Ocean Mesoscale Air-Sea Interactions:
Surface Waves, Aerodynamic Roughness and Air-sea Momentum Flux

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Thanks to Cesar Sauvage & Glenn Liu

WOODS HOLE OCEANOGRAPHIC INSTITUTION

U.S. DEPARTMENT OF ENERGY

How is roughness length parameterized?

$$\tau = \rho_a C_D U_r^2$$

COARE algorithm
Edson et al. (2013)

$$C_D \cong \left[\frac{\kappa}{\ln(z/z_0) - \psi_m(z/L)}\right]^2$$

$$z_0 = z_0^{\text{smooth}} + z_0^{\text{rough}}$$

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

Charnock Coefficient

1. Wind Speed Dependent Formulation (WSDF)

$$\alpha = f_1(U_{10N}) = mU_{10N} + b,$$

m=0.0017. b=0.005

2. Wave-Based Formulation (WBF)

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

inverse wave age

significant wave height

wave phase speed
$C_p = g*(\mathbf{T_p}/2\pi)$

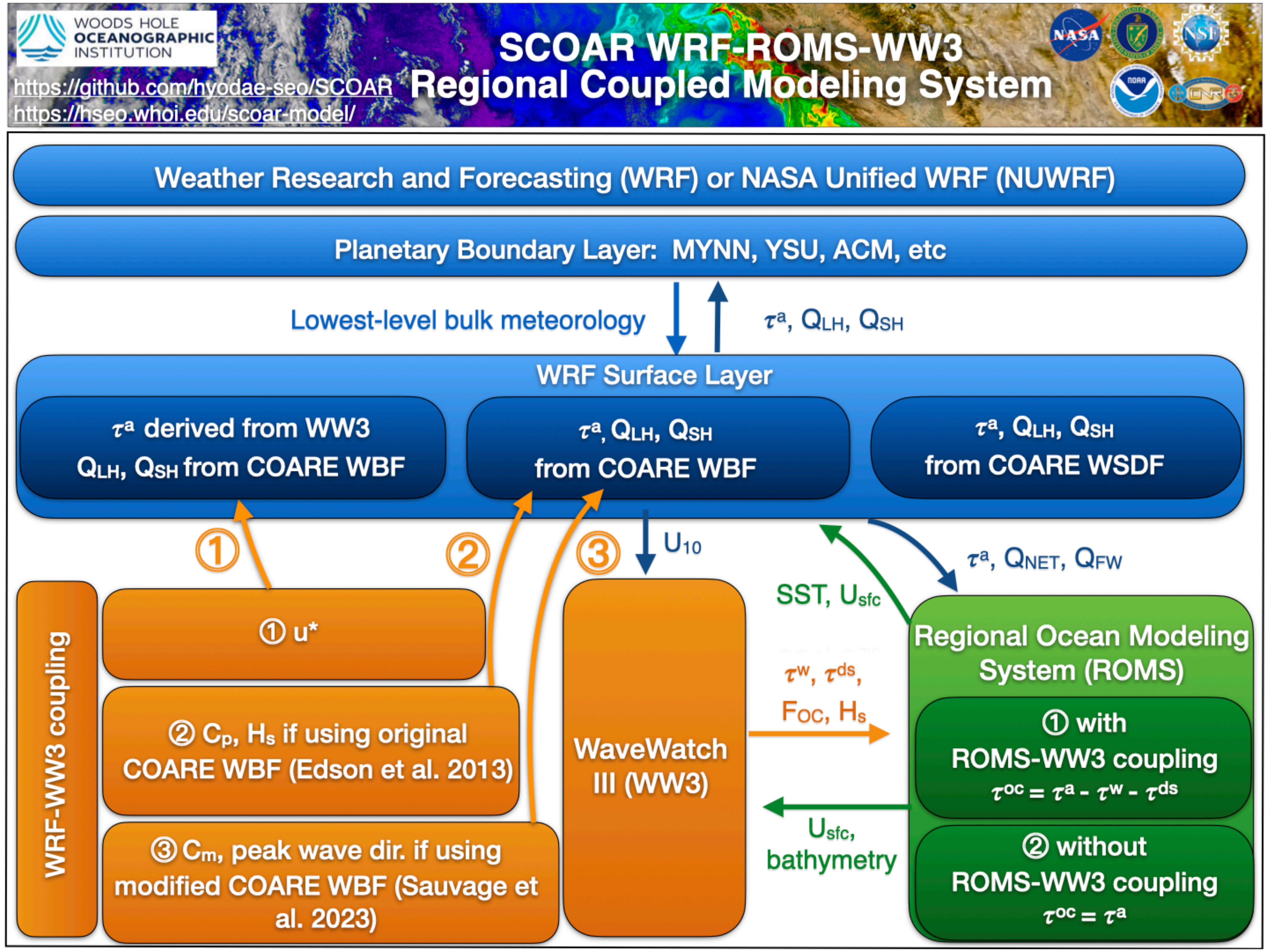
$\mathbf{T_p}$: wave period at the spectral peak

- **Assumption #1**: Wind-wave equilibrium (wave age~1.2)
- **Assumption #2:** Waves aligned with winds (θ=0)
- Violated near strong density/vorticity fronts, shallow & fetch-limited oceans & rapidly translating cyclones

- Still assumes θ=0
- WBF often DOES NOT yield better results!

Fully coupled ocean-wave-atmosphere modeling system at WHOI

https://github.com/hyodae-seo/SCOAR   Seo et al. (2007, 2014)



