Impacts of surface waves on air-sea flux and marine boundary layer processes

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UNIVERSITY of HAWAI'I MĀNOA | WOODS HOLE OCEANOGRAPHIC INSTITUTION | NSF | NOAA | NASA

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Processes influencing momentum flux in bulk formula

$$\boldsymbol{\tau} = \rho_a C_D (W - U)^2$$

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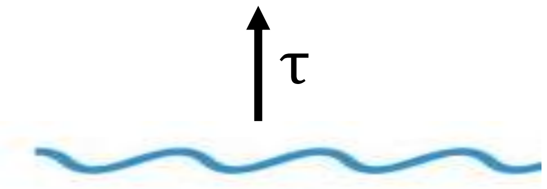
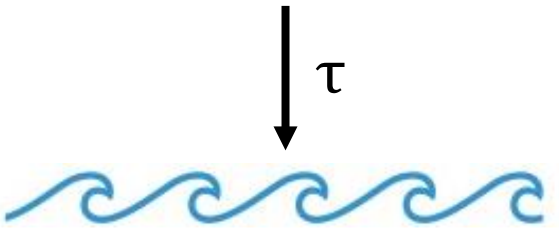
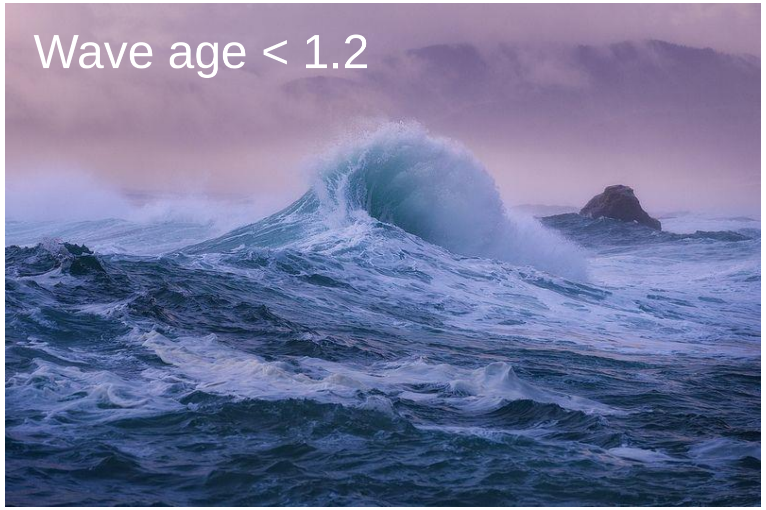


swell



wind-waves

Wave age can be defined as $\mathbf{c_p/W}$
-phase speed of the waves (c_p)



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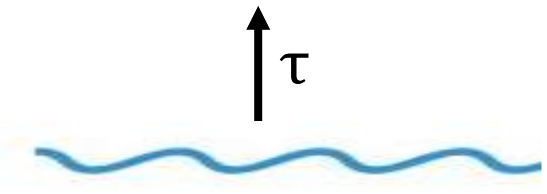

swell

The air-sea momentum flux is supported largely by short wind-waves.

(i.e. Janssen, 1989; Moon et al., 2004 …)

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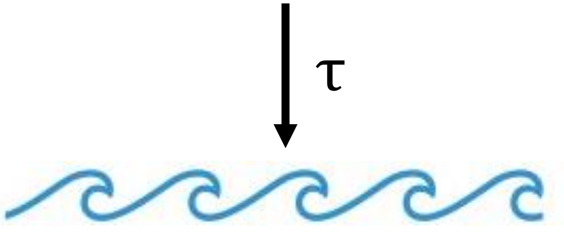
-phase speed of the waves (c_p)



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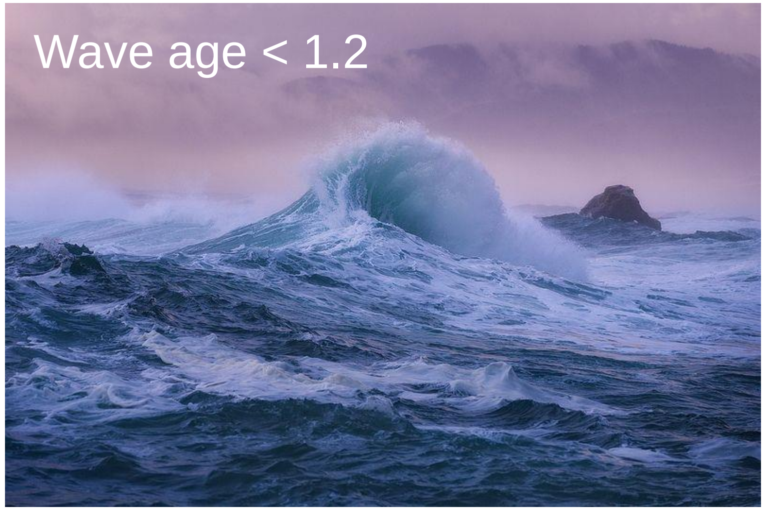
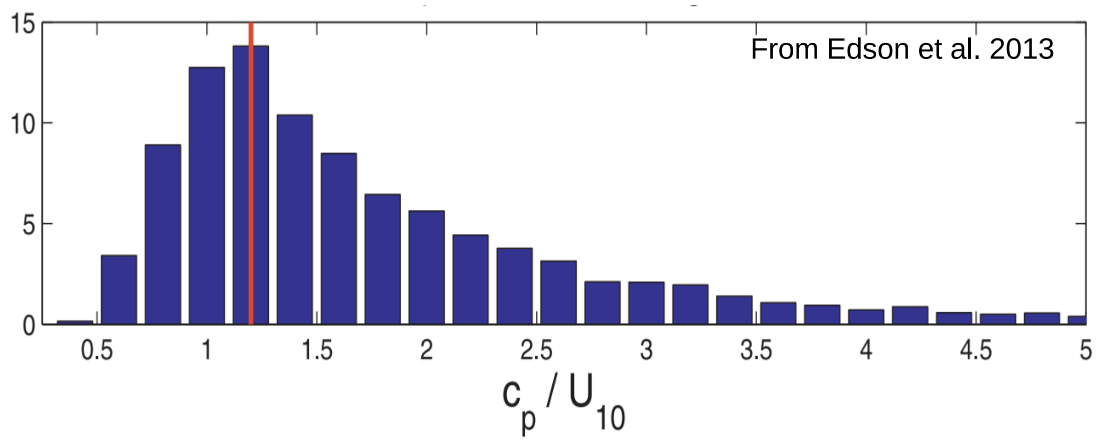


Wave – Wind interaction parameterization

Wave-based formulations exist in many bulk flux algorithms that model z0 as a function of wave age or wave age/slope (e.g,. Taylor & Yelland, 2001; Oost et al., 2002; **Edson et al., 2013**)

→ COARE3.5 (Fairall et al. 1996, 2003; Edson et al. 2013)

Developed and tuned primarily by using the wave data collected from the extratropics



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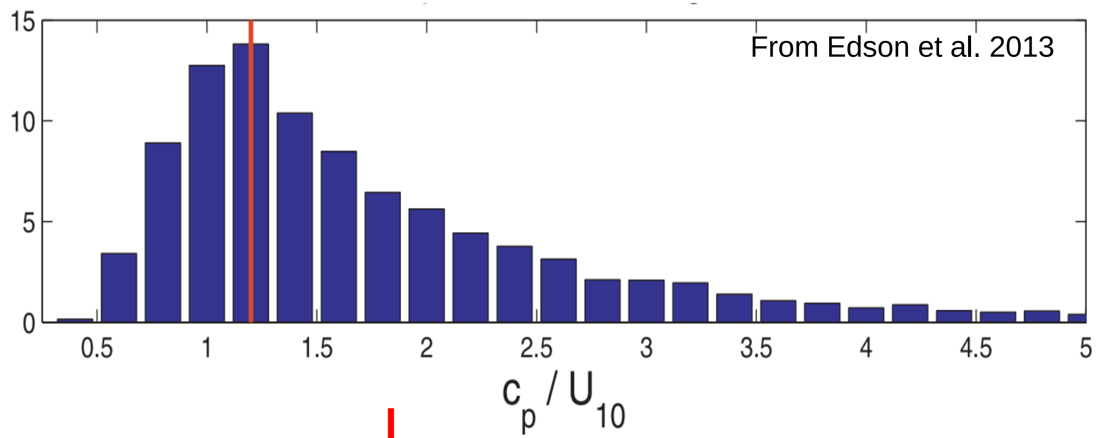
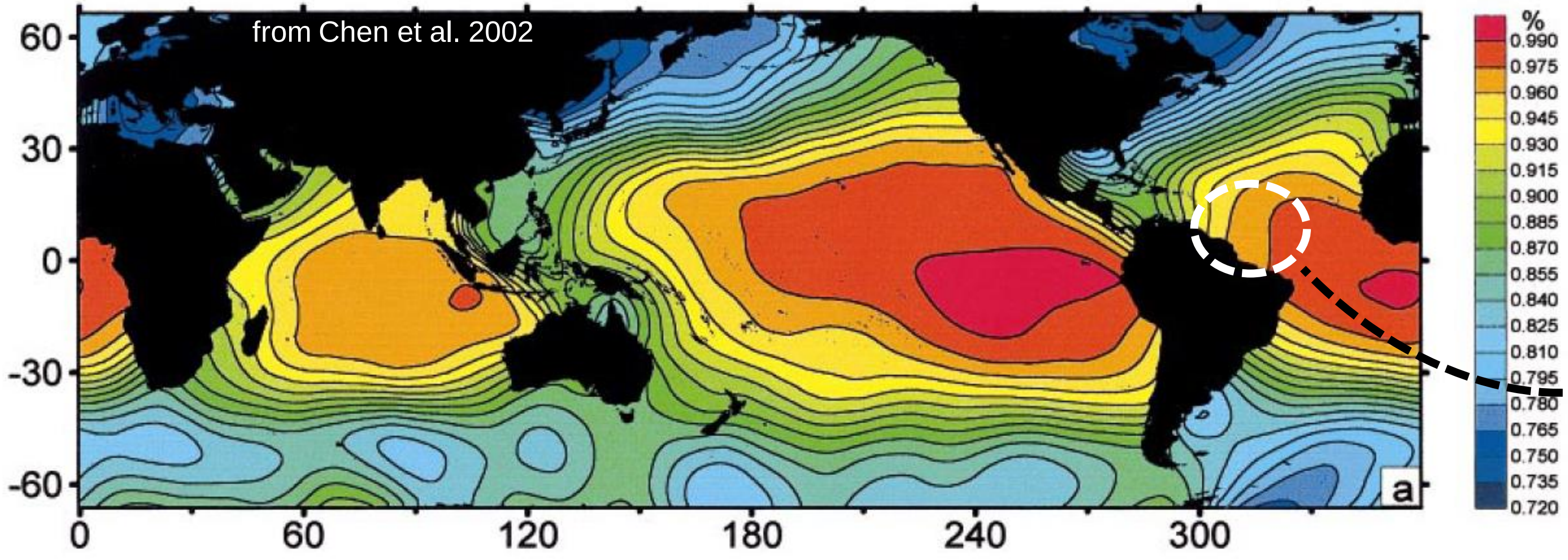
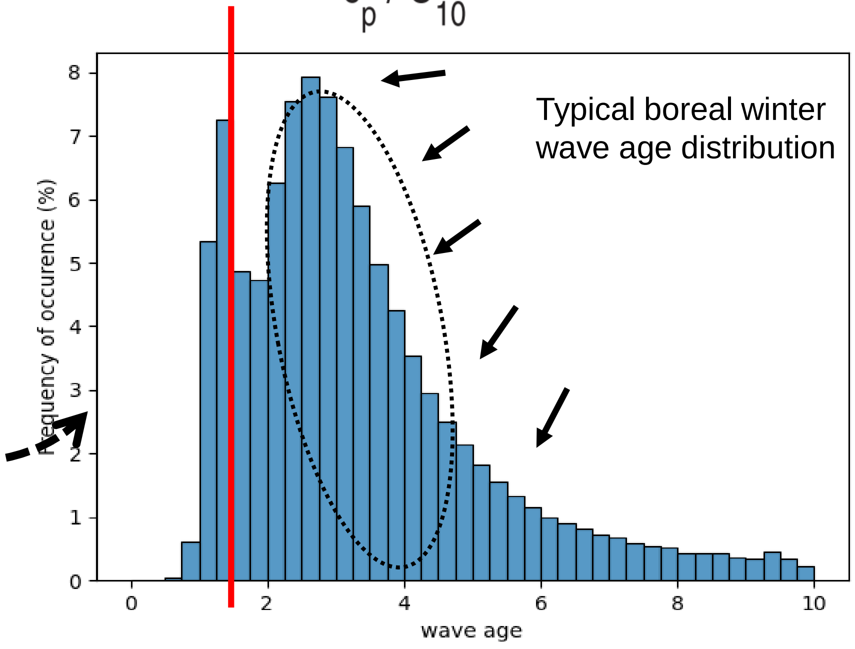


