

Directional Wave–Wind Coupling, Drag Coefficient Rolloff, and Air-Sea Fluxes Under Tropical Cyclones

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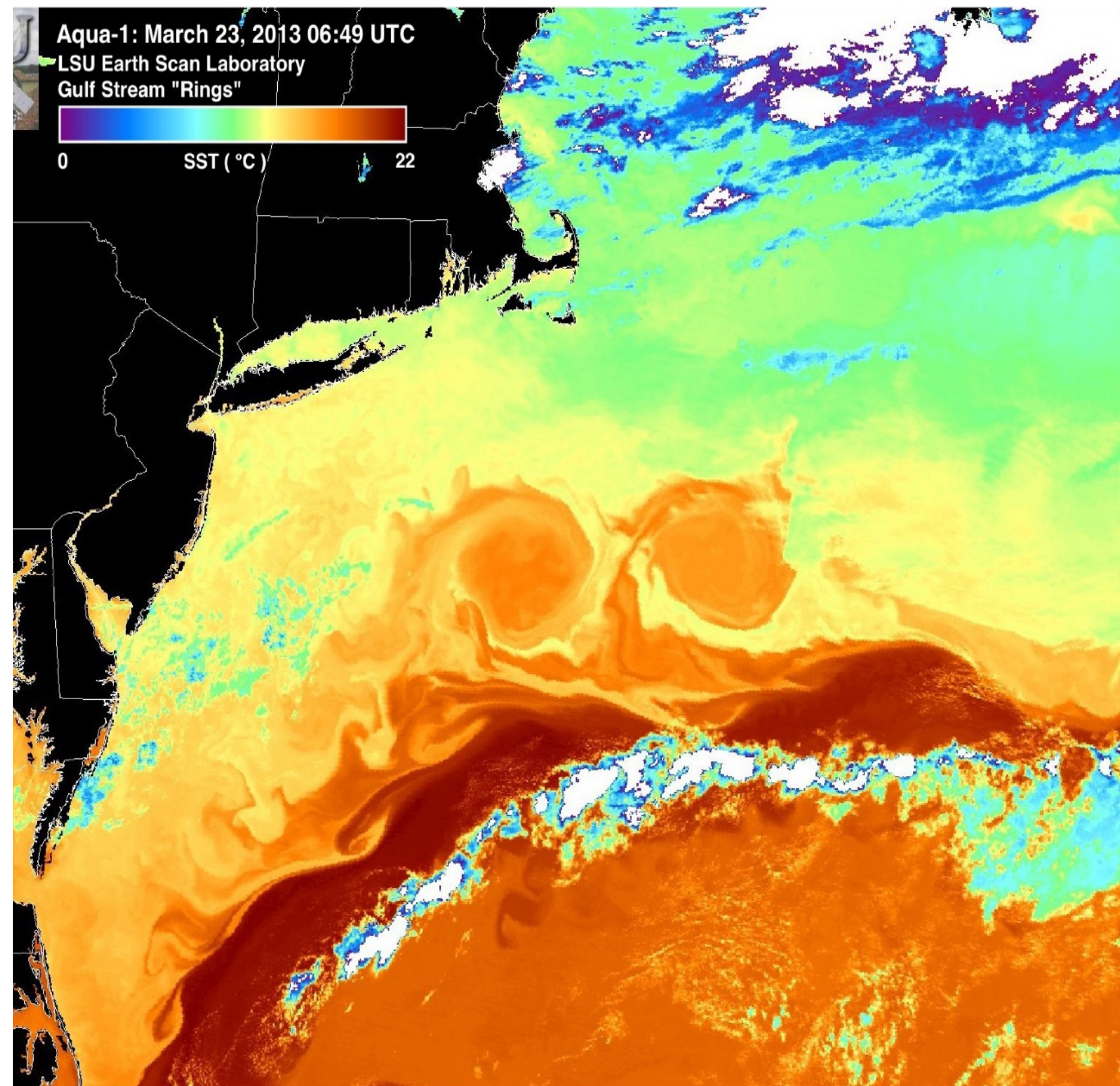
UH: César Sauvage, Wyn Pauly, Sachiko Yoshida, Ben Barr
OIST: Satoshi Mitarai
WHOI: Carol Anne Clayson, Jake Davis



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WOODS HOLE
OCEANOGRAPHIC
INSTITUTION

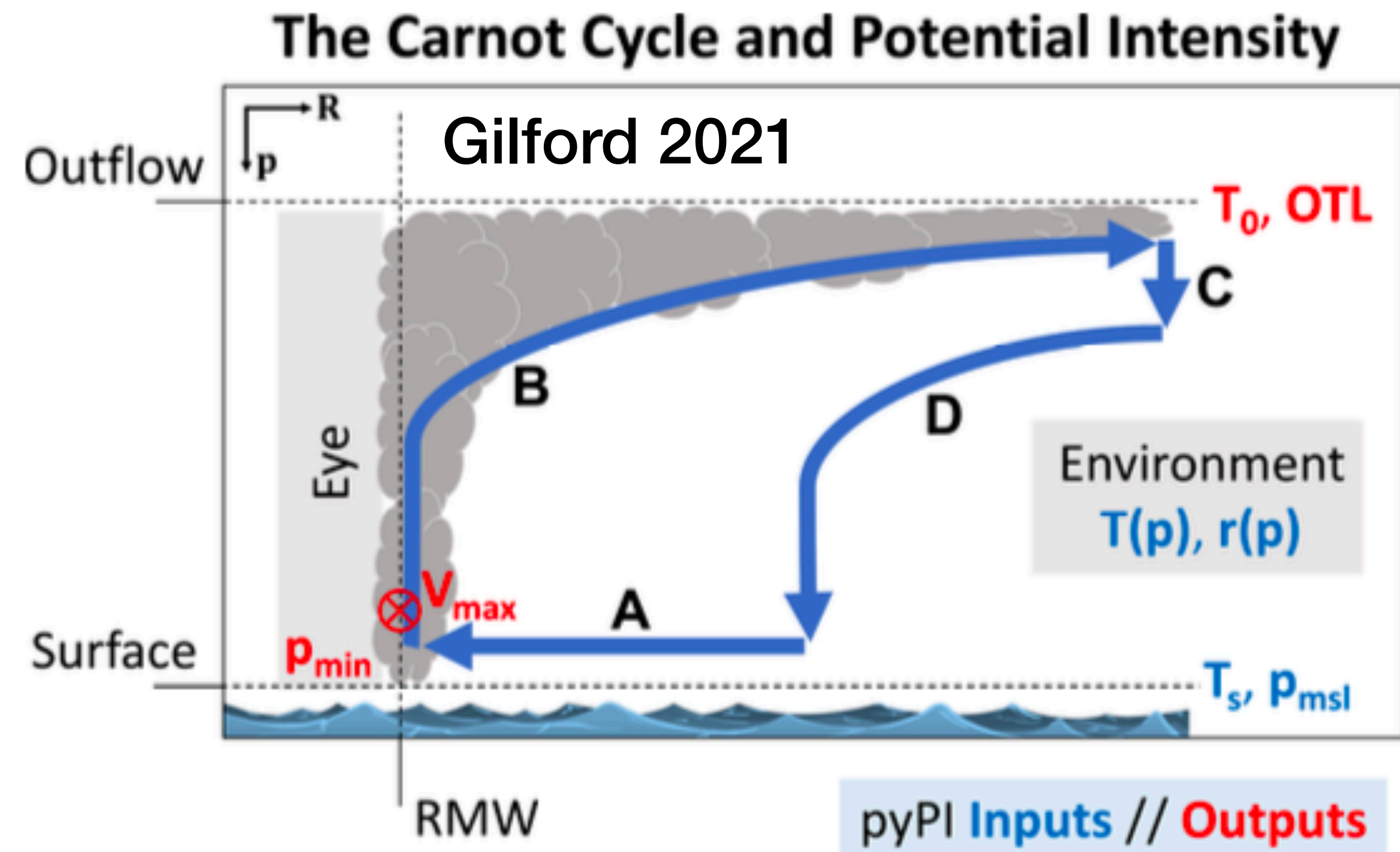
Drag Coefficient and Storm Potential Intensity

In the equilibrium condition, TC intensity is constrained by the balance between energy added at the warm ocean surface and energy lost in the cool outflow region aloft (Emanuel 1988)

The diagram shows the equation for maximum wind speed, V_{max}^2 , with color-coded arrows linking terms to their physical meanings:

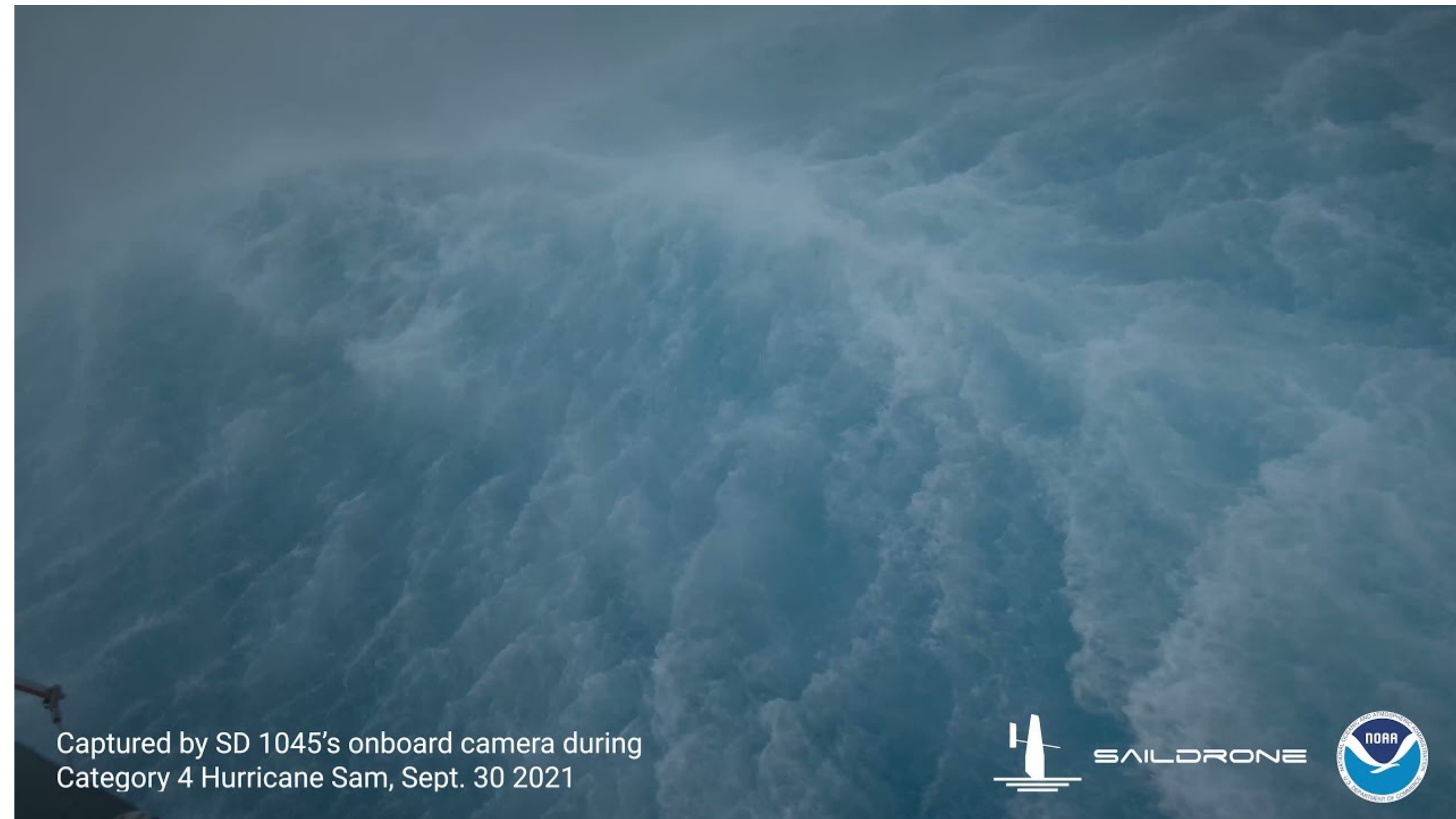
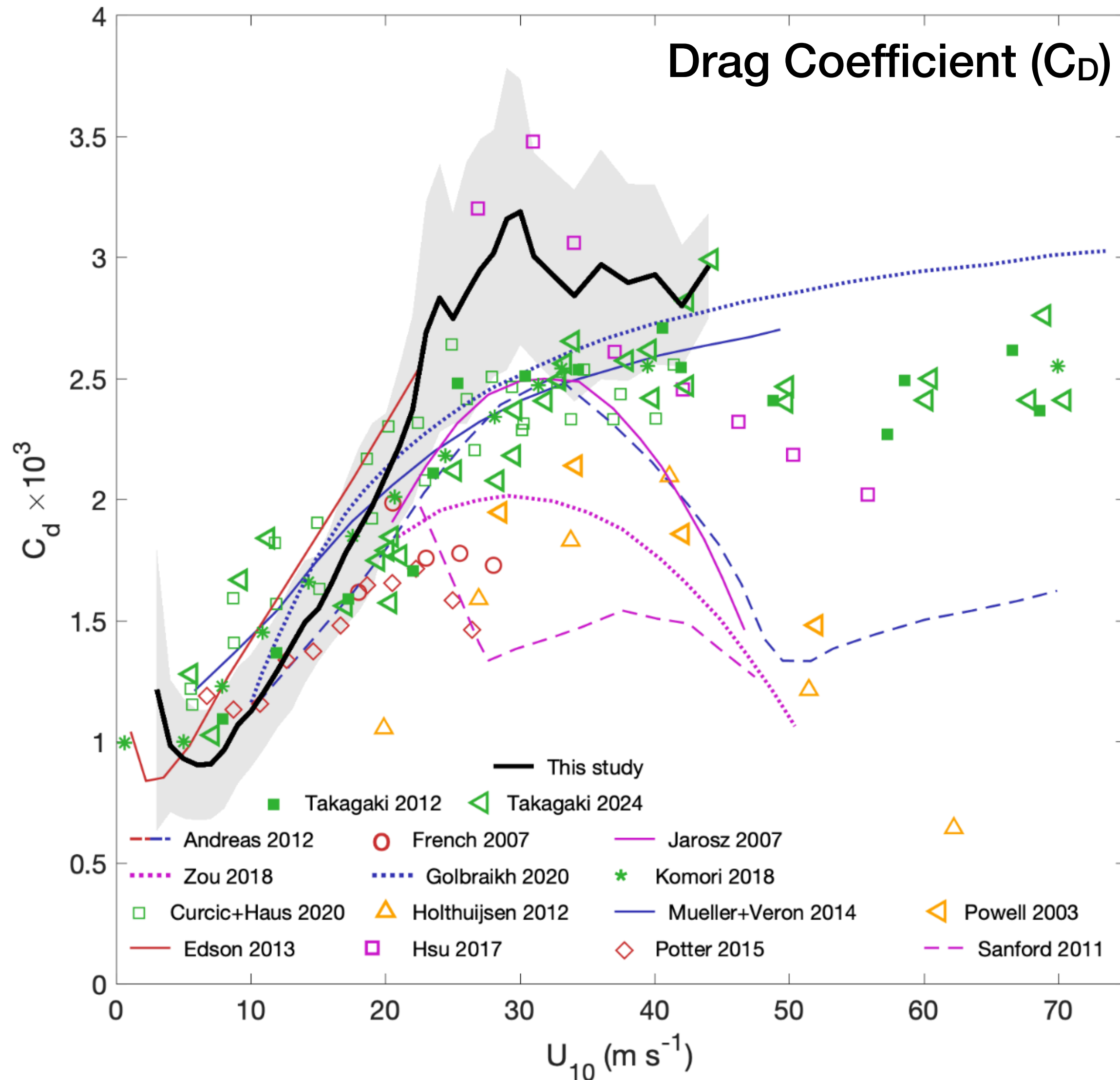
- Blue arrow:** Points from the text "TC outflow tempearture" (note the typo) to the term T_o in the denominator.
- Red arrow:** Points from the text "pre-storm ocean temp." to the term $\bar{T}$ in the numerator.
- Green arrow:** Points from the text "air-sea enthalpy difference" to the term K_{SST} in the numerator.

$$V_{max}^2 = \frac{(\bar{T} - T_o) C_K}{T_o C_D} (K_{SST} - k)$$



C_K , C_D , k , & K_{SST} all vary with sea state and feature strong TC spatial variability. Sea states and wave-supported roughness length are key parameters.

