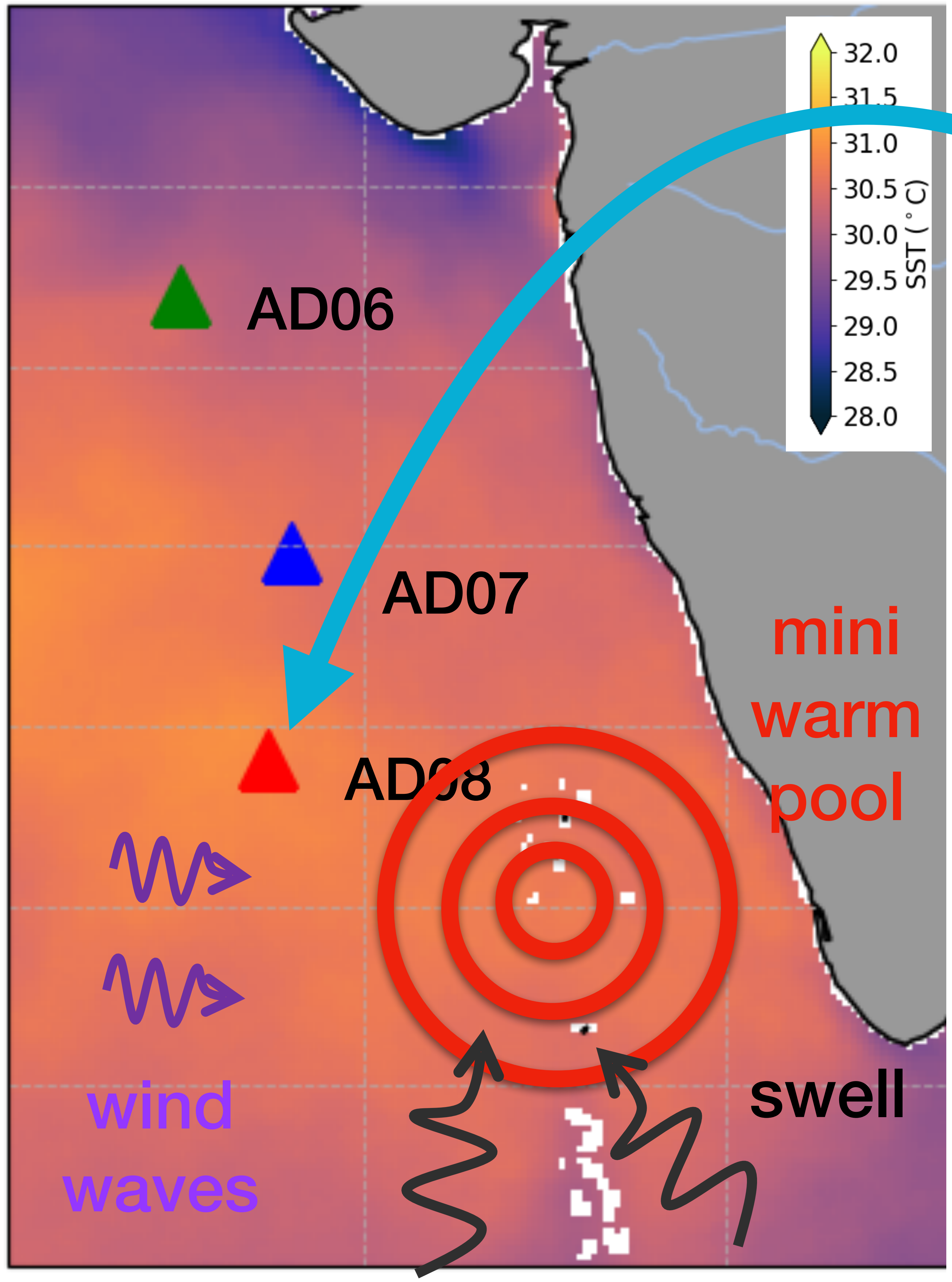
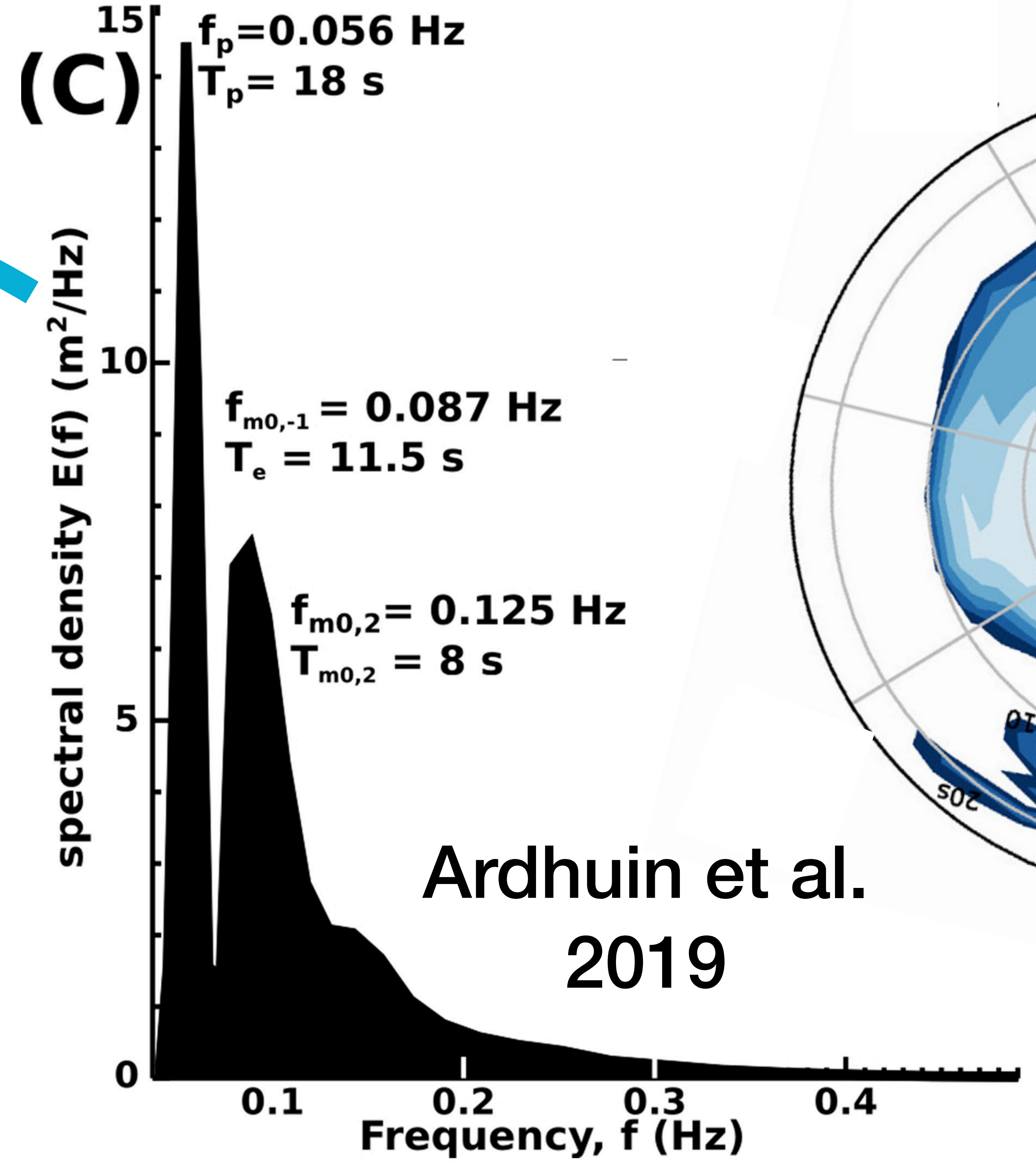
Seasonal Variability of Wave States and Their Influence on Air-Sea Fluxes in the Northern Indian Ocean

