Wind Europe Technology Workshop 2025 | Session: Modelling I

Accurately Modelling Site-Specific Turbulence Intensity Time Series Offshore

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Take-aways:

Atmospheric Boundary Layer (ABL) height and surface **stability matter**

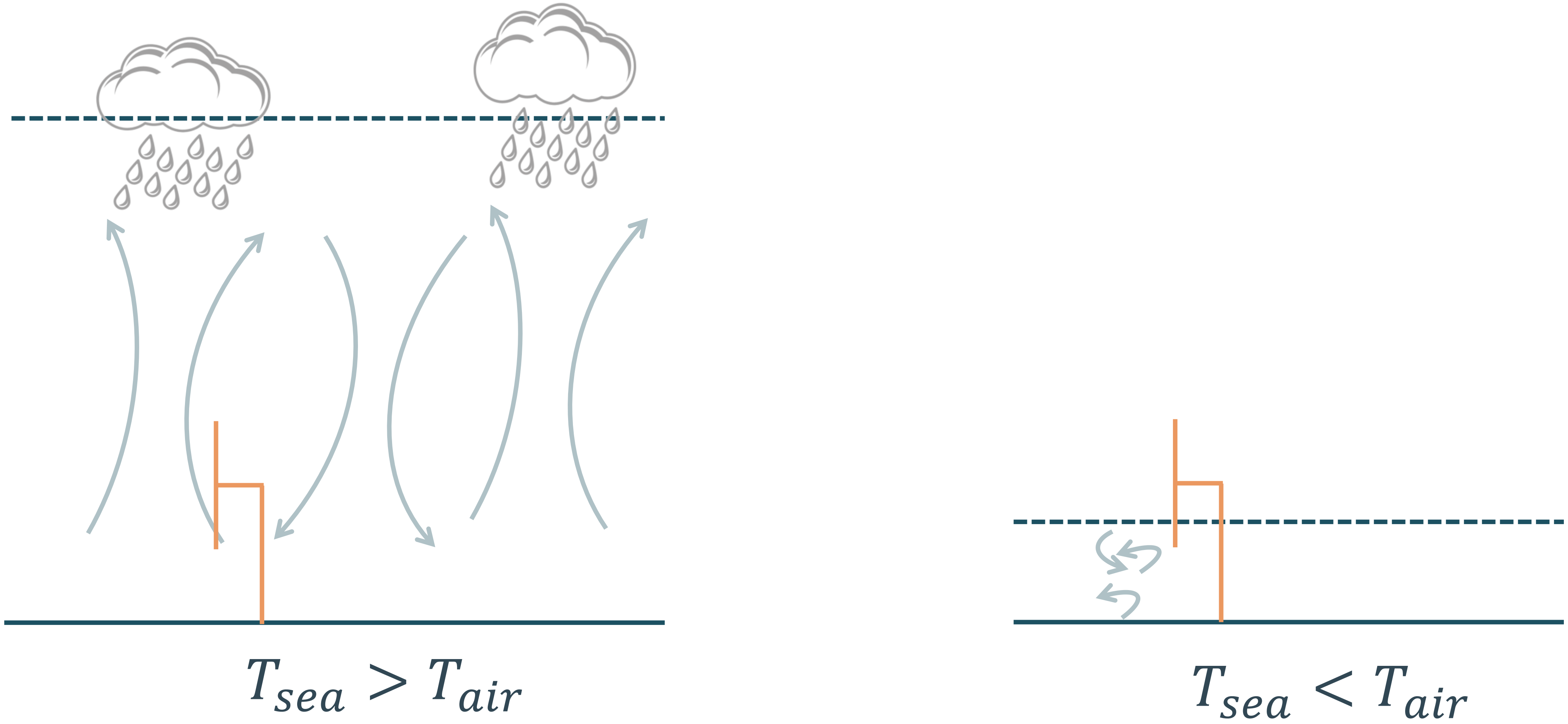
Townsend's law can be applied across regions with varying ABL dynamics, when accounting for convection.

$$TI(z) = \frac{\sigma_U(z)}{U(z)}$$

Turbulence Intensity (*TI*) time series required for **Yield** (wake, power curve) and **Site Conditions Assessment** studies.

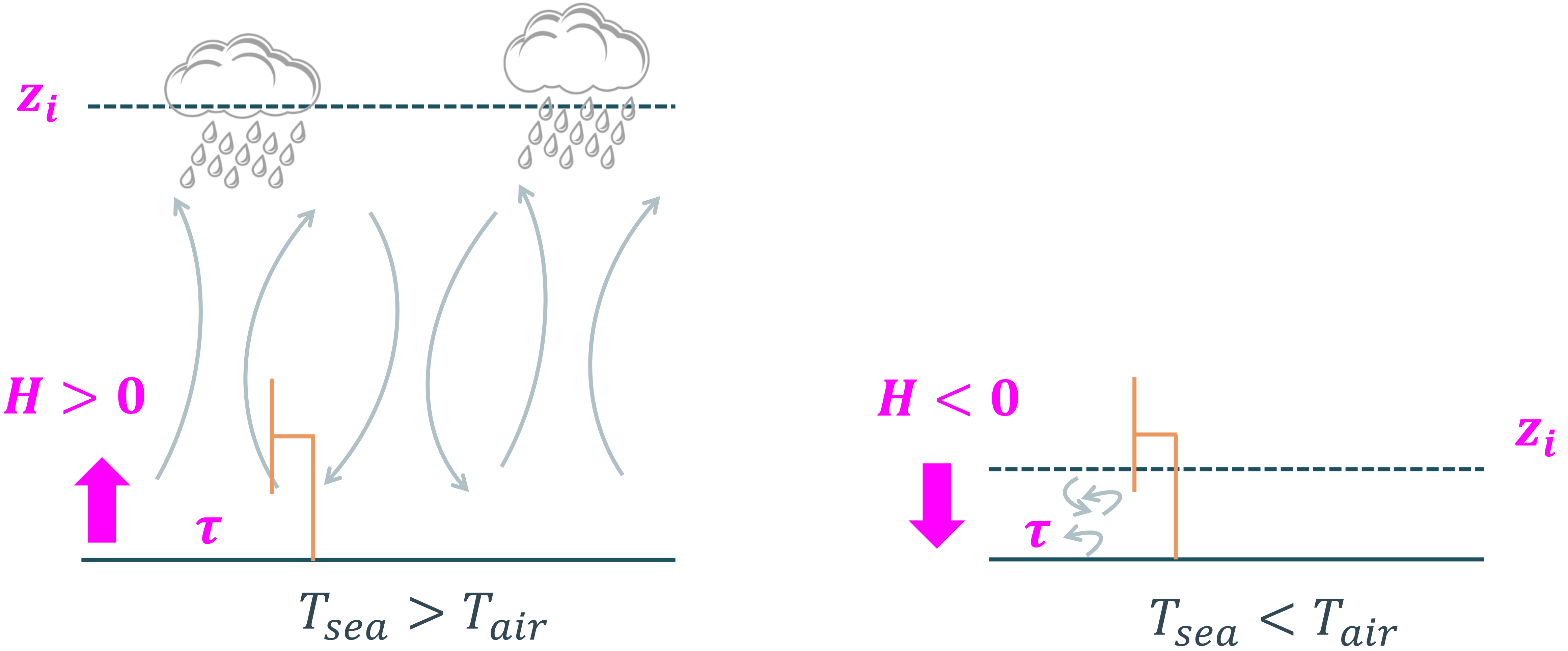
For offshore sites, **valid *TI* in-situ measurements of are often lacking**.

It is a necessity to be able to **model site specific *TI***.


