Air-sea scalar transfer – effects of wind and waves on equivalent roughness length

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WHERE DISCOVERIES BEGIN

Parameterization of air-sea fluxes of momentum and scalar (temperature, humidity, soluble gases)

$\tau = \rho_a u_*^2$: wind stress
ρ_a : air density
u_* : friction velocity
$\theta_* u_*$: scalar flux

C_d : drag coefficient
C_θ : scalar transfer coefficient

z_0 : equivalent surface roughness of wind
z_θ: equivalent surface roughness of scalar

1. We parameterize the fluxes using mean wind speed at 10 meter height (u_{10}), mean scalar concentrations at 10 meter height (θ_{10}) and at sea surface (θ_0):

$$u_*^2 = C_d\, u_{10}^2, \qquad \theta_* u_* = C_\theta (\theta_{10} - \theta_0) u_{10}$$

2. We assume logarithmic profiles (in height z) of mean wind speed (u) and mean scalar concentration (θ), under neutral conditions (air temperature = water temperature), inside the constant stress (flux) layer, but above the direct effects of surface waves:

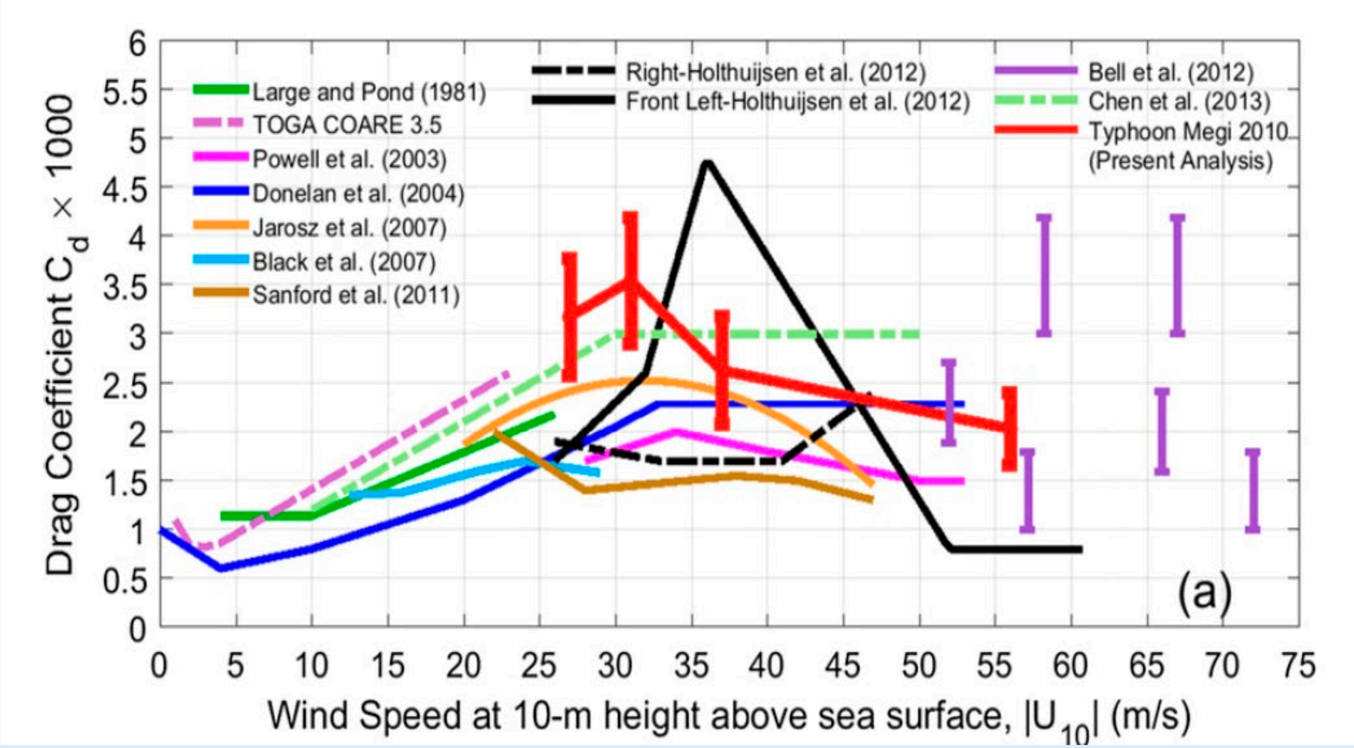
$$\frac{u(z)}{u_*} = \frac{1}{\kappa} log \frac{z}{z_0}\ , \qquad \frac{\theta(z) - \theta_0}{\theta_*} = \frac{0.74}{\kappa} log \frac{z}{z_\theta}$$

Then, C_d and C_θ are expressed as:

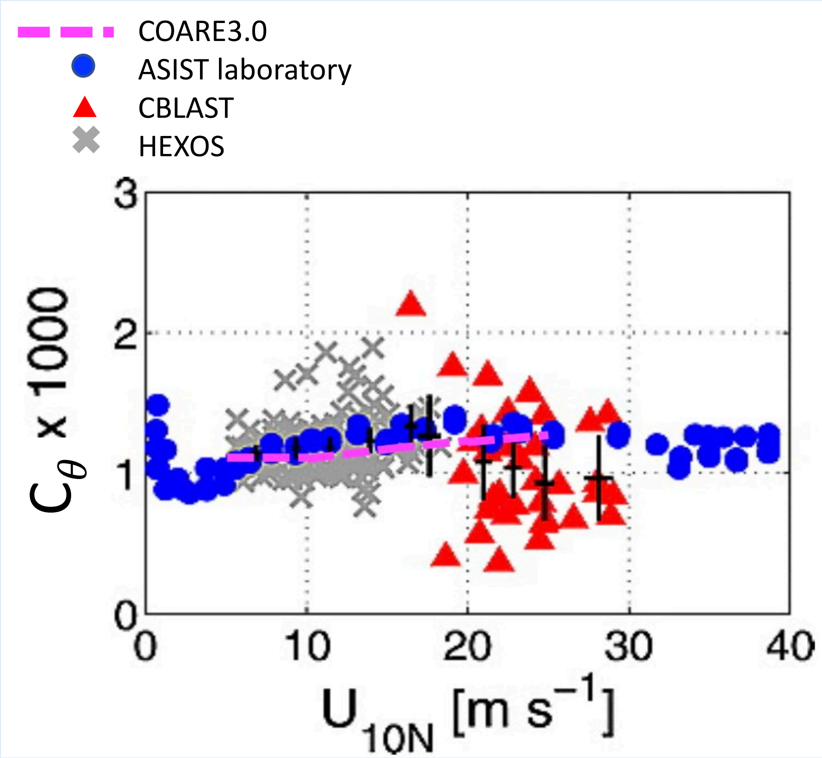
$$C_d = \left(\frac{1}{\kappa} log \frac{10}{z_0}\right)^{-2}, \qquad C_\theta = \left(\frac{1}{\kappa} log \frac{10}{z_0}\right)^{-1} \left(\frac{0.74}{\kappa} log \frac{10}{z_\theta}\right)^{-1}$$

C_d is a function of z_0 alone, but C_θ is a function of both z_0 and z_θ.

We know how C_d and C_θ vary with wind speed u_{10} (on average) quite well, except at very high wind speeds where the uncertainty is large.



Hsu et al. (2017)



Haus et al. (2010)

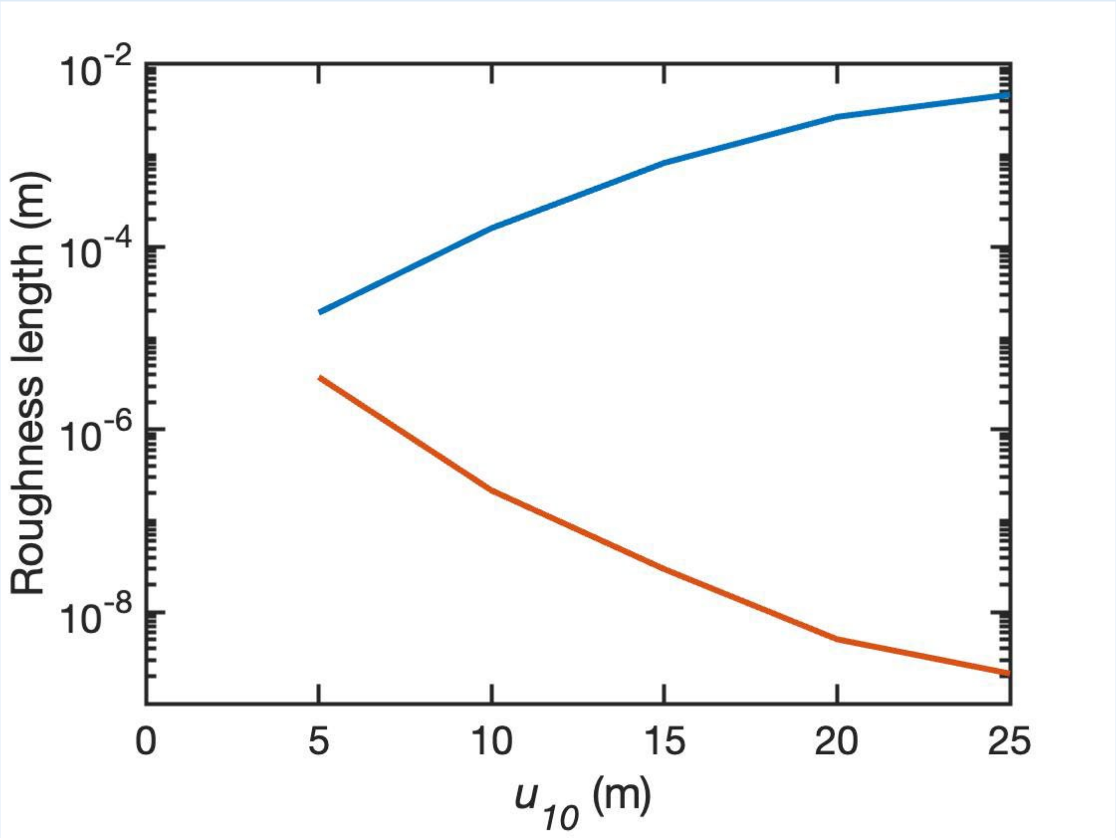
Up to wind speed 20 m/s, C_d rapidly increases but C_θ remains almost constant.

