Rain-driven turbulence in the upper meter of the ocean

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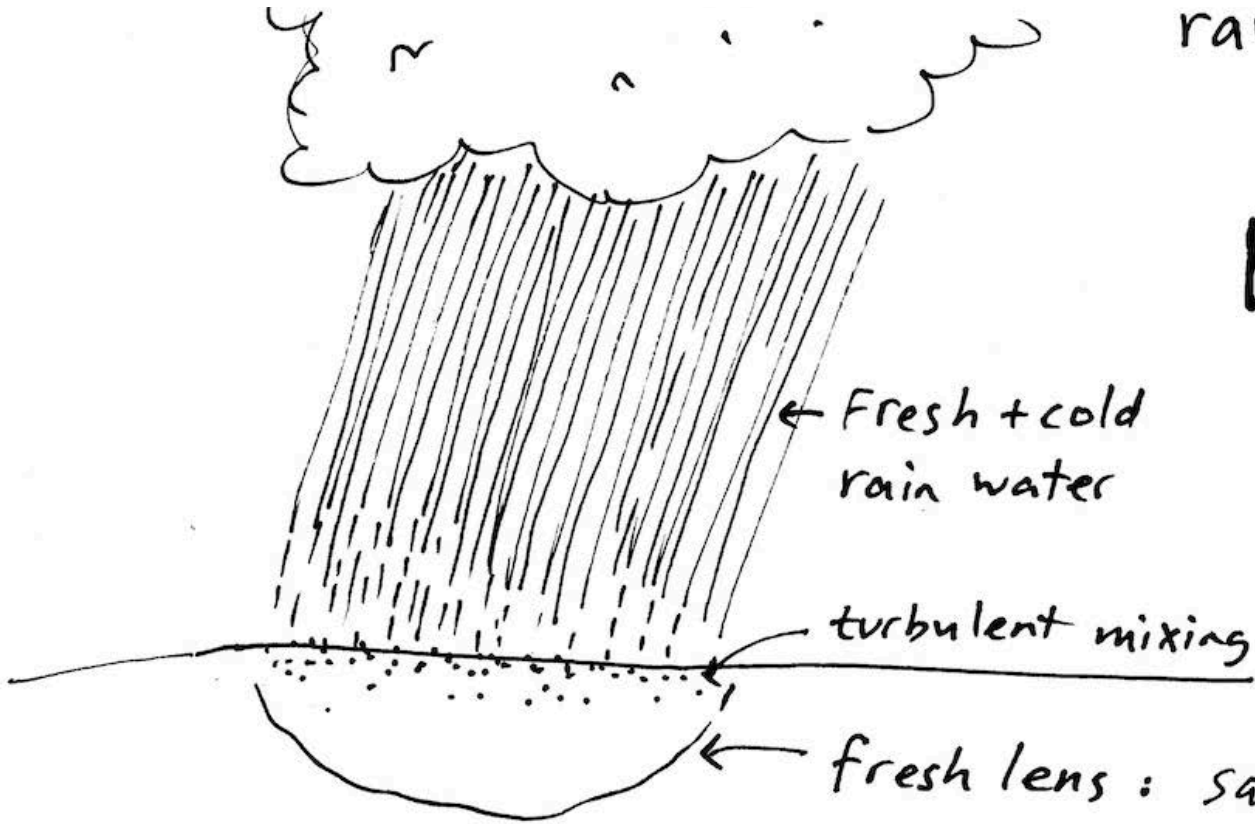
GLOBAL OCEAN SALINITY AND THE WATER CYCLE WORKSHOP – WHOI – 22 MAY 2017

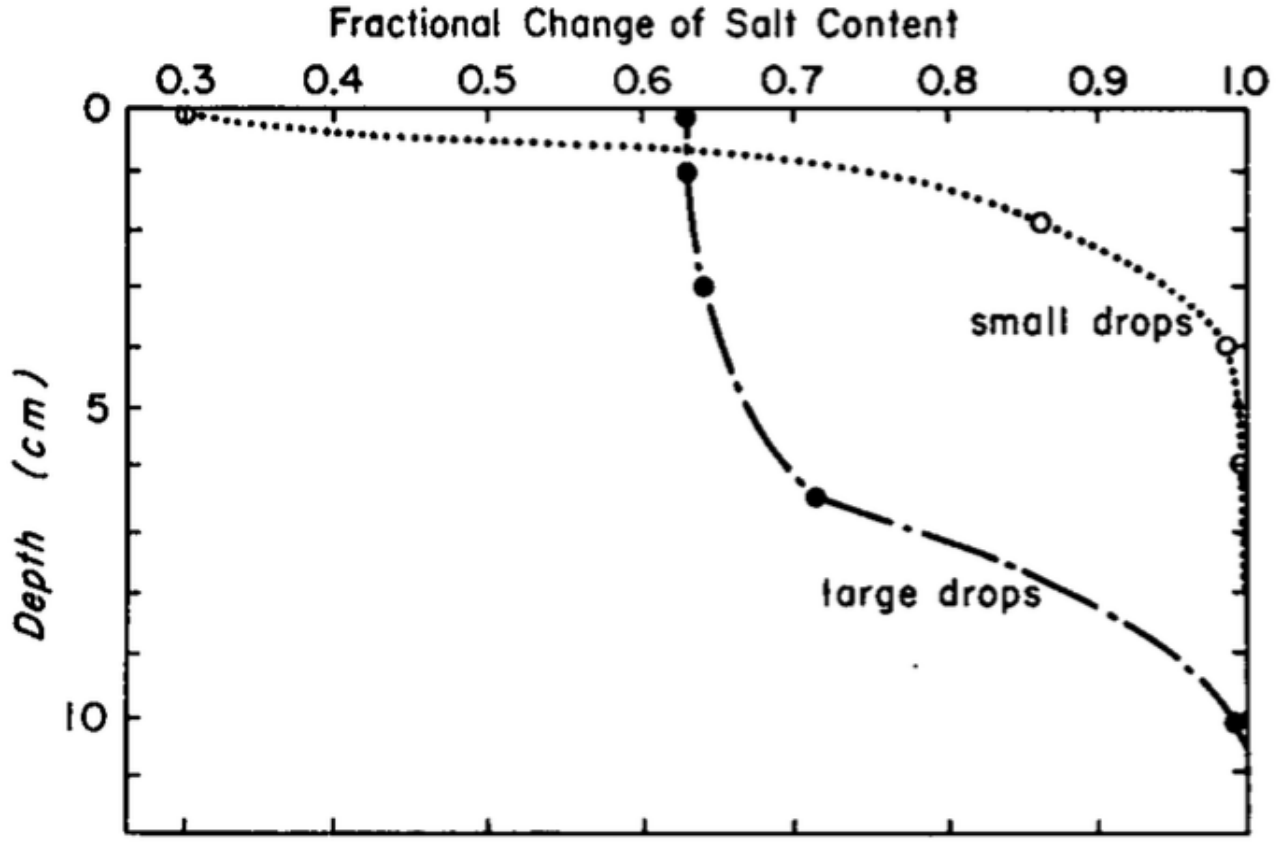
rain - Formed

Fresh Lenses



Depth of rain-induced mixing depends on raindrop size

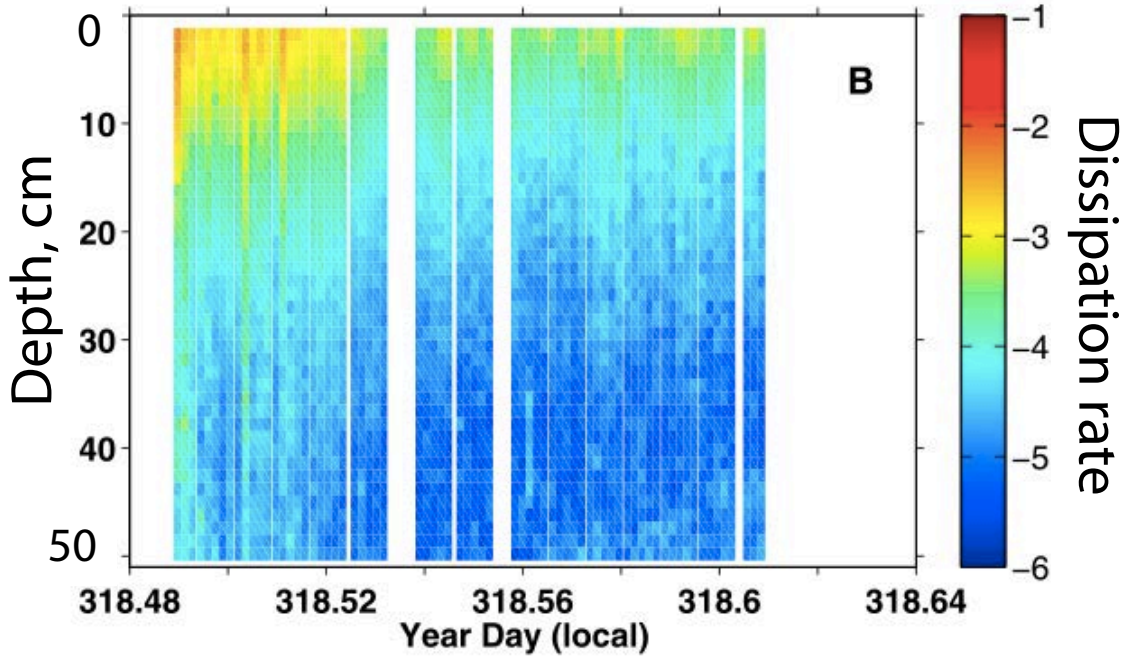
Katsaros & Buettner, 1969 (lab experiments):

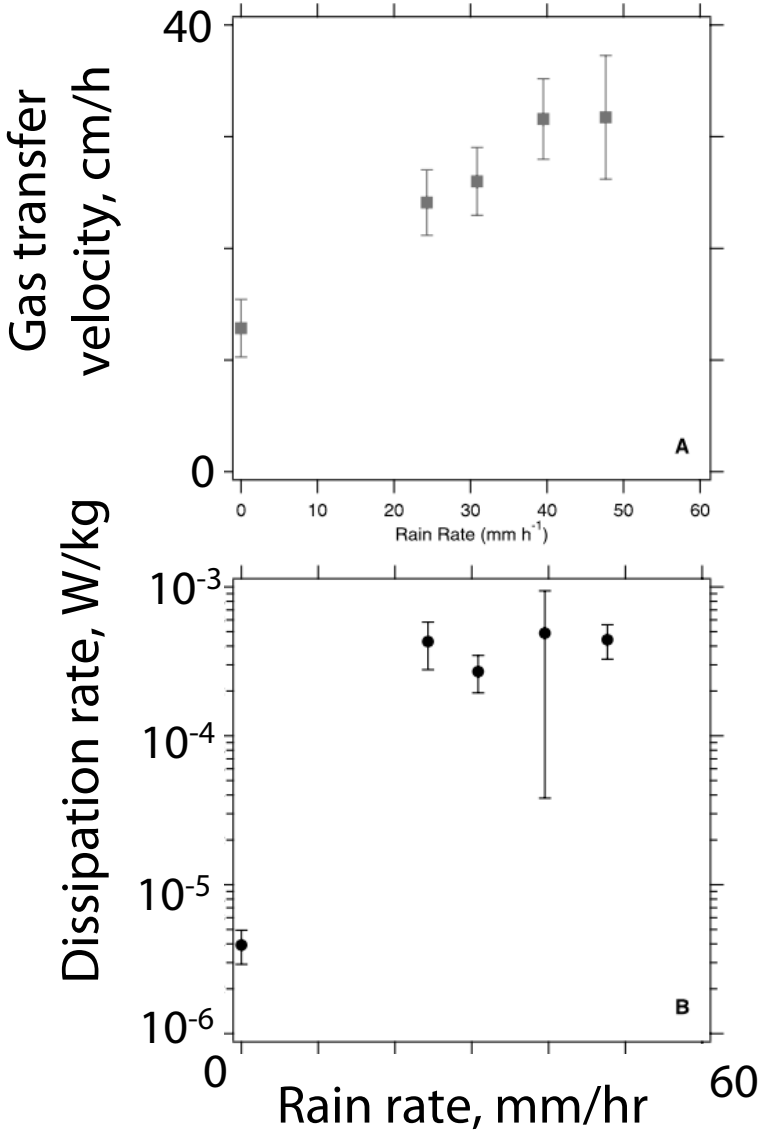


Rain enhances turbulent kinetic energy (TKE) dissipation rate

Zappa et al 2009 (BioSphere-2)