$T_{sea} > T_{air}$
$T_{sea} < T_{air}$

z_i boundary layer height [mASL]

H is the heat flux [Km/s]



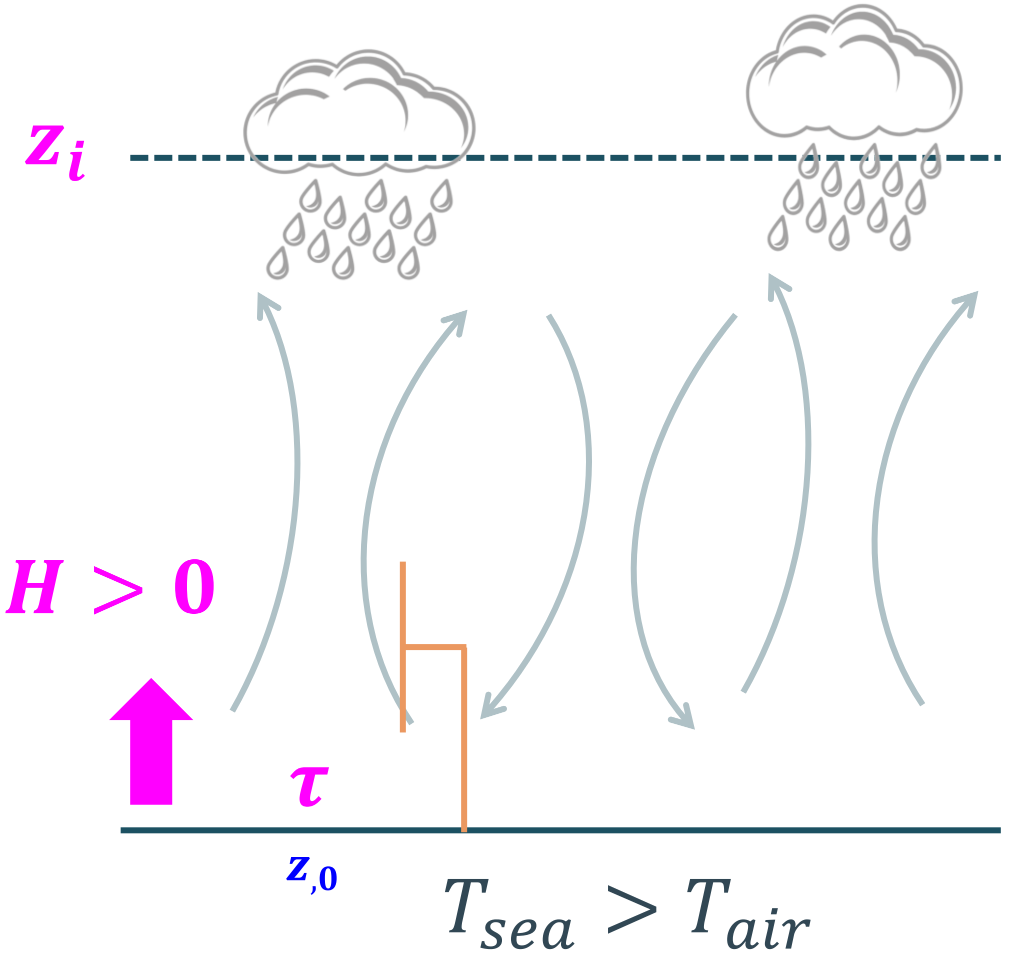
z_i boundary layer height [mASL]

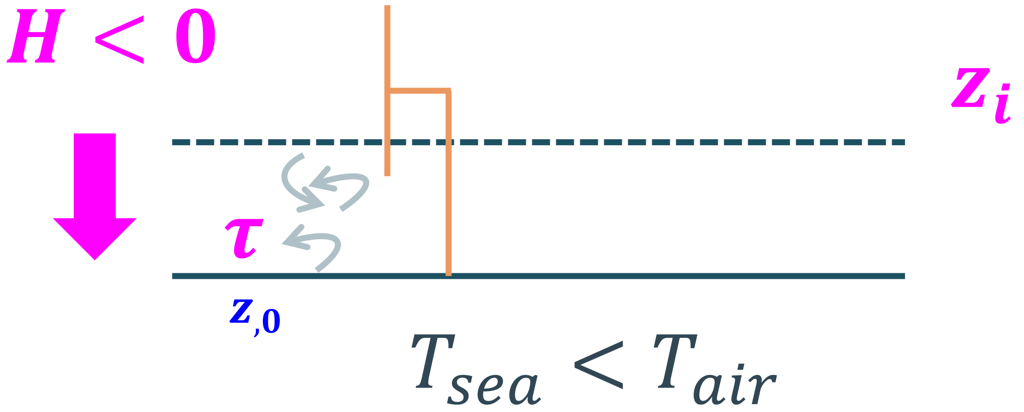
H is the heat flux [Km/s]

$u_{*,0} = \sqrt{\left|\frac{\tau}{\rho}\right|}$ friction velocity at the surface [m/s]

$w_{*,0} = \left(\frac{g}{T_v} z_i H\right)^{1/3}$ convective scale velocity [m/s]

$L = \frac{-u_{*,0}^3 T_v}{kgH}$ the Obukhov length [m]





Mean and variances of the wind speed are **entangled.**

$$U = f\left(z, u_{*,0}, L, z_i\right)$$

$$\sigma_U = g\left(u_{*,0}, w_{*,0}, z_i\right)$$

$$TI = \frac{\sigma_U}{U}$$

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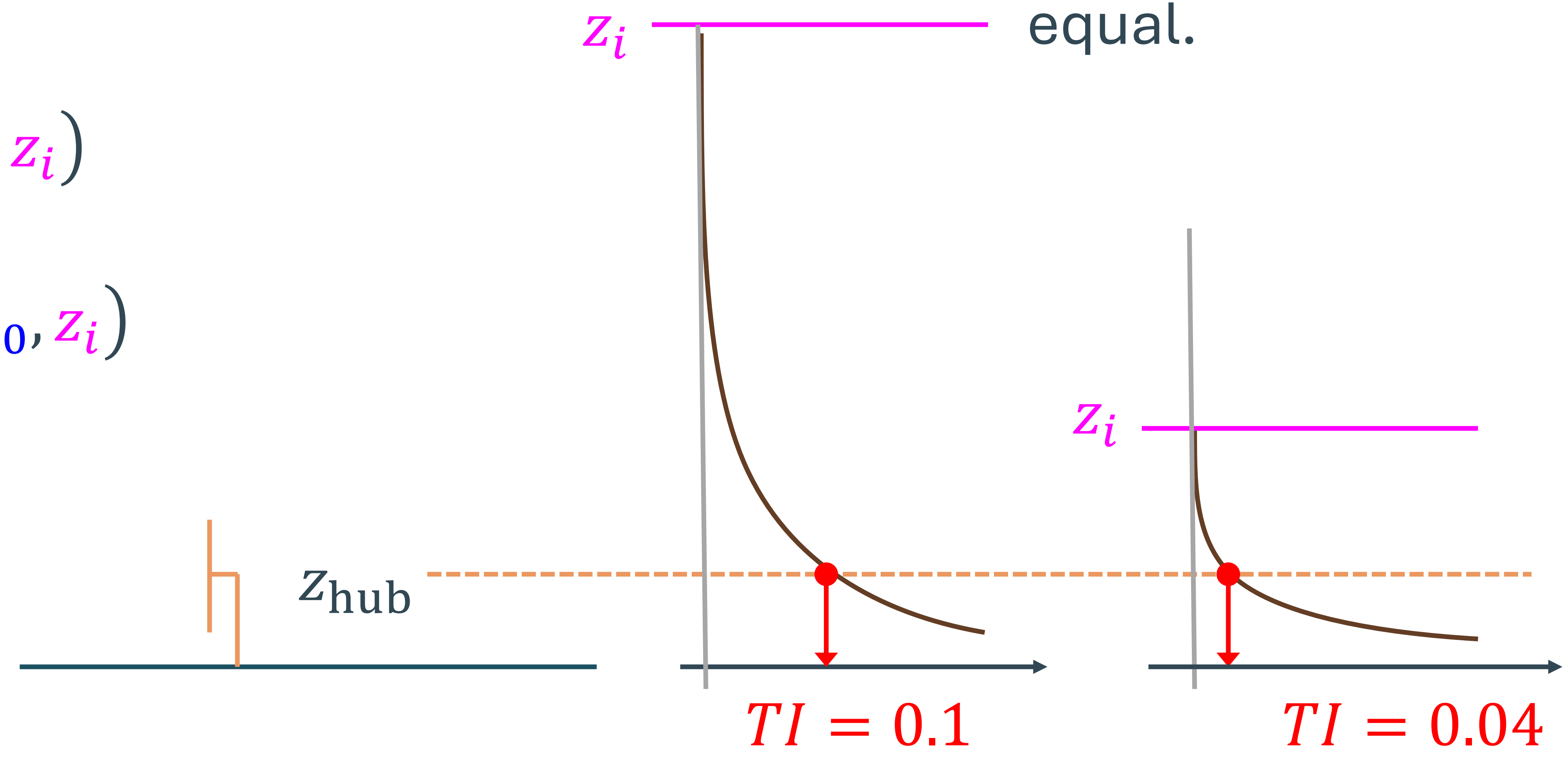
Mean and variances of the wind speed are **entangled.**