OMNI mooring

Venkatesan et al. 2021

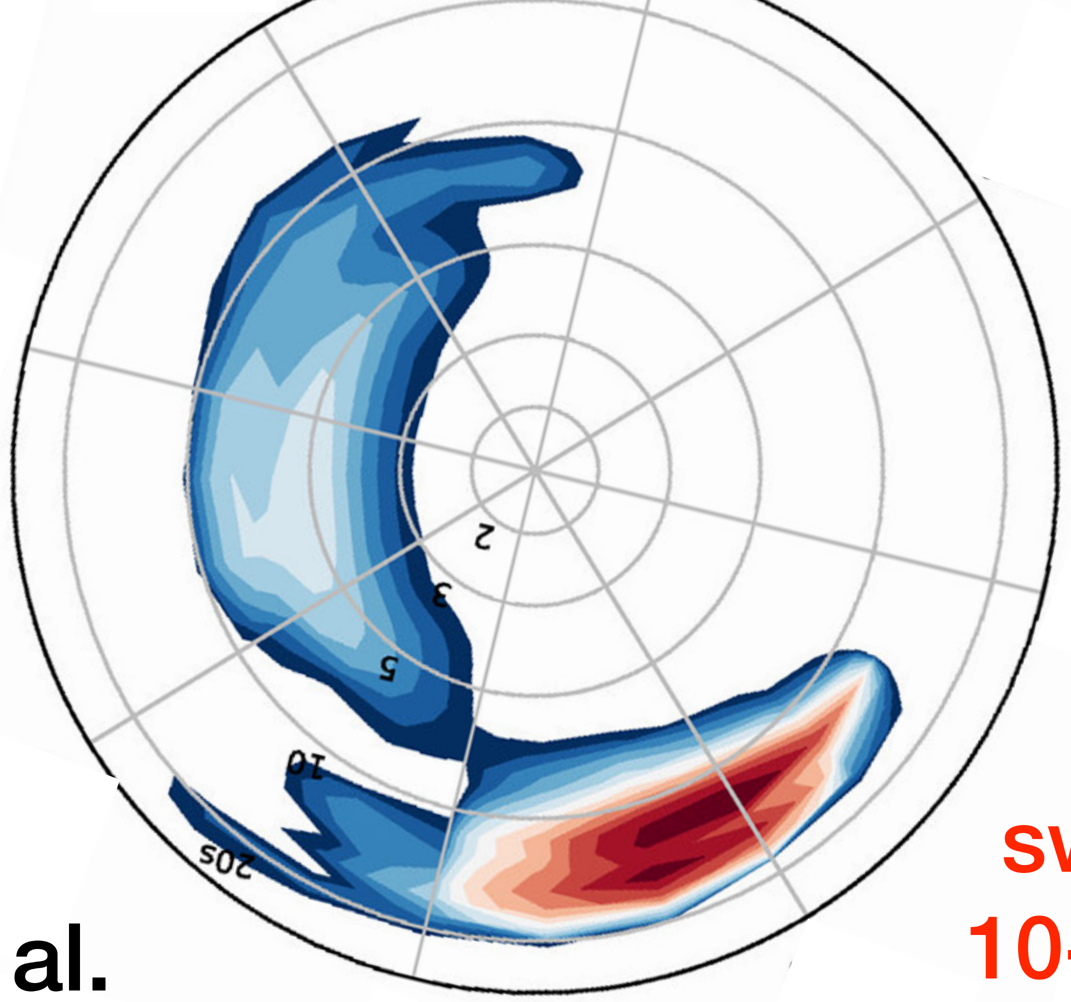
Spring to early summer





Ardhuin et al. 2019

wind waves 5-10s



swell 10-20s

Sauvage et al. 2023

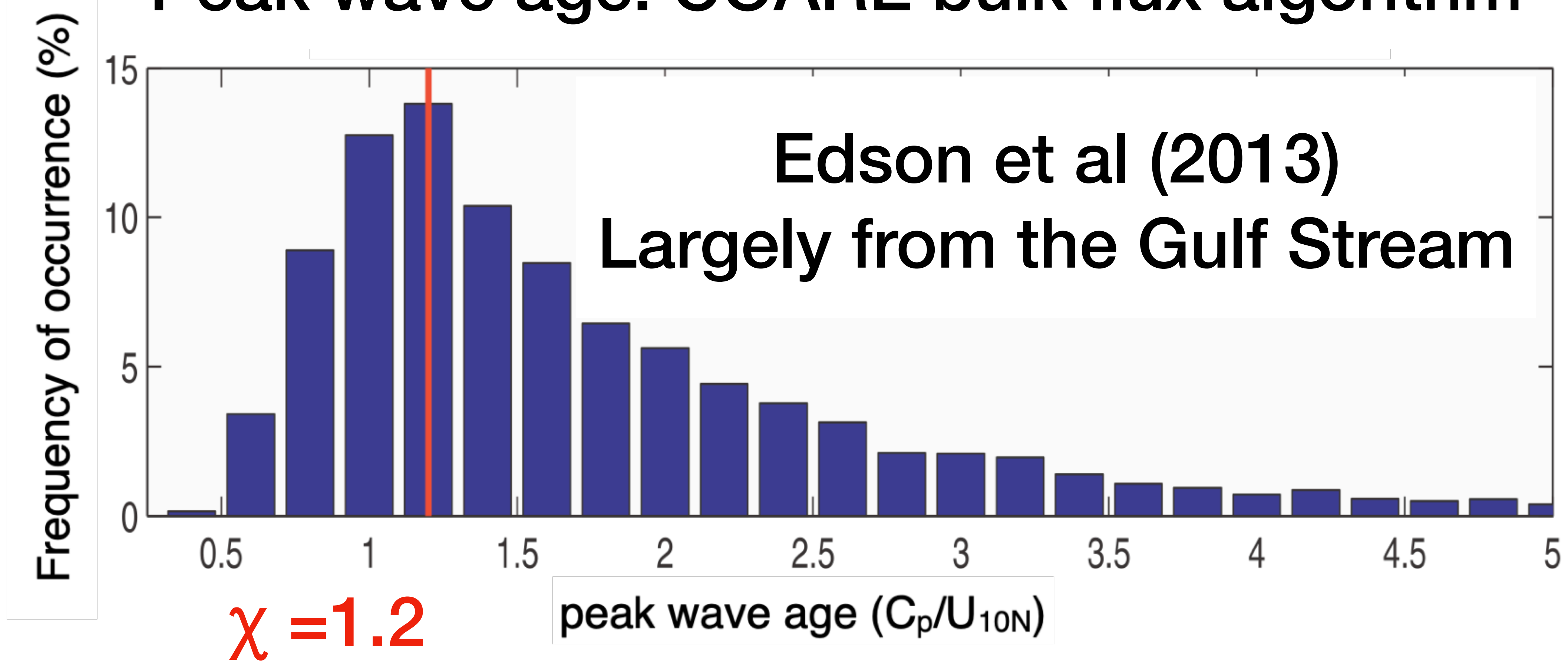
Hyodae Seo, Sid Kerhalkar, César Sauvage (Univ. Hawaii, Manoa), Amit Tandon (UMass Dartmouth)