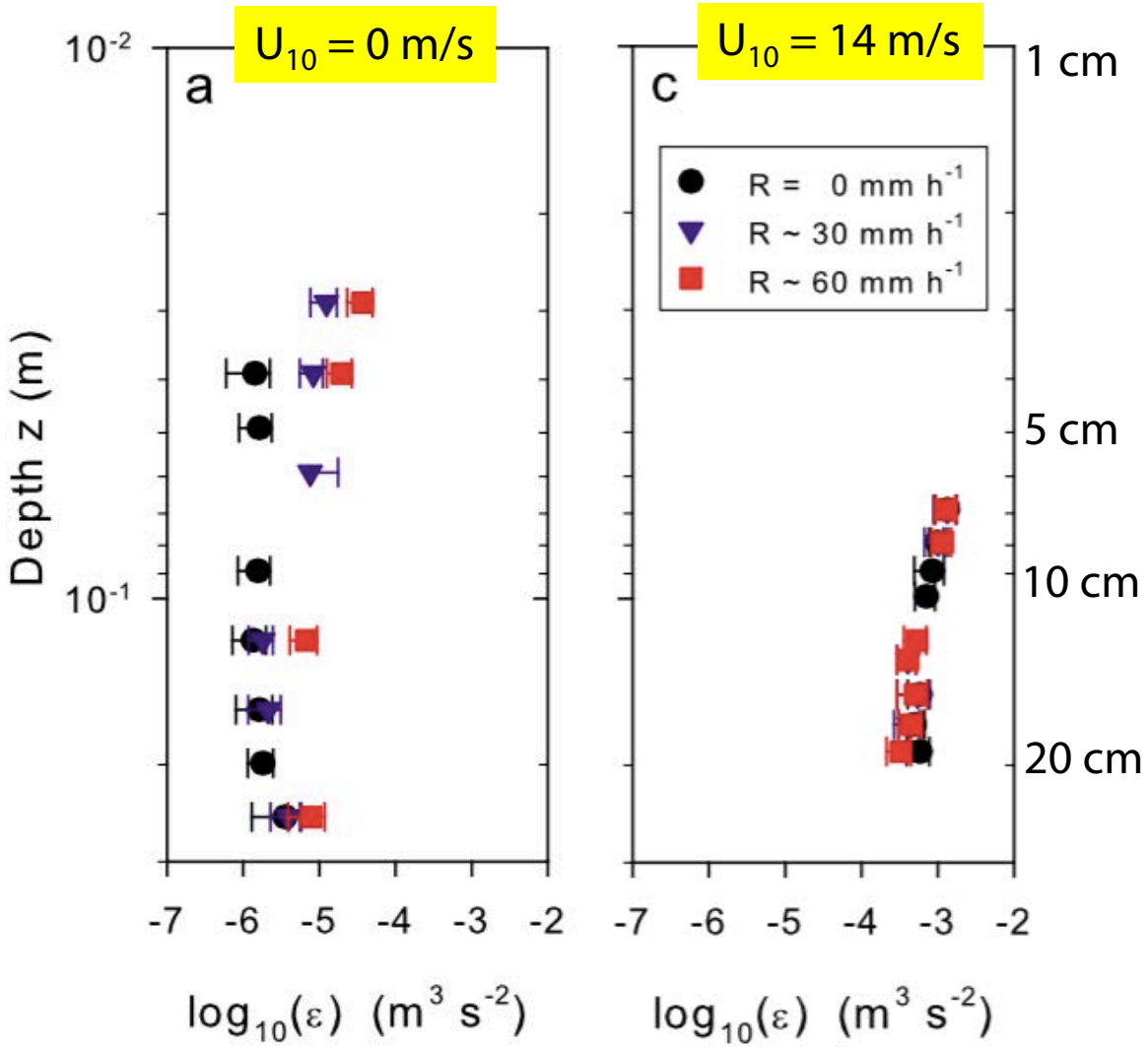
TKE dissipation rate during rain:





Under low winds, rain enhances TKE dissipation rate
Under high winds, dissipation is dominated by wind.

Harrison et al., 2012 (lab experiments)



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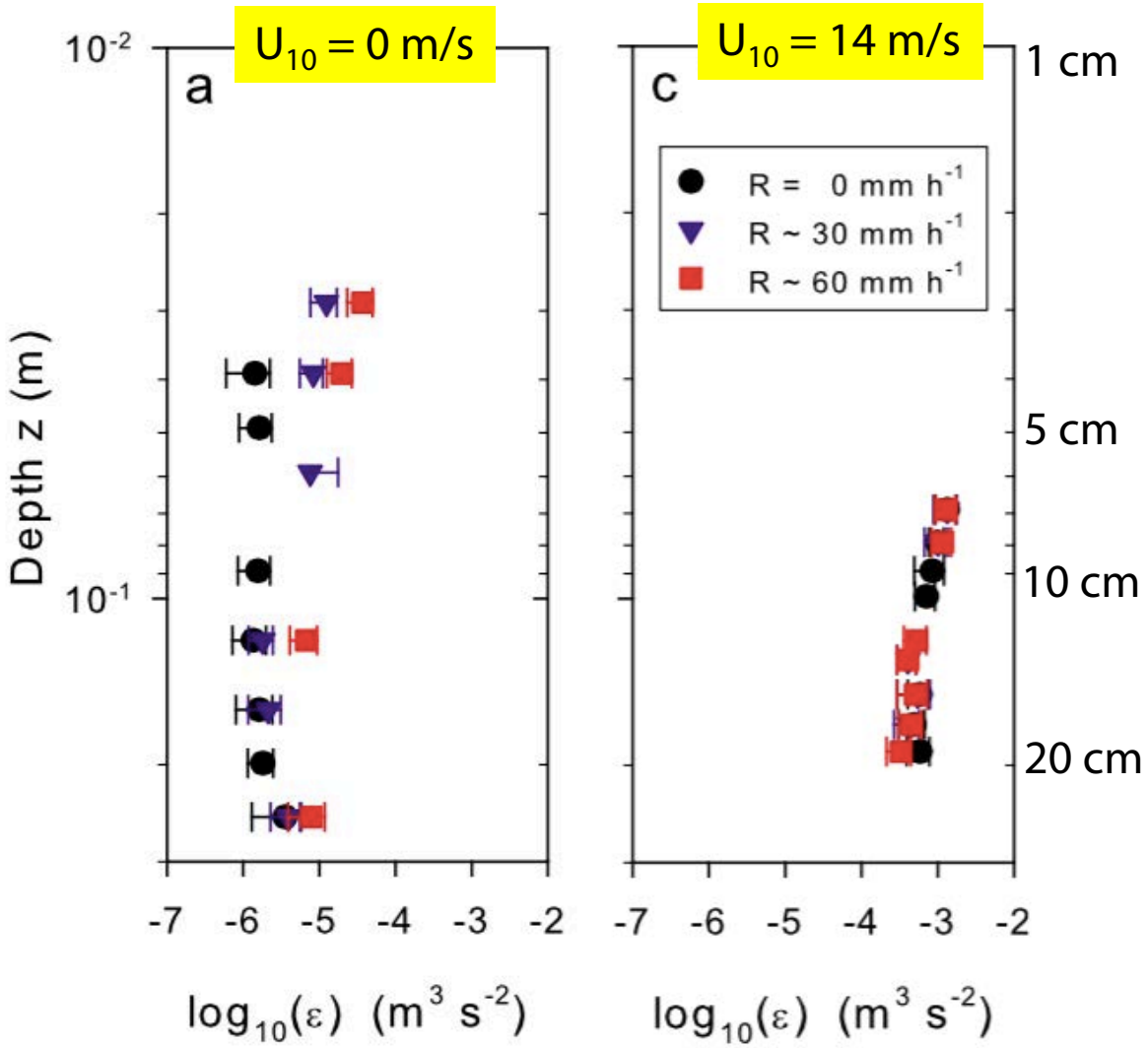


Can be explained by considering the Kinetic Energy Flux (KEF) of rain vs wind:

$$KEF_r = \frac{1}{2}\rho_d w^2 R,$$

$$KEF_w = \rho_a u_*^3$$

R = rain rate,

ρ_d = raindrop density,

ρ_a = air density,

w = vertical raindrop velocity

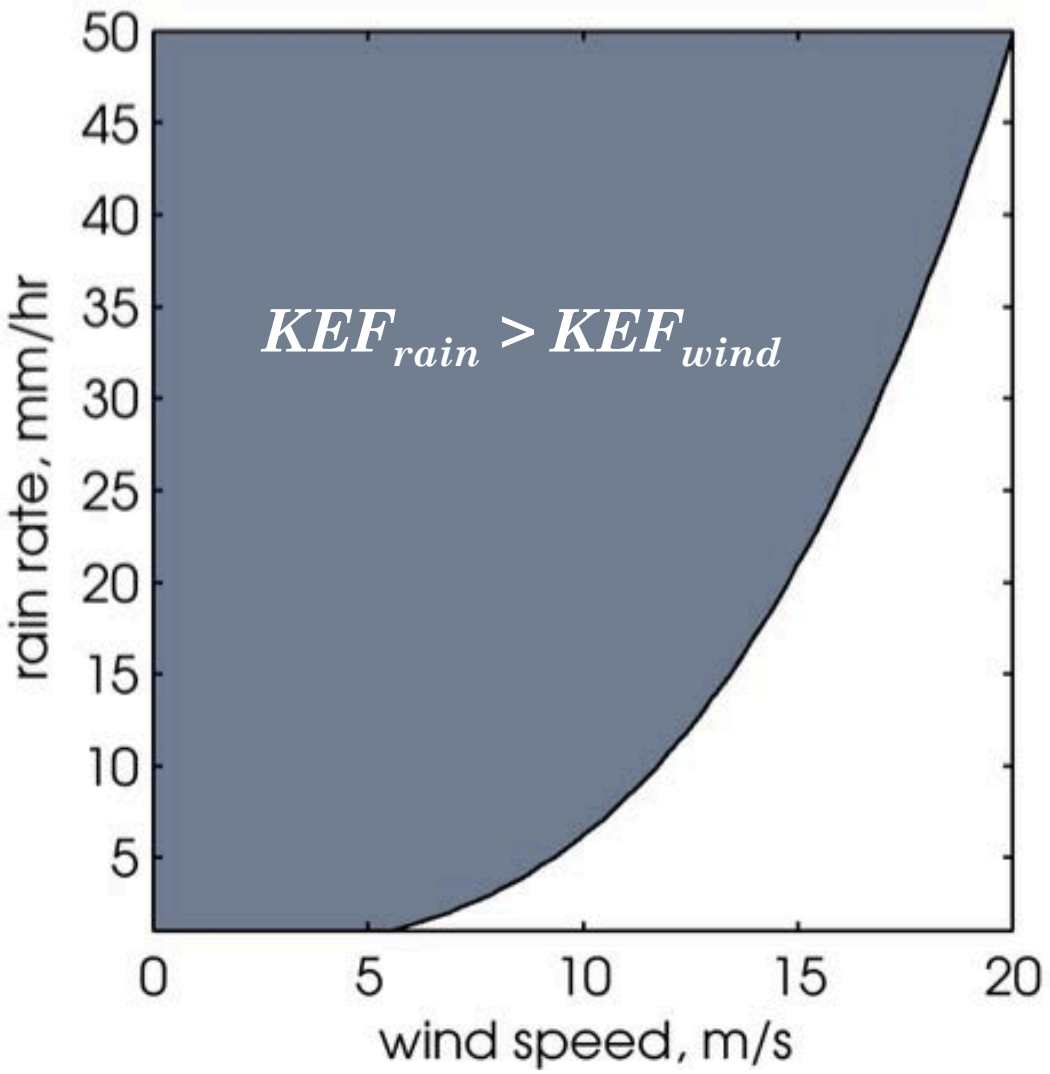
u^* = friction velocity

Rain-driven turbulence matters when $KEF_{rain} > KEF_{wind}$

Theoretical regime for which rain generates stronger turbulence than wind

$$KEF_r = \frac{1}{2}\rho_d w^2 R,$$

$$KEF_w = \rho_a u_*^3$$



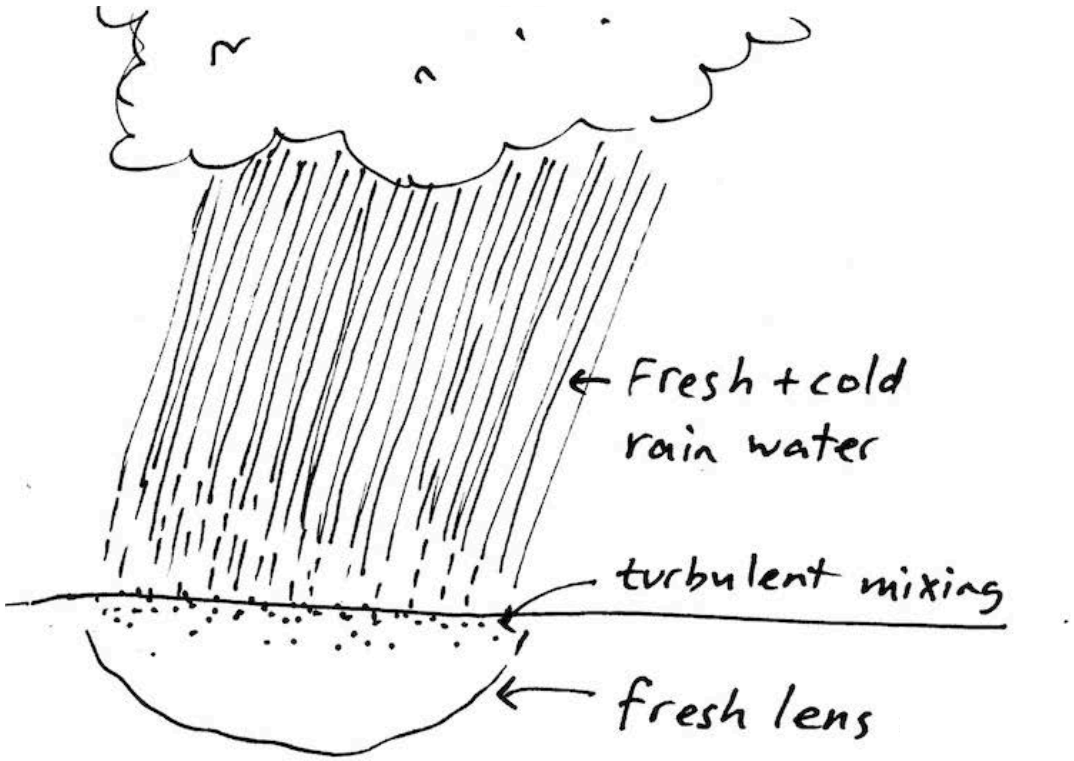
Big Questions

When are rain effects important relative to wind?