Global swell probability





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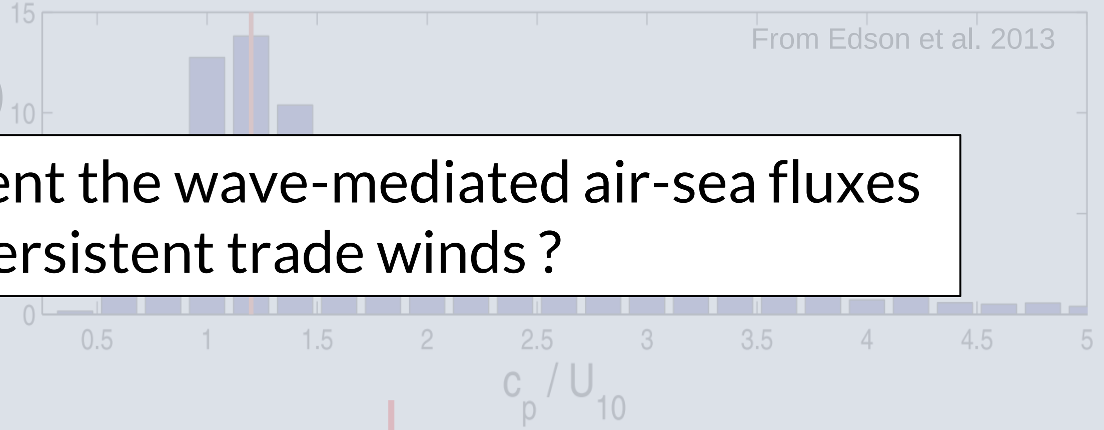
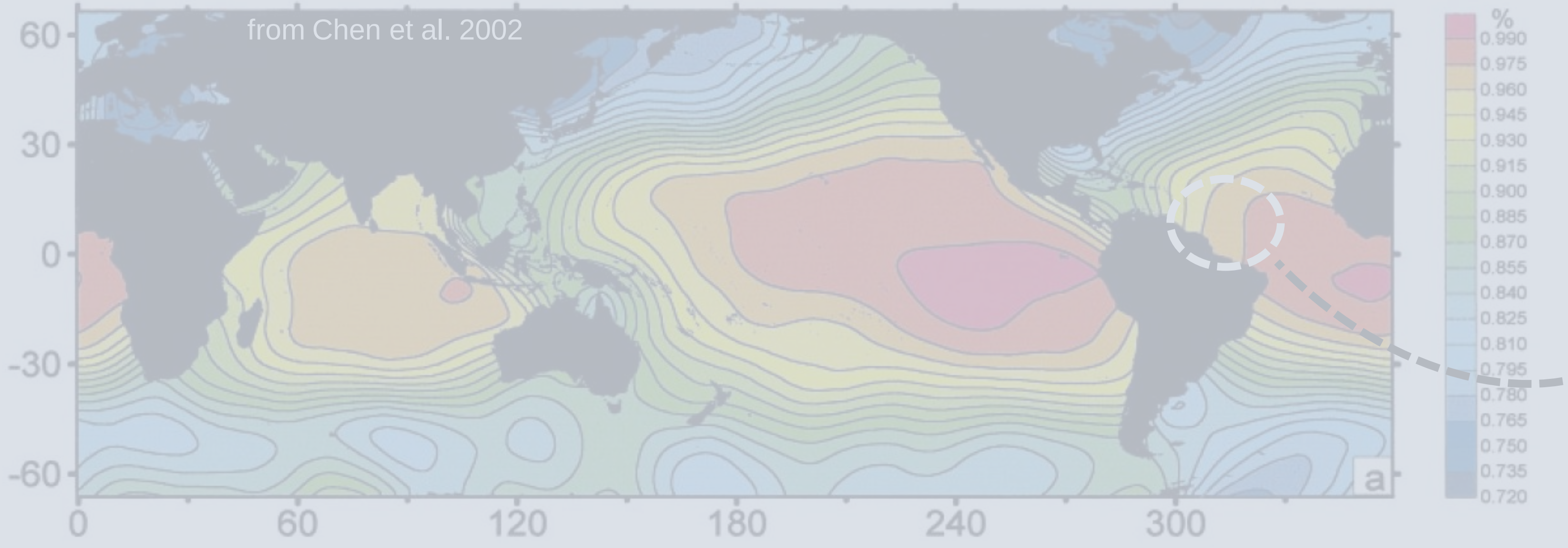
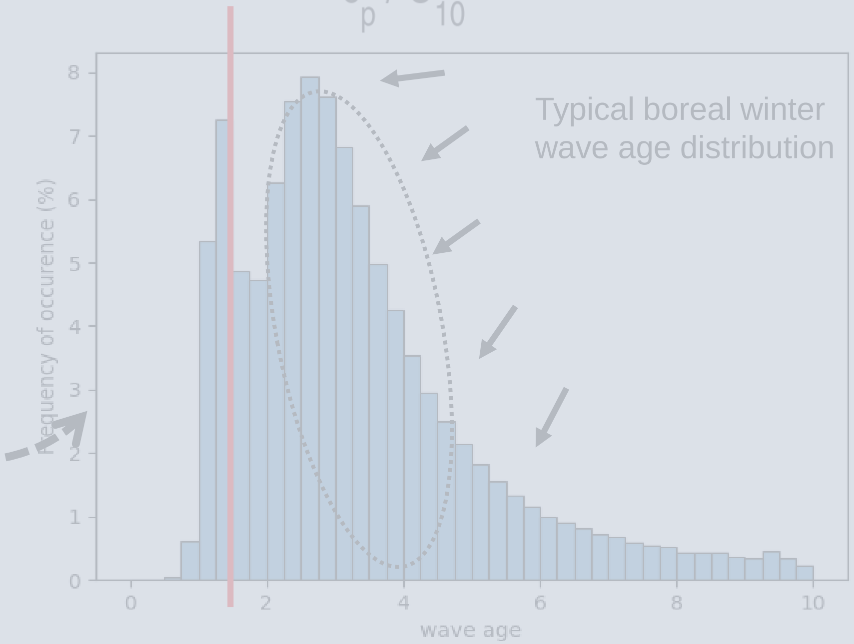


How well do COARE3.5 and coupled model represent the wave-mediated air-sea fluxes in the presence of strong swell and persistent trade winds ?

Global swell probability





Momentum flux in COARE3.5

$$\tau = \rho_a C_D \Delta U^2$$

Ocean roughness length (z0) parameterization in COARE3.5 (Edson et al. 2013)

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

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

1. Wind Speed Dependent Formulation (WSDF)
with wind speed only

$$z_0^{\mathrm{rough}} = \alpha \frac{u_*^2}{g} \qquad \alpha = f_1(U_{10N})$$

Charnock coefficient

- Wind-wave equilibrium: Wind seas under high wind and swell under low wind.
- Waves aligned with winds (θ=0)
- Still, it generally works well under most conditions.

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2. Wave-Based Formulation (WBF)

with wave age and wave slope

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

inverse wave age

significant wave height

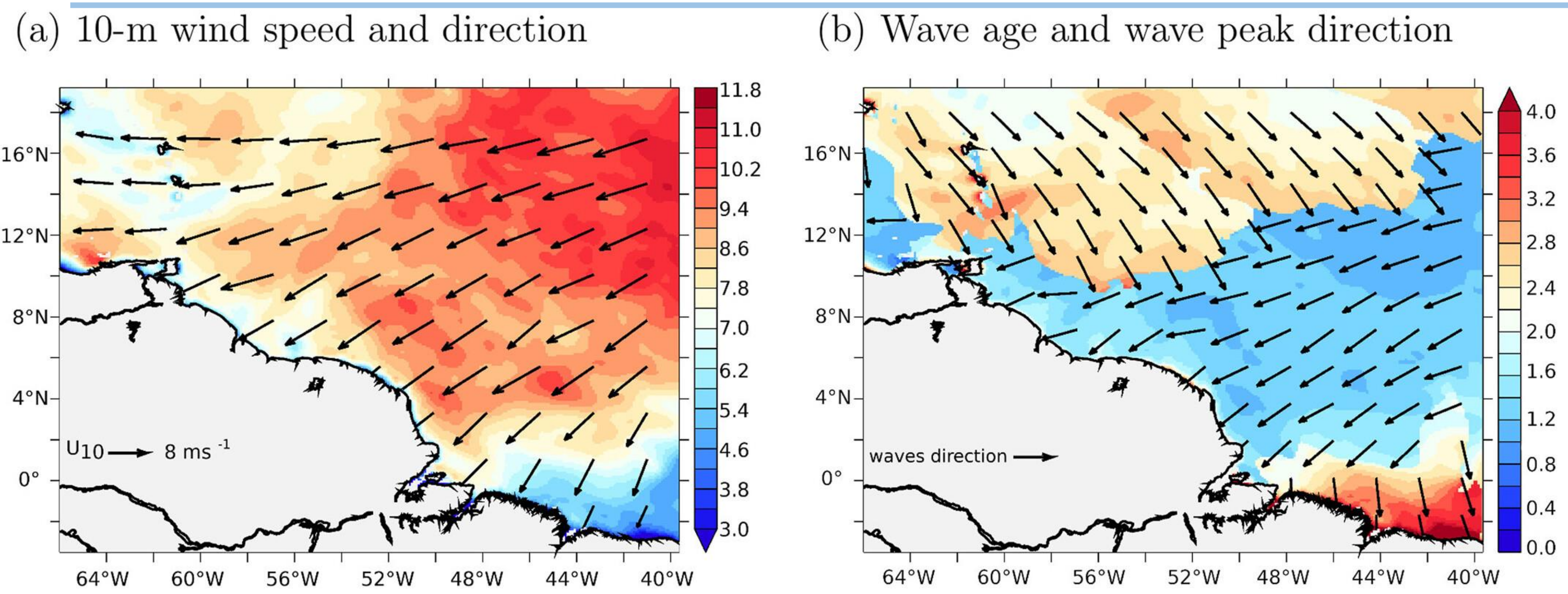
"peak" wave speed $C_p = g*(T_p/2\pi)$

T_p: wave period at the spectral peak

- Waves aligned with winds (θ=0)

Study case: January 8, 2020

Wind speed based formulation (**WSDF**)
Wave based formulation (**WBF**)



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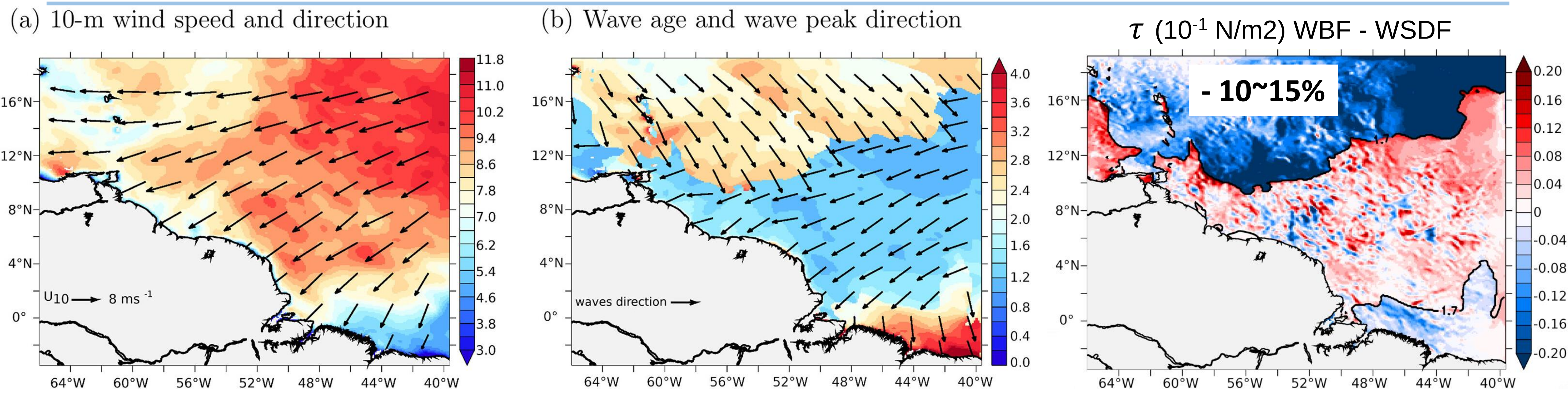

