How do we define wind speed for hurricane force winds?

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1. The Florida State University
2. NOAA

Extreme winds in Tropical Cyclones are Believed to be Modified by Sea Spray

- Observations from hurricane environment (Powell et al. 2023; Holthuijsen et al. 2012) show that the drag coefficient, the proportionality between kinematic stress and wind speed squared, peaks around 30 m/s and decreases as wind speed increases for greater wind speeds.
  - This deviates from the older stress parameterizations based on wind speeds up to 20 m/s, which have a drag coefficient that increases linearly with increasing wind speed.
  - Keep in mind that stress (τ) is proportional to the drag coefficient times wind speed squared
    - A saturated drag coefficient does not mean that stress saturates
    - This is important because wind sensors are thought of as sensitive to stress.
- We will discuss modeling the impacts of spray and sea state on a log-wind profile
- That profile can then be used to determine equivalent neutral winds in a tropical cyclone environment.

THE LOG-PROFILE OF WIND SPEED

d = displacement height

Speed of Surface Current

Friction Velocity

Height Above Surface

$D = d - z_0$

$D \approx d$

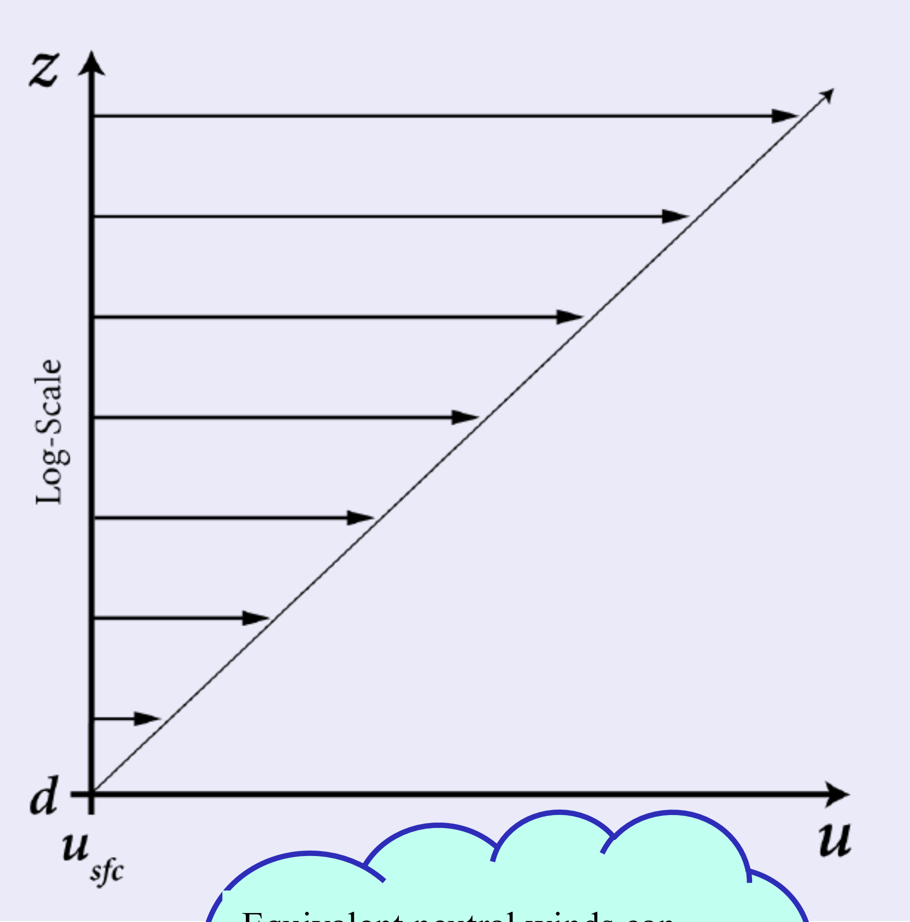
$$u_i = u_{sfc} + \frac{u_*}{k_v}\left[ln\left(\frac{z_i - D}{z_0}\right) - \Psi_M(L, z_i)\right]$$

Mean Wind Speed

Von Kármán Constant ($\approx 0.4 \pm 0.01$)

Roughness Length

Stability Term (a function of u_*, q_*, and θ_*)



Equivalent neutral winds can be determined

- using the u* and z0 from the show equation
- Setting the blue terms to zero

Similarly structured profiles exist for potential temperature (θ) and specific humidity (q)

$$\theta_i = \theta_{sfc} + \frac{\theta_*}{k_v}\left[ln\left(\frac{z_i - D}{z_{0_\theta}}\right) - \Psi_H(L, z)\right]$$

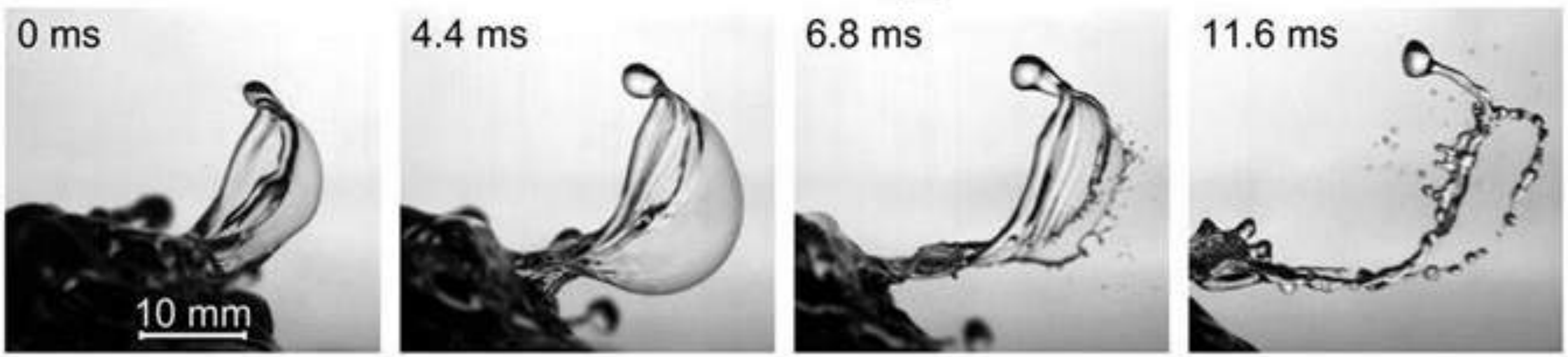
$$q_i = q_{sfc} + \frac{q_*}{k_v}\left[ln\left(\frac{z_i - D}{z_{0_q}}\right) - \Psi_E(L, z)\right]$$

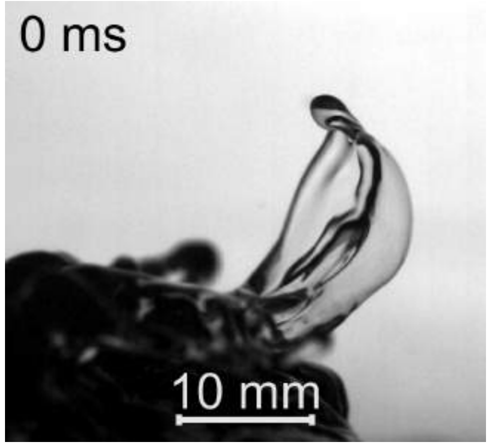
Stress = $\rho|u_*|\,u_*$ Sensible heat flux = $-\rho\, C_p|u_*|\,\theta_*$ Latent heat flux = $-\rho\, L_v|u_*|\,q_*$

Extraction (Reduction) of Stress due to Spray

- Veron et al. (2012, GRL) observed a specific spume generation mechanism in a high wind, wave tank study, which had only been observed in previous fluid dynamics studies.
  - Stated that this mechanism may need to be accounted for in estimates of sea spray generation in “hurricane or strongly forced wave conditions.”

- Troitskaya et al. (2017, SR) not only observed the bag-breakup mechanism in a high wind, wave tank study, but also parameterized the spray generation mechanism.
  - Extraction of atmospheric stress due to ‘Bags’ and ‘droplets.’