What is the turbulence in fresh lenses during and after rain?

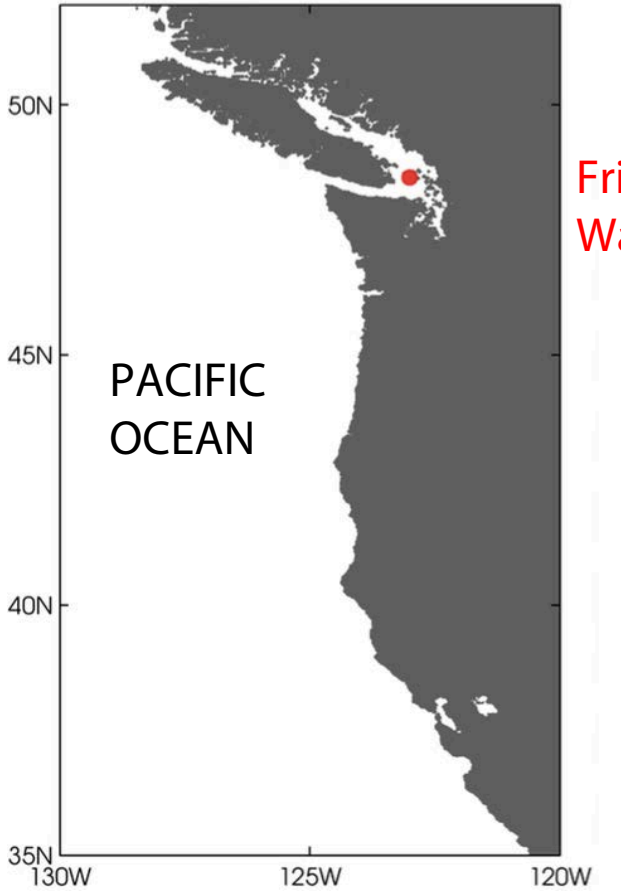
How deep do raindrops mix?

How does dissipation rate decay with depth?



Friday Harbor Rain Experiment

Dec 2015-Mar 2016



Friday Harbor, Washington

Meteorological sensors:
Rain rate, wind speed/direction, air temperature, pressure, humidity

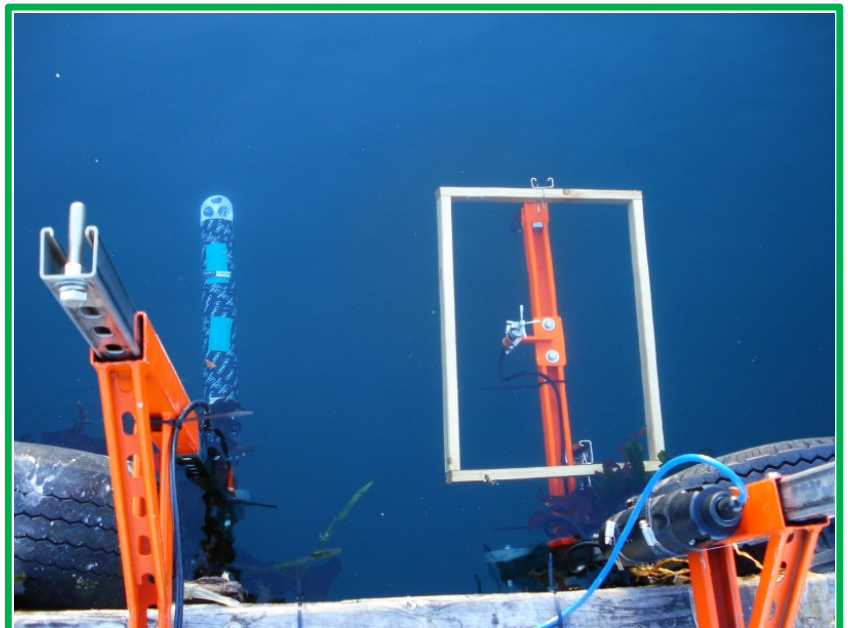
Disdrometer:
Raindrop size distribution

In-water instruments:

Aquadopp: pulse-coherent Doppler velocity profiler → TKE dissipation rate from 20 – 70 cm depth (Thomson 2012)

Vectrino: acoustic Doppler velocimeter → TKE dissipation rate from ~3–5 cm

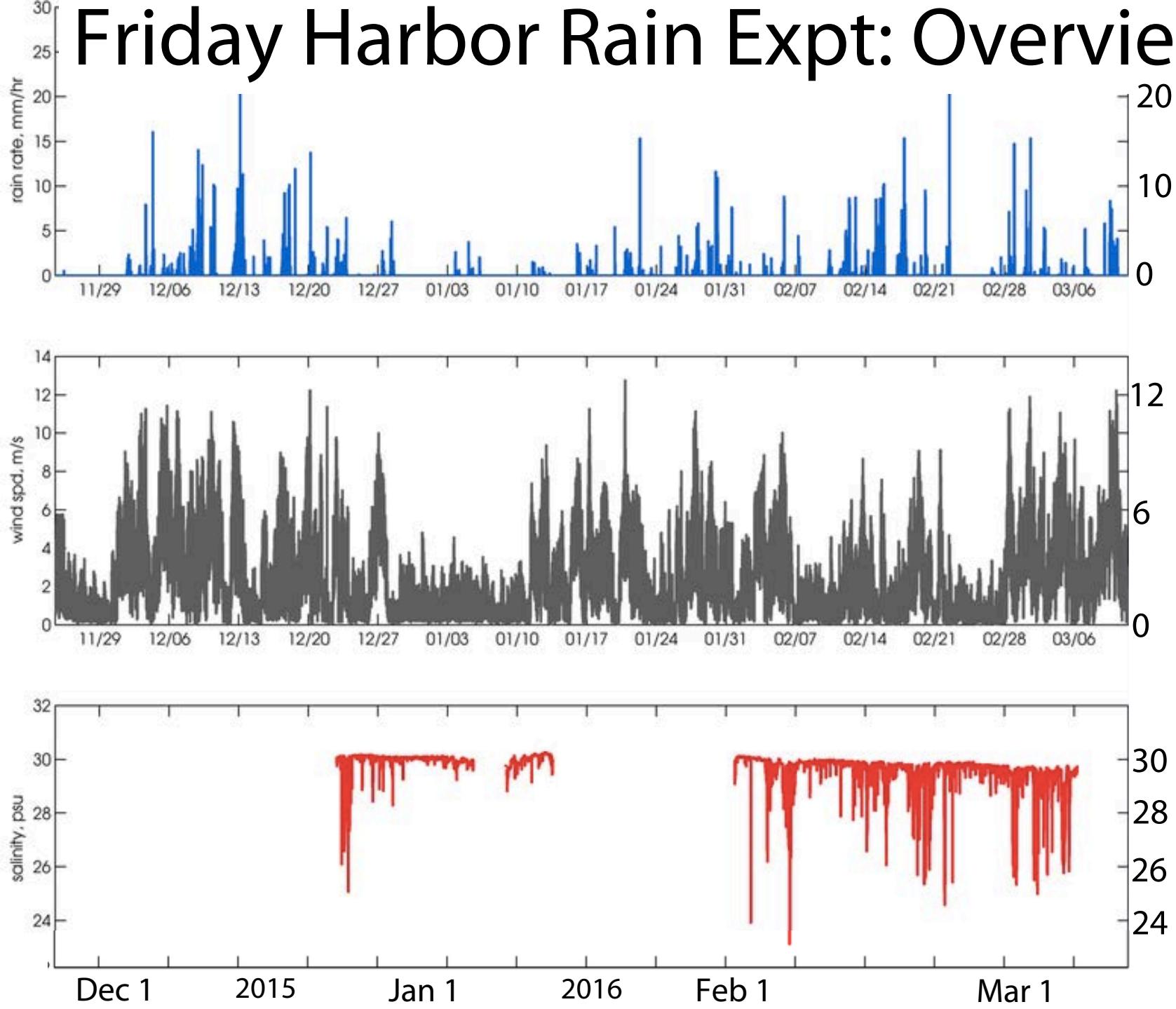
CTD at 80cm



Infrared imager

Thermal structure of the sea surface.