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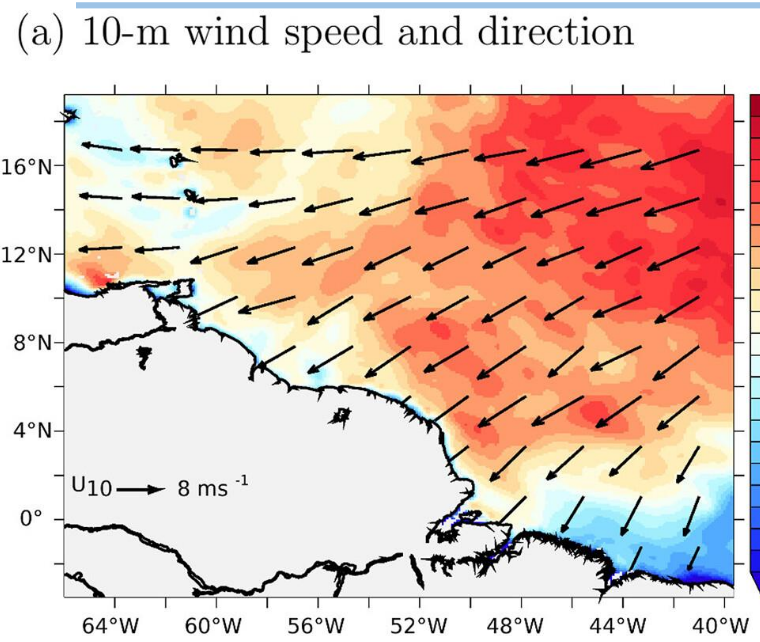
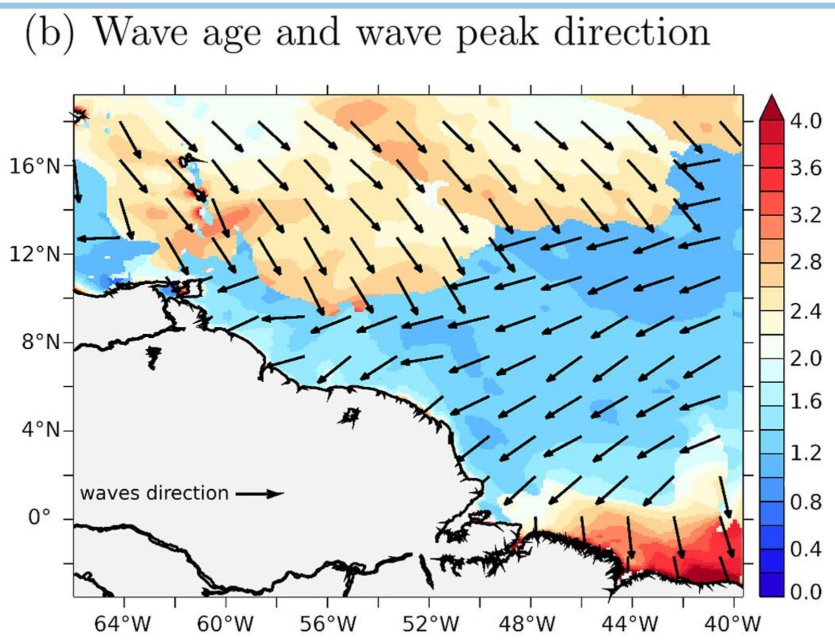
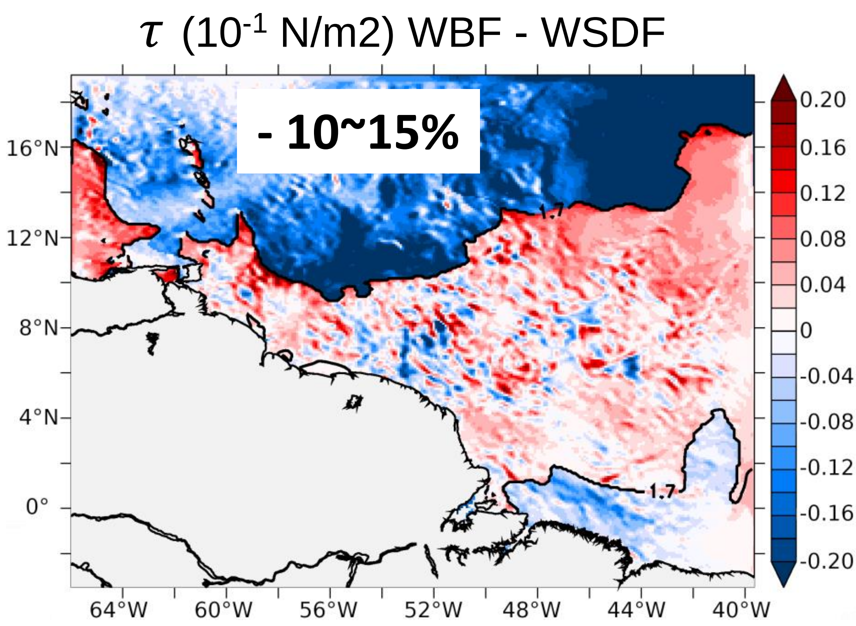
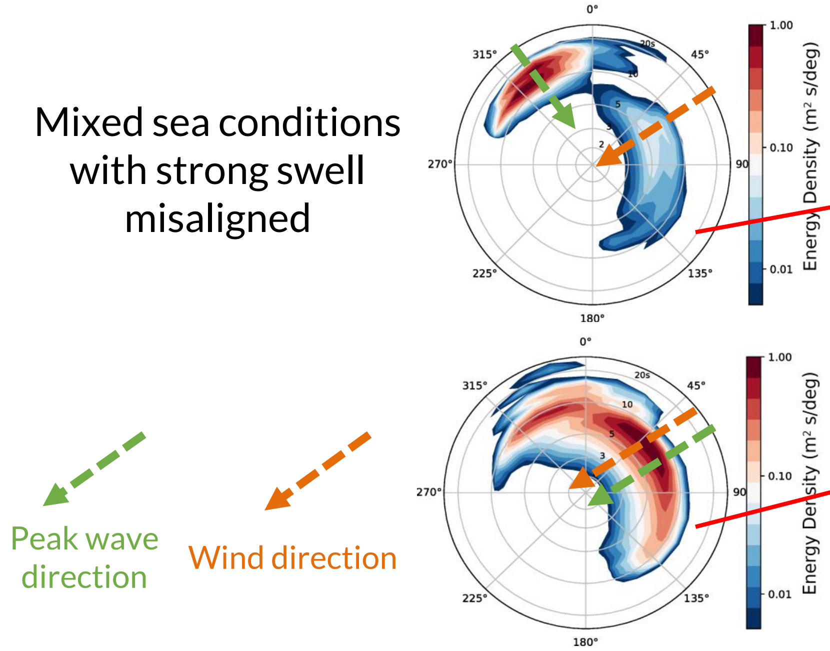
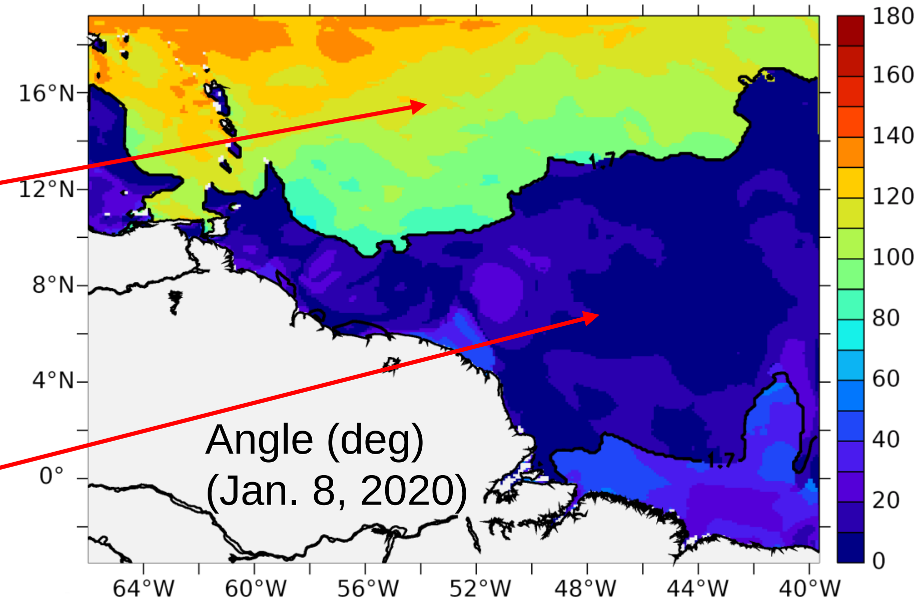






Mixed sea conditions with strong swell misaligned





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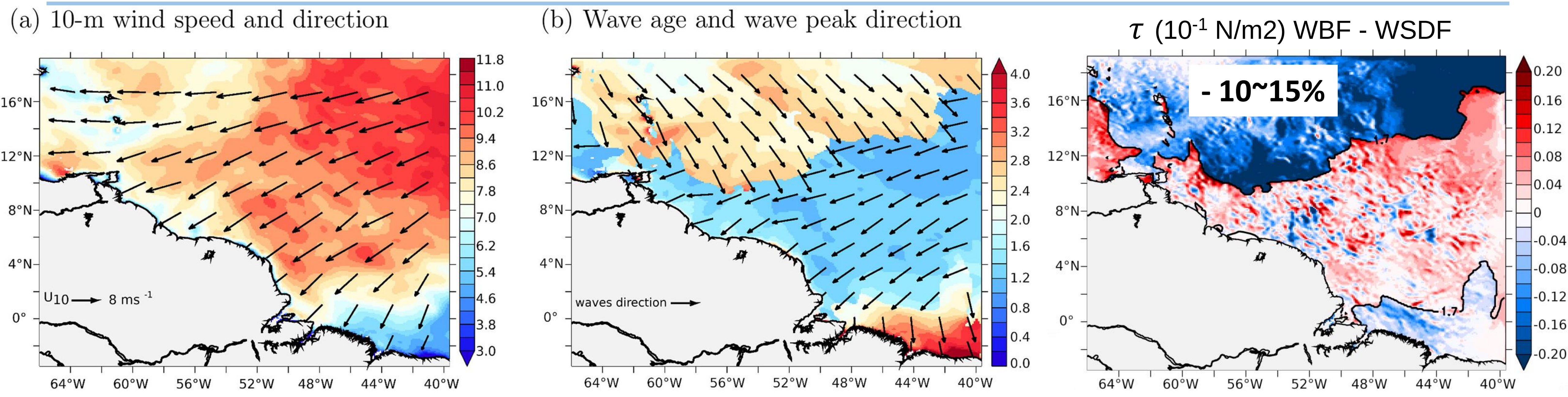
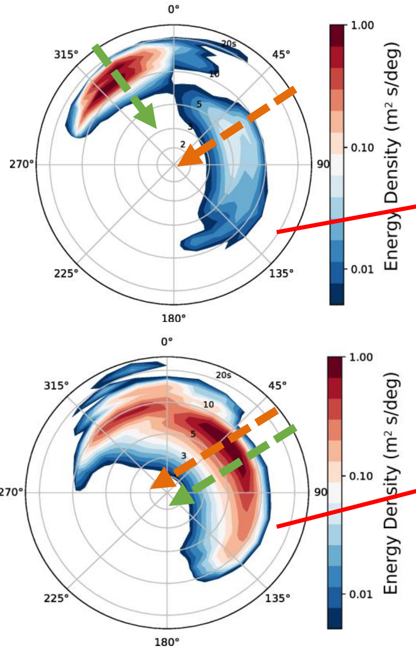
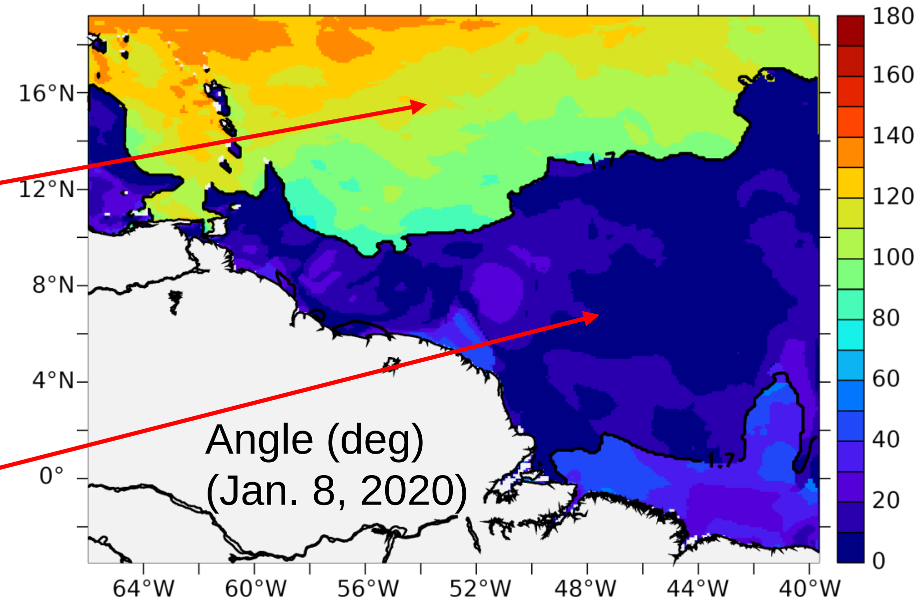


Mixed sea conditions with strong swell misaligned





Wave based formulation tend to <u>significantly</u> underestimate the surface stress by ~10% ~15% in case of misaligned waves.

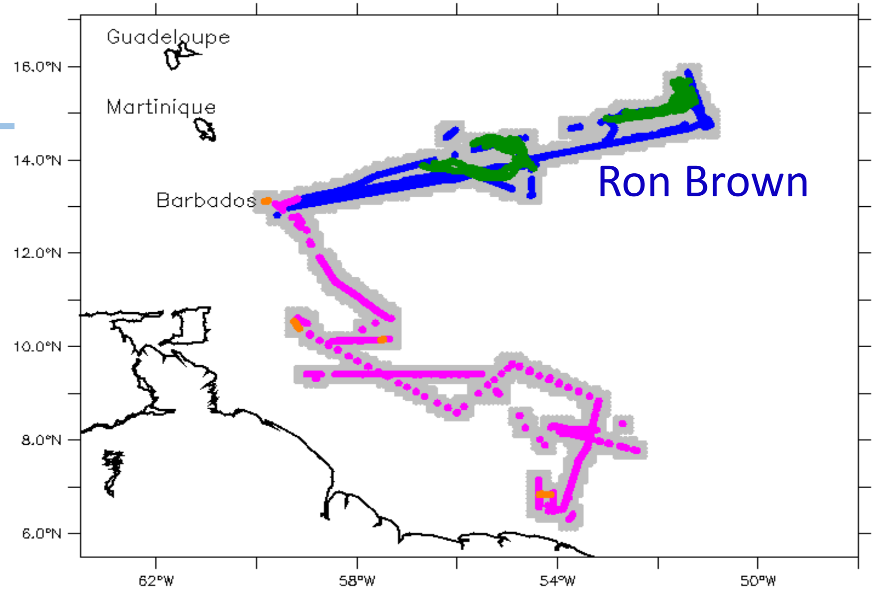
Consistent with Raj et al. 2025 which found an underestimated stress by ~12% under counter-swell conditions in the Bay of Bengal.

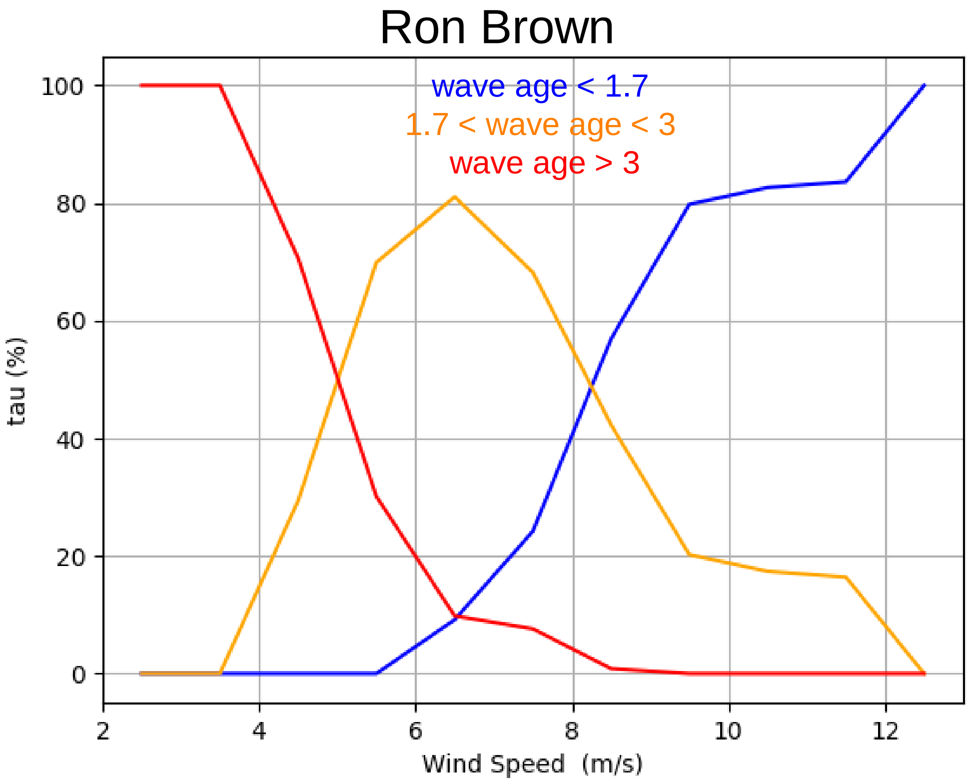
Momentum flux measurements

- Under weak wind, up to ~5 m/s, the stress is dominated by swell

- Between winds ~5 to ~8 m/s the stress is dominated by mixed sea

- At higher wind, above ~9 m/s stress is dominated by the wind sea/equilibrium sea