$$U = f(z, u_{*,0}, L, z_i)$$

$$\sigma_U = g(u_{*,0}, w_{*,0}, z_i)$$

$$TI = \frac{\sigma_U}{U}$$

Illustration of a change in z_i, all other parameters being equal.



Townsend's **attached eddy hypothesis**

$$\left(\frac{\sigma_U}{u_{*0}}\right)^2 = B - A \cdot \ln\left(\frac{z}{z_i}\right) \text{ where } A \text{ is a universal constant } \approx 1.26$$

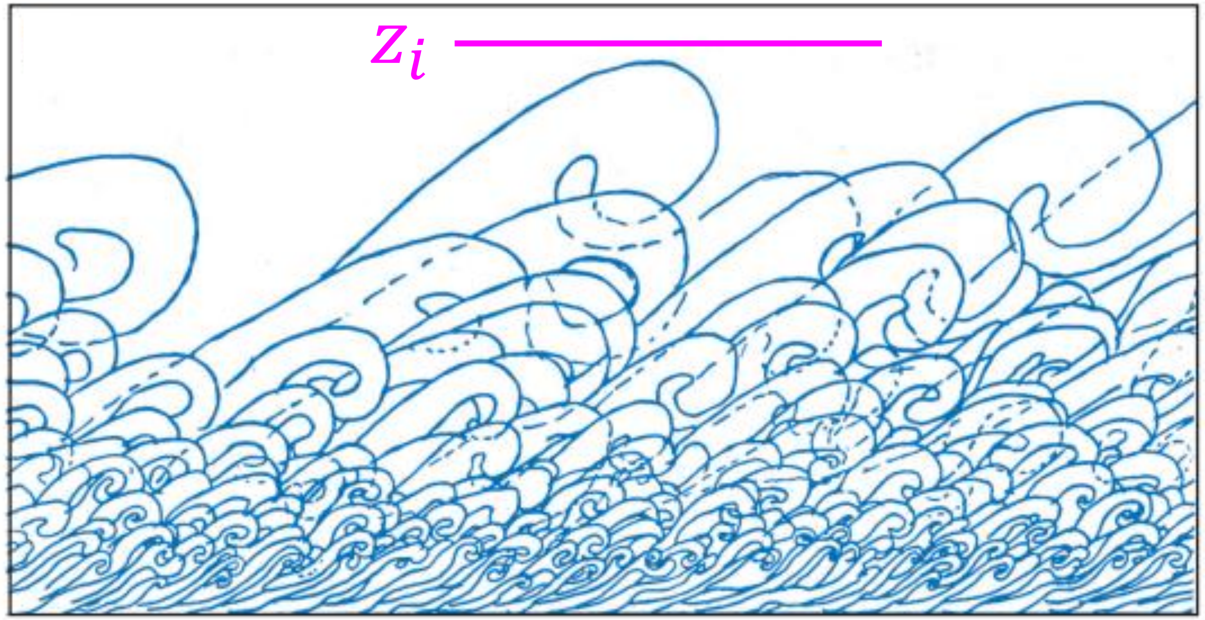
constant scale ratio

…

$L_3 = C^2 \cdot L_1$

$L_2 = C \cdot L_1$

L_1



population density

(Marusic and Monty, 2019) doi.org/10.1146/annurev-fluid-010518-040427

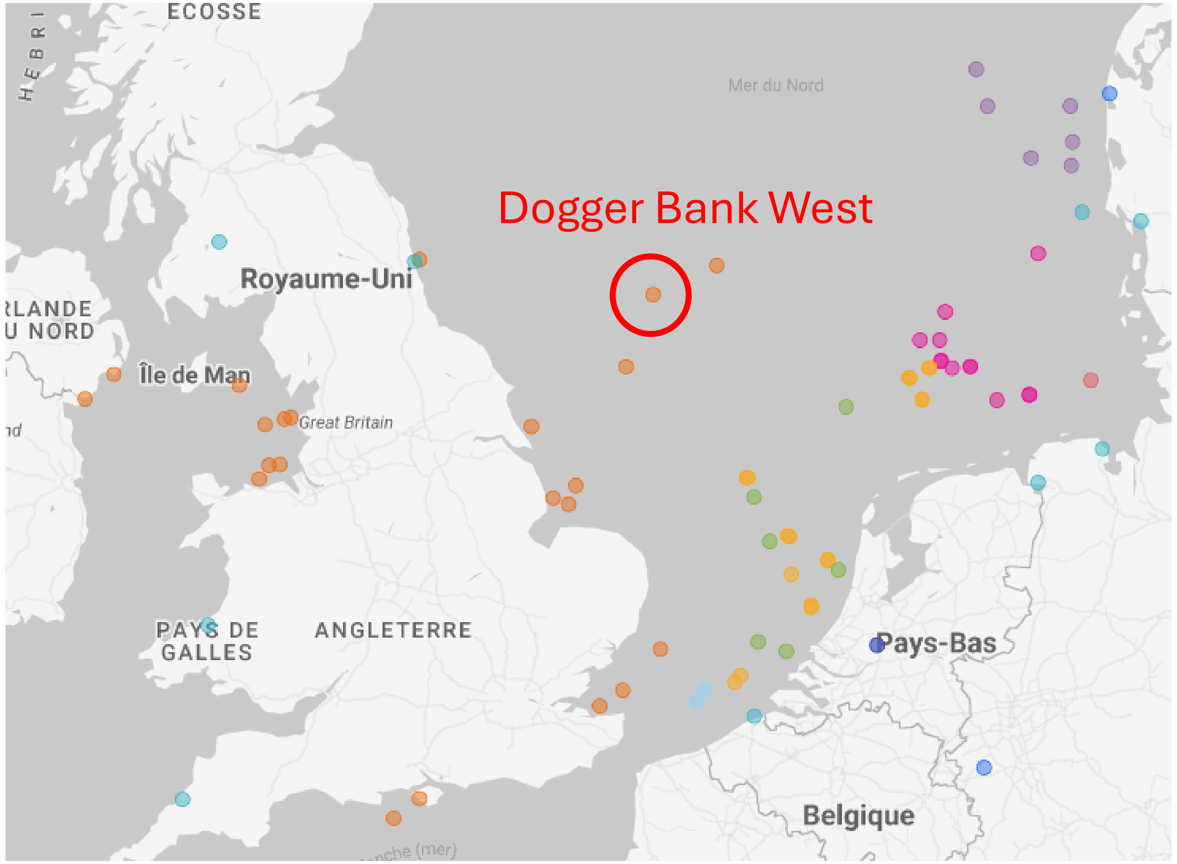
Step 1:

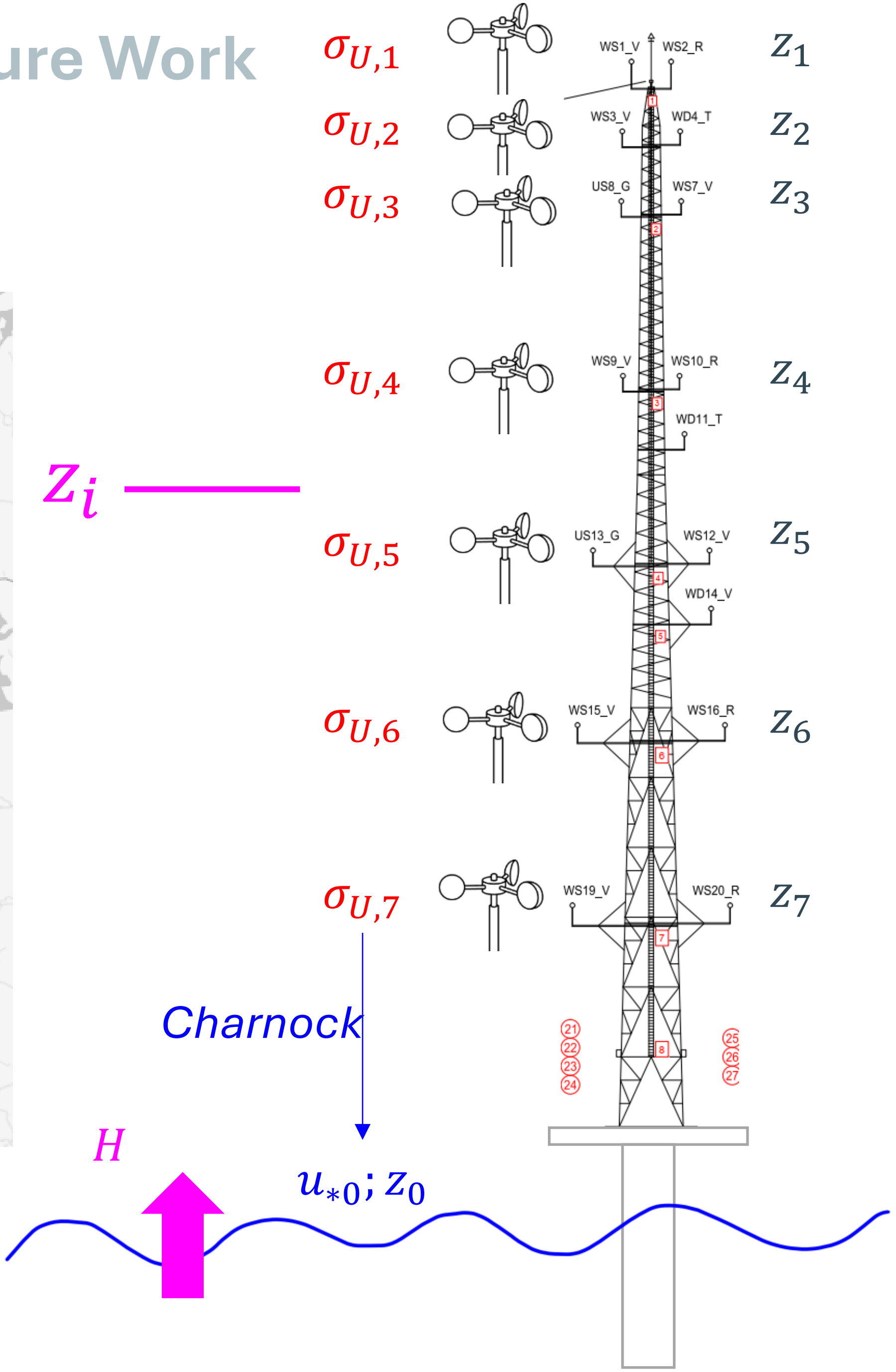
Verify Townsend's model

in strong wind neutral conditions

using

z_i and H from ERA5





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Step 1:

Verify Townsend's model

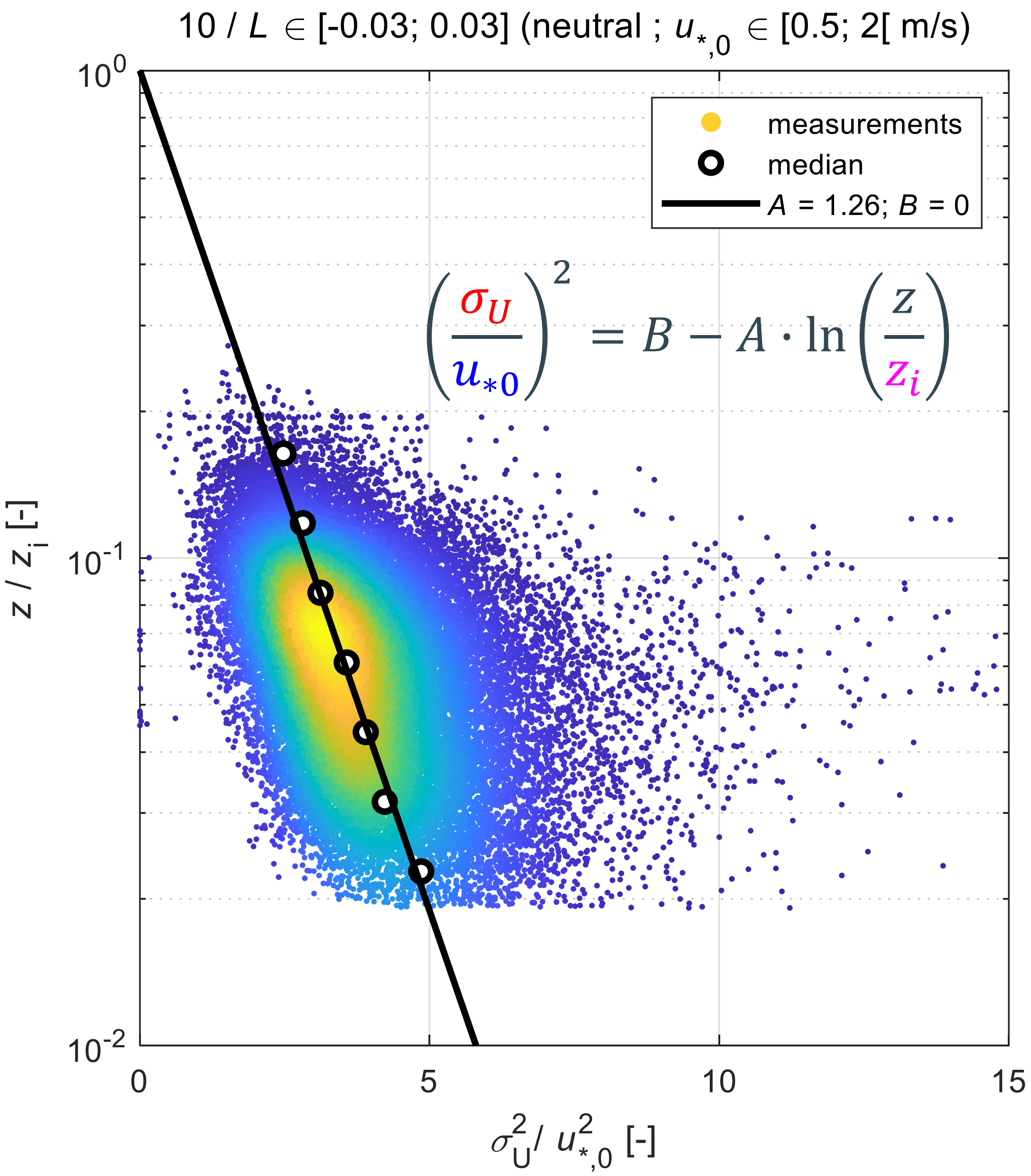
in <u>strong wind neutral conditions</u>