Friday Harbor Rain Expt: Overview

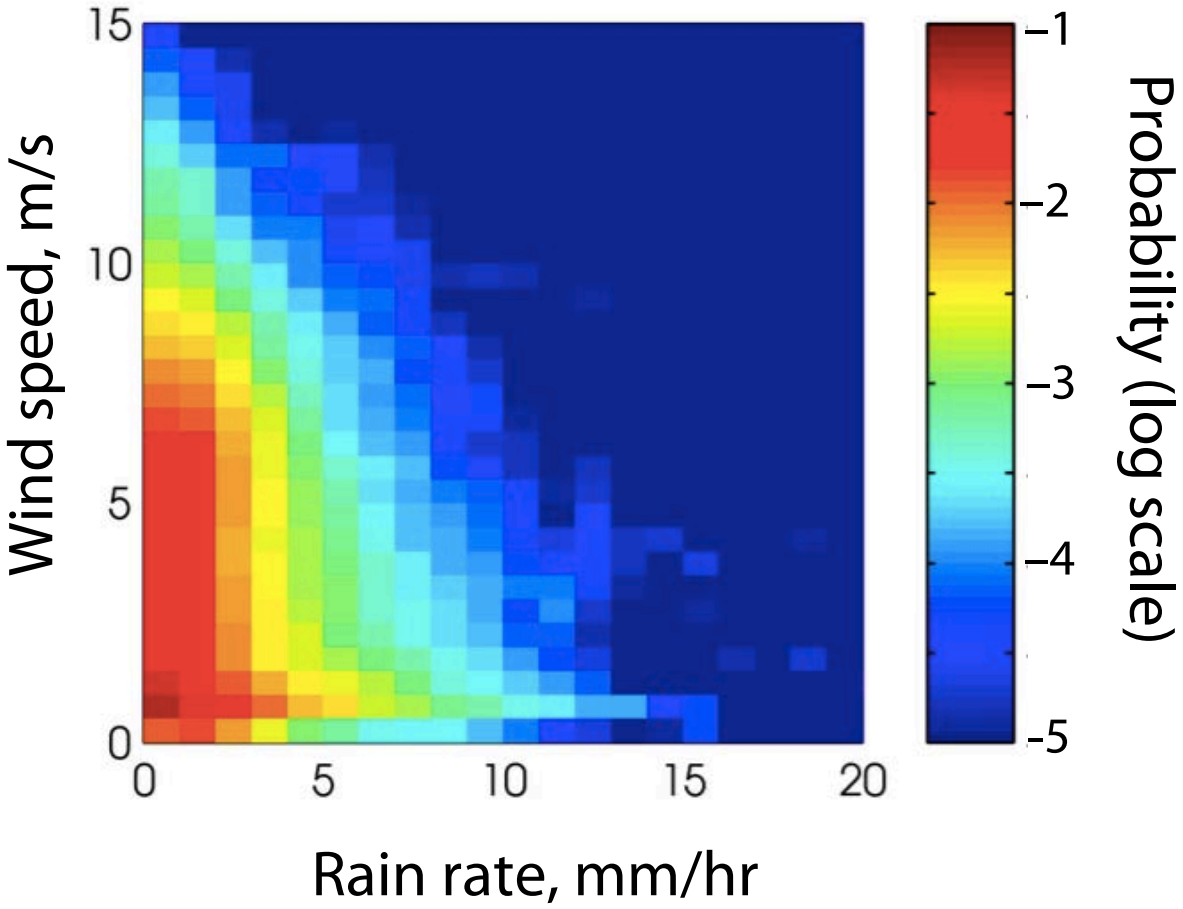


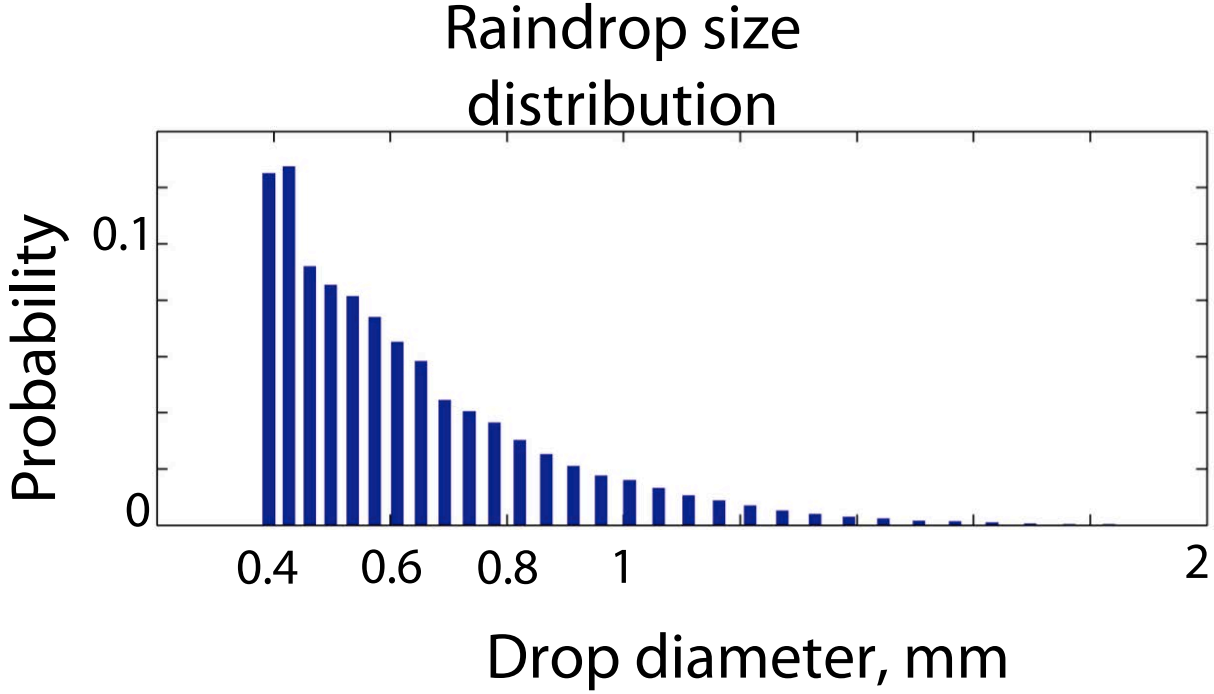
Rain rate, mm/hr

Wind speed, m/s

Salinity @ 80 cm depth, psu

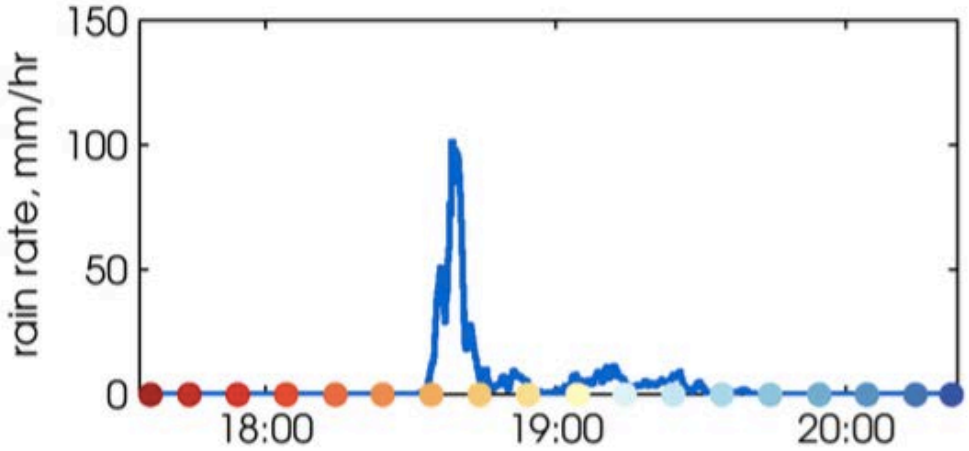
Typically, low winds and low-moderate rain

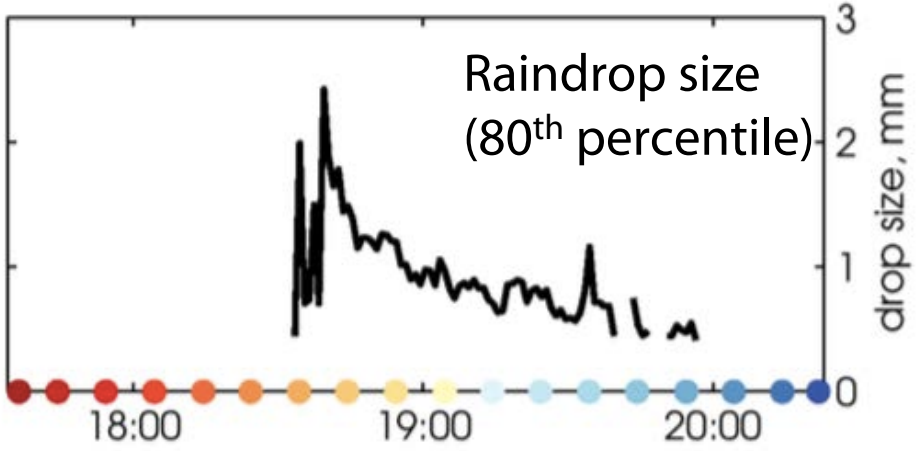




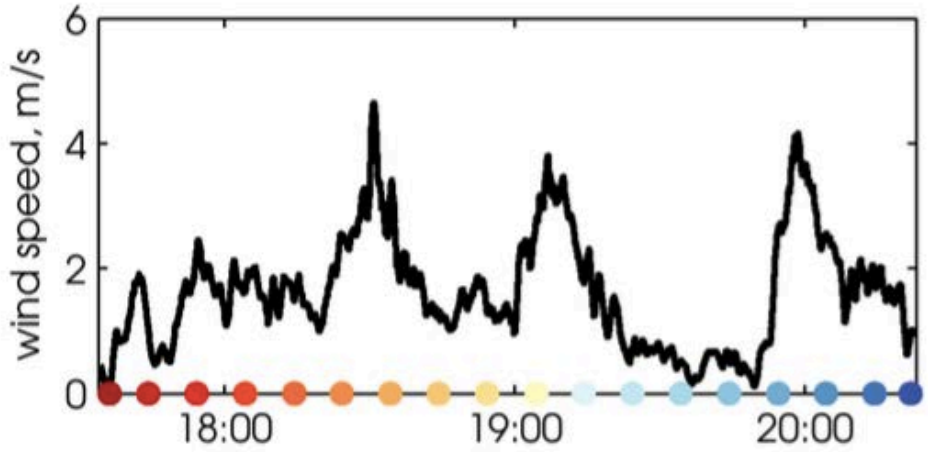
Example 1

Rain rate

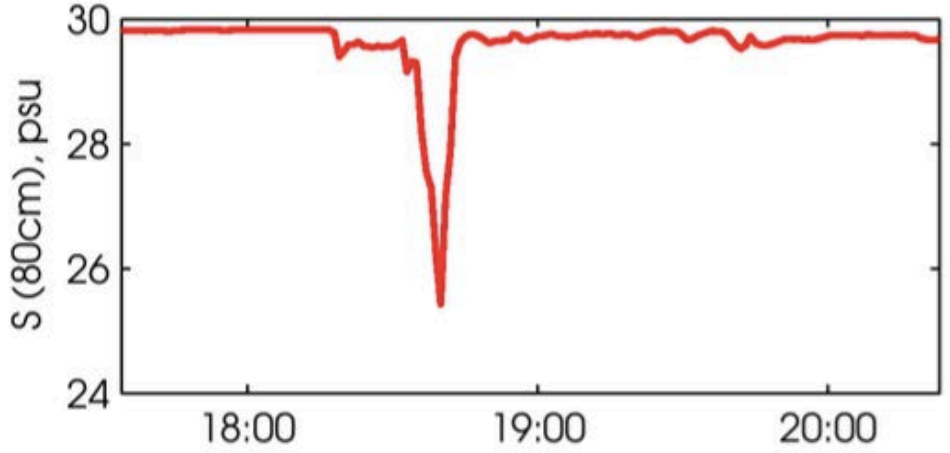




Wind speed



80cm salinity



Very strong, brief rain with large drops

Weak wind (2 m/s, some gusts)

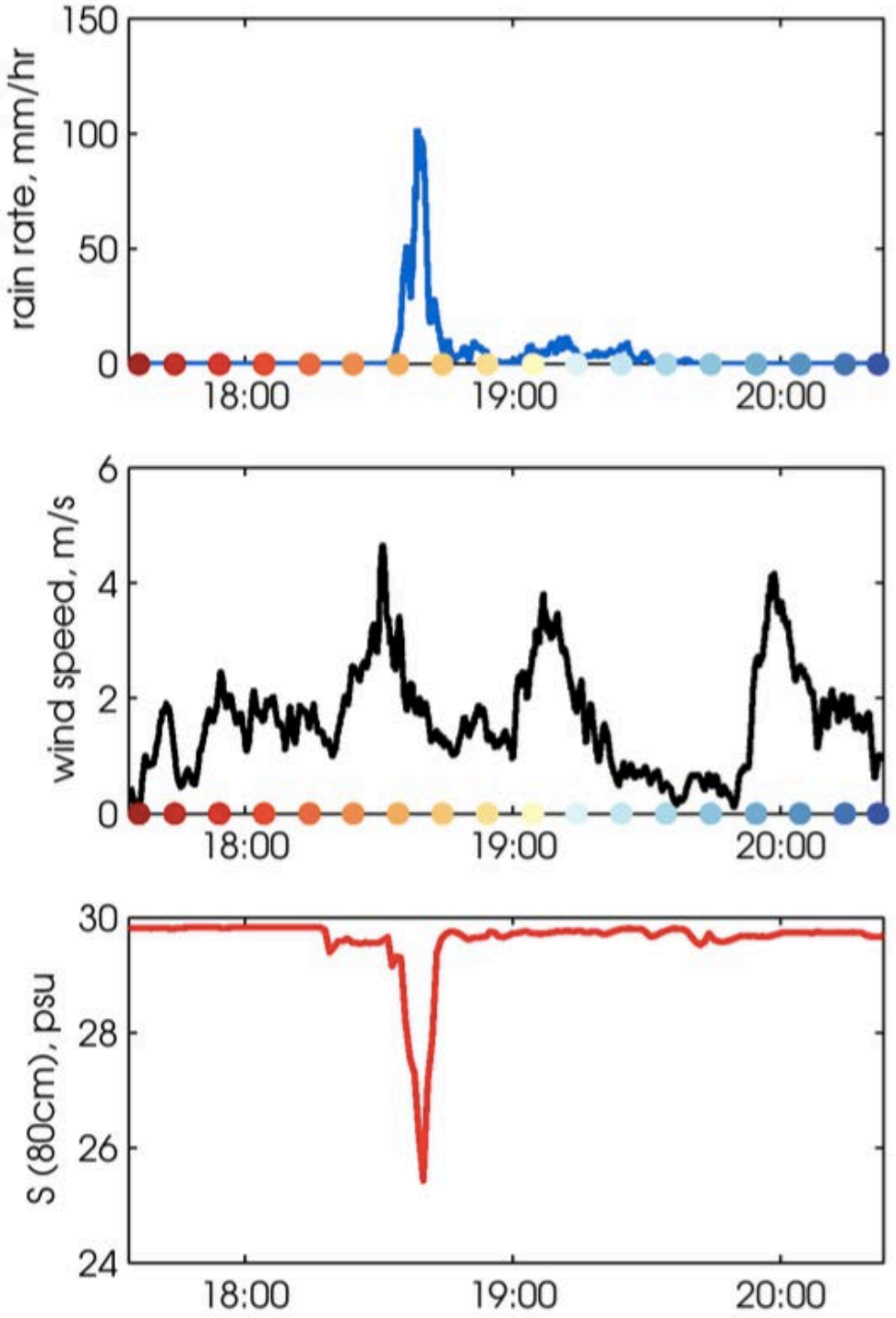
Strong 80-cm salinity drop (4 psu) and immediate recovery