(Peak) Wave age

$$\chi \equiv C_p/U_{10}$$

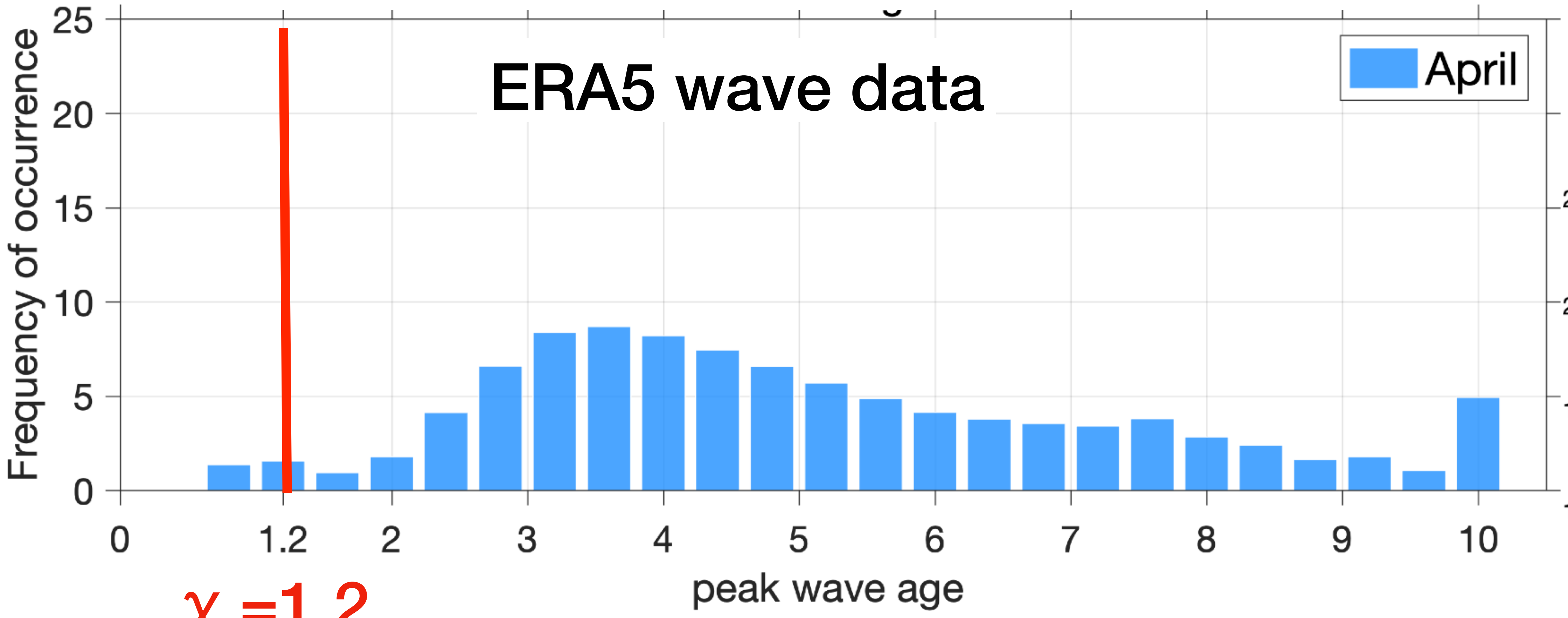
April

Peak wave age: COARE bulk flux algorithm



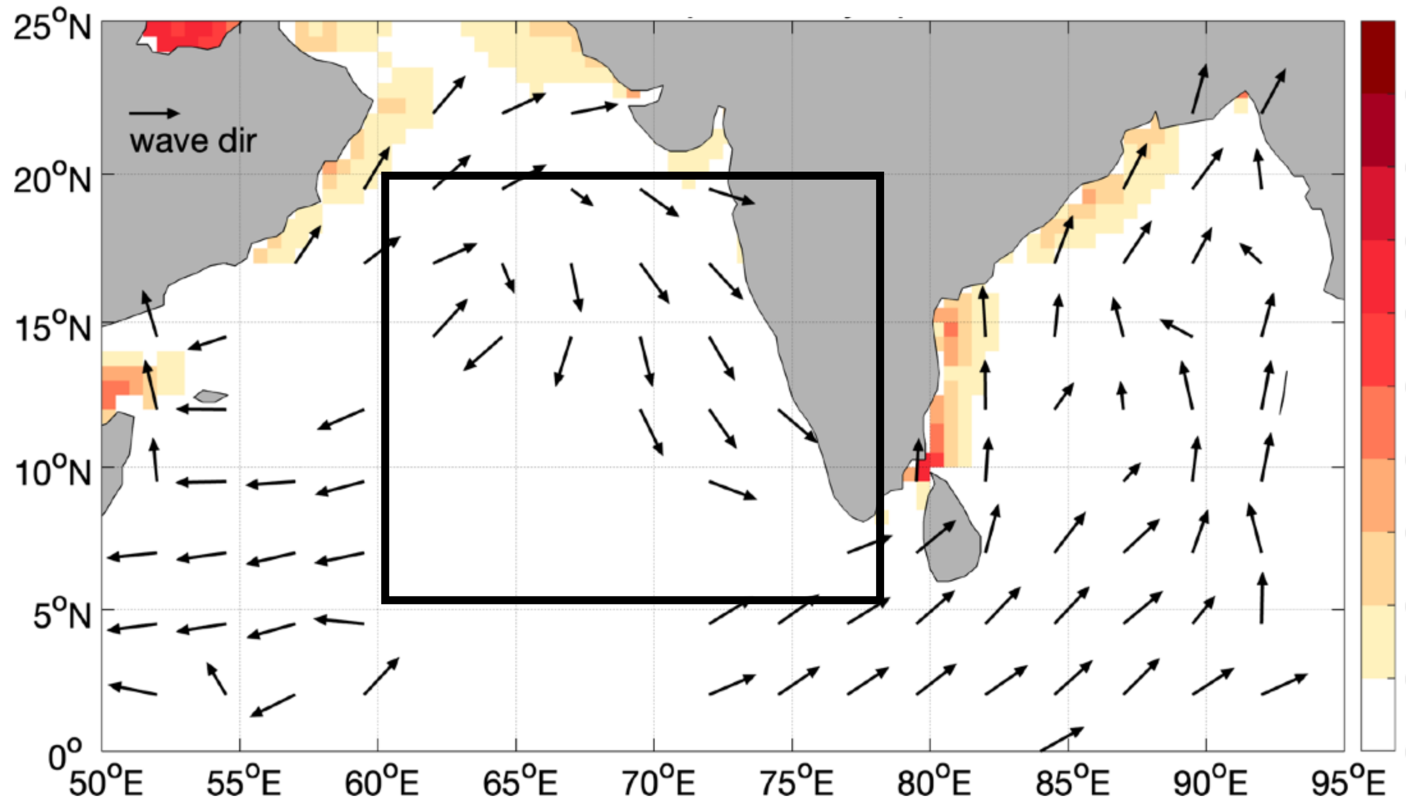
χ =1.2

Peak wave age: Arabian Sea

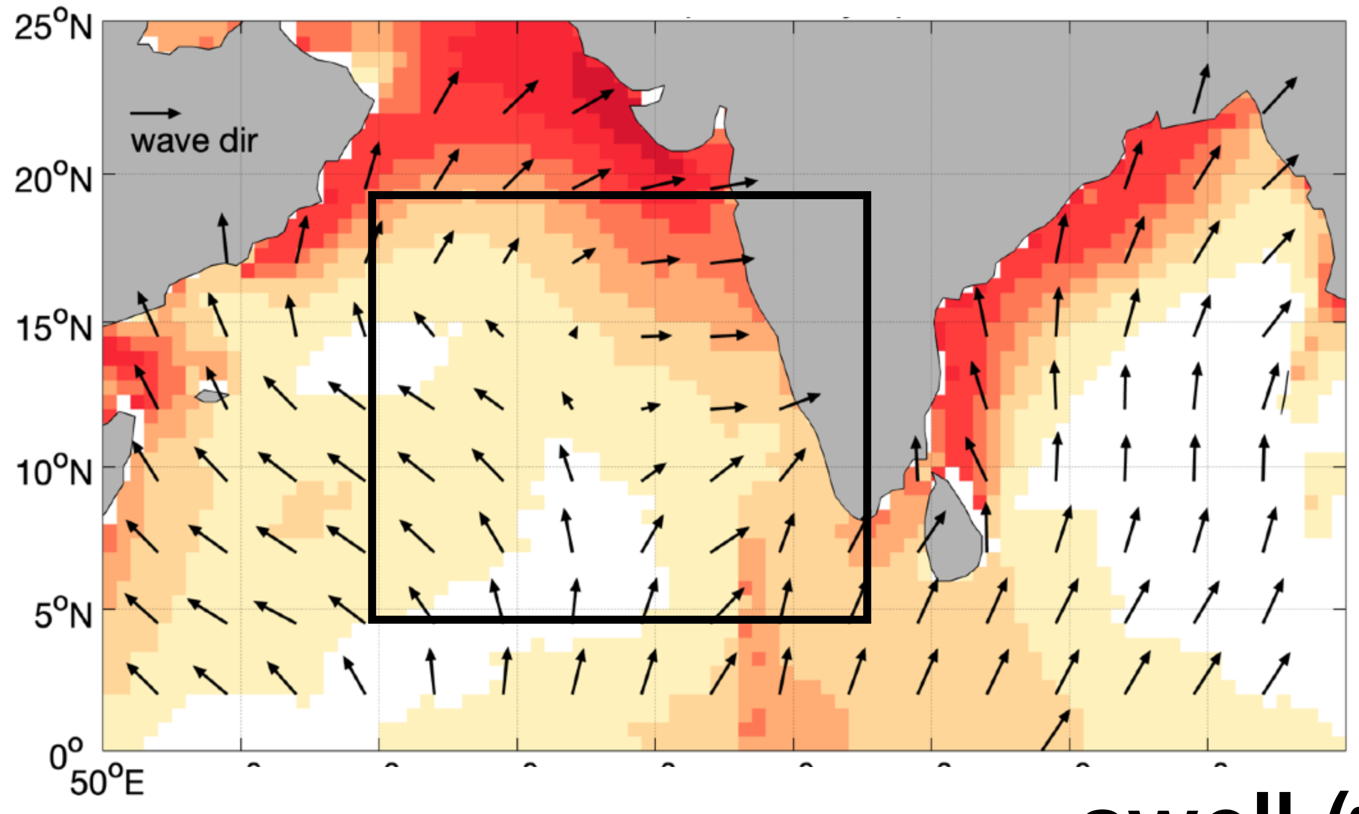


χ =1.2

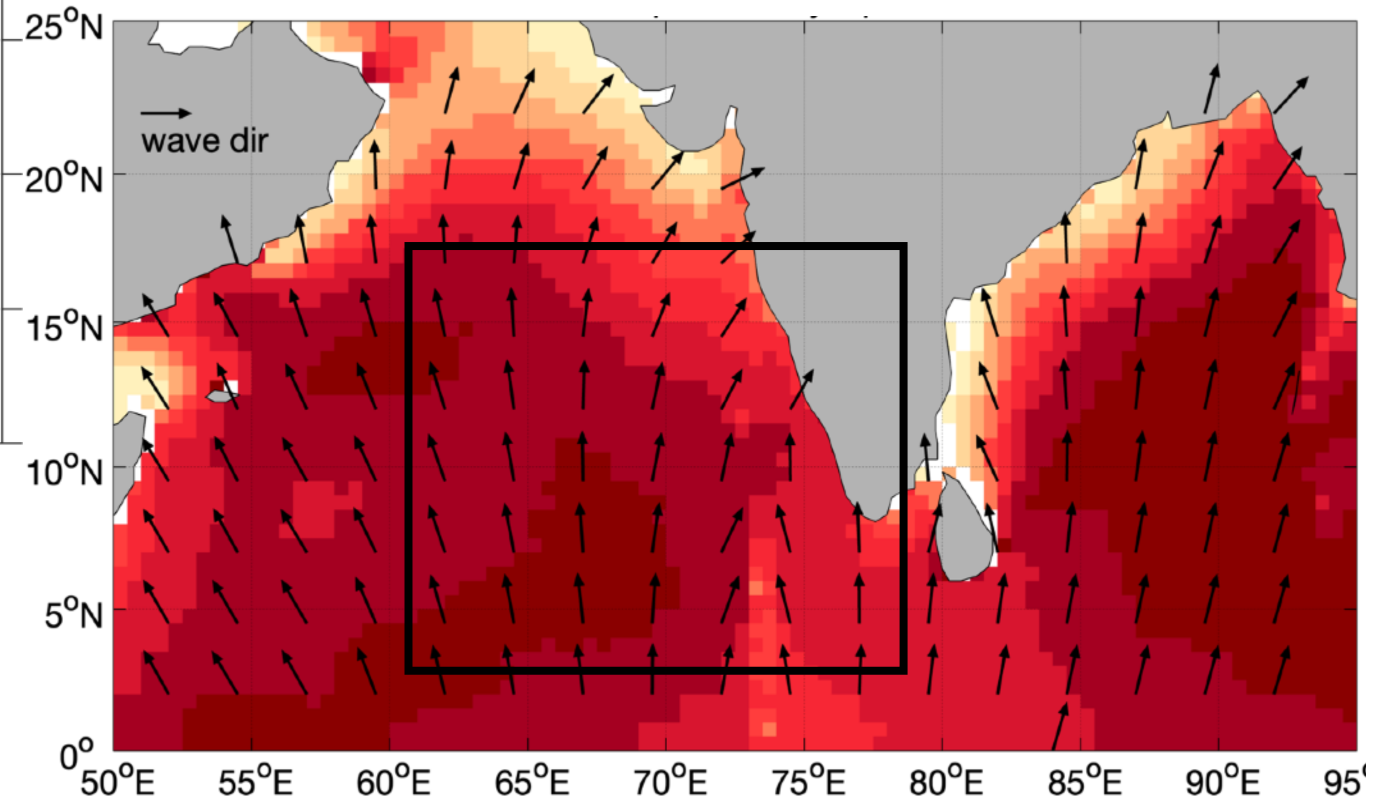
windsea (χ<1.2)

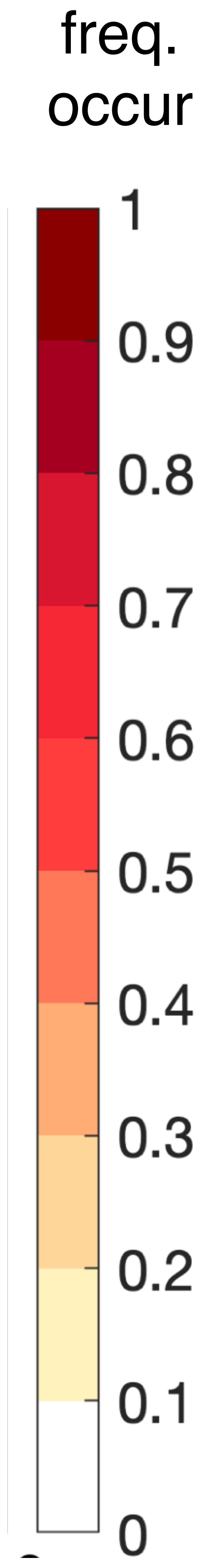


mixed sea (1.2<χ<3)



swell (χ>3)