Recall that C_d and C_θ are expressed as:

$$C_d = \left(\frac{1}{\kappa} log \frac{10}{z_0}\right)^{-2}, \qquad C_\theta = \left(\frac{1}{\kappa} log \frac{10}{z_0}\right)^{-1} \left(\frac{0.74}{\kappa} log \frac{10}{z_\theta}\right)^{-1}$$

- From COARE3.5 C_d and COARE3.0 C_θ, we may calculate both z_0 and z_θ as functions of u_{10}.
- z_0 rapidly increases with u_{10}.
- z_θ rapidly decreases with u_{10}.

- I will demonstrate how ocean surface waves are responsible for increasing z_0 and decreasing z_θ.

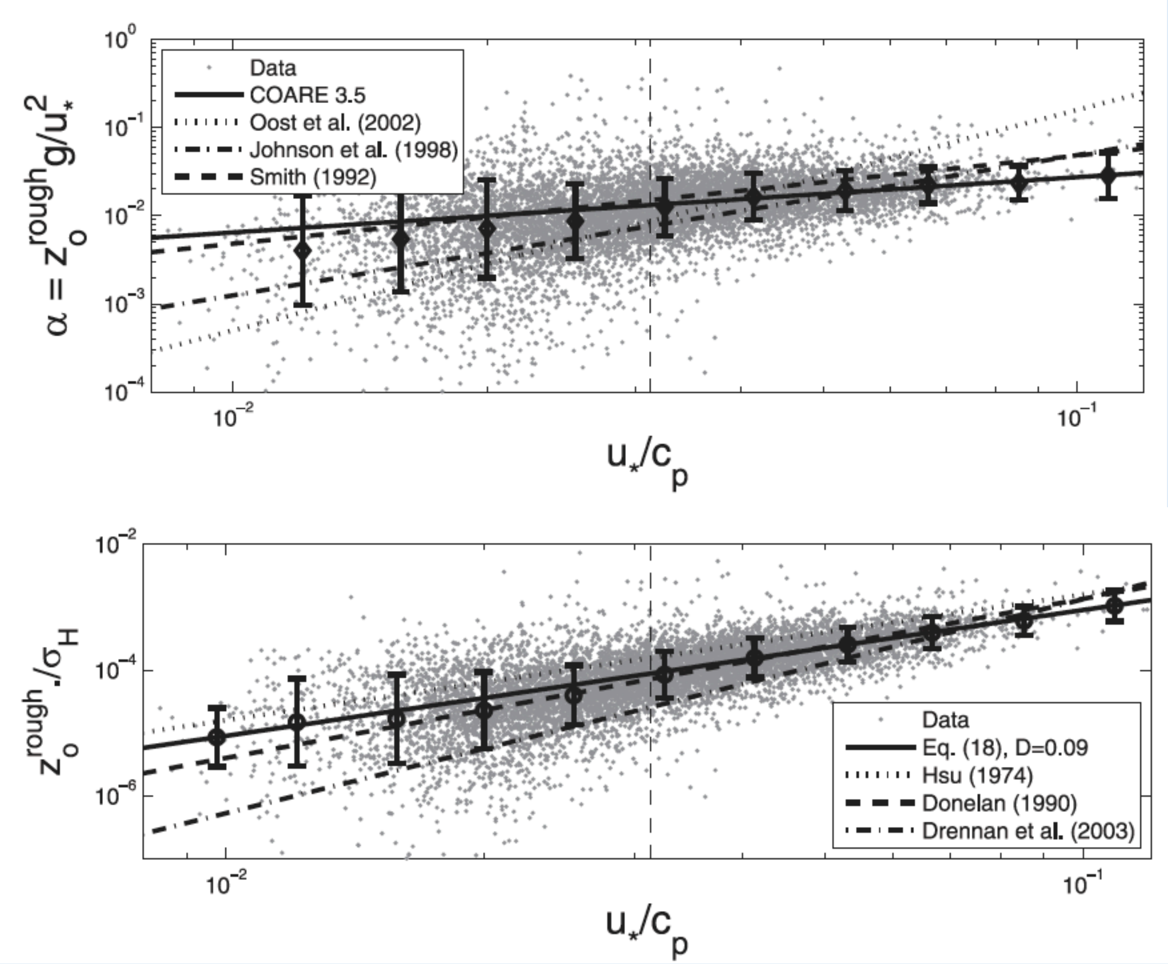


z_0 (blue) and z_θ (red) as functions of u_{10}

Sea state dependence of C_d

- If ocean surface waves are responsible for increasing z_0, it is expected that different sea states yield different z_0 (and C_d), even if wind speed u_{10} is the same.

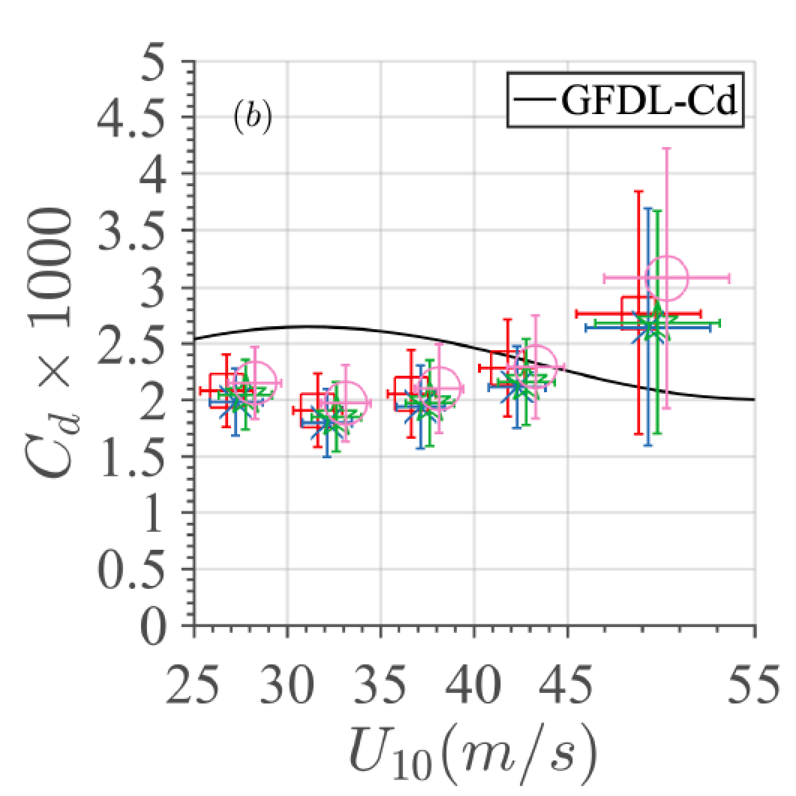
- However, the dependence of z_0 (and C_d) on wave parameters (e.g., wave age, wave steepness) is not always clear and not well constrained.



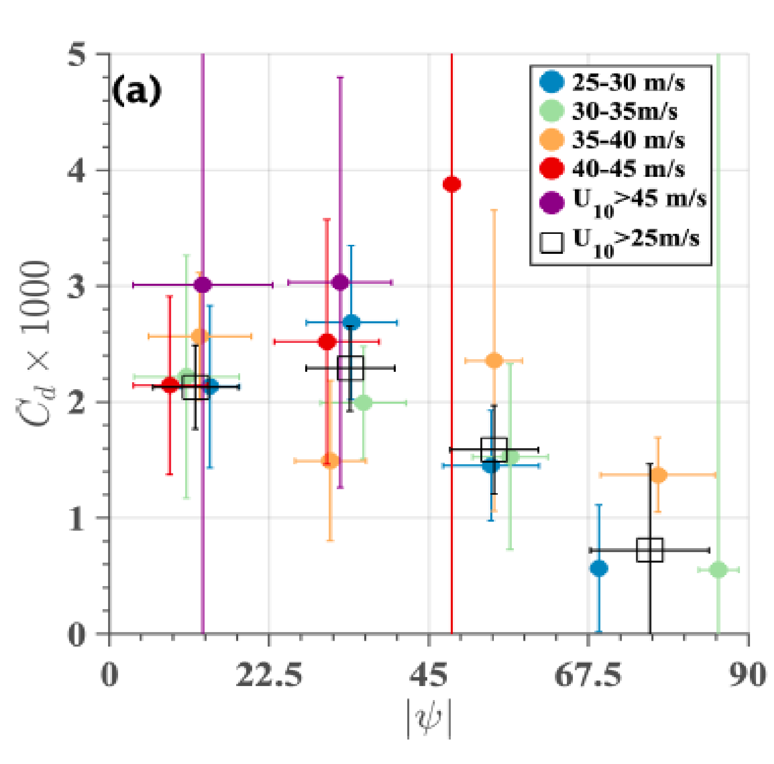
Wave age dependence of normalized roughness z_0 (Edson et al. 2013)

Sea state dependence of C_d

Our recent (observation + model) study suggests C_d weakly depends on u_{10} but **strongly depends on sea states** under **tropical cyclones** (wind speed u_{10} 25-55 m/s) (Zhou et al. 2022).