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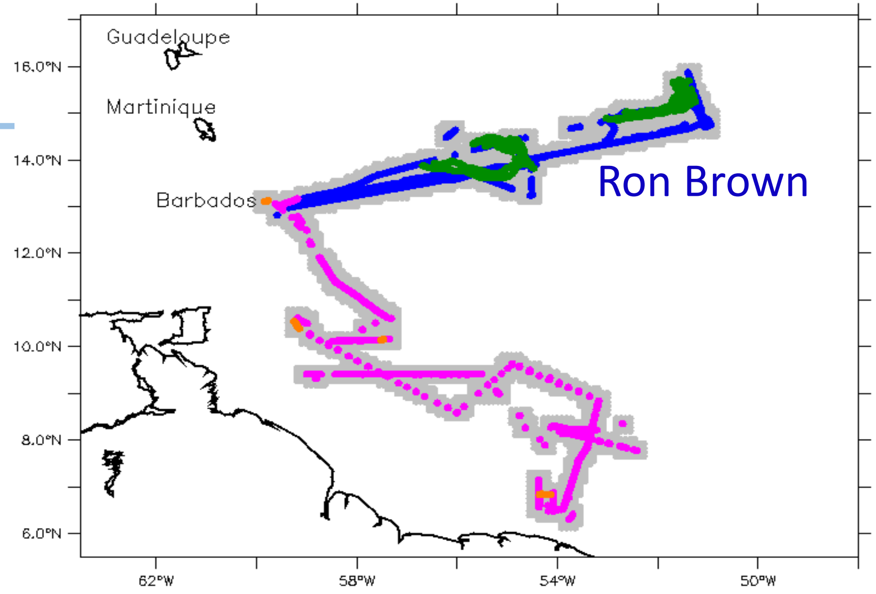

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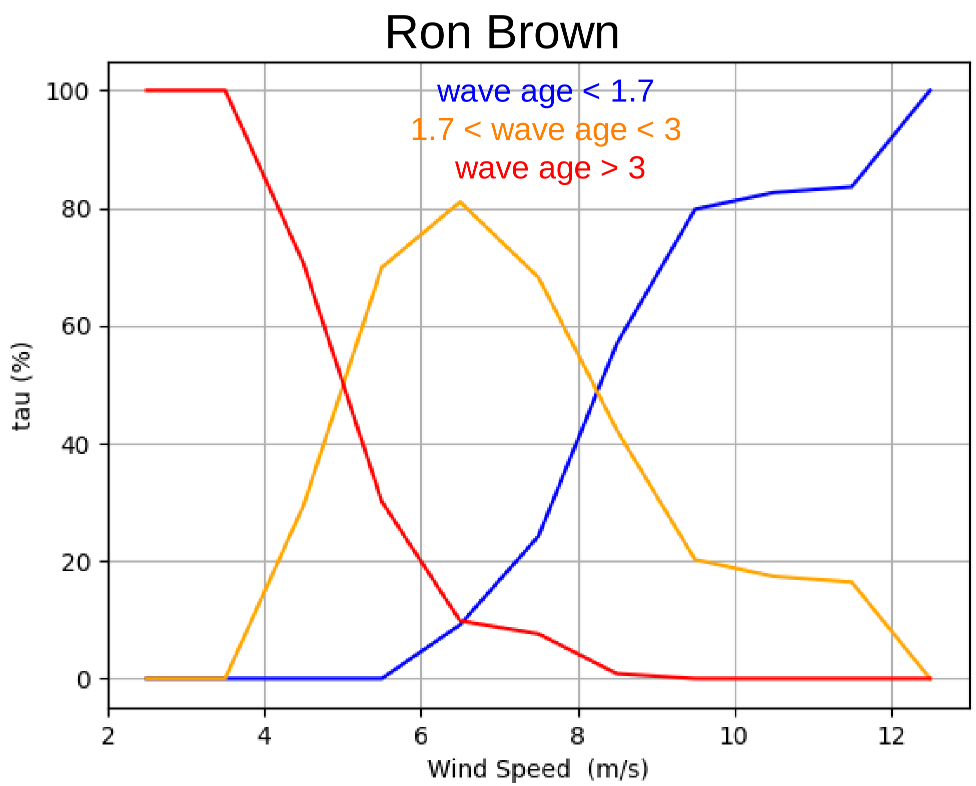

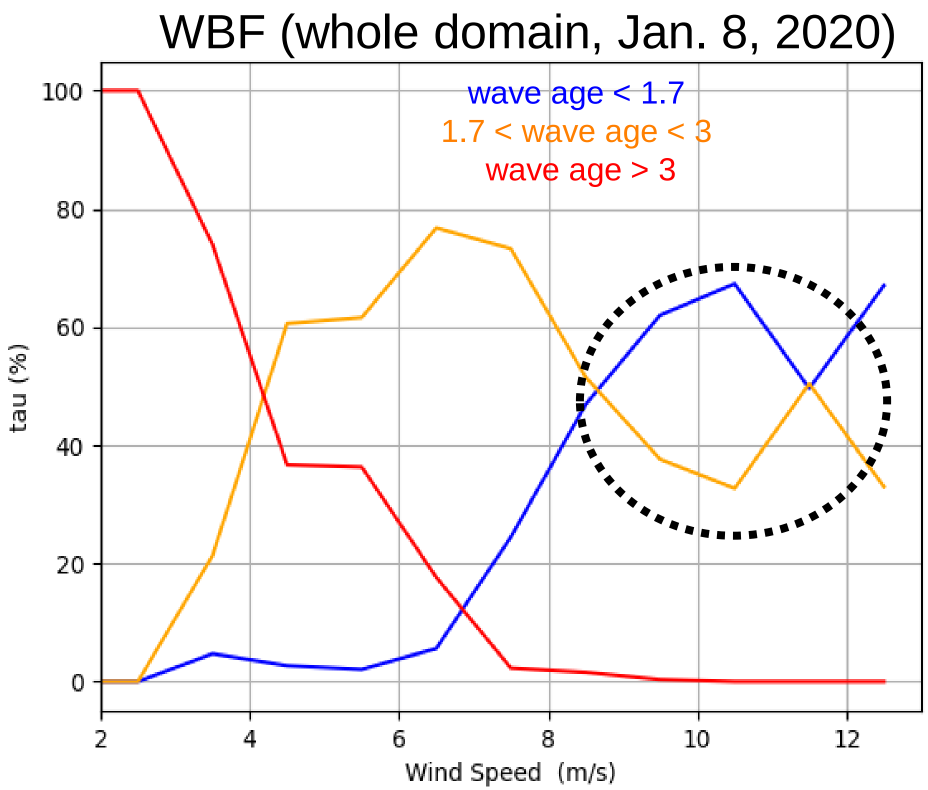

Including waves directionality

The sea state leading to the strong decrease of surface wind stress appears to be strongly misaligned

Based on previous studies (e.g, Patton et al. 2015, Porchetta et al. 2019, 2020)

$$z_{rough} = H_s \cdot 0.09\cos(0.4\theta) \cdot \left(\frac{u_*}{C_p}\right)^{2\cos(0.32\theta)}$$

Where θ varies from 0 to 180

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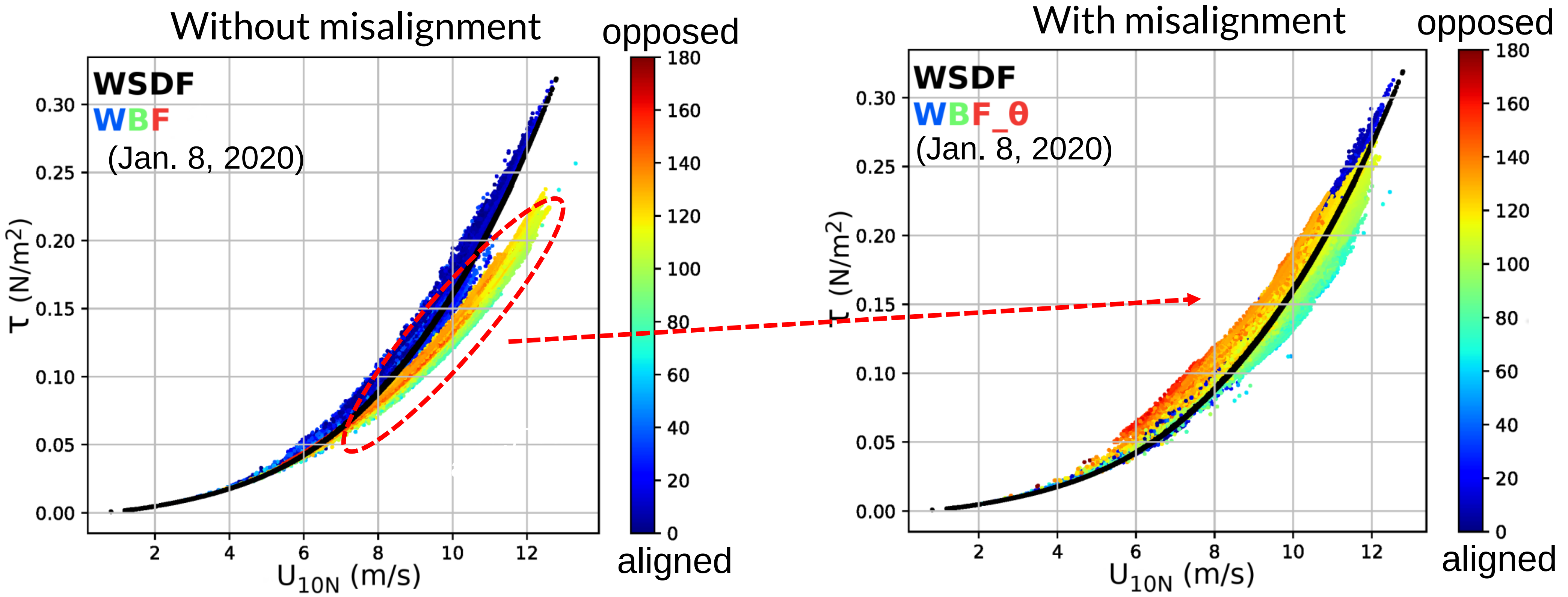

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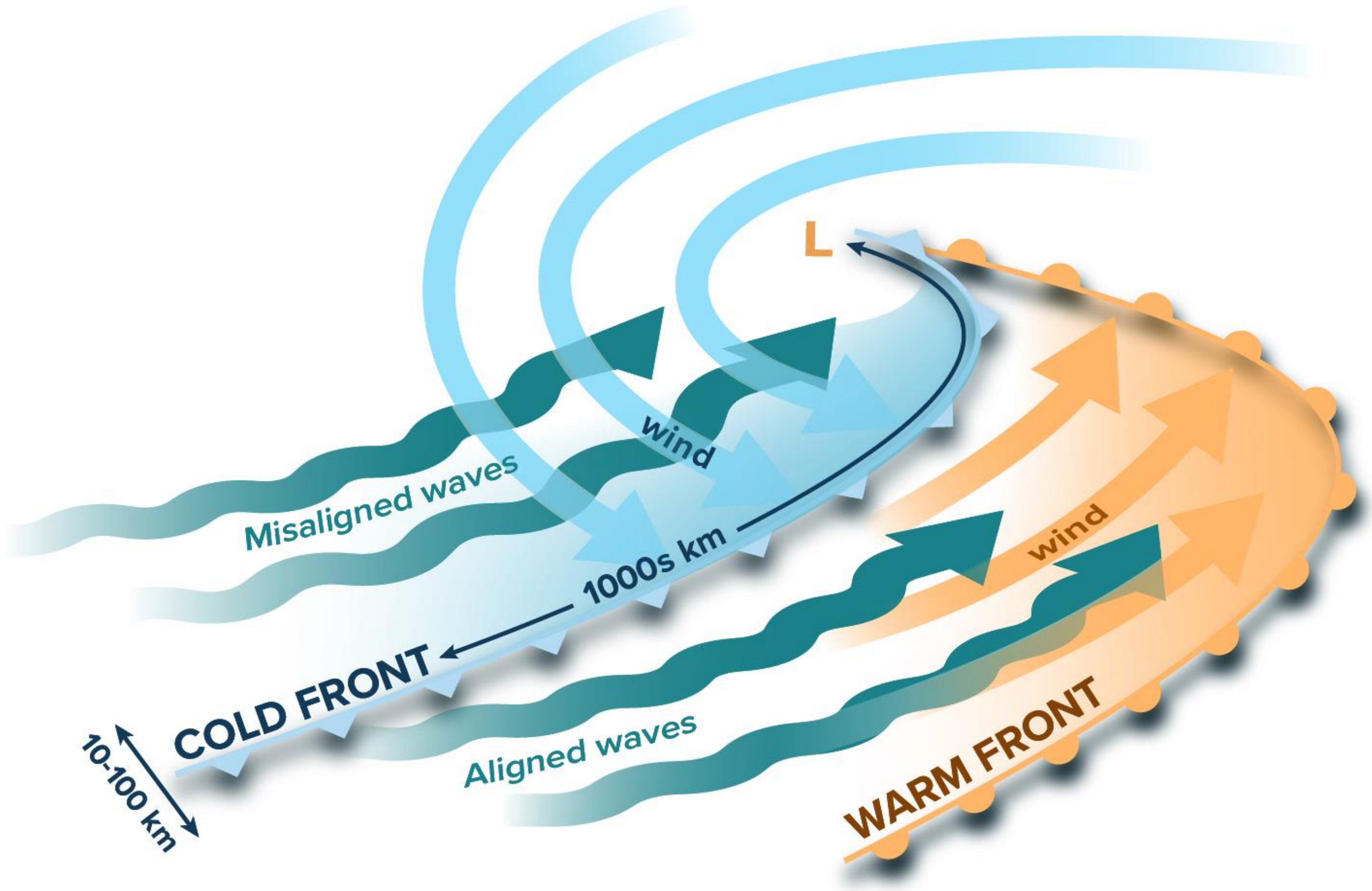
Where θ varies from 0 to 180

The peak wave period does not always represents accurately the sea state and tend to overestimate the impact of mixed sea under moderate wind conditions