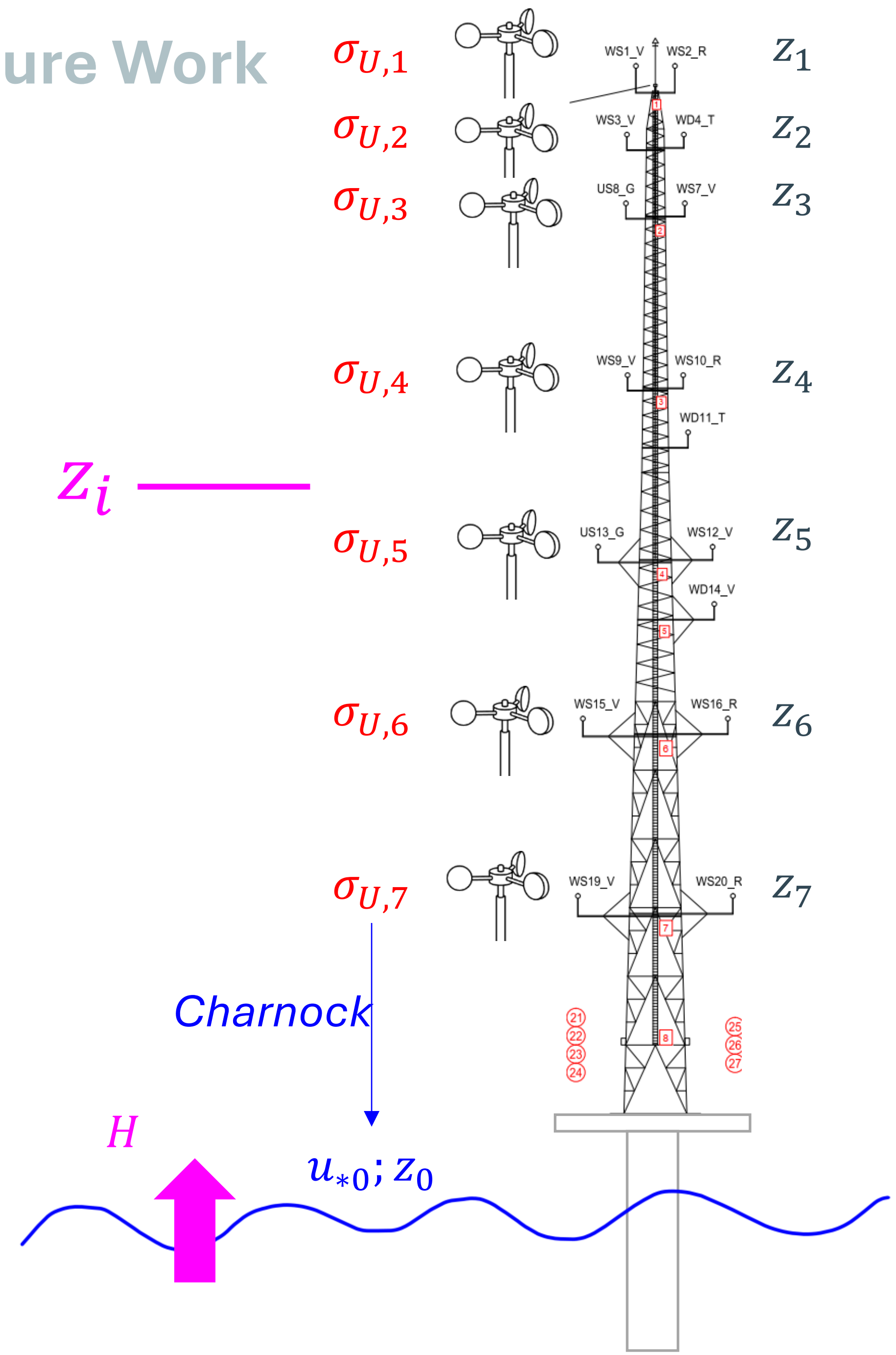
using

z_i and H from ERA5

+ <u>detrended</u> measurements

and z_i /2 for stable atm*





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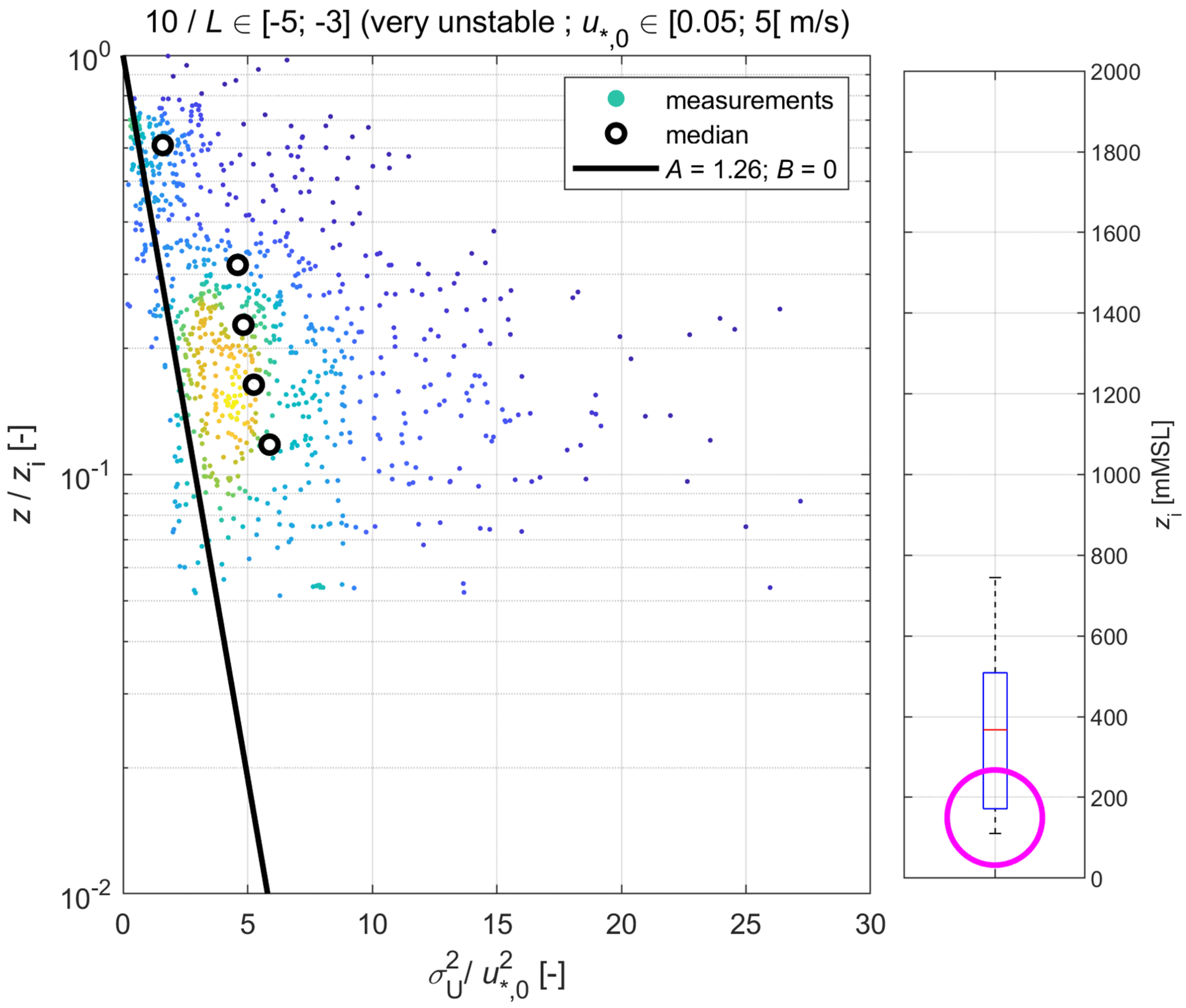
*see argumentation in https://c2wind.com/f/content/23072-04-034---kriegers-flak-ii---wind-assessment.pdf



Step 2:

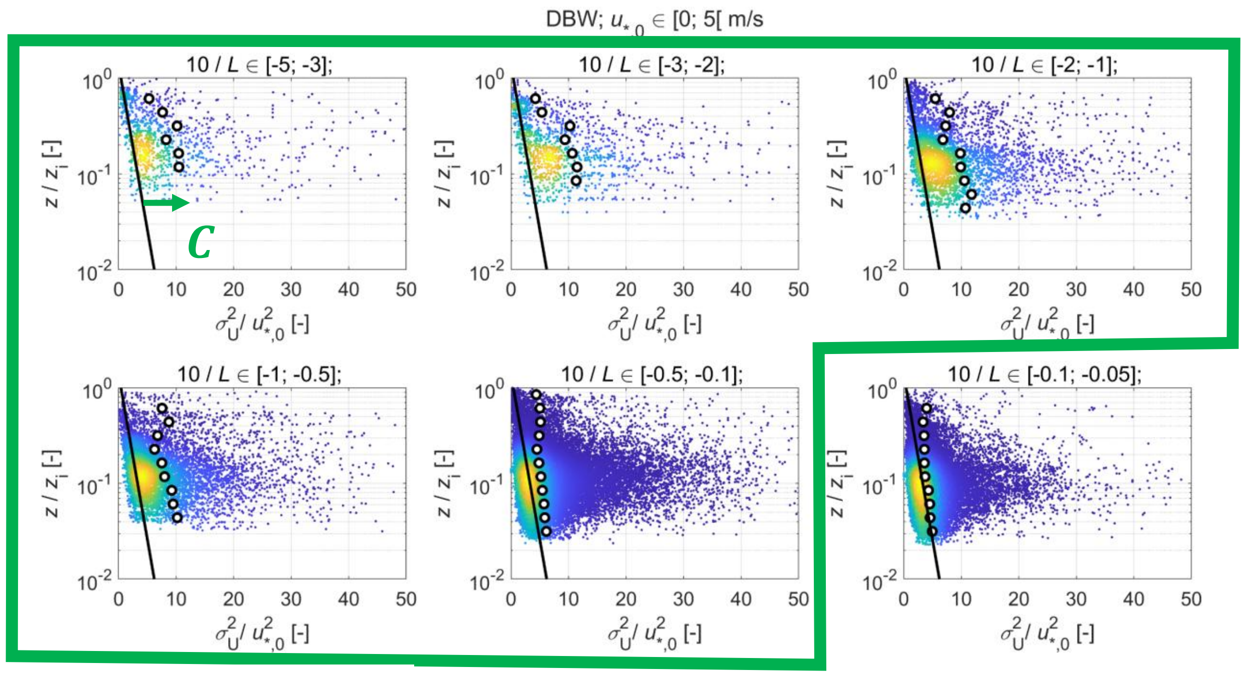
Verify Townsend's model in all stabilities.

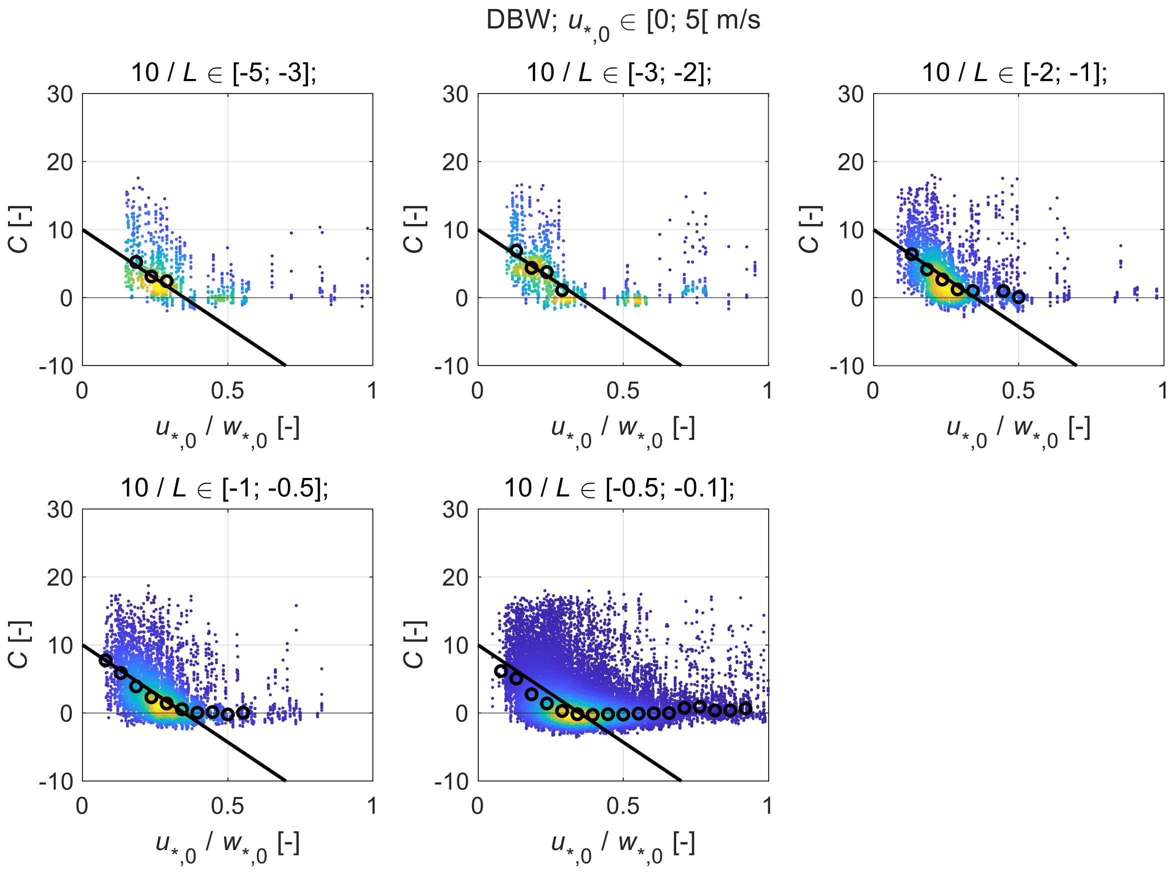
Underestimation in (some but not all) unstable conditions

Step 3: account for convection

$$\left(\frac{\sigma_U}{u_{*0}}\right)^2 = B - A \cdot \ln\left(\frac{z}{z_i}\right) + C$$

Very unstable atm $L < -100\ \mathrm{m}$: $C = f\left(\frac{u_{*,0}}{w_{*0}}\right)$