Wind speed dependence of C_d

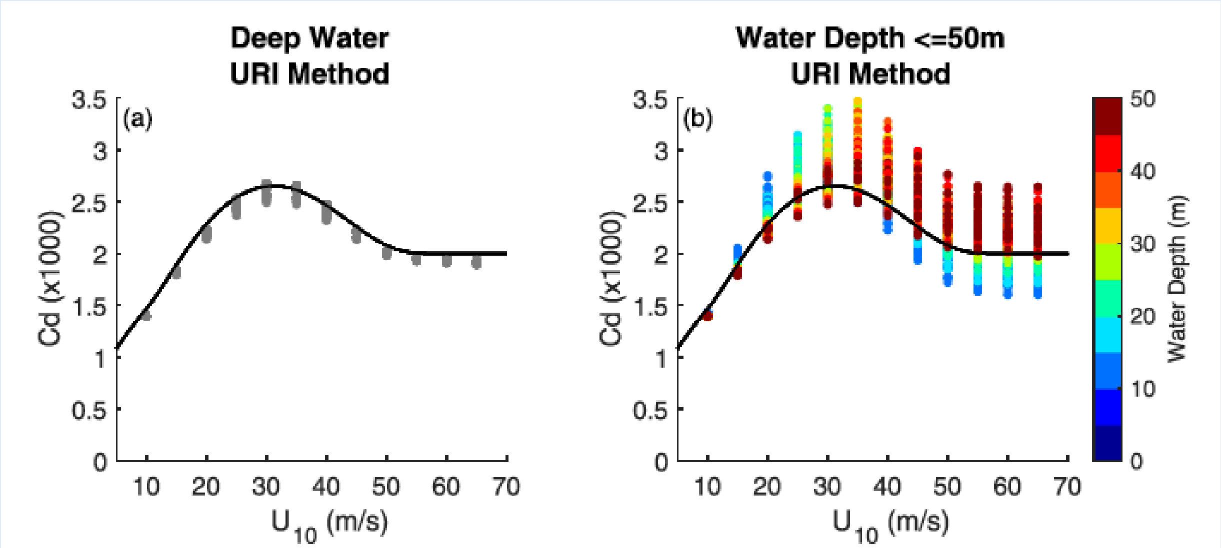


Dependence of C_d on misalignment angle ψ between wind and dominant waves

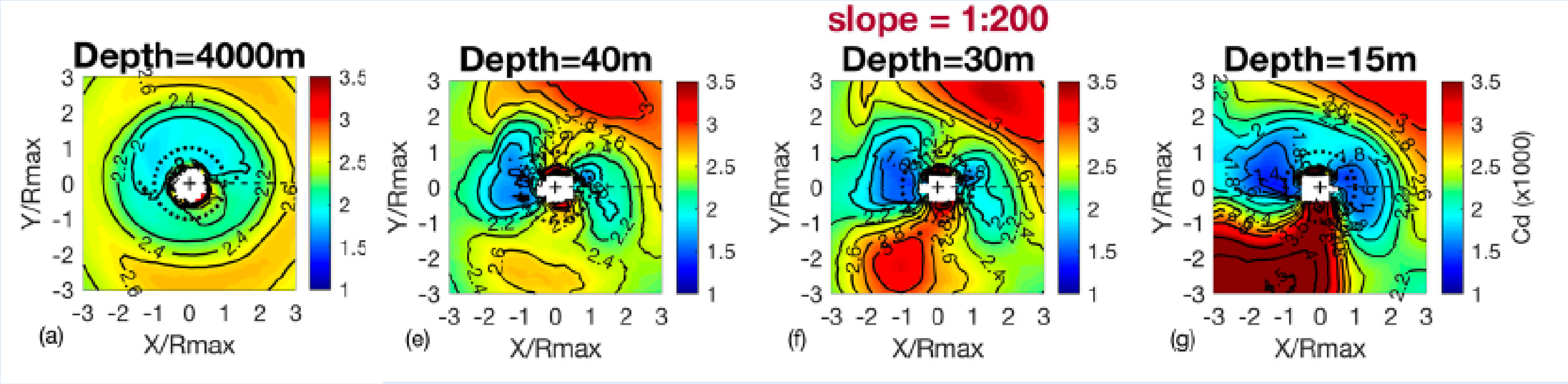
Sea state dependence of C_d

Our recent modeling study suggests C_d **strongly depends on sea states** in **coastal shallow waters** (Chen et al. 2020a,b)

Right panels show that C_d under steady uniform wind significantly increases in shallow waters.



Bottom panels show how sea state dependence of C_d under tropical cyclones is enhanced in shallow waters.



Sea state dependence of C_θ and z_θ ?

$$C_\theta = \left(\frac{1}{\kappa} log \frac{10}{z_0}\right)^{-1} \left(\frac{0.74}{\kappa} log \frac{10}{z_\theta}\right)^{-1}$$

Two key questions:

- If C_d and z_0 are sea state dependent, are C_θ and z_θ also sea state dependent?
- Can the sea state dependence of z_θ compensate (cancel) the sea state dependence of z_0, so that C_θ remains sea state independent?

Large eddy simulation (LES) of wind over a sinusoidal wave train

Surface wave length λ, wavenumber $k = \frac{2\pi}{\lambda}$, wave amplitude a, wave phase speed c

Wave slope $ka = 0.27$

LES domain size: $5\lambda \times 5\lambda \times 2.4\lambda$, LES grids: $256 \times 256 \times 256$

Wind is driven by externally imposed horizontal pressure gradient

Weak heating from bottom for scalar flux simulations

Background surface roughness (due to unresolved small waves) z_{0b},

$$kz_{0b} = 2.7 \times 10^{-3}$$

Background surface roughness of scalar (due to unresolved small waves) $z_{\theta b}$

We vary (relative) wind forcing (c/u_*), wind direction, and $z_{\theta b}$

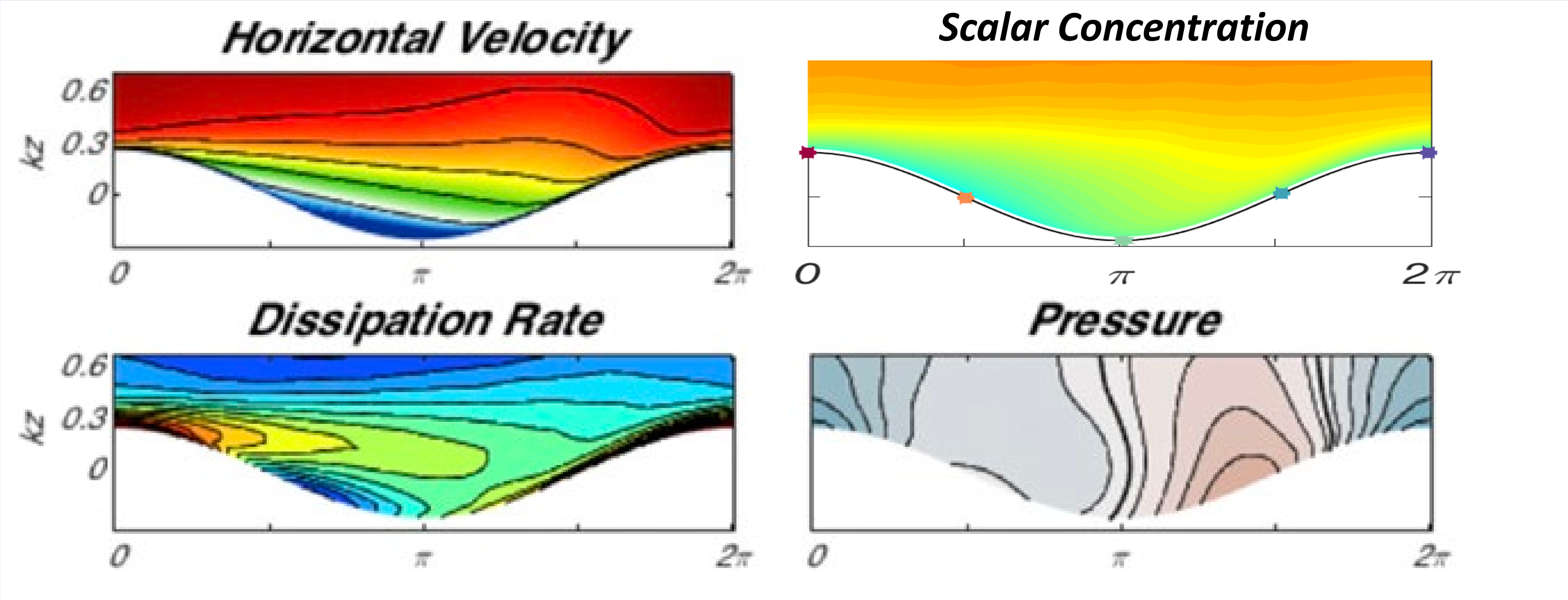
REFERNECES:

LES studies: Hara and Sullivan 2015; Sullivan et al. 2017; Husain et al. 2022a; 2022b

Validation of LES against laboratory observation: Husain et al. 2019

Large eddy simulation (LES) of wind over a sinusoidal wave train

Phase averaged flow fields, c/u_*=1.4 (strongly wind forced). WIND from Left to Right ➔



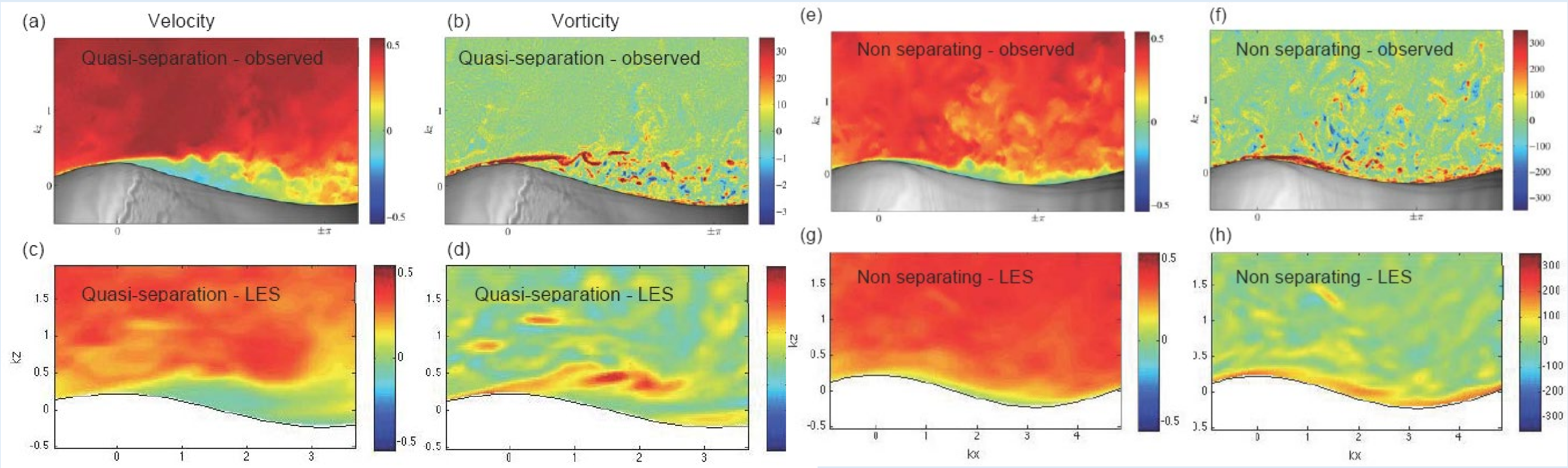
Behind the crest is a region of reduced wind speed, reduced turbulence, and reduced scalar concentration gradient.

Airflow separation

Although we simulate conditions where the “ensemble averaged” flow field does not separate over a non-breaking wave train, instantaneous flow fields often show “separation like” patterns.
Our LES results are consistent with laboratory observations by Buckley and Veron (Univ. of Delaware).

flow separating **flow not separating**

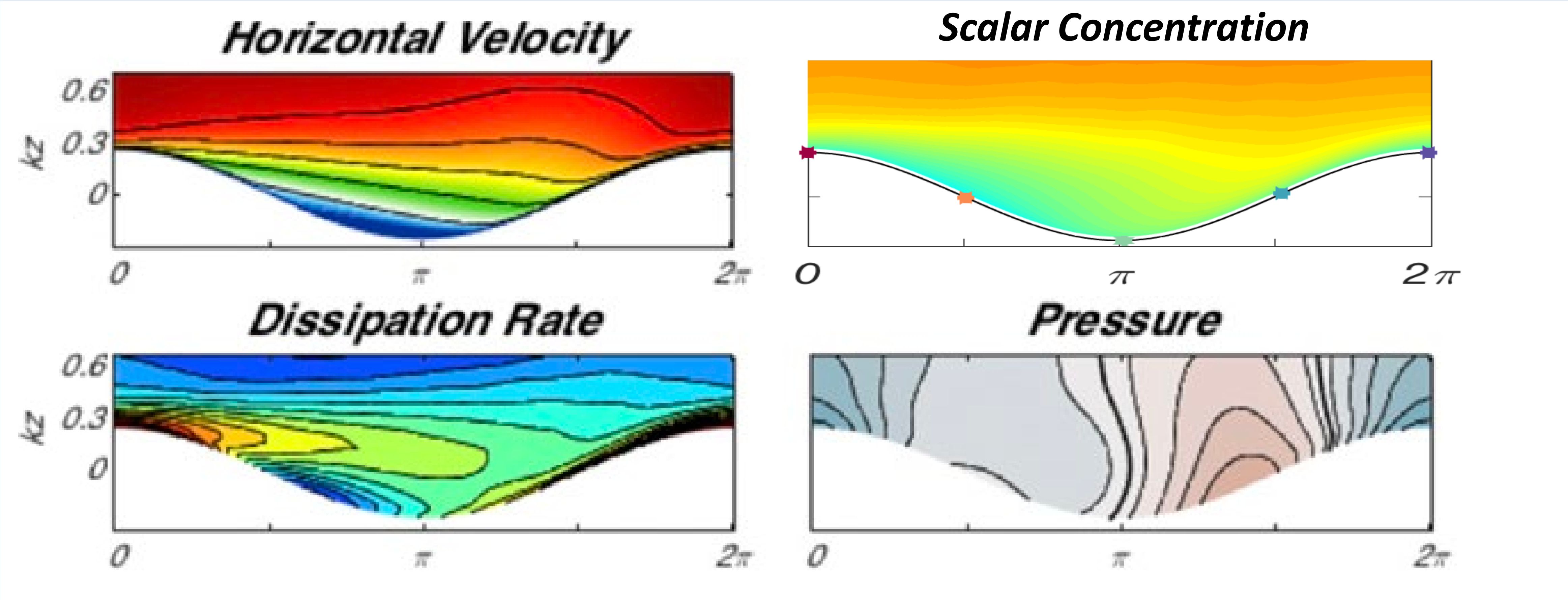
velocity vorticity velocity vorticity



Top: PIV observations, Bottom: LES results

Large eddy simulation (LES) of wind over a sinusoidal wave train

Phase averaged flow fields

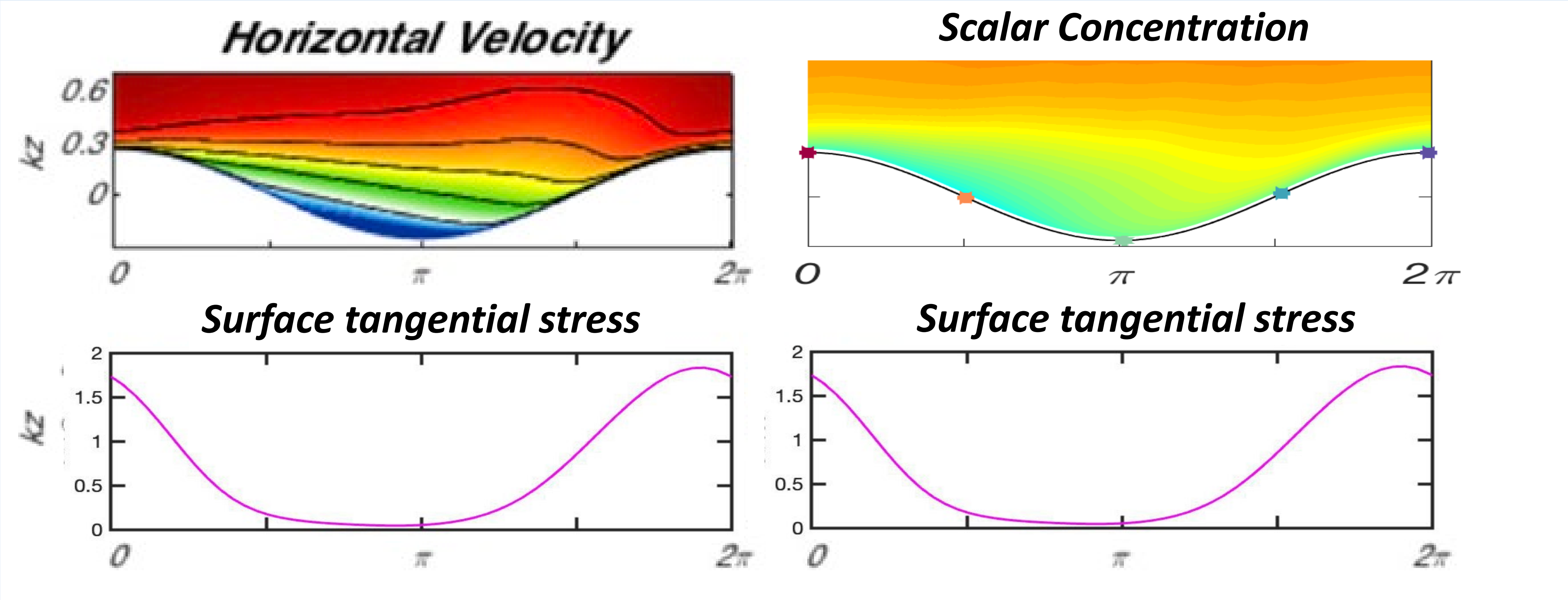


Airflow frequently separates from the crest.