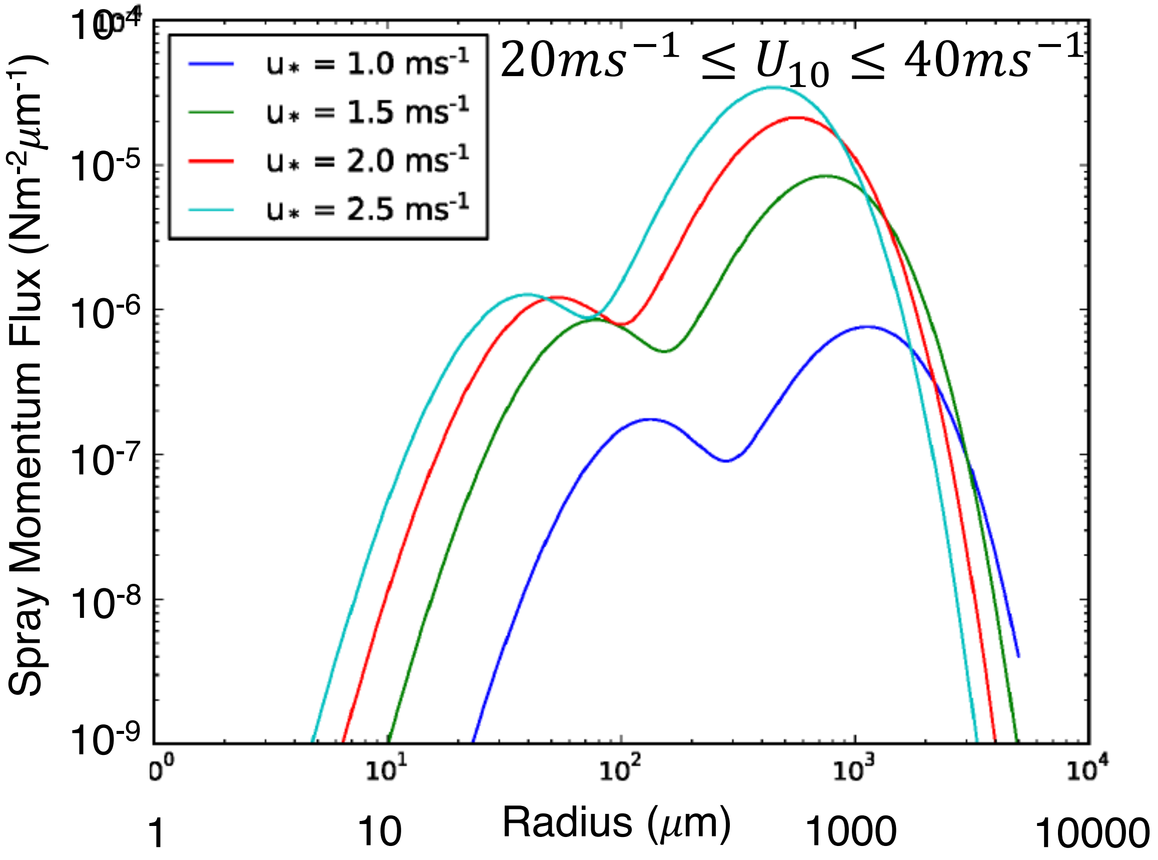


Surface Stress Model – Spray Contribution

- Troitskaya et al. (2017, SR) parameterized the contribution of this sea spray generation mechanism to the total turbulent stress into two separate parts:

$$\tau_{tot} = \tau_{wave} + \tau_{bag} + \tau_{drop}$$

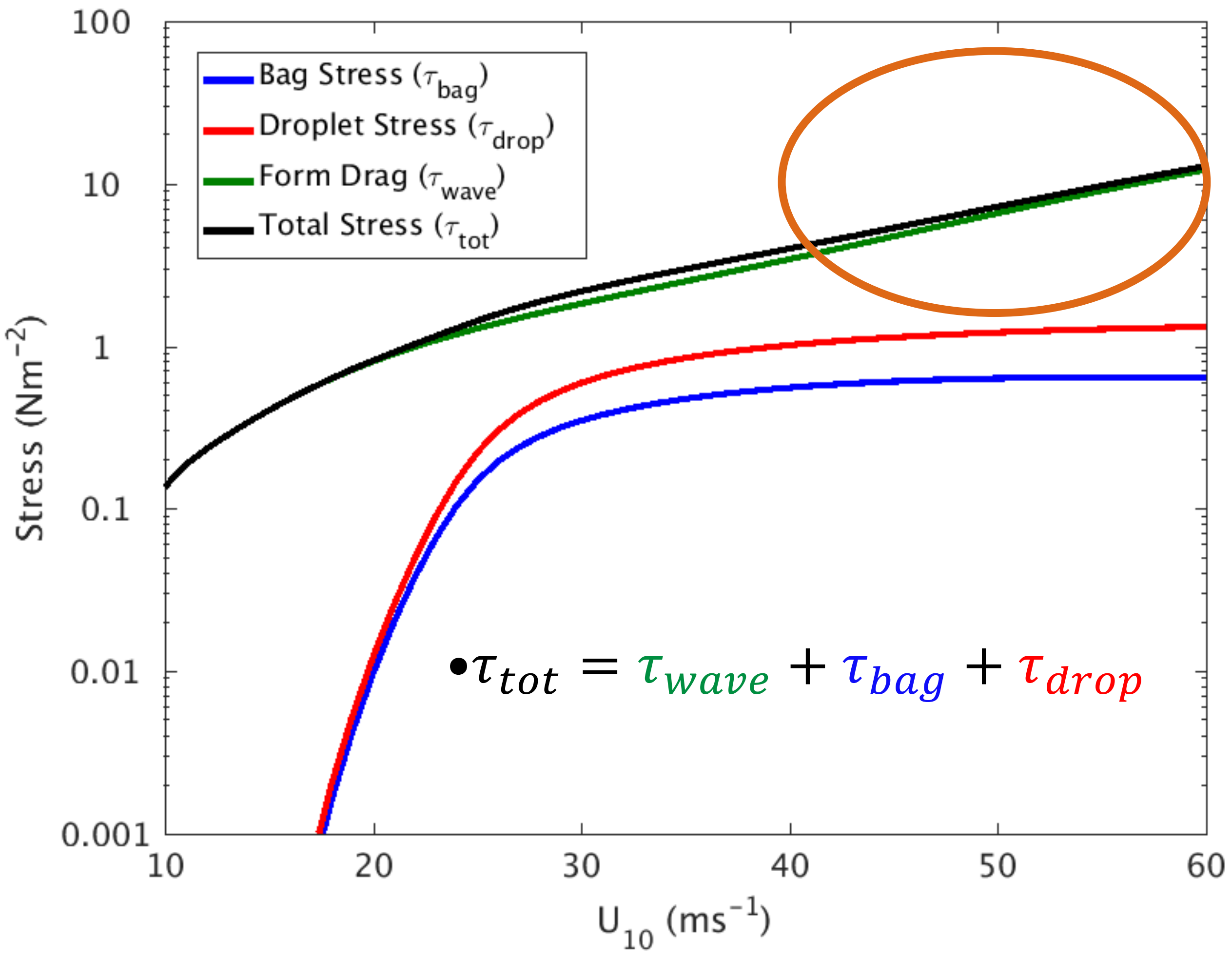
- Drag of surface waves
- ‘Bag’ stress, or the airflow resistance to the microsails
- The droplet stress, or the momentum acquired during the droplet production



Flux Model – Stress Components

- Can momentum extracted by spray account for the observed reduction in the drag coefficient?
  - Tested with a surface flux model that would otherwise have a drag coefficient that increases linearly with wind speed
  - An iterative, air-sea coupling model, the Modularized Flux Testbed (MFT) is used (Bourassa 2006, AOI).