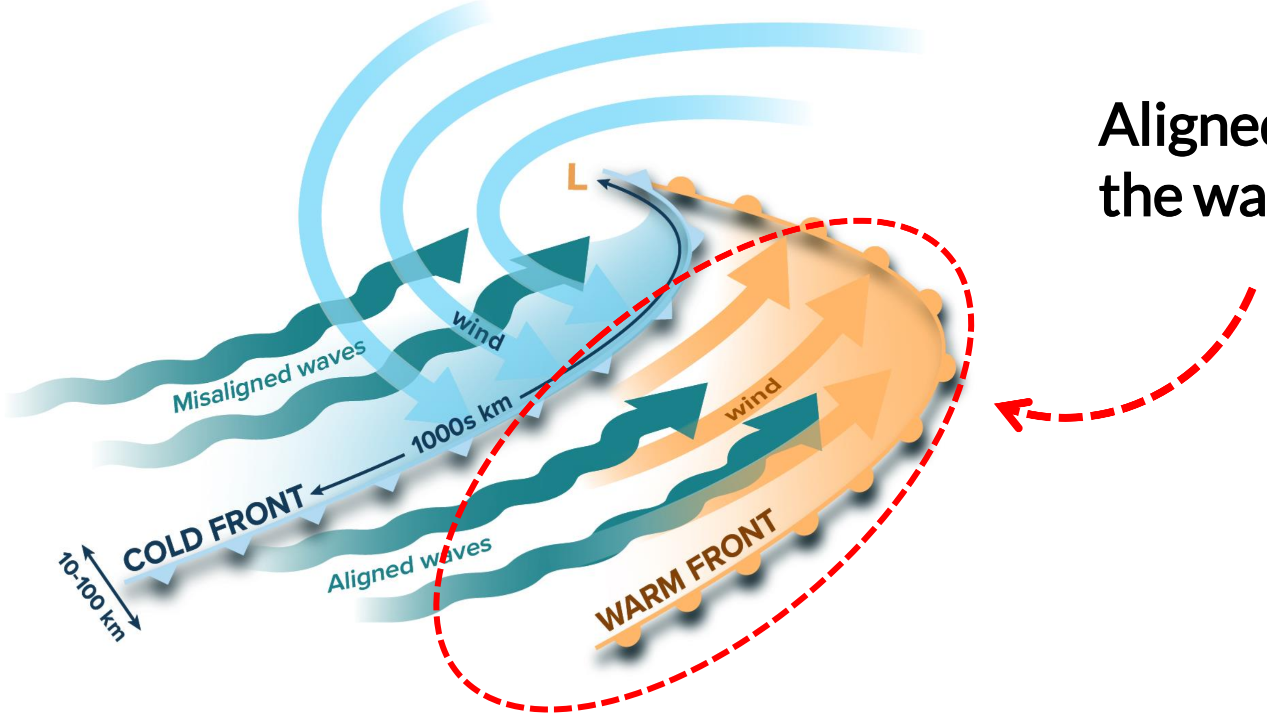
The mean period is more appropriate and shift the wave age distribution to younger waves.

$$z_{rough} = H_s \cdot 0.39 \cdot \left(\frac{u_*}{C_m}\right)^{2.6}$$

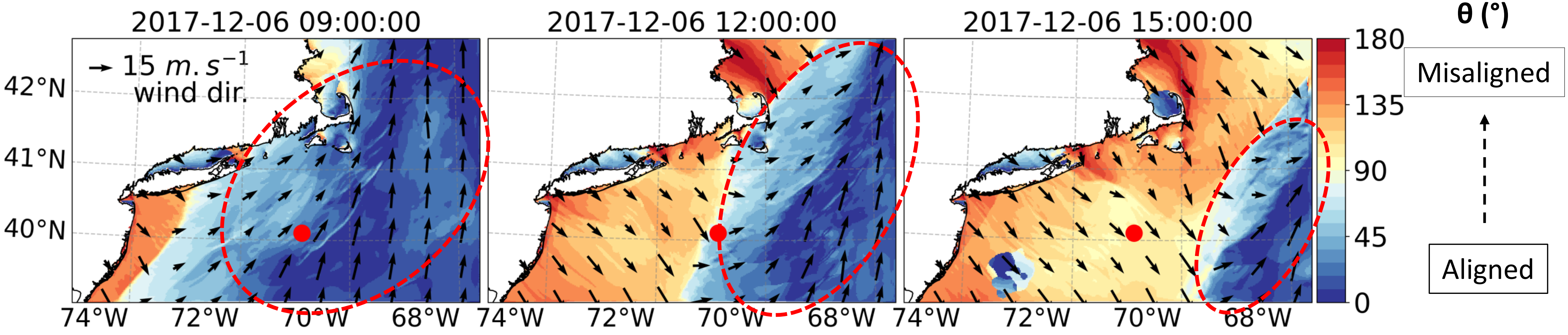
Misaligned wave during atmospheric cold front



Atmospheric cold front passing on December 6th 2017

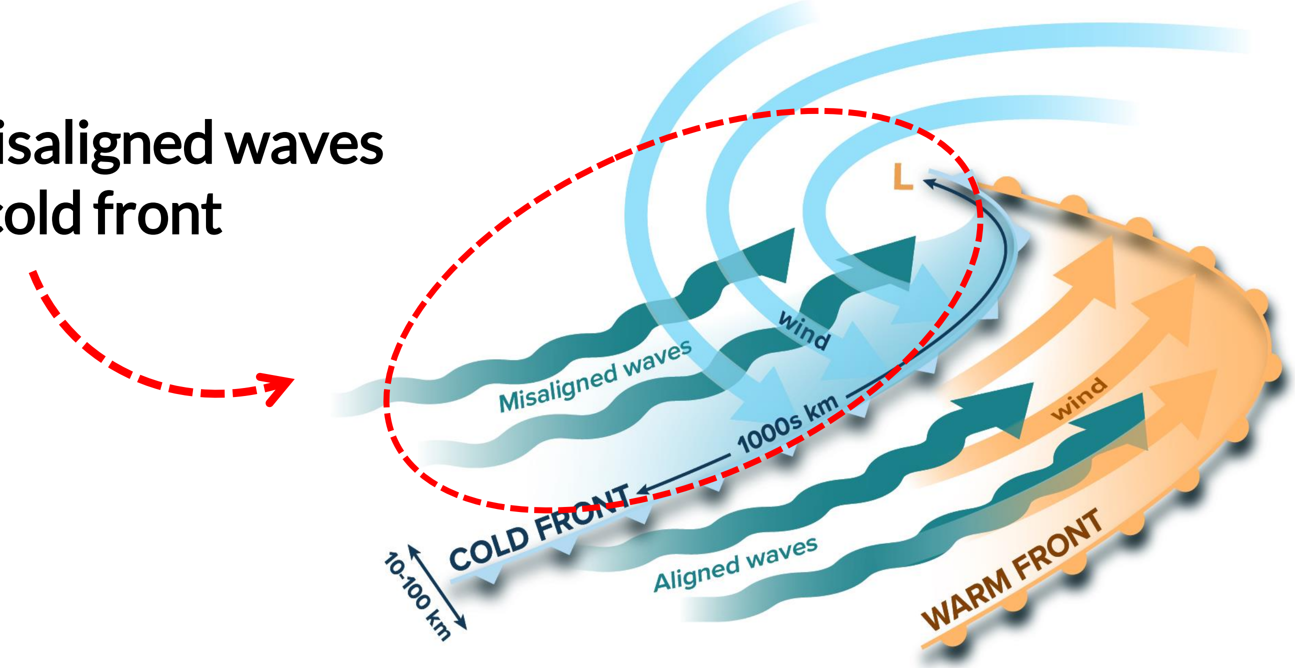


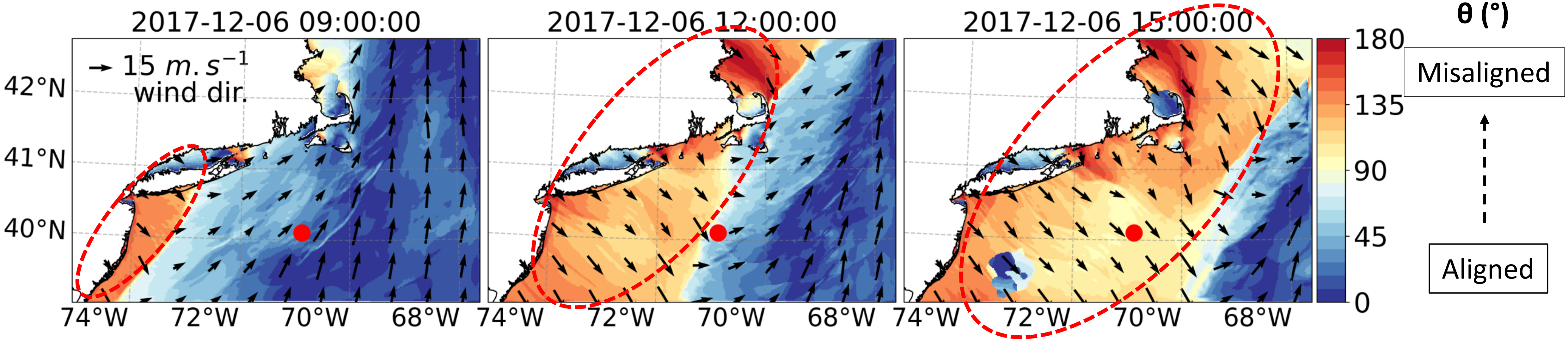
Aligned waves under the warm front



Atmospheric cold front passing on December 6th 2017

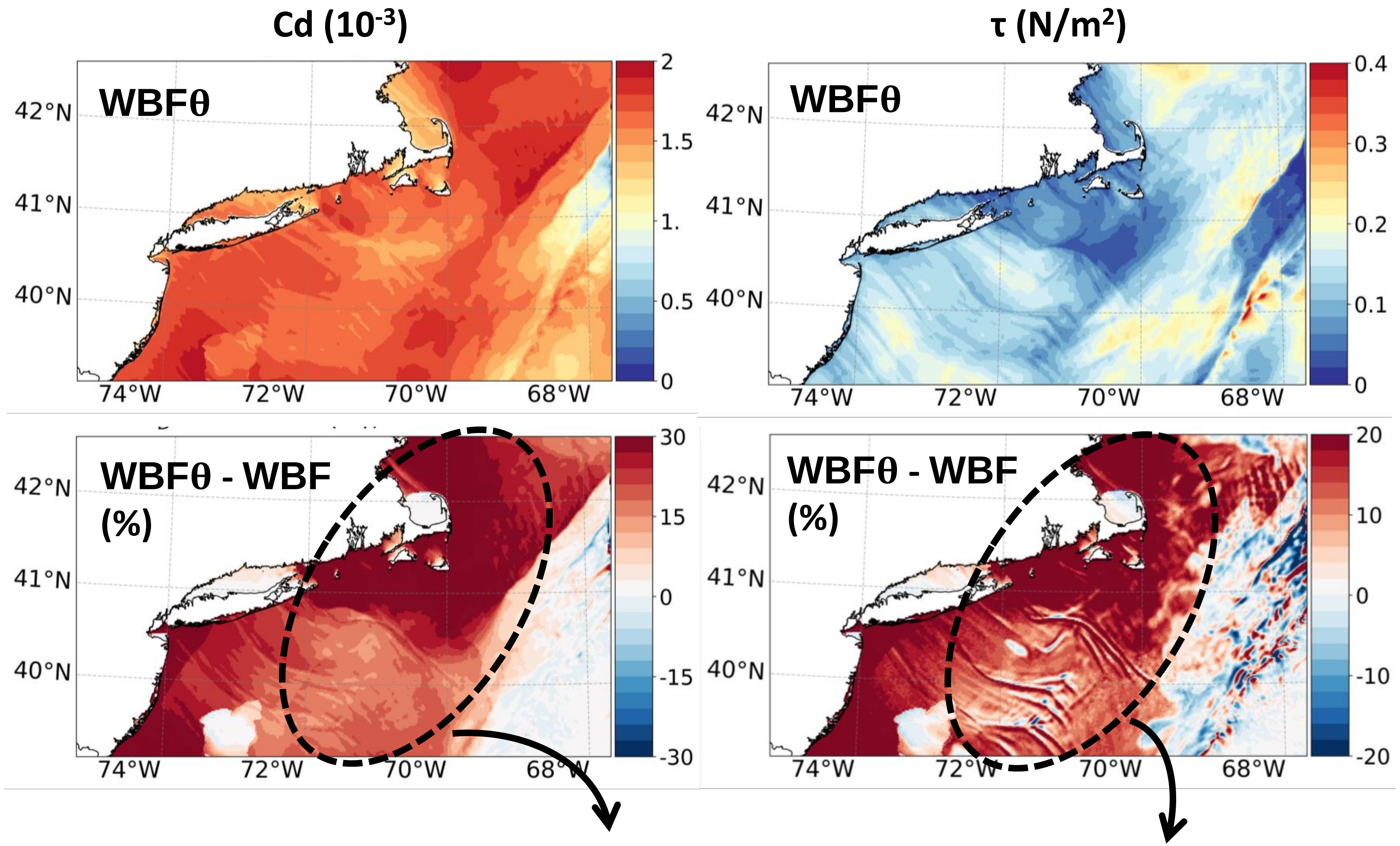
Strongly misaligned waves under the cold front