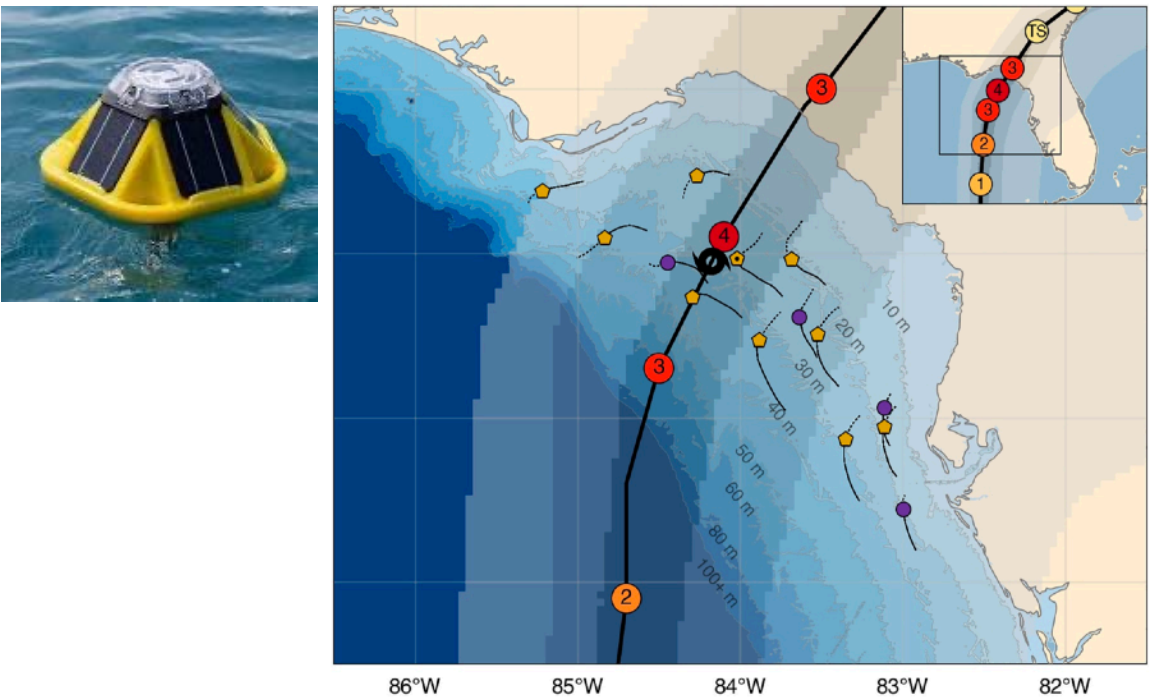
Sea state and drag coefficient under very high winds



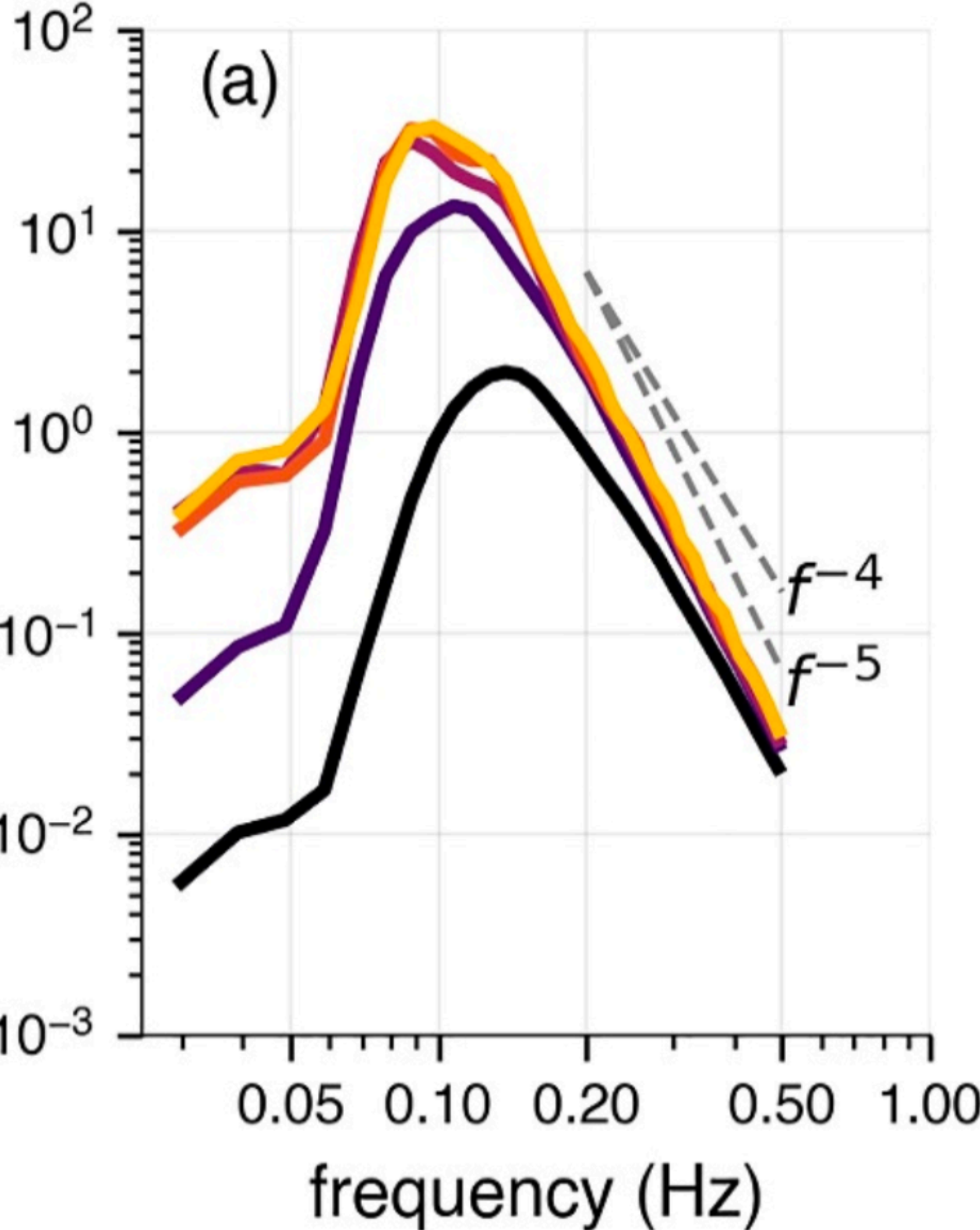
https://www.youtube.com/results?search_query=https%3A%2F%2Fwww.youtube.com%2Fwatch%3Fv%3DTzgdSSb0T98

The hurricane foam coverage and sea spray form a slippery surface: Wind energy input to waves ceases to increase while wind speeds increase

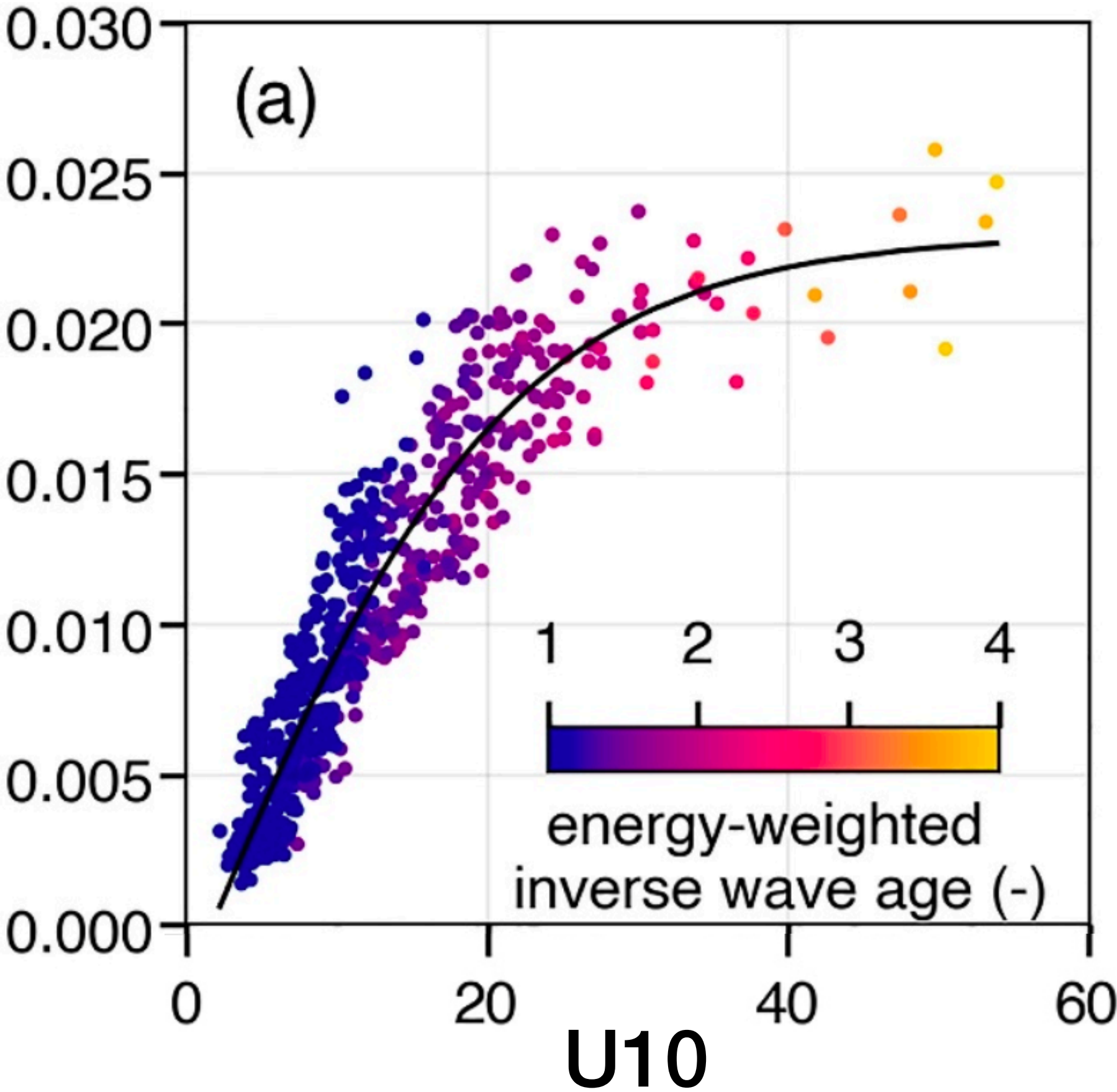
Mean square slope (MSS) and Hurricane Idalia (2023)



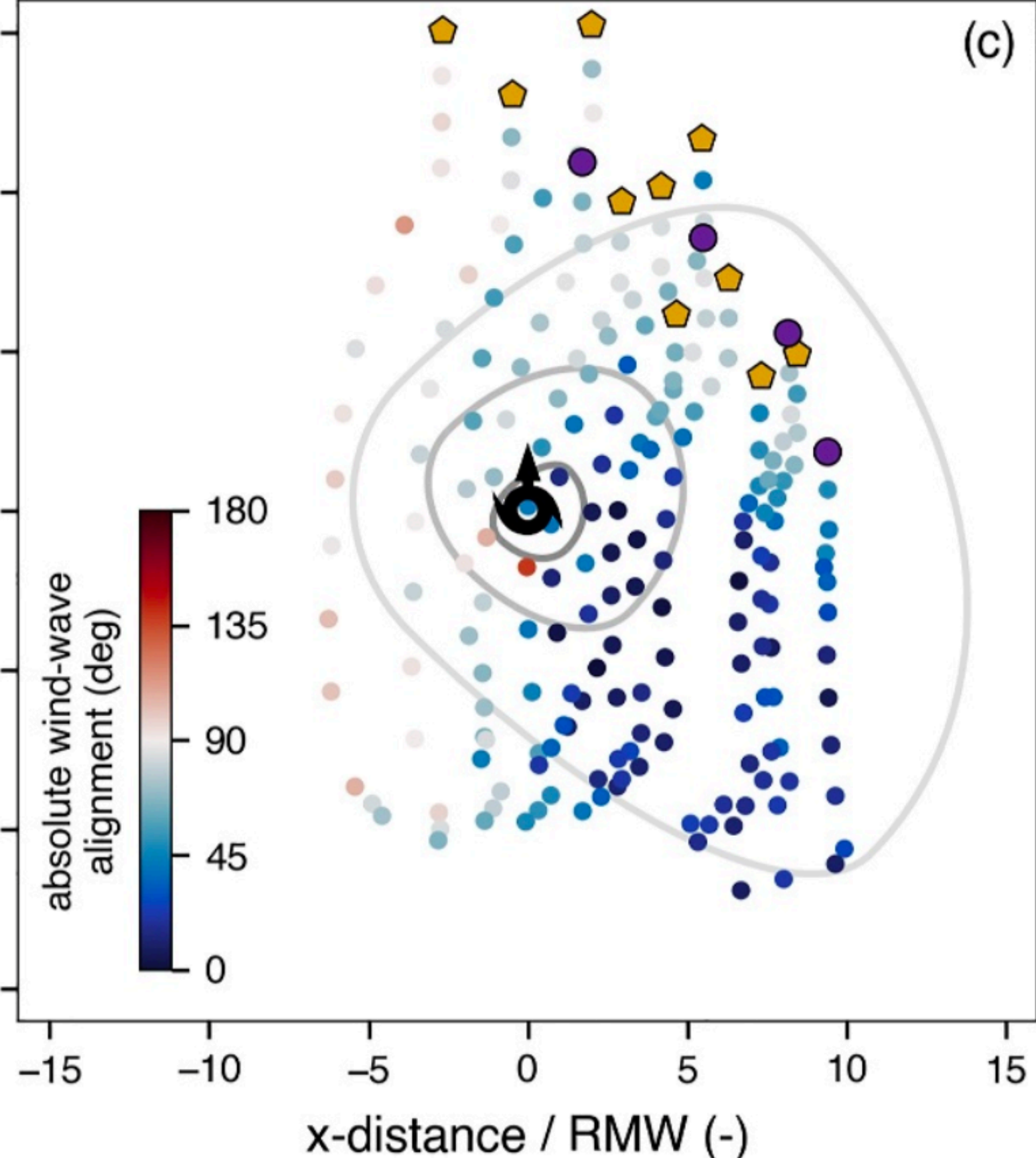
Mean energy density



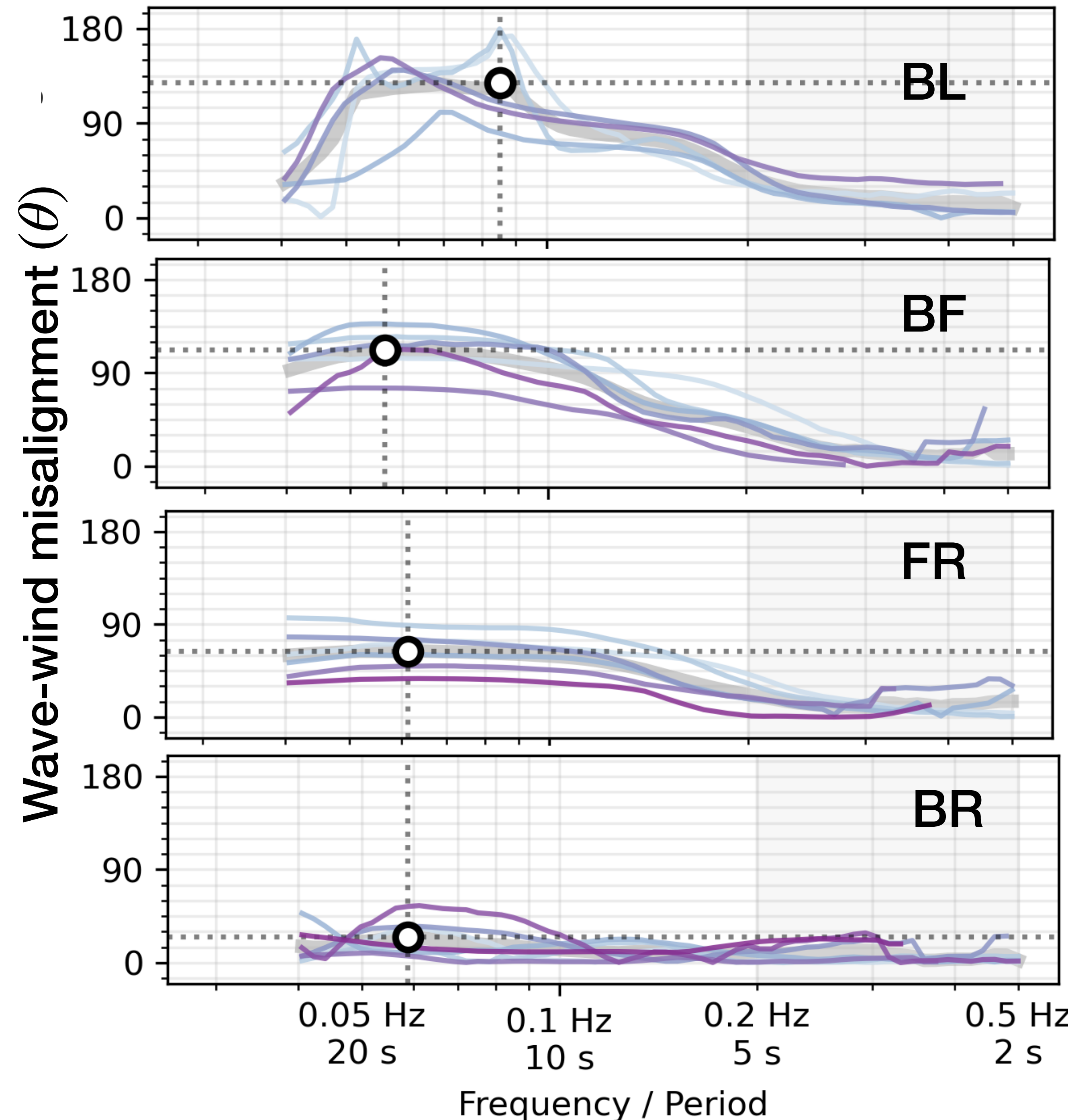
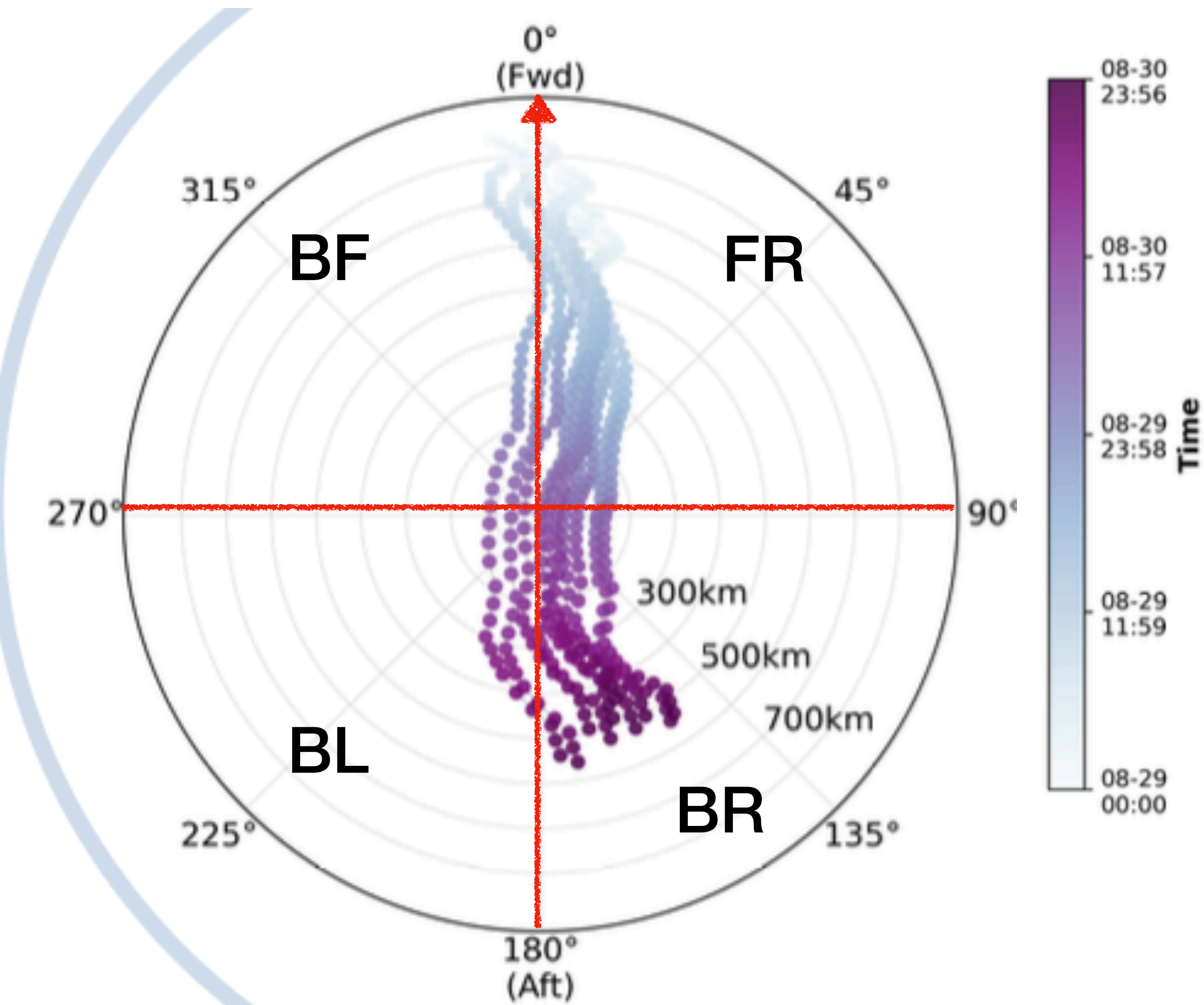
MSS
$$\int_{f_1}^{f_2} \frac{(2\pi f)^4 E(f)}{g^2} df$$



Wave-wind misalignment (θ)



Wave-wind misalignment and Hurricane Idalia (2023)



COARE bulk flux parameterization (Edson et al. 2013)

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

1. Wind Speed Dependent Formulation

$$z_0^{\text{rough}} = \alpha \frac{u_*^2}{g} \quad \alpha = f_1(U_{10N}) = mU_{10N} + b$$

Charnock coefficient

Wind-wave equilibrium, wind-aligned waves

2. Wave-Based Formulation

$$z_0^{\text{rough}} = H_s 0.09 \frac{u_*^2}{C_p}$$

dominant phase speed

significant wave height

Wind-aligned waves, not appropriate for mixed seas

3. Revised Wave-Based Formulation (Sauvage et al. 2023, 2024)

$$z_0^{\text{rough}} = H_s 0.09 \cos(0.45\theta) \left(\frac{u_*}{C_p} \right)^{2\cos(-0.32\theta)}$$

wave-wind misalignment

$$z_0^{\text{rough}} = H_s 0.09 \frac{u_*^2}{C_m}$$

spectrally averaged phase speed

Account for sea states with multiple spectral peaks and waves misaligned with the wind.