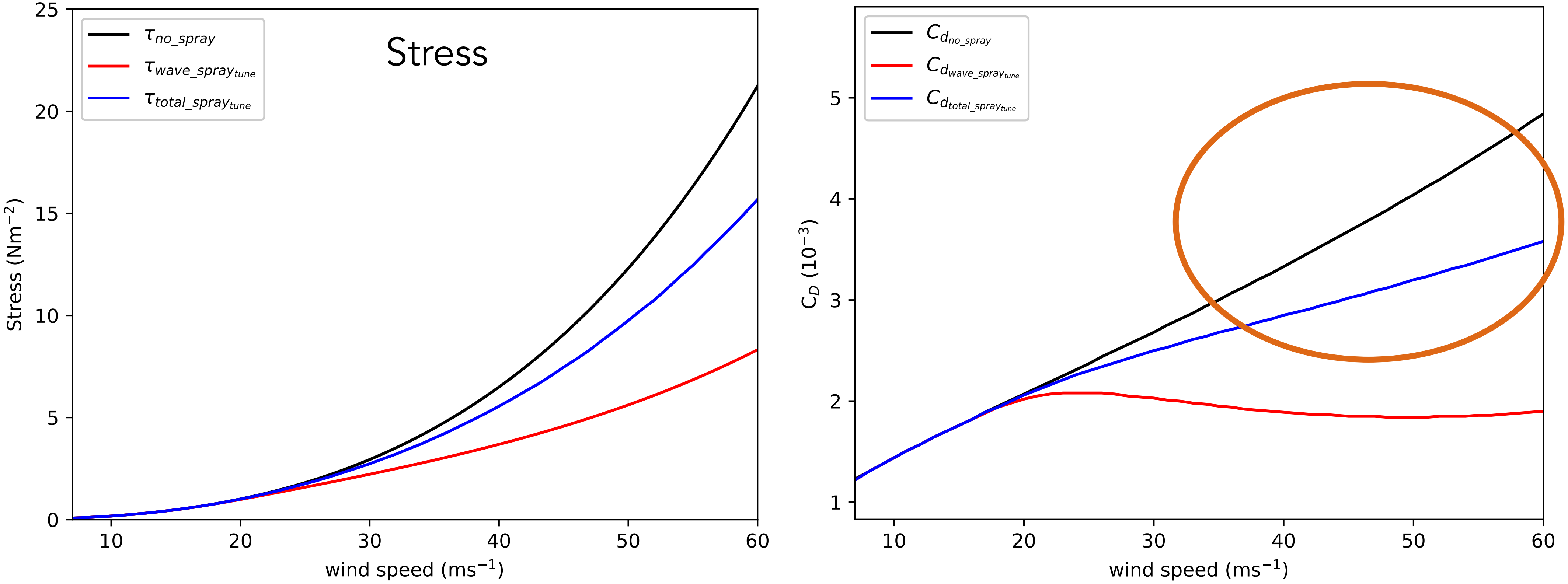
- The waves 'feel' the reduced stress,
  - Which reduces the roughness length
  - Further reducing the stress
  - Countered by a reduction in spray production and its impact on stress



$$\bullet\tau_{tot} = \tau_{wave} + \tau_{bag} + \tau_{drop}$$

Flux Model: Spray vs. No Spray

- There is an obvious reduction in the stress and drag coefficient due to to spray effects. The black line is the model without spray, blue is the atmospheric value with spray, and red is the oceanic value
- The drag coefficient levels off early than previous literature reports. Also, there is an u



PROFILES FROM DROPSONDE OBSERVATIONS

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Speed of Surface Current

Friction Velocity

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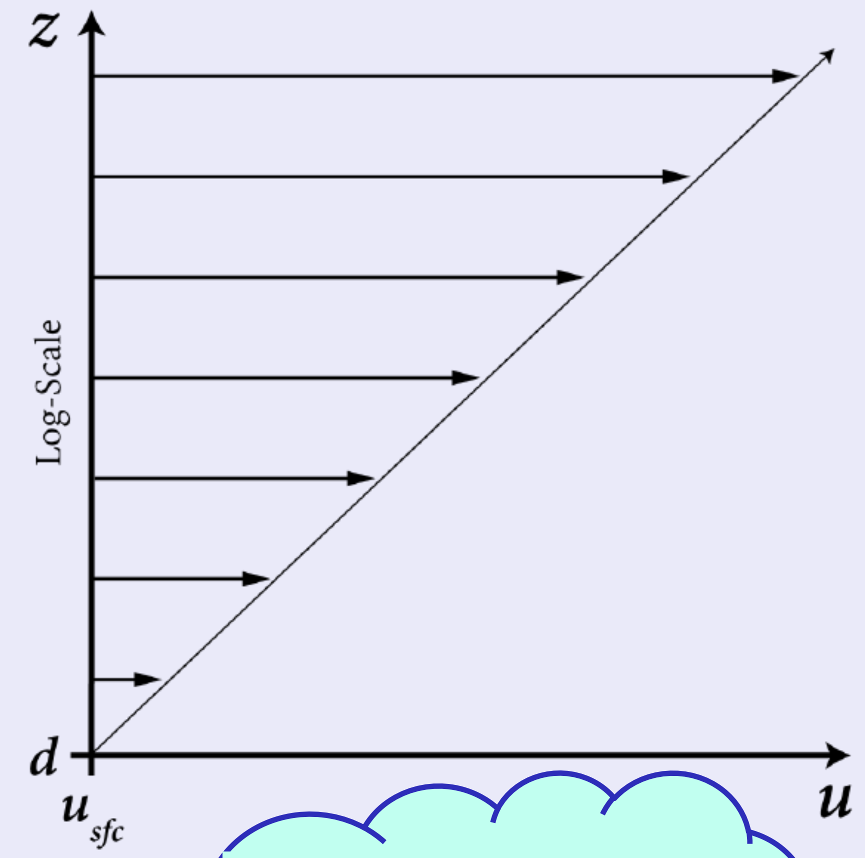

Observations of wind speed, air temperature, and humidity at different heights in a log-layer can be used to solve these three equations

Similarly structured profiles exist for potential temperature (θ) and specific humidity (q)

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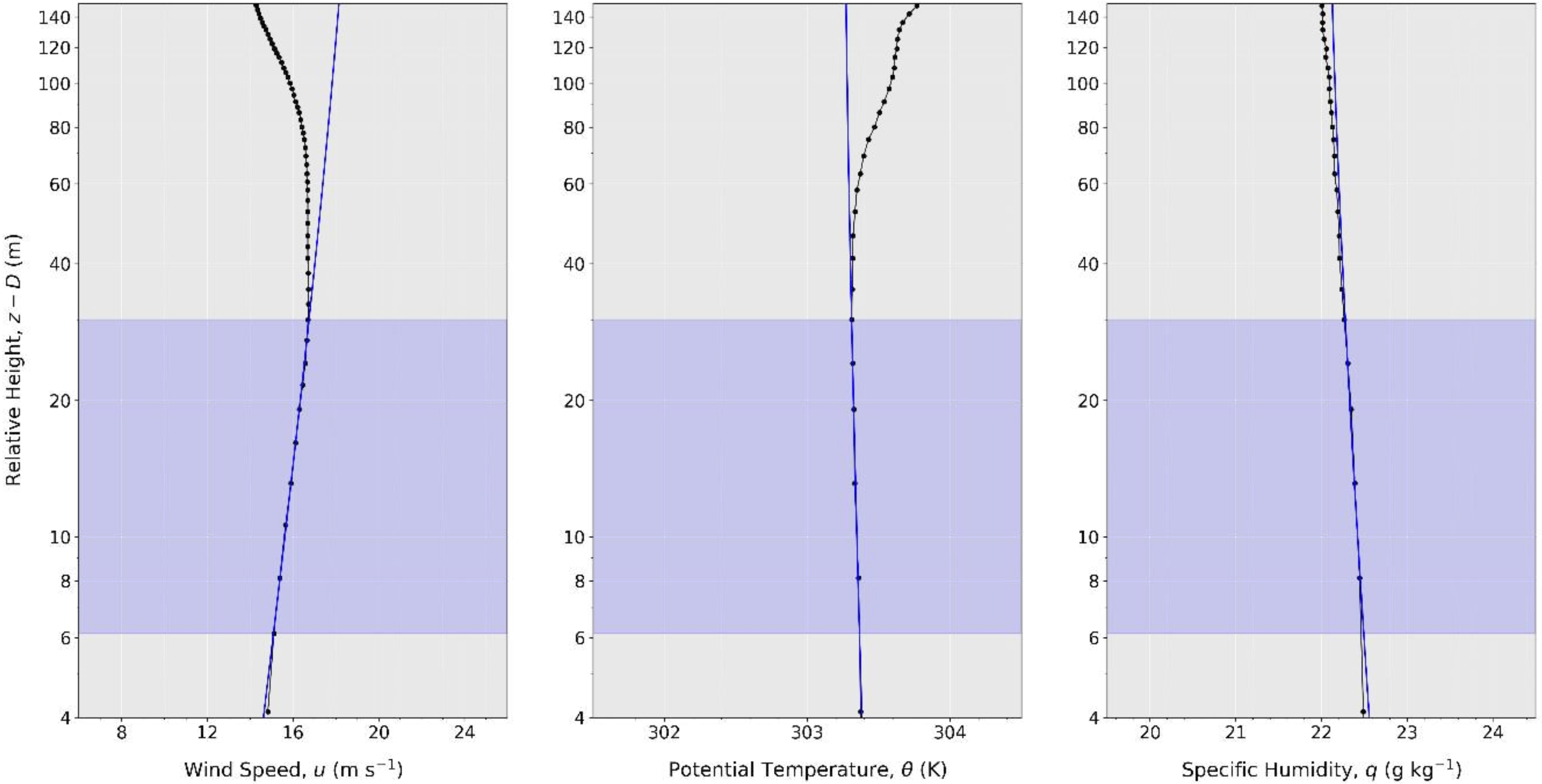
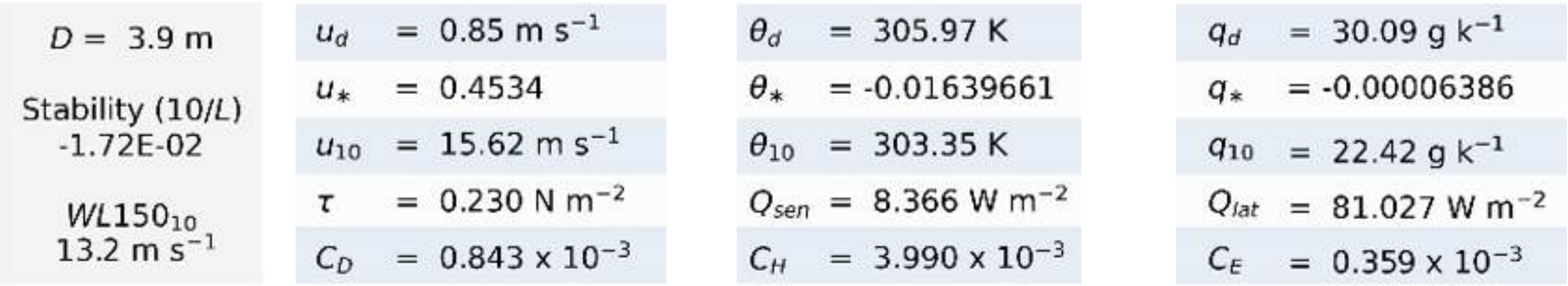
OUTPUT