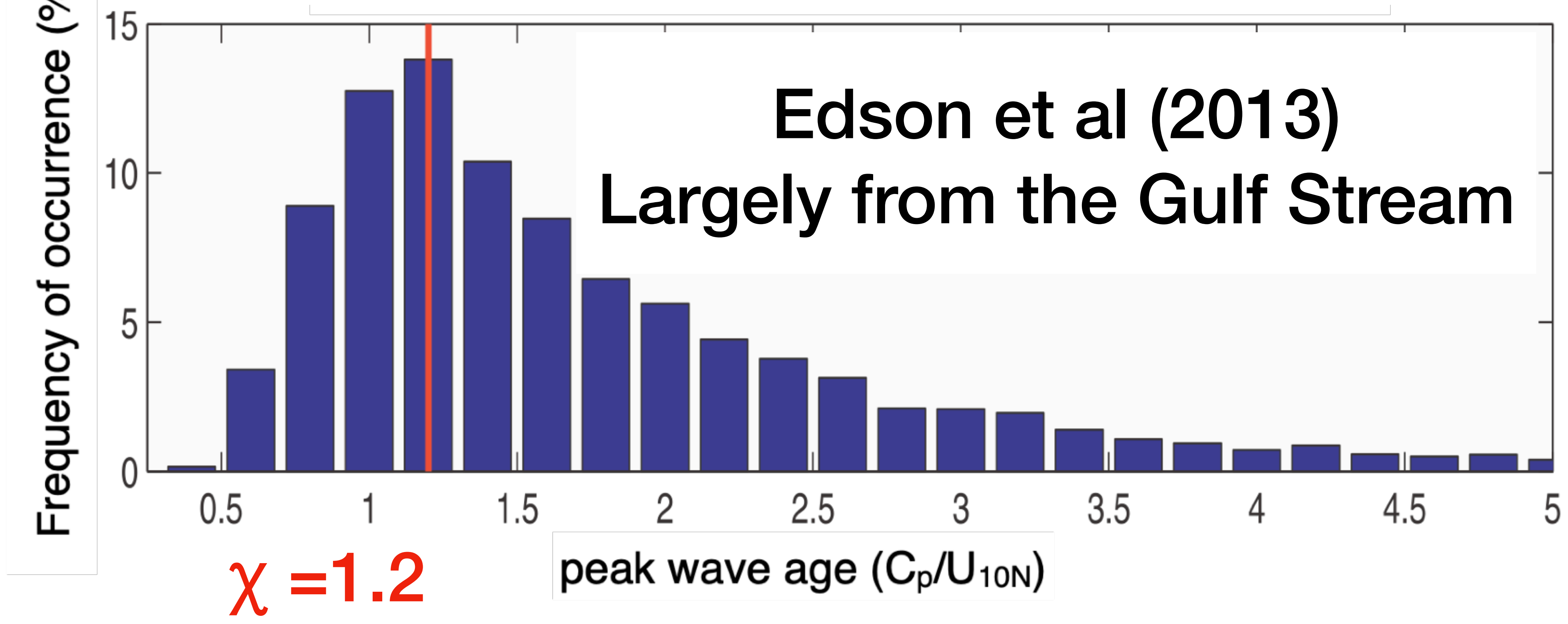




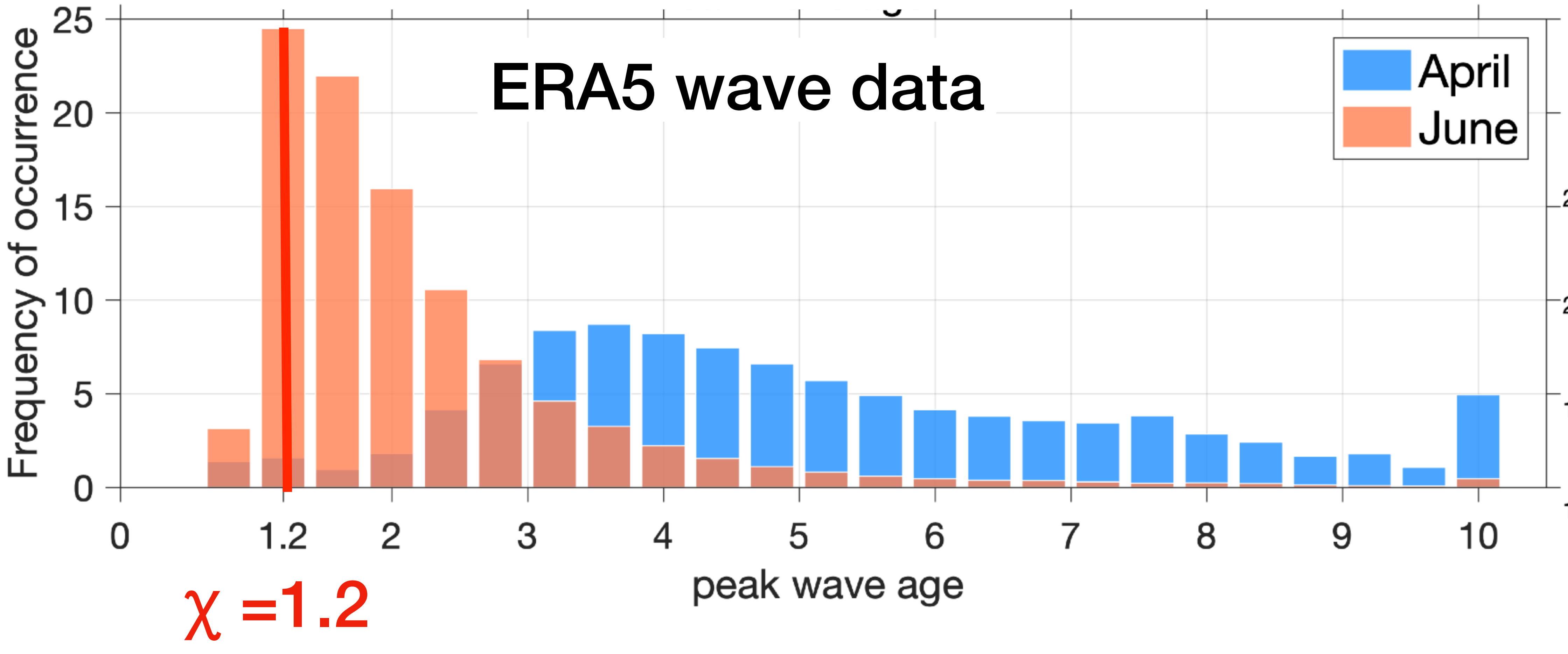
(Peak) Wave age

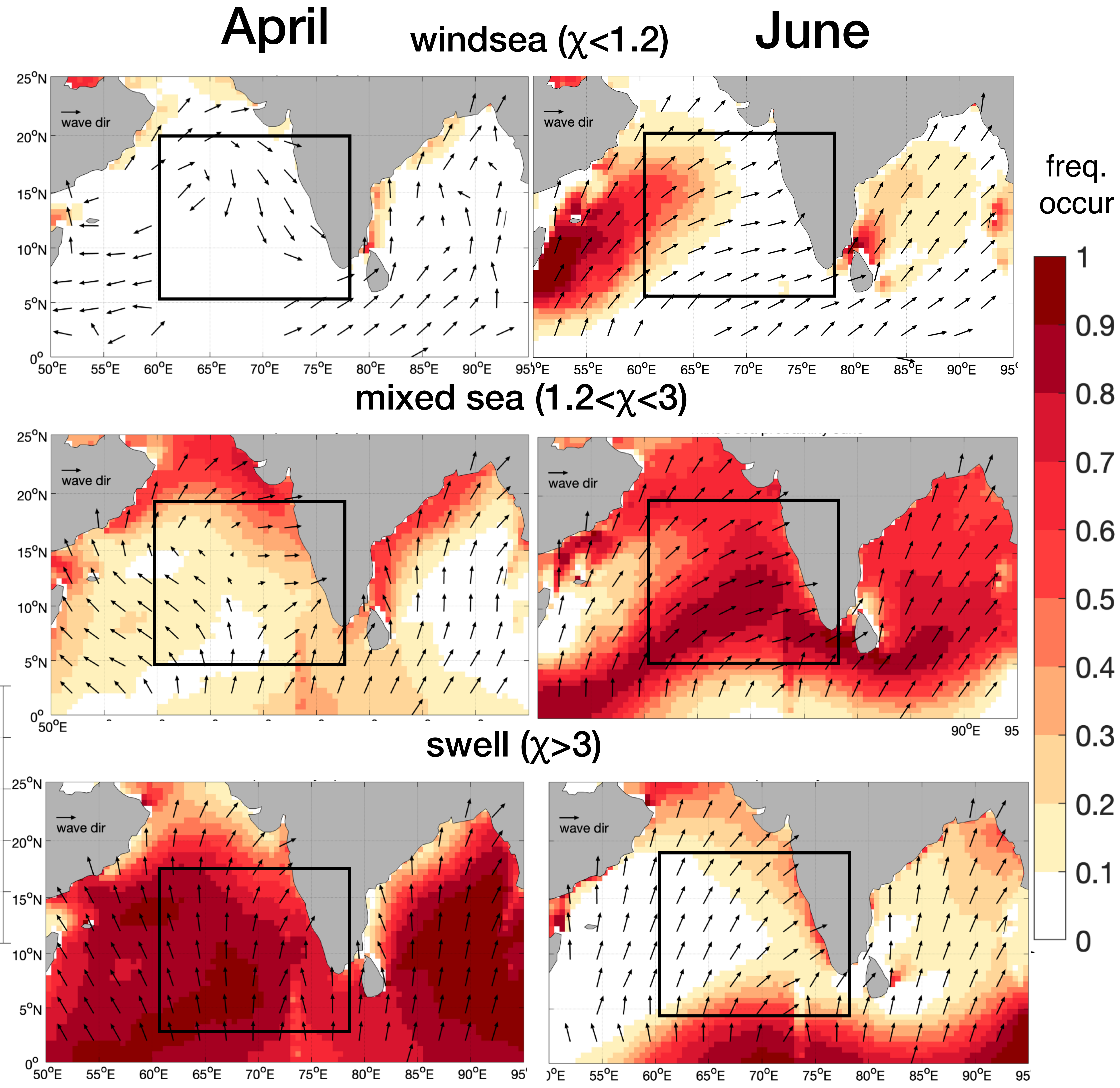
$$\chi \equiv C_p/U_{10} \text{ (or } C_p/u^*)$$

