Sea Spray in Hurricanes: Analysis of Impacts on Surface Processes and Wind Calibration

Mark Bourassa, Danny Wallace, Heather Holbach, and Renee Richardson

There are two related goals:

- Use dropsonde profiles of wind speed, air temperature and moisture in tropical cyclones to determine
  (1) log profile parameters for each profile, including impacts of non-neutral boundary-layer stability,
  (2) use this information to determine air-sea fluxes and transfer coefficients for these fluxes, and
  (3) Compare our wind speeds $u(z{=}d{+}10)$ to NOAA's estimates based on the lowest 150 m of wind speeds (WL150) adjusted for the height range.
- Model the influences of sea spray on stress forcing ocean waves and on stress felt by the atmosphere.
- Both goals have implications on the calibration of scatterometer and radiometer winds
- Showing a physically better definition of 10 m winds
- Showing that the stress felt by the atmosphere can differ from the stress felt by ocean waves.

What do we calibrate to if we're an Oceanographer?

- Traditionally we calibrate to a 10 m equivalent neutral wind speed. Equivalent neutral means that applying a neutral drag coefficient will result in the correct stress (it does not mean we assume neutral conditions).
- The ten-meter wind is defined as the horizontal wind speed at a height 10 m above the displacement height.
  - This displacement height is small under most conditions
    - Wave tank observations indicate that it is *not* zero (Bourassa et al. 1999)
  - Spray can make the displacement height (*d*) substantially above the traditional surface (often *d* = 5-20 m) according to Wallace et al.'s dropsonde profile analysis.
  - To calibrate to a 10 m wind we would need to know the displacement height *OR* **base the conversion on an inferred stress**.
- Since we base our equivalent neutral winds on an inferred stress, this (by itself) is not a serious problem for oceanographers trying to use scatterometer winds to force an ocean model.

What do we calibrate to if we're a Meteorologist?

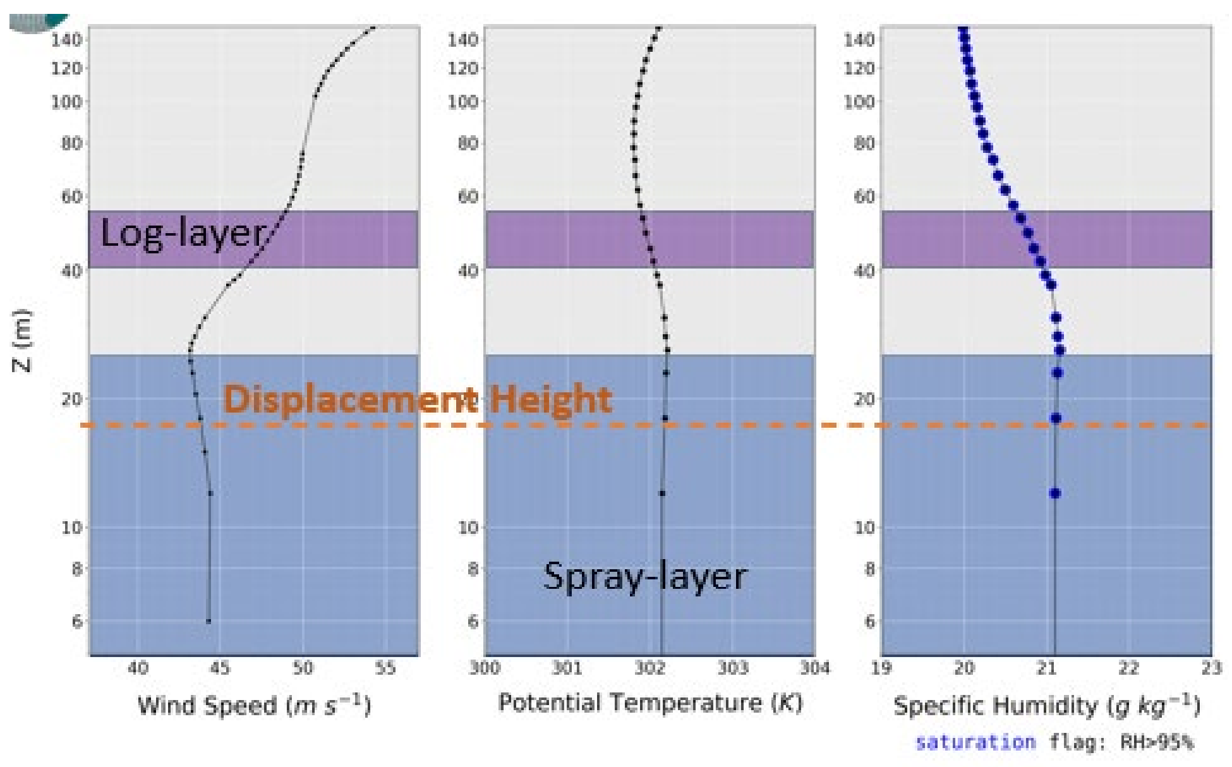
- Equivalent neutral assumes that scatterometers respond to ocean stress.