- Able to find solution profiles for u, θ, and q
- Calculate fluxes
- Interpolate solutions to produce estimated 10m wind that factors in displacement height and follows expected physics
- Here, our u_{10} is close to the estimate using NOAA's WL150 method




$D = 3.9$ m

Stability ($10/L$)
-1.72E-02

$WL150_{10}$
13.2 m s^{-1}

$u_d = 0.85$ m s^{-1}
$u_* = 0.4534$
$u_{10} = 15.62$ m s^{-1}
$\tau = 0.230$ N m^{-2}
$C_D = 0.843 \times 10^{-3}$

$\theta_d = 305.97$ K
$\theta_* = -0.01639661$
$\theta_{10} = 303.35$ K
$Q_{sen} = 8.366$ W m^{-2}
$C_H = 3.990 \times 10^{-3}$

$q_d = 30.09$ g k^{-1}
$q_* = -0.00006386$
$q_{10} = 22.42$ g k^{-1}
$Q_{lat} = 81.027$ W m^{-2}
$C_E = 0.359 \times 10^{-3}$

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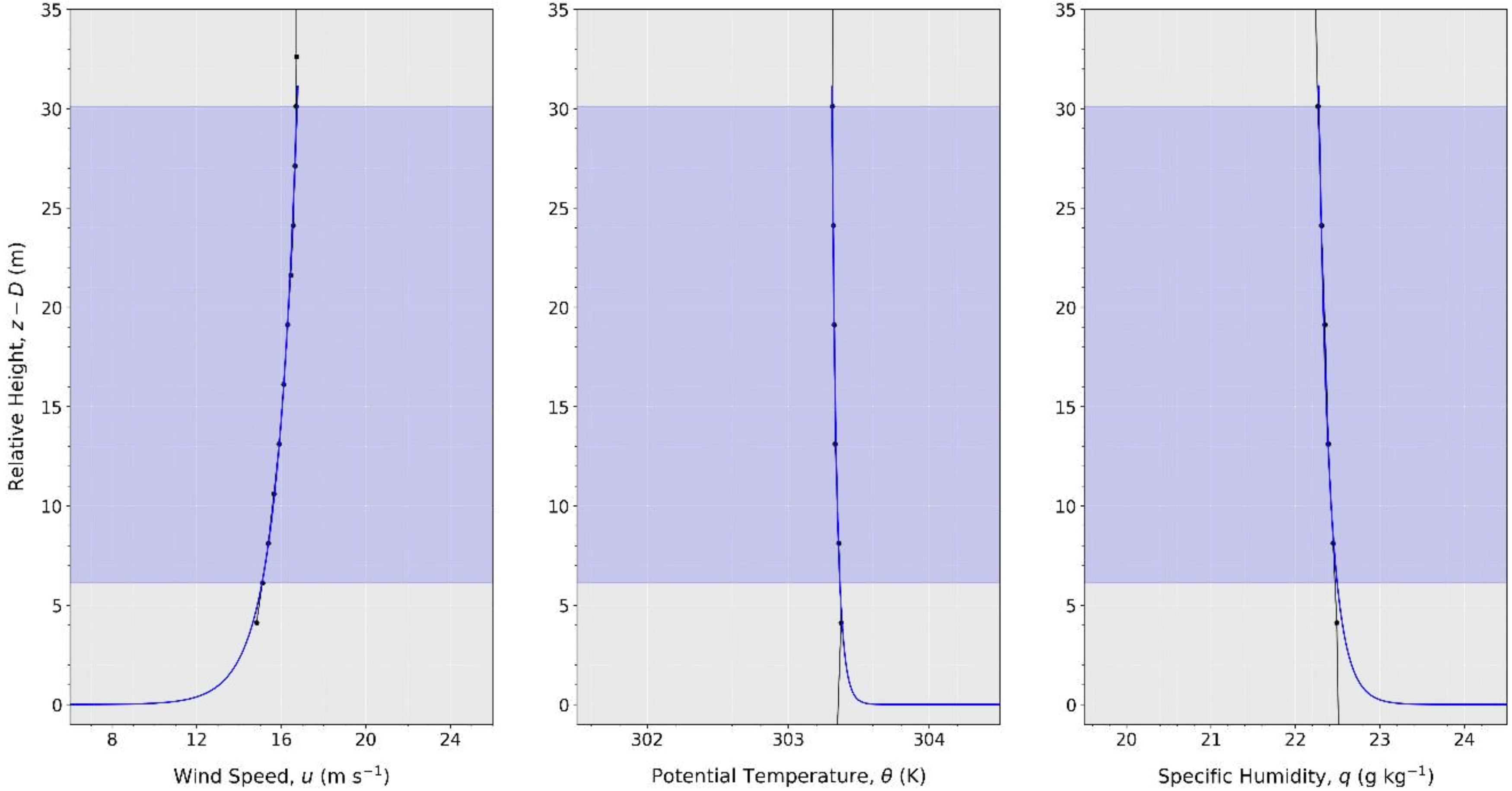