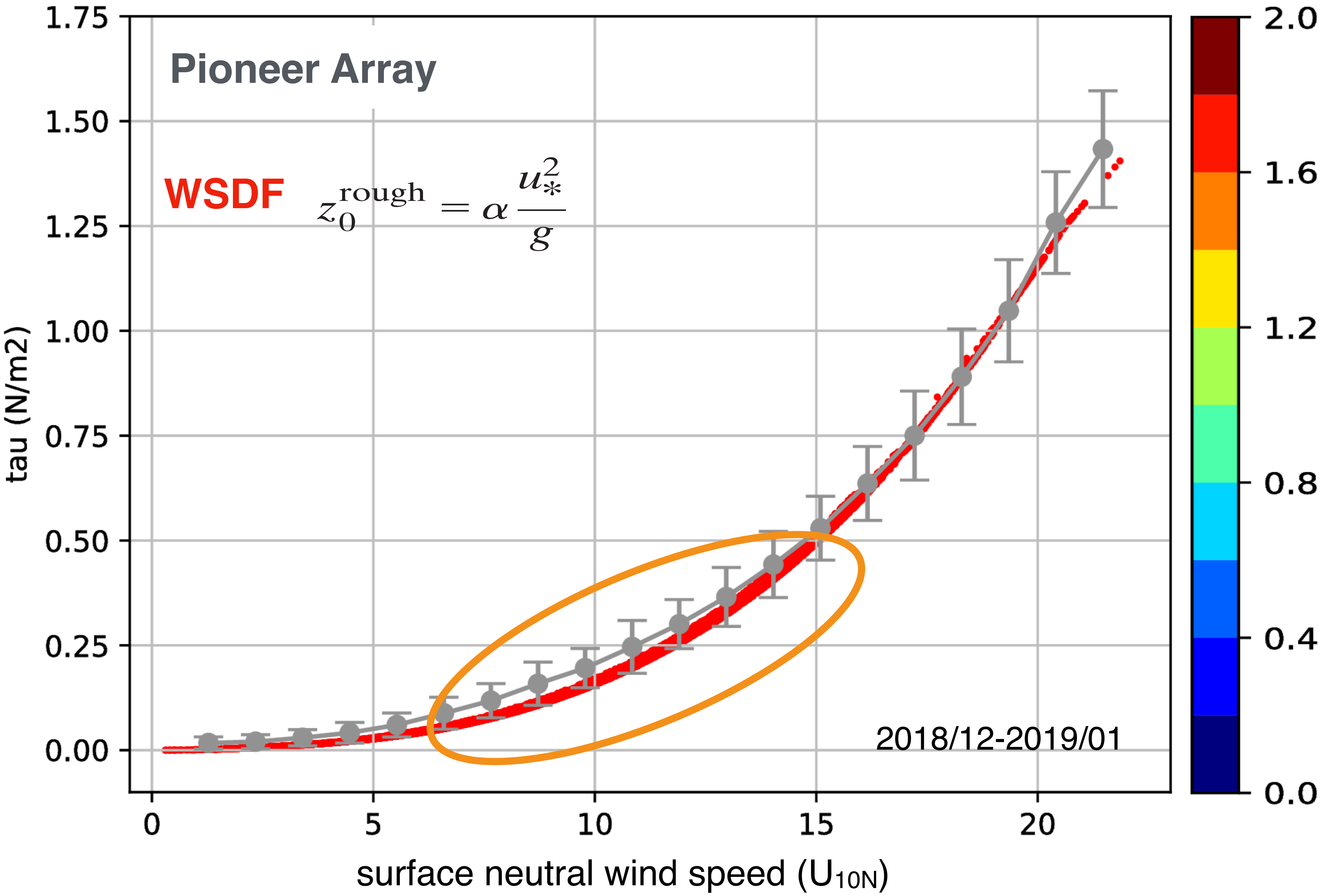
Offering various wave-wind coupling strategies (Sauvage et al. 2023)

Experiments	Coupling	z0 in COARE
WSDF	WRF-ROMS	wind speed only
WBF	WRF-ROMS-WW3 with default WBF	wave-based (T_p, H_s)
WBF_T_m	WRF-ROMS-WW3 with modified WBFs	with T_m instead of T_p
WBF_θ		vector wave stress (θ≠0)

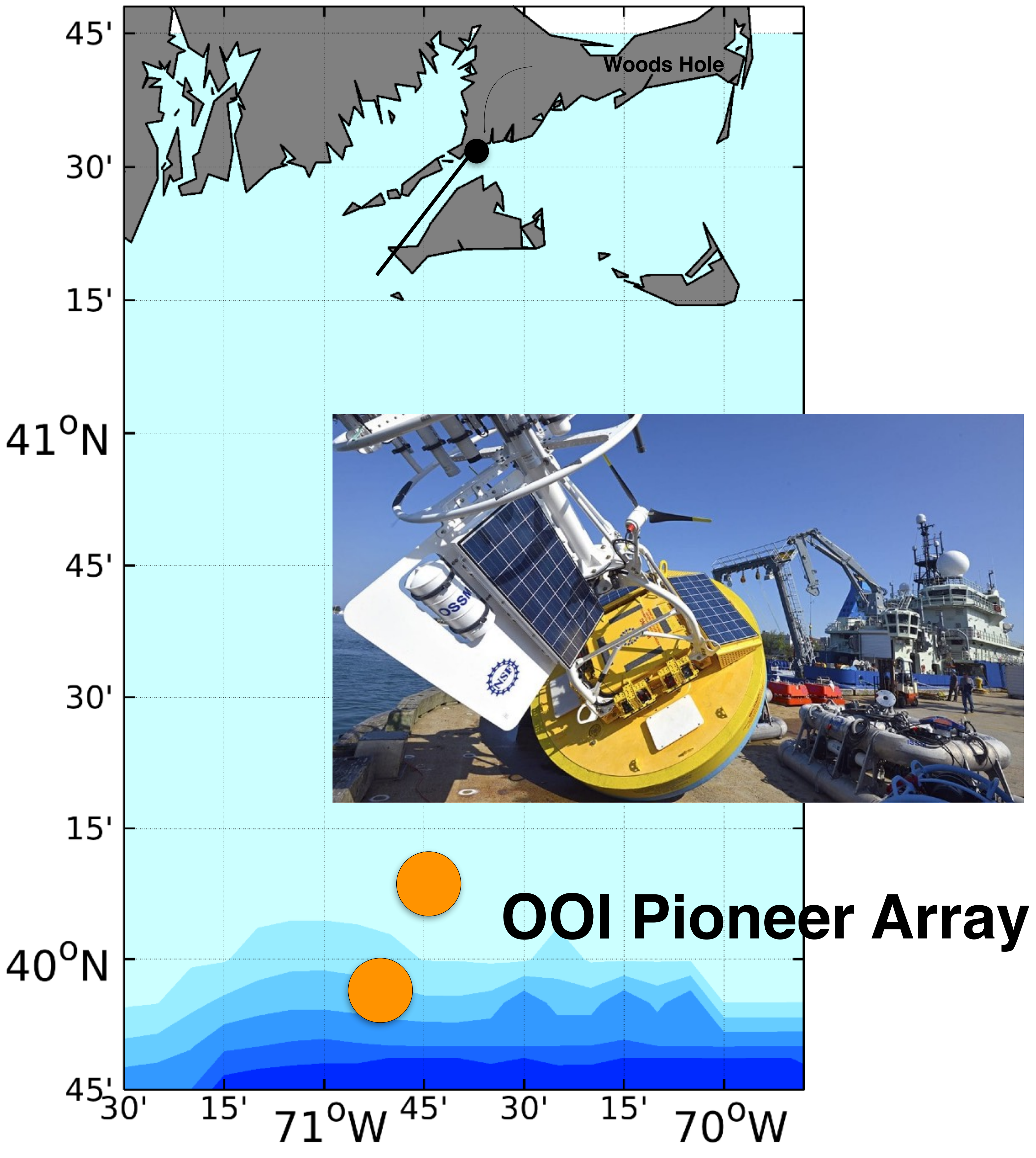
Sea state and z0 under an extratropical cyclone