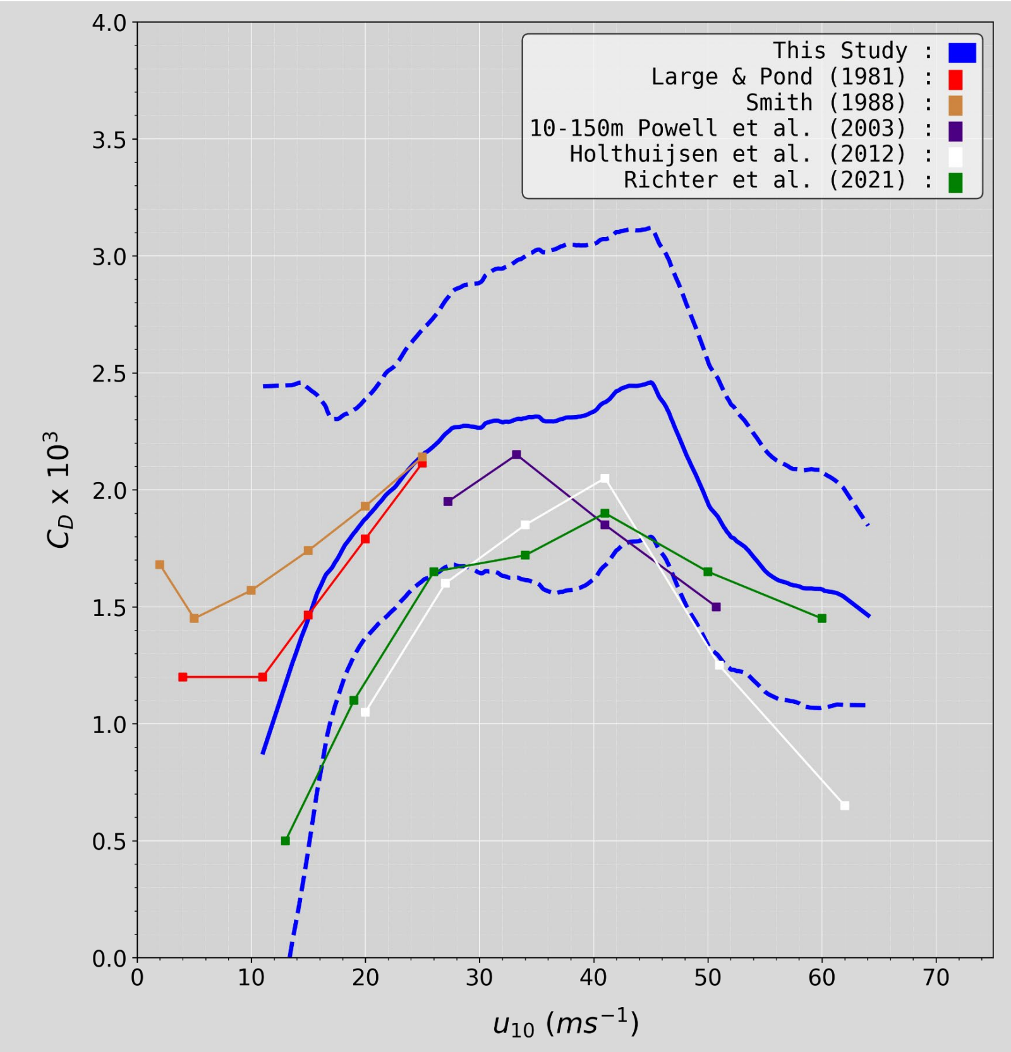
- **Atmospheric Stress = Ocean Wave Stress + Spray 'Stress'**
  - Spray extracts momentum from the air, reducing the stress felt by the ocean surface. This is akin to reducing the ocean's drag coefficient .
  - The atmosphere experience more stress than the ocean IF spray extracts momentum from the air.
  - Suggesting that scatterometer equivalent neutral winds will underestimate the wind speed IF spray extracts momentum from the air.