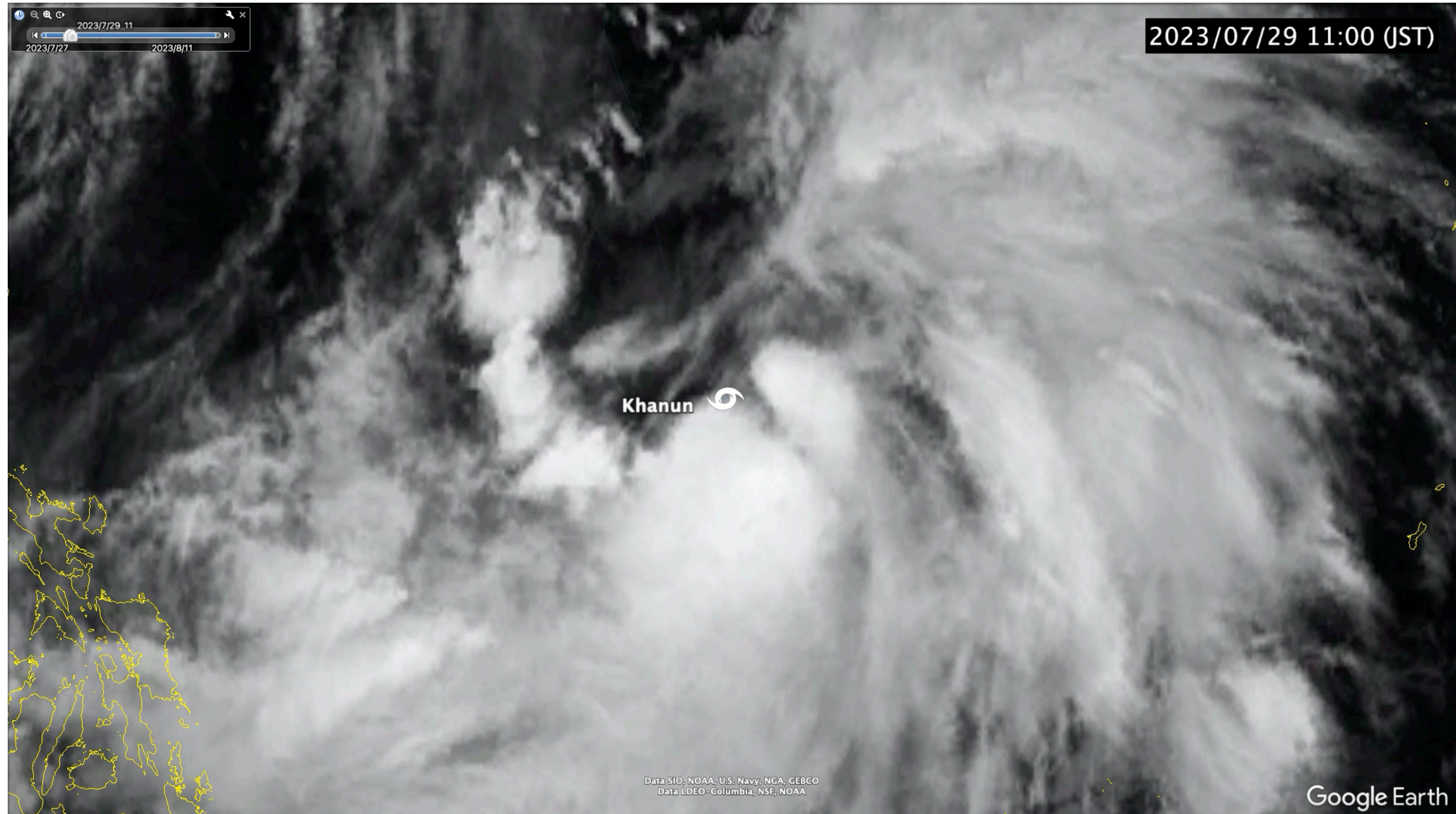
Typhoon Khanun (2023)

5x



(2 survived and neared the storm center twice)

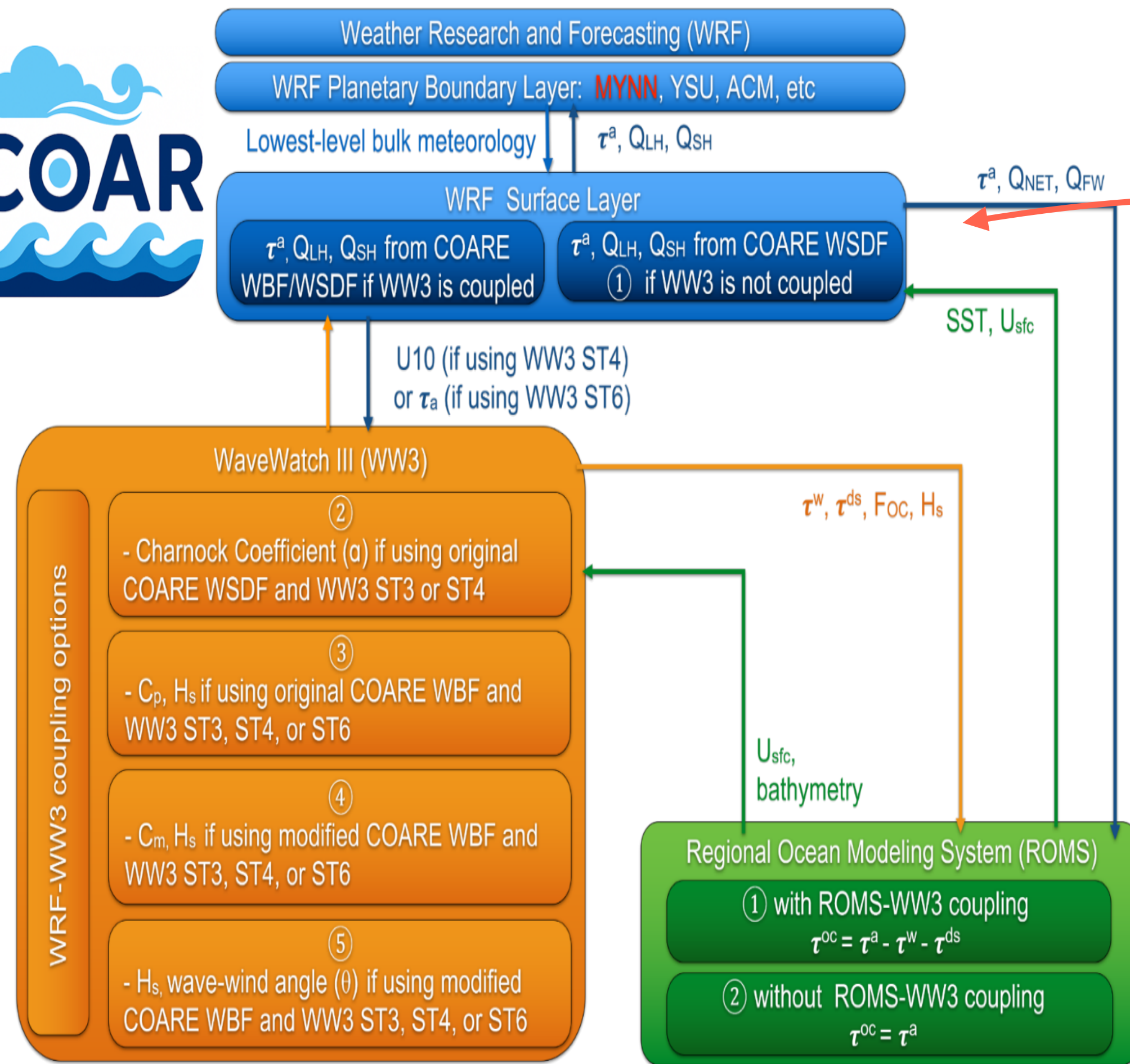
2x



Courtesy: Prof. Satoshi Mitarai (OIST)

SCOAR Regional Coupled Modeling for Typhoon Khanun (2023)

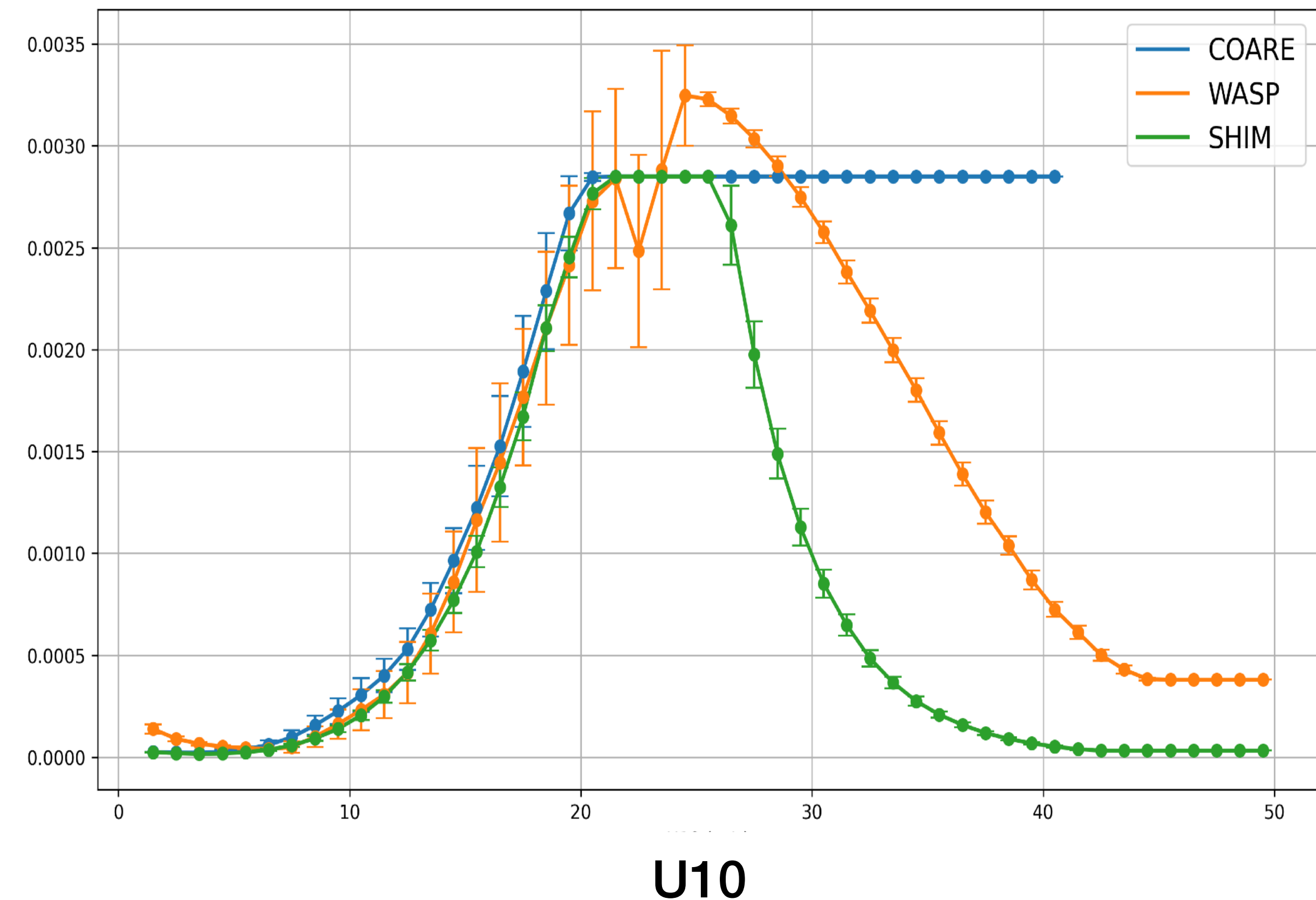
2.5km SCOAR WRF-ROMS-WW3 fully-coupled simulations
using 3 different drag coefficient rolloff scenarios



- COARE (Edson et al. 2013; Sauvage et al. 2023)
- WASP (Bouin et al. 2024)
- SHIM (Shimura et al. 2024)

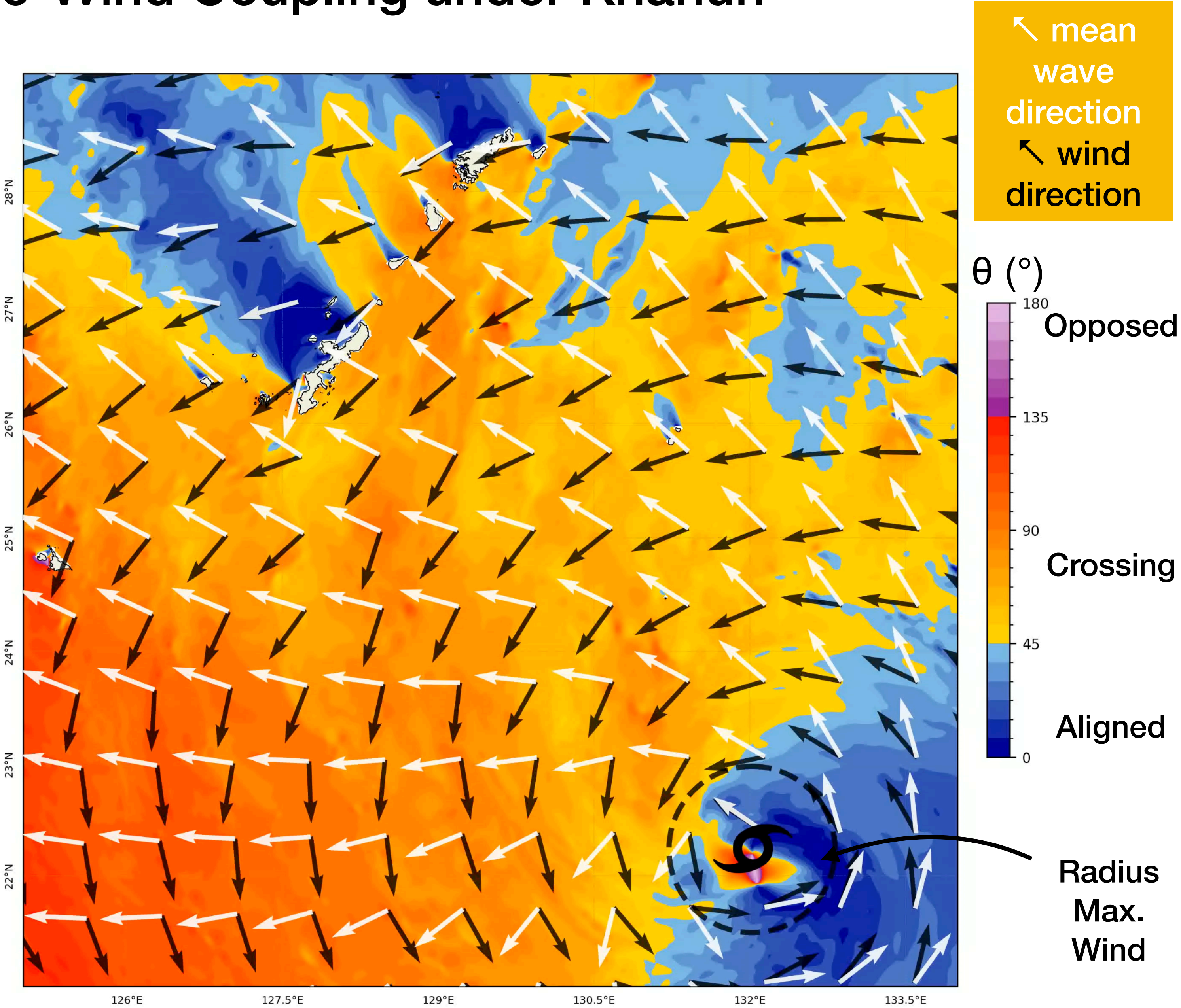
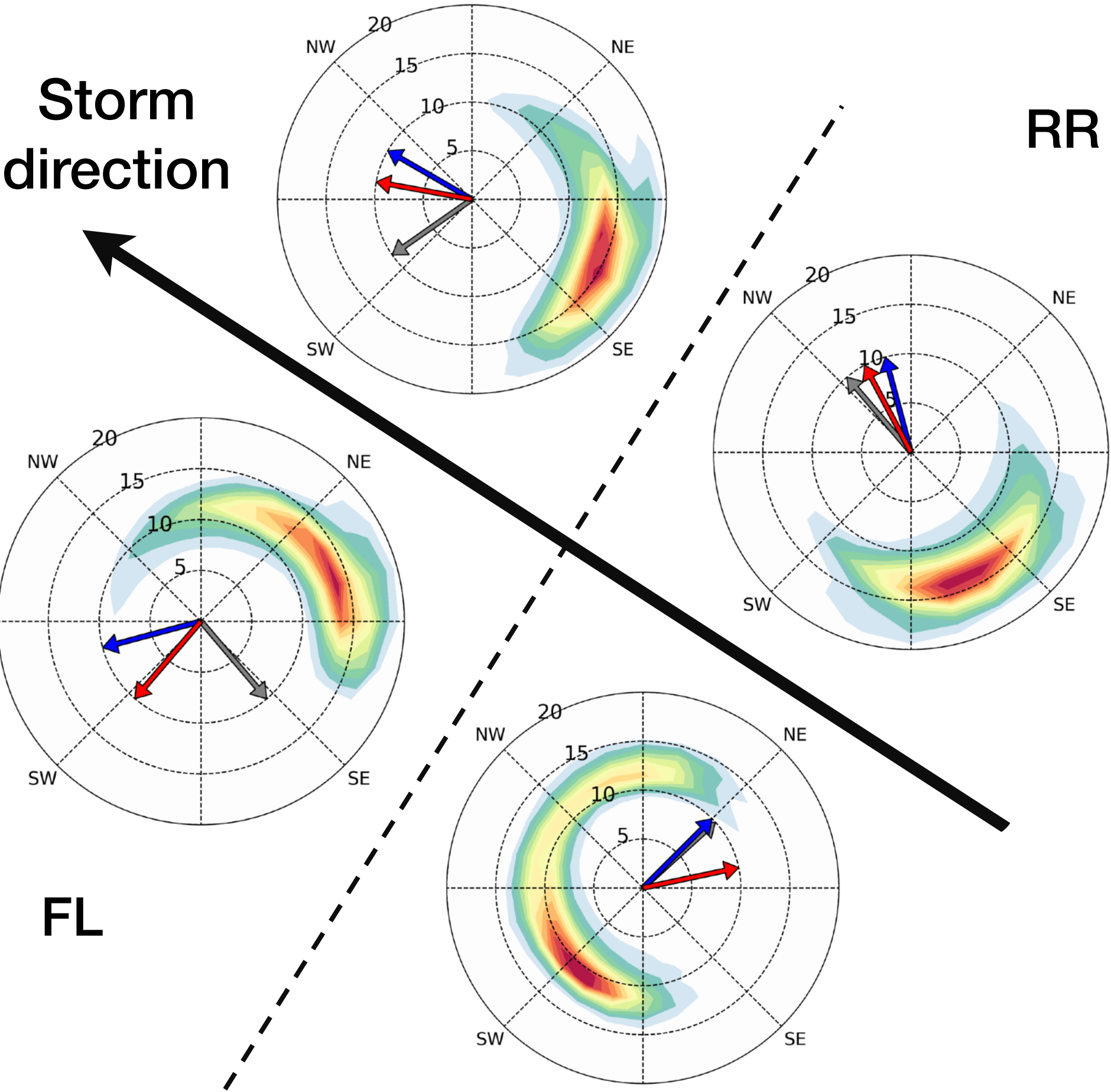
Roughness length (z_0)