$$C = \frac{-10}{0.35} \cdot \frac{u_{*,0}}{w_{*0}} + 10$$

$$C = 0 \text{ for } \frac{u_{*,0}}{w_{*0}} > 0.35$$

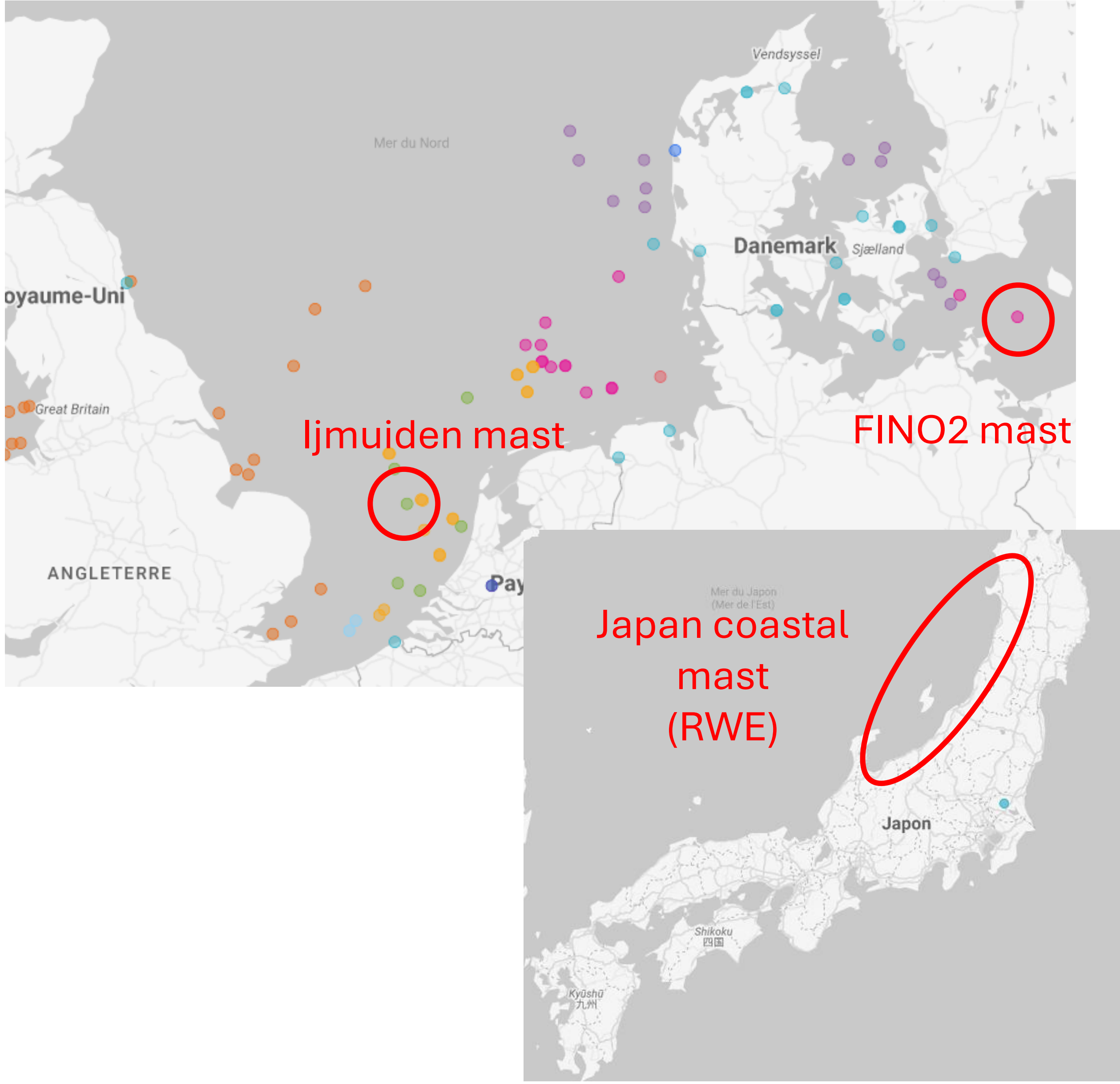
Step 4: Compute *TI* time series

$$\begin{cases} \sigma_U = u_{*0} \cdot \left[B - A \cdot \ln\left(\frac{z}{z_i}\right) + C\left(\frac{u_{*0}}{w_{*0}}\right) \right]^{1/2} \\ U = \frac{u_{*0}}{\kappa}\left[\ln\left(\frac{z}{z_0}\right) - \psi\left(\frac{z}{L}\right) + \cdots \right] \end{cases}$$

from (Gryning, 2007)

(using ERA5 + a stochastic component is added to represent microscale variability)

Step 5: Validate against independent offshore measurements



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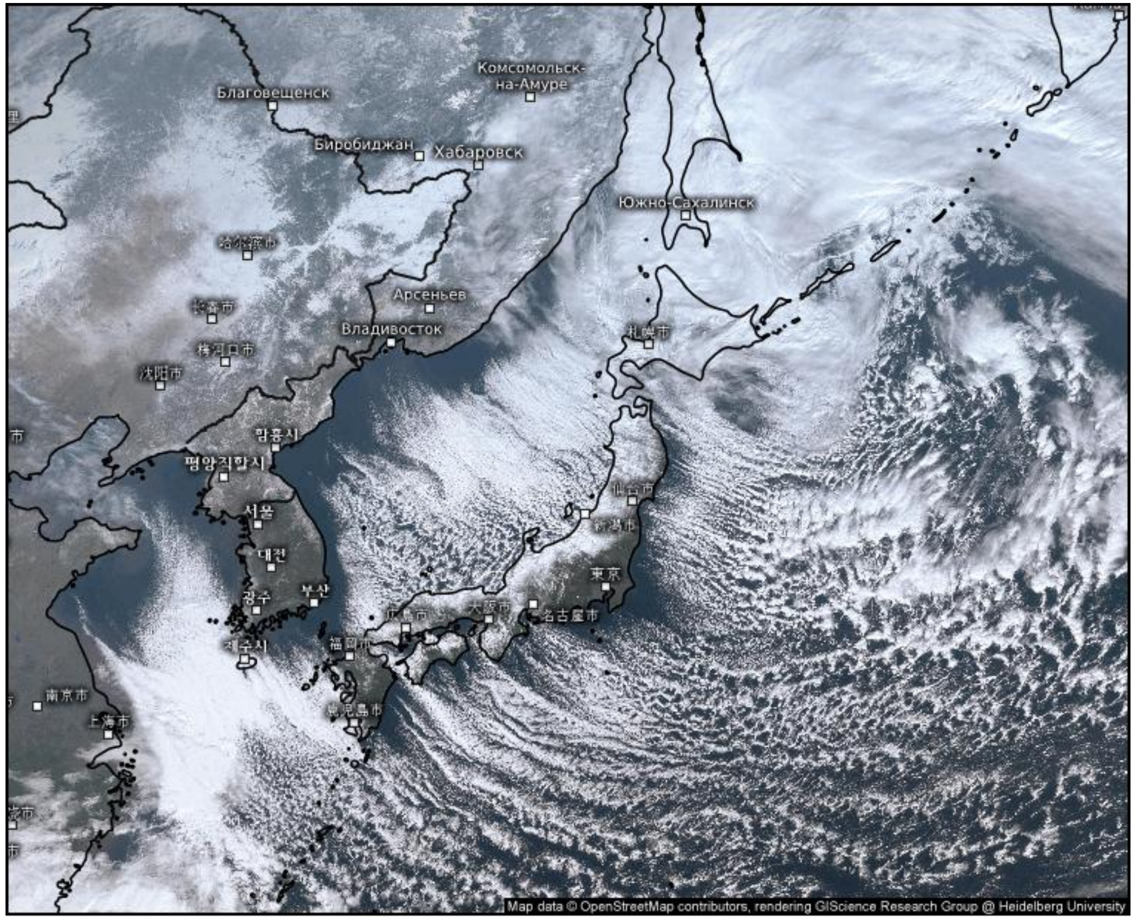
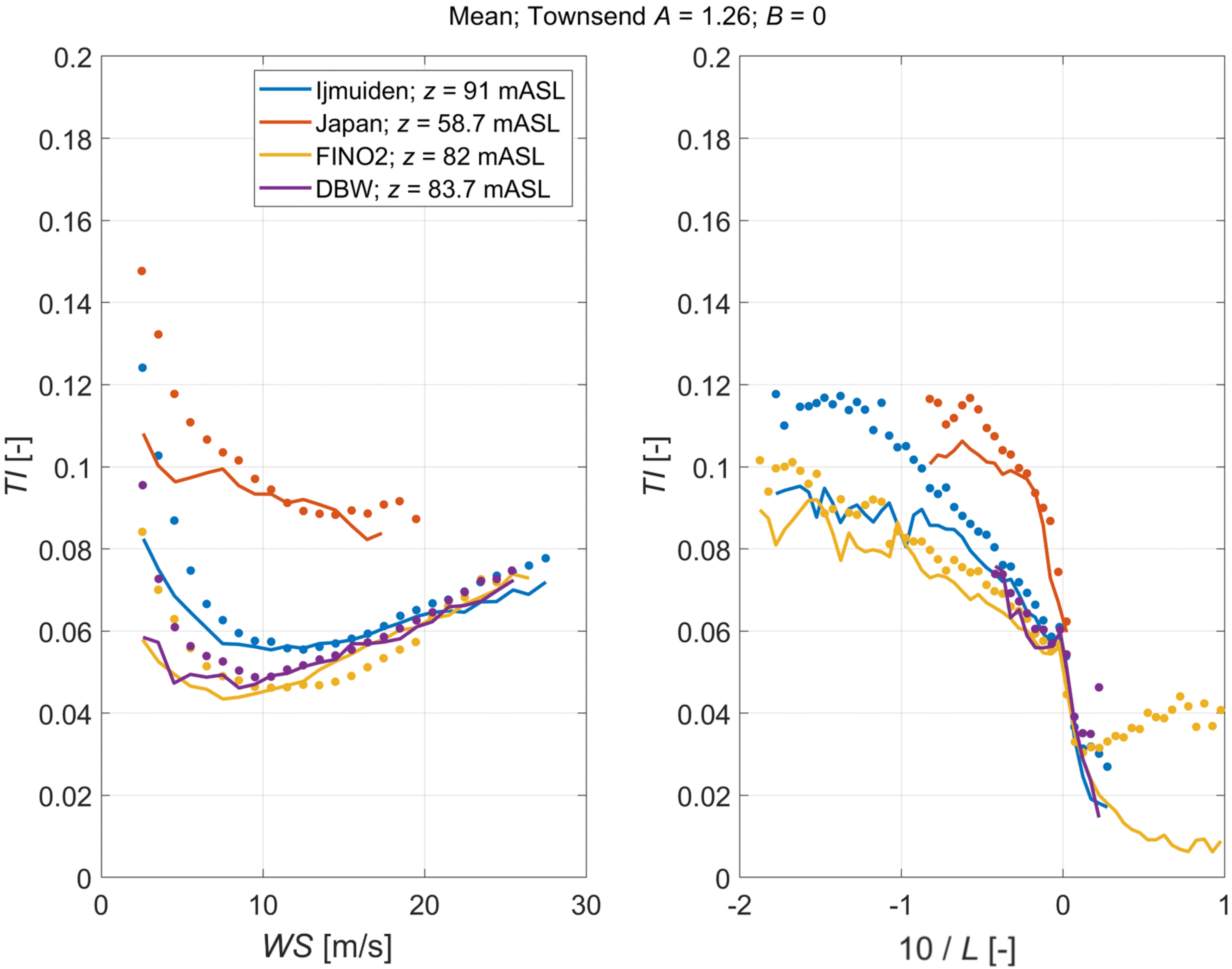
Main drivers: z_i and L.