So, which is better? DCF measurements from Pioneer Array

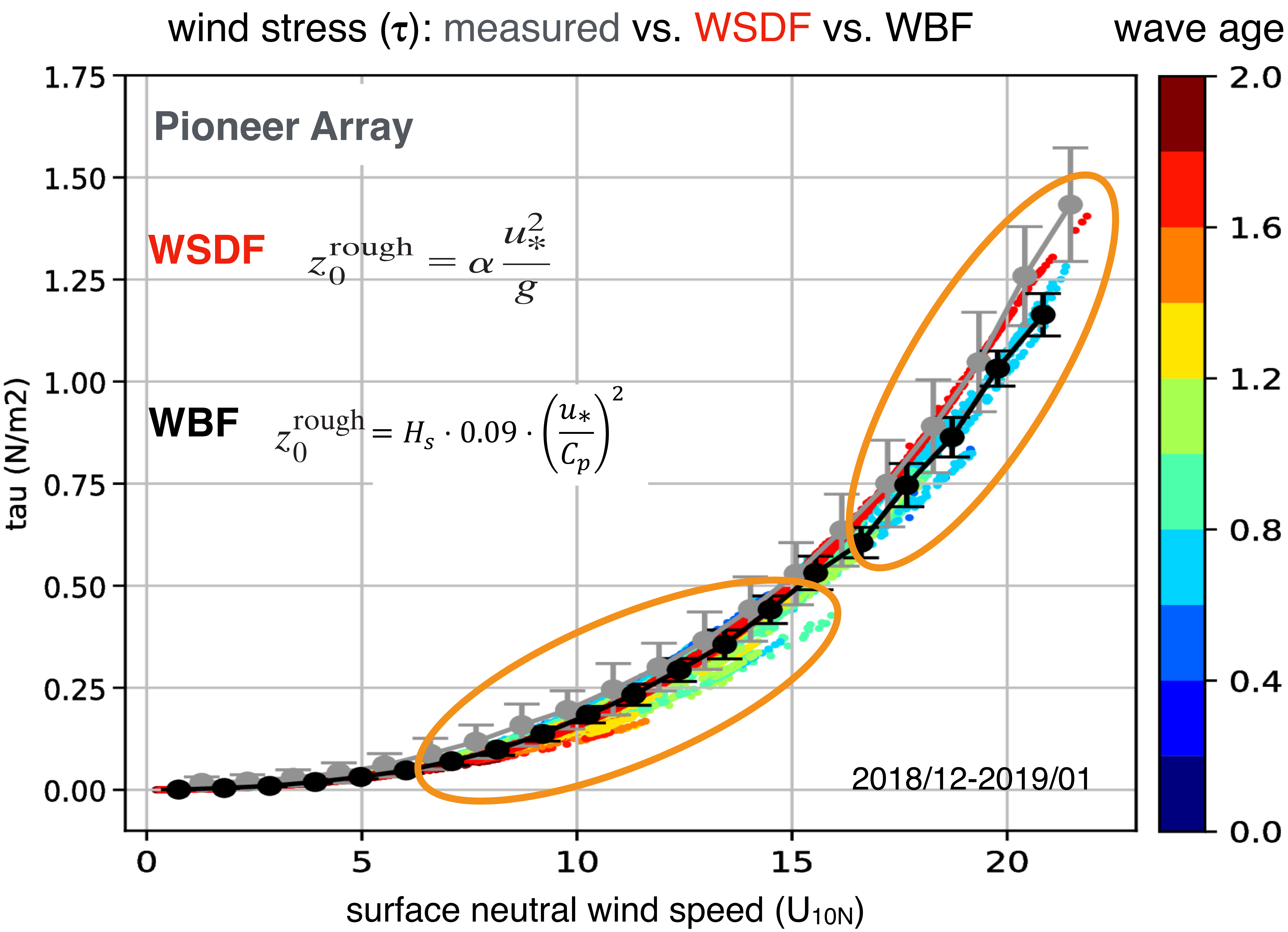
wind stress (τ): measured vs. WSDF



- WSDF underestimates the stress over young seas.