Misaligned waves impact on momentum flux

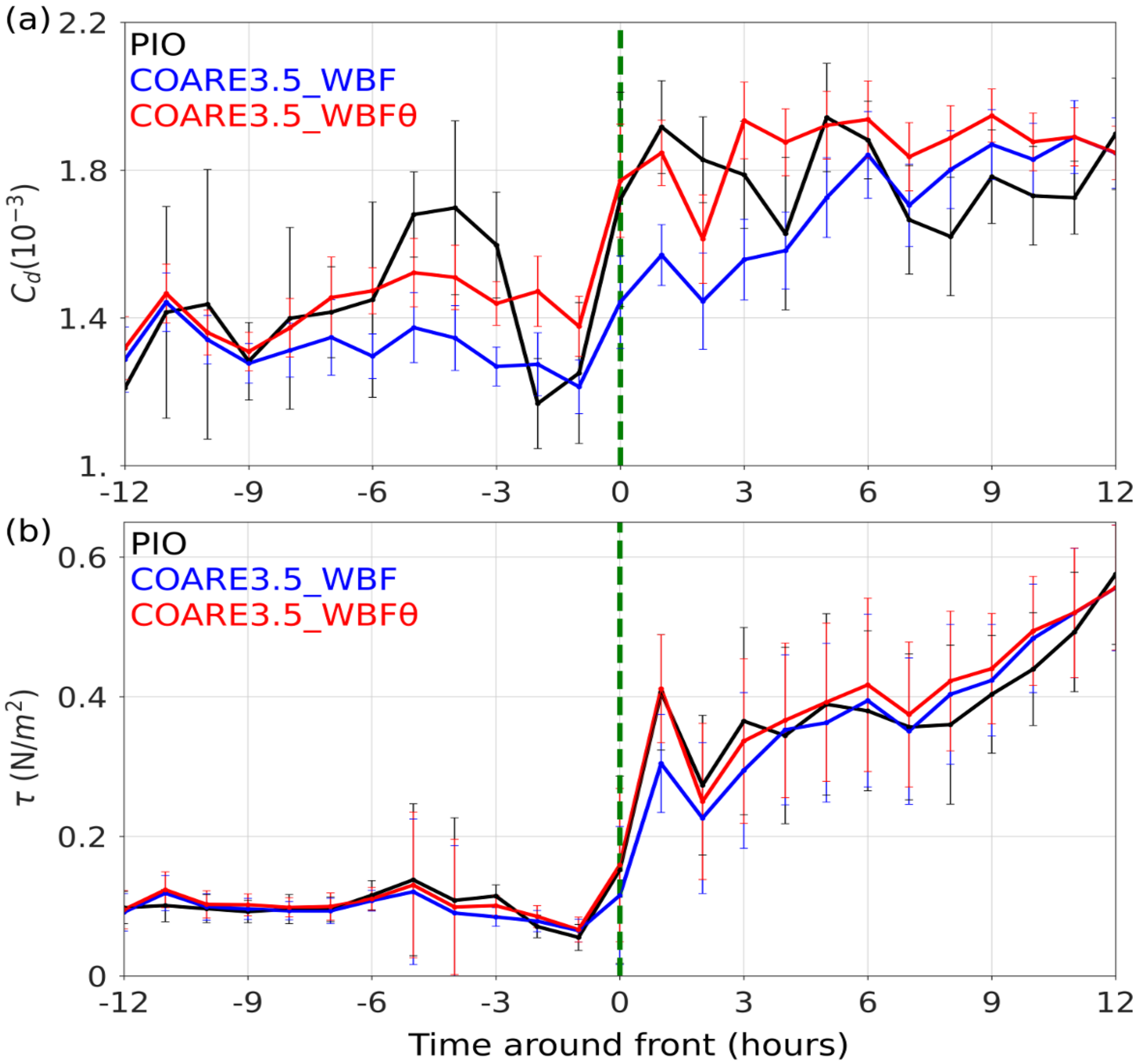
2017-12-06-15:00

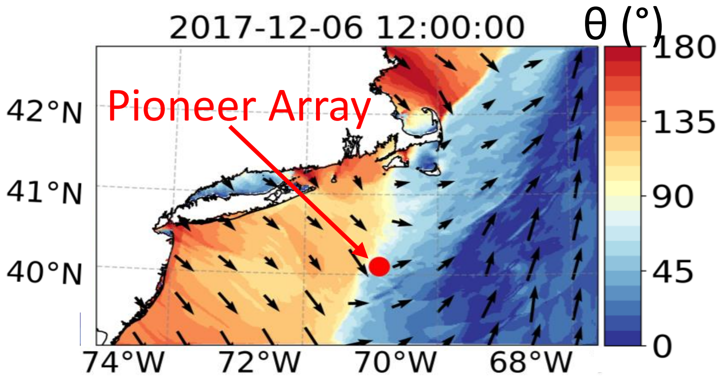


Surface drag coefficient and momentum stress increase by 20% and 11% on average behind the cold front

Wave based formulation + wave directionality (**WBFθ**)
Wave based formulation (**WBF**)

Direct covariance flux system measurements at Pioneer Array



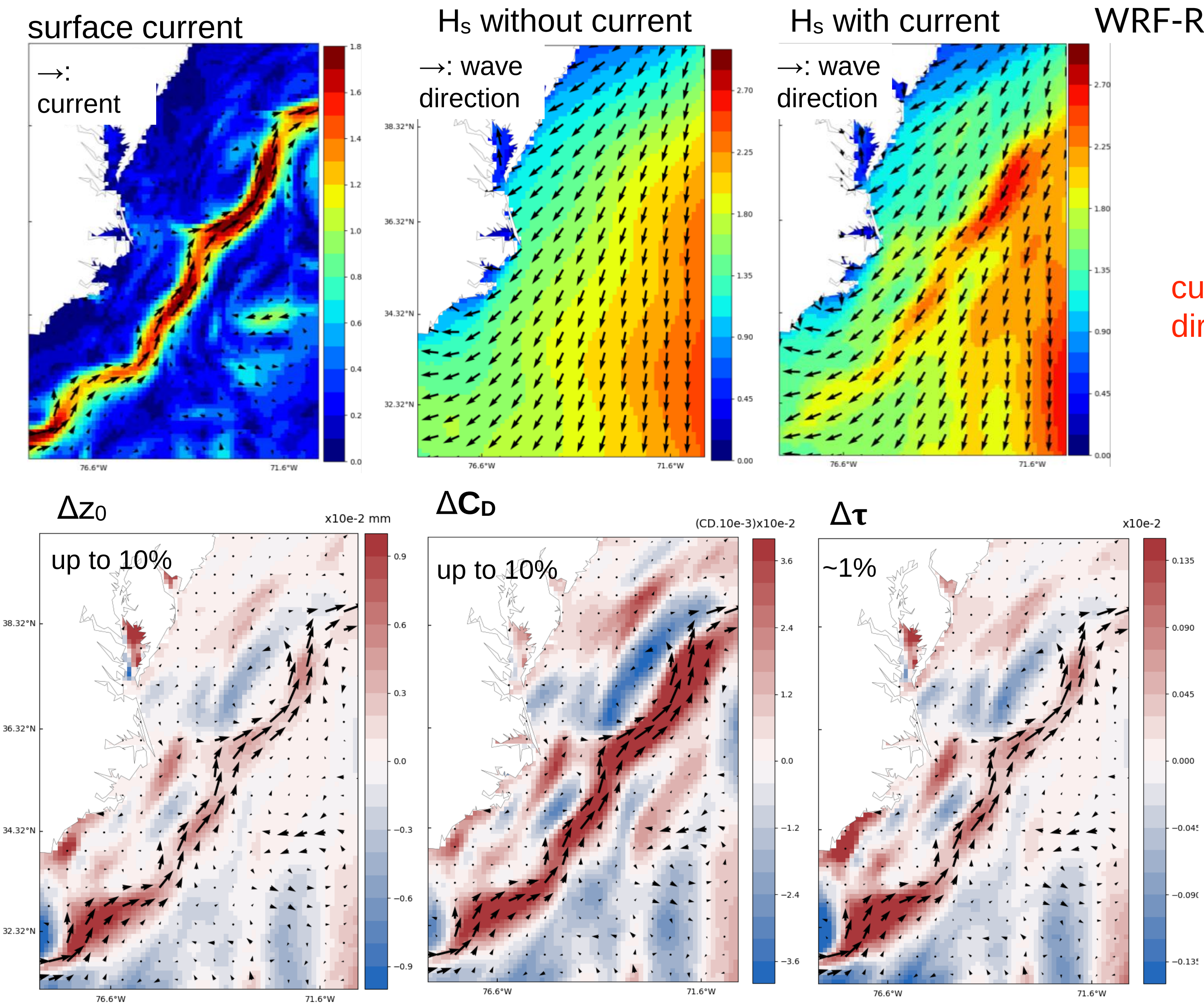


20 atmospheric cold fronts detected during the period when momentum flux observations are available.

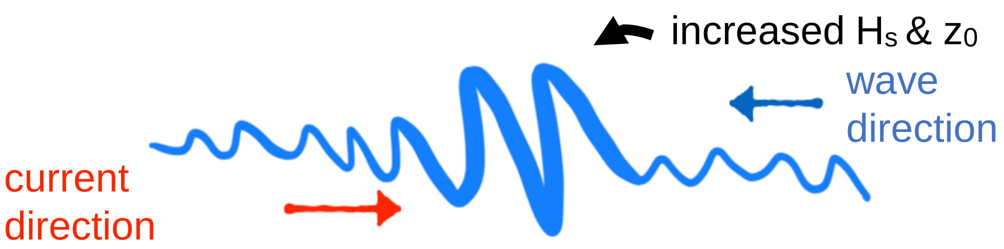
Using **WBF** $\boldsymbol{\theta}$ generally increases the flux by 7% (up to 16%) in case of strongly misaligned waves after the cold front.

Taking into account misalignment generally reduces the bias from -4.8% in **WBF** to 1.7% in **WBF** $\boldsymbol{\theta}$.

Wave-Current interactions



WRF-ROMS-WW3 simulations with and without surface current effects on waves



The spatial variability in ocean currents affects the wave properties and thus air-sea flux (i,.e, Ardhuin et al. 2017, Marechal and Ardhuin 2021, Villas Bôas et al. 2025)

Consistent with Iyer et al. 2022 which found that wave slopes are 5%–10% higher when surface currents oppose the waves and variations in air-sea momentum flux of at least 6% at wind speeds over 8 ms^{-1}

Conclusions

Investigating the impact of sea state on momentum flux through coupled Ocean-Atmosphere-Wave simulations using the sea surface fluxes parameterization COARE3.5

→ COARE3.5 wave-based formulation tends to over-emphasizes the mixed seas and swell impacts on momentum flux.

→ Two possible remedies for low stress bias:

-Wave-wind directional misalignment ($\theta \neq 0$): increases the drag for misaligned waves

-Mean wave period (Tm): emphasizes the presence of wind waves in the mixed sea state

→ Atmospheric cold fronts lead to large areas of mixed sea conditions misaligned with local wind for up to 5 to 10h after the passage of the cold front

→ Taking into account misalignment in the flux parameterization generally reduces the bias compared to observations

→ Keep working toward a better understanding of the misalignment in different wind-waves-currents regimes (i.e., high wind regimes, cross-swell vs opposed swell…)

→ Need more long-term co-located observations (surface wind, directional waves, ocean currents, momentum flux) like the OOI Pioneer Array.

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Thank you !

→ Sauvage, C., Seo, H., Barr, B., Clayson, C-A., Edson, J. (2024). Misaligned Wind-Waves Behind Atmospheric Cold Fronts. In JGR: Oceans. DOI: 10.1029/2024JC021162

→ Sauvage, C., Seo, H., Clayson, C-A., Edson, J. (2023). Improving Wave-Based Air-Sea Momentum Flux Parameterization in Mixed Seas. In JGR: Oceans. DOI: 10.1029/2022JC019277

→ COARE3.5 modified: https://github.com/cesarsauvage/COARE3.5_modified_Sauvage-et-al._2023

Contact: csauvage@hawaii.edu

Supplementary Slides

SCOAR regional coupled model (Seo et al. 2007)

<u>Sensitivity runs to COARE3.5:</u>

Wave-based formulation (WBF)

Wind speed only formulation (WSDF)

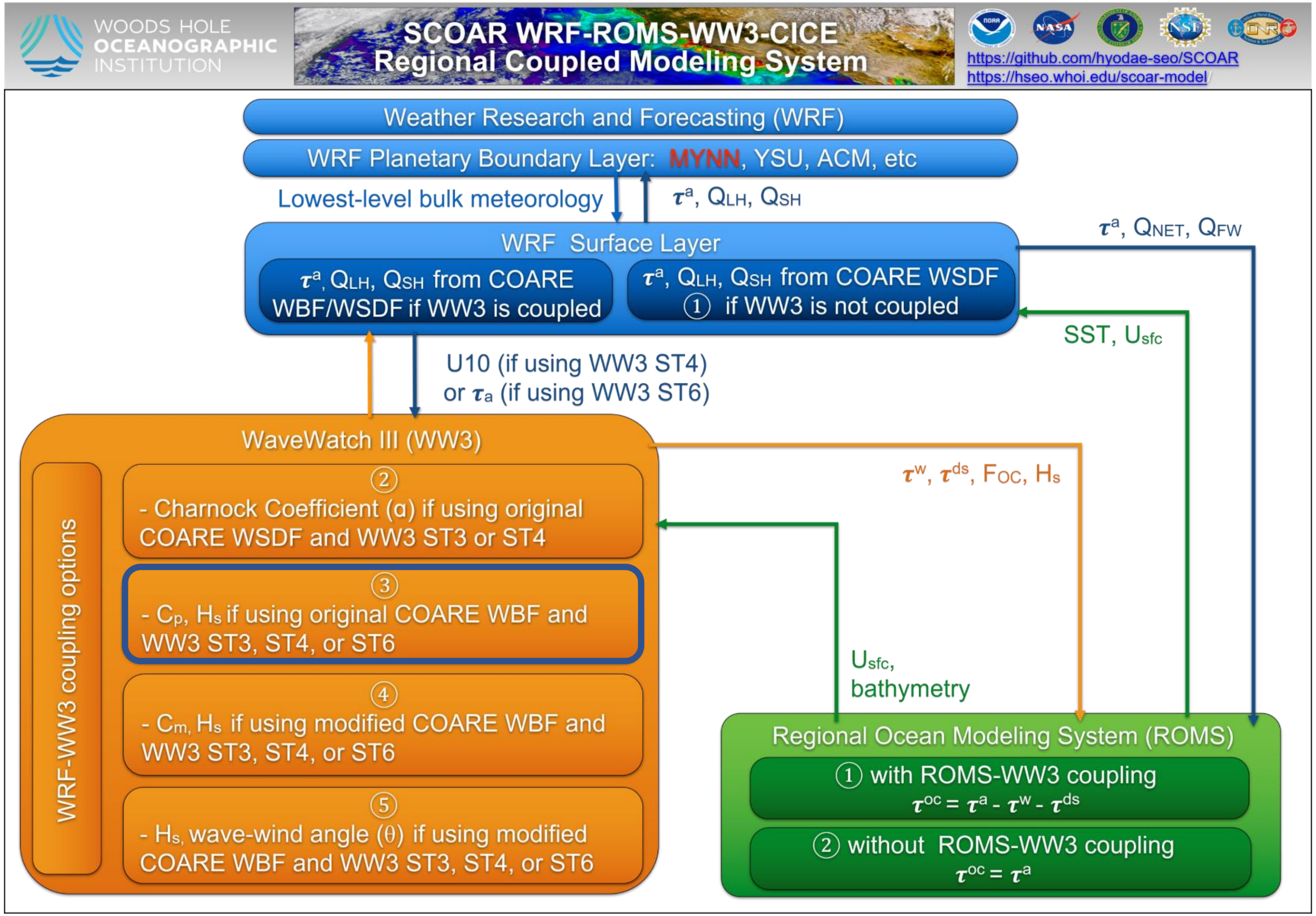
Coupling frequency 3h
Horizontal resolution : 10km

Boundary forcing:

Atmospheric forcing:
hourly ERA5

Ocean forcing:
Daily Mercator Ocean Inter.