- What do we do that makes sense physically and operationally?
  - The answer to this question depends on the relative importance of the momentum extracted by spray.
    - If relatively little momentum is extracted, then we don't need to change our approach to stress, but we might still have issues with displacement height modifying the wind speed.
    - If spray extraction of momentum is non-negligible, then we might need to rethink our approaches to estimating wind and stress.

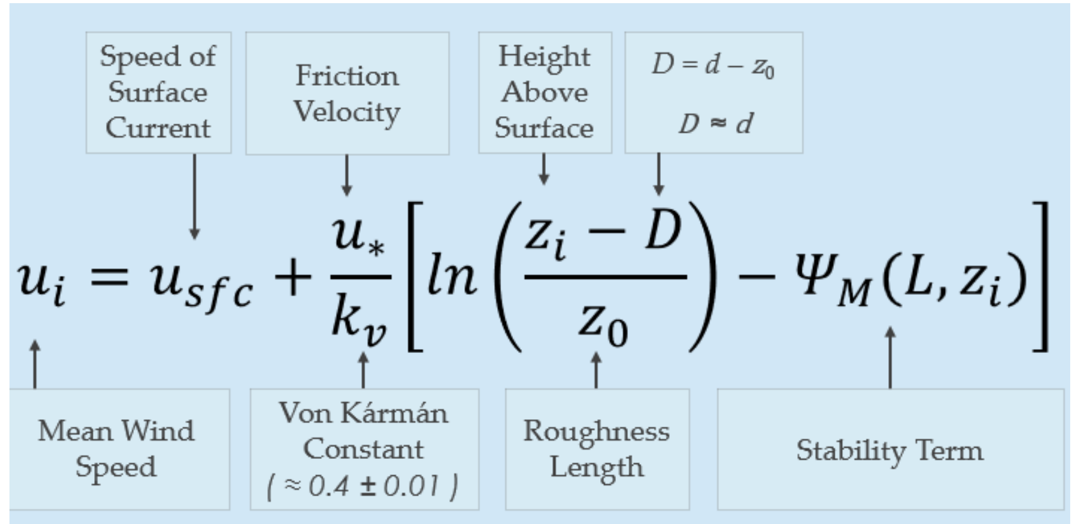
Three Assessments of the wind speeds for which spray matters

- (1) We use the observed drag coefficient as one guide to identifying the wind speed above which spray has a significant impact on momentum.
  - Early work by Powell et al. Suggests that the dependence of the drag coefficient on wind speed changes around 40 to 50 ms^{-1}.
  - Holthuijsen et al. (2012) and Richter et al. (2021) suggest this change occurs around 30 ms^{-1}.
  - Our dropsonde-based analysis is more consistent with Holthuijsen et al. (2012) and Richter et al. (2021)
- (2) Comparisons can also be made between our dropsonde-based 10 meter wind speed and wind speeds estimated by the WL150 method. This tests to see of our estimated wind speeds are loosely consistent with estimates from NOAA's Hurricane Research Division, and if there might be a problem with calibrating remotely sensed winds to dropsonde-based WL150 winds (assuming there aren't other issues like beam filling and sensitivity to rain).
  - Comparisons (see figure) are
  - remarkably similar up to 35 ms^{-1},
  - noticeably shift a little from 35 to 50 ms^{-1}, and
  - Suggest that winds > 55 ms^{-1} are underestimated by WL150 (few observations in this range were available when WL150 was developed (personal communication, James Franklin, 2022)
  - There results indirectly suggest that changes start to be noticeable around 35 ms^{-1}and become large above 55 ms^{-1} and point to calibration concerns.
- (3) Momentum absorption by spray can be added to bulk flux models (see lower right column for details.
  - Confirms a noticeable change in stress for U_{10} > 35 ms^{-1}, and for drag coefficient for U_{10} > 25 ms^{-1}.