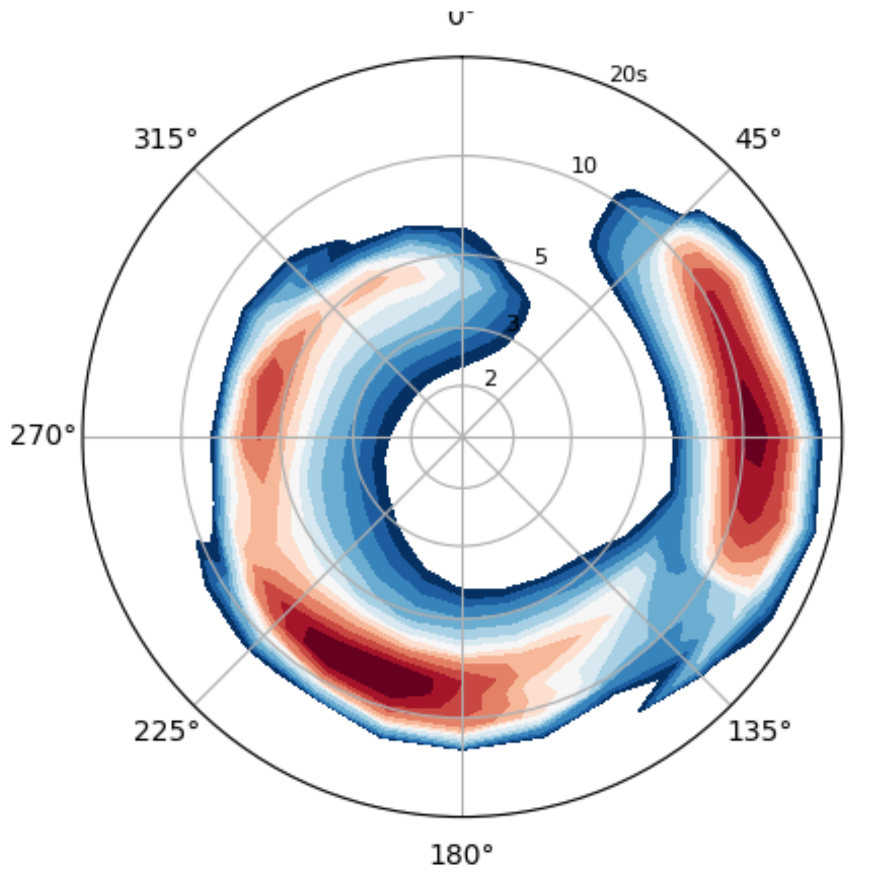


So, which is better? DCF measurements from Pioneer Array



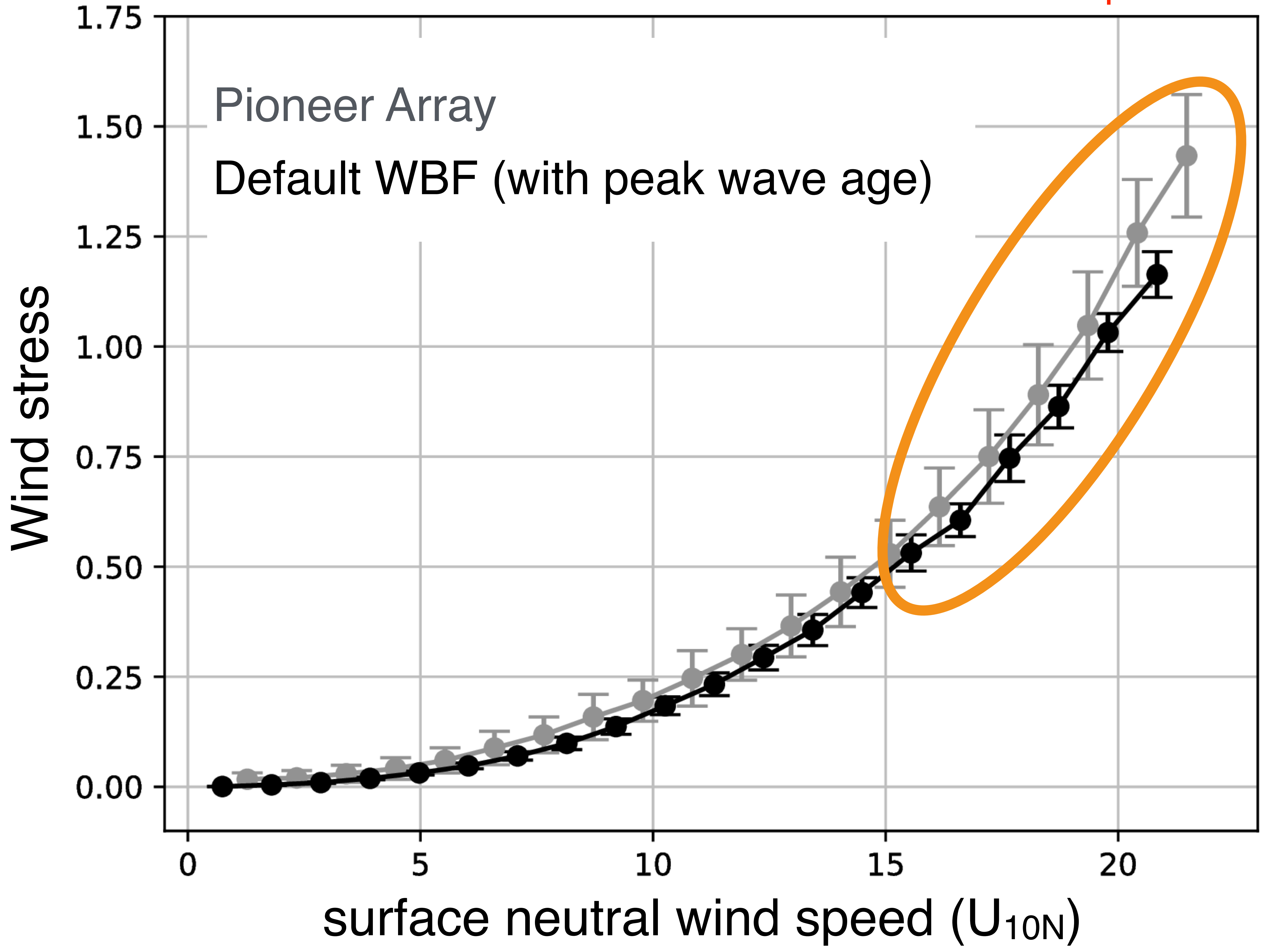
- WSDF underestimates the stress over young seas.
- WBF alleviates the low stress bias.
- BUT a low stress bias in mixed seas (high wind and high wave age condition)