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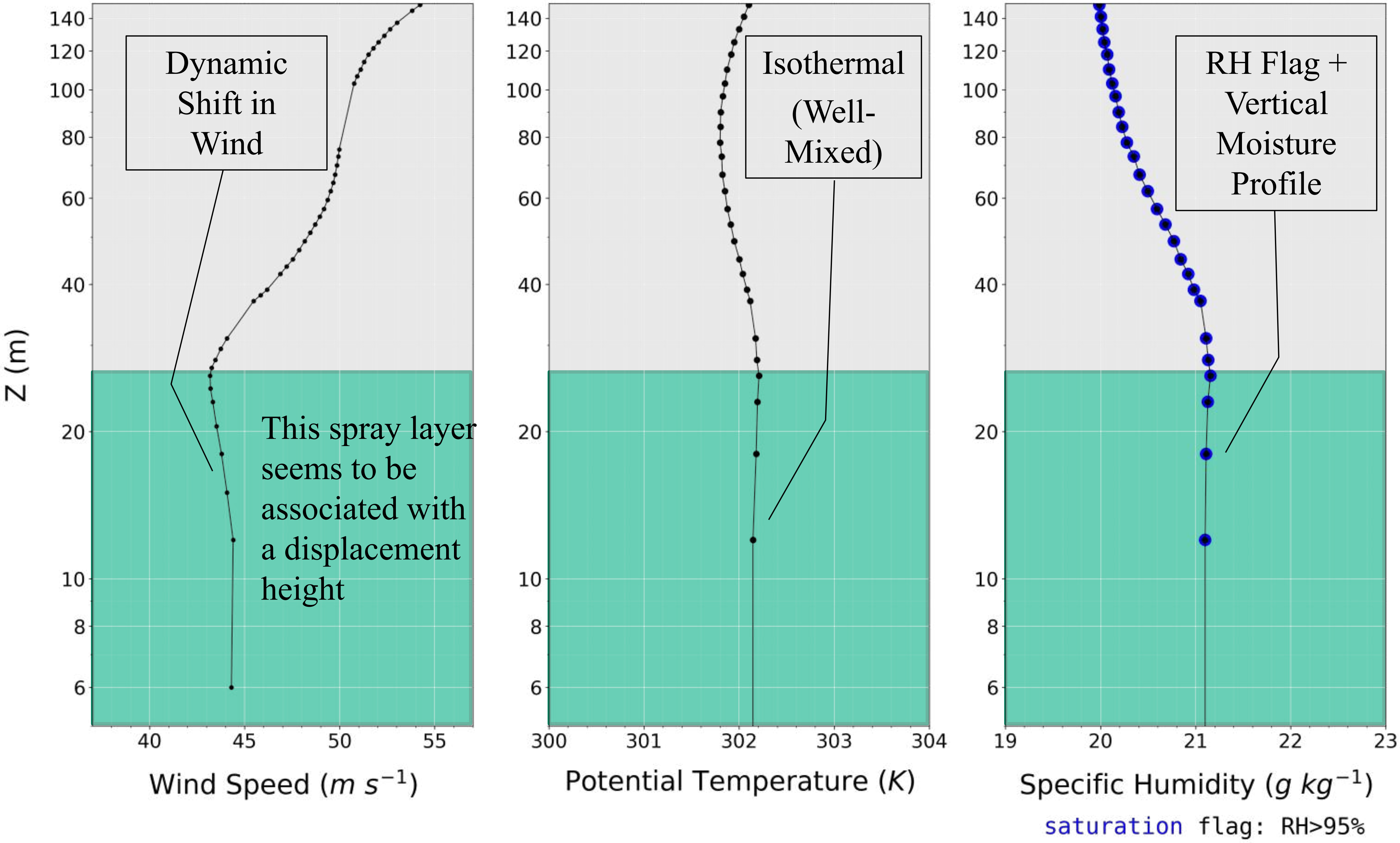


Dynamic Shift in Wind

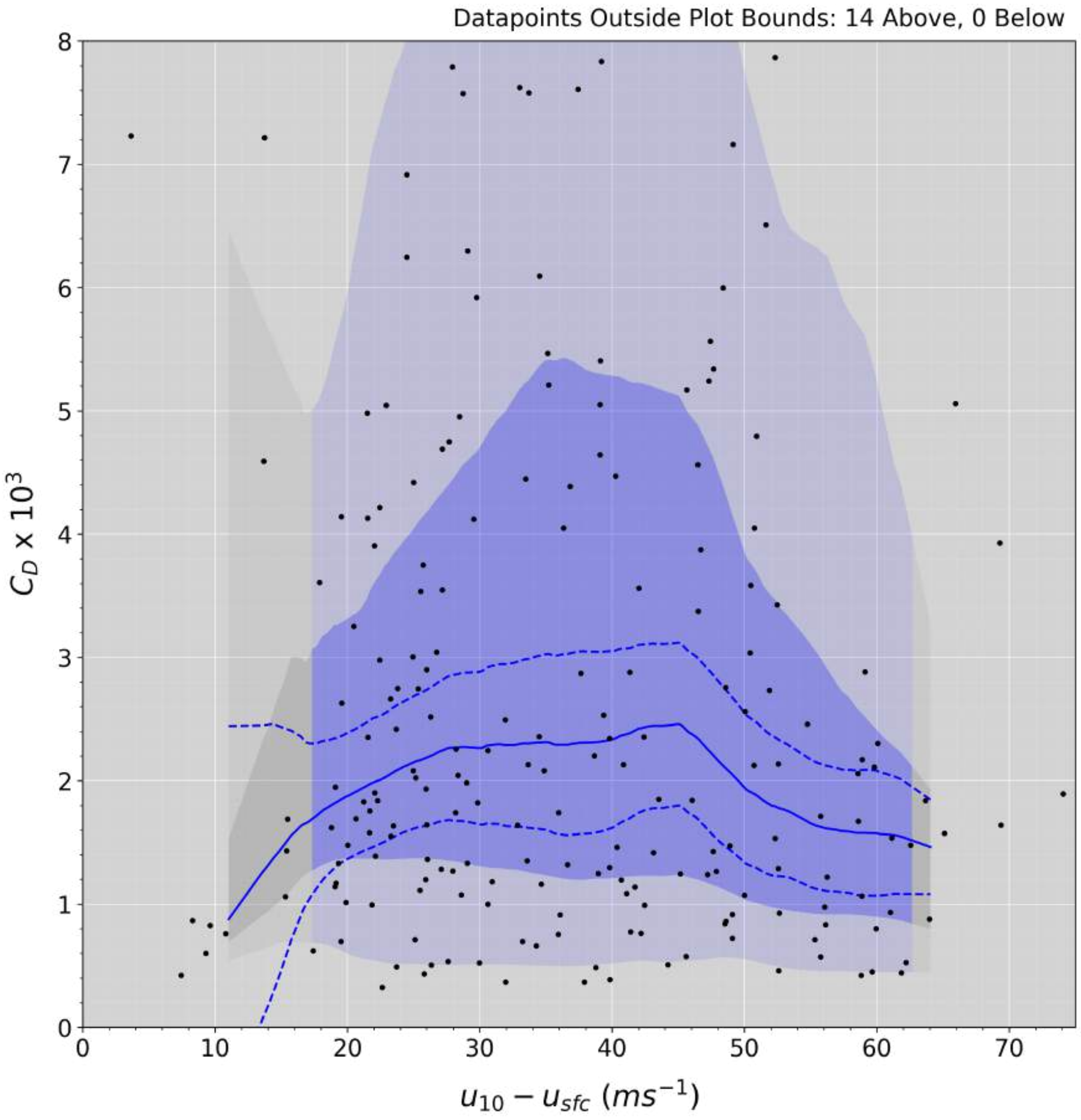
This spray layer seems to be associated with a displacement height

Isothermal (Well-Mixed)

