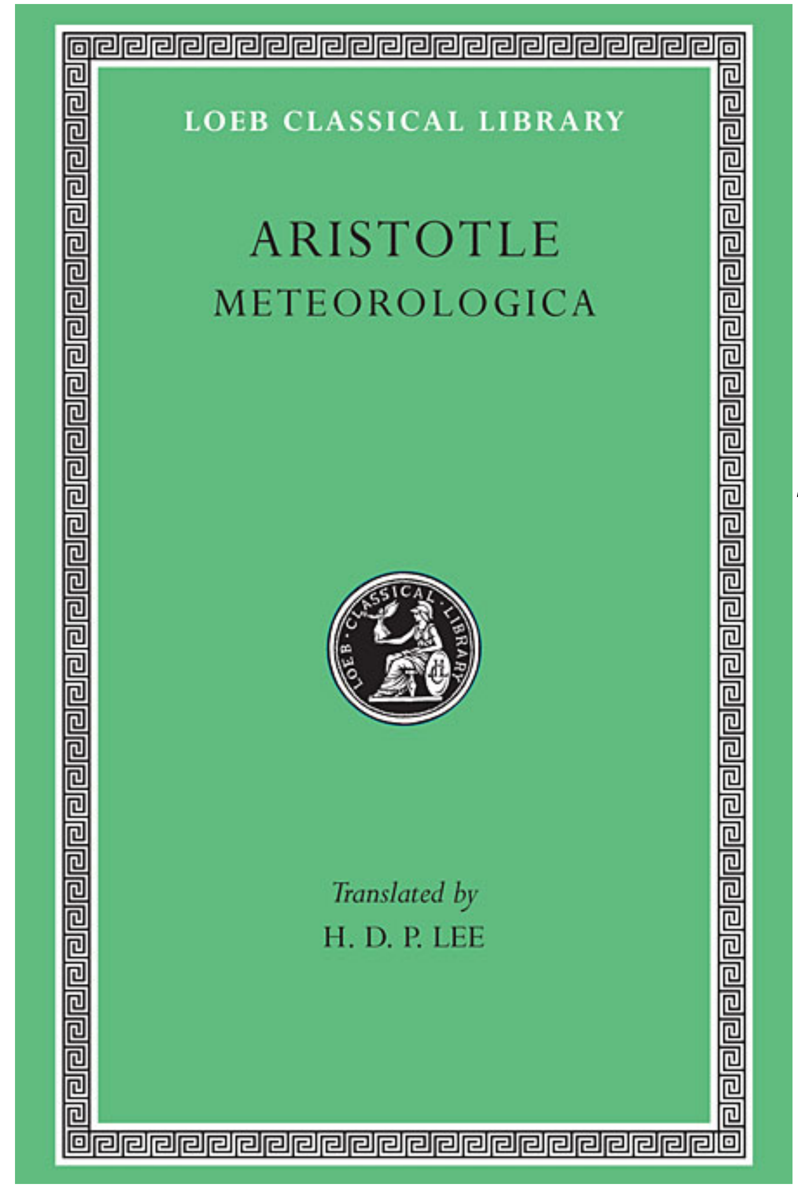





The Sea Breeze
21 July 2020 4:44 PM LT
Riis Park Rockaway NY

- A local circulation (but see below!) that occurs at coastal locations throughout the world, during quiescent weather conditions.
- Observed from polar regions to the equator.
- Provides relief from oppressive hot weather, triggers thunderstorms, provide moisture for fog, blows away beach umbrellas
- Can produce either improved or reduced air quality near coastal regions (fresh air mass or re-circulate polluted air—see Great Lakes study)
- Crucial in siting of offshore wind energy facilities (see below)
- Can affect marine and aviation interests (small craft, large vertical wind shear in the MABL)

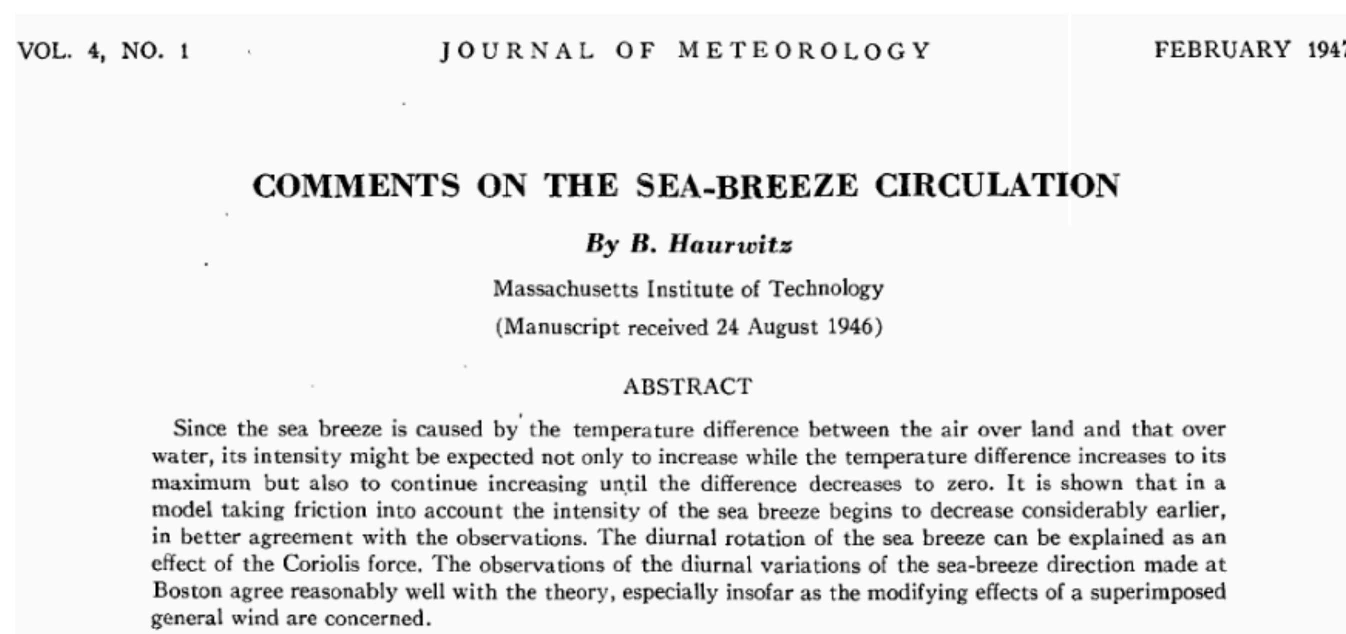




Aristotle: " as a rule a considerable area may be expected to be similarly affected, because neighboring places lie in a similar relation to the Sun, unless they have some local peculiarity. The prevailing wind in Athens is from the north or south, and the Etesian wind, a persistent, northerly or northeasterly wind, occurs after the summer solstice. Aristotle attributed local-scale winds to the unequal distribution of Earth s moist and dry " exhalations" and variations in local topography.

From Miller et al. (2003): Theophratus De Ventis was written about 300 B.C.E, 30 years after Meteorologica , and discusses the importance of the Sun in driving the wind and a distinct sea breeze from the south or southwest that occurred during the period of the Etesian wind.

Then not much until….



VOL. 4, NO. 1 JOURNAL OF METEOROLOGY FEBRUARY 1947

COMMENTS ON THE SEA-BREEZE CIRCULATION

By B. Haurwitz

Massachusetts Institute of Technology

(Manuscript received 24 August 1946)

ABSTRACT

Since the sea breeze is caused by the temperature difference between the air over land and that over water, its intensity might be expected not only to increase while the temperature difference increases to its maximum but also to continue increasing until the difference decreases to zero. It is shown that in a model taking friction into account the intensity of the sea breeze begins to decrease considerably earlier, in better agreement with the observations. The diurnal rotation of the sea breeze can be explained as an effect of the Coriolis force. The observations of the diurnal variations of the sea-breeze direction made at Boston agree reasonably well with the theory, especially insofar as the modifying effects of a superimposed general wind are concerned.

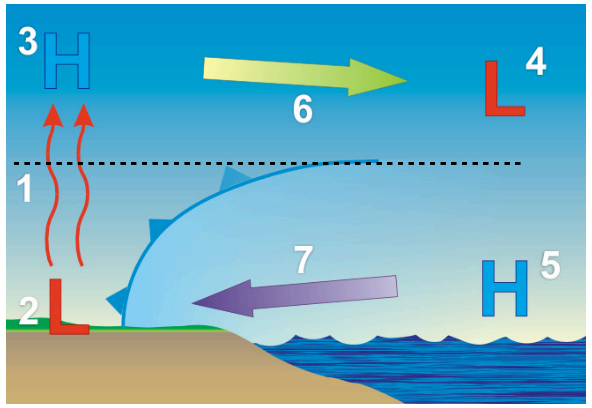
Mechanisms

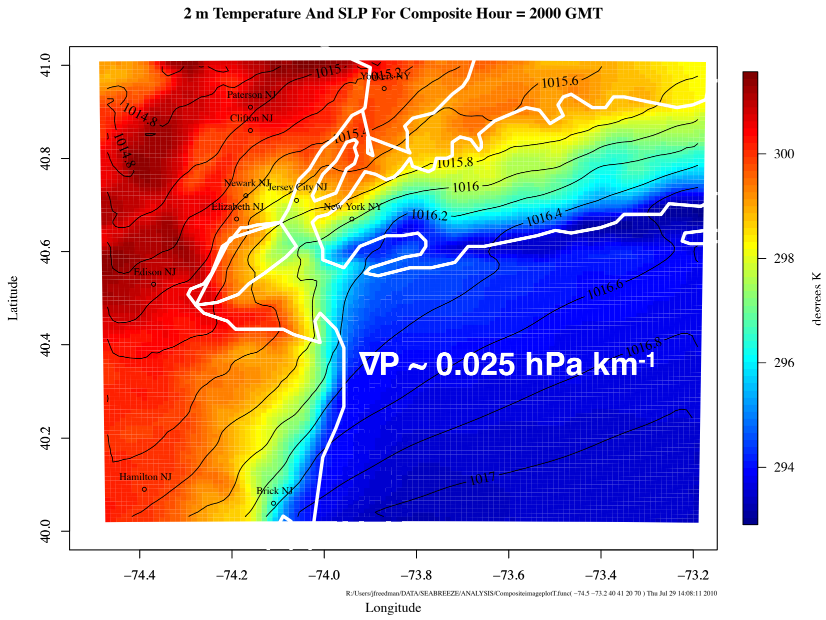
1. The sea breeze is caused by the temperature difference between the hot land and cool sea surface

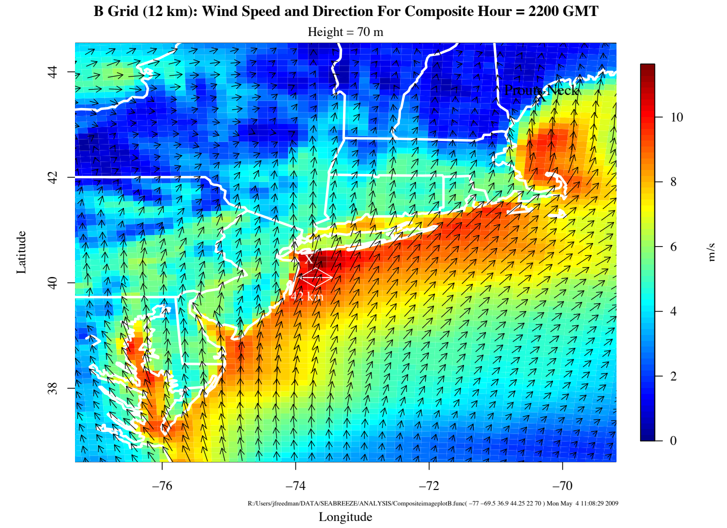
2. As the temperature difference increases (*ΔT*), a mesoscale pressure gradient develops

3. *Tijm and van Delden (1999)*: Hydrostatic adjustment—via sound waves generated over land when the air expands because of diabatic heating and then propagate at 300 ms^{-1} in all directions

4. Waves propagating horizontally induce pressure falls over land, and surface pressure increases over the sea. The resulting horizontal pressure gradient initiates the landward movement of the marine air mass







Mechanisms— Bjerknes Circulation Theorem

From Miller et al. (2003)

ing physical mechanisms. The Bjerknes circulation theorem is a relatively simple model that begins with the presence of a cross-shore mesoscale PGF and reproduces the SBC from an initially stationary atmosphere. Circulation is a scalar quantity that represents a macroscopic measure of rotation over a finite area of fluid in two dimensions [*Holton*, 1992]. Mathematically, circulation about a closed contour in a fluid is defined as the line integral about the contour of the component of the velocity vector that is locally tangent to the contour [*Holton*, 1992]. The Bjerknes circulation theorem is given by

$$\frac{D_a C_a}{Dt} = -\oint \frac{dP}{\rho}, \qquad (1)$$

where D_a/D_t indicates the material derivative in the fixed reference frame, C_a is circulation, P is pressure [Pa], and ρ is density [kg m^{-3}].

[18] The application of the circulation theorem to the SBC begins with equation (1) and substitutes $\rho = P/RT$ (from the ideal gas law), where T is temperature [K] and R is the gas constant for dry air (287 J kg^{-1} K^{-1}). By integrating around the closed path beginning on the land surface (Figure 2, lower left) and using the fact that the line integral about a closed loop of a perfect differential is zero, one obtains

$$\frac{DC_a}{Dt} = R\ln\left(\frac{p_0}{p_1}\right)(\overline{T}2 - \overline{T}1), \qquad (2)$$

where p_0 represents atmospheric pressure near Earth's surface [Pa], p_1 represents atmospheric pressure near the top of the circulation cell [Pa], and $\overline{T}$ indicates the average temperature through the vertical column [*Holton*, 1992].