z_0



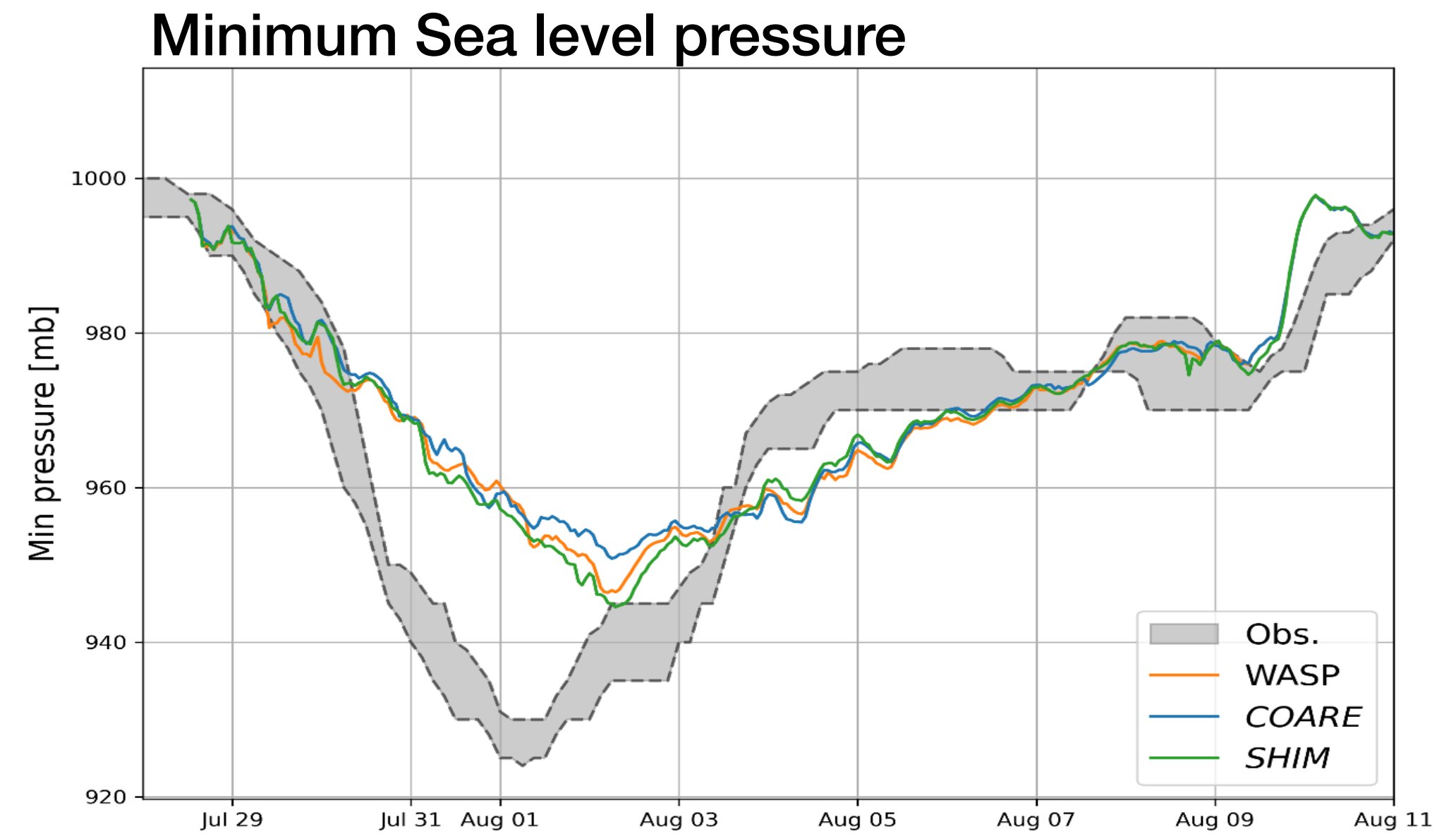
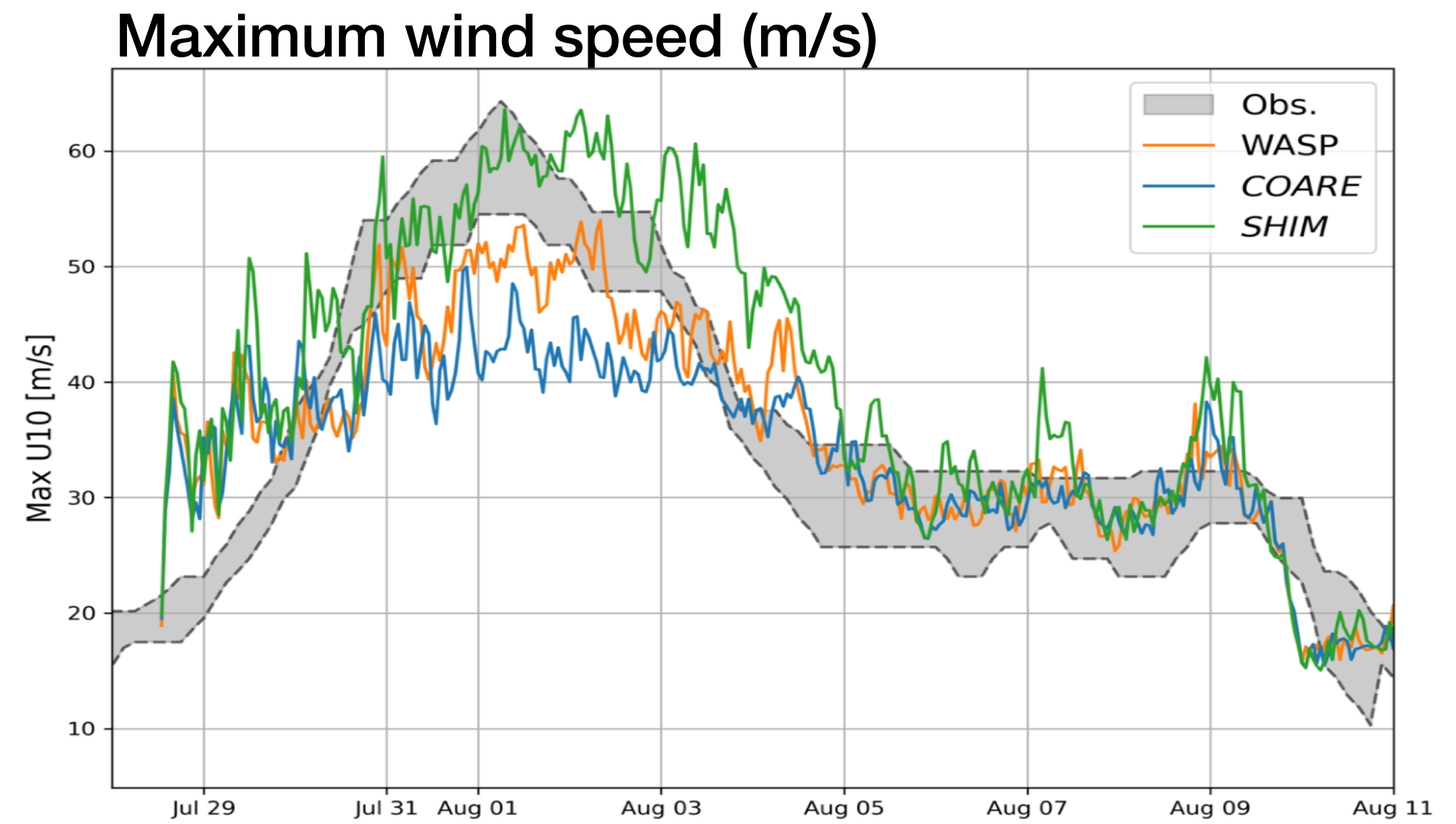
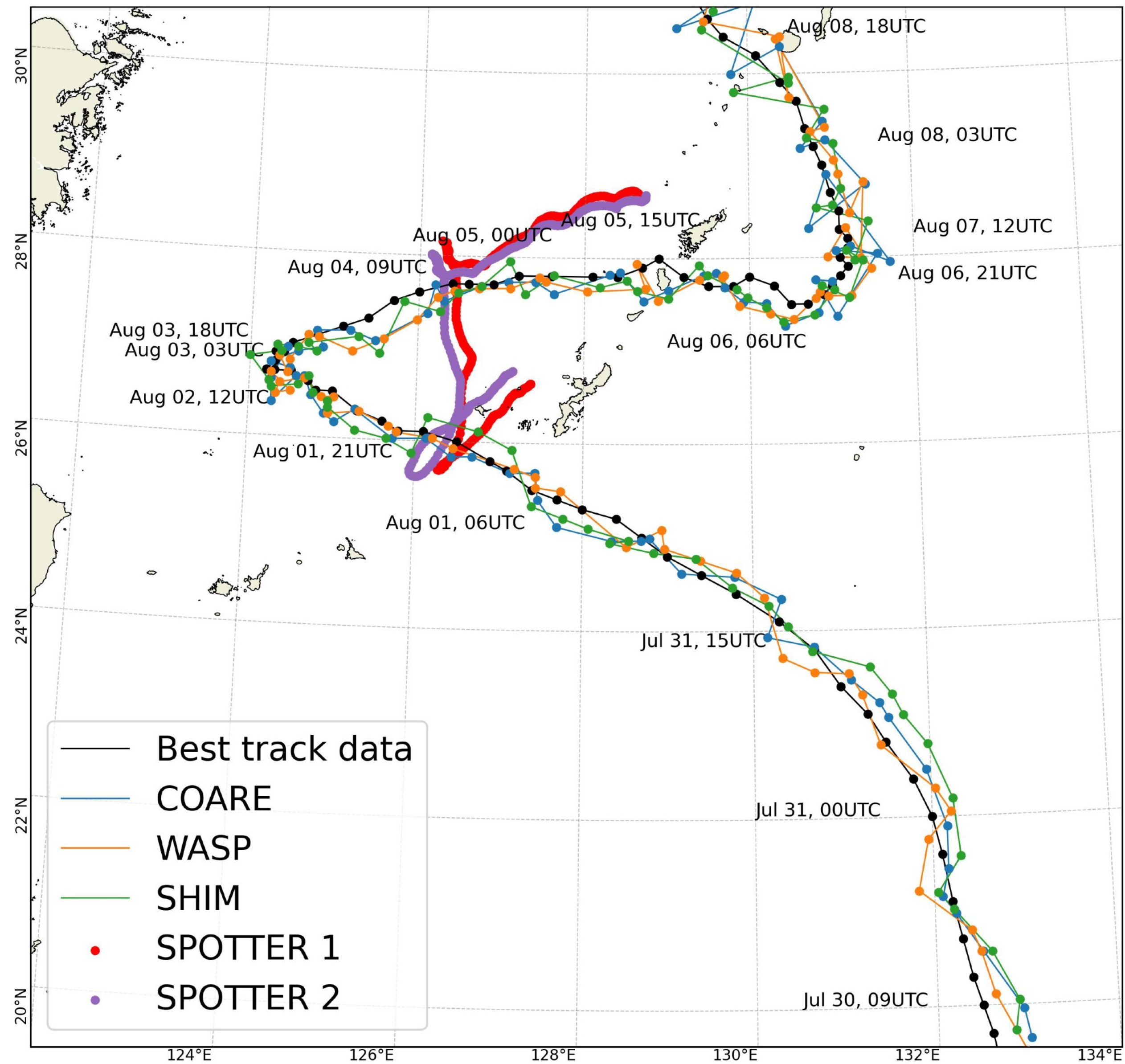
Seo et al. (2017, 2016) Sauvage et al. (2023, 2024)