RH Flag + Vertical Moisture Profile

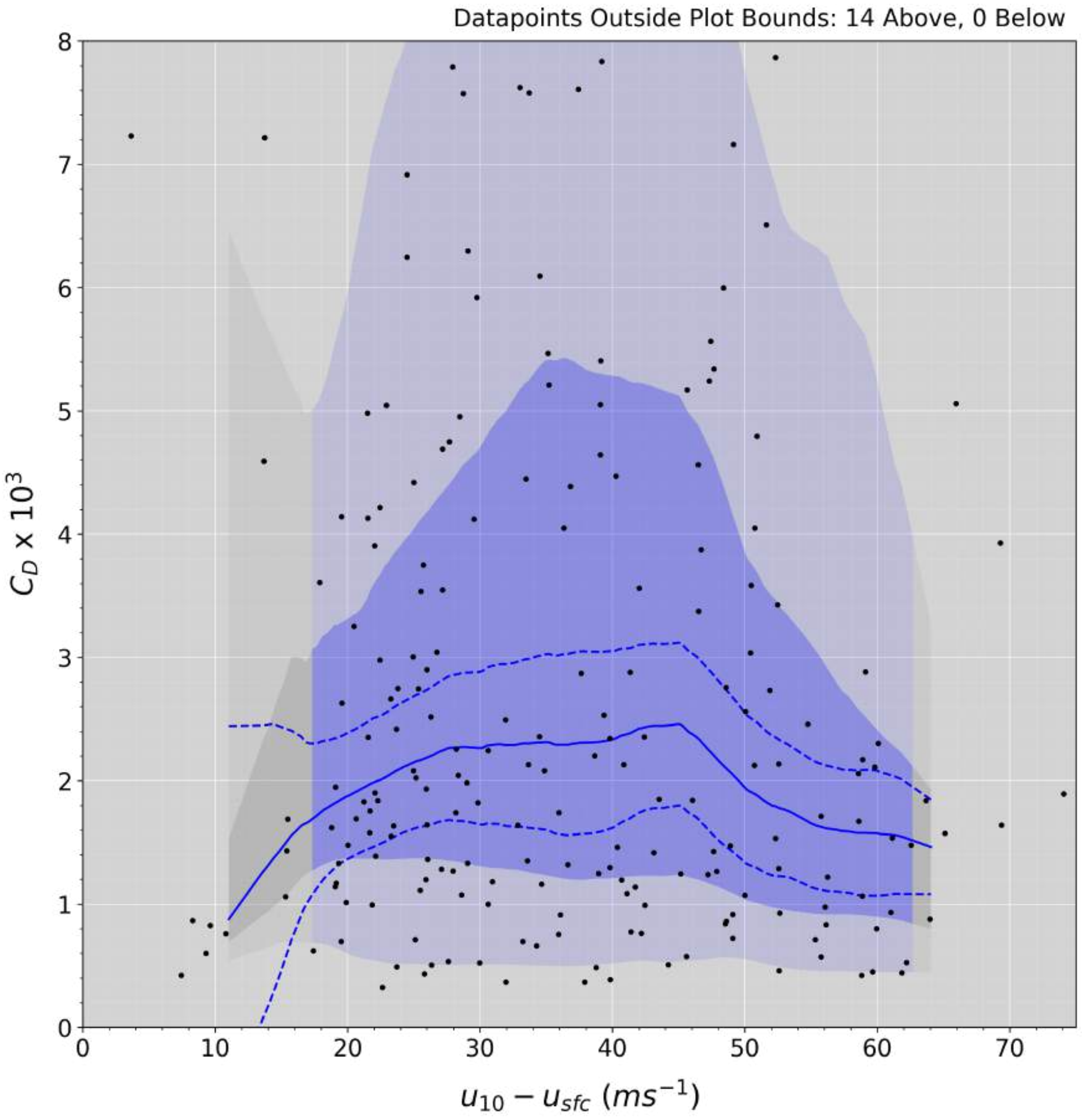
PLOT EXPLANATION

- Points: individual dropsonde profiles
- Rolling bins used to make lines
  - Solid blue = Median (on bin centers)
  - Dashed blue = uncertainty ($\pm \frac{2\sigma}{\sqrt{N}}$)
- Shading:
  - Dark = quartiles (25-75 percentile)
  - Light = 05-95 percentiles
  - Blue = higher confidence ($N \geq 30$)
  - Gray = lower confidence ($N < 30$)



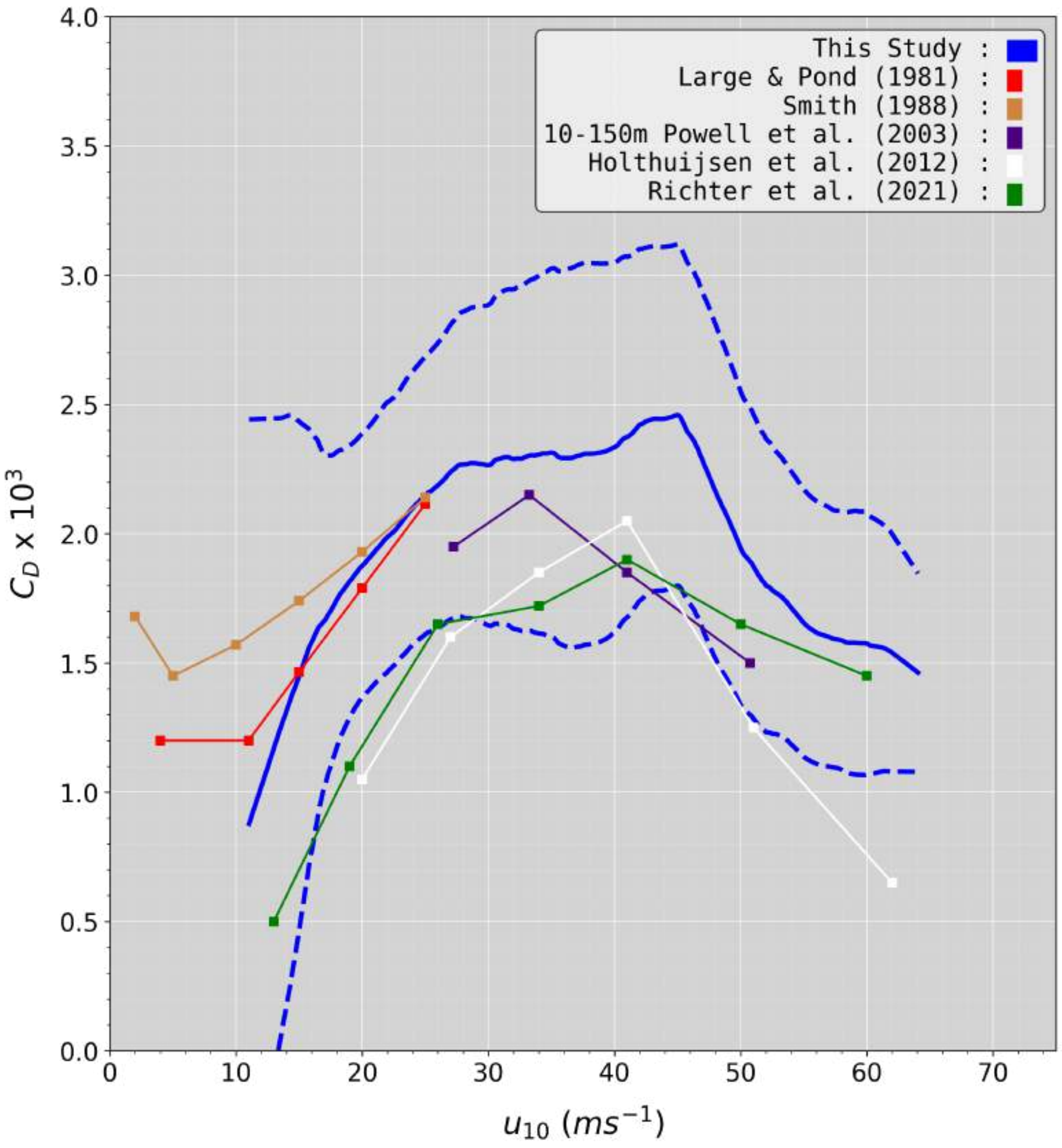
DRAG COEFFICIENT (C_D)

- $C_D(10m) = \left(\frac{u_*}{u_{10} - u_{sfc}}\right)^2$
- Used in parameterizations of stress and drag – very important to TC models!
  - Stress: $\tau = \rho C_D (u - u_{sfc})^2$
- A roll-off at very high wind speeds (TC environment) has been shown in past studies – the extent of the roll-off is hotly debated, however!