[19] To extract the mean wind speed ($\overline{U}$) associated with the SBS, one uses

$$\overline{U} = \frac{C_a}{2(H+L)}, \qquad (3)$$

where H is the height of the circulation and L is its cross-shore length (Figure 2). Combining equations (2) and (3) yields

$$\frac{D\overline{U}}{Dt} = \frac{R\ln\left(\frac{p_0}{p_1}\right)(\overline{T}2 - \overline{T}1)}{2(H+L)}, \qquad (4)$$

which is an expression for the mean acceleration of the wind over time, as a result of the SBC. Realistic values for the right-hand side of equation (4) are p_0 = 1000 hPa, p_1 = 900 hPa, $(\overline{T}2 - \overline{T}1)$ = 10 K, L = 20 km, and H = 1 km, which yields an acceleration of 7.2 $\times 10^{-3}$ m s^{-2}. Beginning at rest, after 1 hour the mean wind speed around the perimeter is 25.9 m s^{-1} or ~50 knots [*Holton*, 1992].

[20] Wind speeds actually produced by the SBS are generally much lower than those suggested by the circulation theorem. *Simpson* [1994] suggested that surface wind speeds of 6 or 7 m s^{-1} can reasonably be expected. Other authors [e.g., *Masselink and Pattiaratchi*, 1998] have suggested that speeds as high as 10 m s^{-1} are common. The main reason for this overestimate is that in the initial formulation the Bjerknes circulation theorem assumes friction (in its various forms) is too small to be of importance. Another weakness of this application, perhaps just as important, is that it ignores the alongshore dimension.

But see later on!

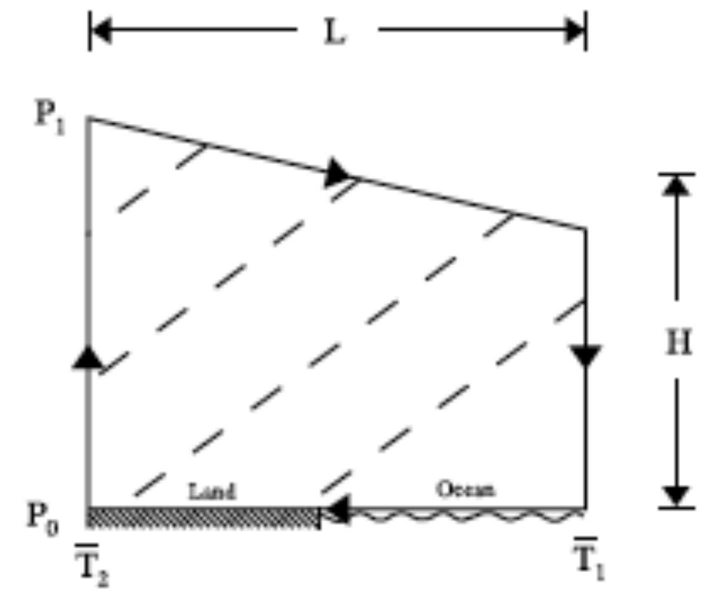


Figure 2. Sea breeze and the Bjerknes circulation theorem. Land is on the left, ocean is on the right. The integration path for equation (1) is indicated by arrows along the perimeter. $\overline{T}$ indicates the average temperature through the vertical columns over the land or ocean surfaces. Dashed diagonal lines are isopycnals, with denser air at lower right. P_0 and P_1 are the pressure on the surface and at the top of the circulation cell, respectively. Redrawn from *Holton* [1992]. Reprinted with permission from Elsevier Science.

Sea or lake breeze circulation: Daytime

http://www.srh.noaa.gov/srh/jetstream/ocean/sb_circ.htm

From Miller et al. 2003

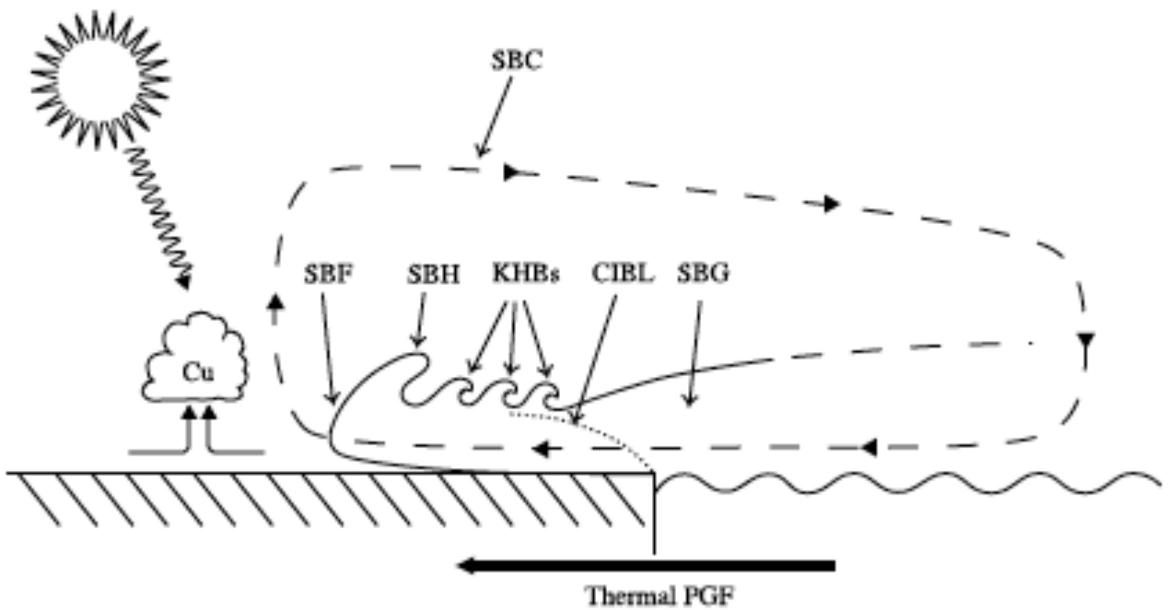


Figure 1. Sea breeze system (SBS). Details are discussed in the text.

1. **Sea breeze circulation** (SBC) is a vertically rotating mesoscale cell, with shoreward flow near Earth s surface, rising air currents inland, diffuse sinking currents several kilometers out to sea, and (usually) seaward return flow near 900 hPa .

2. **Sea breeze gravity current** (SBG) is the landward flow of cool, moist marine air in the lower horizontal arm of the SBC.

3. **Sea breeze front** (SBF) is the landward edge of the SBG and the SBC, often associated with sharp changes in temperature, moisture, and wind. Its approach may be marked by the development of fair-weather cumulus clouds (Cu) and convergence (friction or opposing synoptic scale winds) can produce thunderstorms.

4. **Sea breeze head** (SBH) is the raised head above and immediately behind the SBF, created by updrafts within both the continental and marine air masses. It is about twice as high as the following “feeder” flow behind the SBF.

5. **Kelvin-Helmholtz billows** (KHBs) are waves that develop along the upper boundary of the SBG during periods of low static stability (midday).

6. **Convective internal boundary layer** (CIBL) is an unstable region within the marine air mass, appearing at the coast and growing in depth with distance inland, in which low-level pollutants may become trapped and concentrated.

Or if you prefer Stull.....

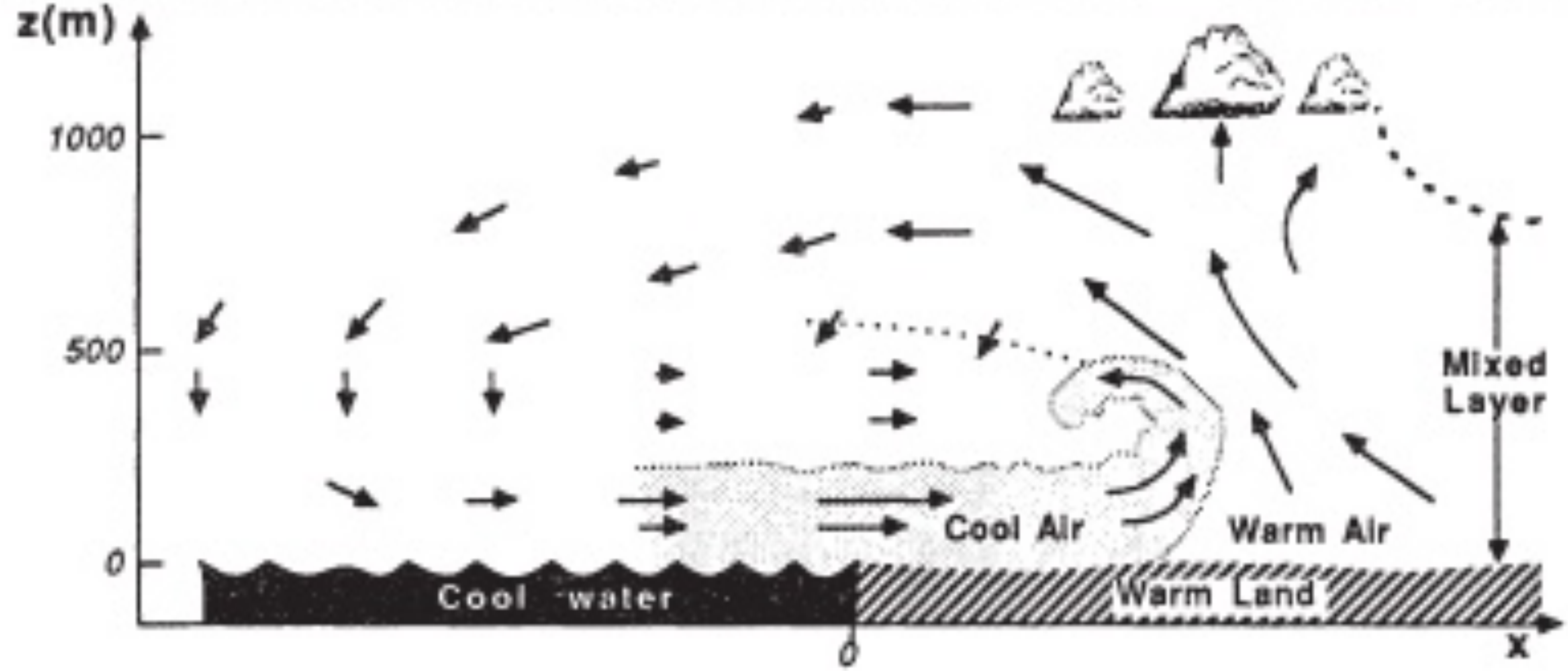


Fig. 14.7 Idealized sea or lake-breeze circulation. (After Lyons (1975) and Ogawa, et al., 1986).

Other Factors

- Complex terrain—inland topography—California marine layer

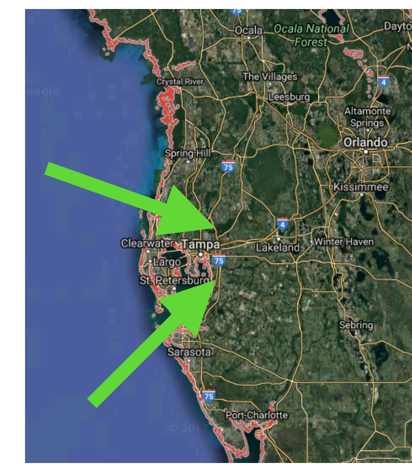
- Coastal morphology—shape of coastline (concave, convex, orientation—see below), bays, inlets, convergence can lead to favored thunderstorm development (e.g. Tampa Bay)

- Marine characteristics—SST, currents, depth—determine intensity and persistence of SBC

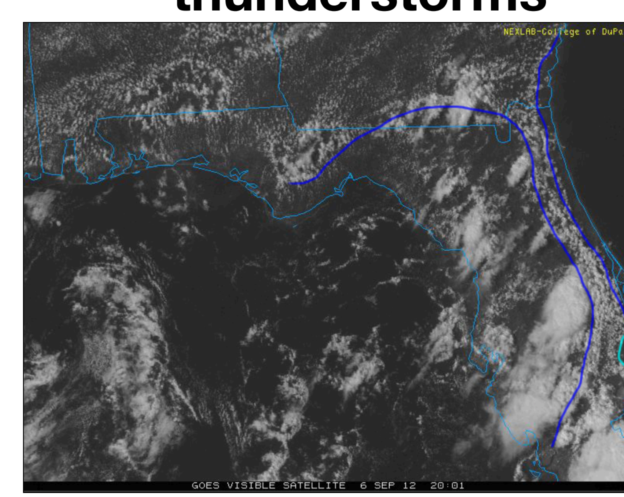
- Overlying synoptic flow regime—development potential, intensity and persistence of SBC

- Simultaneous development of low-level jet—coastal topology, orientation (more to come on this).