The median of a rolling average of our drag coefficients (solid blue line) is (1) a good match to parameterizations for wind speeds from 10 to 20 m/s and (2) shows the expected fall off for wind speeds greater than approximately 45 m/s. Dashed blue lines are the median plus and minus two standard deviations in the mean.



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

Notation: Subscript *i* denotes a data record where all variables with same value of *i* come from the same layer and time

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

θ is potential temperature

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

q is specific humidity

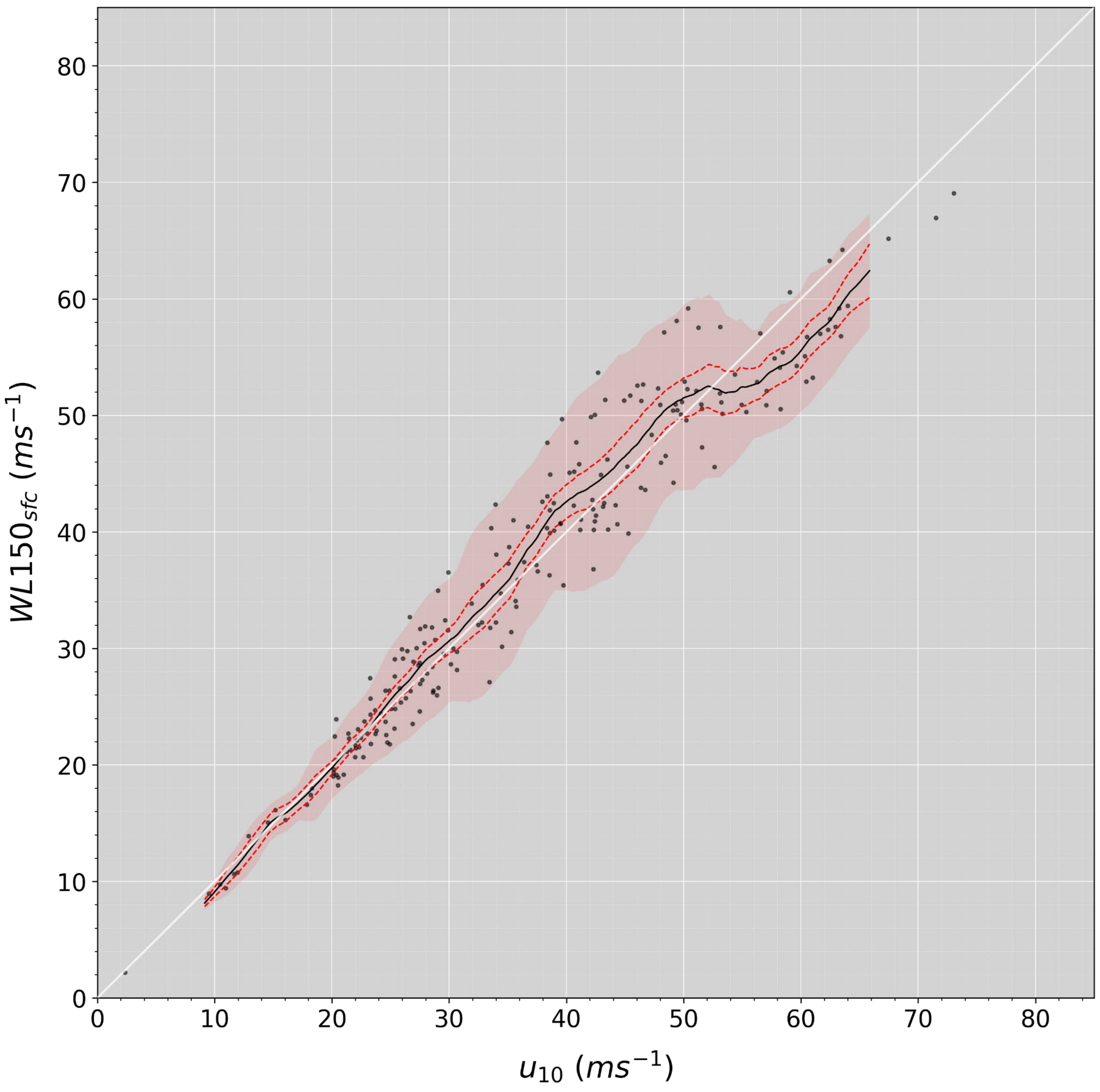
Heat Fluxes

$$\tau = \rho u_* |u_*|$$
$$Q_{sen} = -\rho C_P |u_*| \theta_*$$
$$Q_{lat} = -\rho L_V |u_*| q_*$$