Peak wave age: COARE bulk flux algorithm

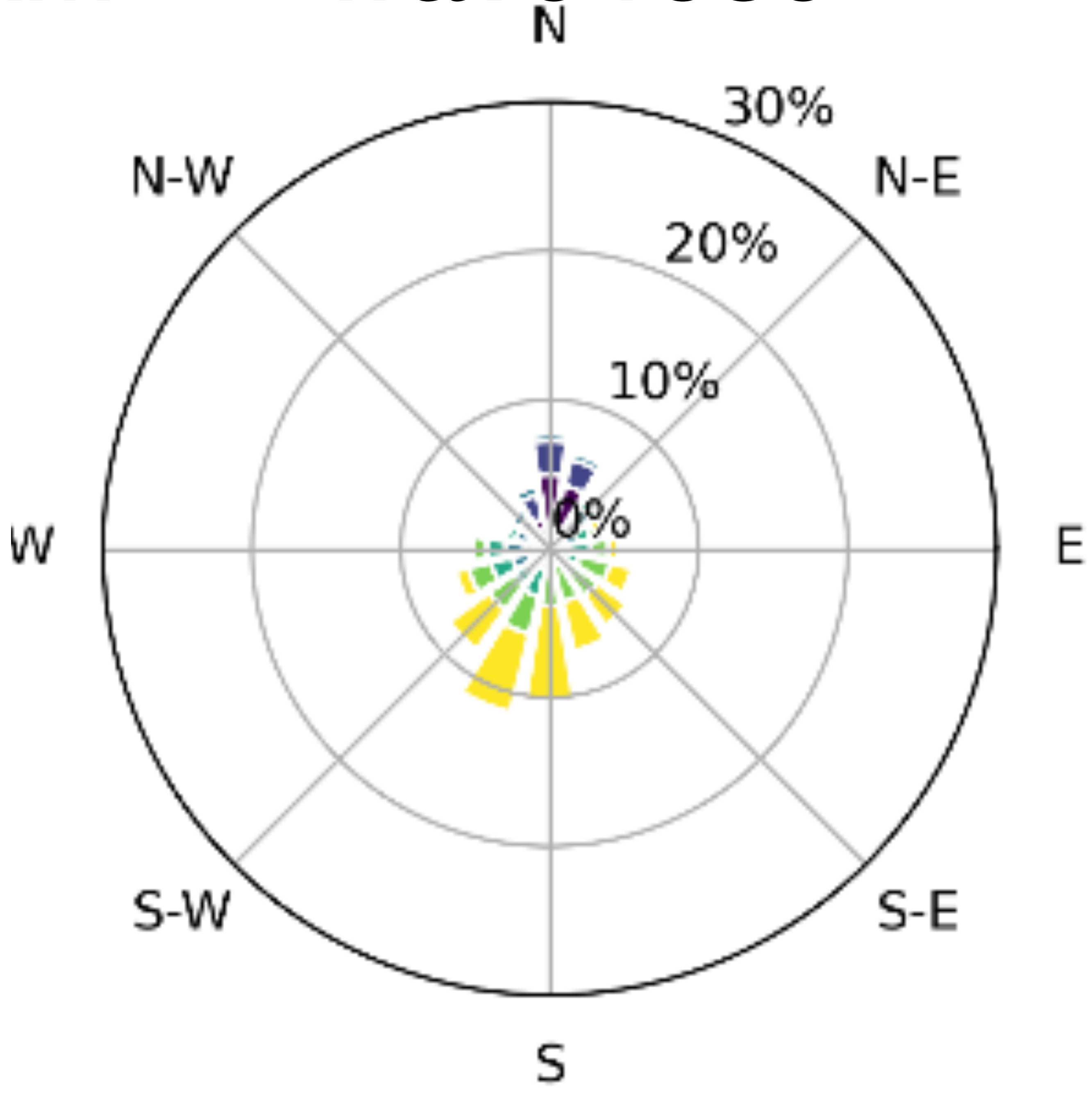


Peak wave age: Arabian Sea

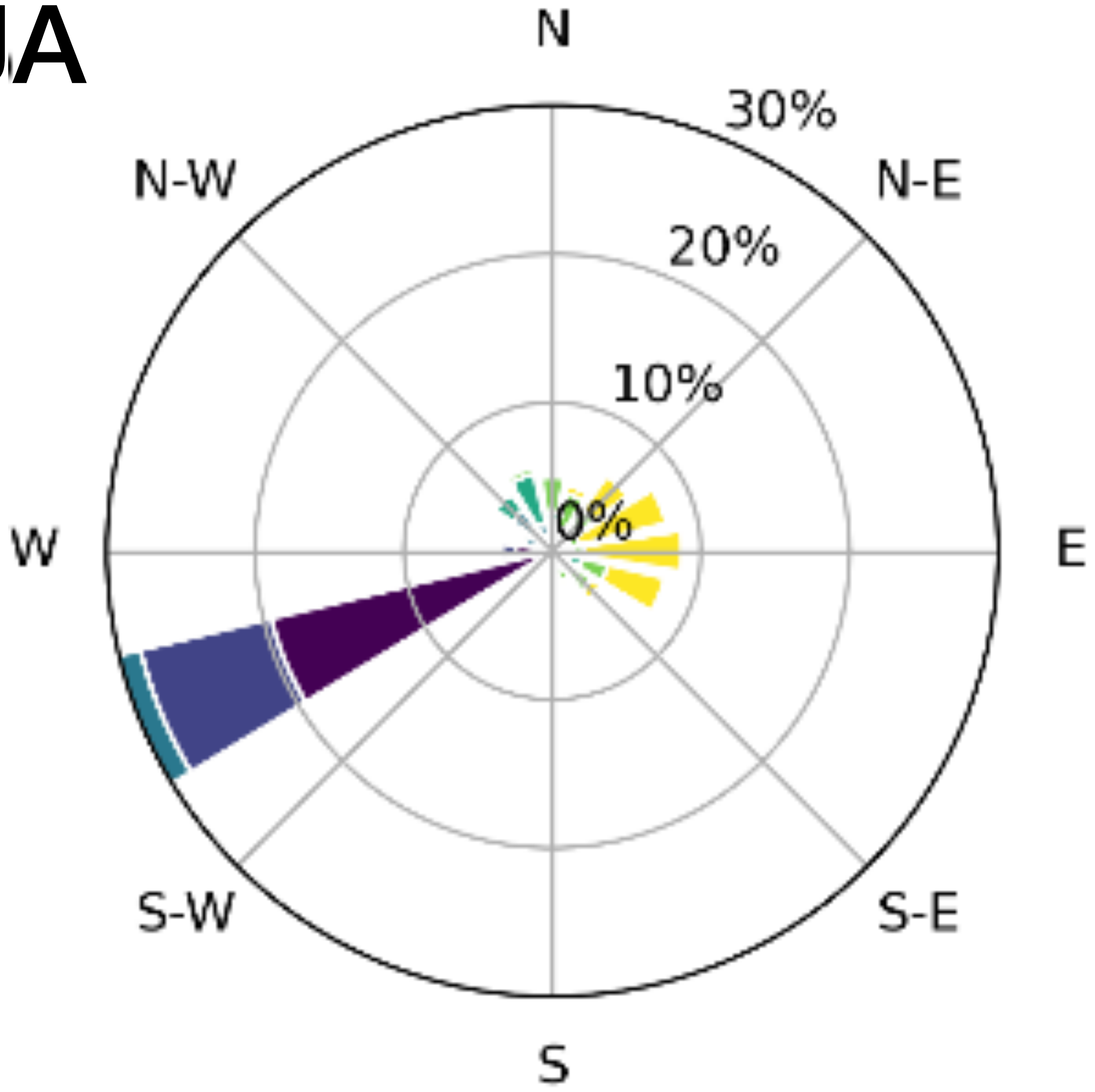


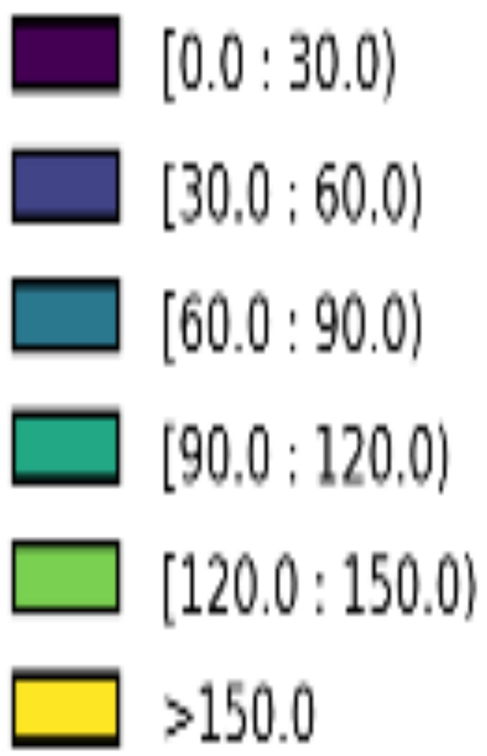


MAM wave rose



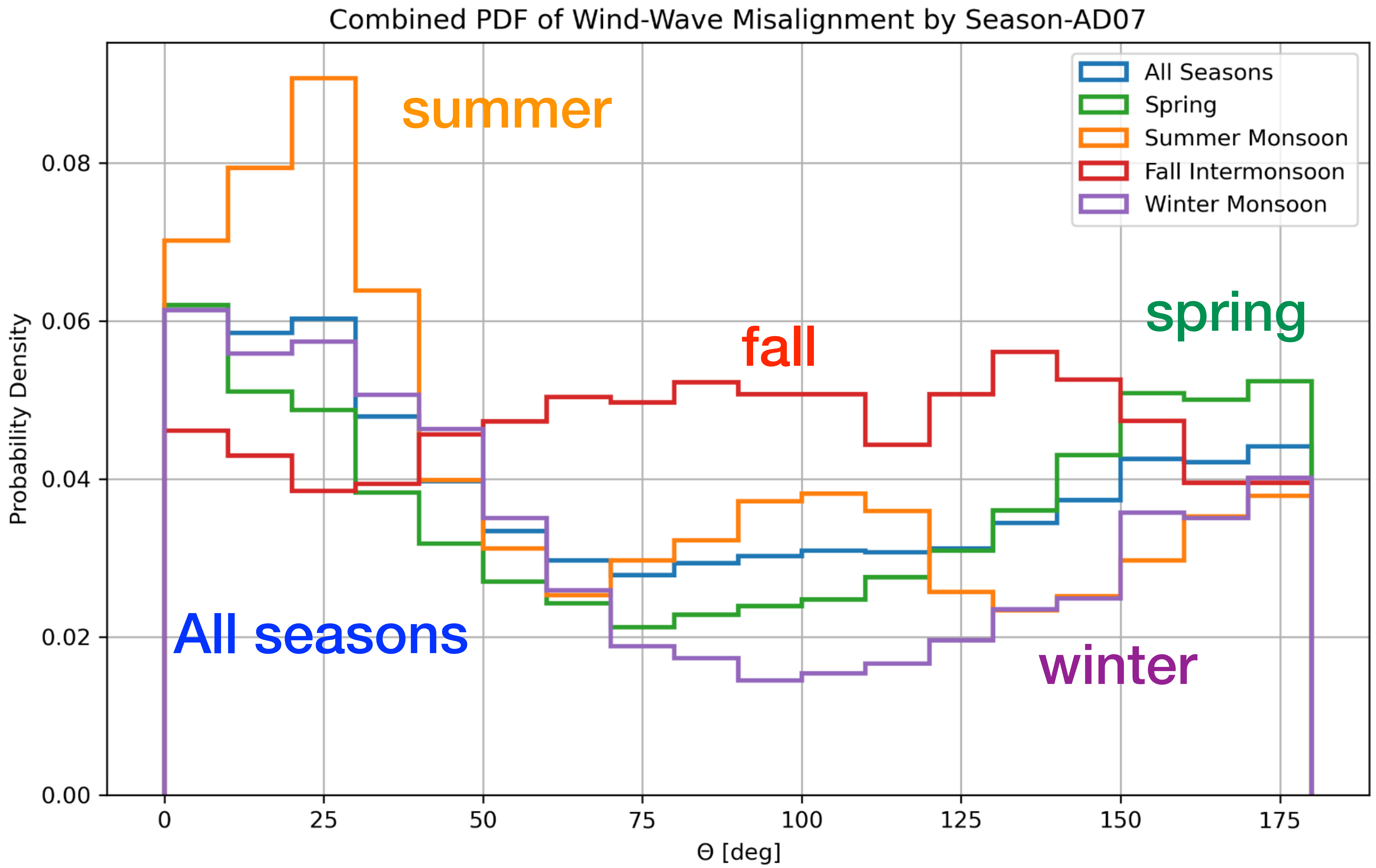
JJA





Observed wave-wind misaligment at AD07

See also Raj et al. (2025)

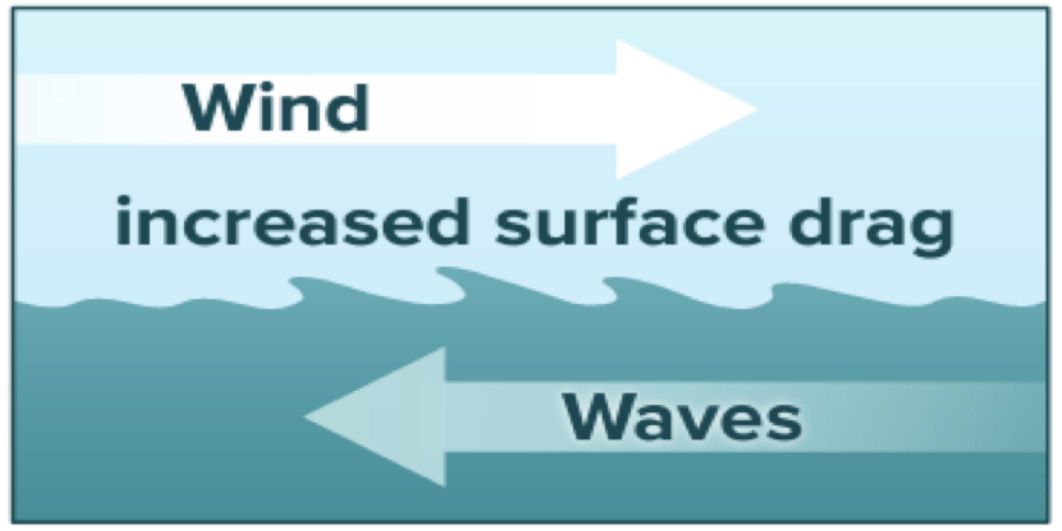


Misaligned waves observed ubiquitously throughout the year

OMNI mooring AD07 Hourly wind and wave data: 2012-2024

How is surface roughness parameterized?