Columbia Gorge



Florida sea breeze convergence—thunderstorms



Focus—Northeast—NY Bight Region And some Offshore Wind Applications

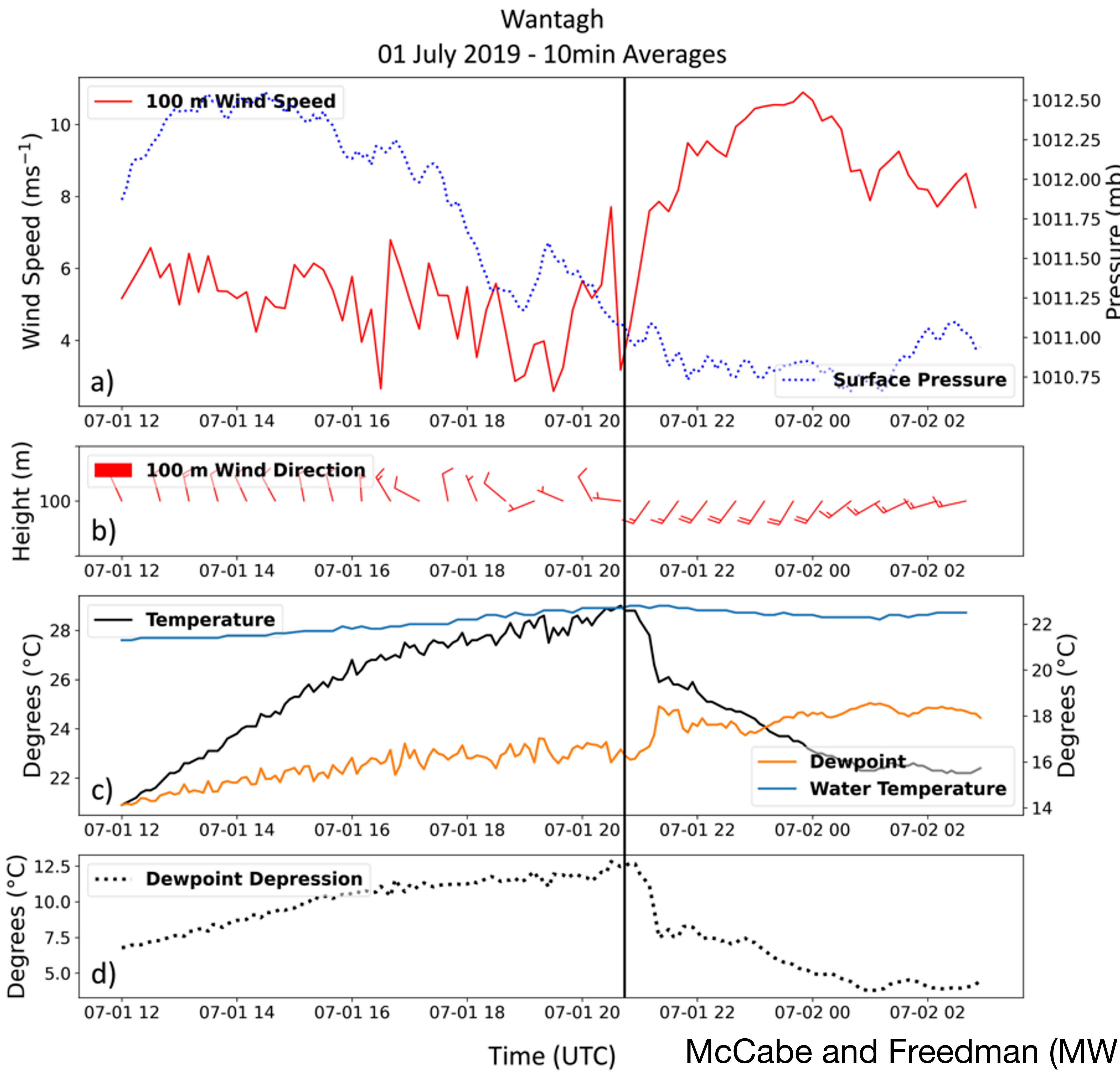
Mid-Atlantic, northeast coastal waters--areas that will see rapid development of offshore wind farms in the next few years (e.g. Cape Wind)

Data and modeling studies from offshore research project focused on the wind energy environment

Phenomena: enhanced sea breeze, low level jet (LLJ) - more like a sheet

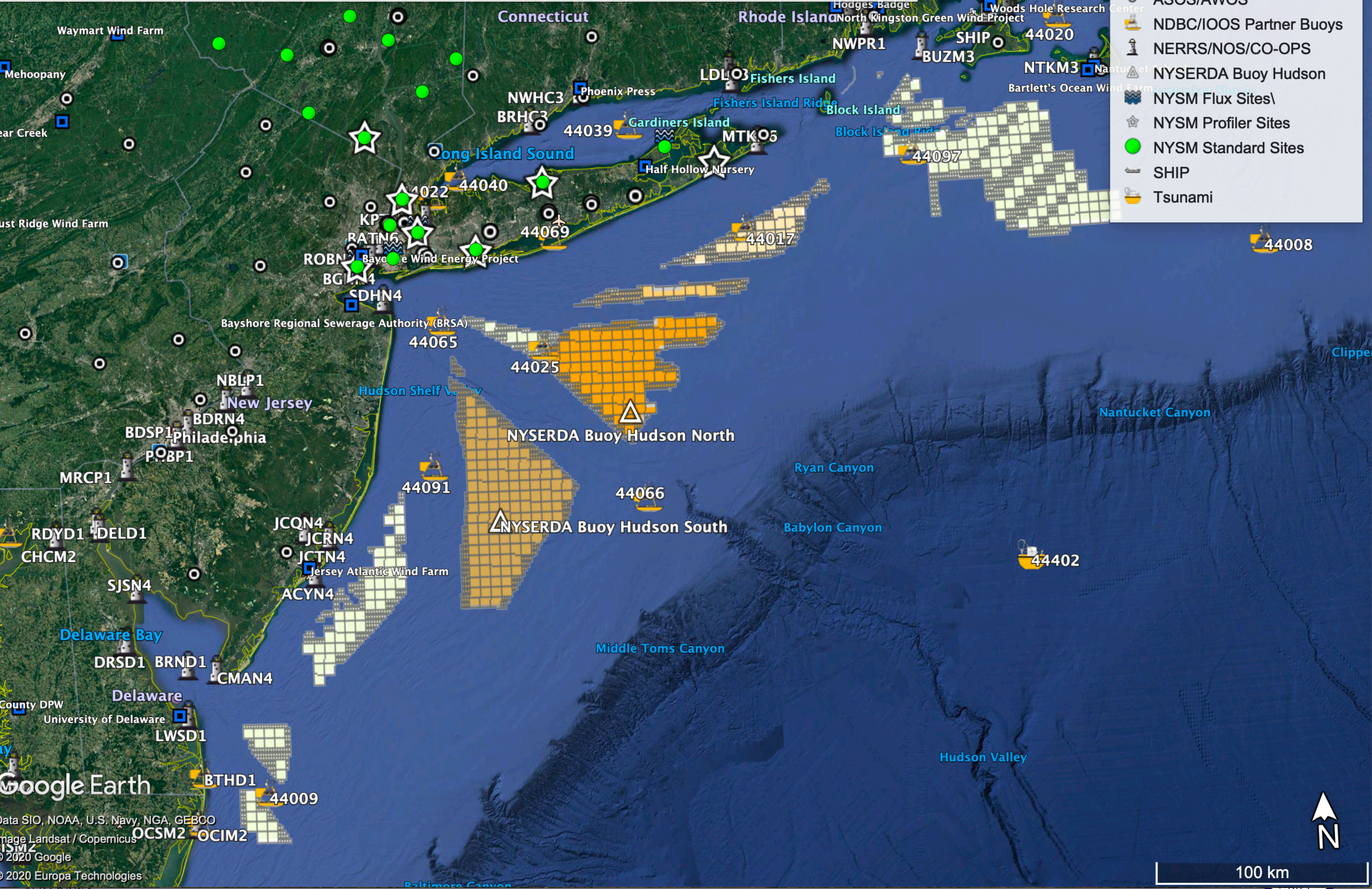
Horizontal, vertical structure

Some cool season thoughts

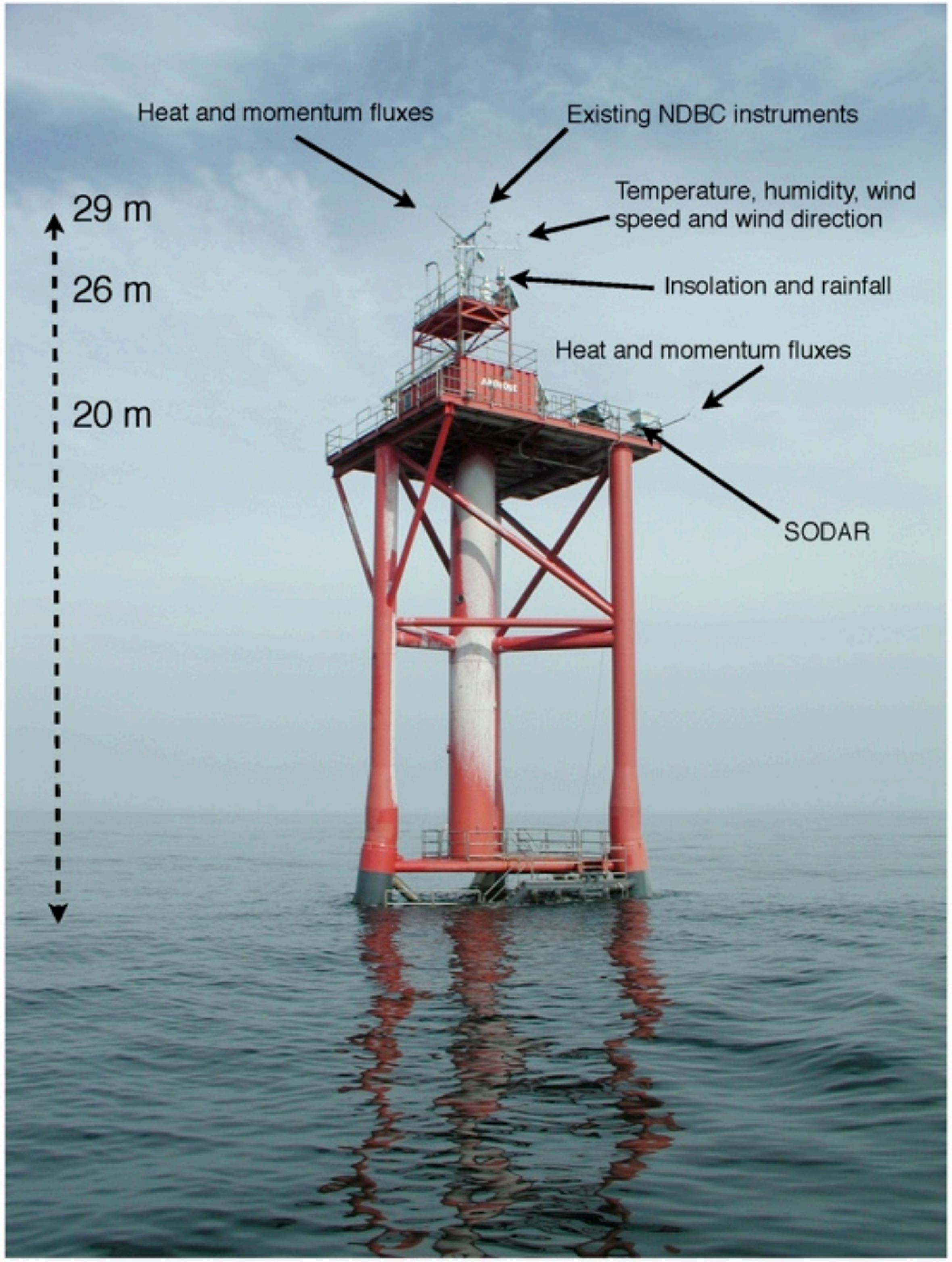


McCabe and Freedman (MWR 2023)

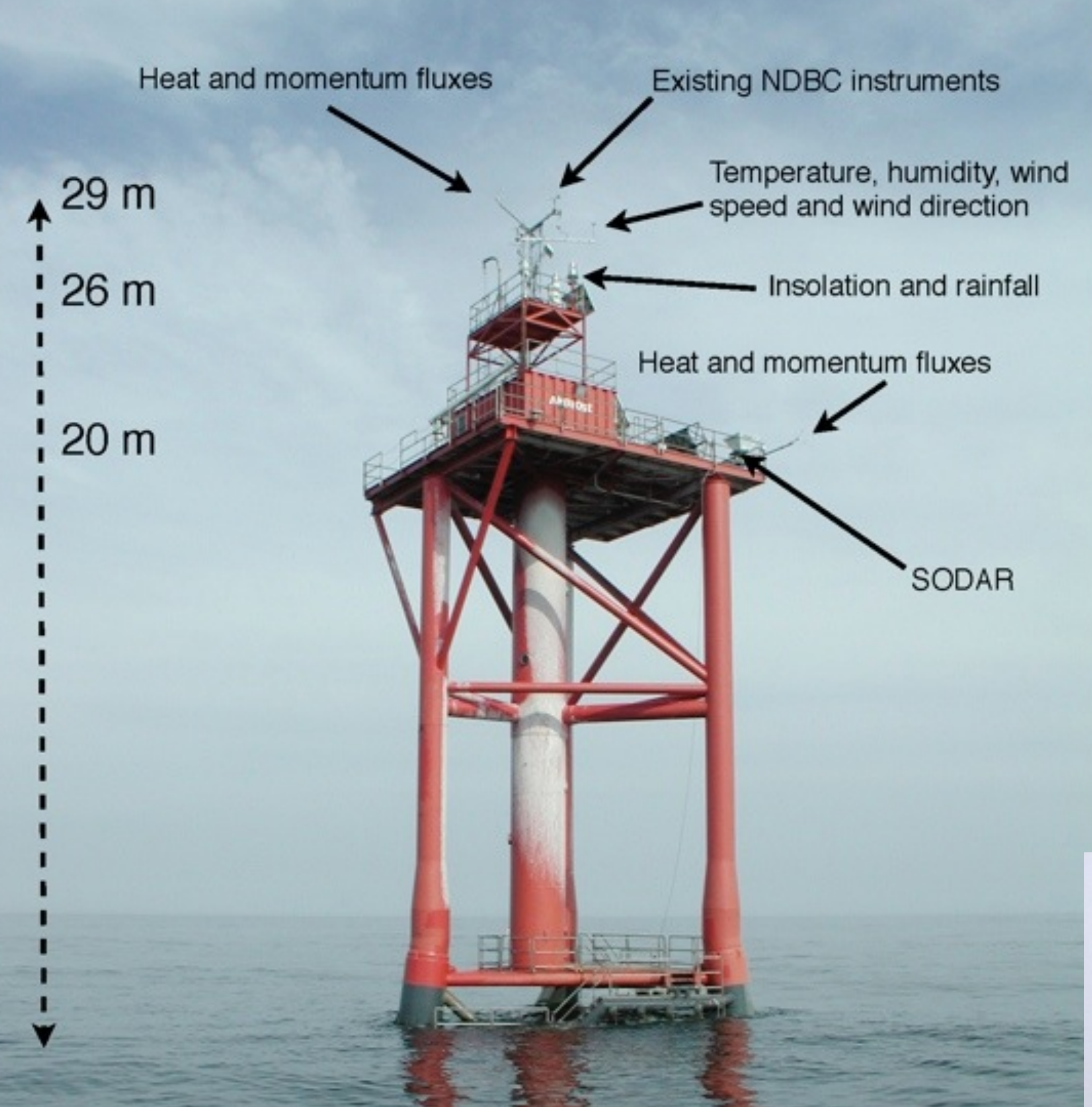
Coastal and Offshore Networks and BOEM Offshore Wind Lease/Planning Areas