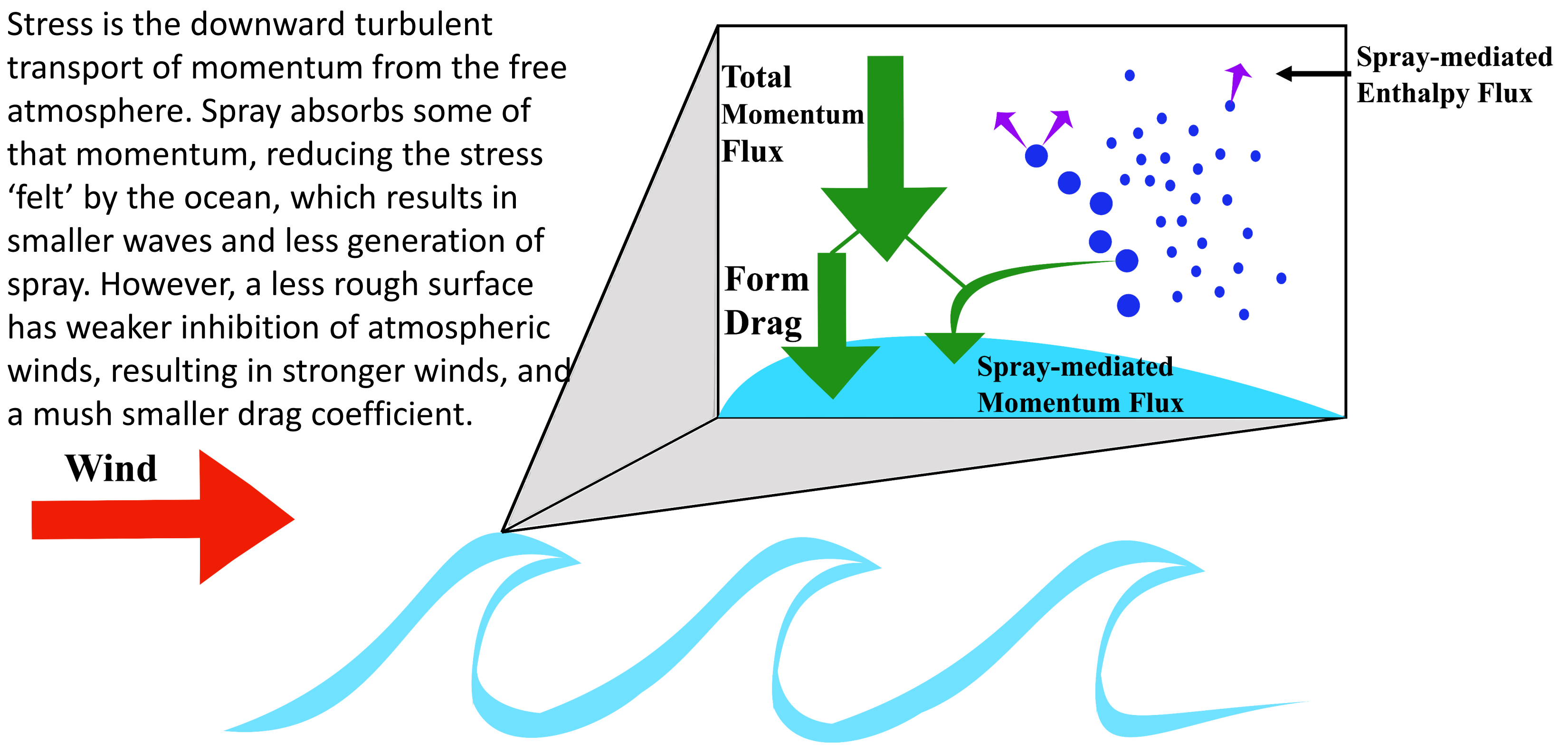
Where the variables are determined from the solutions to the log profile equations, ρ is the density of air, C_p is the heat capacity of air, and L_V is the latent heat of vaporization.