Highly convective conditions in Japan: large TI.





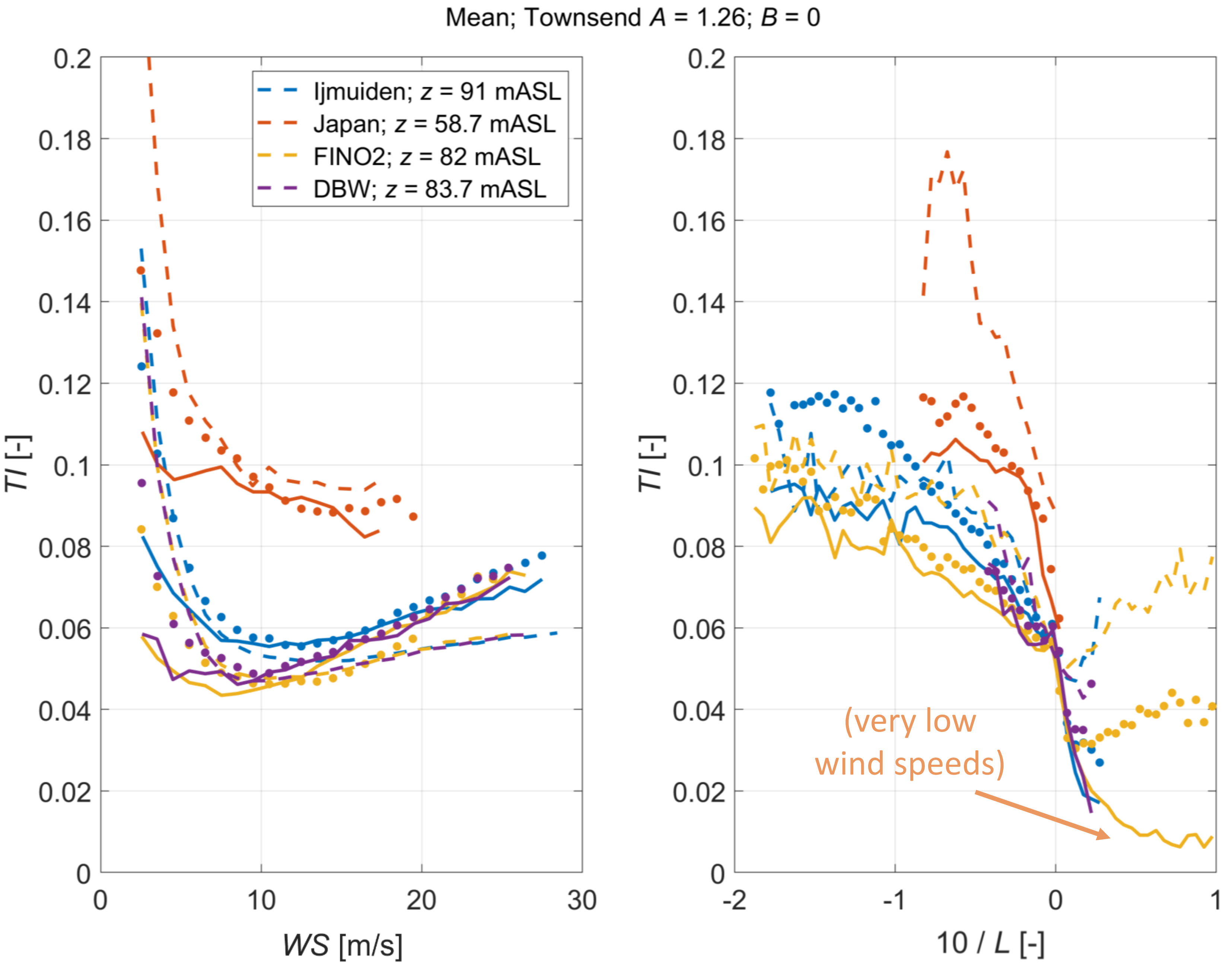
Now adding WRF

(dashed lines --)

$$TKE = \frac{1}{2}\sqrt{\overline{u'^2} + \overline{v'^2} + \overline{w'^2}}$$

$$\begin{cases} \frac{\sigma_u}{u_*} \approx 2.5 \\ \frac{\sigma_v}{u_*} = \alpha \approx 1.9; \frac{\sigma_w}{u_*} = \beta \approx 1.3 \end{cases}$$

$$\sigma_u = \sqrt{\frac{2 \cdot TKE}{1 + \frac{1}{\alpha} + \frac{1}{\beta}}}$$



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- ABL dynamics vary from site to site and can be checked with ERA5 ♥
- TI time series can be derived solely using ERA5 and Townsend's law
- The WRF configuration tested here gives satisfactory results

- More validations.
- < 1/600s stochasticity leads to biased statistics
- How to properly account for < 1/600 s frequencies in Load Cases

References:

- (Stull, 2017) and (Townsend, 1976) for the basics
- (Gryning, 2007) and (Peña, 2008) for dependency of U on surface stability, boundary layer height.
- (Ortiz-Suslow et al., 2021) for challenging surface layer assumptions
- (Svenningsen, 2018) for inspiration on deriving analytical formulations of TI in the surface layer.
- (Puccioni, 2023) for application of Townsend law to lidar measurements onshore in Texas.
- (Heitmann, 2005) for critical ratio of convective and friction velocities.
- (Larsén, 2024) for derivation of TI using WRF TKE

- And Nicolai Nygaard for asking me if I had heard about the Townsend model (I had not)