Directional Wave-Wind Coupling under Khanun

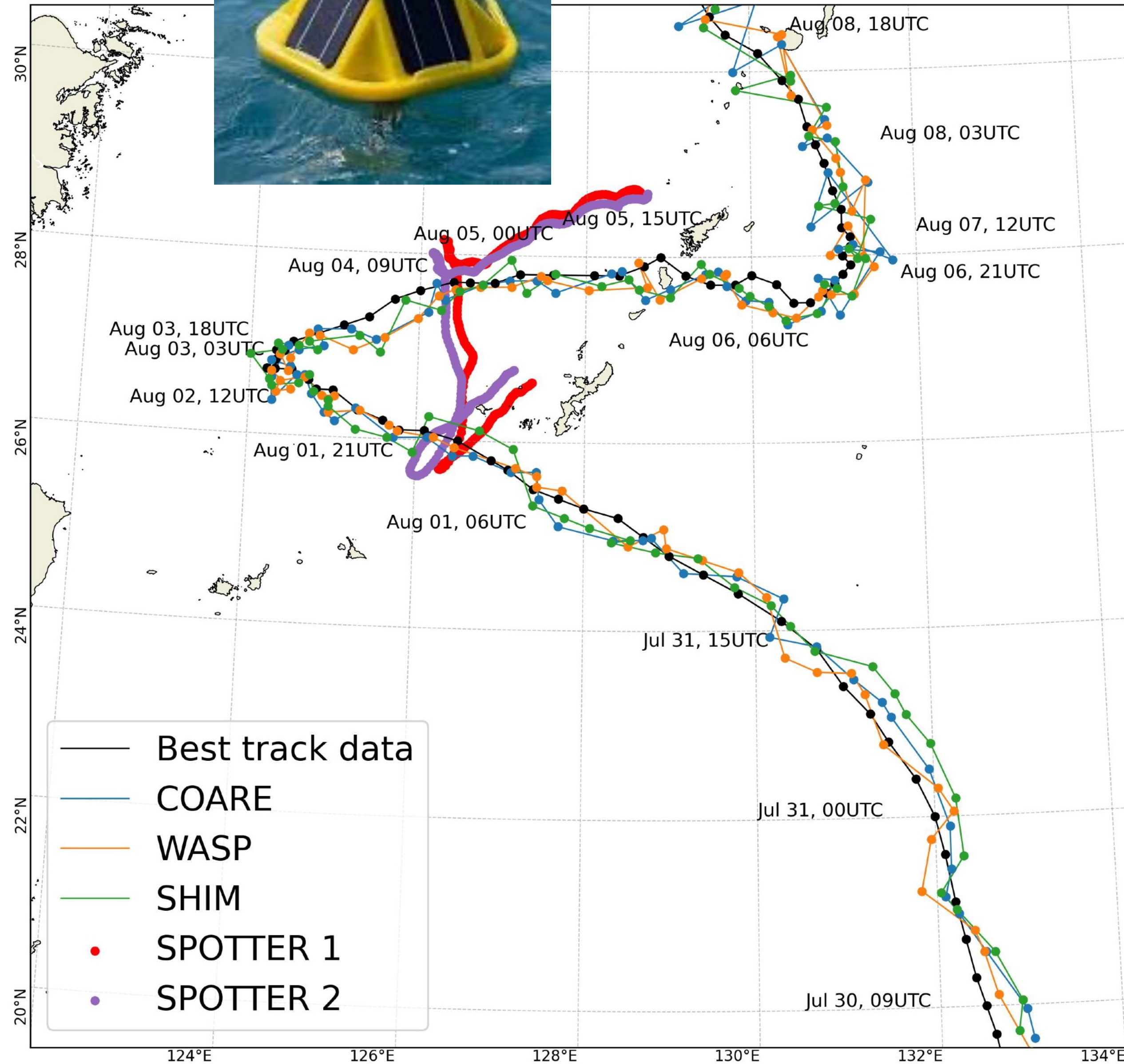


July 31 — Aug 2

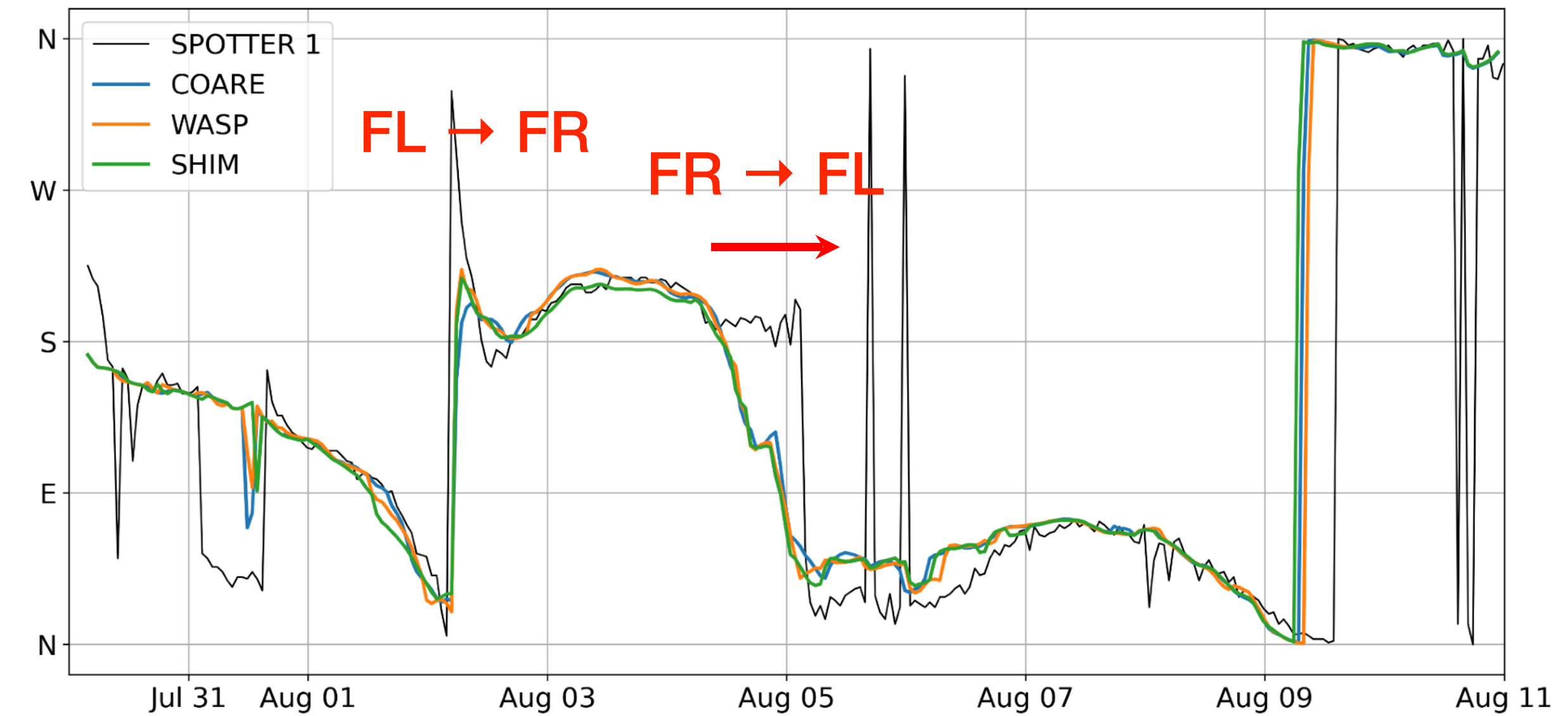
Typhoon Khanun (2023): Storm Intensity



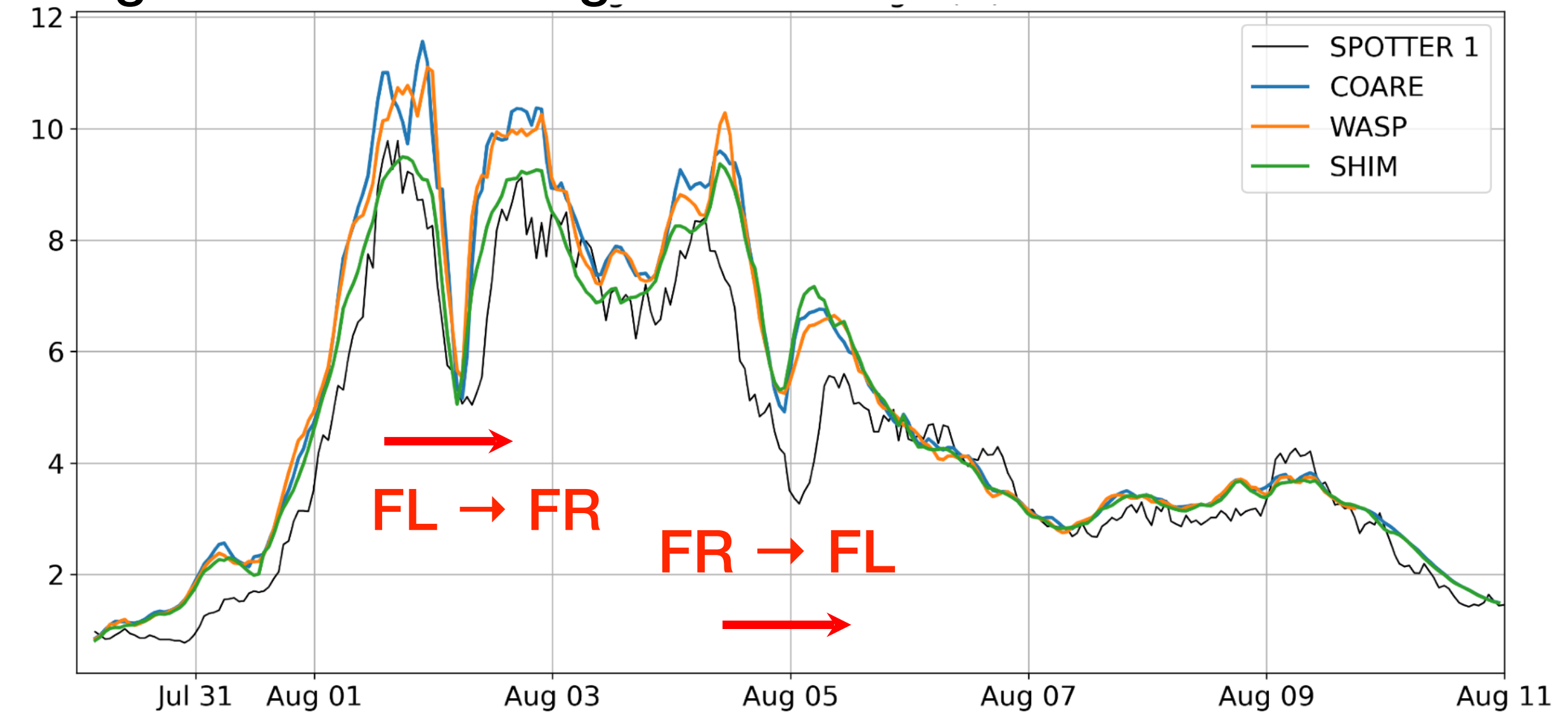
Typhoon Khanun (2023): Sea states



Peak wave direction

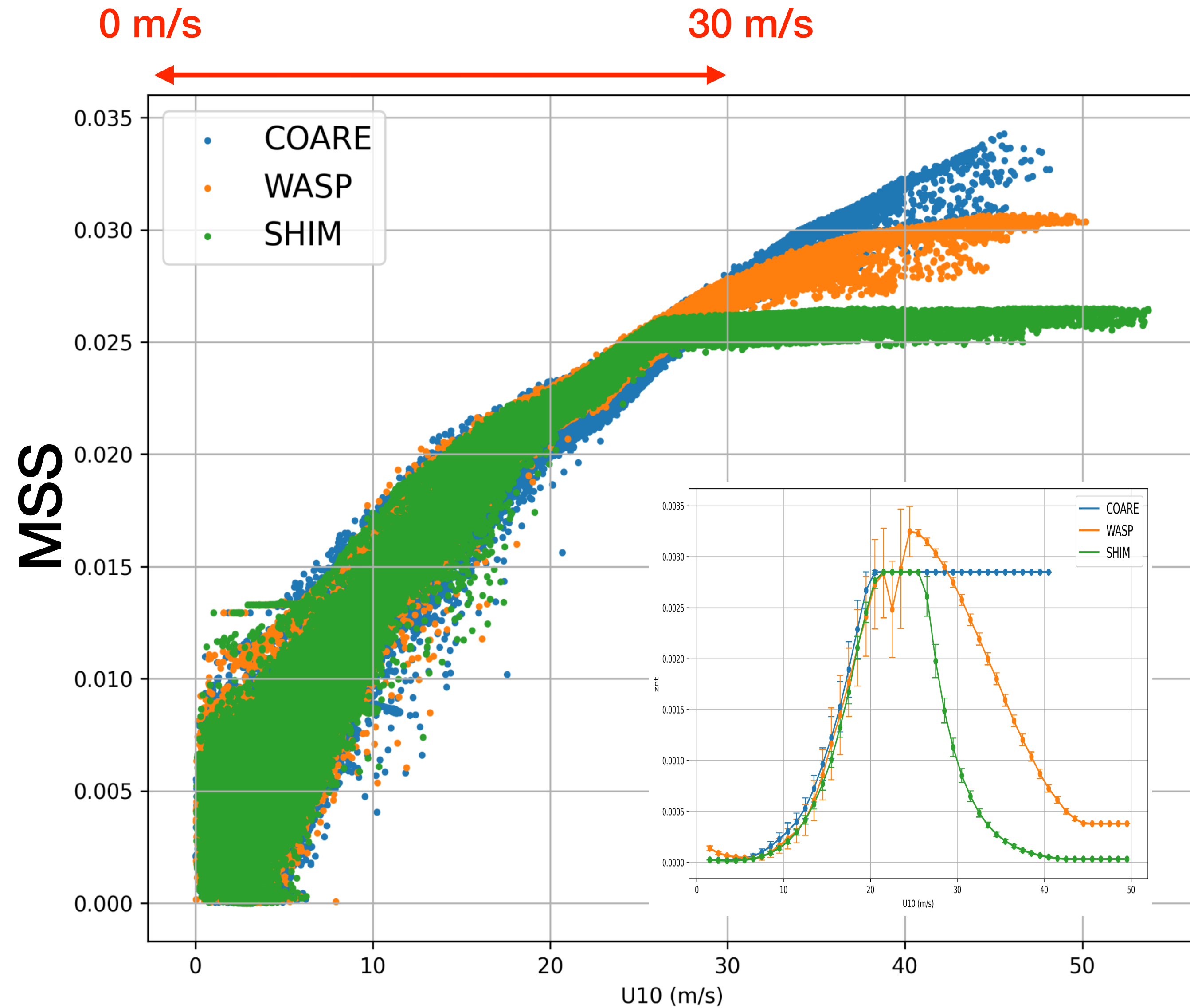
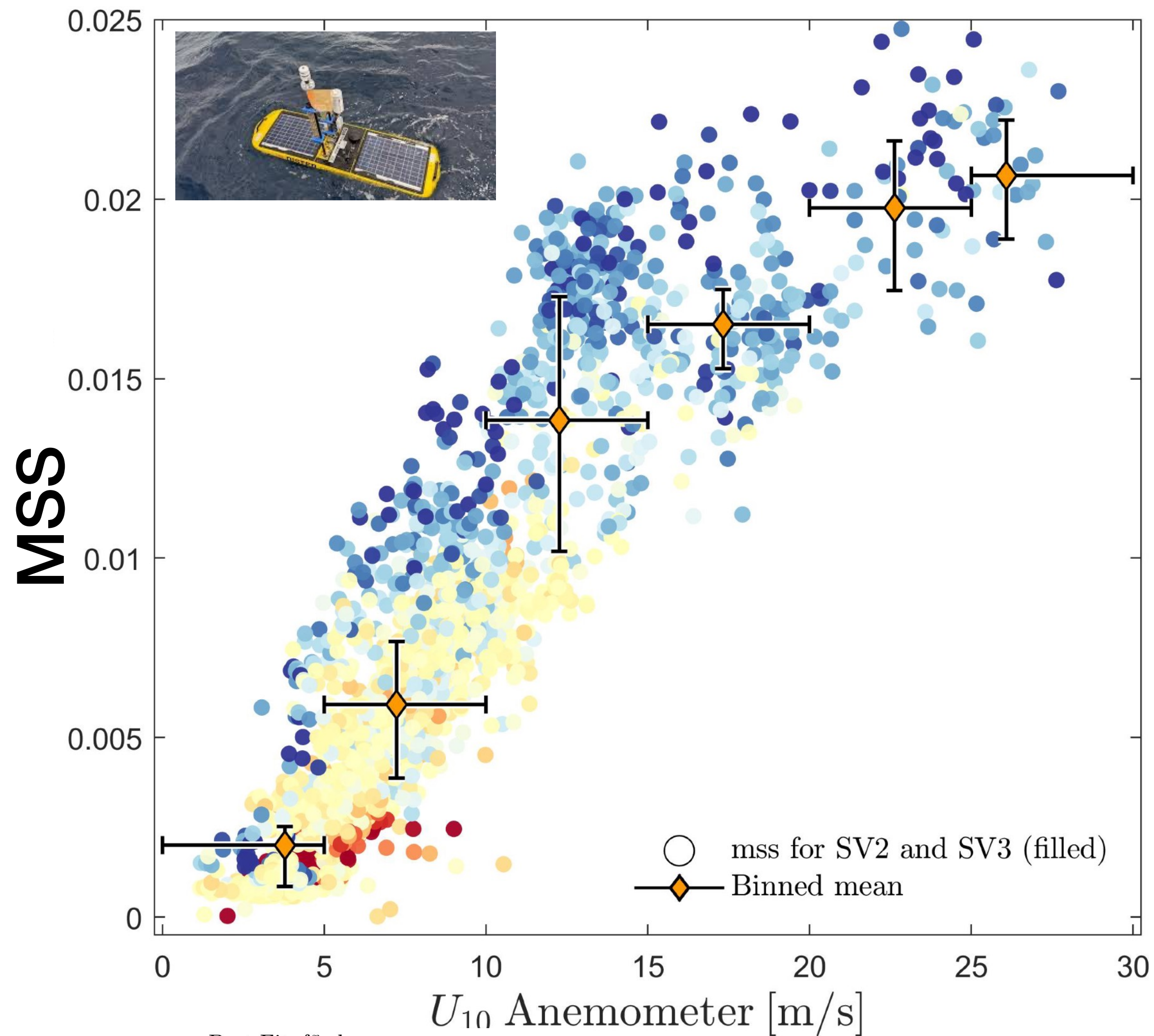