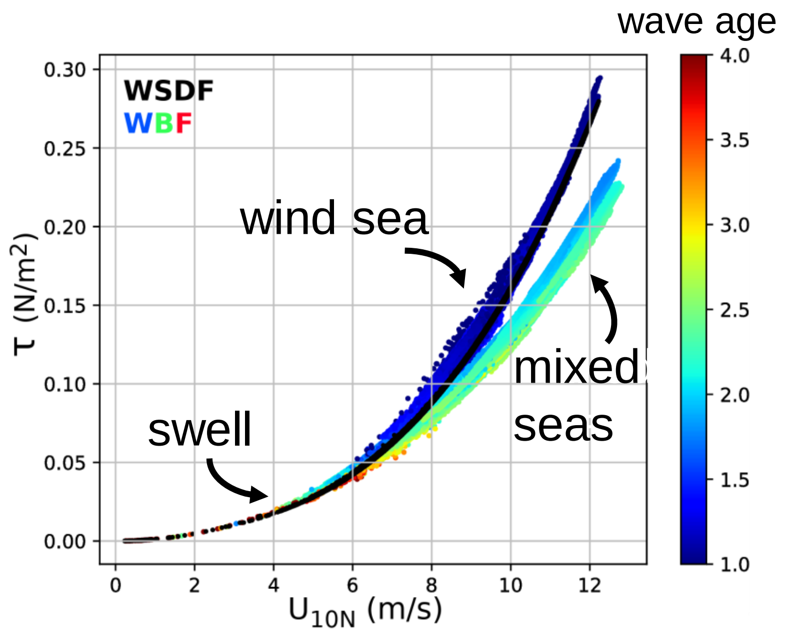
Wave forcing:
3-hourly spectral points
(Ifremer global runs)

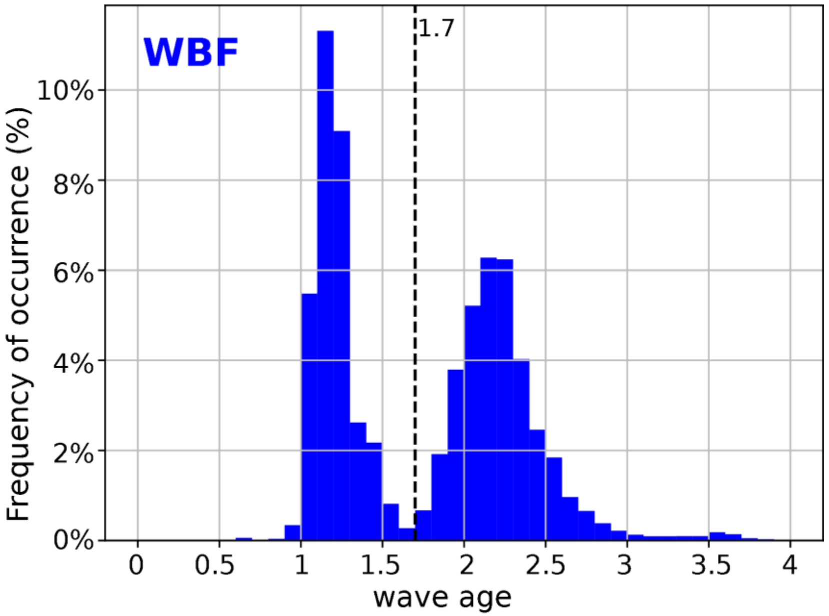


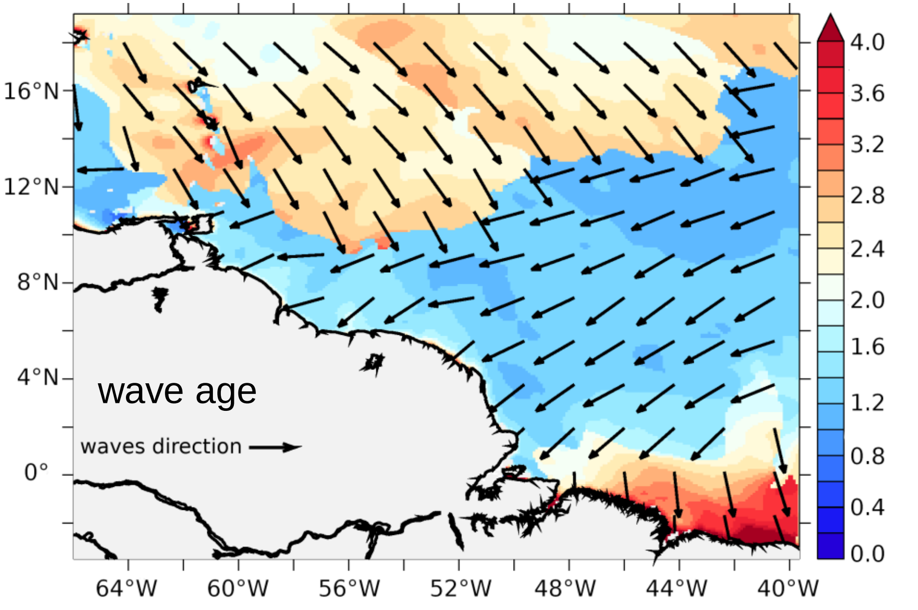
Study case: January 8, 2020

Wind speed based formulation (**WSDF**)
Wave based formulation (**WBF**)

- Northwesterly swell entering the domain under persistent trade winds
- Young waves and equilibrium waves tend to increase the surface stress
- Swell and mixed seas tend to significantly decrease the surface stress under moderate wind







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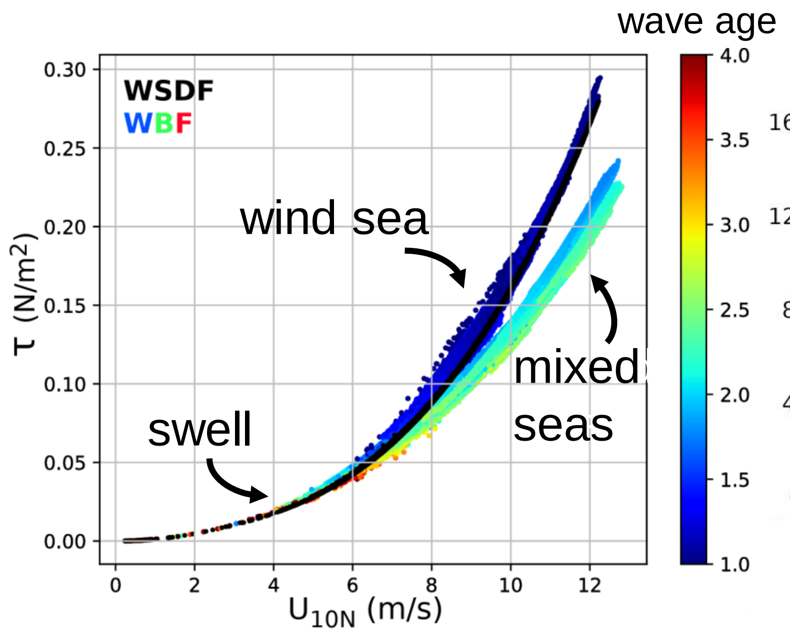
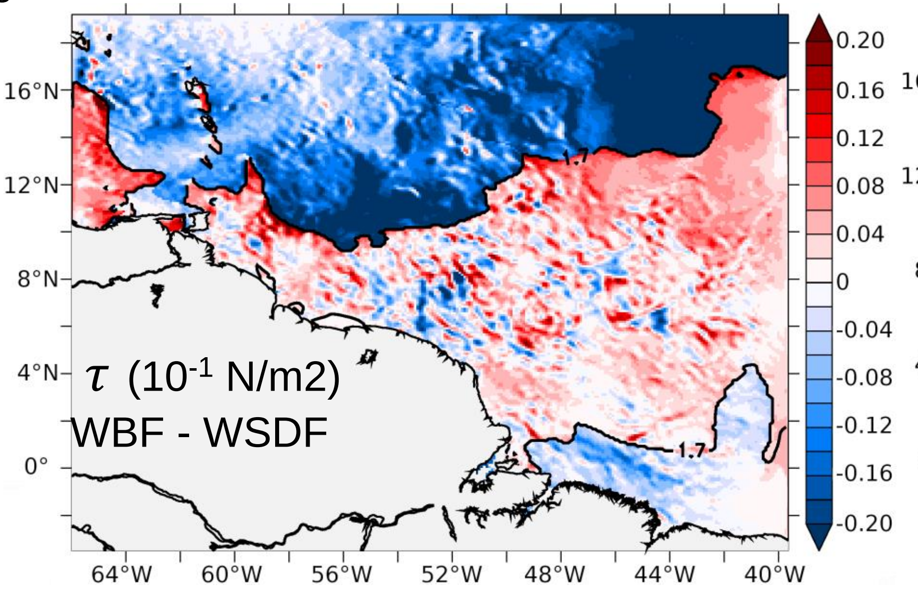
Large spatial differences of the surface stress :

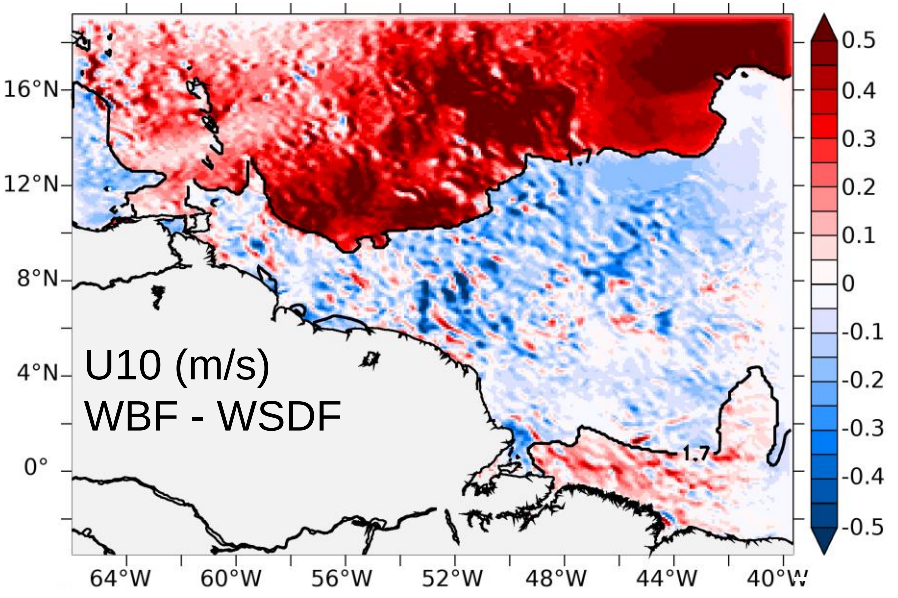
- large decrease of the stress above the northerly swell
- Increase above the youngest waves

} +/- 0.2 $*10^{-1}$ N/m2 difference (~10% - 15%)

Lead to large impact on the near surface wind with differences +/- 0.5 m/s (~ 5%)