Behind the crest is a region of reduced wind speed, reduced turbulence, and reduced scalar concentration gradient.

Large eddy simulation (LES) of wind over a sinusoidal wave train

Phase averaged flow fields

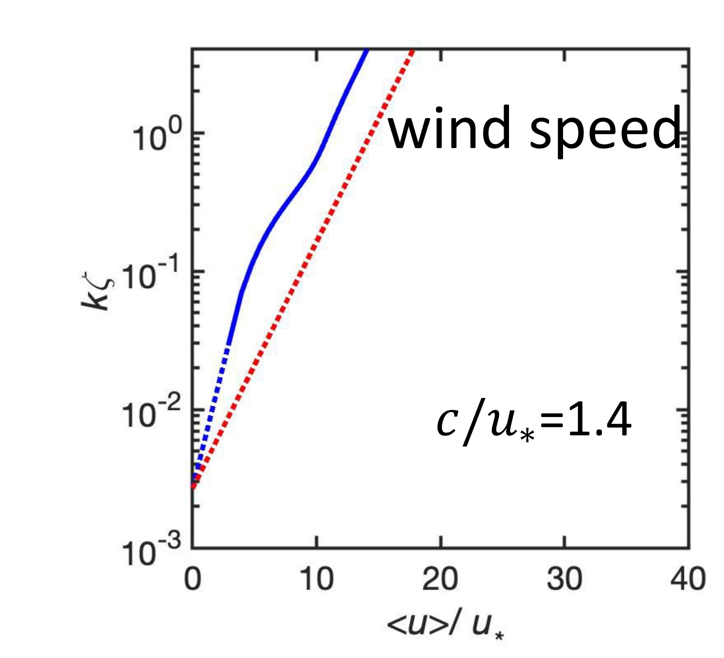


Airflow frequently separates from the crest.

Behind the crest is a region of reduced wind speed, reduced turbulence, and reduced scalar concentration gradient, where the surface tangential stress becomes close to zero.

Horizontally averaged analyses using a mapped vertical coordinate ζ (Hara and Sullivan, 2015).

How are the mean wind speed profile $\langle u(\zeta) \rangle$ modified from a flat surface to a wavy surface (if wind stress and scalar flux remain the same)?



$\langle u \rangle$ over a wave train (blue) is shifted to the left of $\langle u \rangle$ over a flat surface (red) away from the surface.

Roughness z_0 increases over a wave train.

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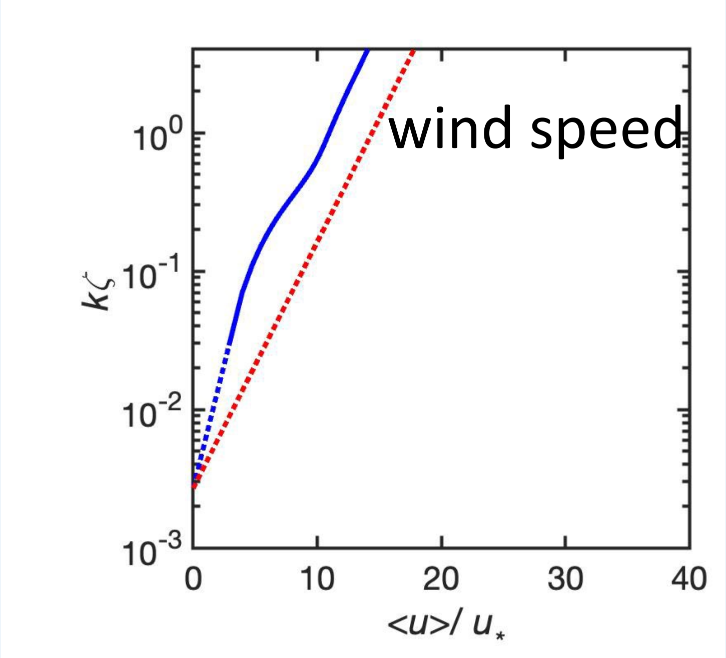

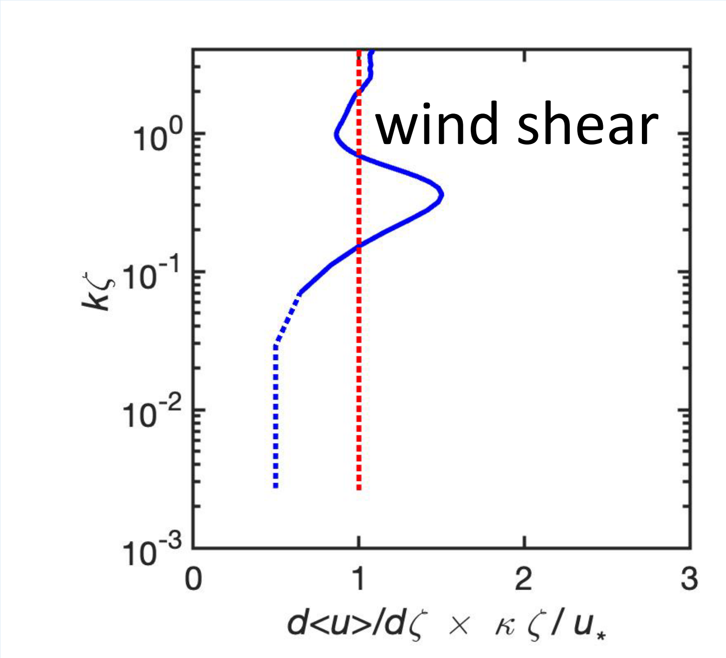

$\langle u\rangle$ over a wave train (blue) is shifted to the left of $\langle u\rangle$ over a flat surface (red) away from the surface.

Roughness z_0 increases over a wave train.

Wind shear is reduced over a wave train (blue) than over a flat surface (red) near the surface, hence, z_0 increases.

Wind shear is enhanced near the height of wave crest. (Airflow separation makes the surface smoother?)

Horizontally averaged analyses using a mapped vertical coordinate ζ (Hara and Sullivan, 2015).

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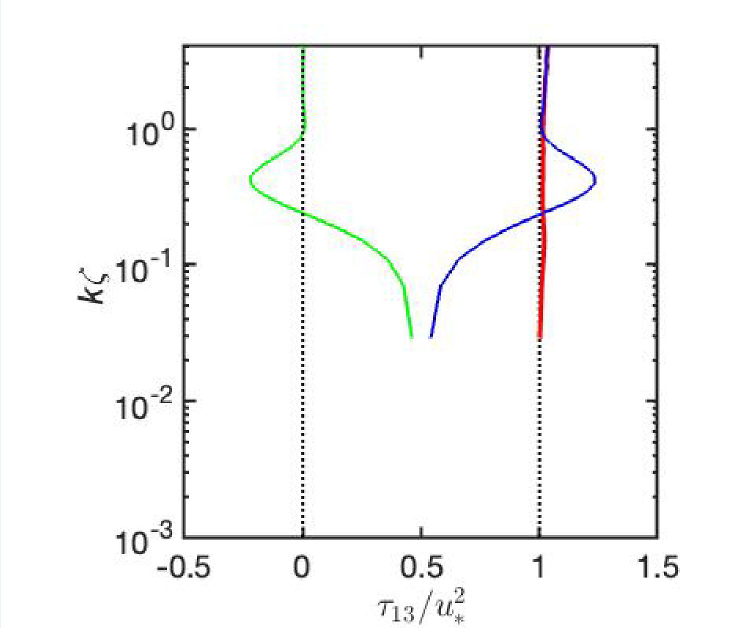