Significant wave height



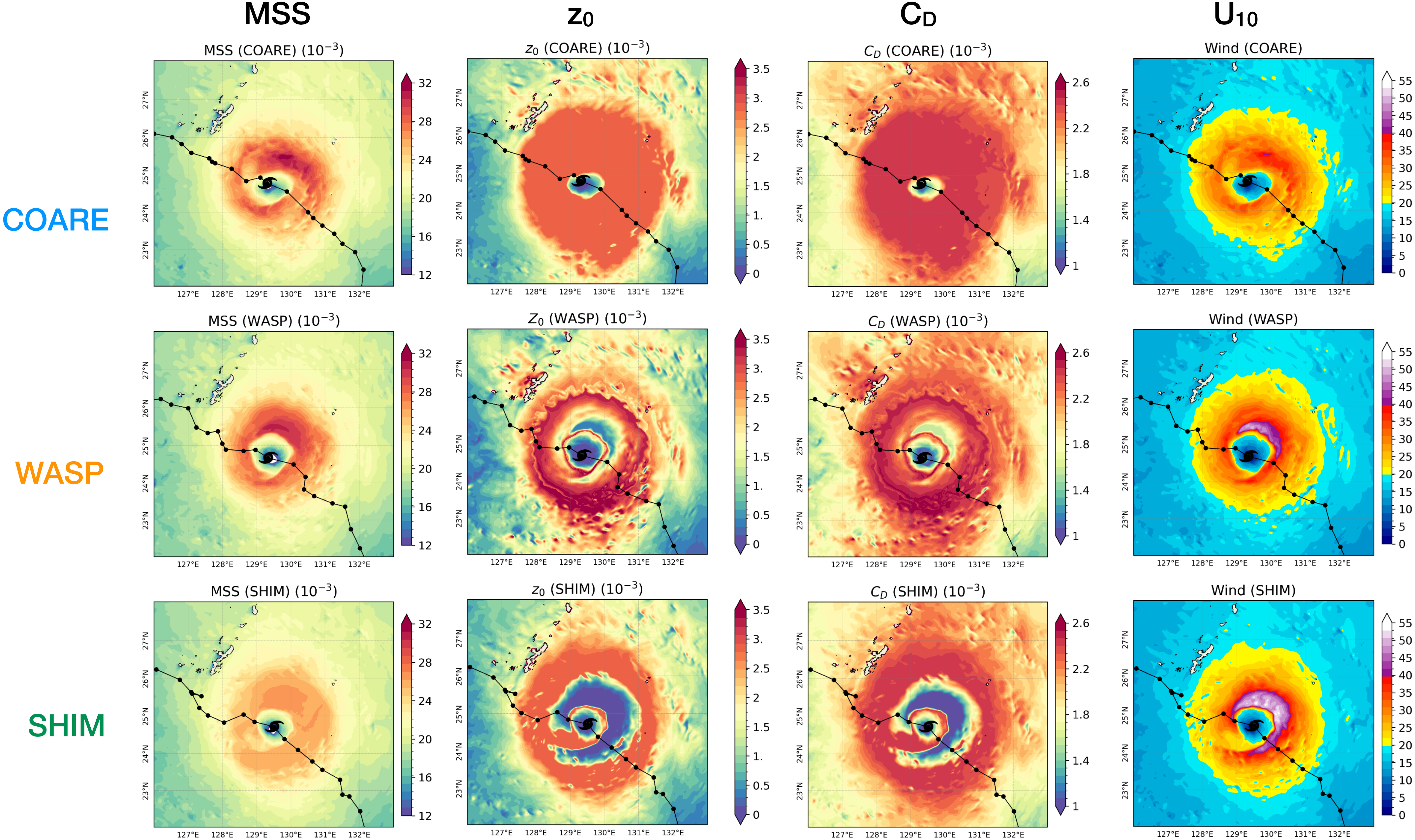
MSS Saturation

Waveglider-based estimates

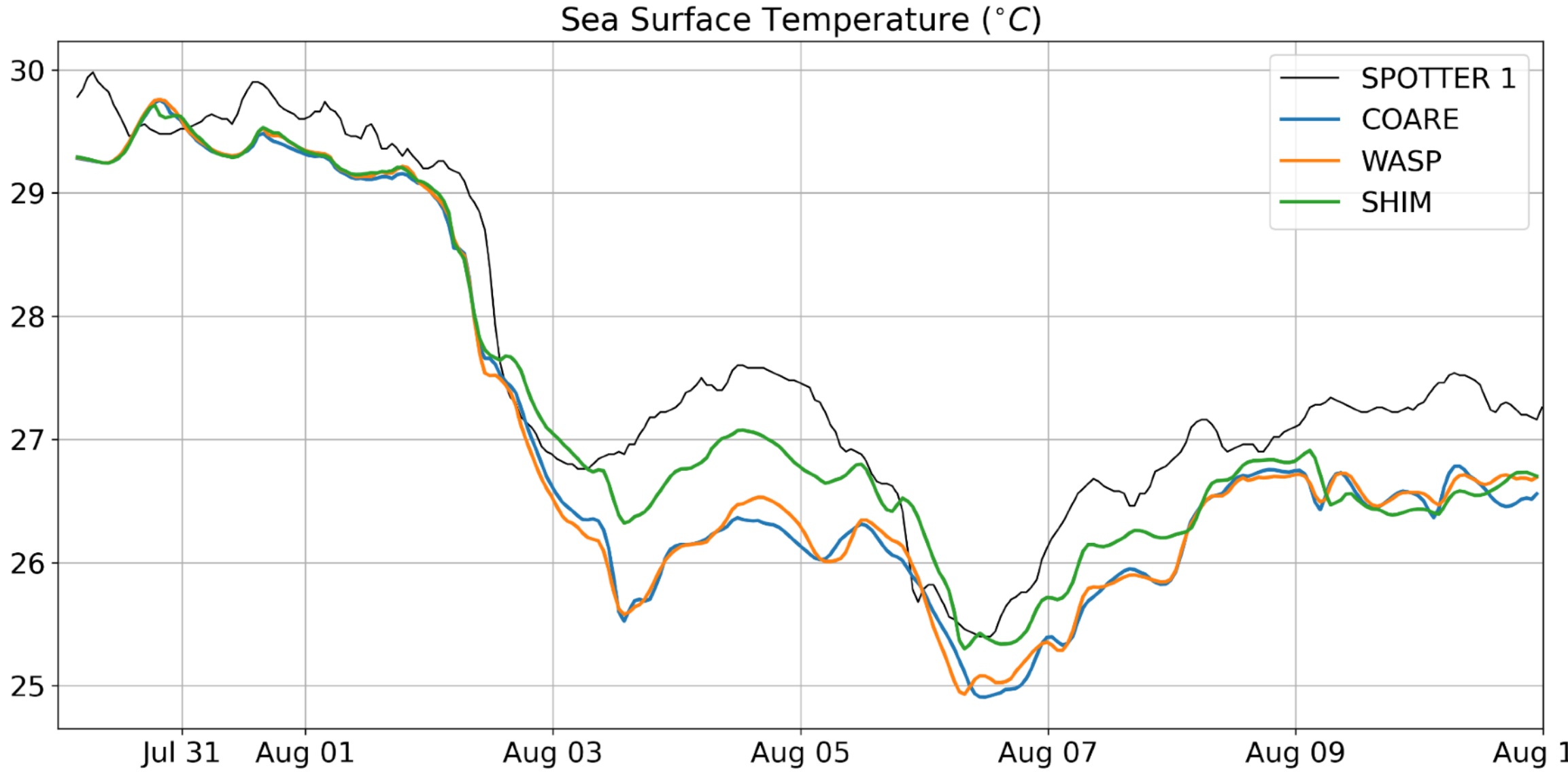
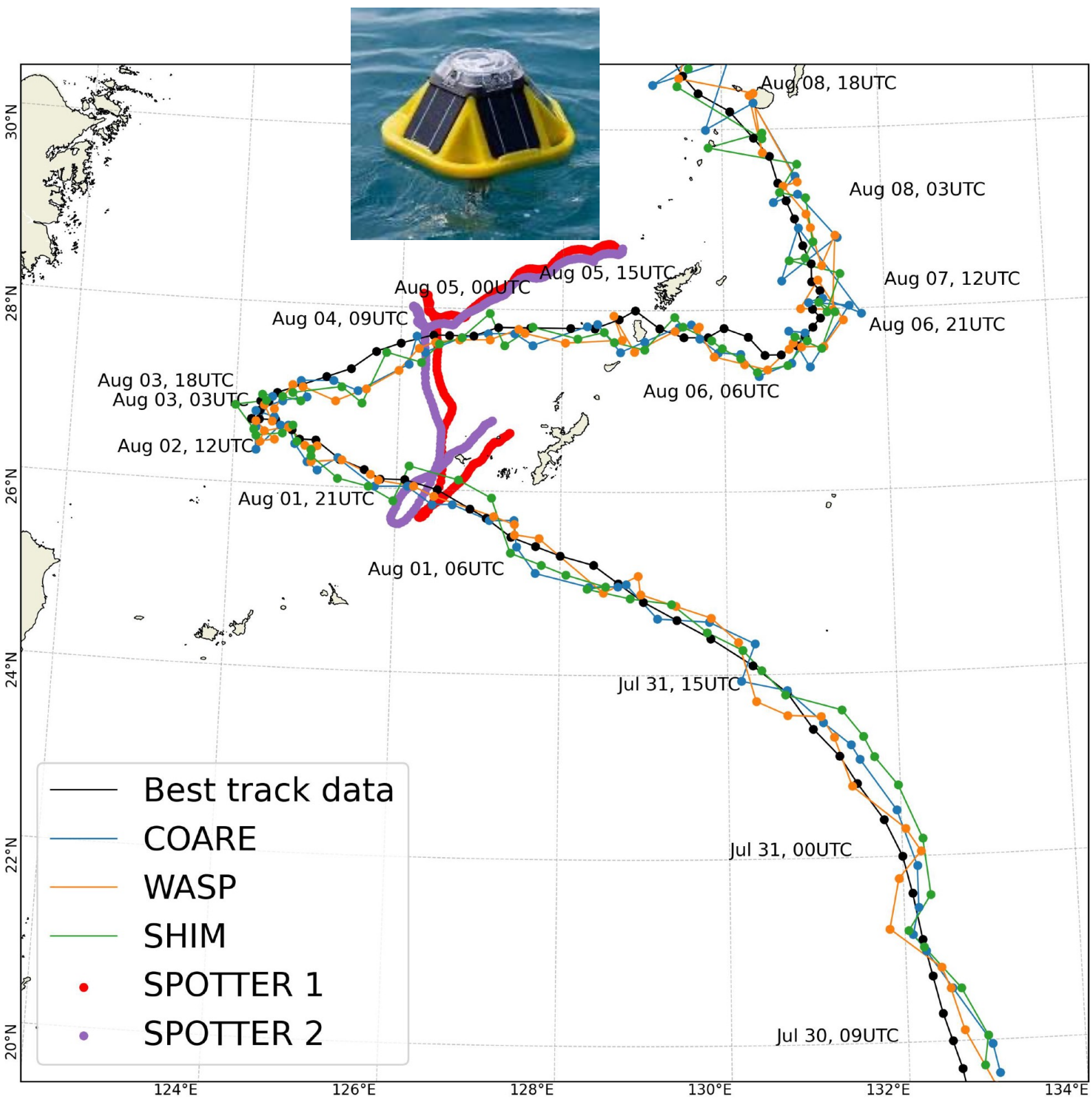
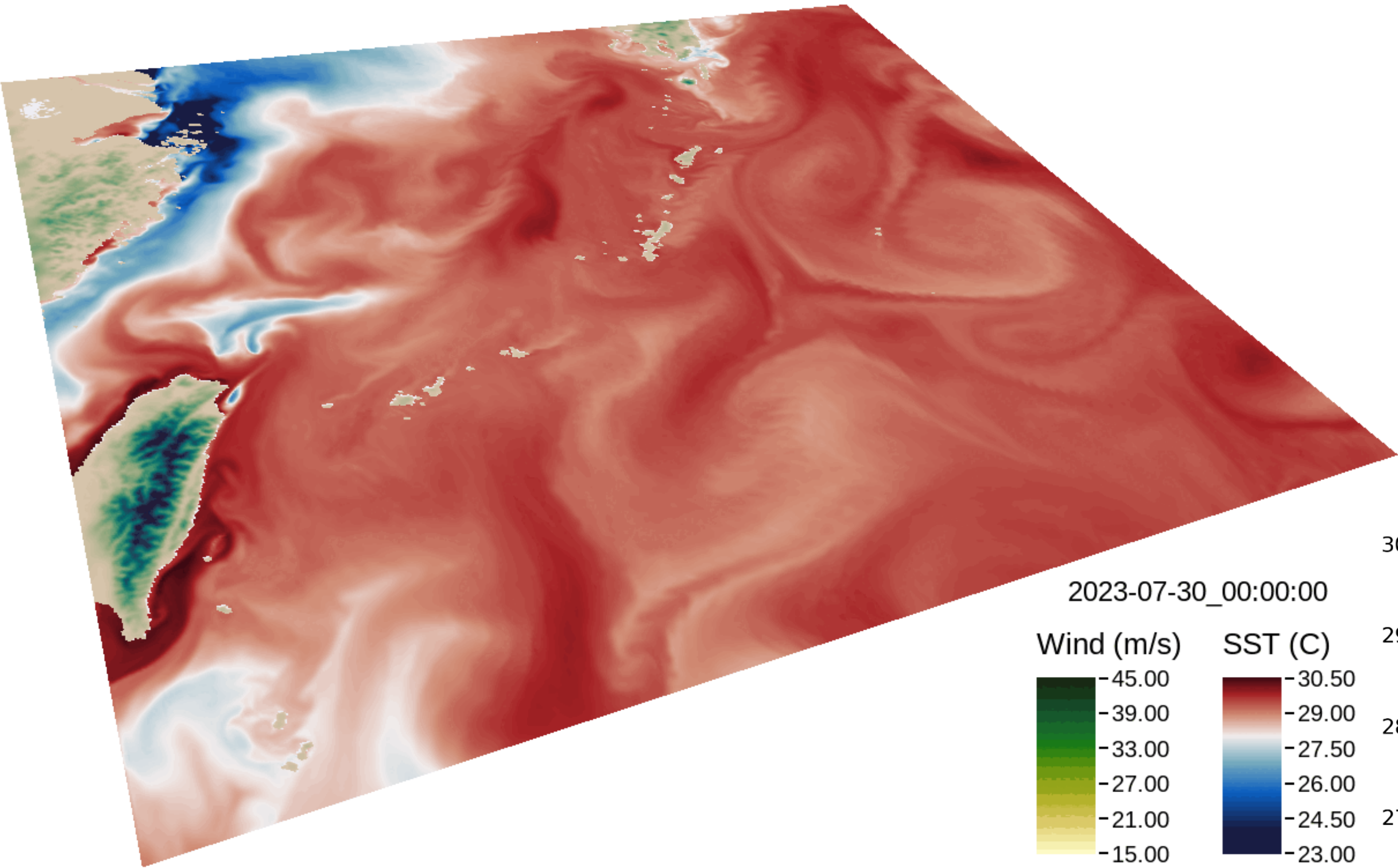


Bhirawa et al. (submitted)

Drag Coefficients, Wave Energies, and Air-Sea Momentum Exchanges



Typhoon Khanun (2023) Cold Wakes



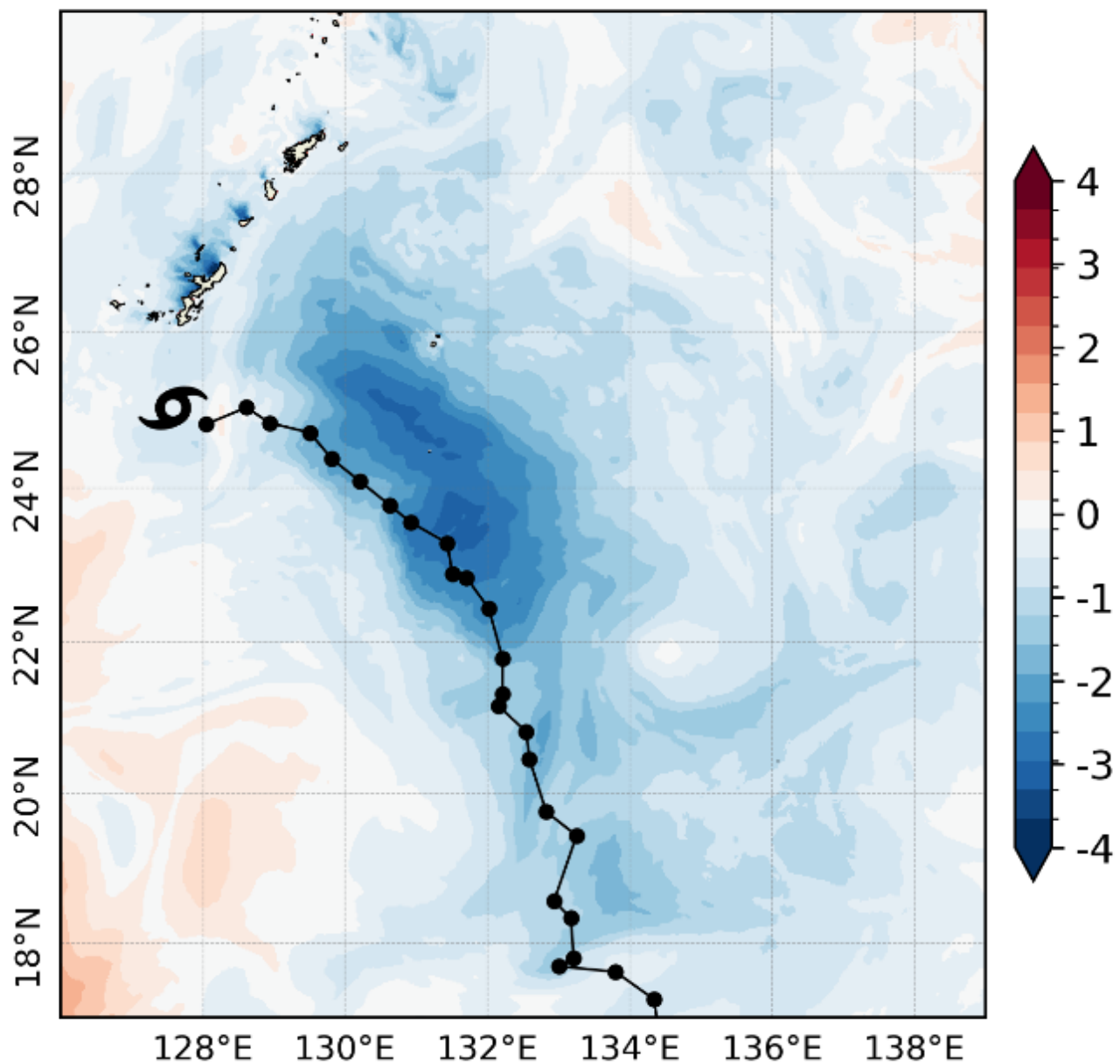
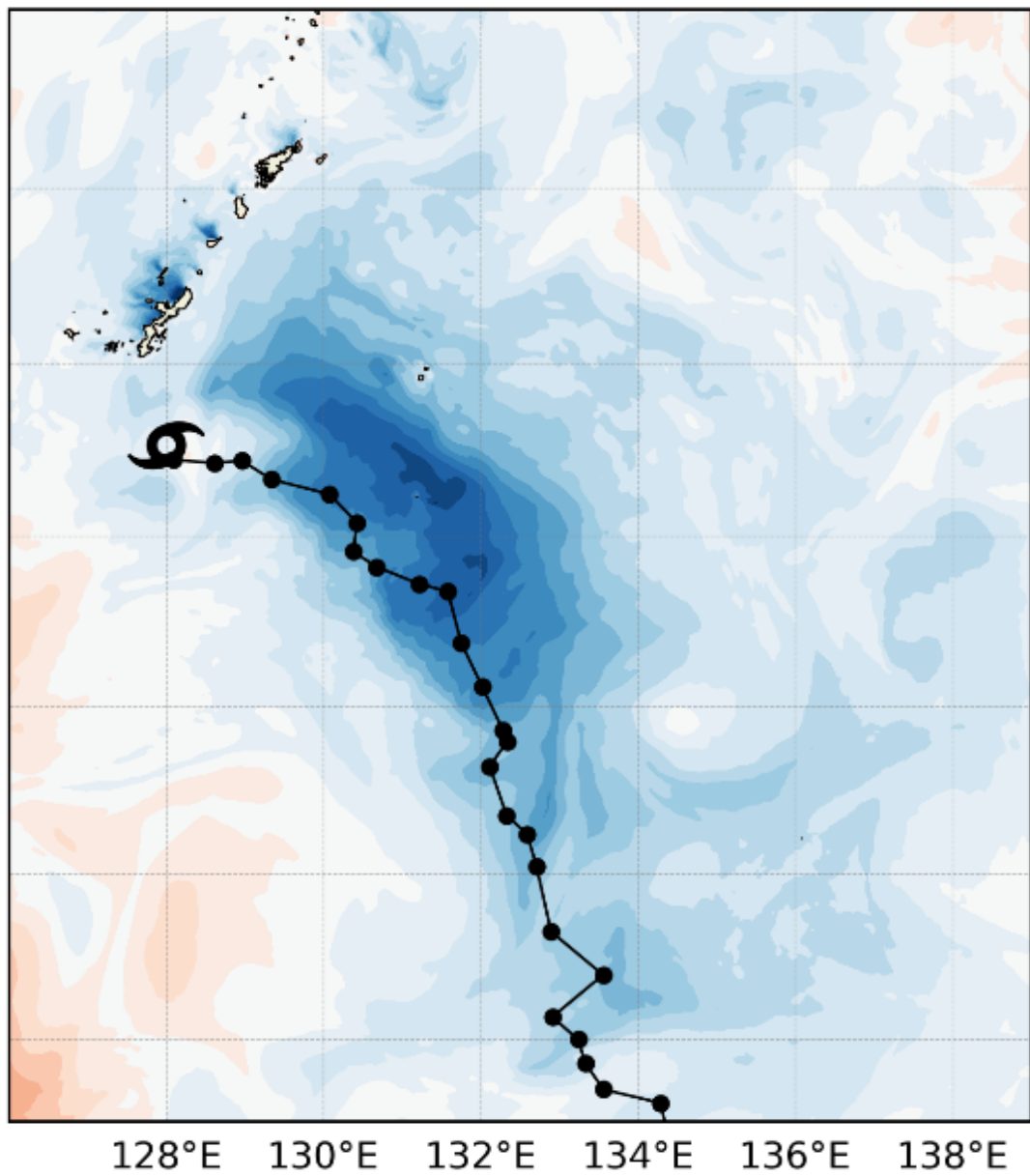
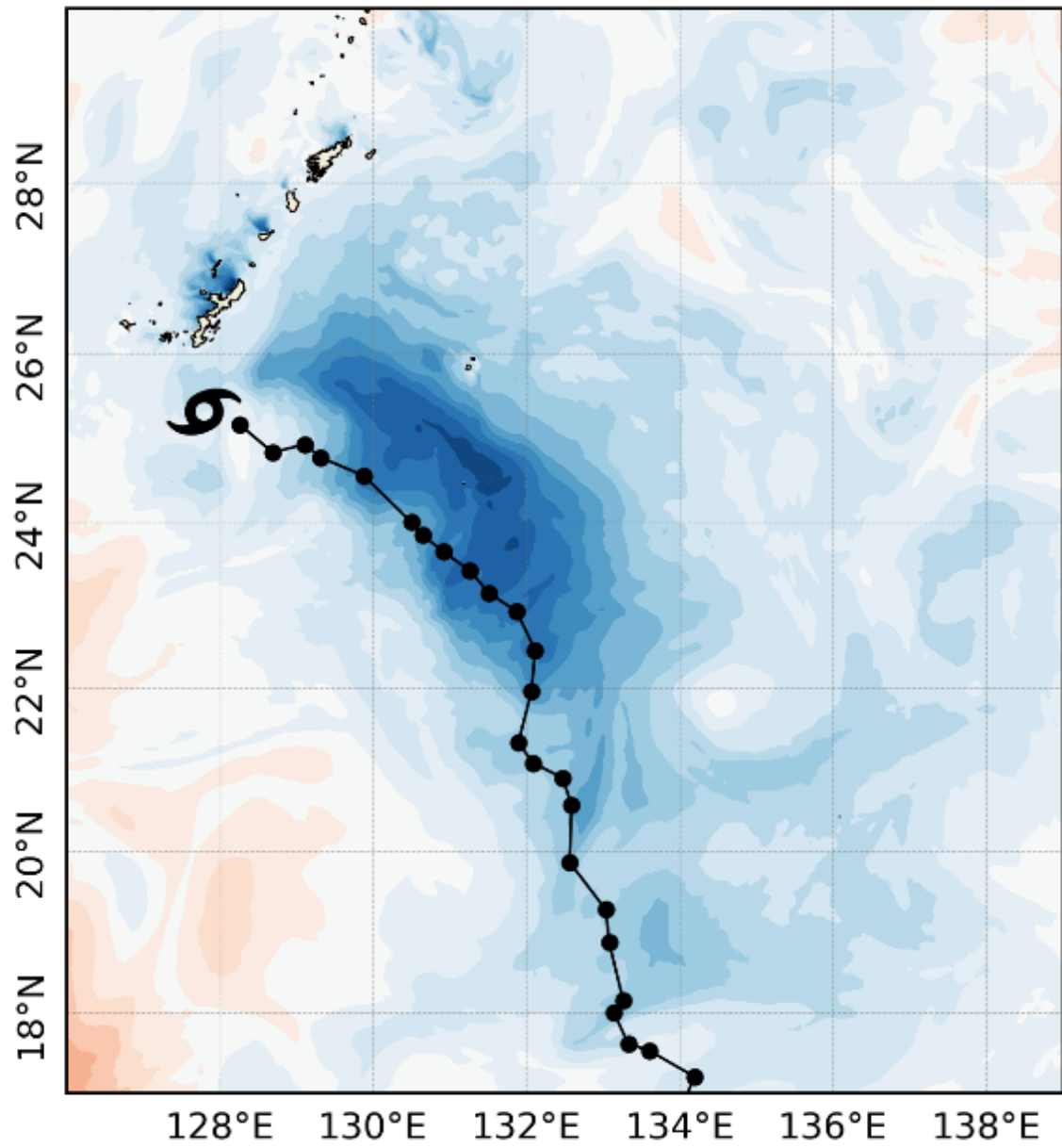
Typhoon Khanun (2023) Cold Wakes