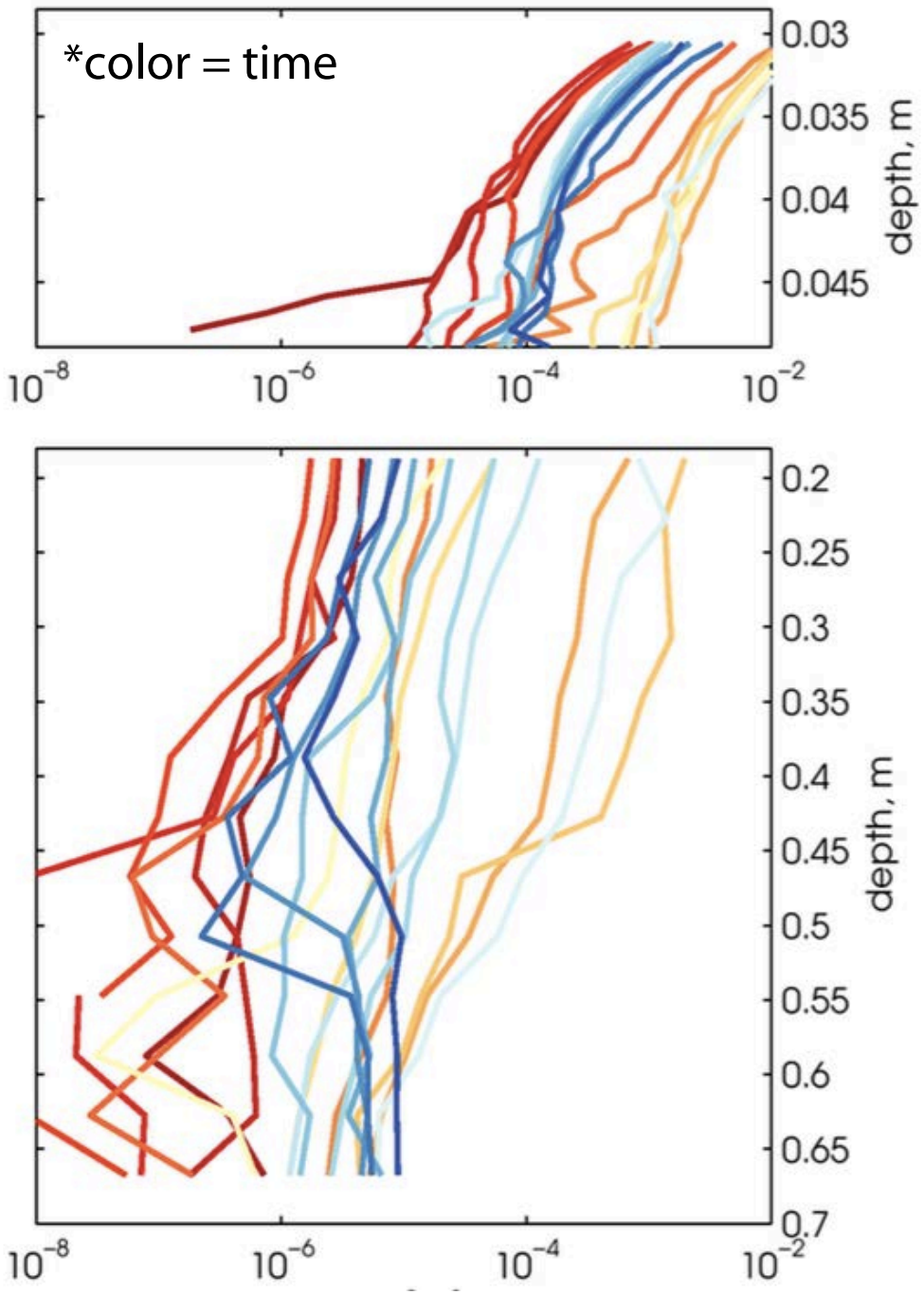
Example 1

Rain rate

Wind speed

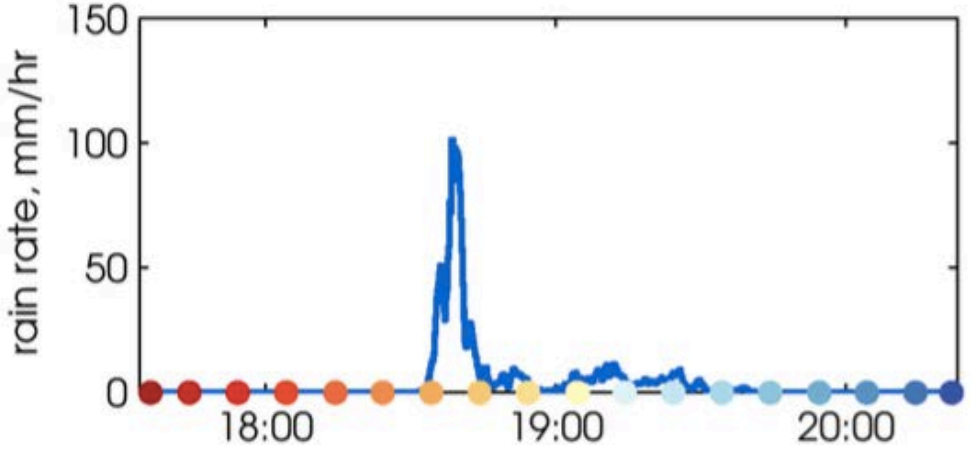
80cm salinity



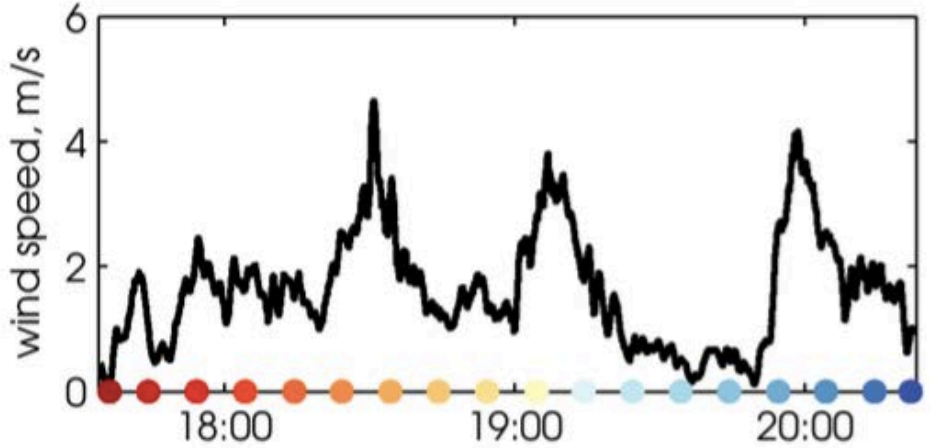


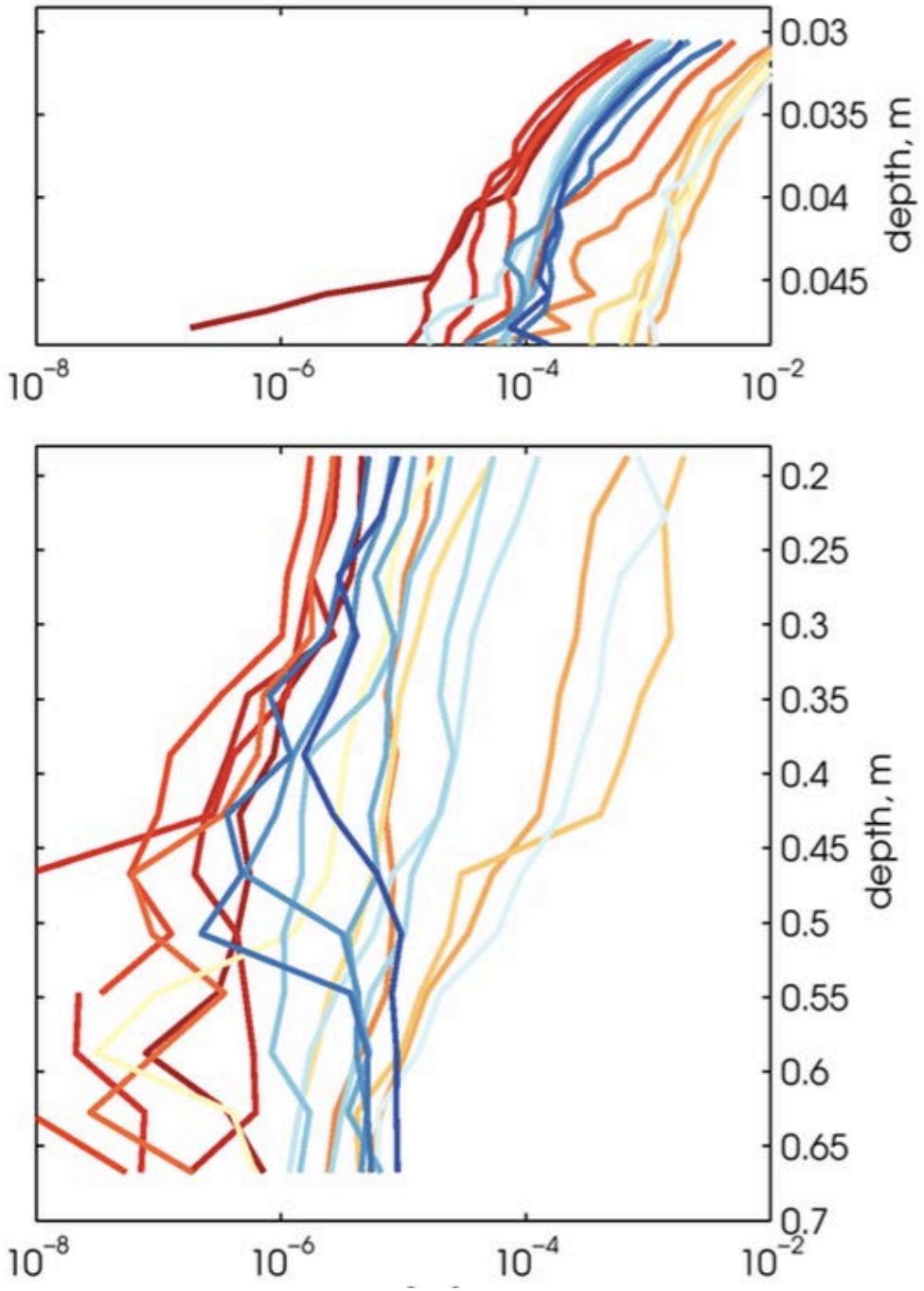
Example 1

Rain rate



Wind speed



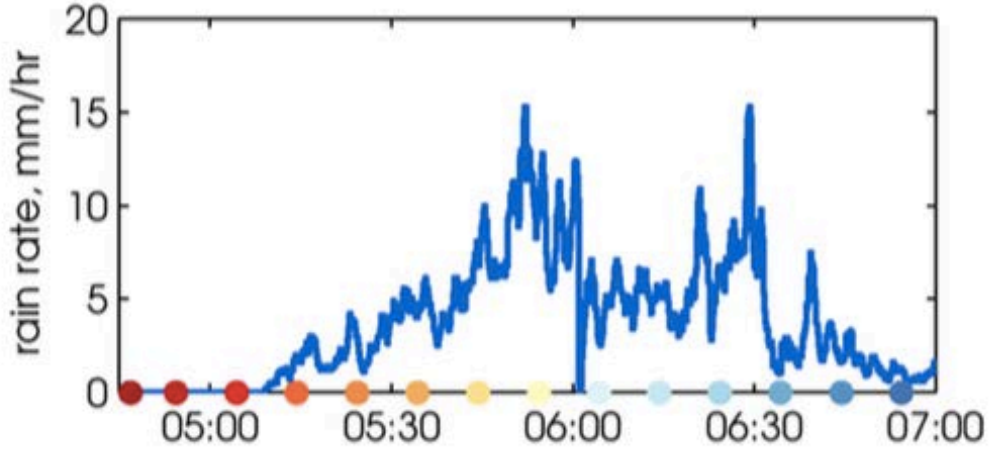


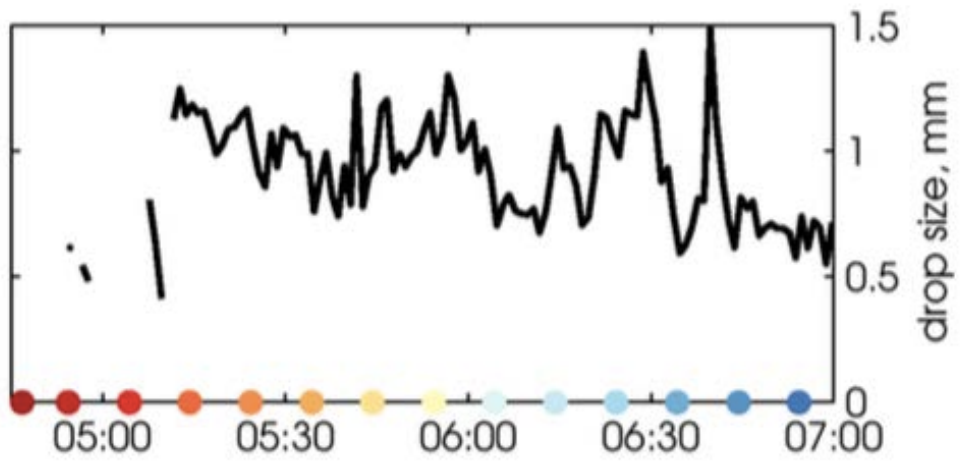
Dissipation rate increases during rain