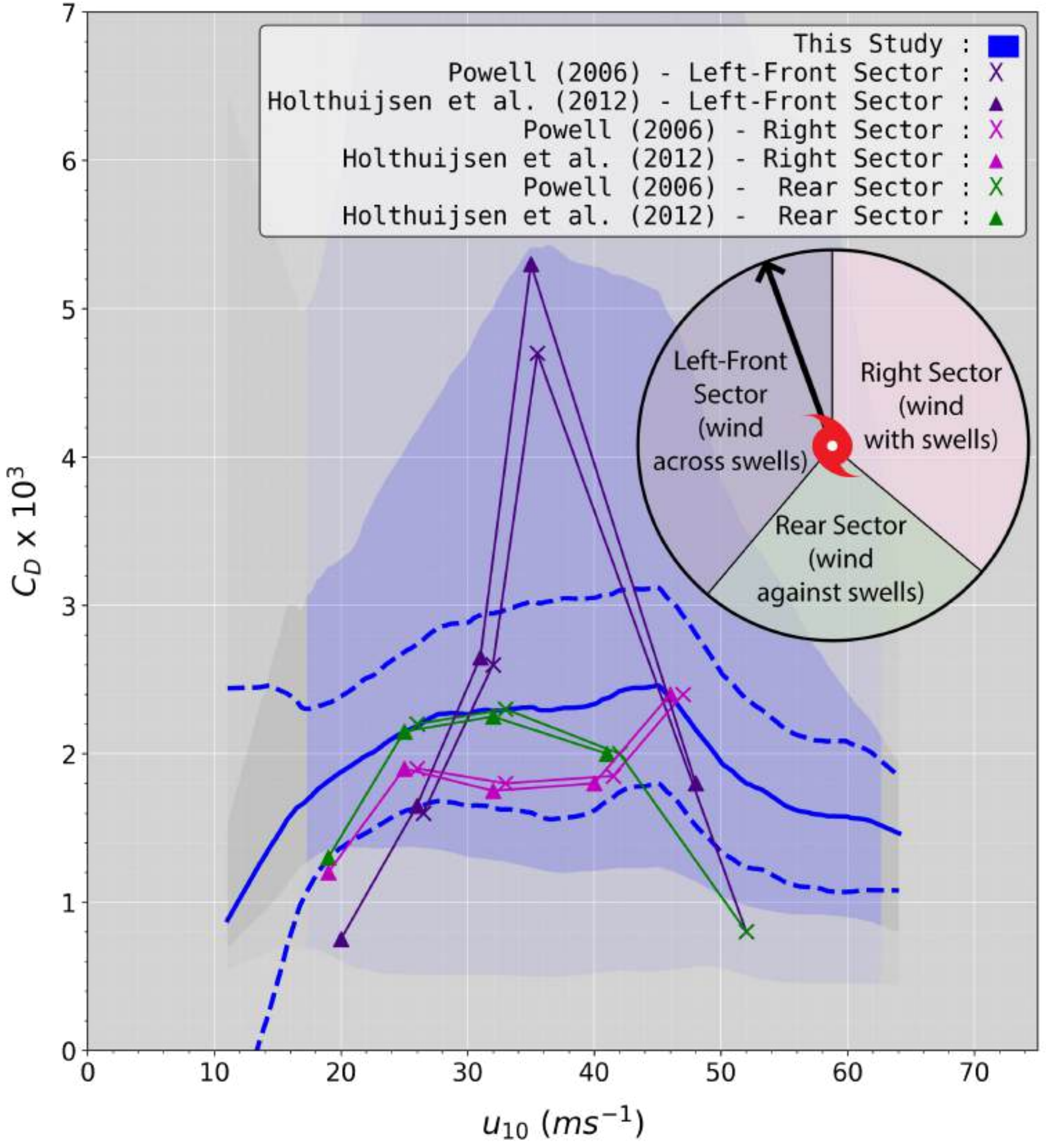
C_D VS. PAST WORK

- Most previous studies within bounds of uncertainty
- Fairly good agreement in the mean
  - Large & Pond 1981 and Smith 1988 parameterizations are ship-based observations – only meant to be used up to at most 25 ms^{-1}
    - However, being close to them is a good sign
  - Powell et al. 2003, Holthuijsen et al. 2012, and Richter et al. 2021 are all hurricane studies
    - Aggregate dropsonde profiles are used in these (many sondes averaged together)

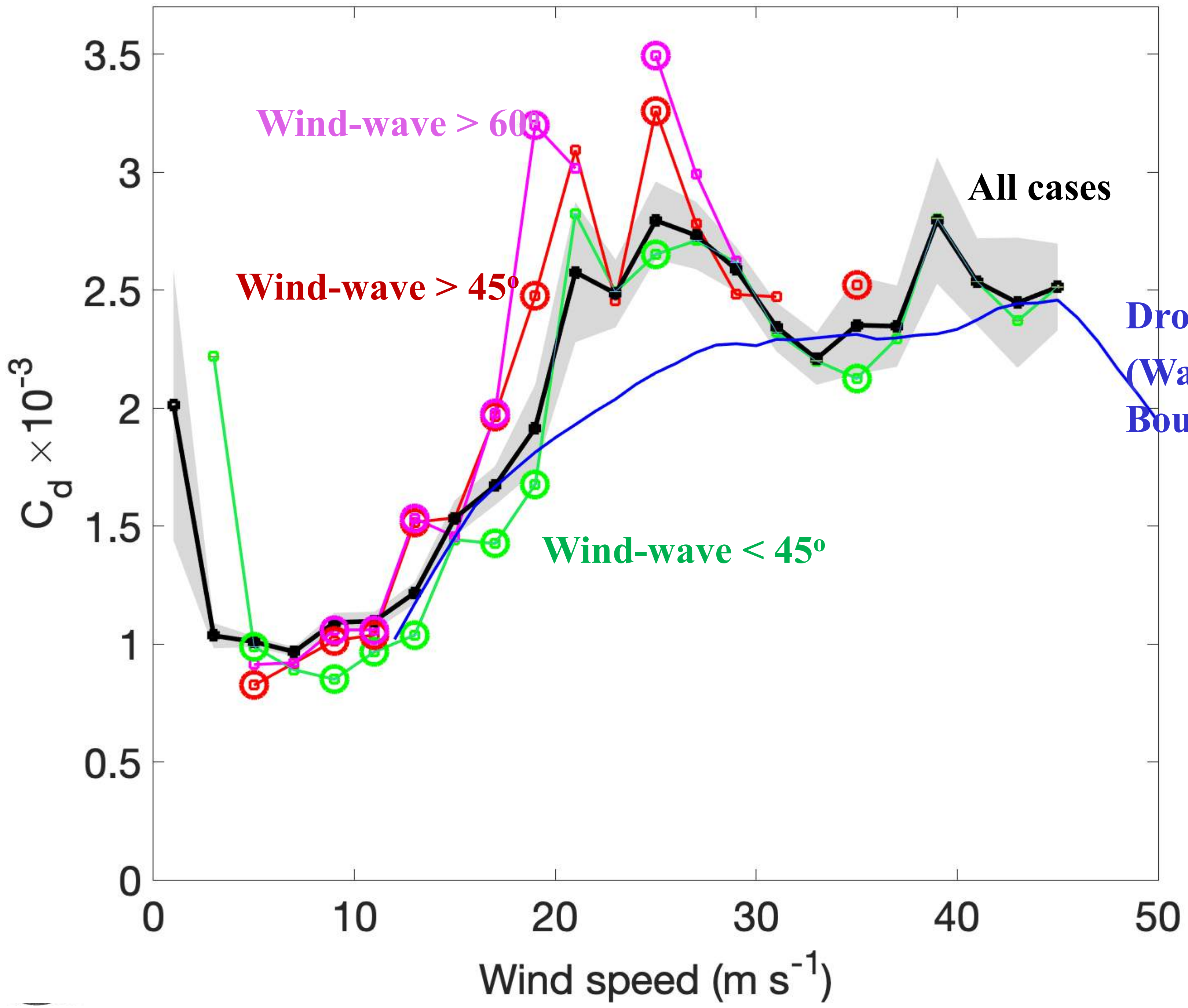


C_D VS. PAST WORK (SPLIT BY STORM SECTOR)

- Two prior studies show large spike in drag for cross-swell (Left-Front sector) dropsondes
  - Powell (2006)
  - Holthuijsen et al. (2012)
- Lines up well with our quartiles
- The sea state is very different in these sectors
- Strongly suggests that increased drag is due to a different process – possibly sea state modifying roughness



Mean C_d binned based on wind speed



- SailDrone C_D are remarkably consistent with dropsonde results
- Except for 20 to 30 m/s

Graphic from Greg Foltz

Summary and Conclusions

- A sea spray model can (with some adjustment) can explain the drop in observed stress and drag coefficients dependencies are a function of wind speed. (some tuning is required)
- Dropsonde data suggest that spray causes a non-negligible displacement height for wind speeds greater than about 30 m/s.
  - SailDrone drag coefficients are remarkably similar to dropsonde drag coefficients.
  - However, that implies that the extraction of stress due to spray either
    - Happens at height below the height of the SailDrone anemometer (about 2 m), or
    - Some other process is responsible for the reduction in drag dependency on wind speed.
- Observations are pretty consistent that another process is coming in to play for wind speeds from about 20 to 30 m/s that is increasing the stress.
- For calculating equivalent neutral winds:
  - The displacement height is important for determining the correct value of friction velocity.
  - The roughness length probably depends on sea state for winds in the 20 to 30 m/s range.
    - The actual dependency is far from clear.