COARE algorithm (Edson et al. 2013)



$$\tau = \rho_a C_D U_r^2 \qquad C_D \cong \left[\frac{\kappa}{\ln(z/z_0) - \psi_m(z/L)}\right]^2 \qquad z_0 = z_0^{\text{smooth}} + z_0^{\text{rough}}$$

1. Wind Speed Dependent Formulation (WSDF)

$$z_0^{\text{rough}} = \alpha \frac{u_*^2}{g} \qquad \alpha = mU_{10N} + b$$

Charnock coefficient

2. Wave-Based Formulation (WBF)

$$z_0^{\text{rough}} = H_s \cdot 0.09 \cdot \left(\frac{u_*}{C_p}\right)^2$$

inverse "peak" wave age

significant wave height

- Assumes wind-wave equilibrium (χ~1.2)
- **Assumes waves are aligned with winds (θ=0)**
- Violated in mixed seas, as well as near strong density/vorticity fronts, shallow fetch-limited oceans, and rapidly translating cyclones

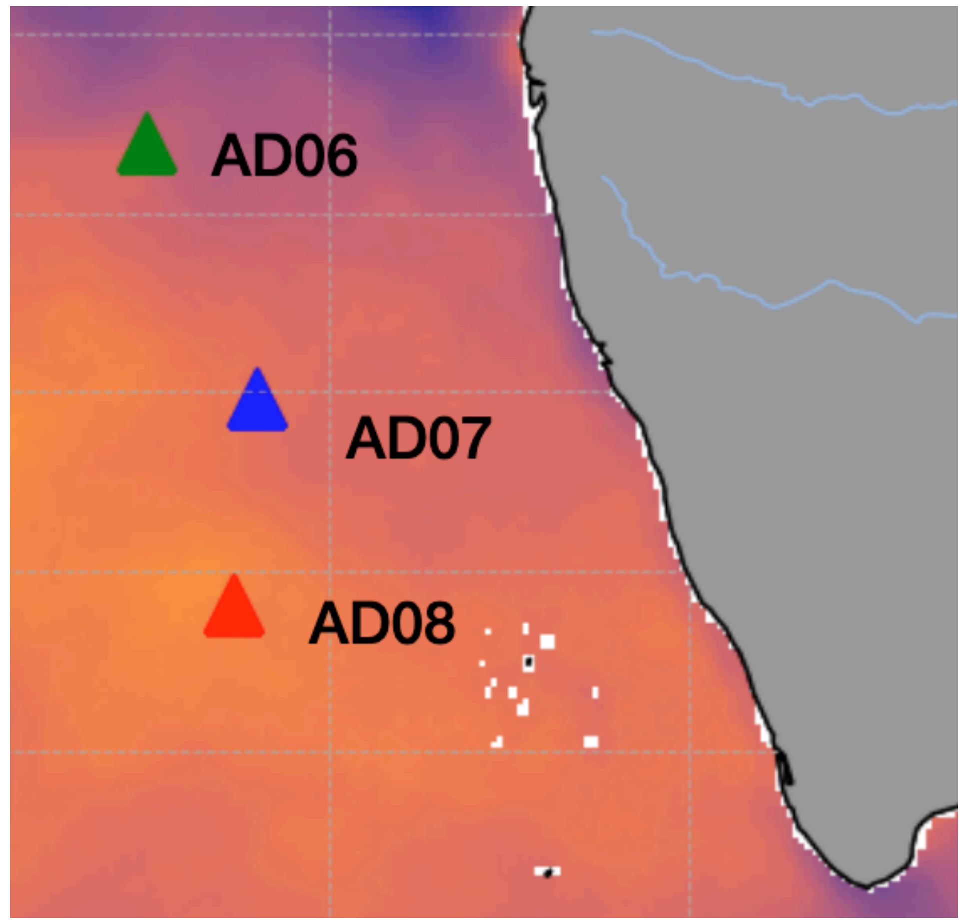
- **Still assumes θ=0**

Sauvage et al. (2023, 2024)

WBF_θ $\quad z_0 = H_s \cdot 0.09 \cdot \cos(0.45\,\theta) \cdot \left(\frac{u_*}{C_p}\right)^{2\cdot\cos(-0.32\,\theta)}$

- Based on geographically biased wave datasets (e.g., no wave data from the low latitudes)

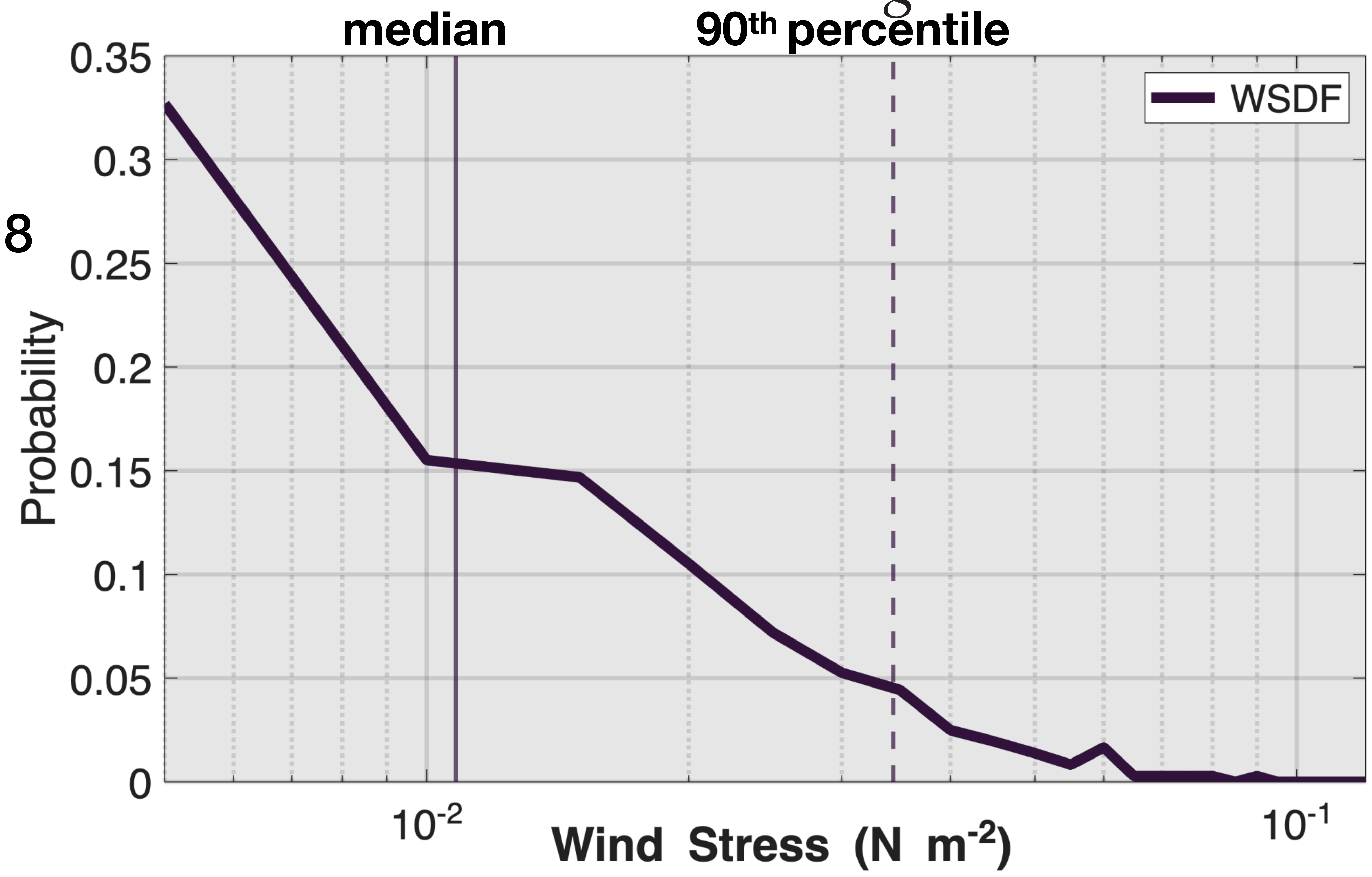
Wind stres estimated at AD08

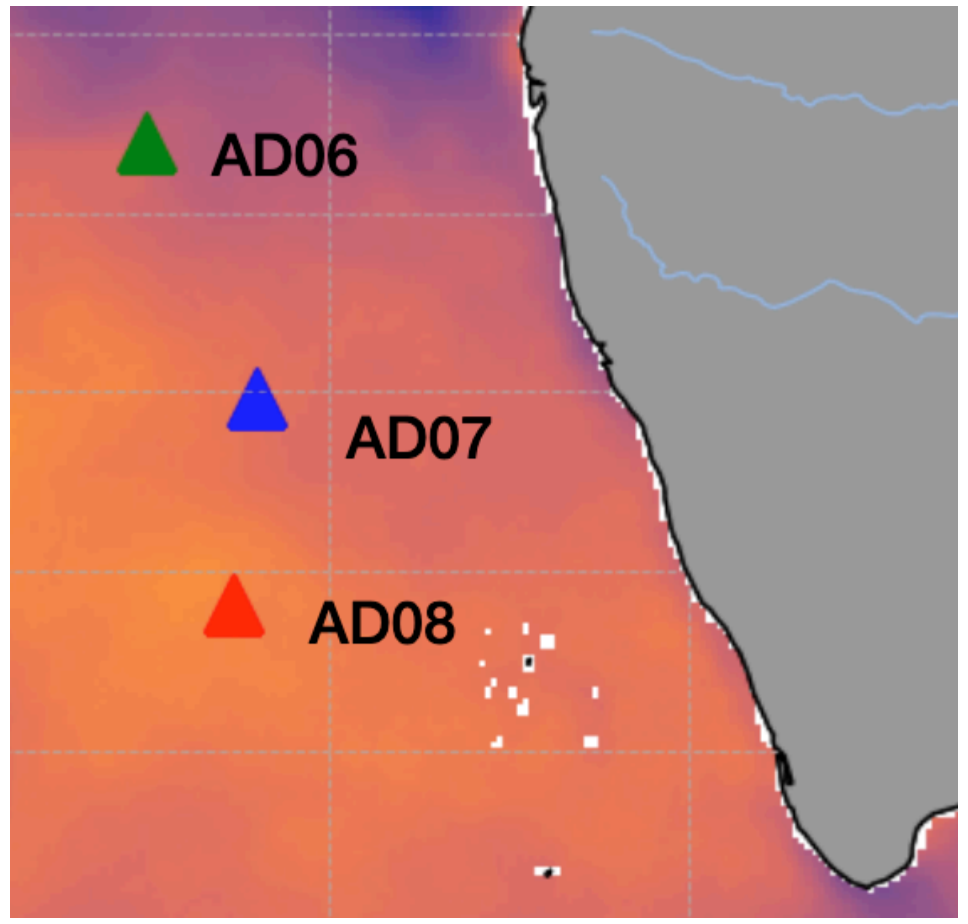


April 26— May 10, 2018

$$z_0^{\text{rough}} = \alpha \frac{u_*^2}{g}$$

WSDF: Edson et al. (2013)