State University of New York

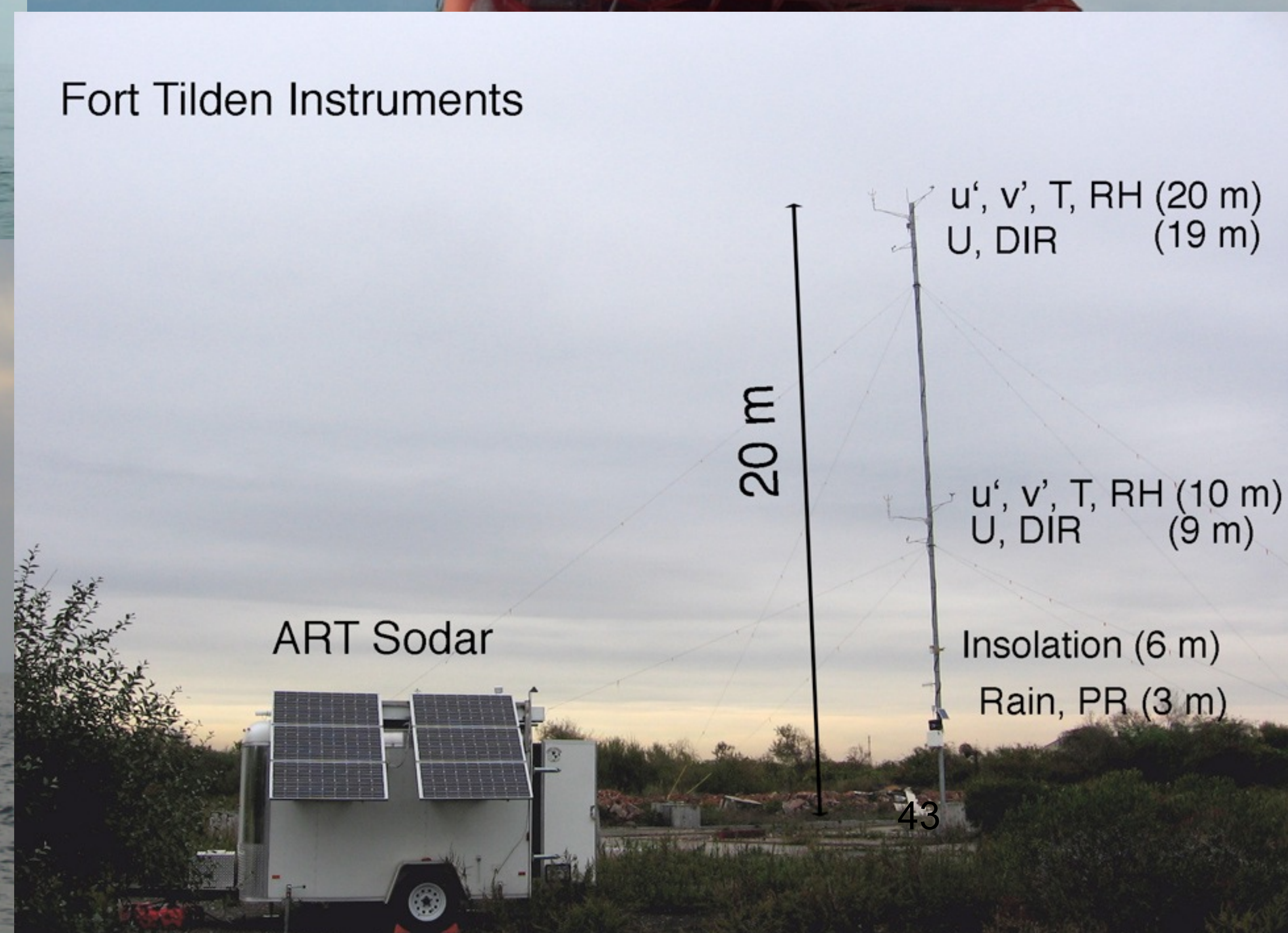


DOE NREL Project (2005 - 2006; Freedman and Bailey): Developing Techniques to Evaluate the Designs and Operating Environments of Offshore Wind Turbines in the Mid Atlantic and Lower Great Lakes Regions. (Other sponsors: LIPA, NYSERDA)


Heat and momentum fluxes
Existing NDBC instruments
Temperature, humidity, wind speed and wind direction
Insolation and rainfall
Heat and momentum fluxes
SODAR
29 m
26 m
20 m


Alas, poor Ambrose….
"Allision" of Bahamas-Registered Tankship
M/T Axel Spirit with Ambrose Light
November 3, 2007


OSI Buoy…
disappeared after 2 months


Fort Tilden Instruments
u', v', T, RH (20 m)
U, DIR (19 m)
20 m
u', v', T, RH (10 m)
U, DIR (9 m)
ART Sodar
Insolation (6 m)
Rain, PR (3 m)

Birds!

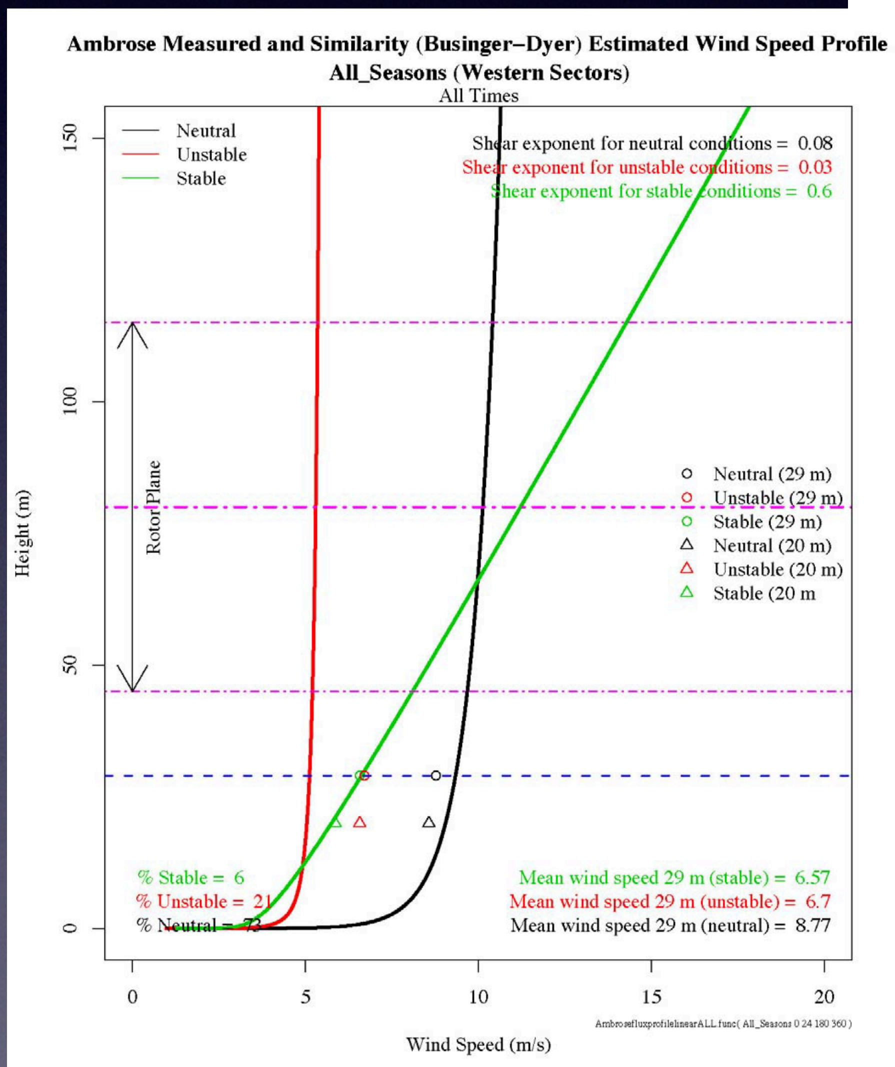
Perils of offshore measurements

plus sodar on an isolated tower in the middle of the ocean....

Did get some good measurements and insights

DOE Report: Freedman et al. (2007)

Historical Data Analysis and Field Measurement Assimilation: July 2005 – June 2006 Results



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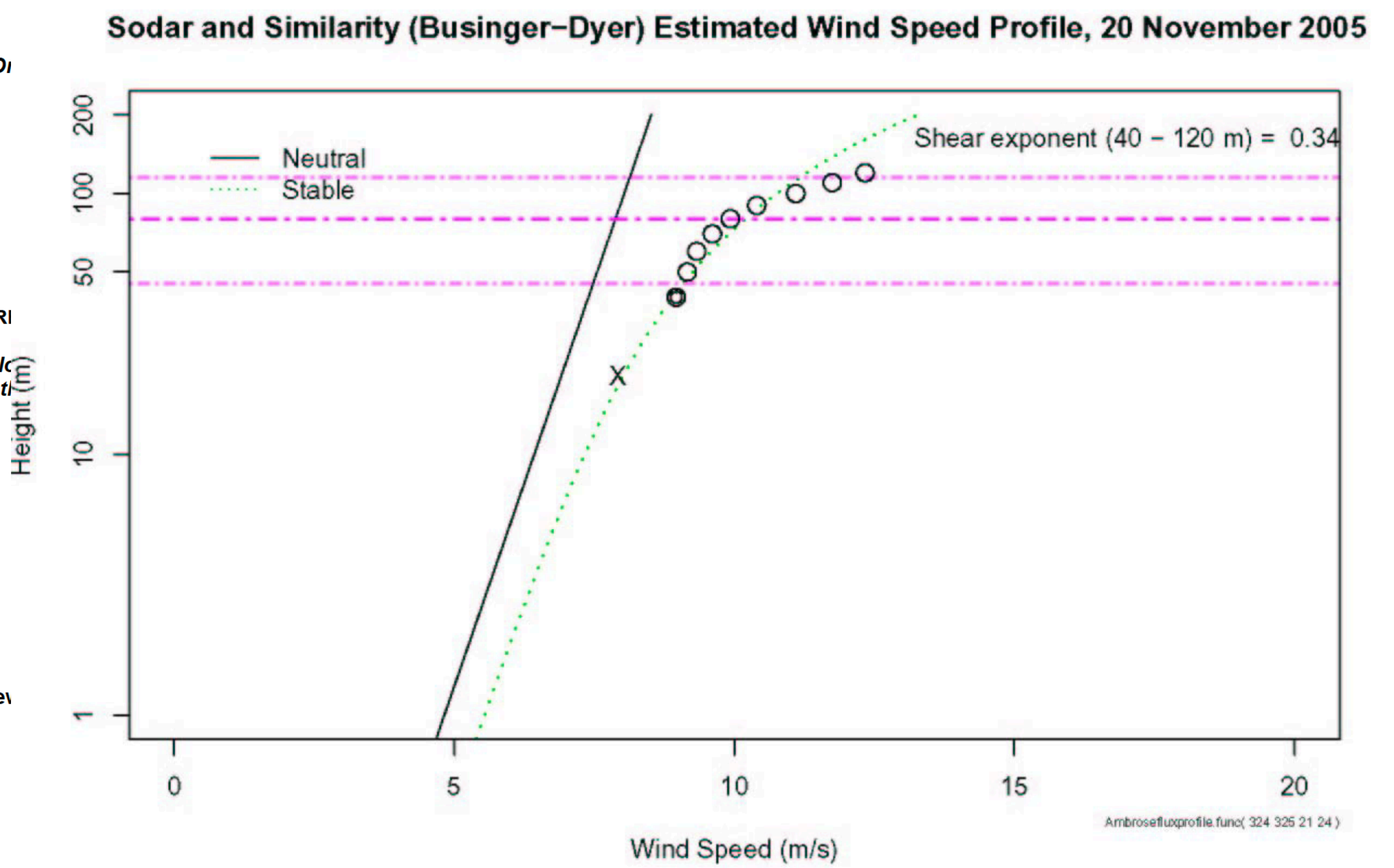
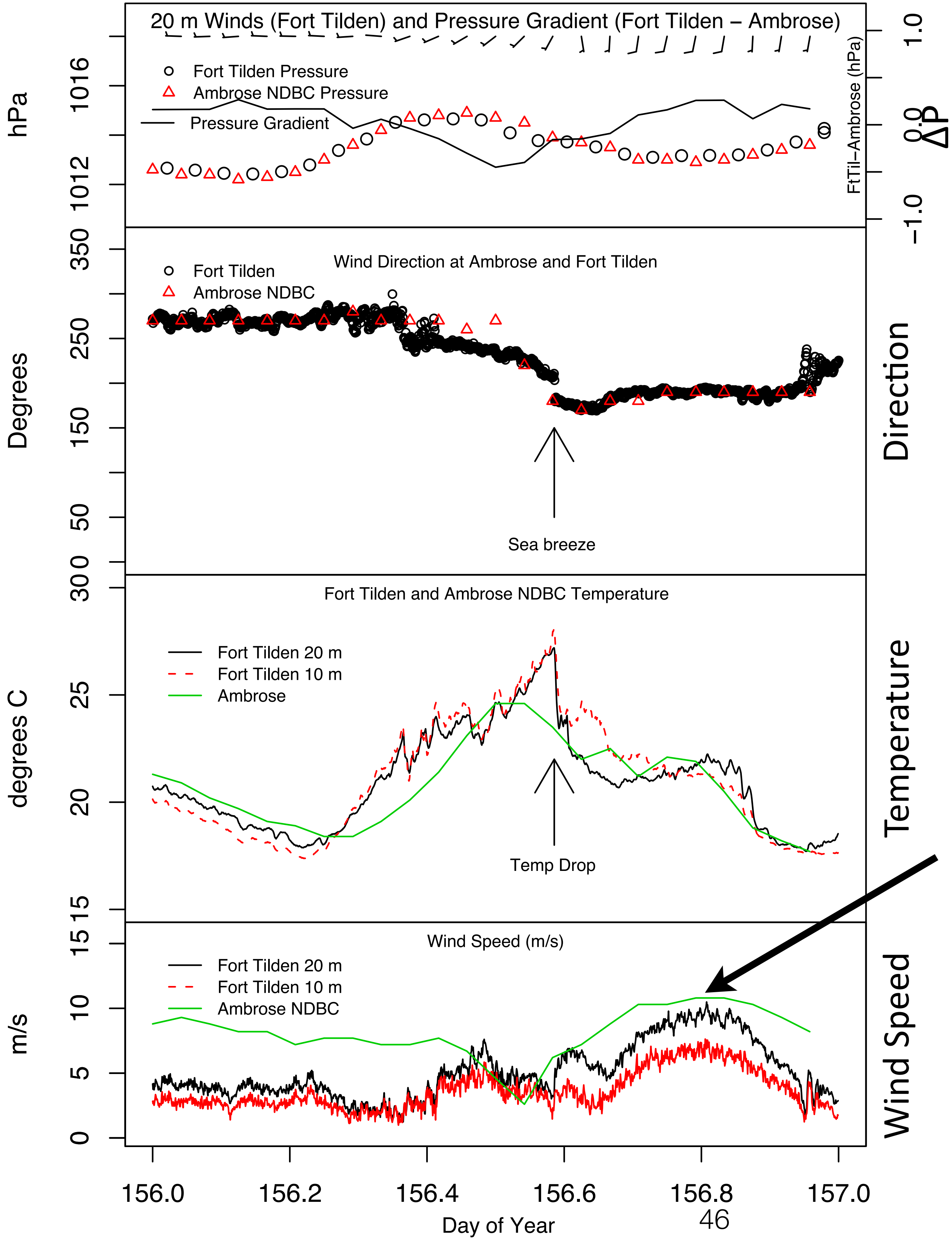