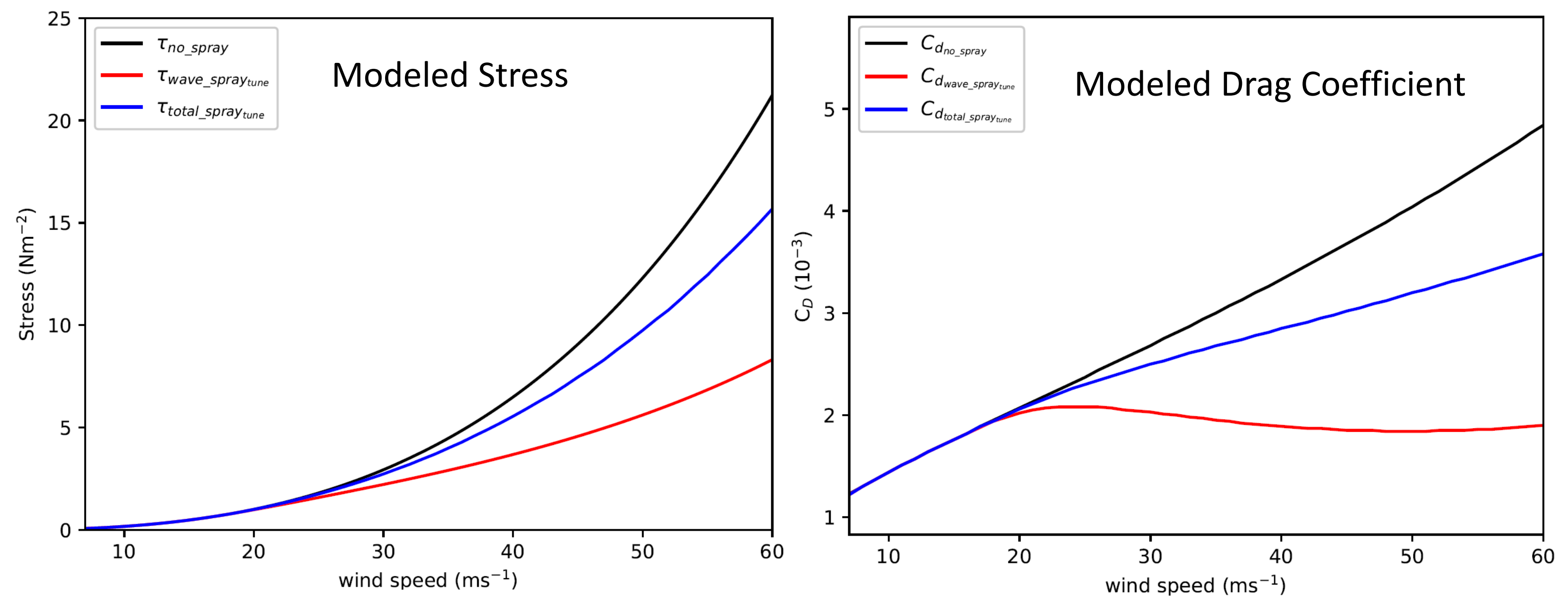
Our fluxes are currently rather noisy. We are working on improving the methodology and increasing the number of calculated fluxes.

Our drag coefficients are also noisy, but the median is consistent with traditional observations for the 10 to 10 ms^{-1} range! This is a departure from methods that average profiles for similar wind speeds.



Stress is the downward turbulent transport of momentum from the free atmosphere. Spray absorbs some of that momentum, reducing the stress 'felt' by the ocean, which results in smaller waves and less generation of spray. However, a less rough surface has weaker inhibition of atmospheric winds, resulting in stronger winds, and a mush smaller drag coefficient.





Modeled stress (left) and drag coefficient (right) as a function of 10 meter wind speed (U_{10}). The black line shows an increase in stress and the drag coefficient as wind speed increases, as expected if modeling that works well for U_{10} < 20 ms^{-1} applies at stronger wind speeds. The red line shows the wave stress and C_D same model modified to include the extraction of momentum by spray, adapted from Troitskaya et al. (2017) with minor tuning to improve the results for U_{10} > 35 ms^{-1} . The blue line shows the spray-modified stress and C_D for the atmosphere for the model used to determine the red line.