Remedy: Use spectrally-averaged wave information for a mixed sea

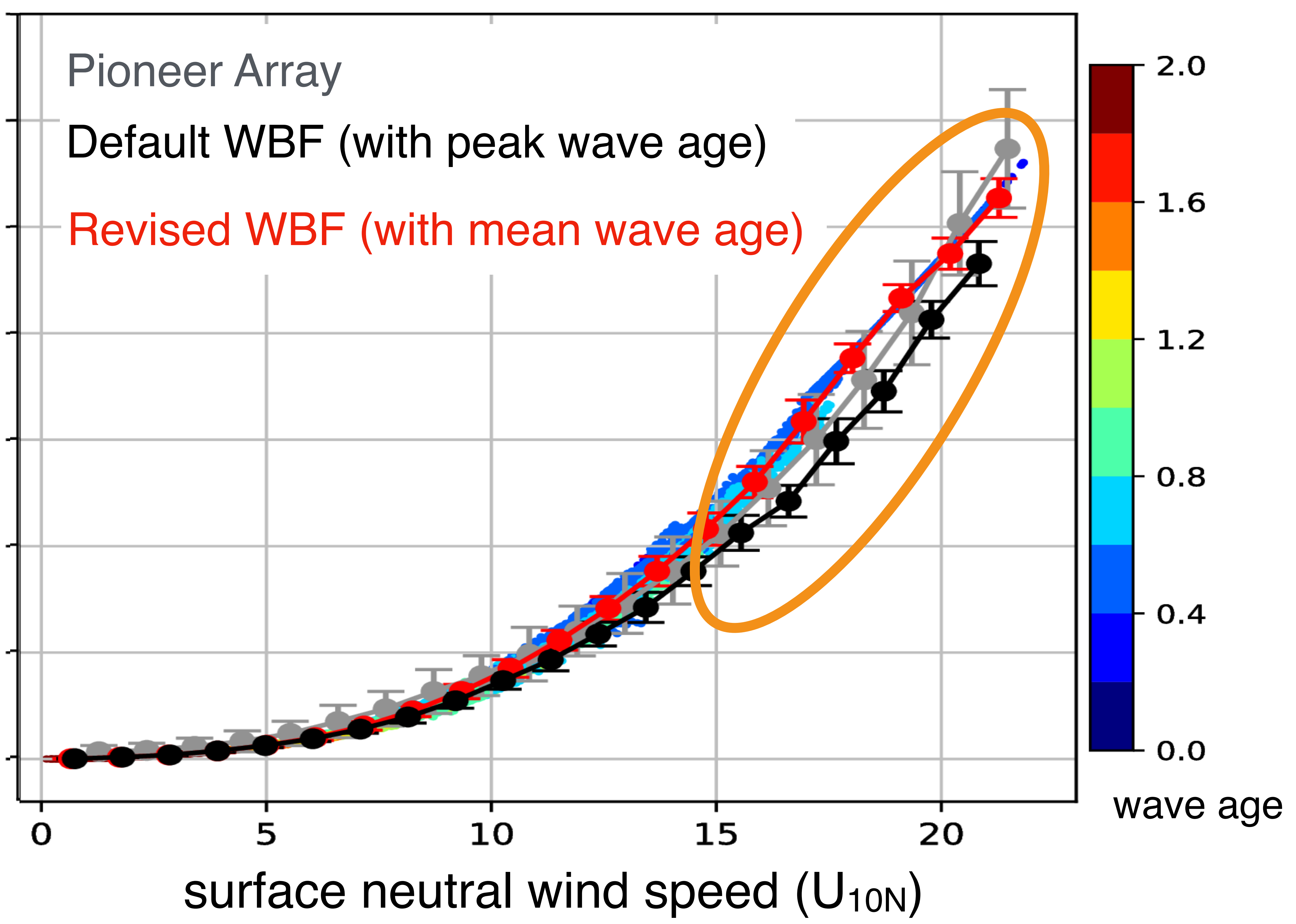


directional wave spectra for a mixed sea

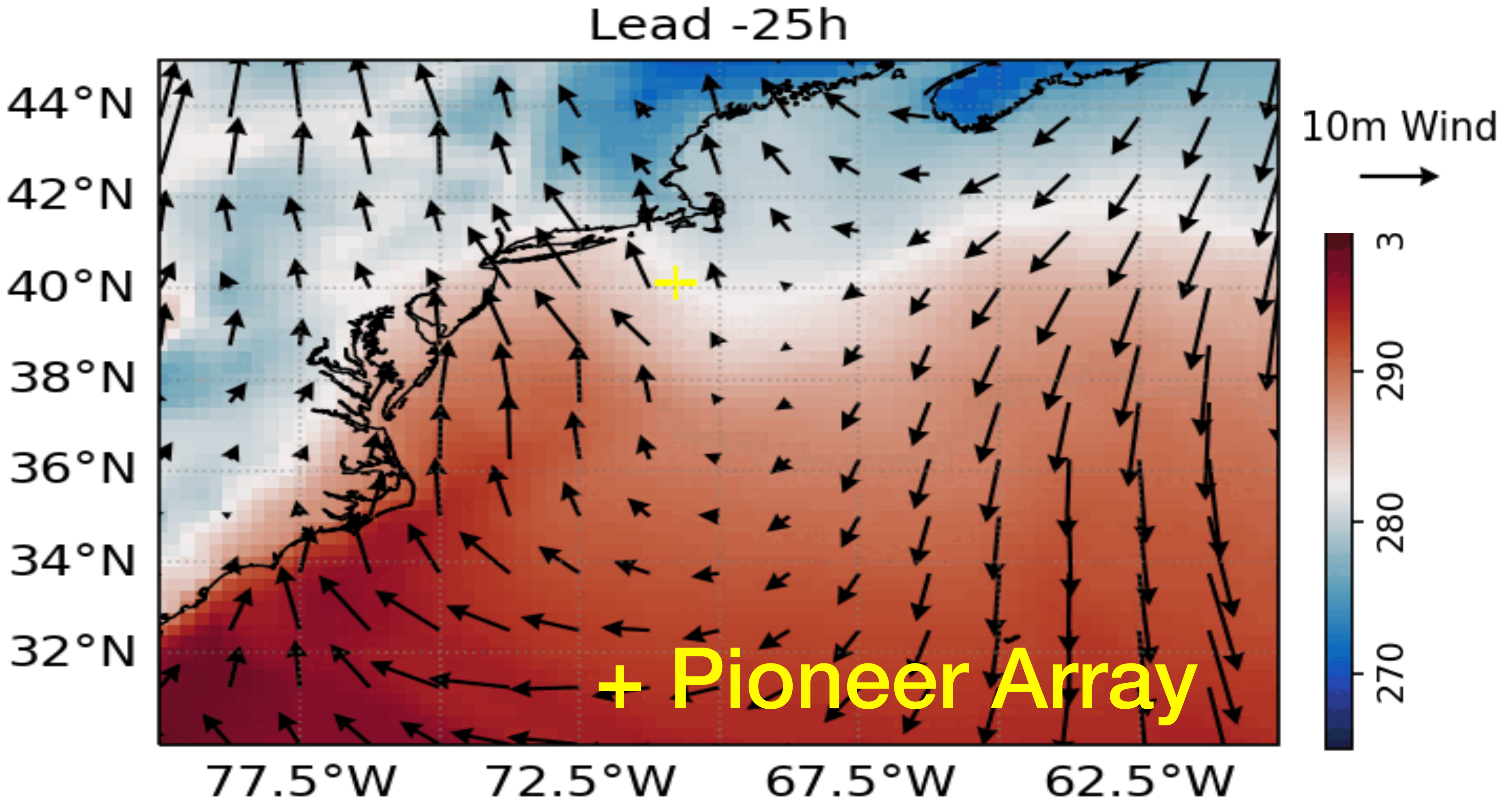
Edson et al. (2013) $z_{rough} = H_s.D.(\frac{u_*}{c_p})^B$