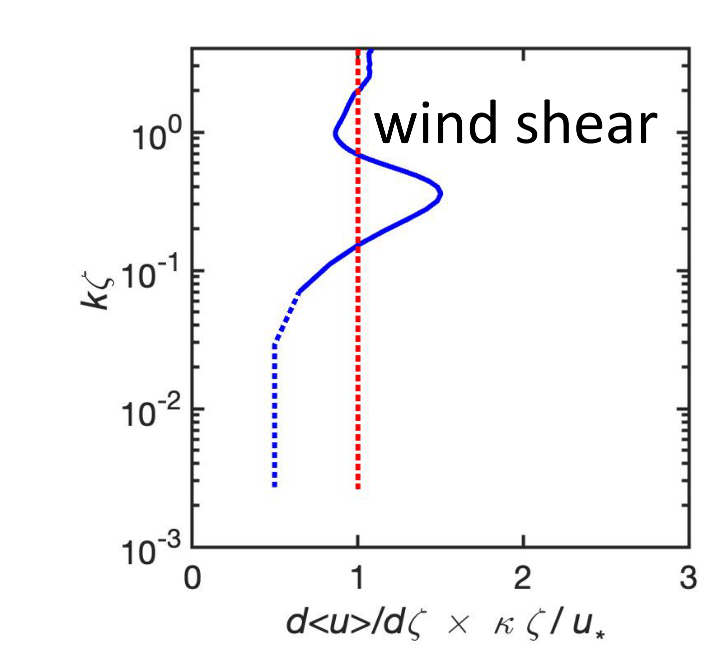
Momentum flux budget

Green: wave coherent stress

Blue: turbulent stress

Red: total stress

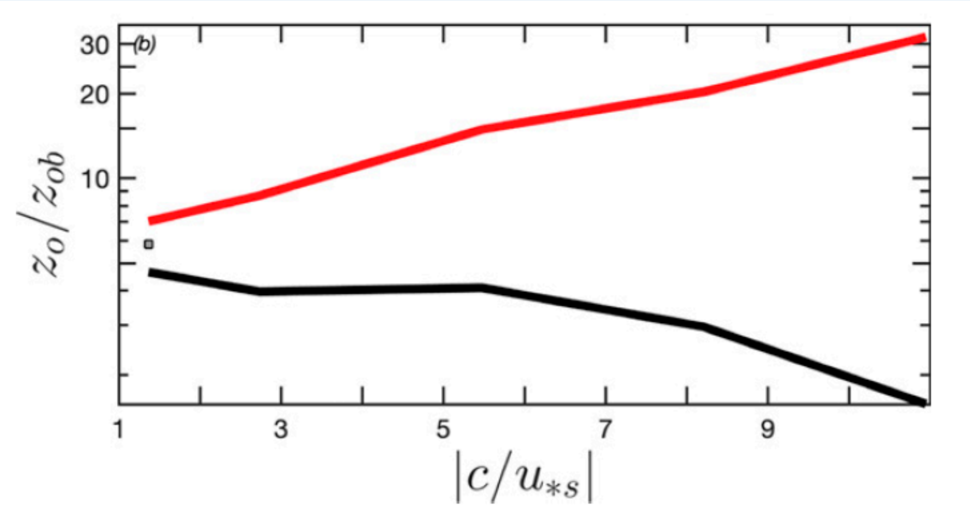
Turbulent stress is significantly reduced near the surface, causing the reduced wind shear.



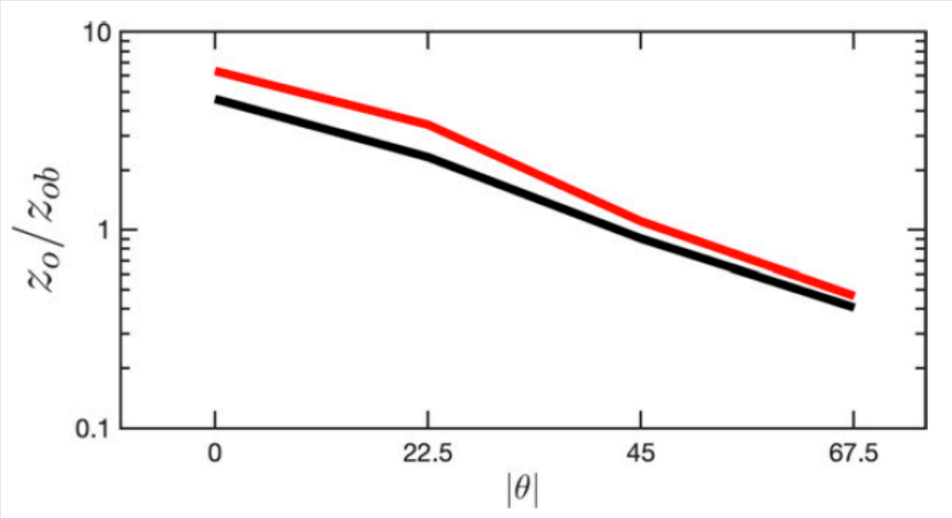
Wind shear is reduced over a wave train (blue) than over a flat surface (red) near the surface, hence, z_0 increases.

Wind shear is enhanced near the height of wave crest. (Airflow separation makes the surface smoother?)

We may estimate z_0/z_{0b} , i.e., how much roughness has increased over a wave train compared to a flat surface. (Husain et al. 2022a,b)



← strong wind *weak wind →*



wind and wave misaligned →

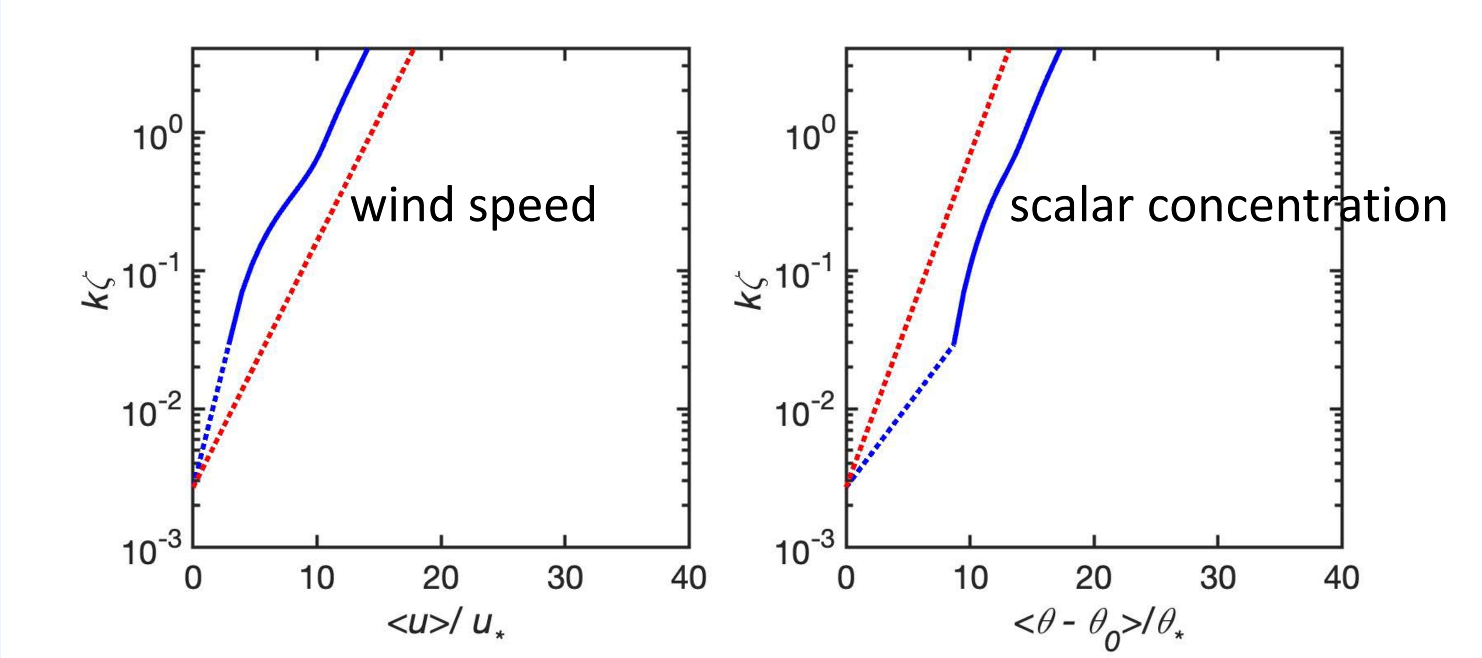
With waves following wind (black), roughness is more enhanced with stronger wind forcing.

With wave opposing wind (red), roughness is more enhanced with weaker wind forcing.

If wave direction is close to wind direction, roughness is enhanced.

If wave direction is misaligned from wind direction by more than 45 degrees, roughness is reduced compared to a flat surface.

How are the mean wind speed profile $\langle u(\zeta)\rangle$ and mean scalar concentration profile $\langle \theta(\zeta)\rangle$ modified from a flat surface to a wavy surface (if wind stress and scalar flux remain the same)?