Rain-induced mixing down to 45 cm

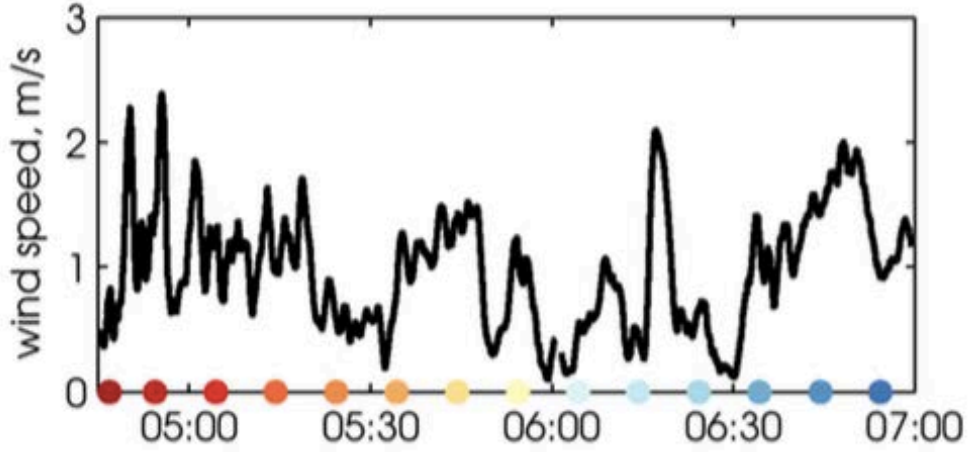
Example 2

Rain rate

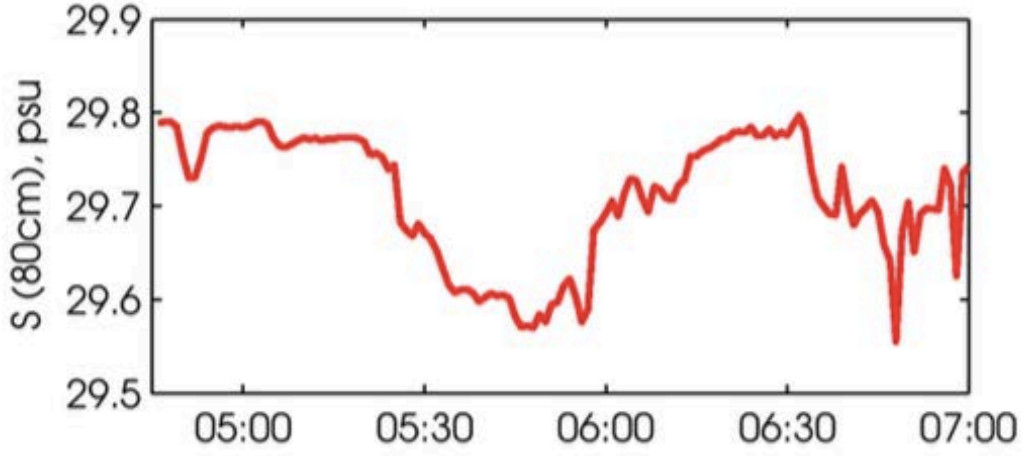




Wind speed



80cm salinity



Moderate, steady rains for 2 hours with consistent moderate drop size

Very weak winds (<1-2 m/s)

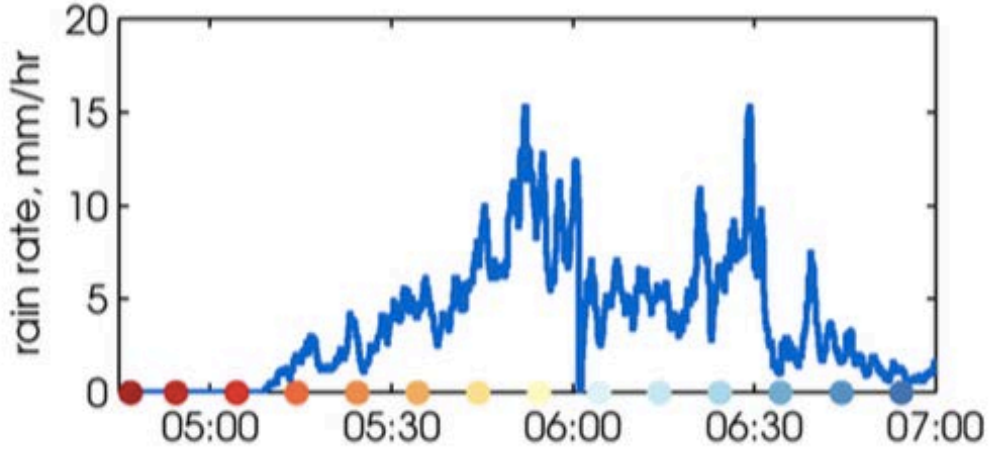
Salinity initially drops by 0.2 psu, recovers, then drops again as winds increase