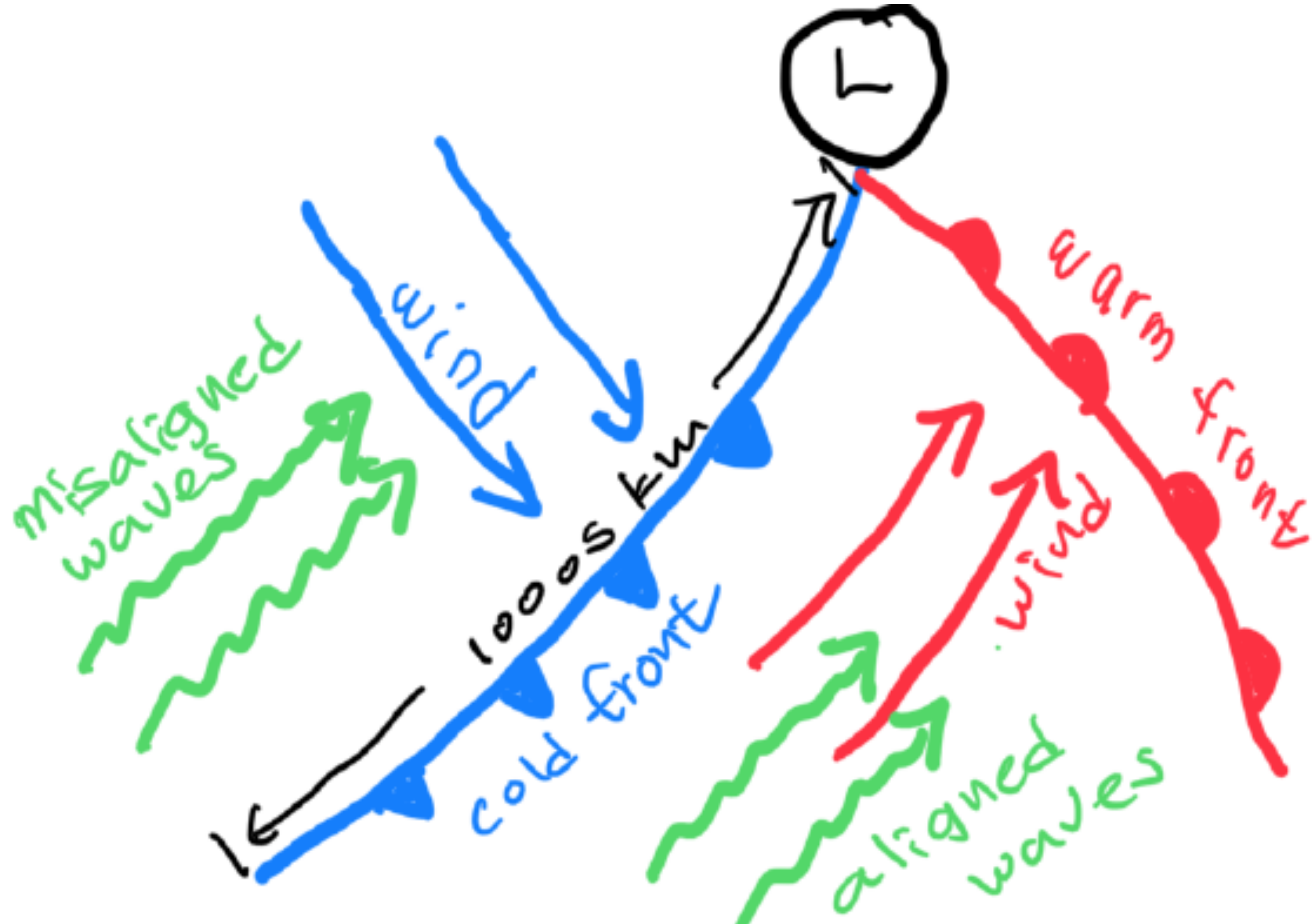


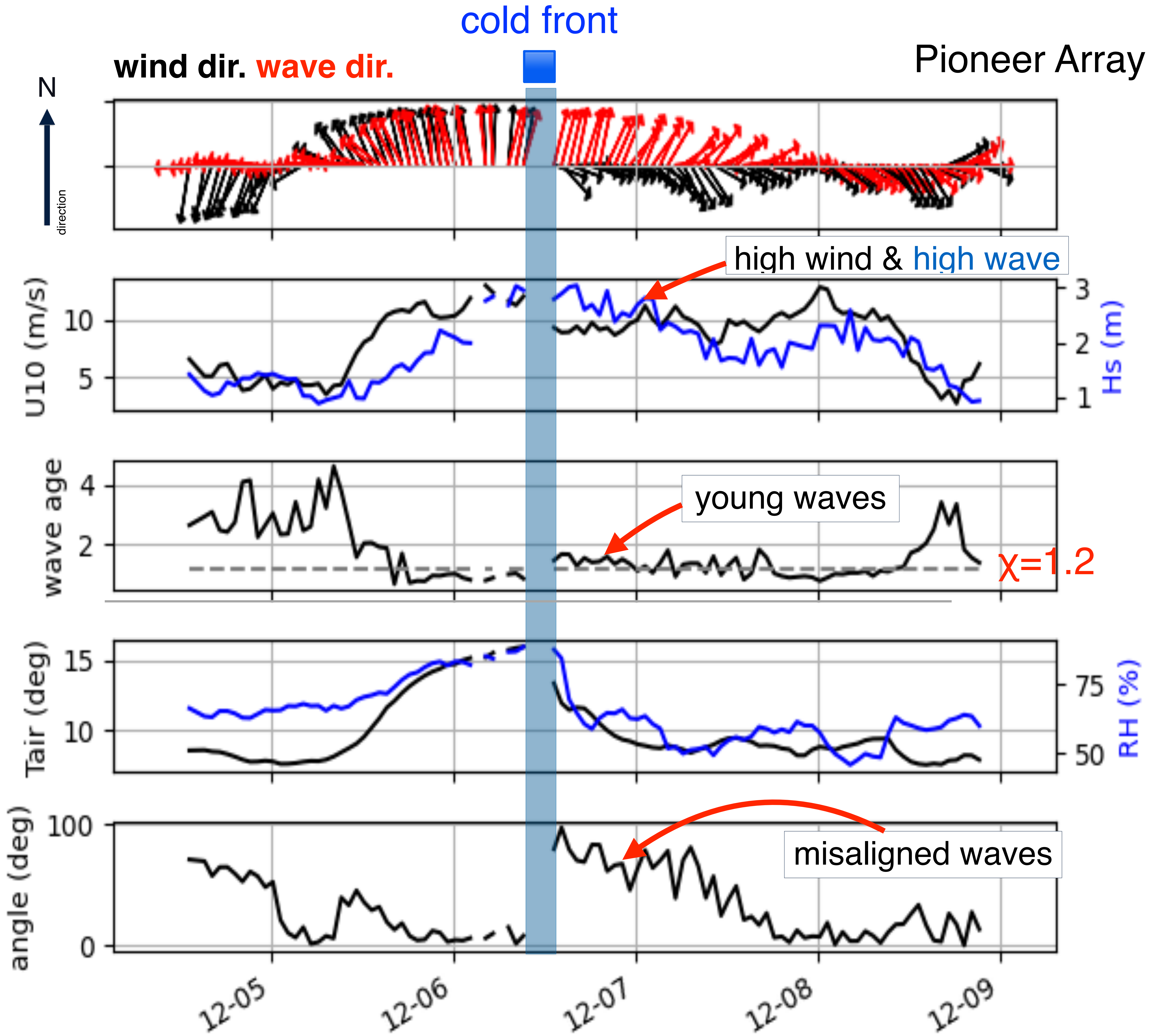
Sauvage et al. (2023) $z_{rough} = H_s.D.(\frac{u_*}{c_m})^B$