How do we do fit the profiles of wind, temperature and humidity?

- Theory and observations indicate that there is an atmospheric layer (a range of heights near the surface) with constant surface turbulent vertical fluxes (e.g., stress (τ), sensible heat (Q_{sen}) and latent heat (Q_{lat})).
- We were worried that sea spray might overwhelm this layer.
  - Or maybe it simply eroded the bottom of the layer?
  - Or the log-layer simply formed about the spray layer?
- Dropsonde observations show log-linear layers above what appears to be spray layers.
  - Spray layers have relatively uniform values of potential temperature (but this is normal in a hurricane)
  - Spray layers have relative uniform layers of specific humidity (moisture), which is not normal,
  - Wind speeds often are greater in a spray layer than the for the air just above the spray layer.
    - Spray gains momentum from the winds and falls back towards the ocean surface (downward transport).
- For conditions of neutral stratification ($L = \infty$ & $\Psi = 0$), the profiles of wind speed, potential temperature and specific humidity could be solved for independently.
- But Ralph Foster pointed out that departures from neutral conditions were too large to ignore.
- Therefore, we solve all three profiles simultaneously,
  - Determining *L* from u_*, θ_*, q_*, and average near surface variables used to determine u_*, θ_*, q_* .
  - We confirm Ralph Foster's finding that considering stability is important.
- Challenges:
  - We manually determine the bounds of the log-layers.
  - Roughness lengths are too noisy.
    - This has non-negligible impacts on u_*, θ_*, q_* .
    - Like other researchers, we have to average to get a stable median, but we average after fitting the log-profiles.
  - We can use only about 50% of dropsondes.
  - Lower wind speeds require a thicker log-layer to get good solutions (about 7 wind observations compared to 5 for wind speeds >20 ms^{-1}).
- Strengths:
  - We can use approximately 50% of dropsondes.
  - Results are consistent with routine observations from 10 – 20 ms^{-1}.
  - We see a reduced drag coefficient for extreme winds, consistent with expectations.
  - We can calculate fluxes and drag coefficients.
  - We can calculate 10 meter winds that account for a displacement height.

Modeling Reduction of Momentum Due to Spray

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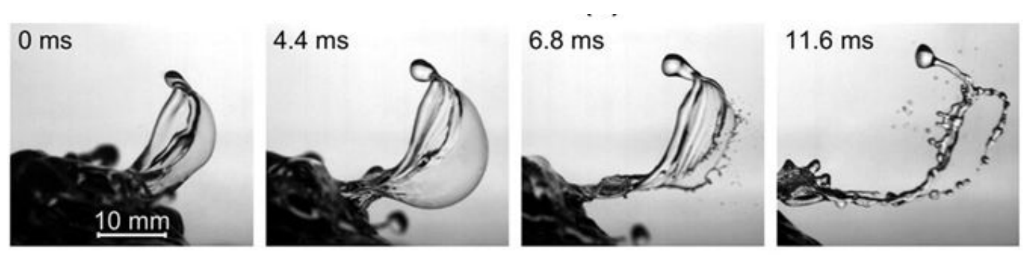

$$\tau_{tot} = \tau_{wave} + \tau_{bag} + \tau_{drop}$$

The total stress in the spray layer is assumed to be comprised of three additive components:

- Form drag of surface waves
- 'bag' stress, or the airflow resistance to the microsails
- The droplet stress, or the momentum acquired during the droplet production

The wave component is based on a Charnock parameterization for roughness due to gravity waves (following Blair et al. 2021), which has a drag coefficient that increases linearly with wind speed for U_{10} > 8 ms^{-1}.

Spray removes momentum from the air

- reducing the stress on the ocean surface,
- Reducing the roughness of waves,
- Causing surface winds to increase.
- Causing a net decrease in atmospheric stress, and
- Decreasing the drag coefficient

The model for stress from bags and drops seems to work well for U_{10} < 35 ms^{-1}.

- Very minor changes in the parameterizations can remove the increase in drag for U_{10} > 35 ms^{-1}.
- But how should they be tuned?

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