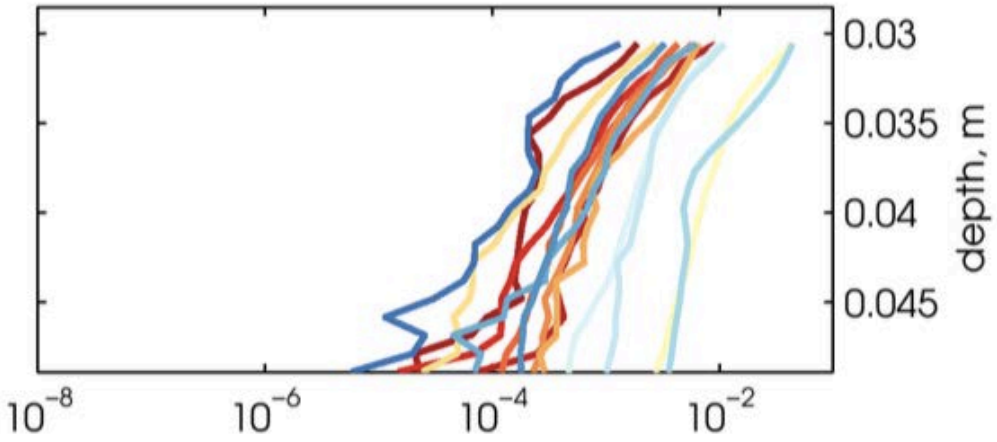
Example 2

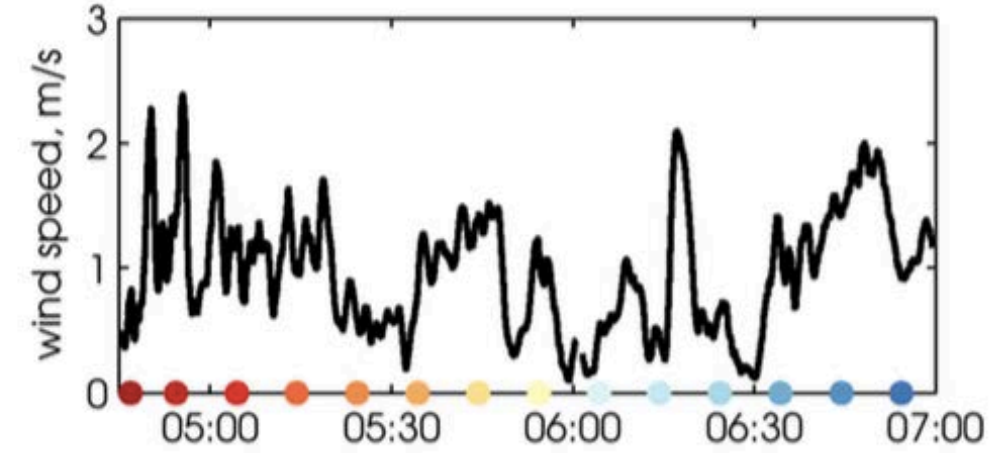
Rain rate

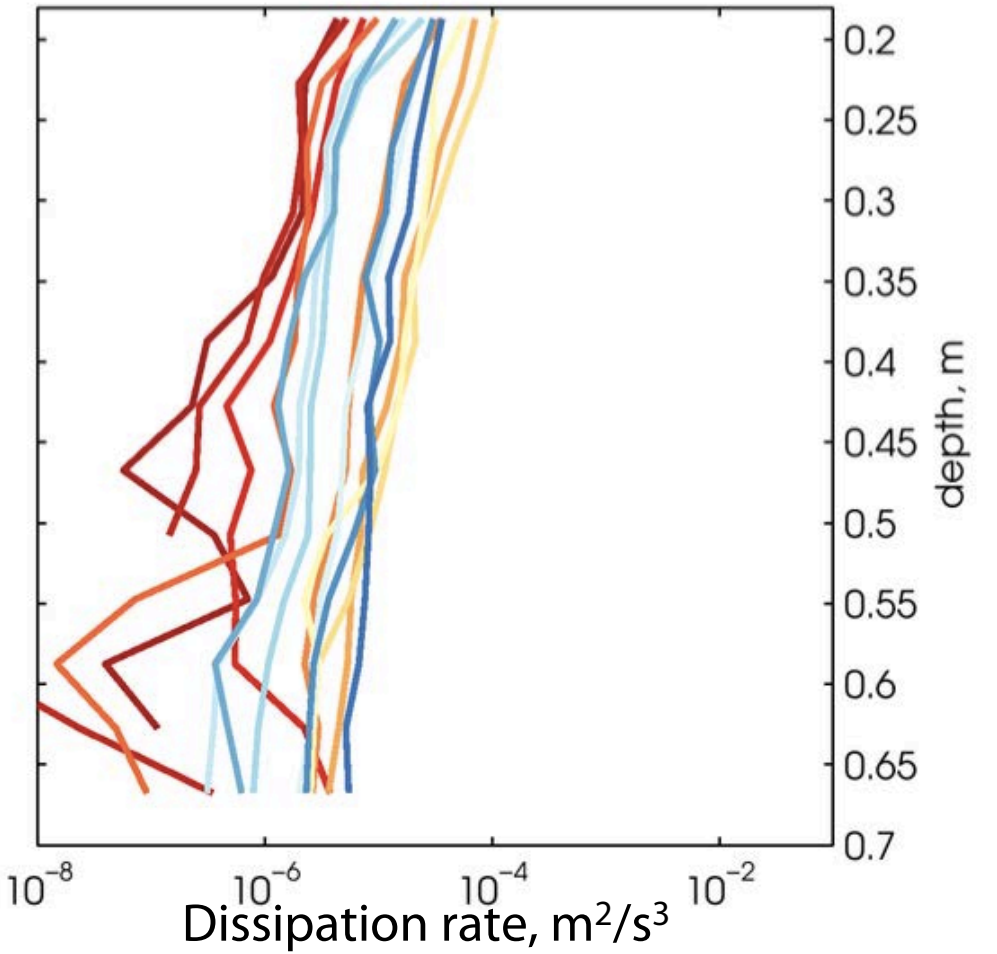
Wind speed

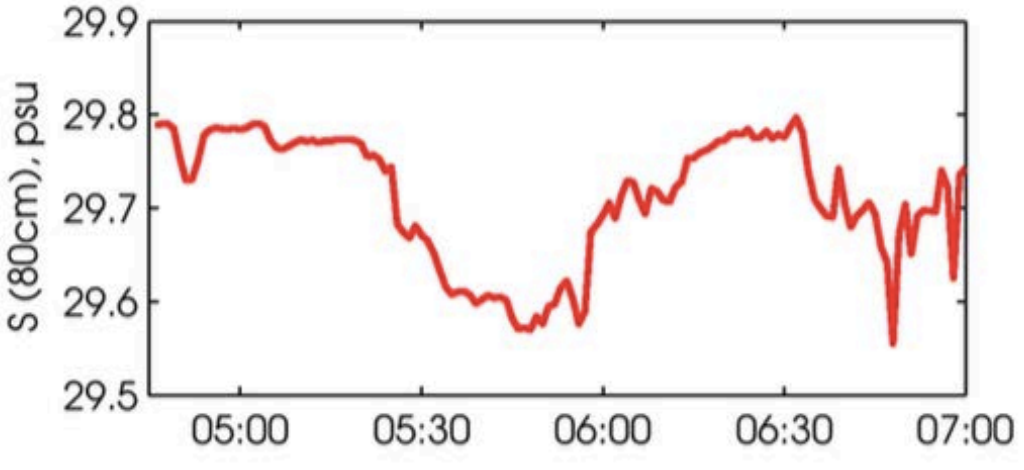
80cm salinity











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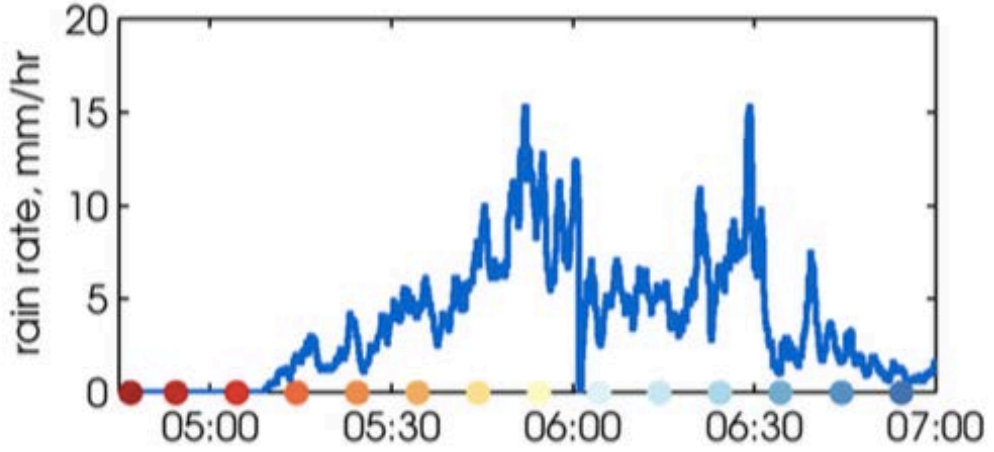
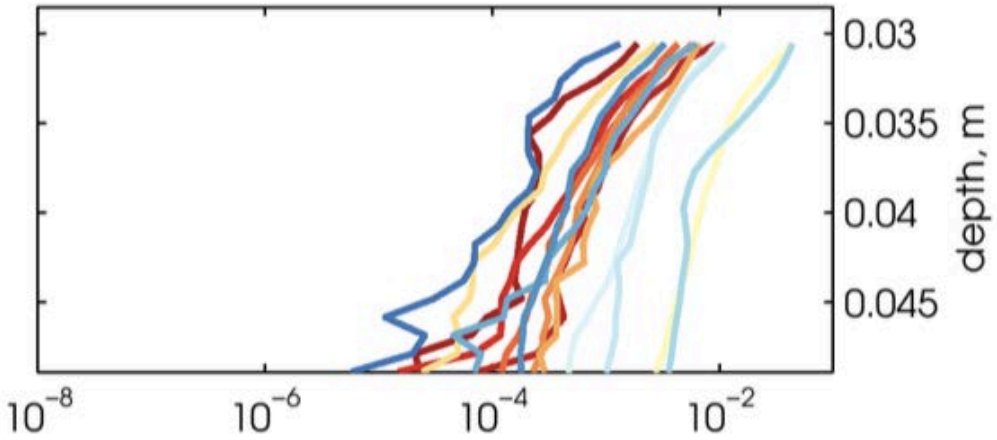
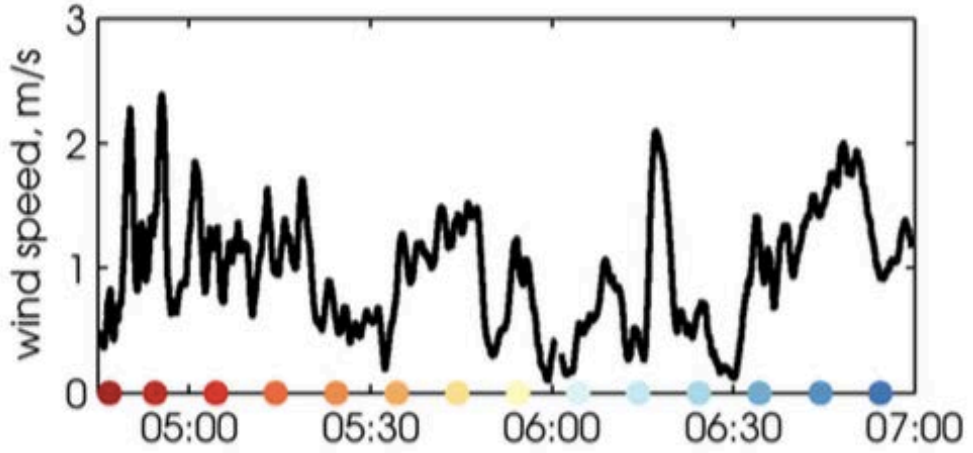
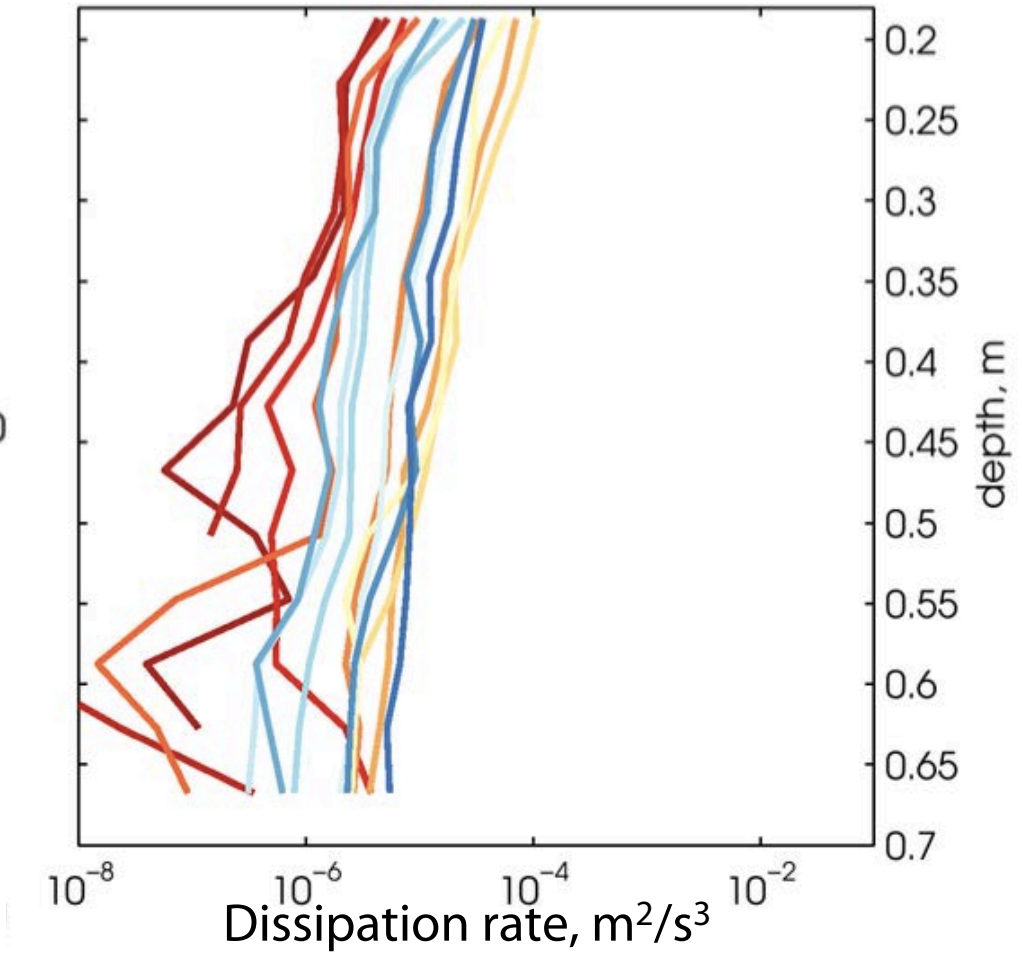
Rain rate





Wind speed



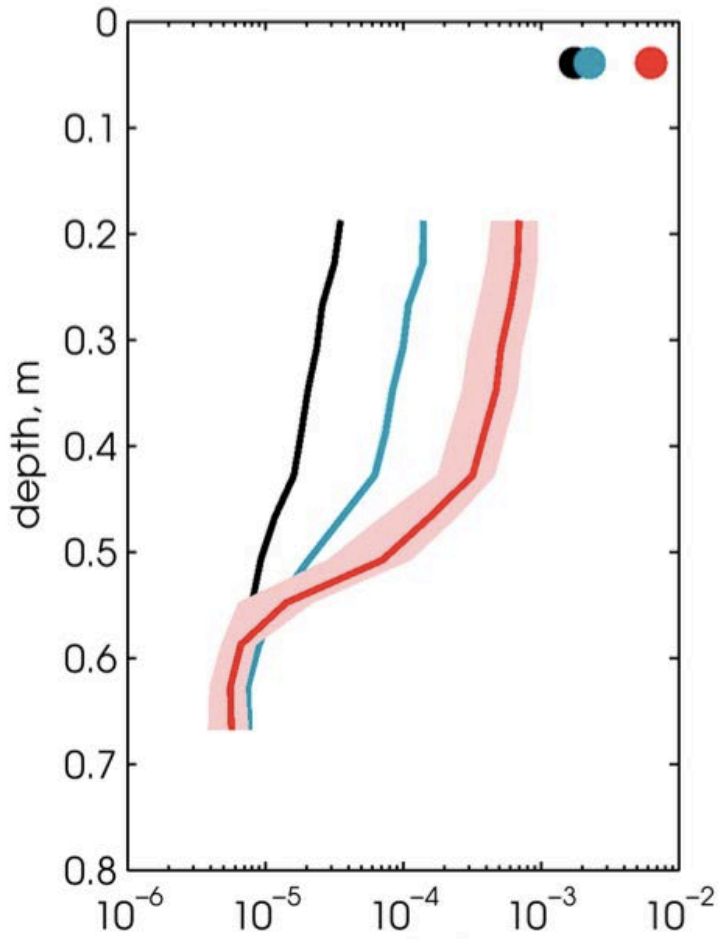


3cm and 20cm dissipation both follow rain rate, with peakier (smoother) response near the surface (deeper)