COARE

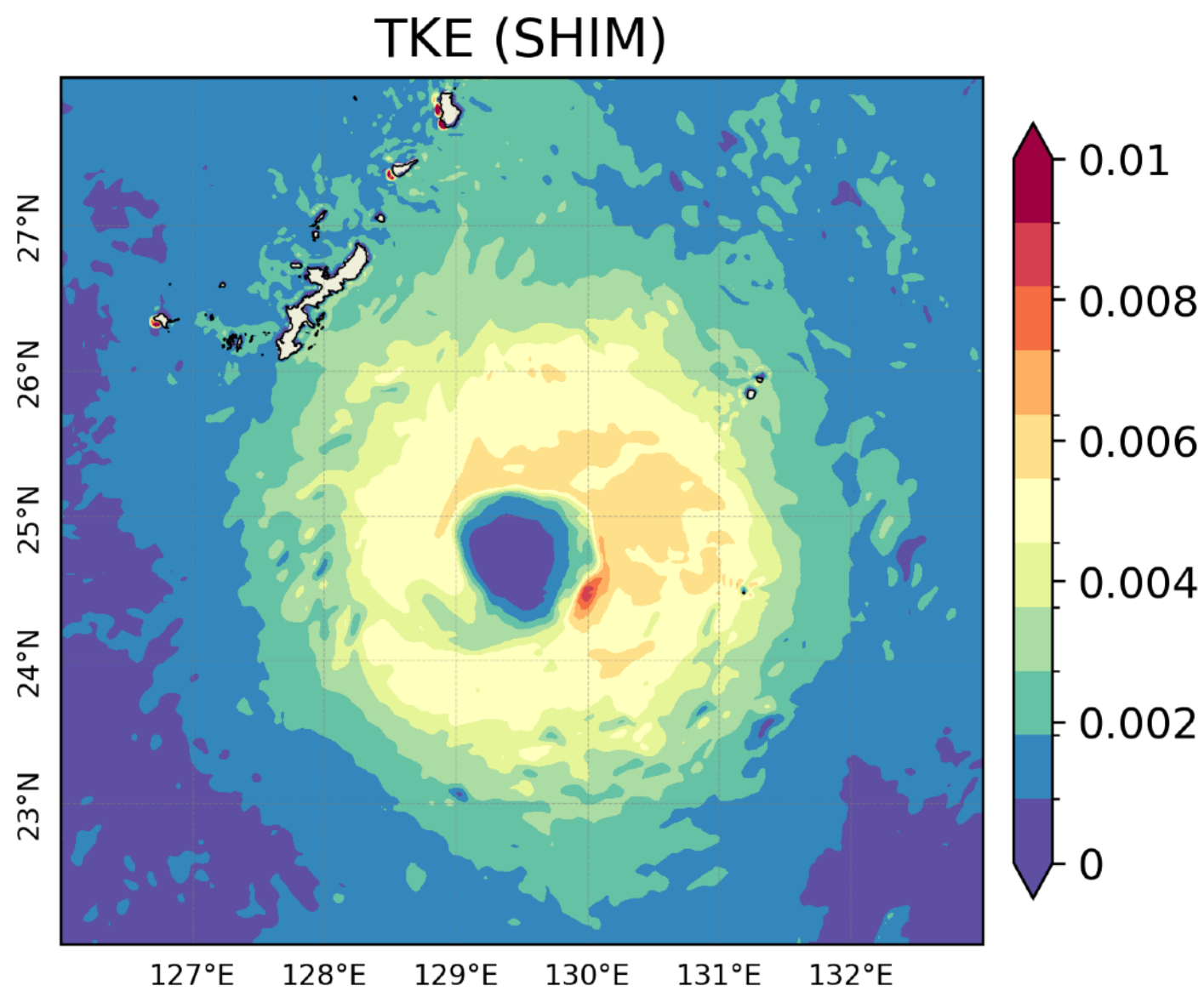
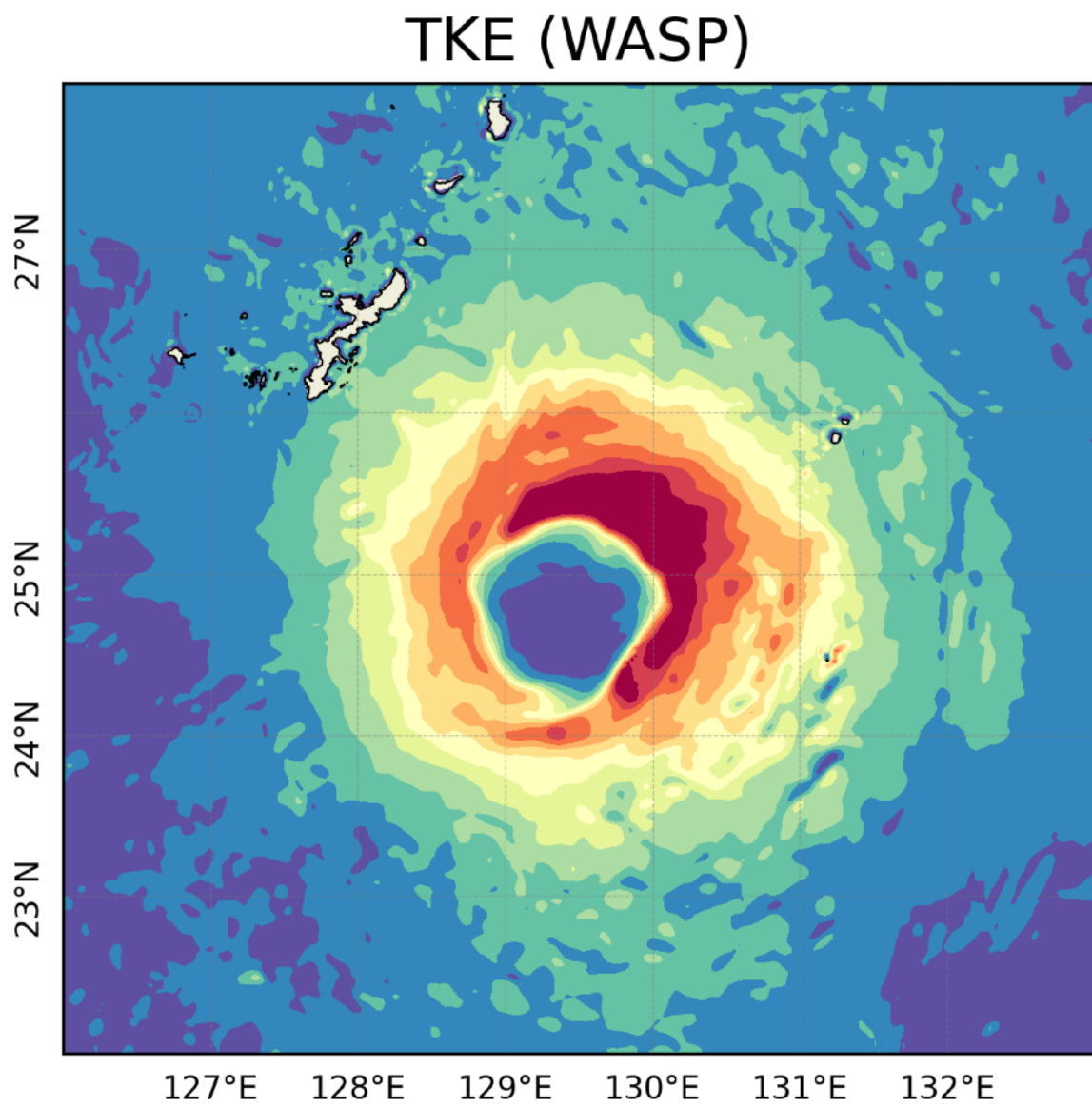
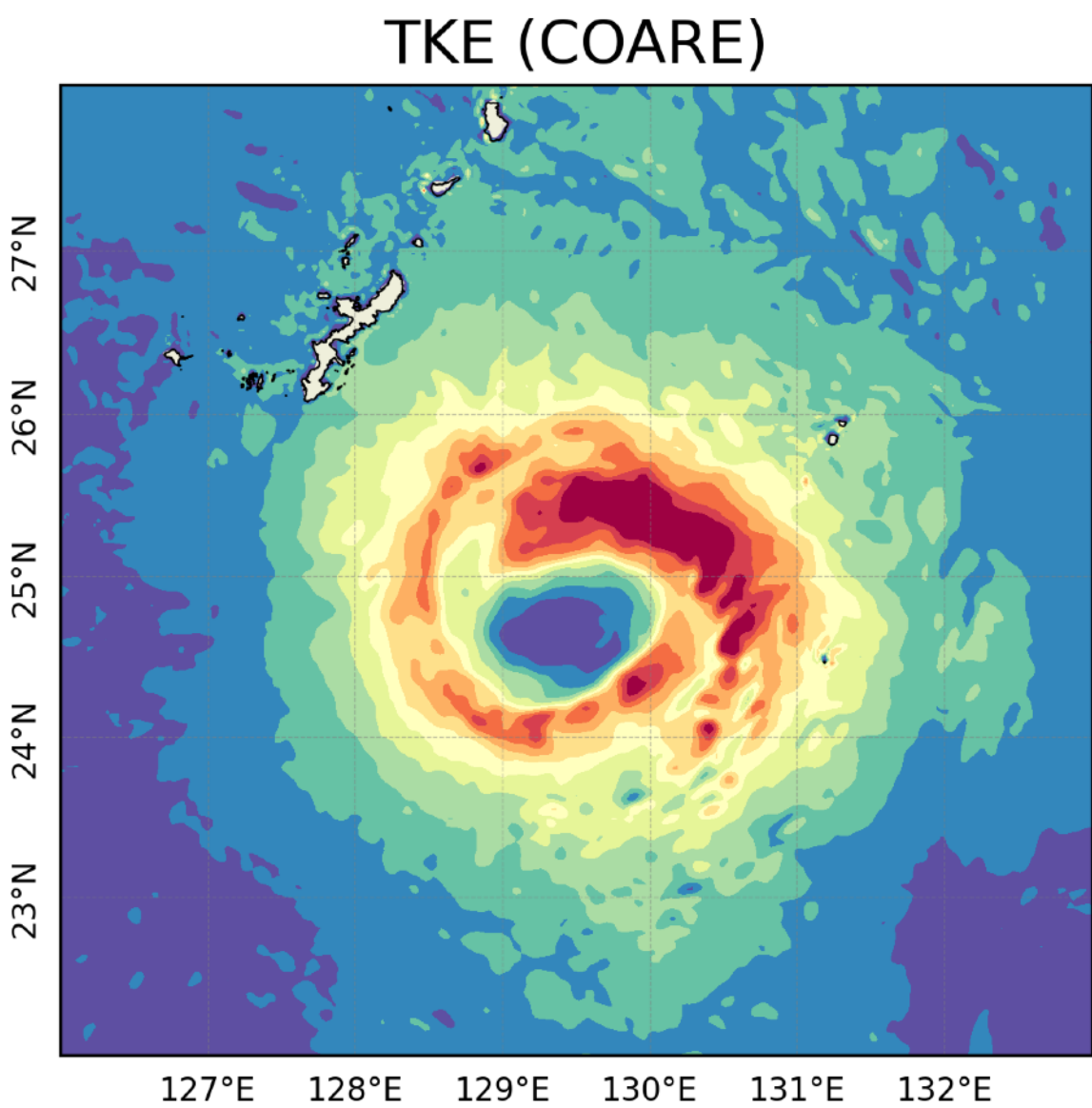
WASP

SHIM

ΔSST
(8/1/26 -
prestorm)