Figure 12. Comparison of observed sodar speed profile with profile predicted by Monin-Obukhov similarity theory for a stable stability case

Fort Tilden Tower and Ambrose Light, Days 156 – 157 (Local Time)

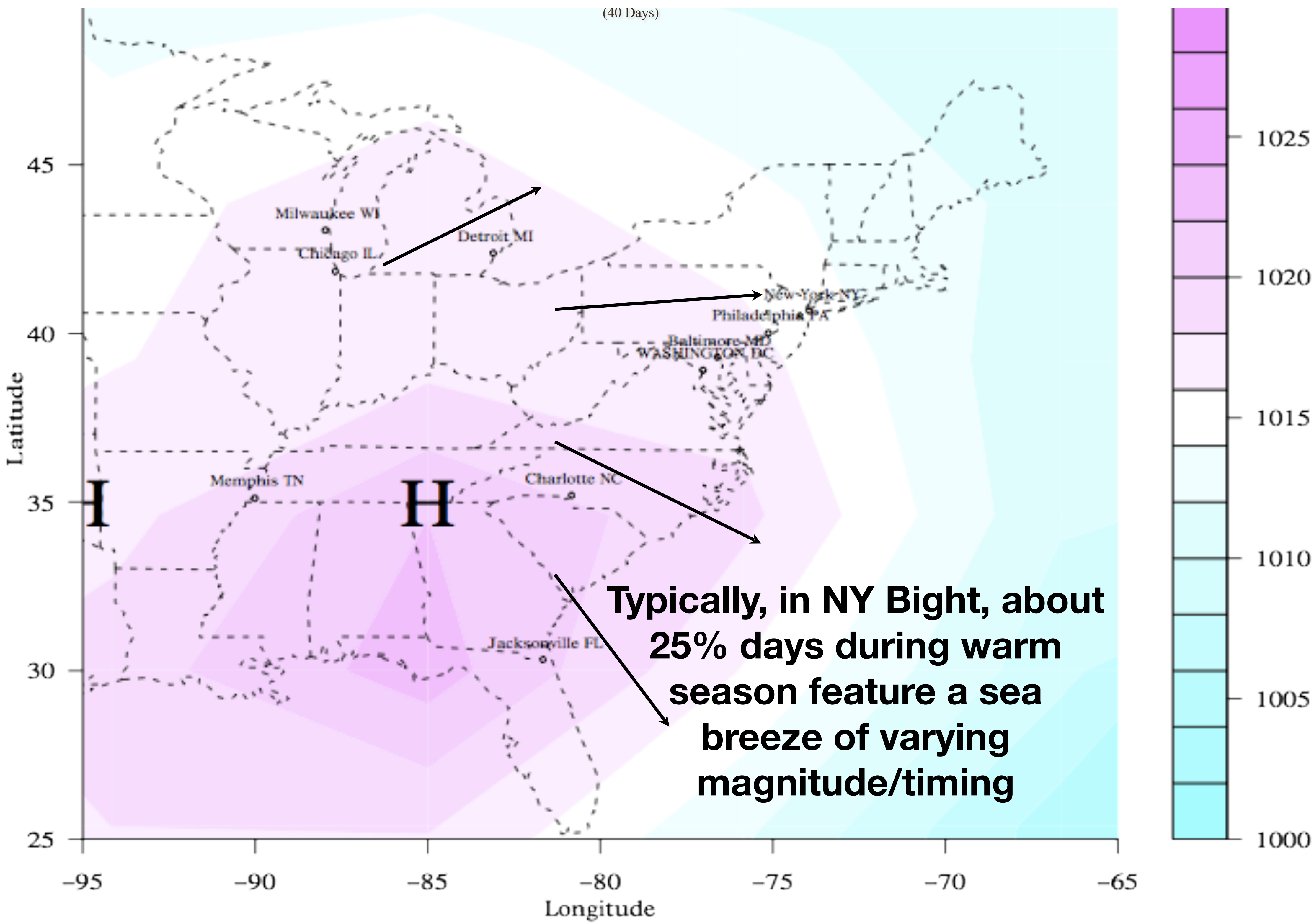
2005



Typical sea breeze day along coastal NYC (5 June 2005)

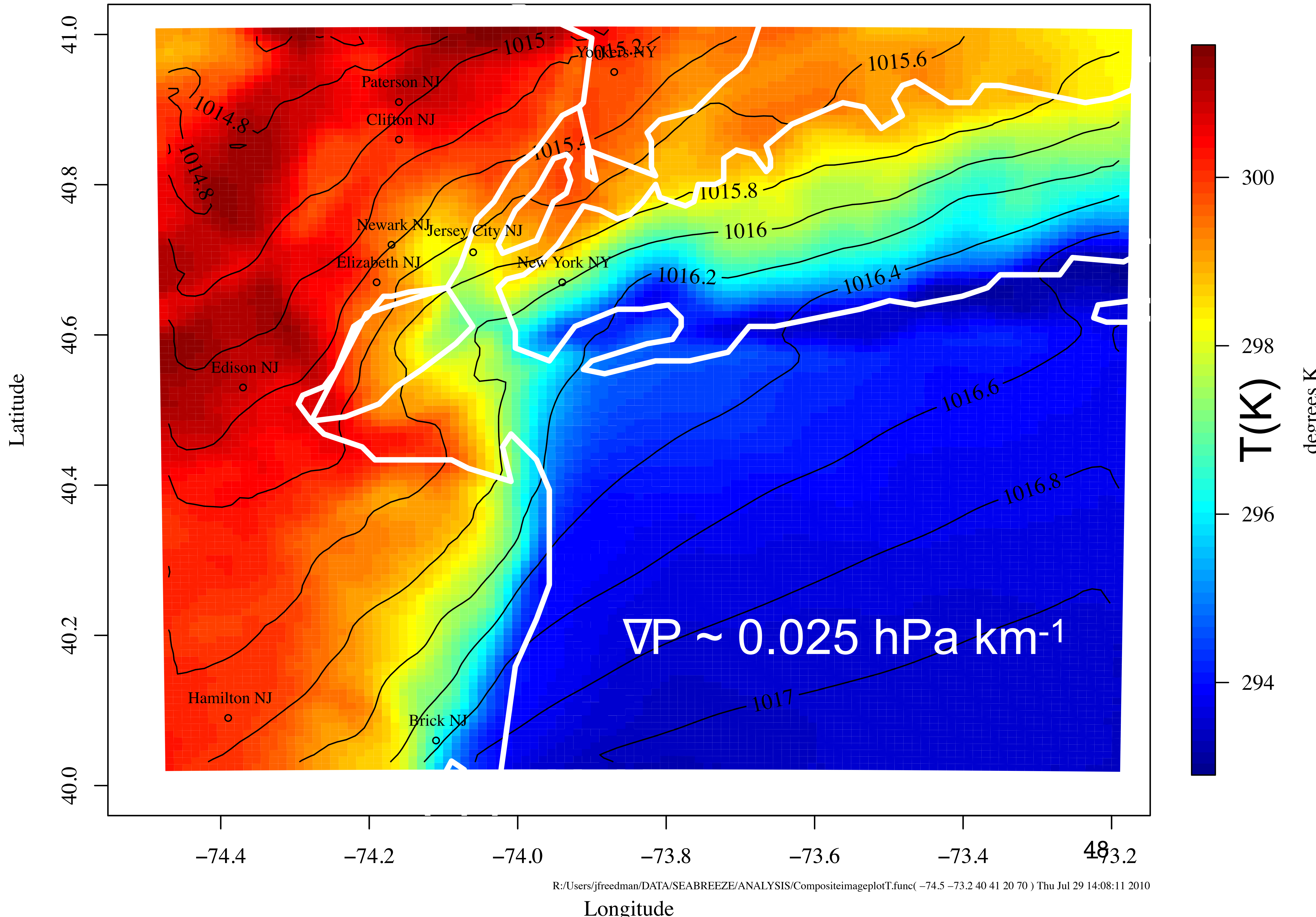
<u>New York Bight (Ambrose) "jet"</u> -- noted by Colle and Novak (MWR June 2010)

Composite Surface Map (40 Sea Breeze Cases)



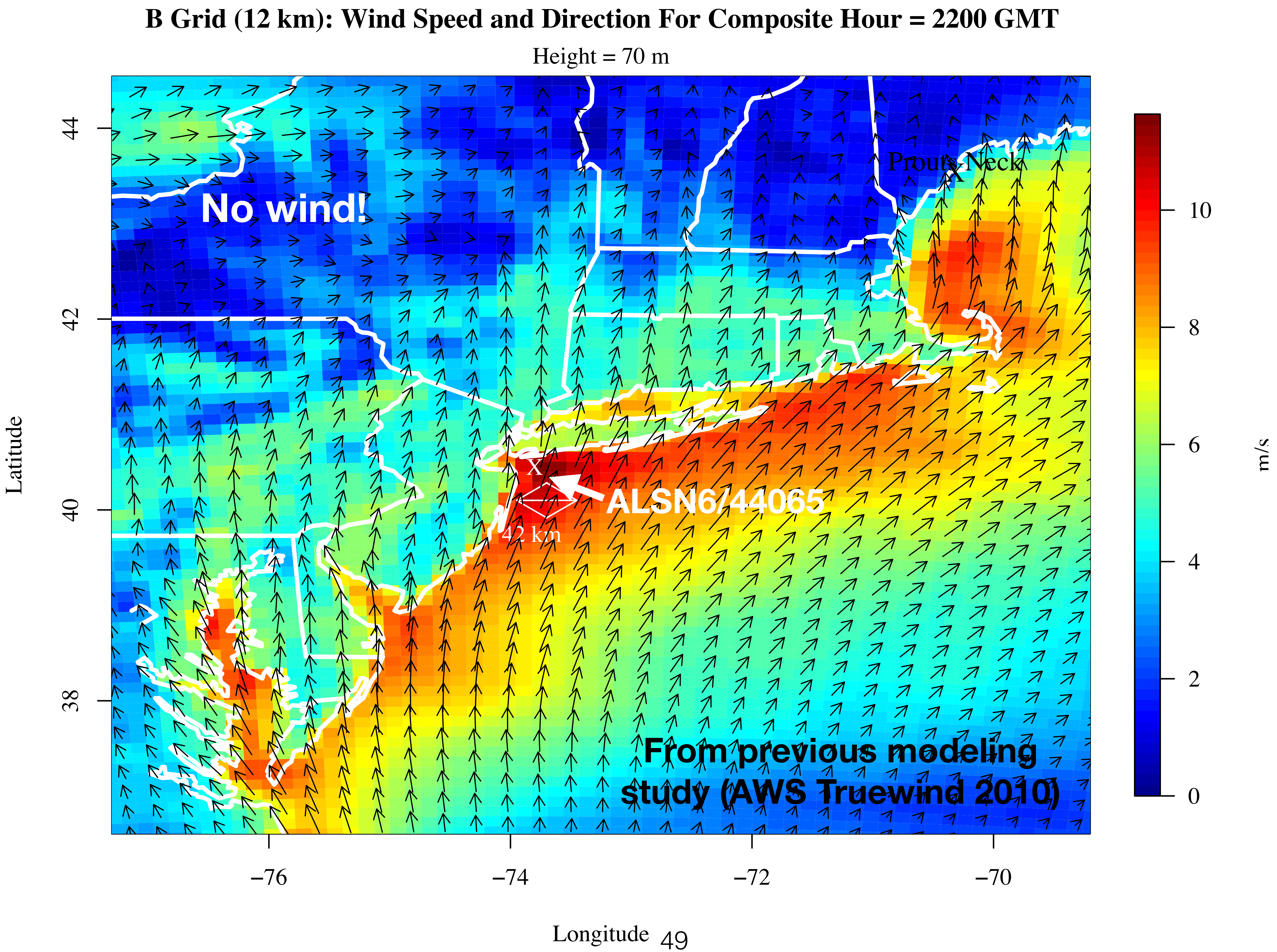
Typically, in NY Bight, about 25% days during warm season feature a sea breeze of varying magnitude/timing