Direct mixing down to above 20cm

Binned dissipation profiles: rain/wind dependence

Wind speed
< 4 m/s



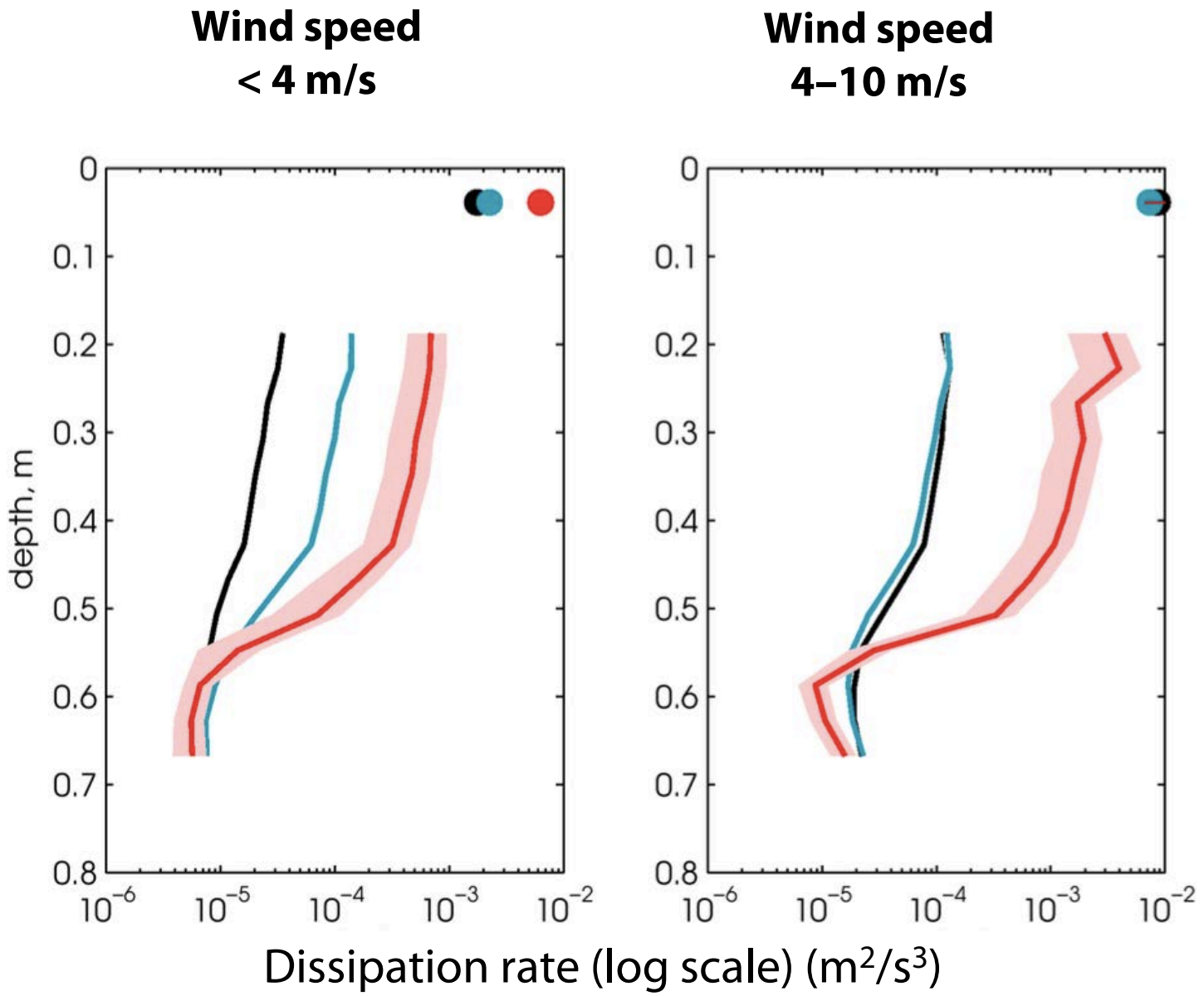
No rain
Rain 0–10 mm/hr
Rain >10 mm/hr

Low winds: strong rain enhances TKE dissipation by a factor of 10-100

Dissipation rate enhancement stronger below 20 cm than at 3 cm

Rain mixing down to ~55 cm

Binned dissipation profiles: rain/wind dependence

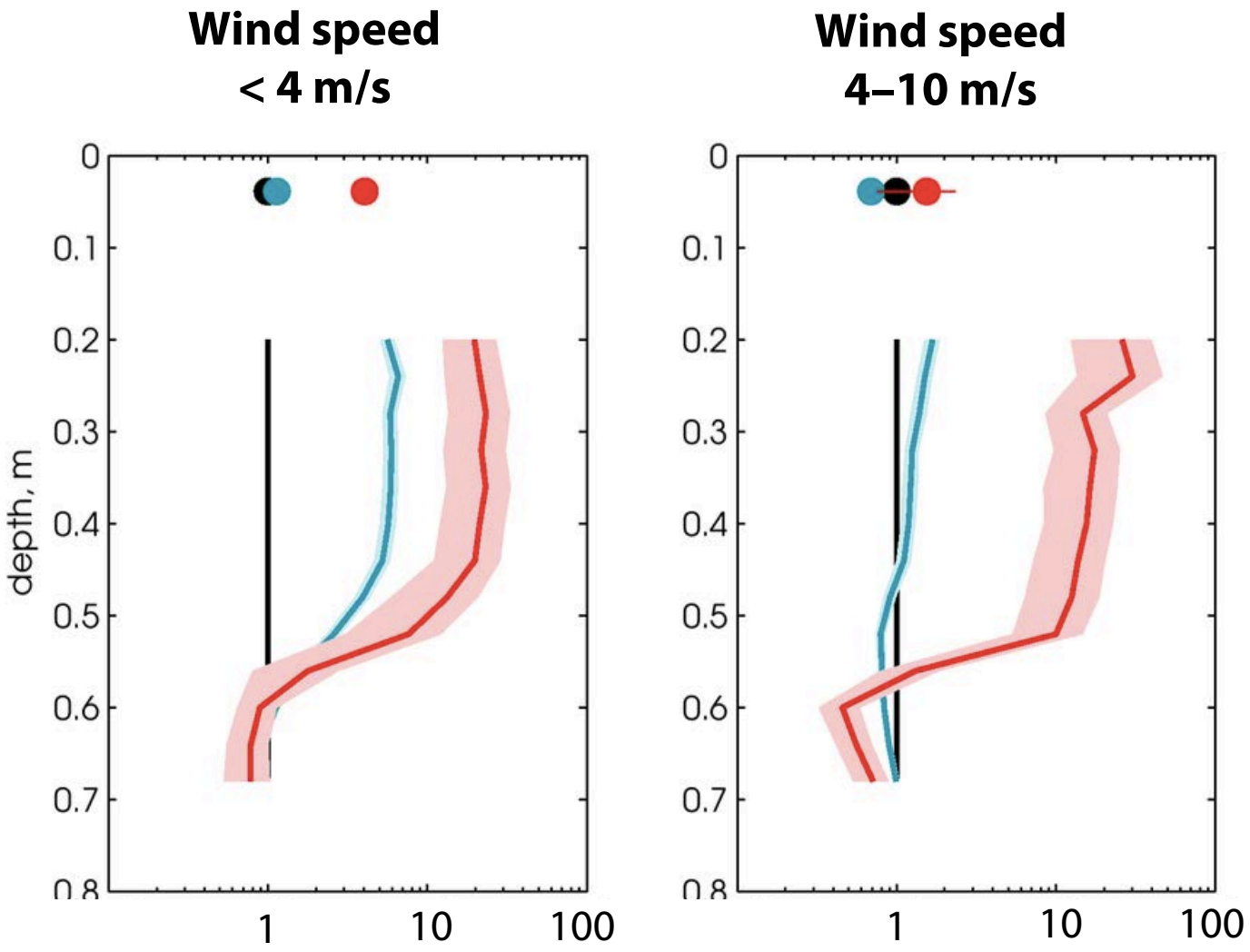


No rain
Rain 0–10 mm/hr
Rain >10 mm/hr

Moderate winds: only the strongest rain generates appreciable turbulence.

Near the surface, rain effect is less apparent.

Turbulence enhancement due to rain: $\frac{\varepsilon_{rain}}{\varepsilon_{no\text{-}rain}}$

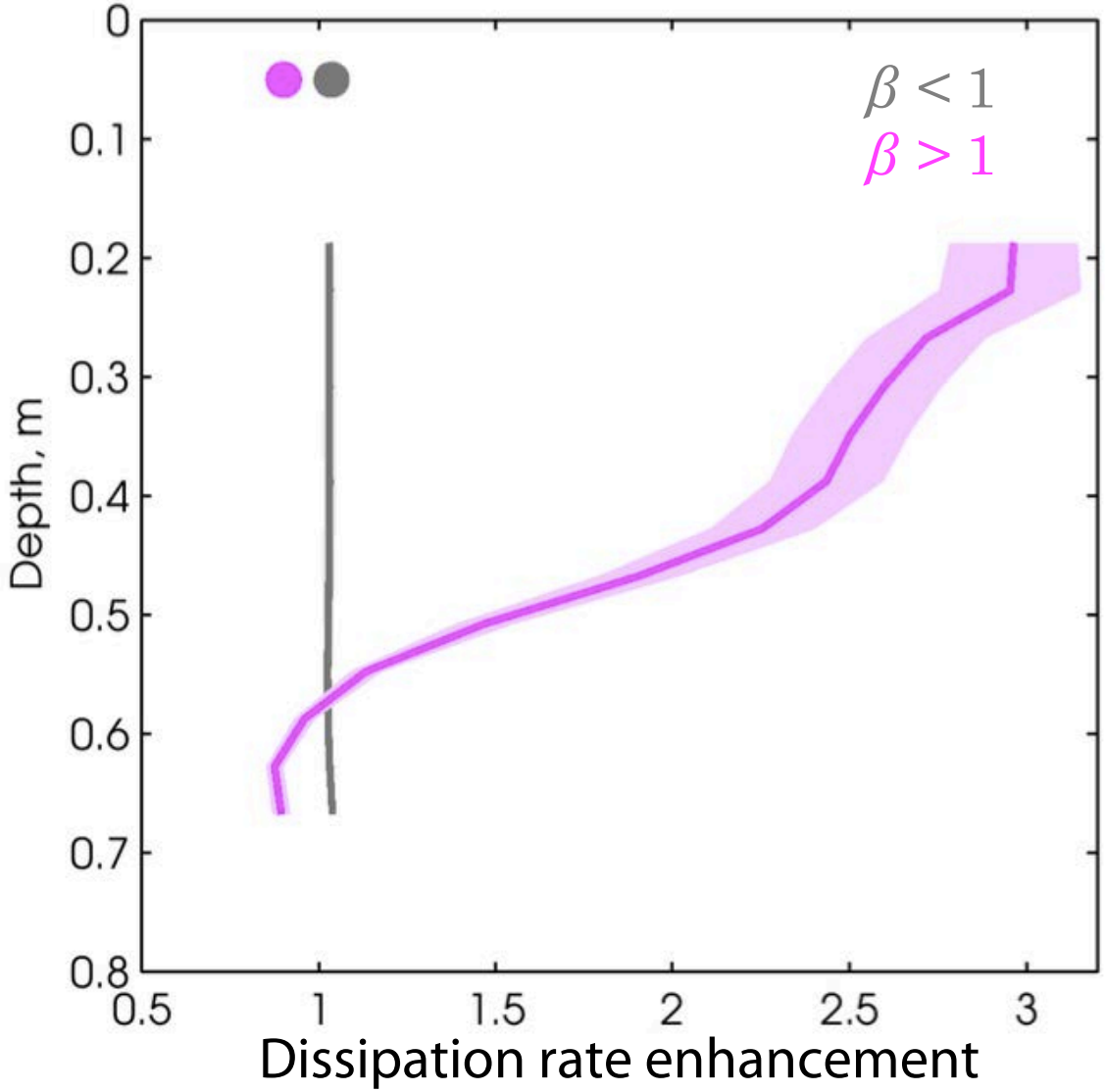


No rain

Rain 0–10 mm/hr

Rain >10 mm/hr

The relative importance of rain and wind can be determined from Kinetic Energy Flux (KEF)



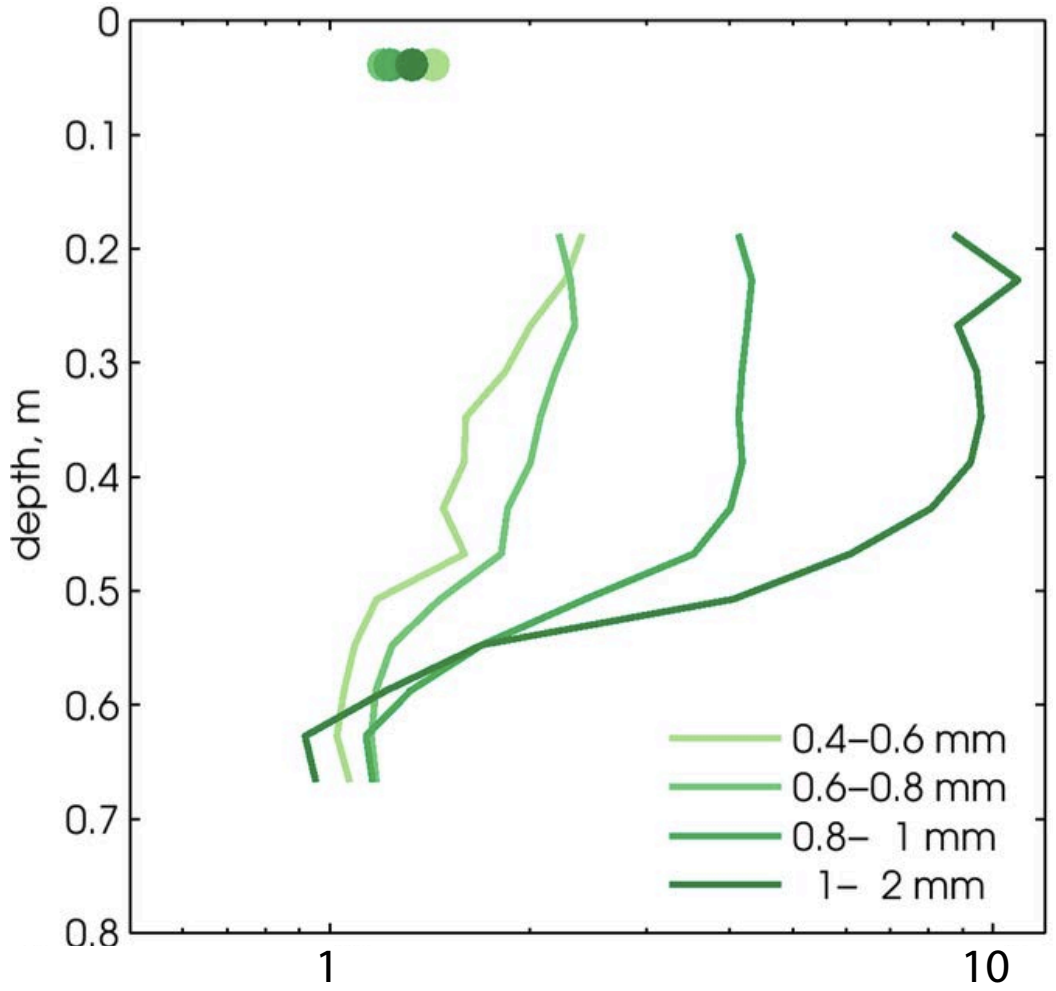
$$\beta = \frac{KEF_{rain}}{KEF_{wind}}$$

Below 20 cm, rain generates enhanced turbulence when $KEF_{rain} > KEF_{wind}$

Near the surface, turbulence is *suppressed* for $KEF_{rain} > KEF_{wind}$ …!?!

… thin rain layer suppresses mixing?

Dissipation rate enhancement for different raindrop sizes (wind < 5 m/s)



Dissipation rate enhancement (log scale)

Below 20 cm, bigger raindrops = stronger turbulence.

Mixing depth does not appear to depend on drop size.

At the surface, no relationship between dissipation rate and drop size.

Summary

- Turbulence generated by rain penetrates to ~50cm, independent of drop size and rain rate – much deeper than suggested by lab experiments (~10cm).
- Kinetic energy flux of rain vs. wind can be used to predict when rain “matters” for turbulence.
- Stronger rain drives stronger turbulence below ~20 cm, but at the surface rain suppresses turbulence.