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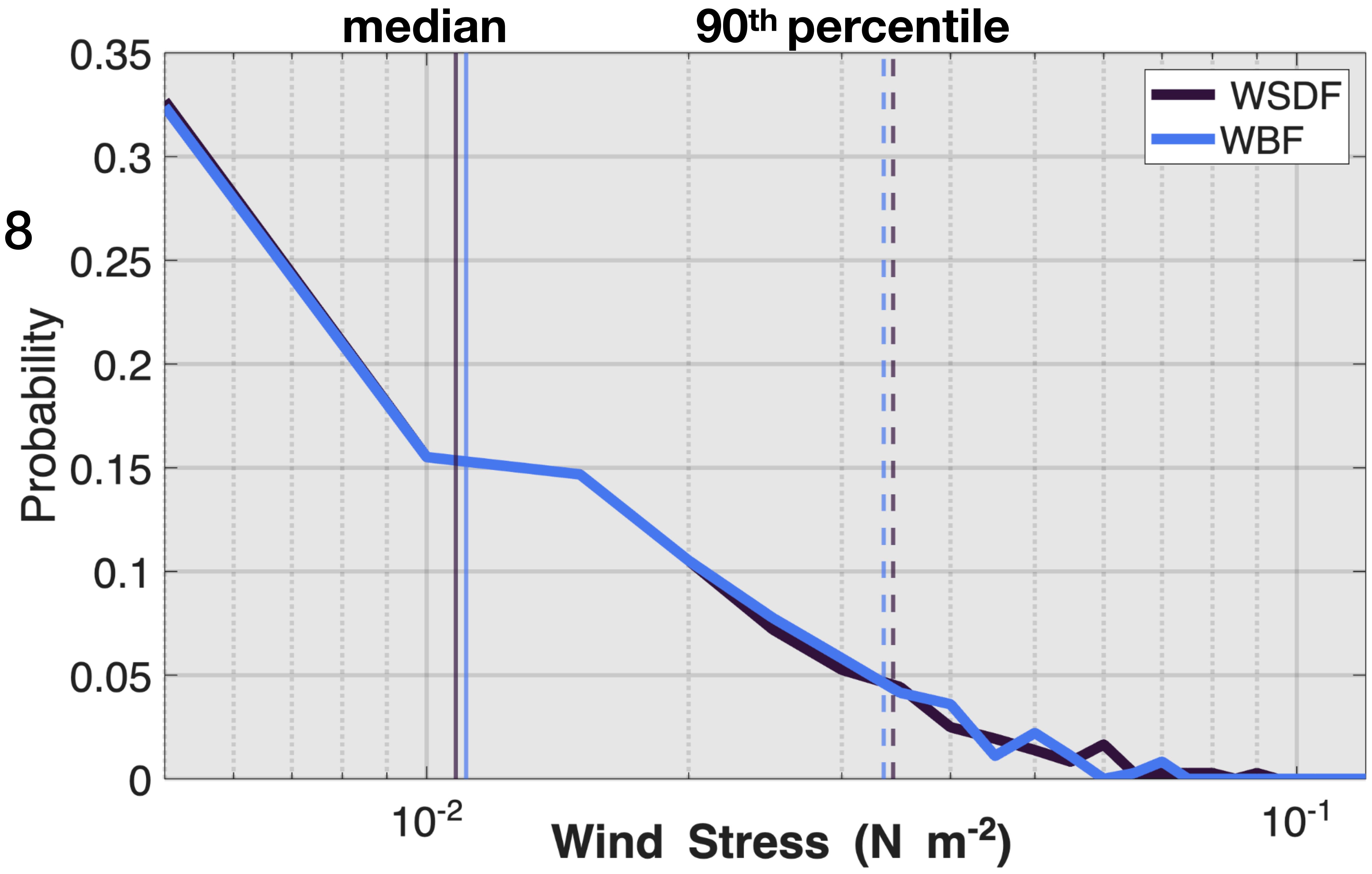

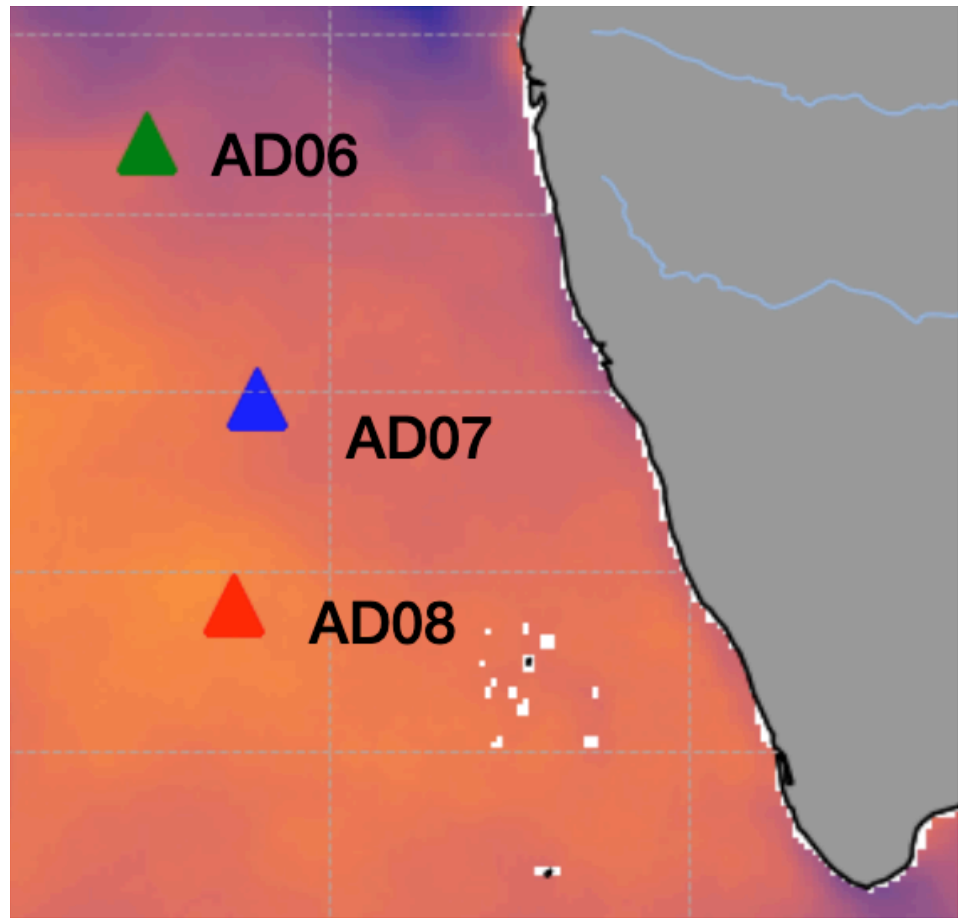

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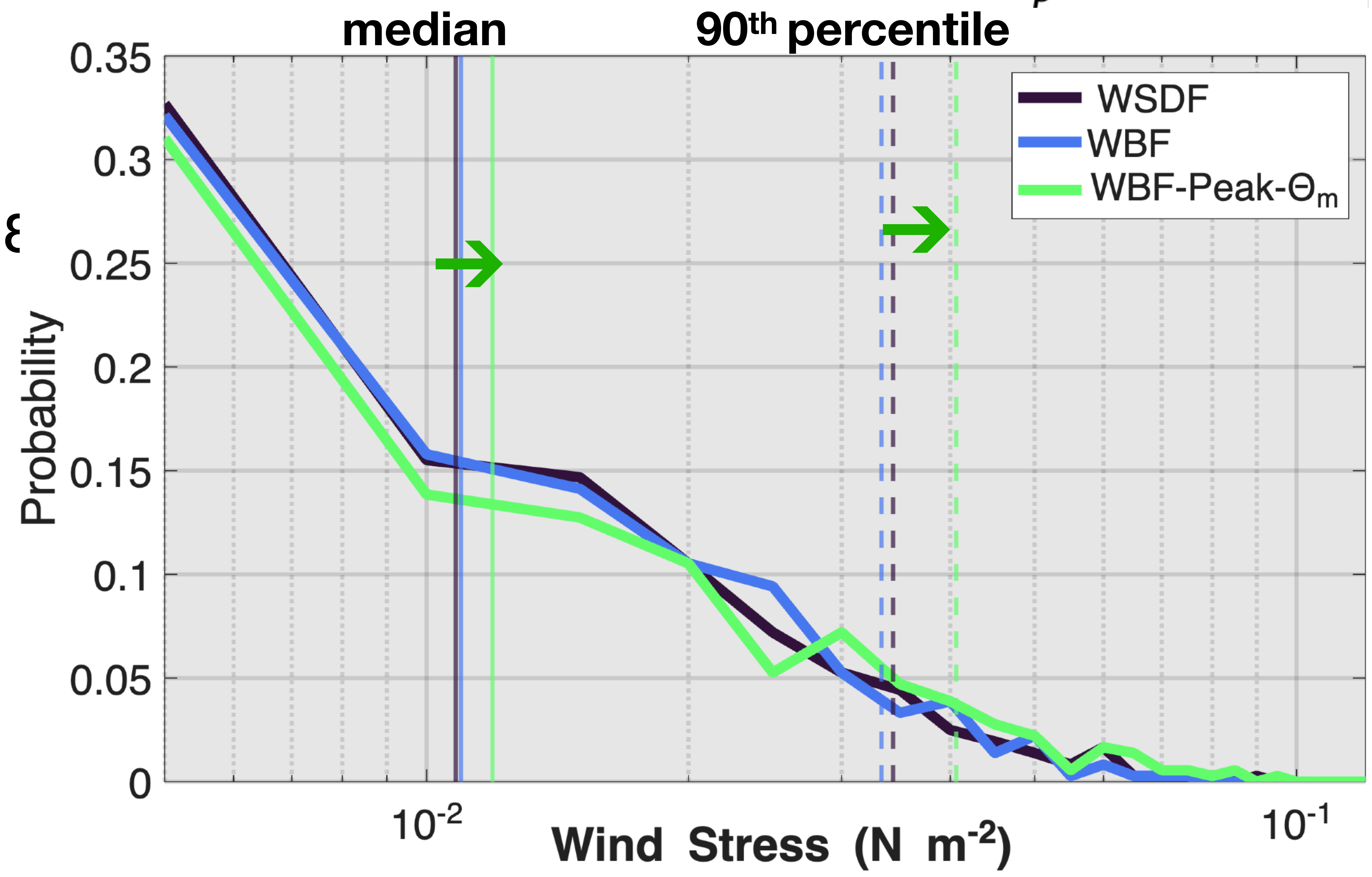
WBFθ: Sauvage et al. (2023)