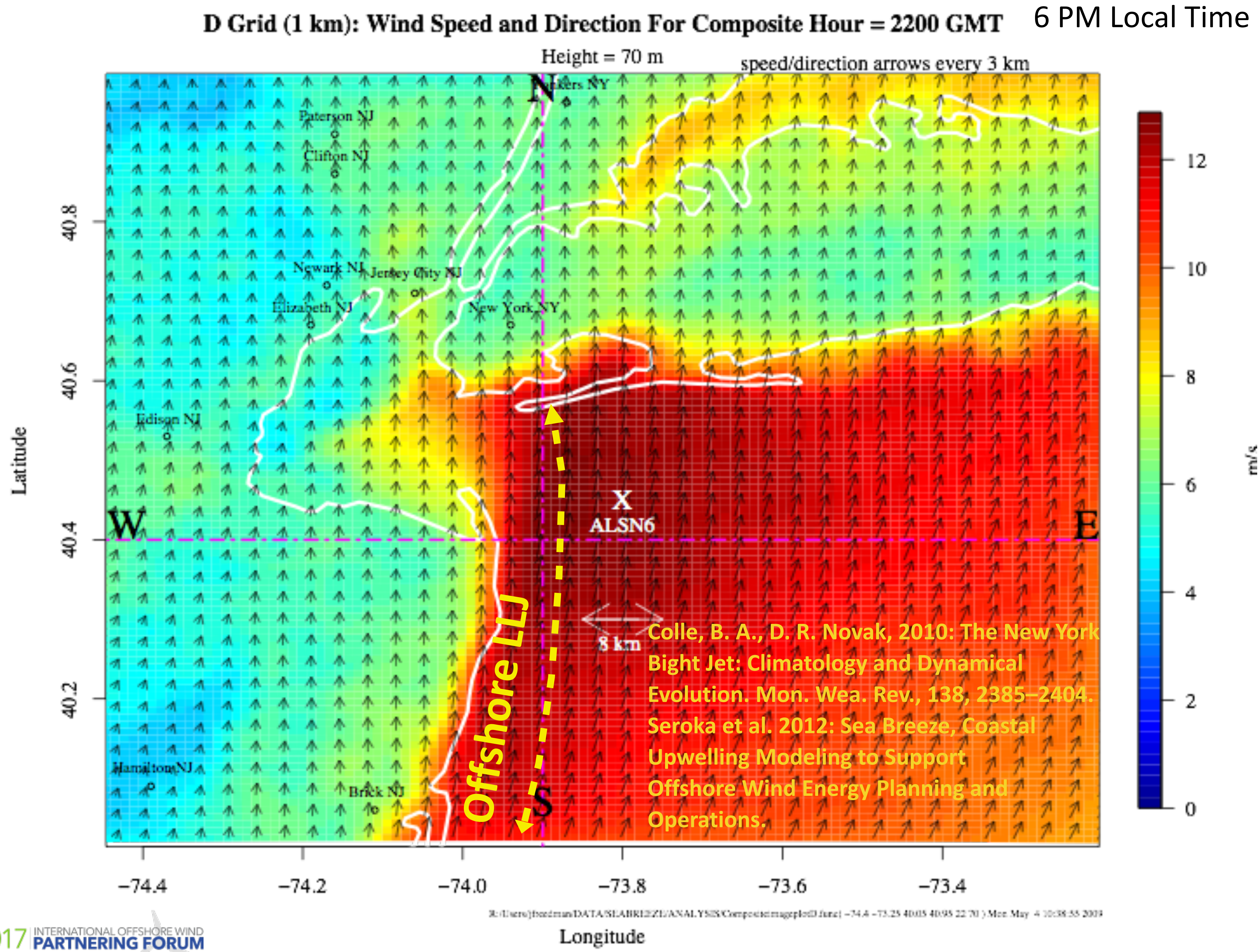
2 m Temperature And SLP For Composite Hour = 2000 GMT



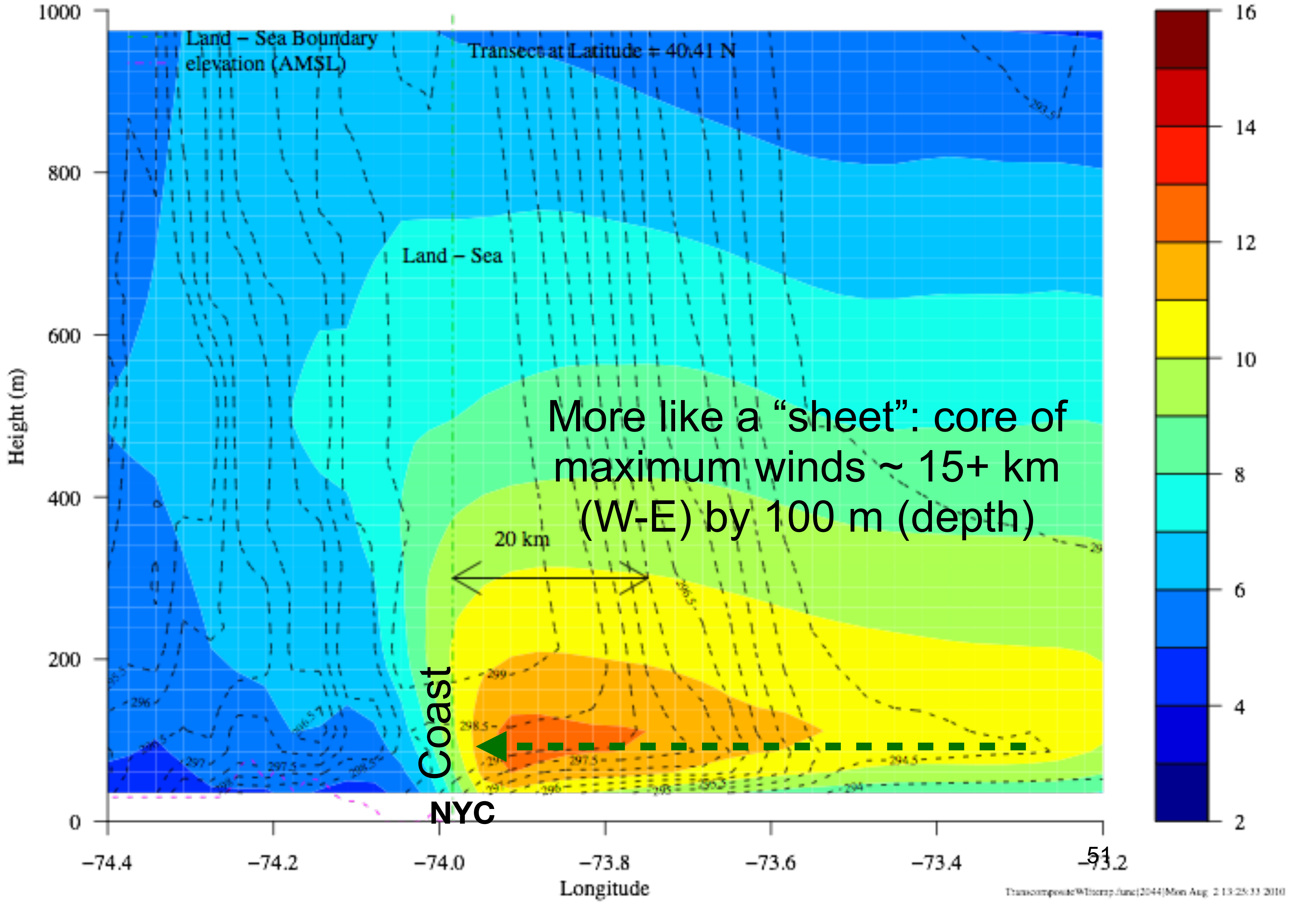
Enhanced Thermal Circulation….