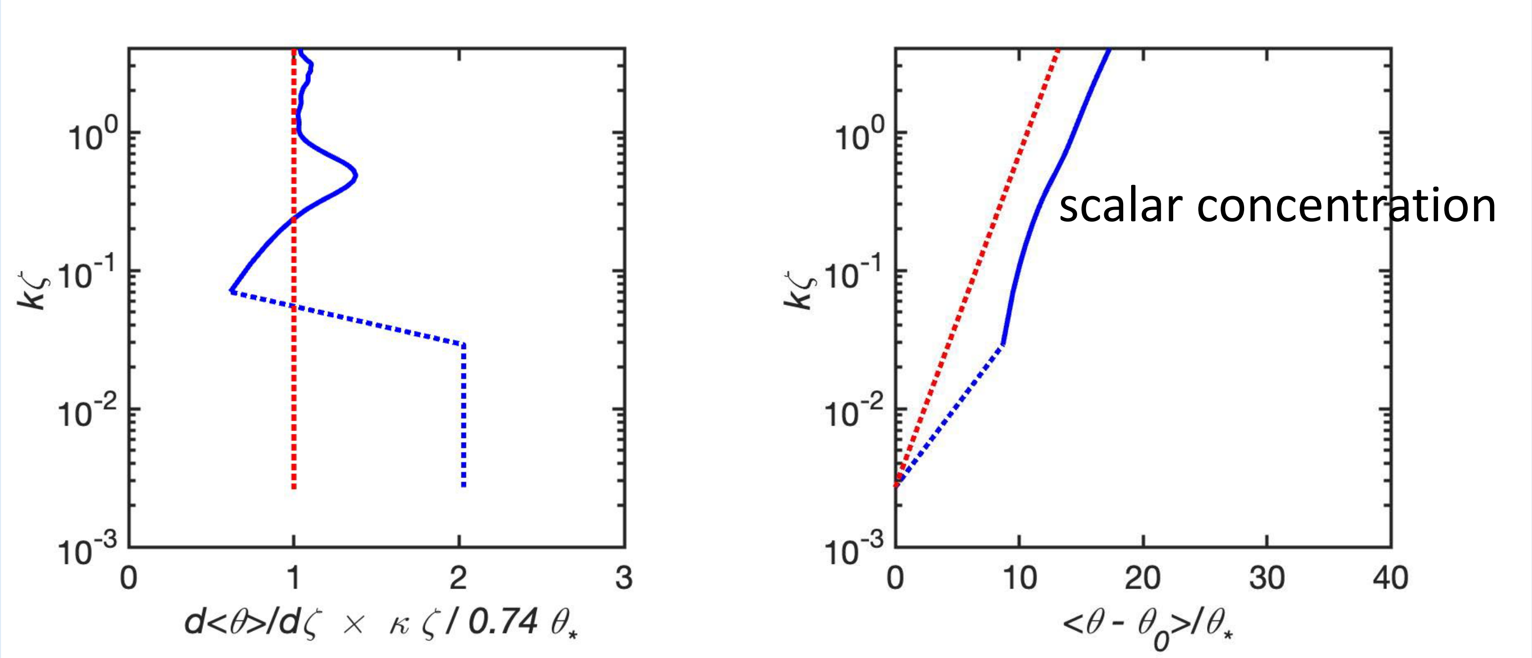
$\langle u\rangle$ over a wave train (blue) is shifted to the left of $\langle u\rangle$ over a flat surface (red) away from the surface.

Roughness z_0 has increased by a factor of ~5.
C_d has increased by ~40%

$\langle \theta\rangle$ over a wave train (blue) is shifted to the right of $\langle \theta\rangle$ over a flat surface (red) away from the surface.

Roughness z_θ has decreased by a factor of ~5.
C_θ remains almost unchanged.

How are the mean wind speed profile $\langle u(\zeta) \rangle$ and mean scalar concentration profile $\langle \theta(\zeta) \rangle$ modified from a flat surface to a wavy surface (if wind stress and scalar flux remain the same)?

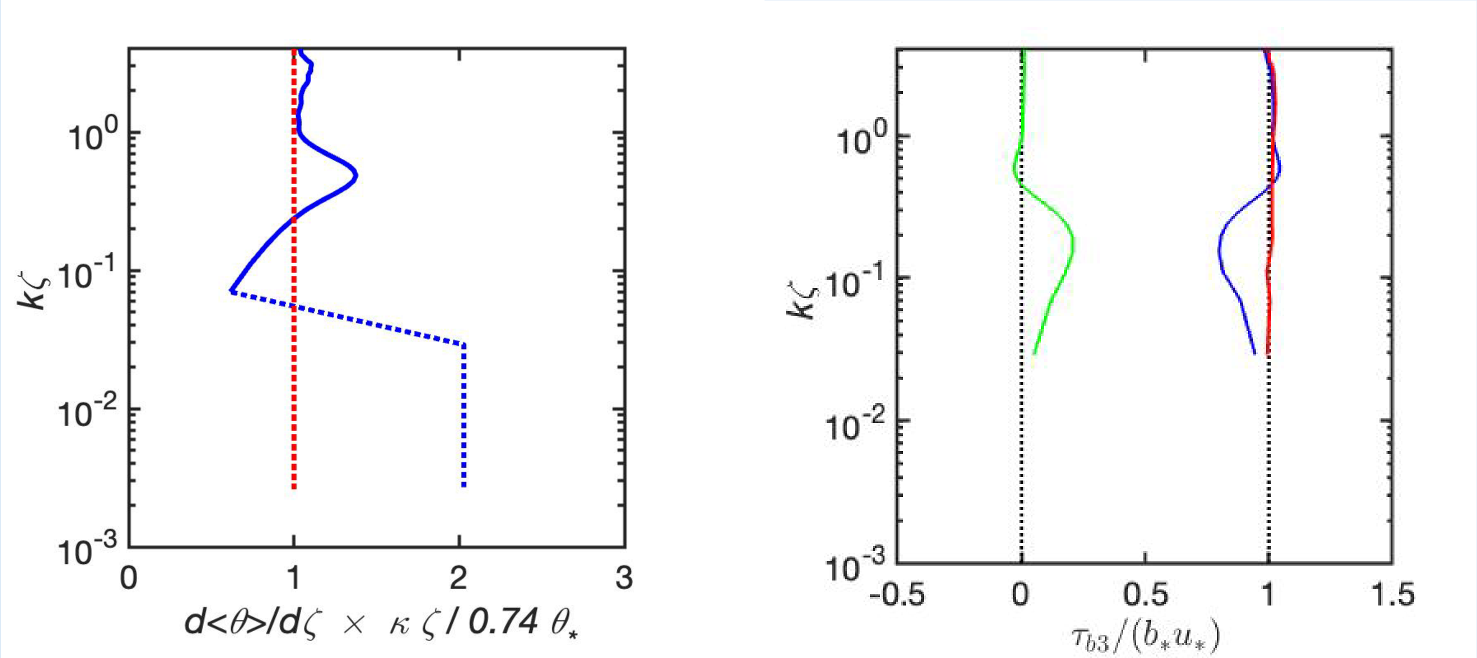


$\langle \theta \rangle$ is shifted to the left because the vertical gradient of $\langle \theta \rangle$ is significantly enhanced near the surface.

$\langle \theta \rangle$ over a wave train (blue) is shifted to the left of $\langle \theta \rangle$ over a flat surface (red) away from the surface.

Roughness z_θ has decreased.

How are the mean wind speed profile $\langle u(\zeta)\rangle$ and mean scalar concentration profile $\langle \theta(\zeta)\rangle$ modified from a flat surface to a wavy surface (if wind stress and scalar flux remain the same)?



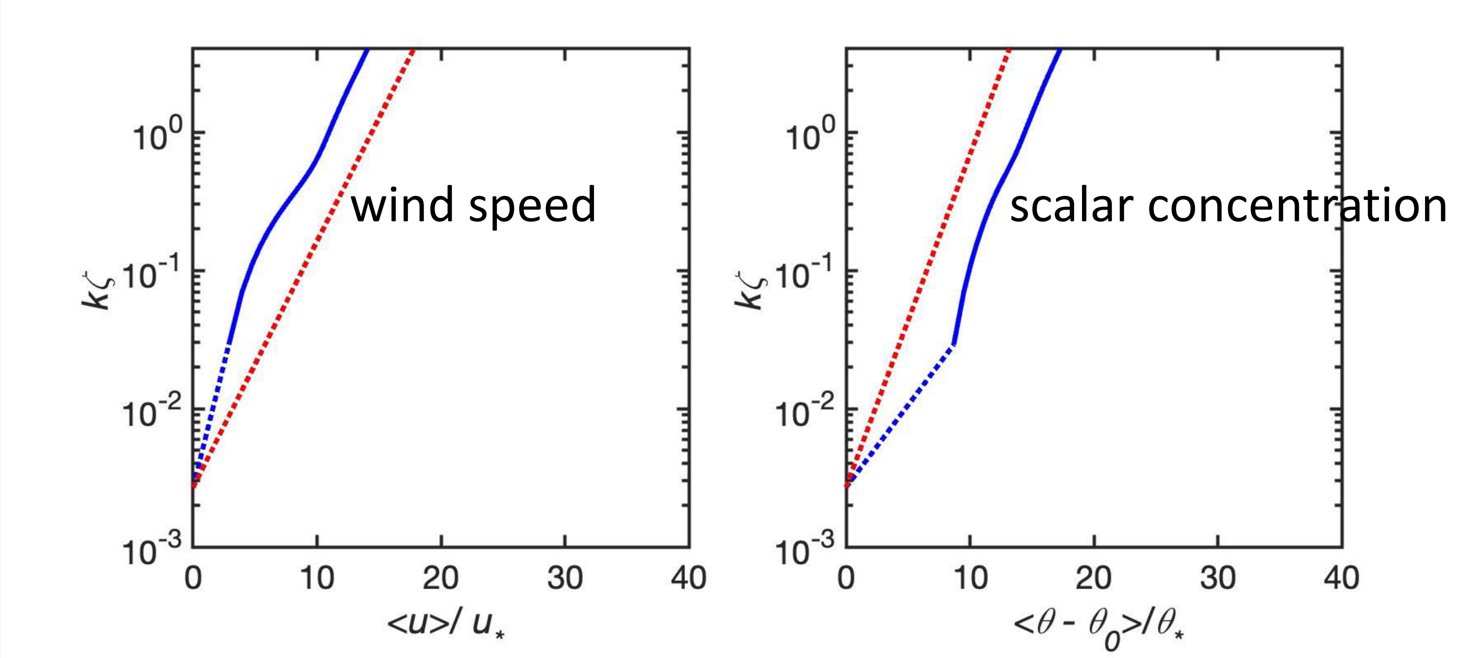
$\langle \theta \rangle$ is shifted to the left because the vertical gradient of $\langle \theta \rangle$ is significantly enhanced near the surface.