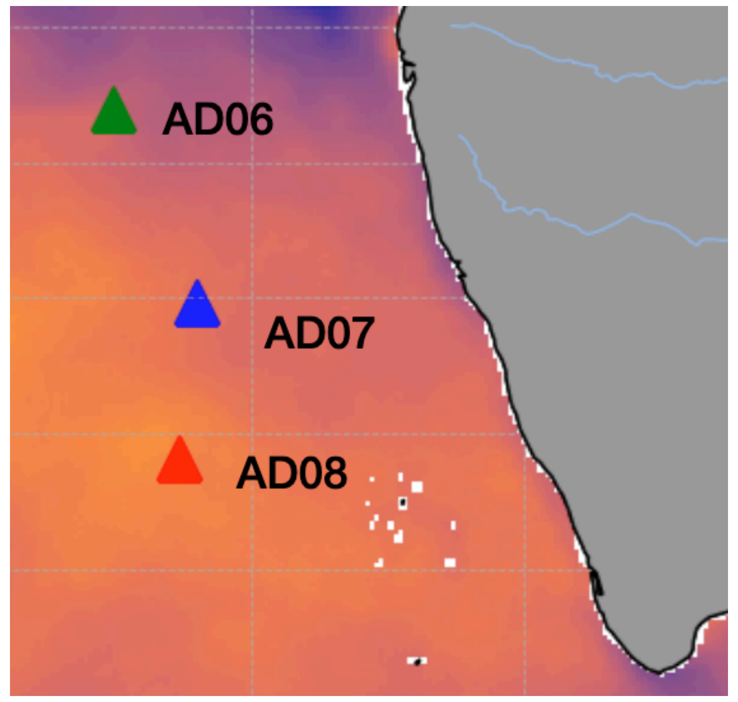


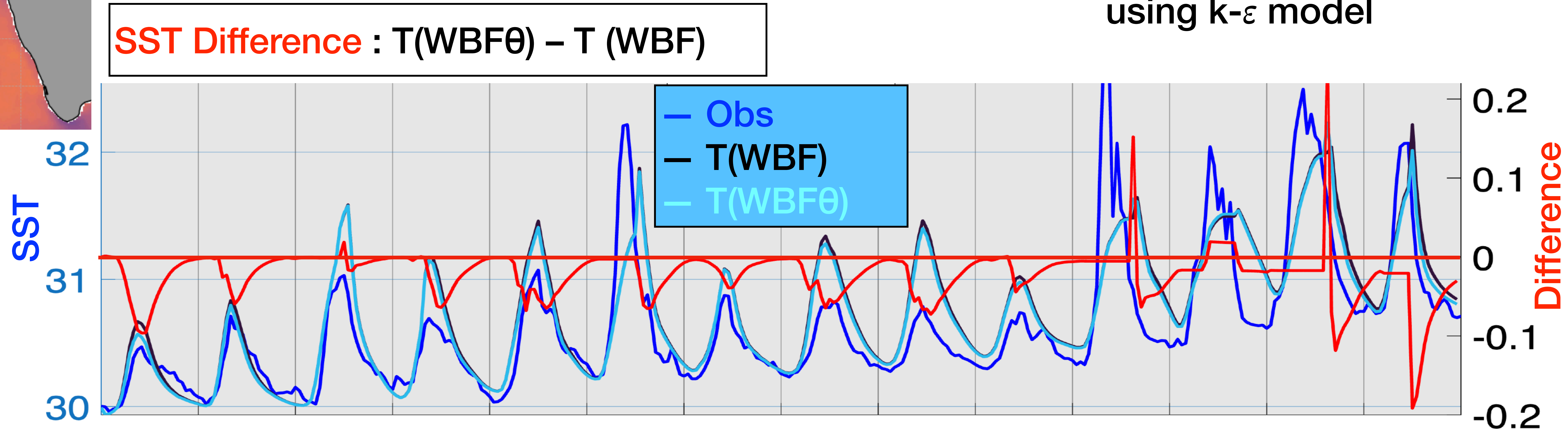
← Wind Stress is increased by 10-20% if accounting for wind-wave misalignment.

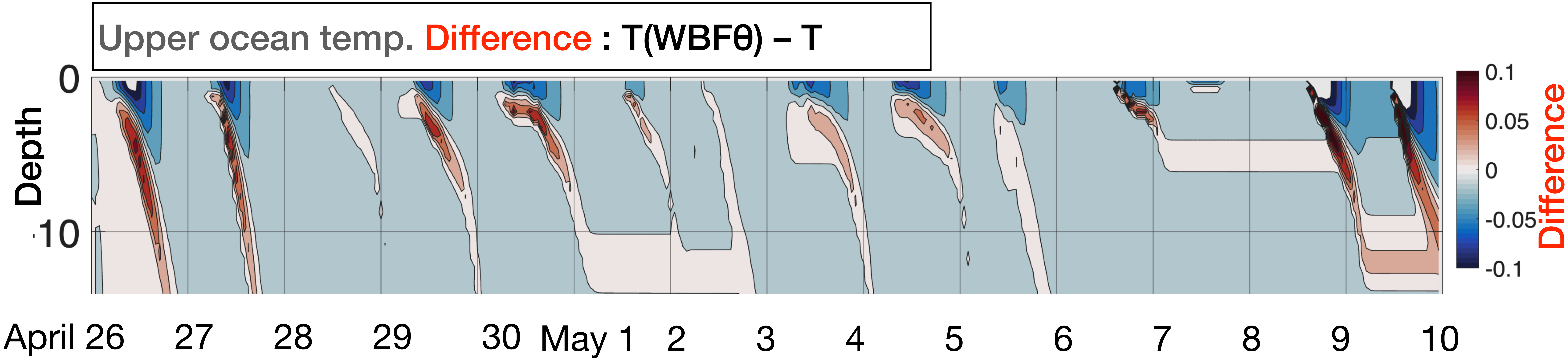
- There is no publically available direct covariance flux dataset to validate these parameterizations

Upper ocean tempreature response at AD08

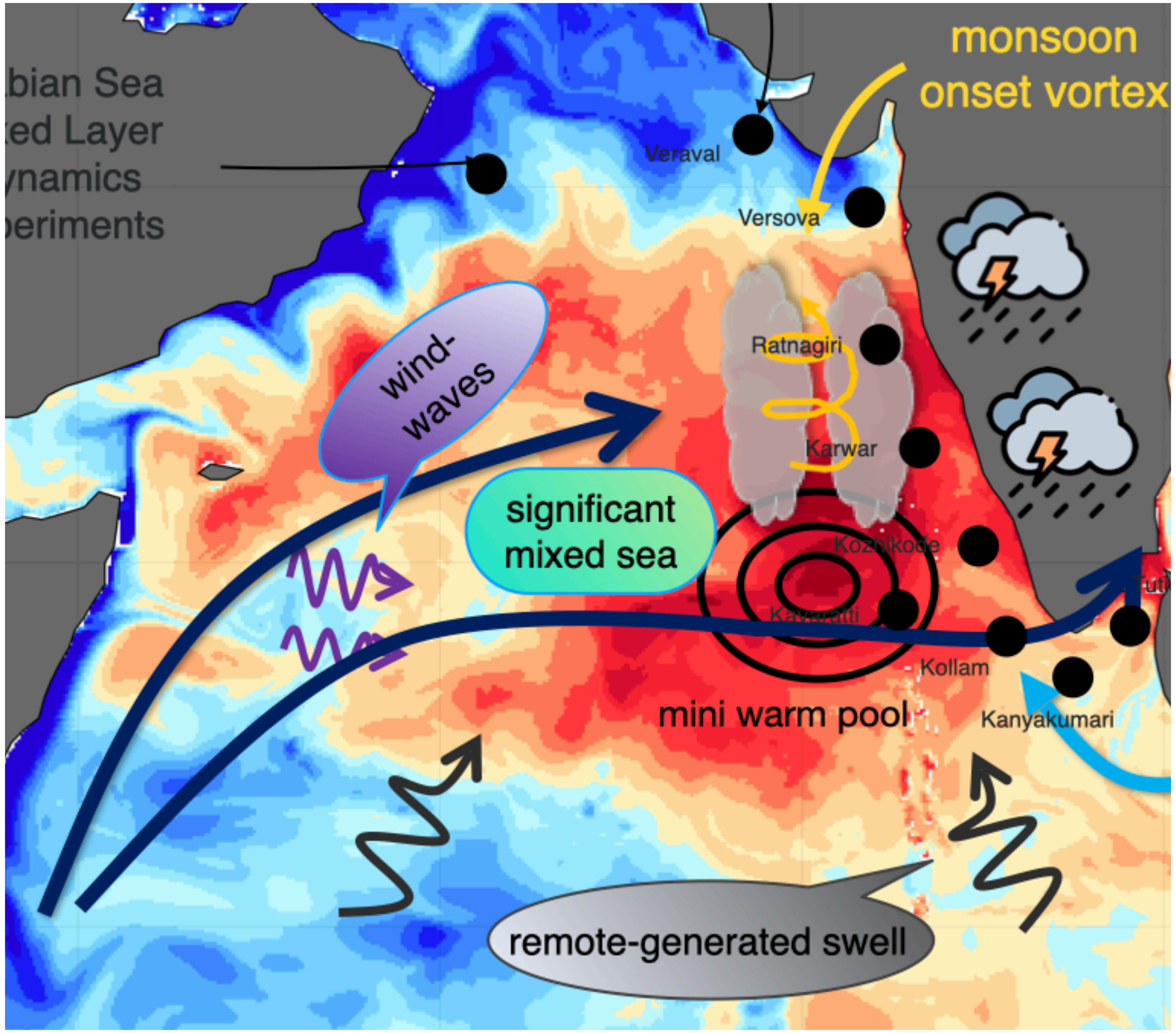
using k-ε model







Summary:
Misaligned waves, air-sea fluxes, and mini-warm pool SST



- A ubiquitous feature (**Raj et al. 2025**)
- Representing the effects on surface drag and upper-ocean turbulence challenging.
  → Especially in regions of strong density gradients and stratification
- Misaligned waves increase surface drag
  → Leading to enhanced turbulent mixing on diurnal time scales.
  → No publically available dataset yet; impossible to validate this.
  → Rectified effects on onset vortex
- More DCF data are needed.
  → Jim Edson: “COARE is not designed for low latitudes.”