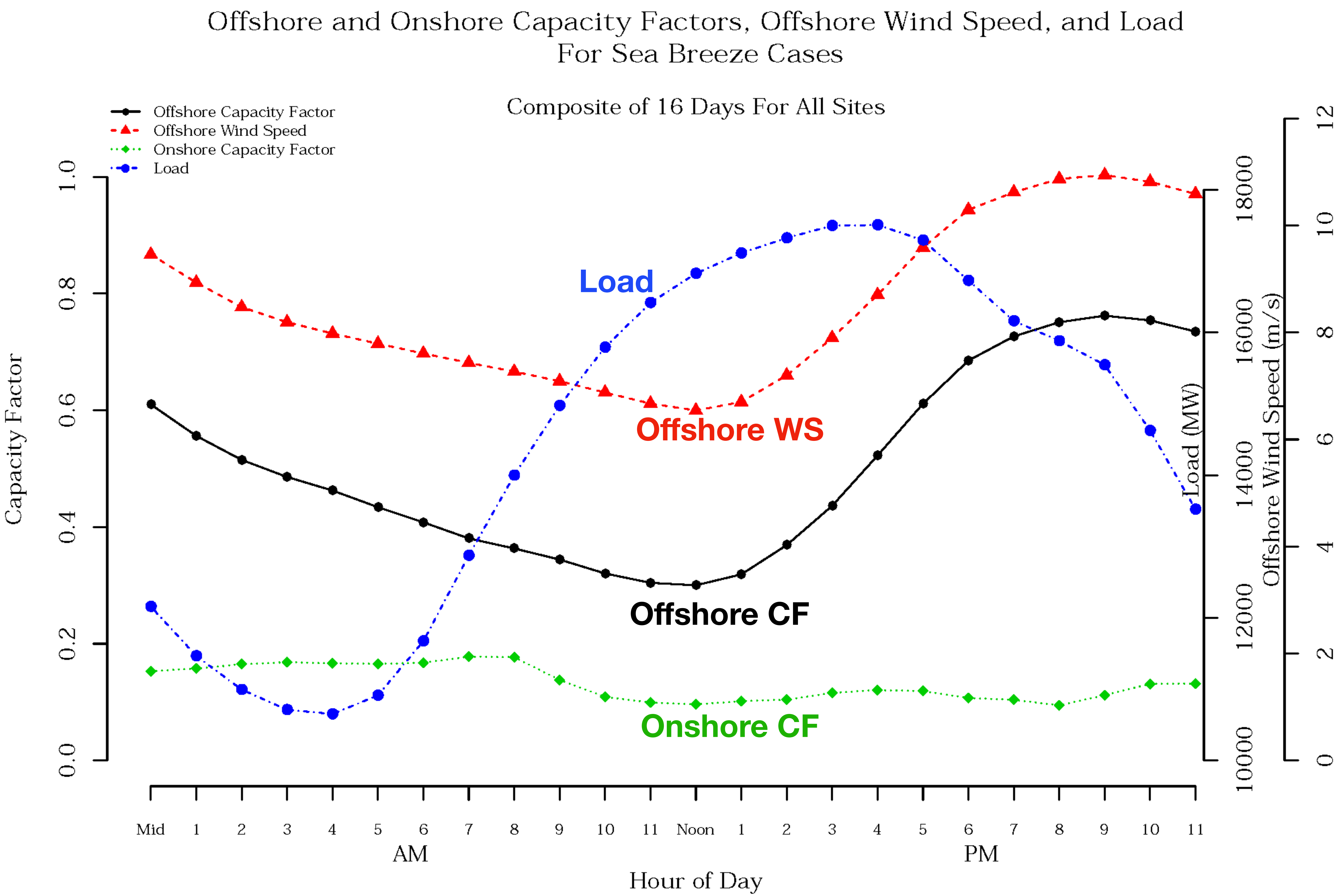
Composite of 16 sea breeze days

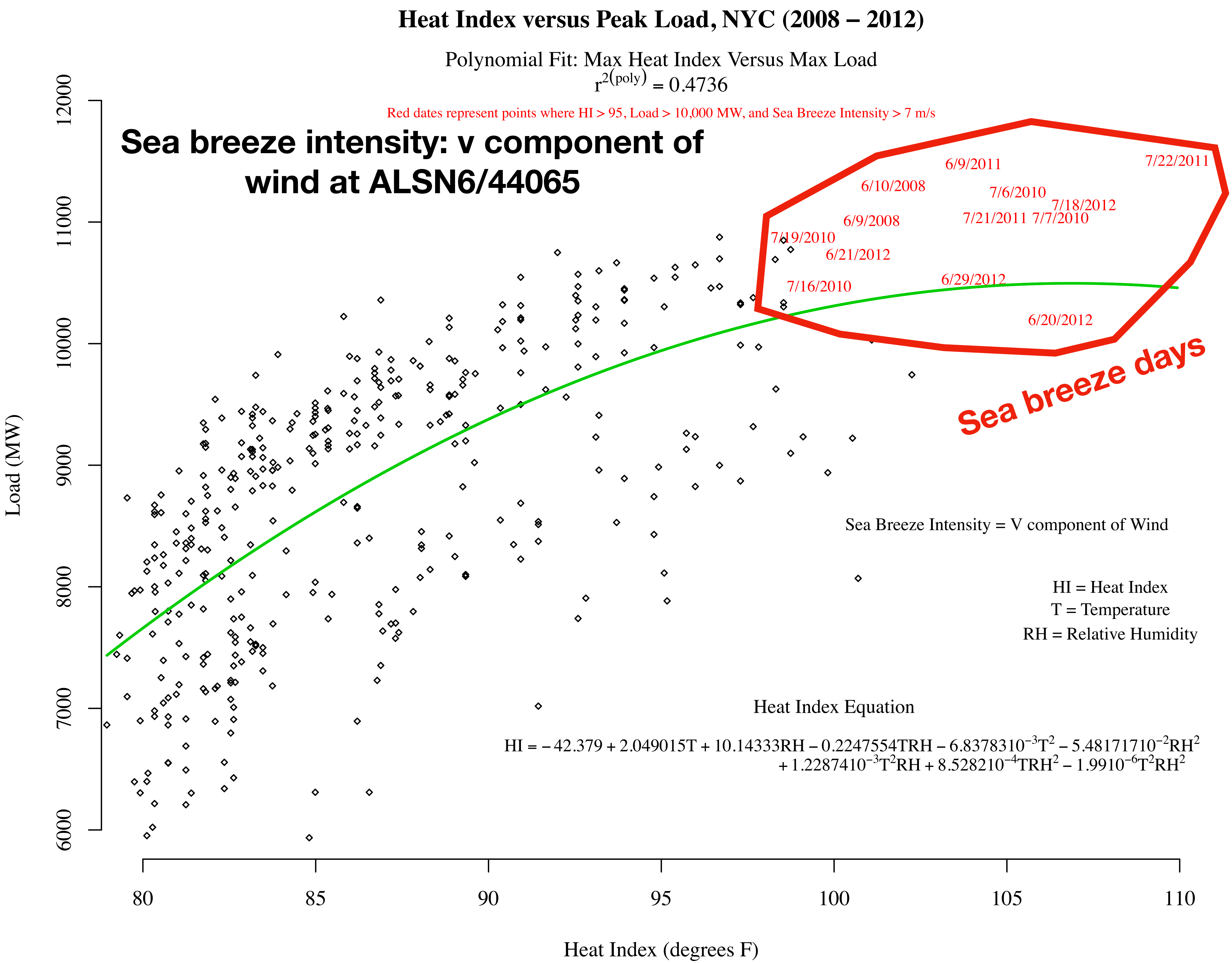



D Grid (1 km): Wind Speed and Direction For Composite Hour = 2200 GMT
6 PM Local Time
Height = 70 m
speed/direction arrows every 3 km
Paterson NJ
Clifton NJ
Newark NJ
Jersey City NJ
Elizabeth NJ
New York NY
Edison NJ
Hamilton NJ
Brick NJ
N
S
W
E
X
ALSN6
8 km
Offshore LLJ
Colle, B. A., D. R. Novak, 2010: The New York Bight Jet: Climatology and Dynamical Evolution. Mon. Wea. Rev., 138, 2385–2404.
Seroka et al. 2012: Sea Breeze, Coastal Upwelling Modeling to Support Offshore Wind Energy Planning and Operations.
Latitude
Longitude
40.2
40.4
40.6
40.8
−74.4
−74.2
−74.0
−73.8
−73.6
−73.4
m/s
0
2
4
6
8
10
12

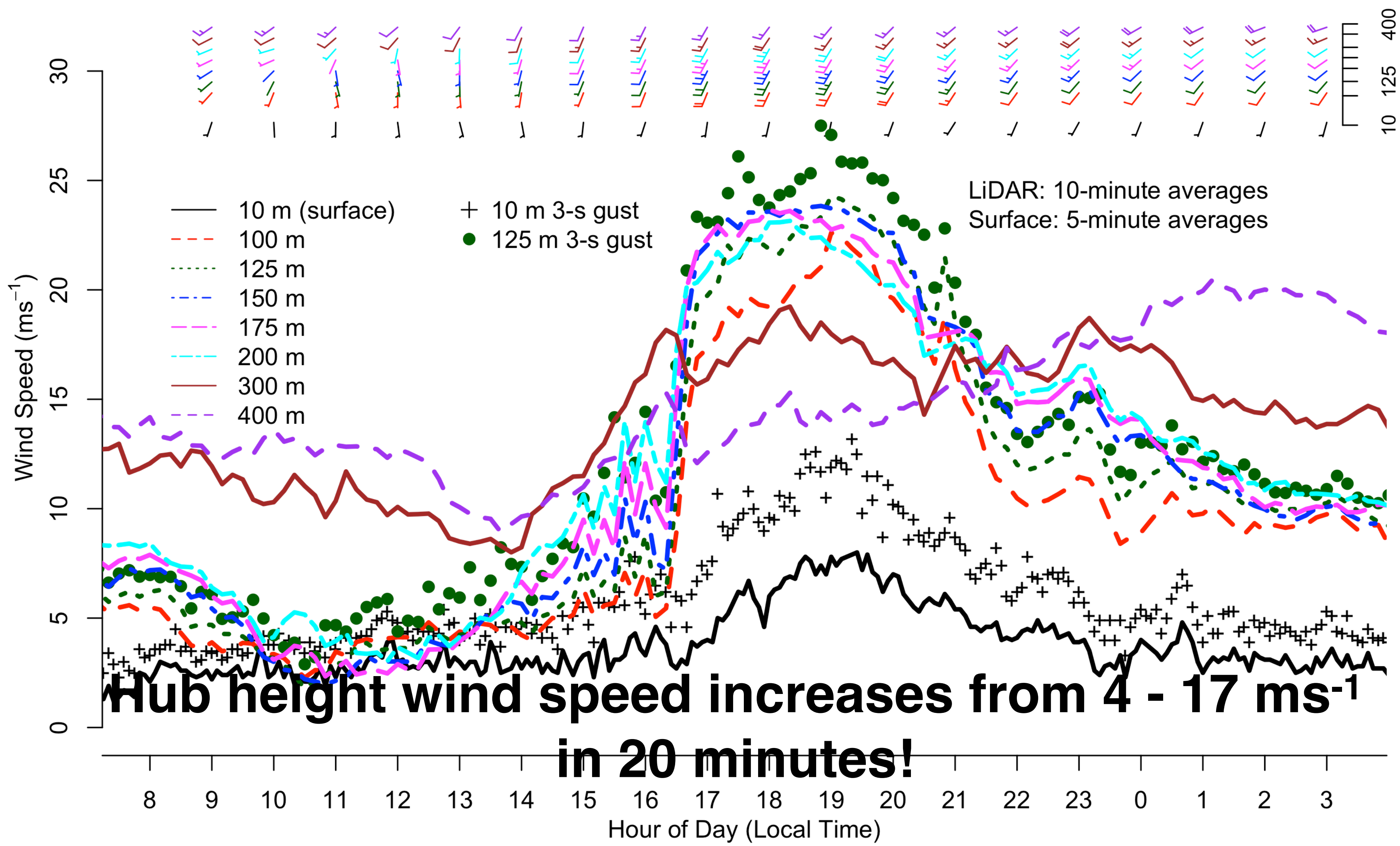
Composite Cross–section of Wind Speed/Theta versus Height For W–E Transect At 20 GMT




Offshore and Onshore Capacity Factors, Offshore Wind Speed, and Load
For Sea Breeze Cases
Composite of 16 Days For All Sites
Offshore Capacity Factor
Offshore Wind Speed
Onshore Capacity Factor
Load
Capacity Factor
Load (MW)
Offshore Wind Speed (m/s)
Load
Offshore WS
Offshore CF
Onshore CF
Mid
Noon
AM
PM
Hour of Day


Heat Index versus Peak Load, NYC (2008 – 2012)
Polynomial Fit: Max Heat Index Versus Max Load
r2(poly) = 0.4736
Red dates represent points where HI > 95, Load > 10,000 MW, and Sea Breeze Intensity > 7 m/s
Sea breeze intensity: v component of wind at ALSN6/44065
6/9/2011
7/22/2011
6/10/2008
7/6/2010
7/18/2012
6/9/2008
7/21/2011 7/7/2010
7/19/2010
6/21/2012
7/16/2010
6/29/2012
6/20/2012
Sea breeze days
Sea Breeze Intensity = V component of Wind
HI = Heat Index
T = Temperature
RH = Relative Humidity
Heat Index Equation
HI = −42.379 + 2.049015T + 10.14333RH − 0.2247554TRH − 6.8378310−3T2 − 5.48171710−2RH2
+ 1.2287410−3T2RH + 8.528210−4TRH2 − 1.9910−6T2RH2
Load (MW)
12000
11000
10000
9000
8000
7000
6000
80
85
90
95
100
105
110
Heat Index (degrees F)

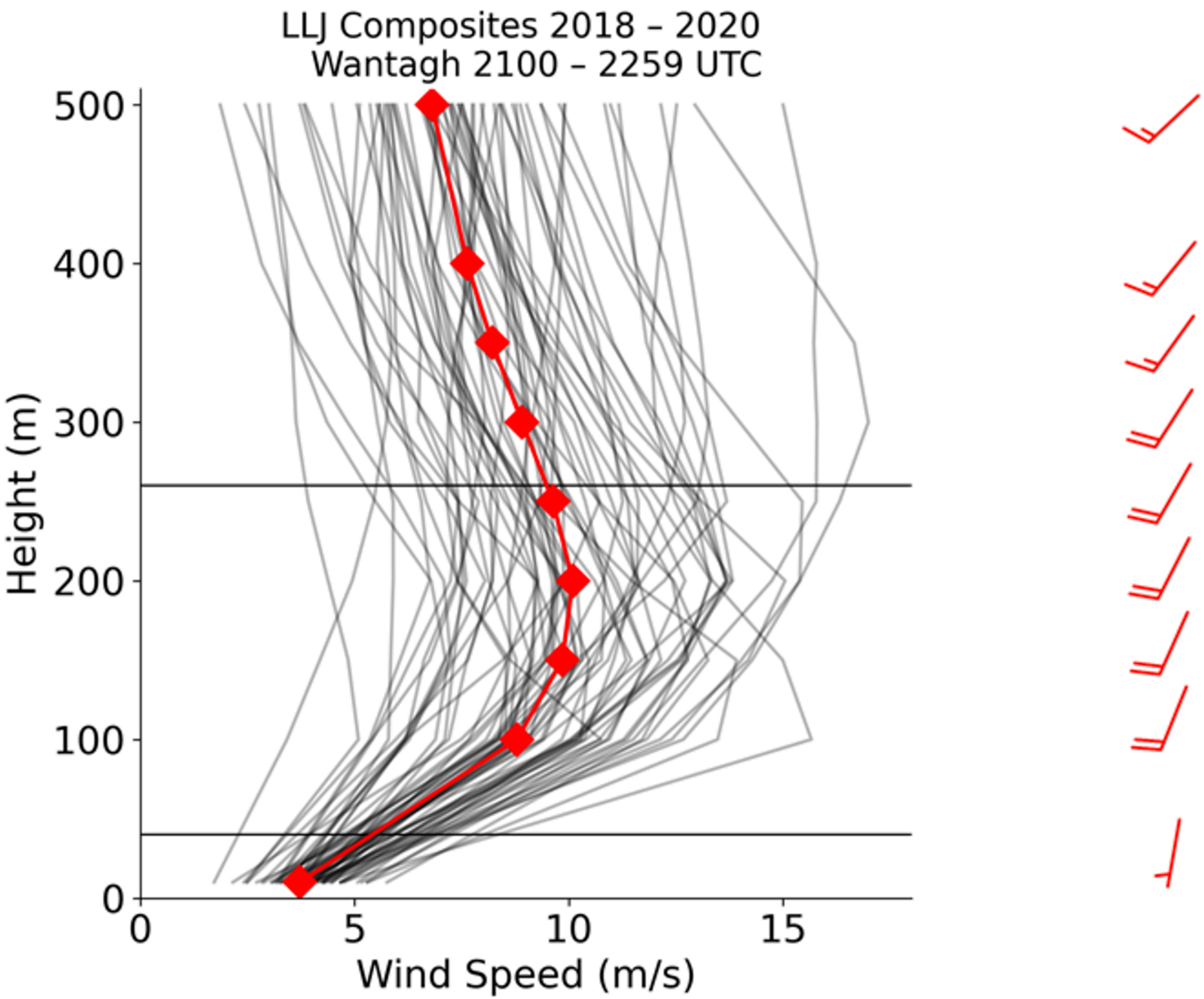
Wantagh, NY Seabreeze (10 April 2017)

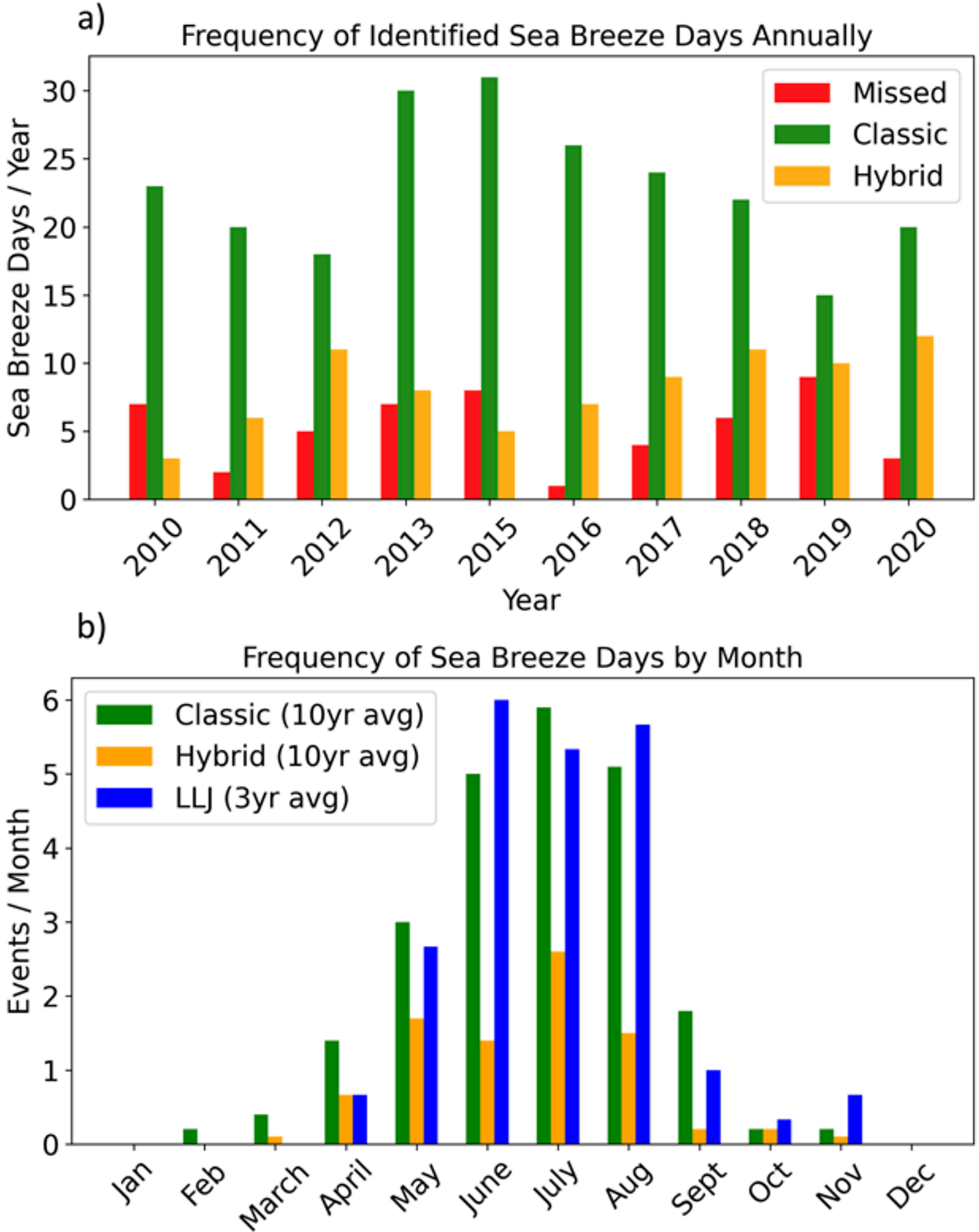


Hub height wind speed increases from 4 - 17 ms^{-1} in 20 minutes!