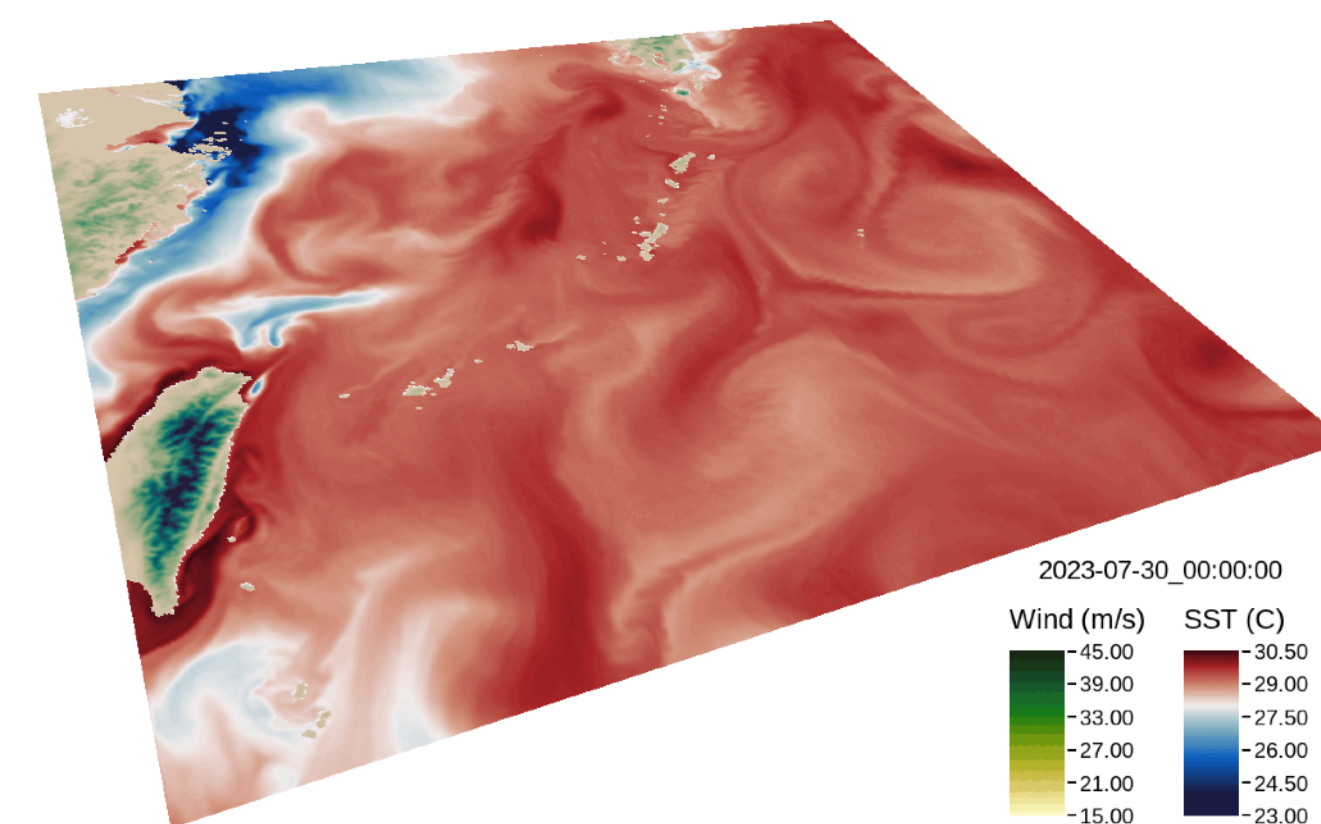
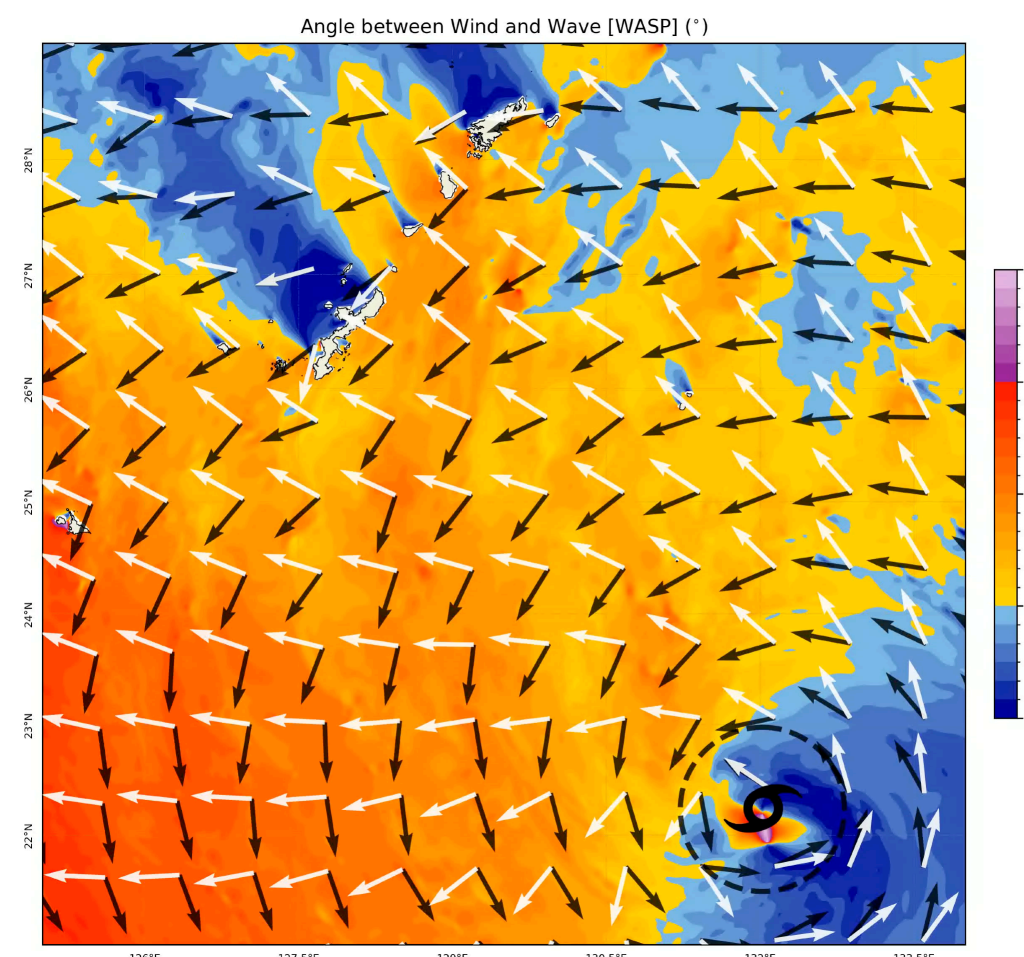
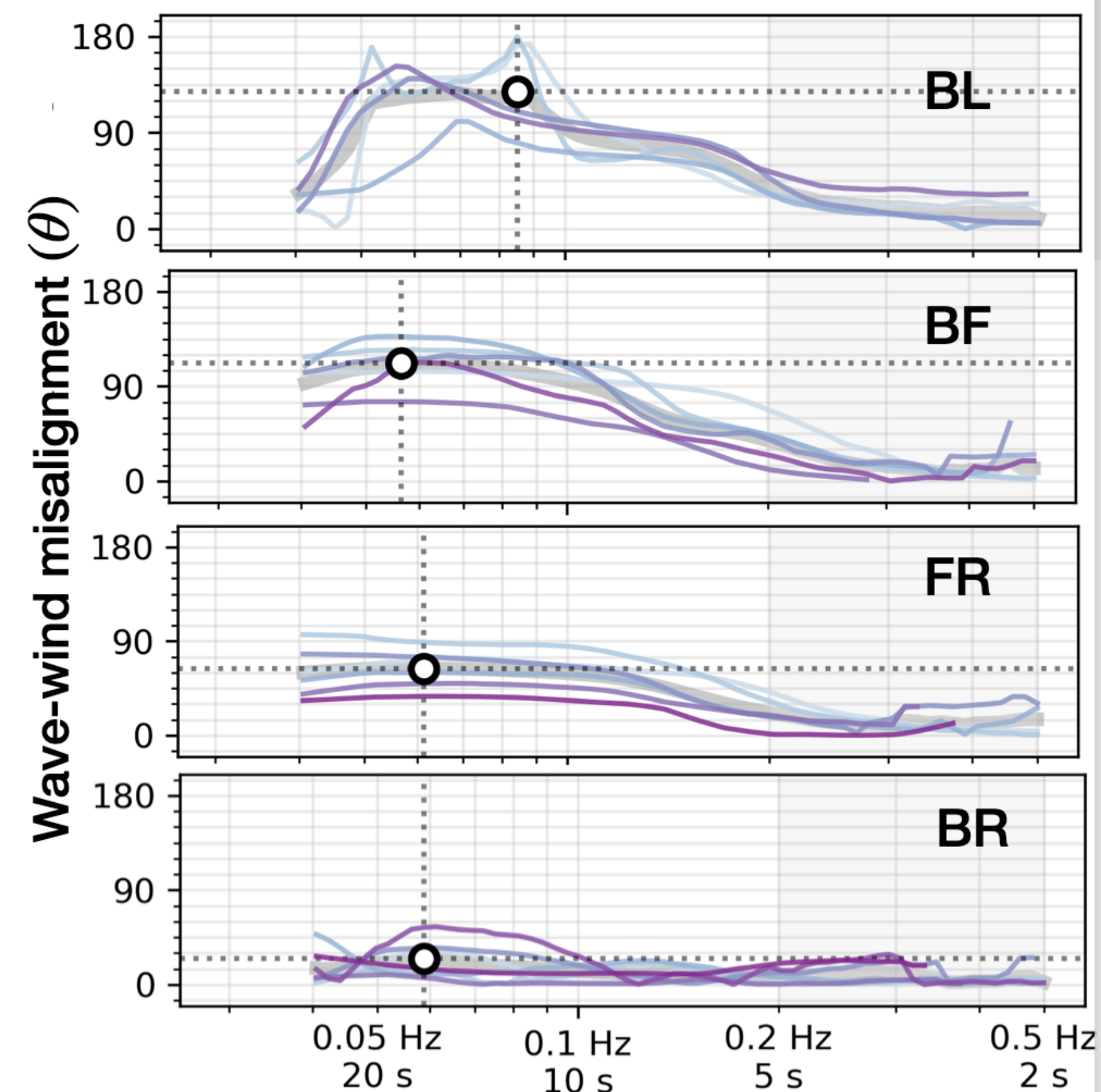


Near-surface
TKE



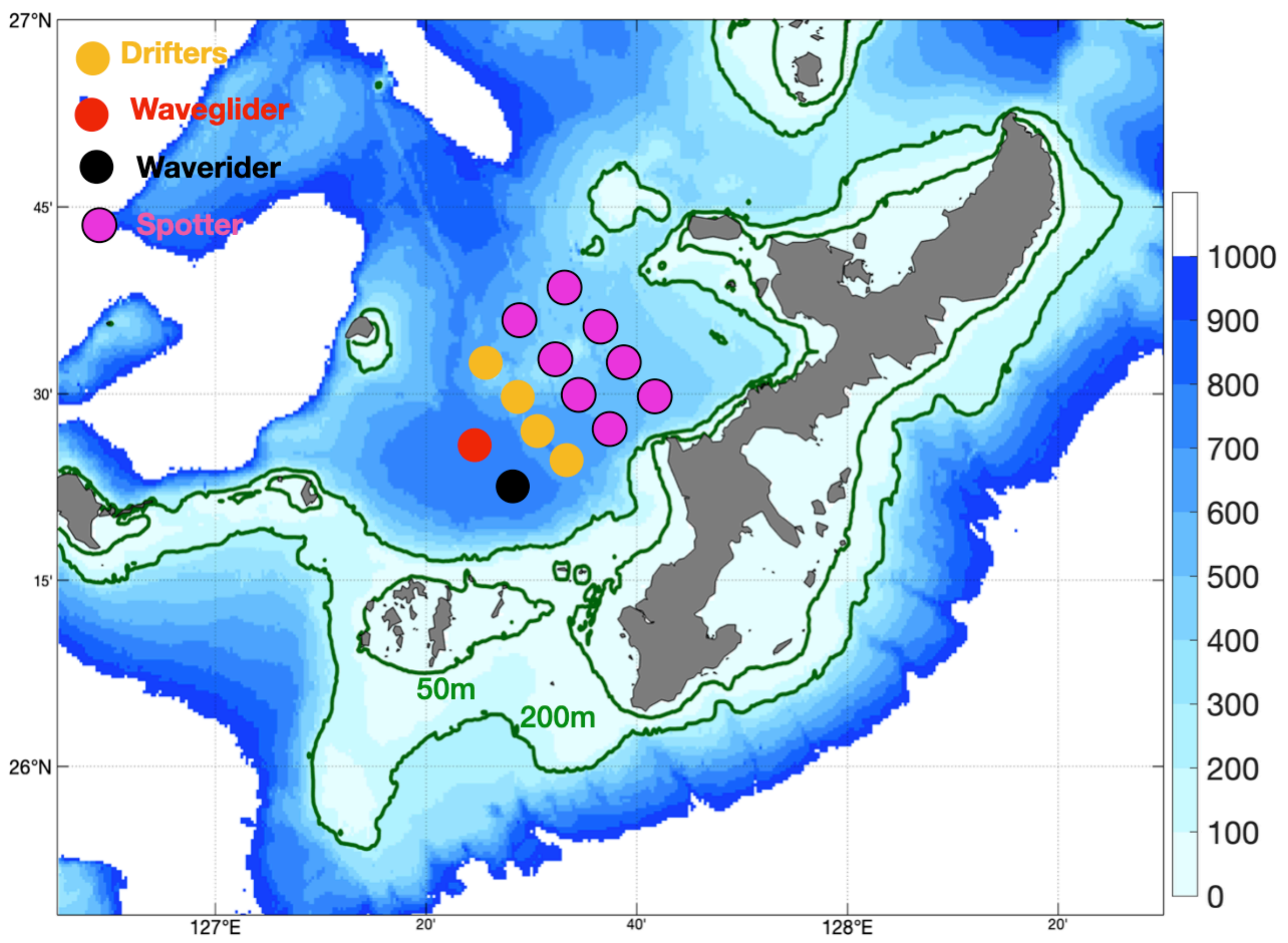
Conclusion

- Observed strong quadrant (and storm radius)-dependent spatial variability in MSS, wind-wave misalignment, and drag coefficient.
- The observationally constrained formulation for z_0 of Shimura et al. (2024) produces the best agreement, with pronounced quadrant-dependent reductions in C_D and MSS.
- The choice of the z_0 formulation in high winds has a substantial impact on storm intensity.
- In this study, Lower z_0/C_D leads to
→ higher winds, weaker cold wake, weakly increased enthalpy fluxes (despite reduced C_K).



Planned Observations : August 2026

Collaboration: UHM & OIST +SIO & WHOI



1x UH
PacIOOS
wave buoy



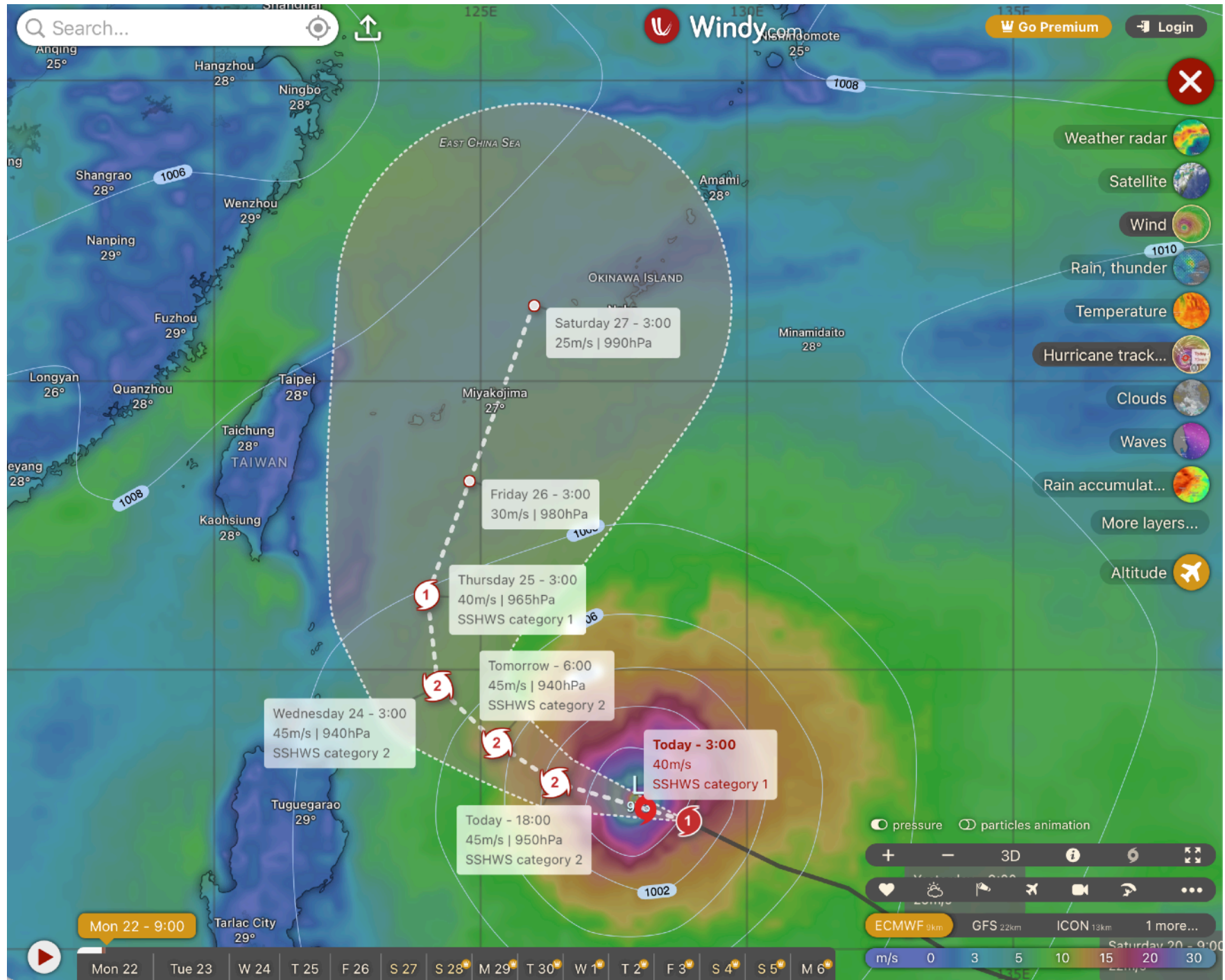
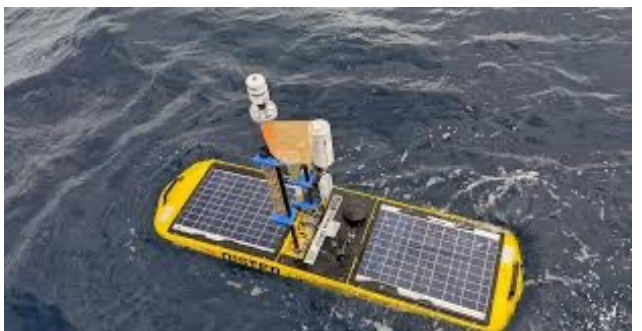
9x OIST
2x Kyoto U
4x UH



x20
CODE
Drifters



1x (SIO-
OIST)



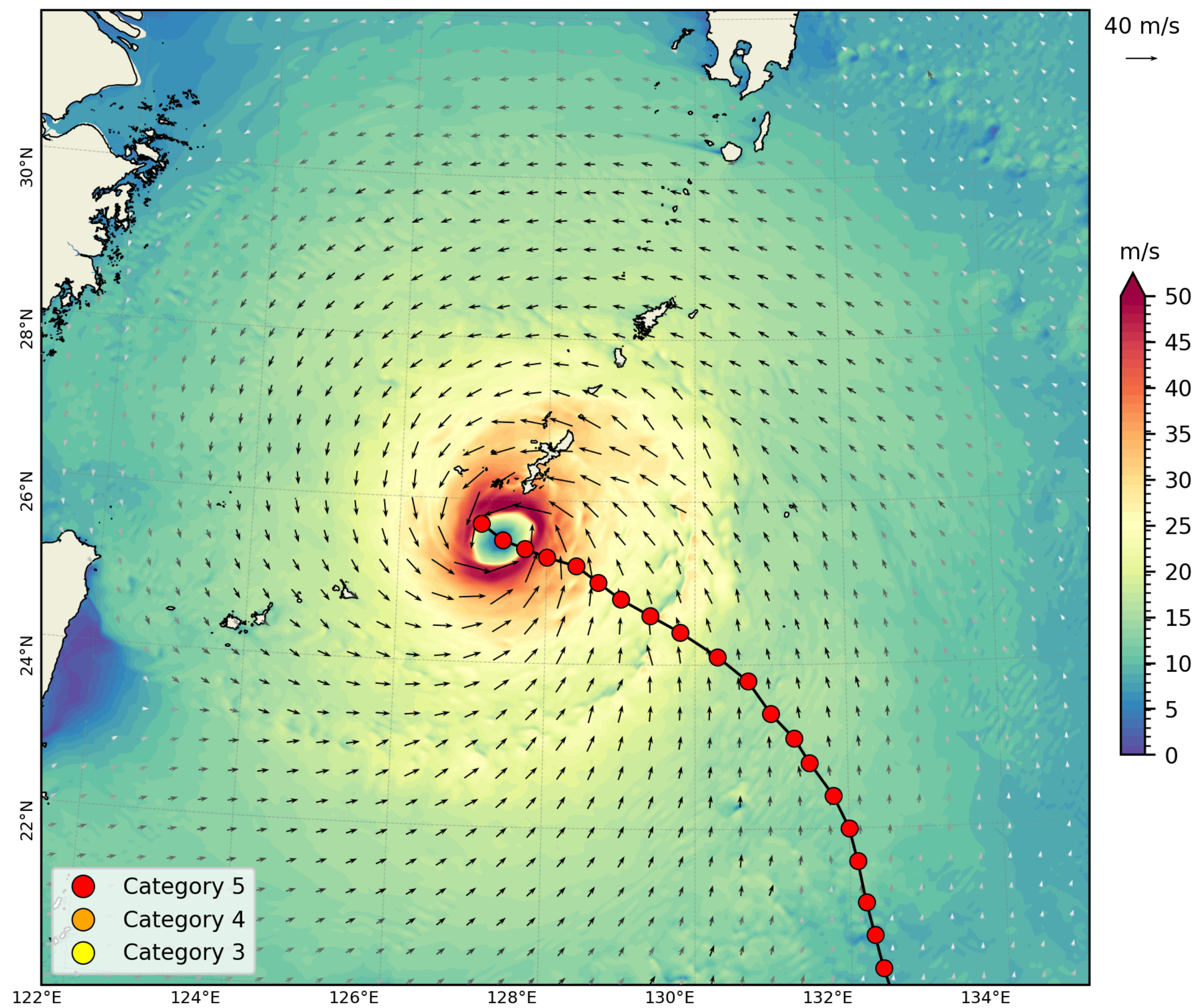
Typhoon Mekkhal

Typhoon Khanun (2023): Simulation

U10

Hs

Simulated wind speed on August 01 2023, 18:00 UTC



Simulated Significant Wave Height on August 01 2023, 18:00 UTC