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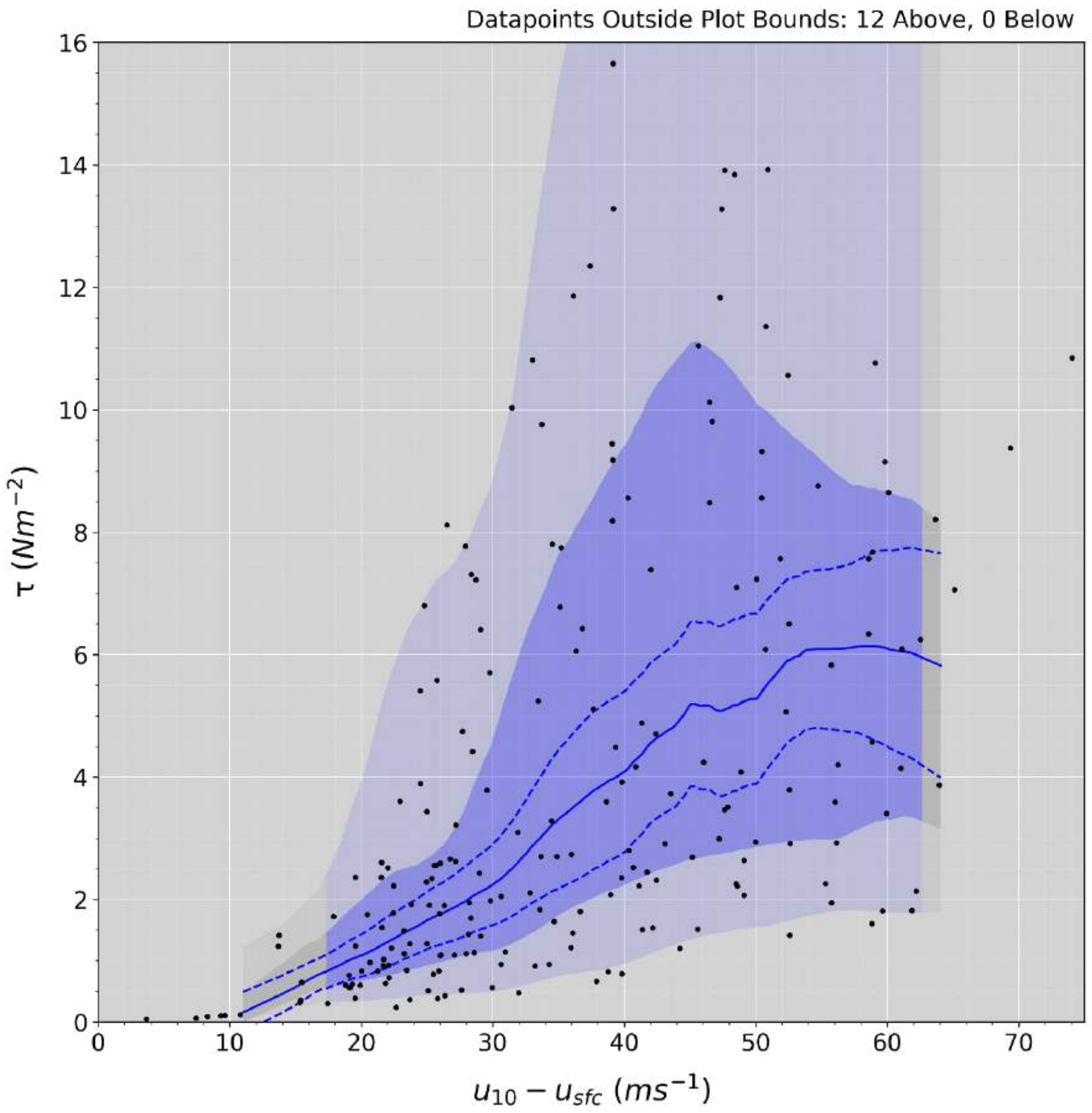
Momentum Flux (Stress)

$$\tau = \rho u_* |u_*| = \rho C_D \left(u - u_{sfc}\right)^2$$

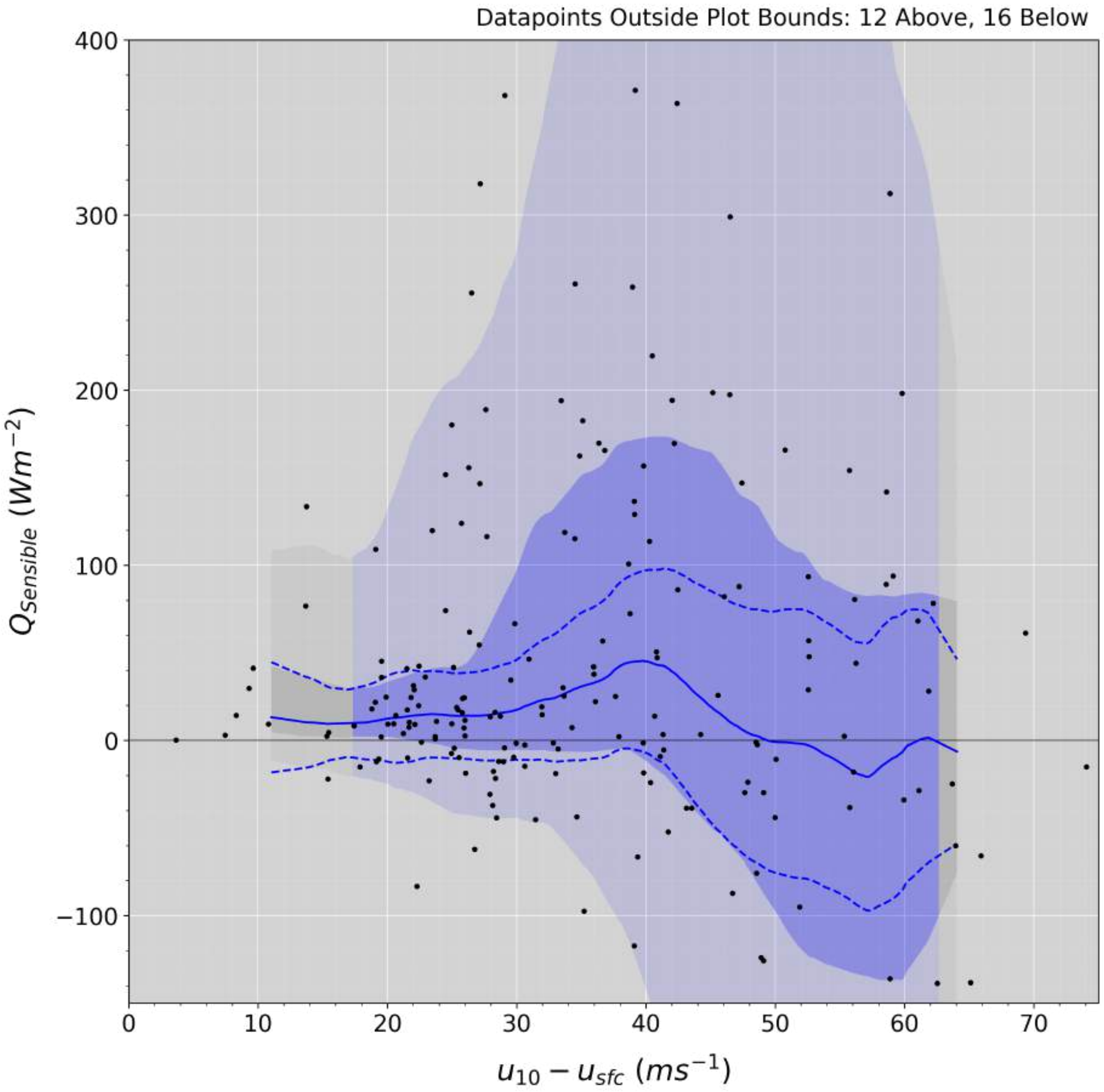
- Stress increases with wind speed
  - With a slight roll-off at highest speeds
  - Roll-off signal is smaller than our uncertainty



SENSIBLE HEAT FLUX

$$Q_{sen} = -\rho C_P u_* \theta_*$$

- Ocean warms atmosphere above… this effect increases as wind moves faster across surface – up to ~35 ms^{-1}
- At ~35 ms^{-1} we begin to see evaporative cooling at the top of the spray layer, which presumably cools the near surface air enough to result in a negative sensible heat flux
  - More cautiously stated: the evaporative cooling results in a near zero sensible heat flux



LATENT HEAT FLUX

$$Q_{lat} = -\rho L_V u_* q_*$$

- Steady increase of latent heat flux with wind speed with a slight roll-off at highest speeds
- The component due to stress ($u_* = \sqrt{\tau/\rho}$) is largely responsible for the downturn