NY Bight

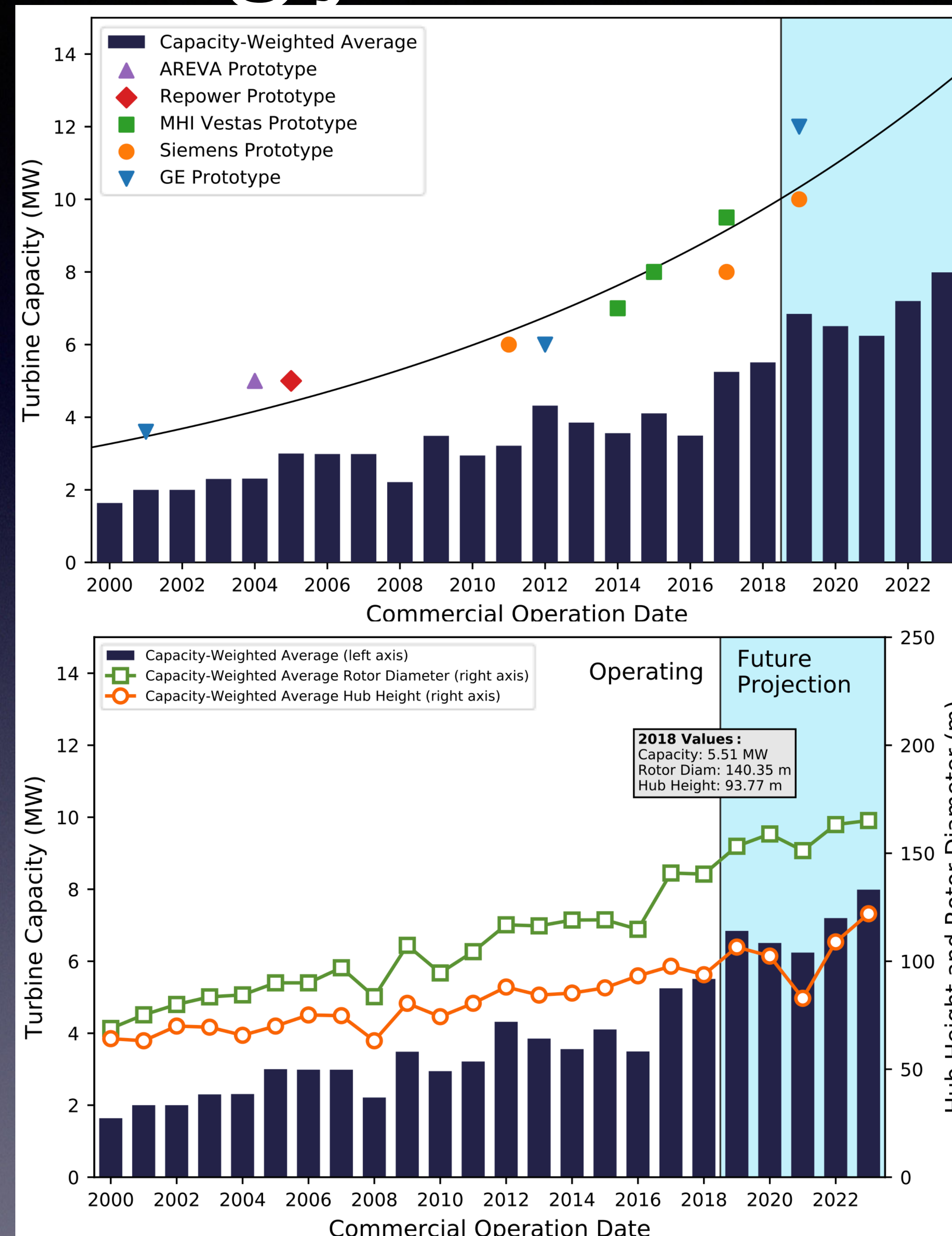
McCabe and Freedman (MWR 2023)





Sea breeze and LLJ Climatology (McCabe and Freedman 2023)

Technology

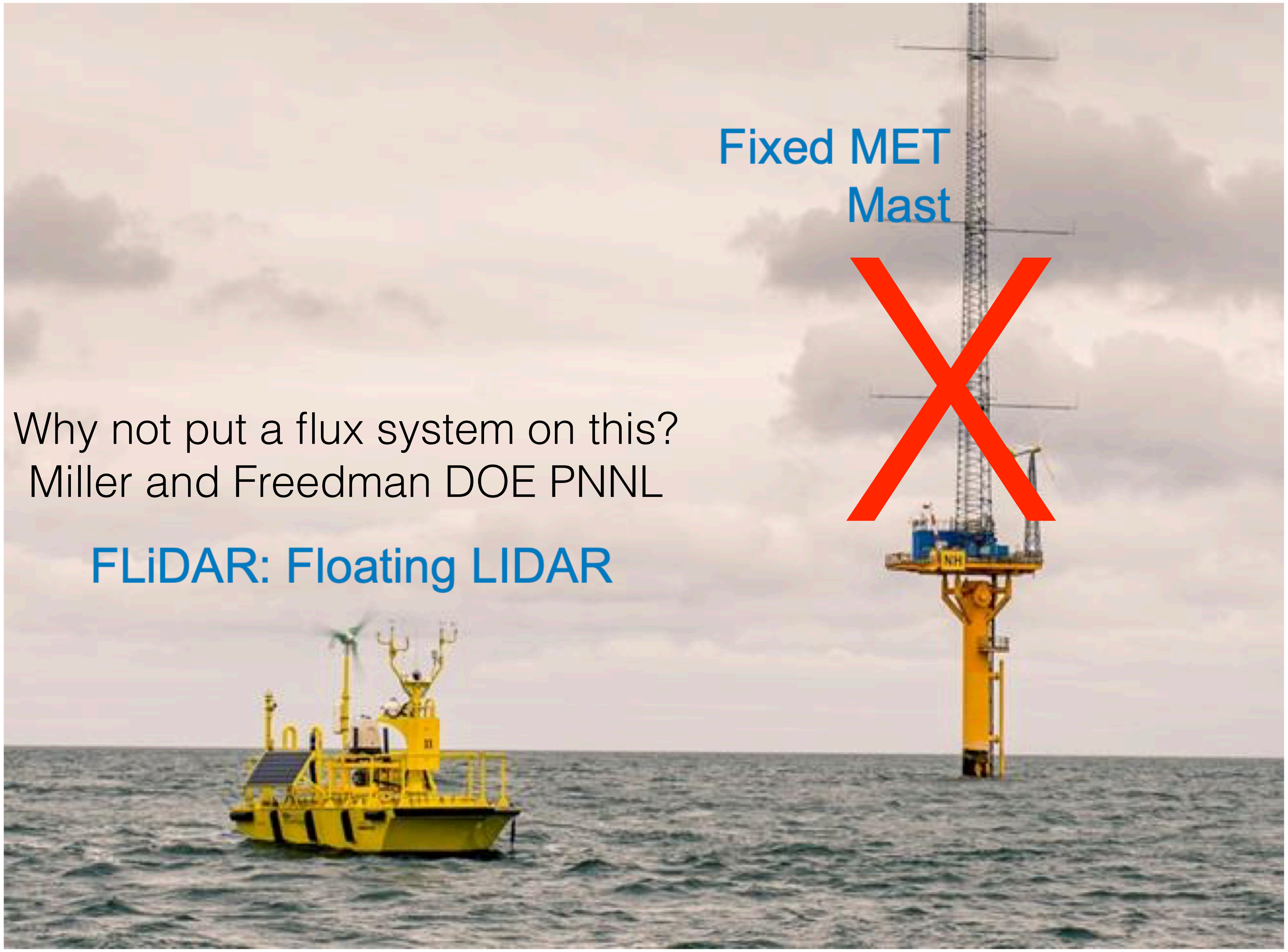


USDOE EERE 2018 Offshore Wind Technologies Market Report

UNIVERSITY AT ALBANY
State University of New York

Measurements

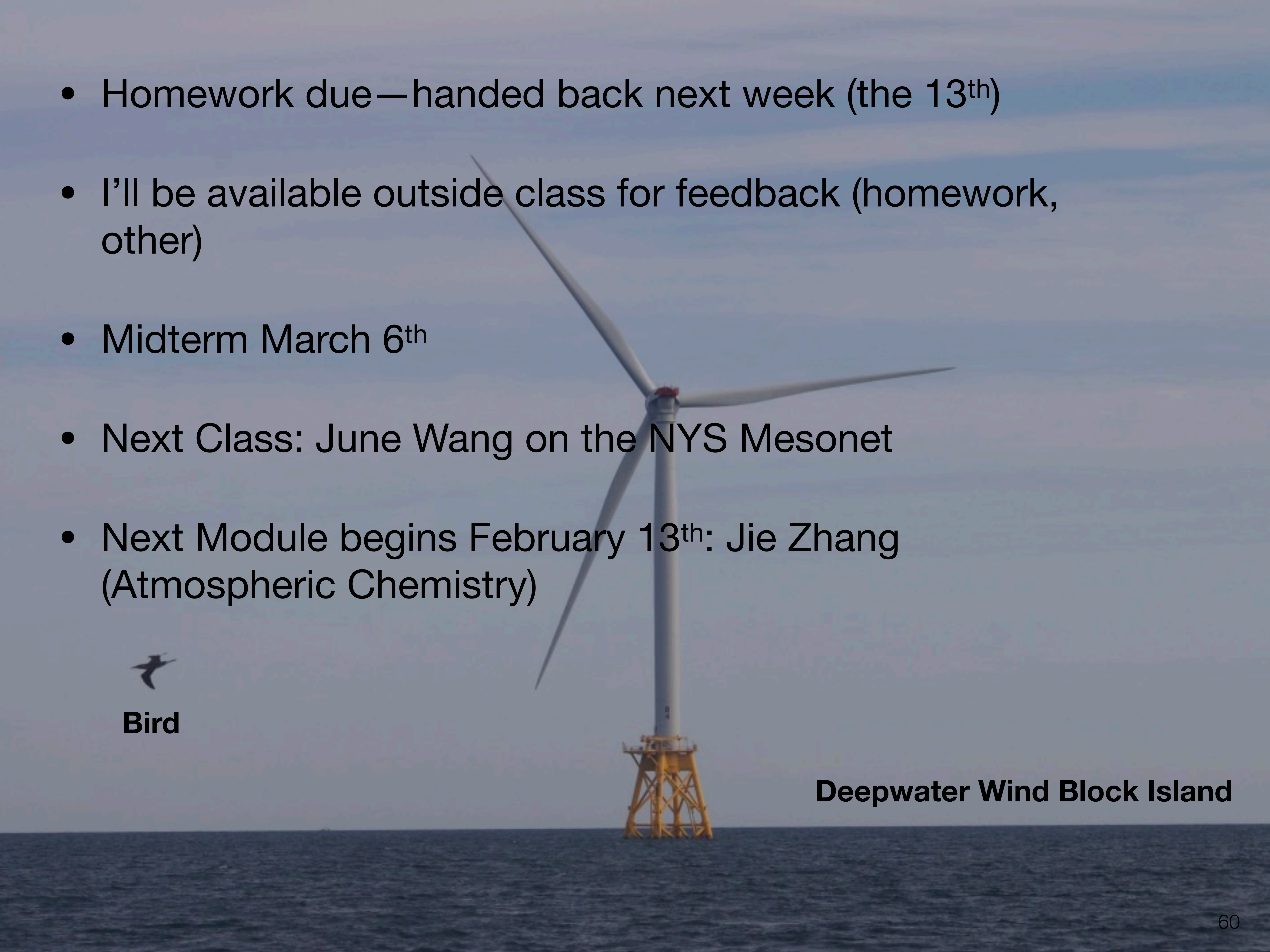
- Fixed MET masts are expensive and are being replaced by floating LIDAR buoys.
- Site specific measurements are needed for:
    - ❑ Resource validation
    - ❑ Power production



AXYS FLiDAR 6-m buoy typically used for wind and wave assessments installed near a fixed meteorological mast.
Photo courtesy of AXYS Technologies

Integrated Buoy-based Atmosphere Ocean Measurement System

- Homework due—handed back next week (the 13th)
- I'll be available outside class for feedback (homework, other)
- Midterm March 6th
- Next Class: June Wang on the NYS Mesonet
- Next Module begins February 13th: Jie Zhang (Atmospheric Chemistry)



Dogs