Scalar flux budget

Green: wave coherent flux
Blue: turbulent flux
Red: total flux

Turbulent scalar flux is not reduced near the surface.
But, turbulent stress is reduced near the surface.
Therefore, the vertical gradient of $\langle \theta \rangle$ increases.
(Near the surface, u_* decreases but $\theta_* u_*$ does not change. Therefore, θ_* increases.)

How are the mean wind speed profile $\langle u(\zeta)\rangle$ and mean scalar concentration profile $\langle \theta(\zeta)\rangle$ modified from a flat surface to a wavy surface (if wind stress and scalar flux remain the same)?



$\langle u\rangle$ over a wave train (blue) is shifted to the left of $\langle u\rangle$ over a flat surface (red) away from the surface.

Roughness z_0 has increased.

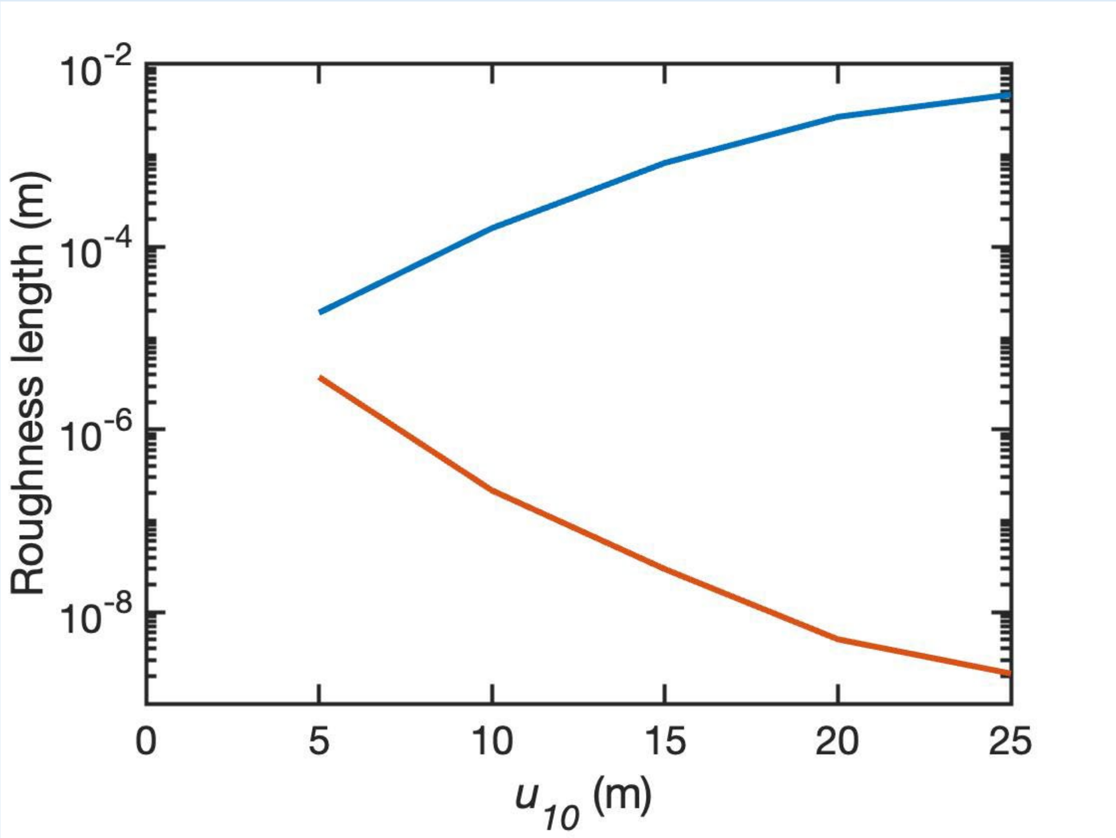
$\langle \theta\rangle$ over a wave train (blue) is shifted to the right of $\langle \theta\rangle$ over a flat surface (red) away from the surface.

Roughness z_θ has decreased.

Increase of z_0 and decrease of z_θ seem to (roughly) cancel each other, i.e., C_θ remains (roughly) unchanged, if the background roughness z_{0b} and $z_{\theta b}$ are the same.

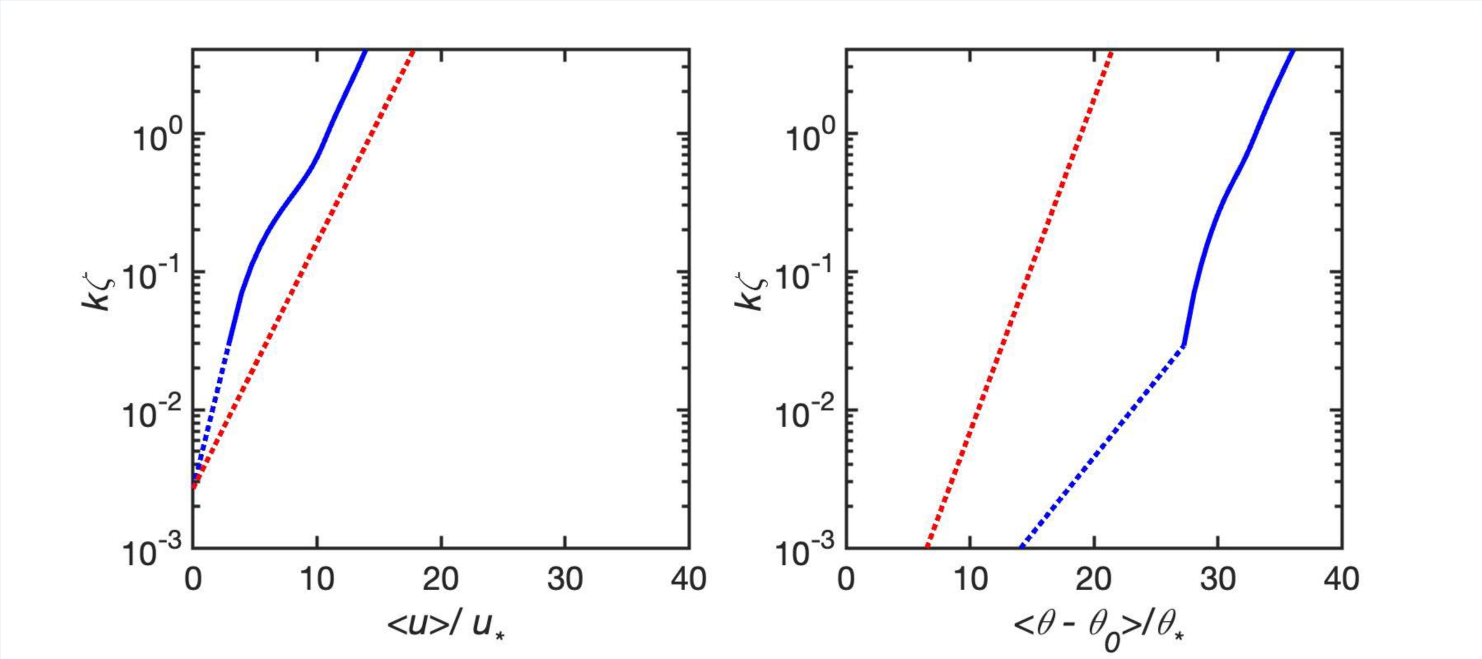
Recall that z_0 is much larger than z_θ except for very low wind speeds.

Therefore, the background roughness (due to unresolved small waves) $z_{\theta b}$ should be much less than the background roughness z_{0b}.



z_0 (blue) and z_θ (red) as functions of u_{10}

We repeat the same LES experiment but reduces $z_{\theta b}$ ($z_{\theta b}/z_{0b} = 0.01$), which is more realistic.



Increase of z_0 and decrease of z_θ do not cancel each other, and C_θ is significantly (~20%) reduced by the waves, if the background roughness $z_{\theta b}$ is much less than the background roughness z_{0b}.

Conclusion:

- Scalar transfer coefficient C_θ is a function of both z_0 and z_θ.
- Recent studies show that z_0 can be strongly sea state dependent, particularly under tropical cyclones and in coastal shallow waters.
- Our LES study shows that z_0 is significantly modified (usually increased) over a sinusoidal wave train (compared to a flat surface), depending on wind strength and direction. Airflow separations may play a significant role in modifying z_0.
- Our preliminary LES study shows that:
  - When z_0 increases over a sinusoidal wave tarin (because the turbulent stress is reduced), z_θ decreases (because the scalar flux is NOT reduced).
  - The effects of increasing z_0 and decreasing z_θ on C_θ do not always cancel. C_θ can be significantly reduced by waves.