Misaligned wind waves behind atmospheric cold fronts

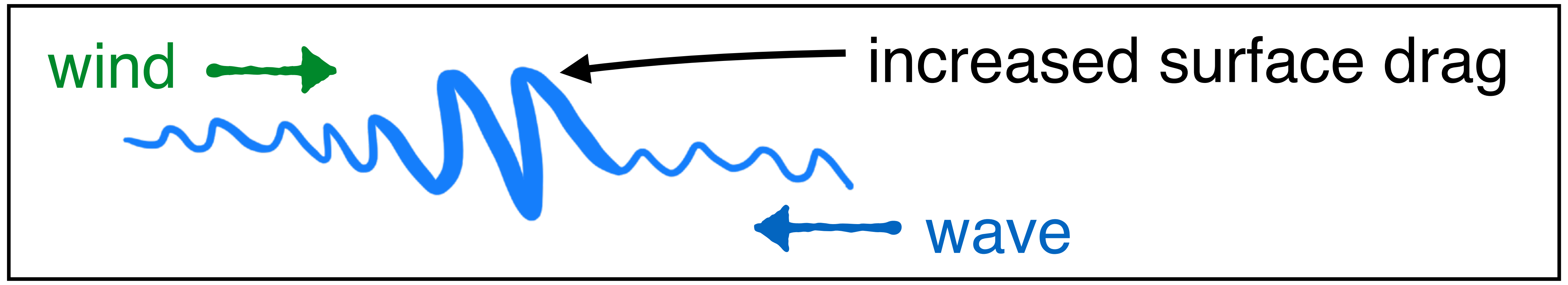




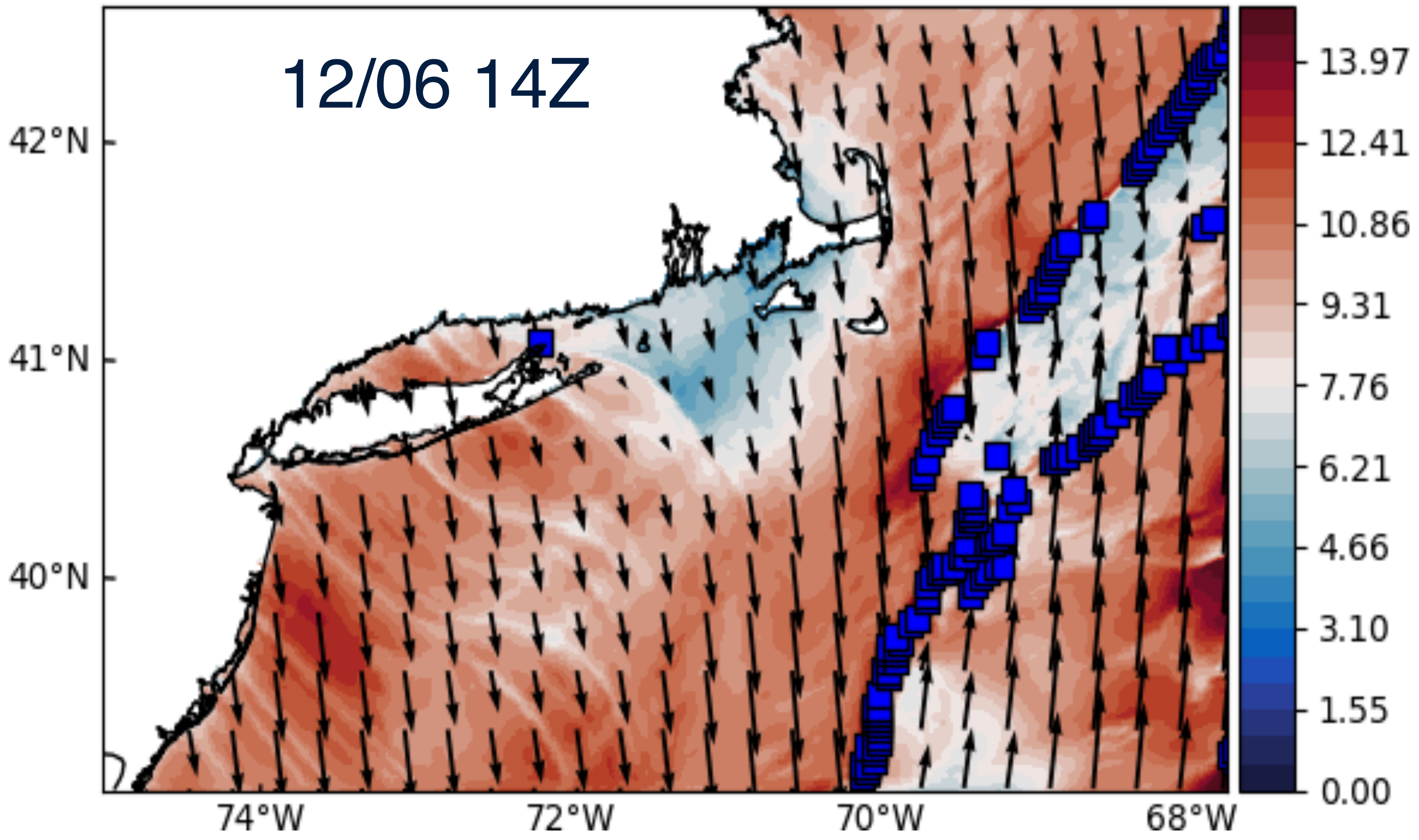


Impacts reaching beyond the surface layer

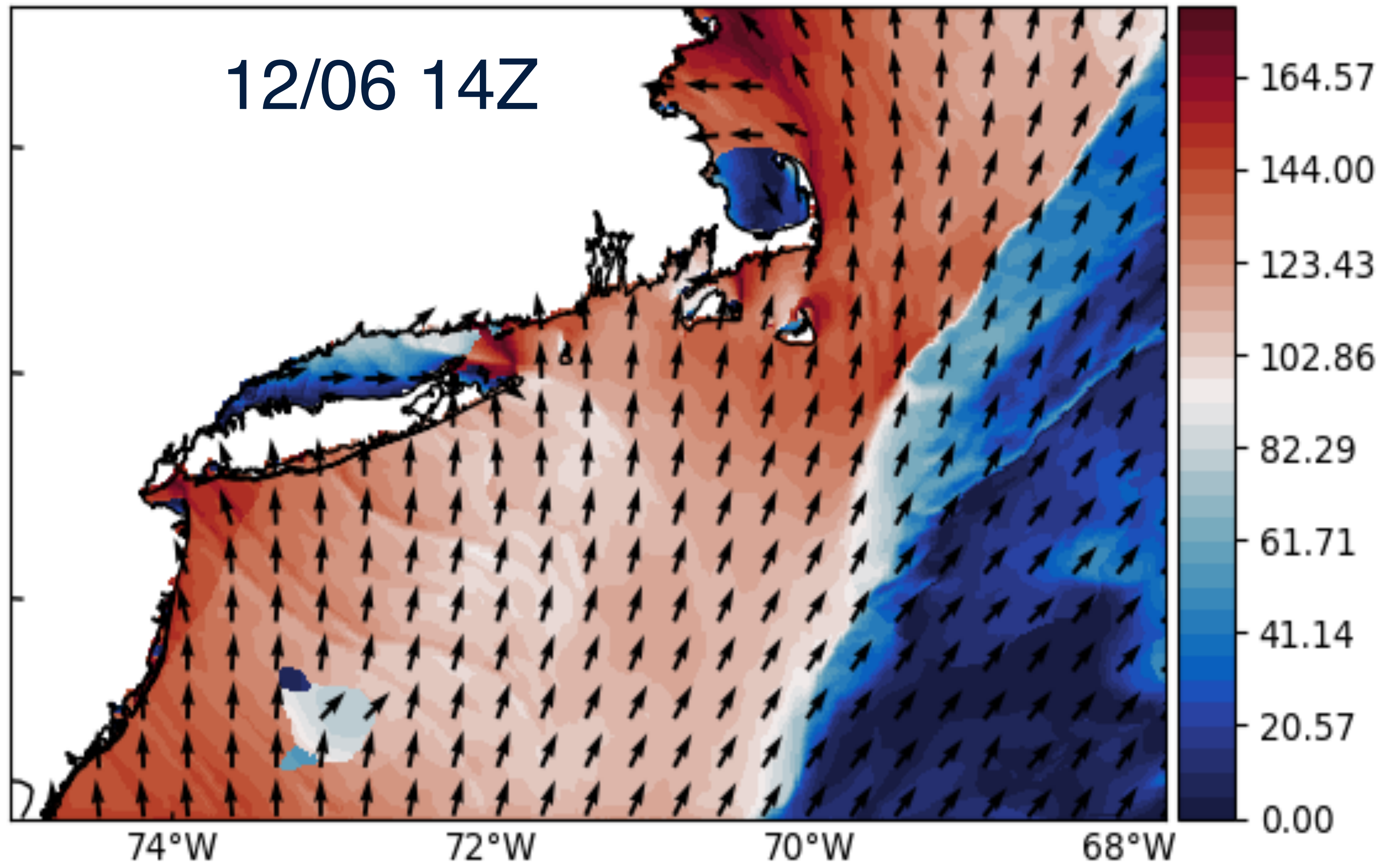
wave-wind interactions



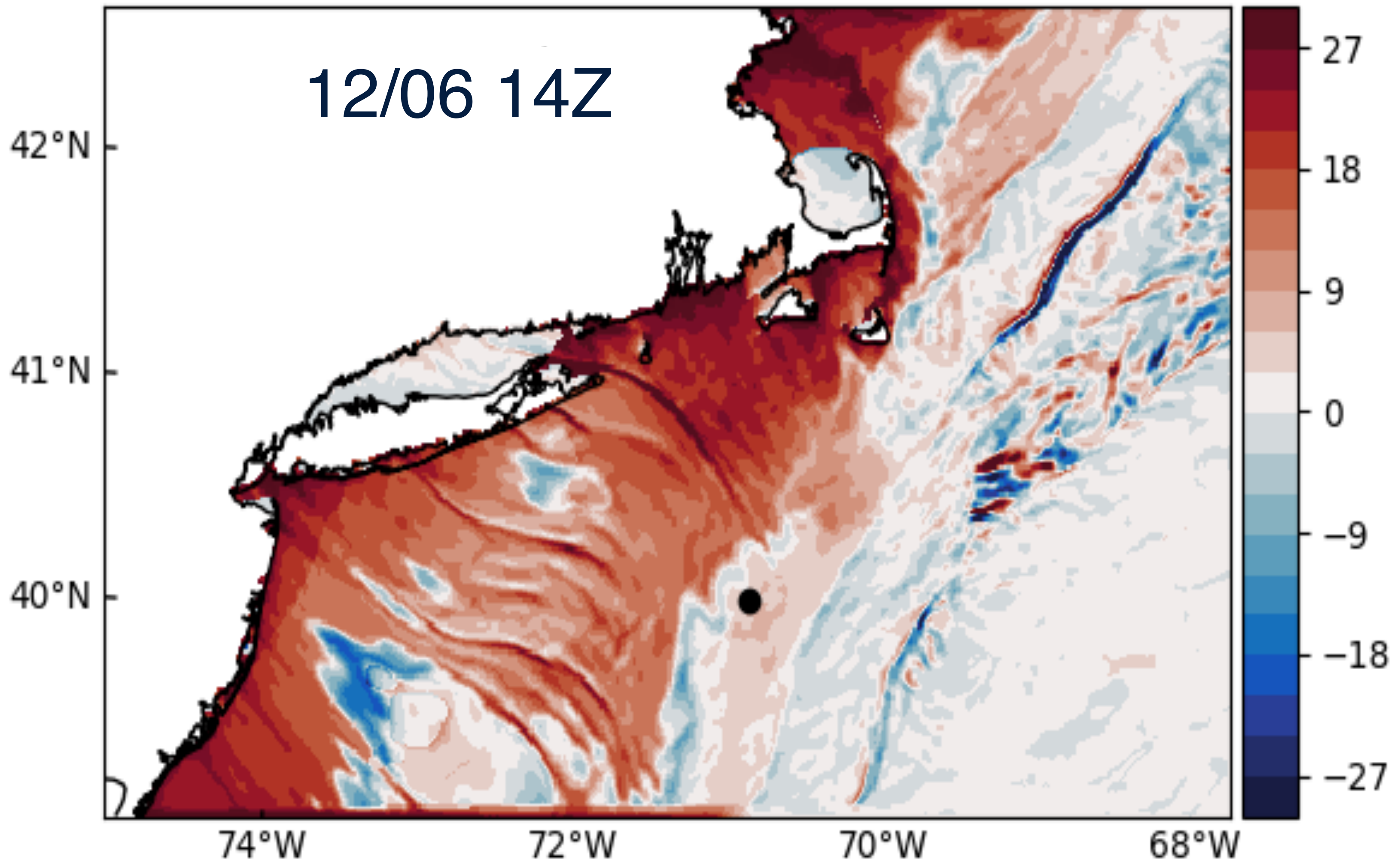
surface wind



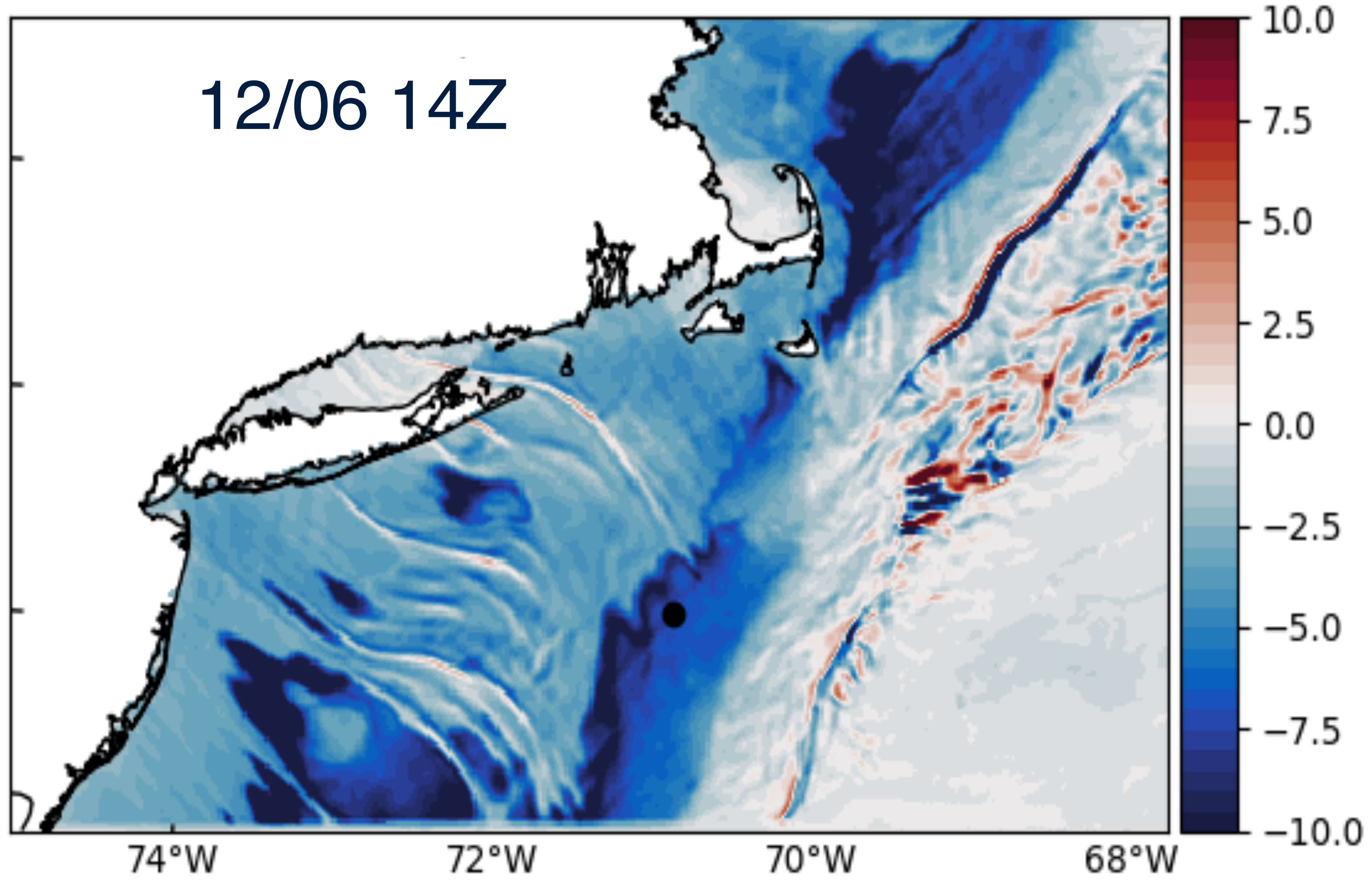
wave-wind angle (θ)



τ difference: WBFθ – WBF



surface wind diff: WBFθ – WBF



Edson et al. (2013)

WBF $$z_0^{rough} = H_s D \left(\frac{u_*}{c_p}\right)^{B},$$

Sauvage et al. (2023)

WBFθ $$z_{rough} = H_s D\cos(a\theta)\left(\frac{u_*}{c_p}\right)^{B\cos(b\theta)}.$$

- Vast areas of misaligned wind waves, with enhanced wind stress and lower wind speed
- Long-term characterization of the effect is currently underway.

Sauvage et al. (in prep)

Summary

- Bulk flux parameterizations are based on many **assumptions:**
  - Stationarity, horizontal homogeneity, and **wind-wave equilibrium**
- Frontal-scale air-sea interaction corresponds to situations where these assumptions are likely **invalid**.
- We proposed two paths to mitigate the deficiencies
  - using spectrally-averaged wave information or
  - representing misaligned wave effect on surface drag
- The parameterizations require **site-specific tuning** for optimal regional applications.

Thanks (hseo@whoi.edu)

Sauvage et al., 2023: Improving wave-based air-sea momentum flux parameterization in mixed seas. *J. Geophys. Res. Oceans*, 128, e2022JC019277