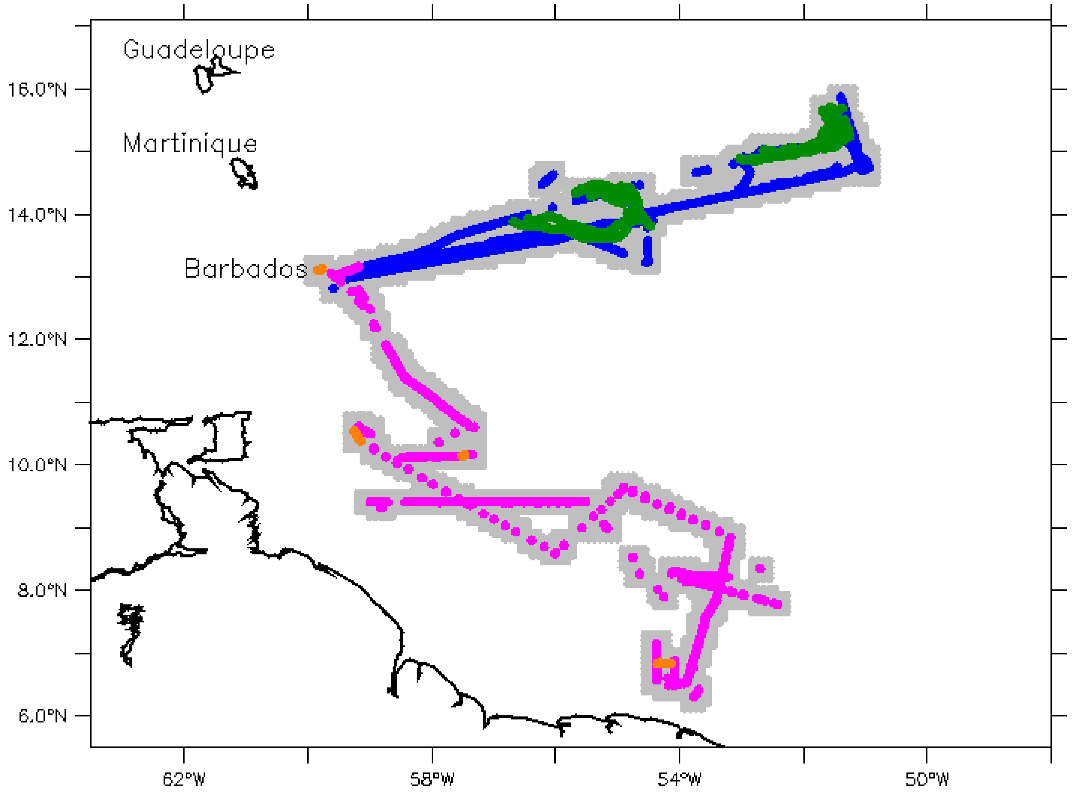


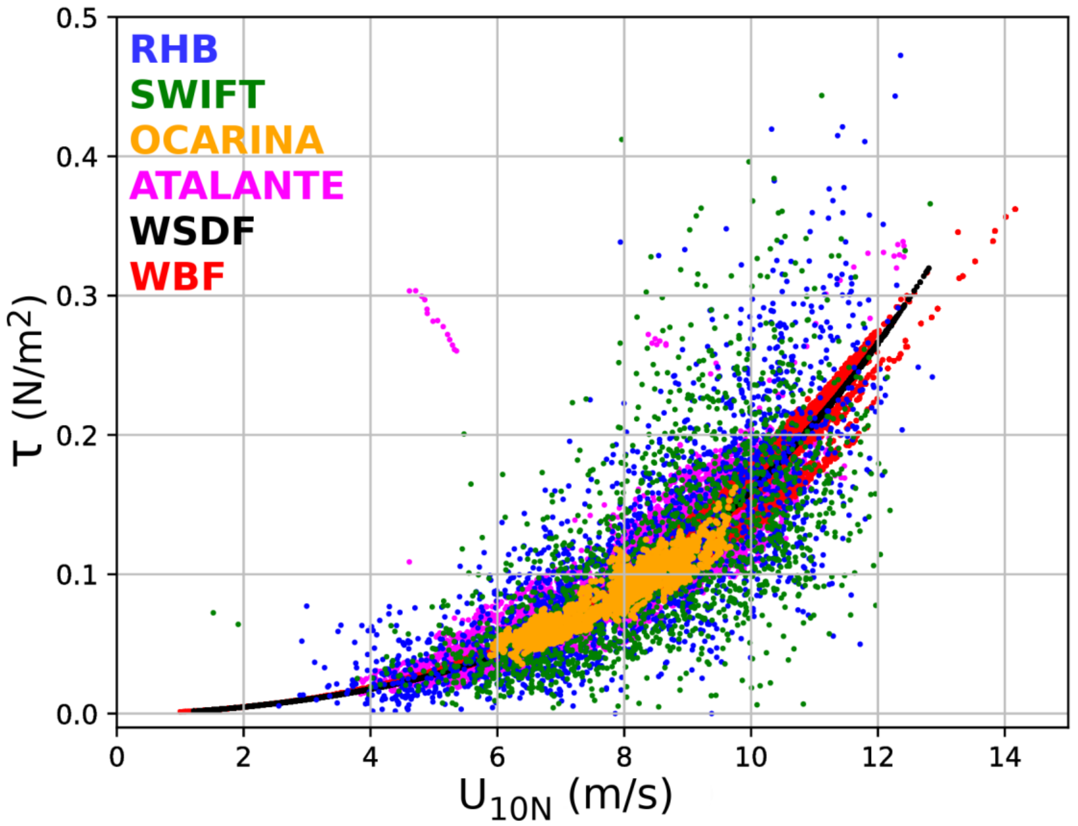


Momentum flux measurements

Ron Brown and Ocarina → eddy covariance method
Atalante → inertial dissipation method
SWIFT → estimation of friction velocity from the equilibrium frequency range of the wave spectrum

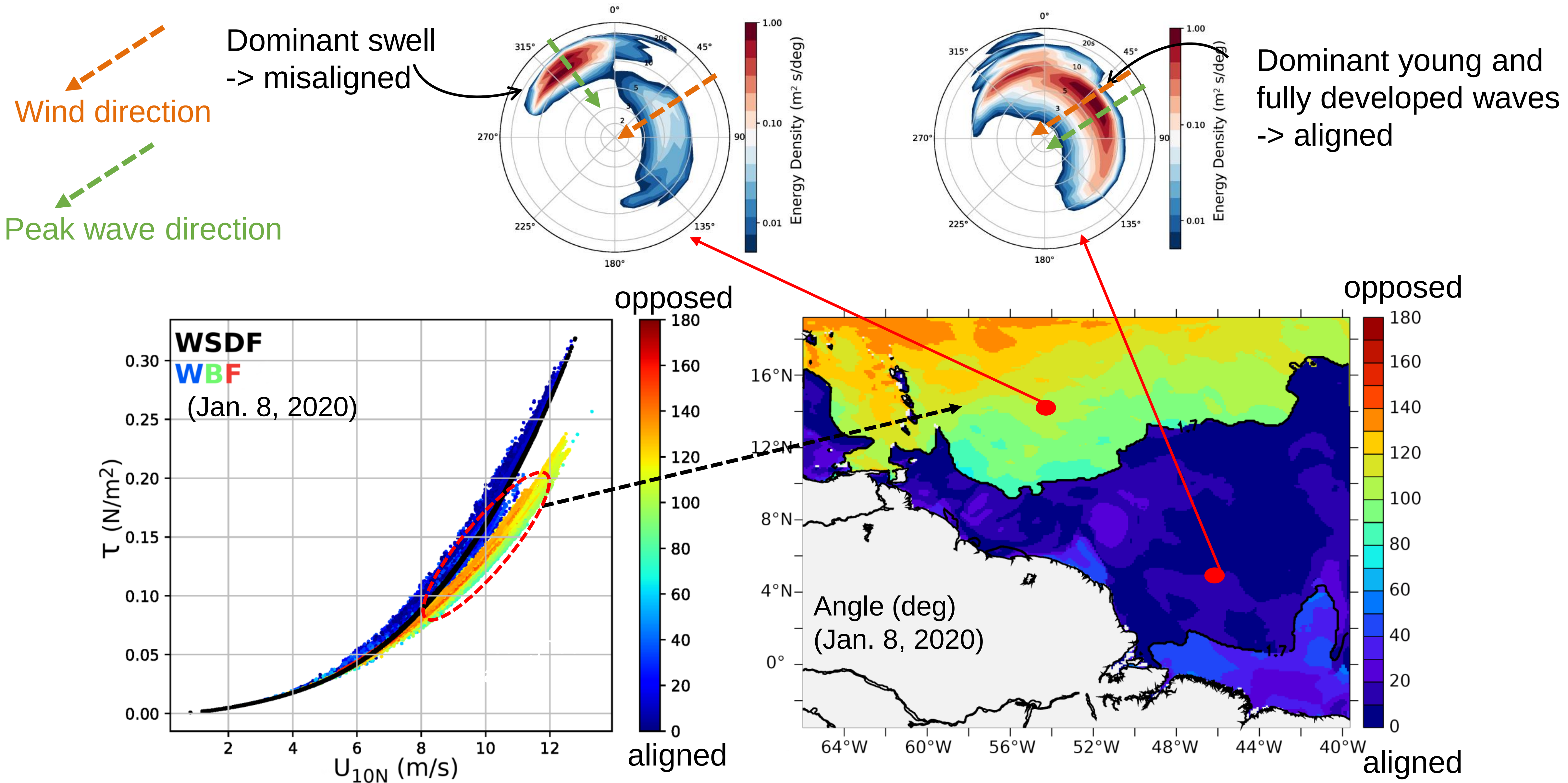
The model is sample along the gray zone on the map





Including waves directionality

The sea state leading to the strong decrease of surface wind stress appears to be strongly misaligned



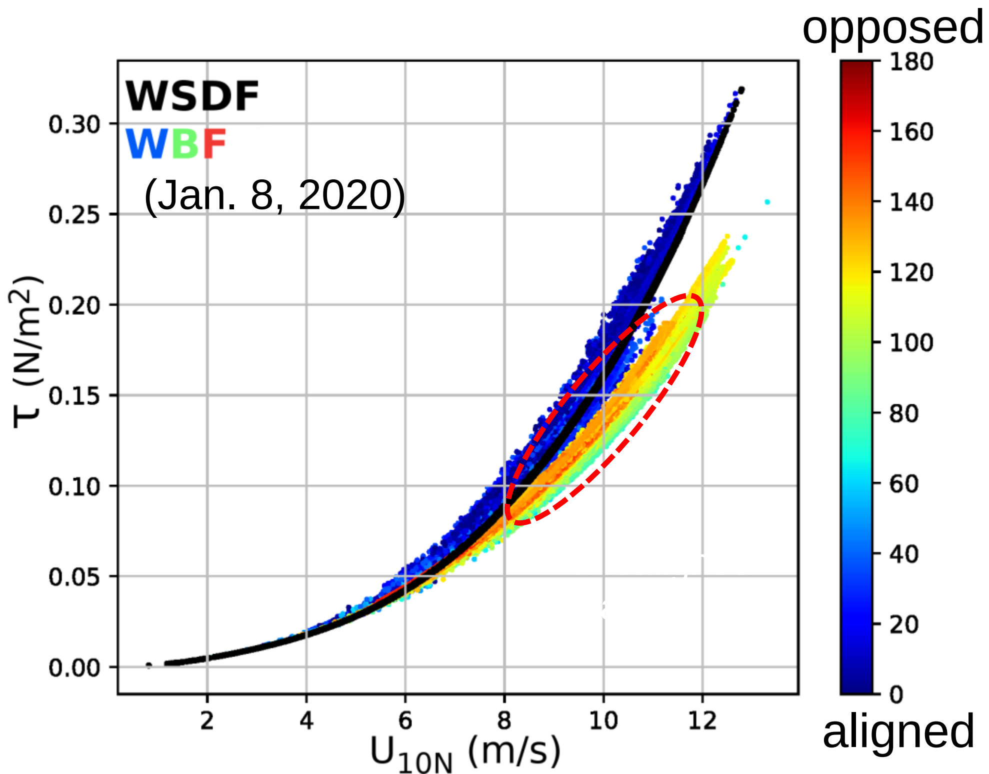
Including waves directionality

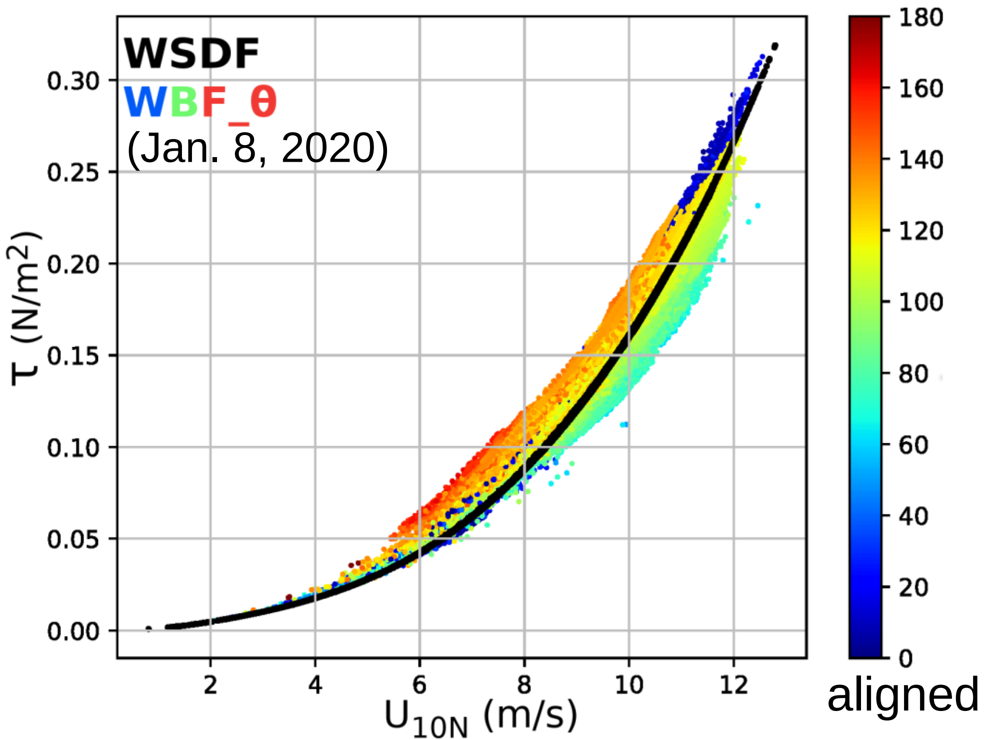
The sea state leading to the strong decrease of surface wind stress appears to be strongly misaligned

Based on previous studies (Patton et al. 2015, Porchetta et al. 2019)

$$z_{rough} = H_s \cdot 0.09\cos(0.4\theta) \cdot \left(\frac{u_*}{C_p}\right)^{2\cos(0.32\theta)}$$

Where θ varies from 0 to 180





Supplementary figures

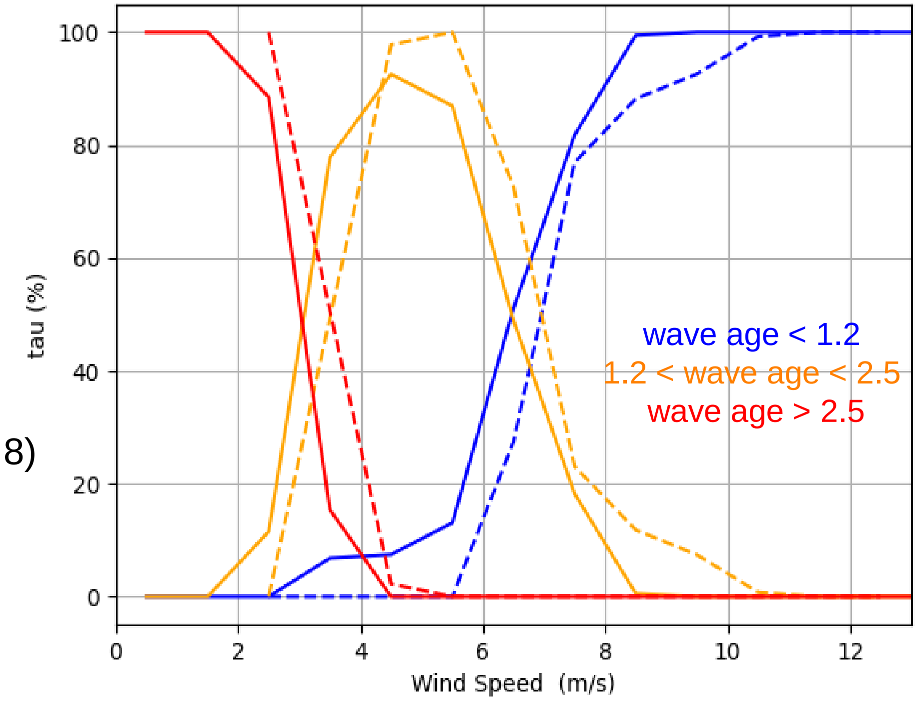
The peak wave period does not always represents accurately the sea state and tend to overestimate the impact of mixed sea under moderate wind conditions

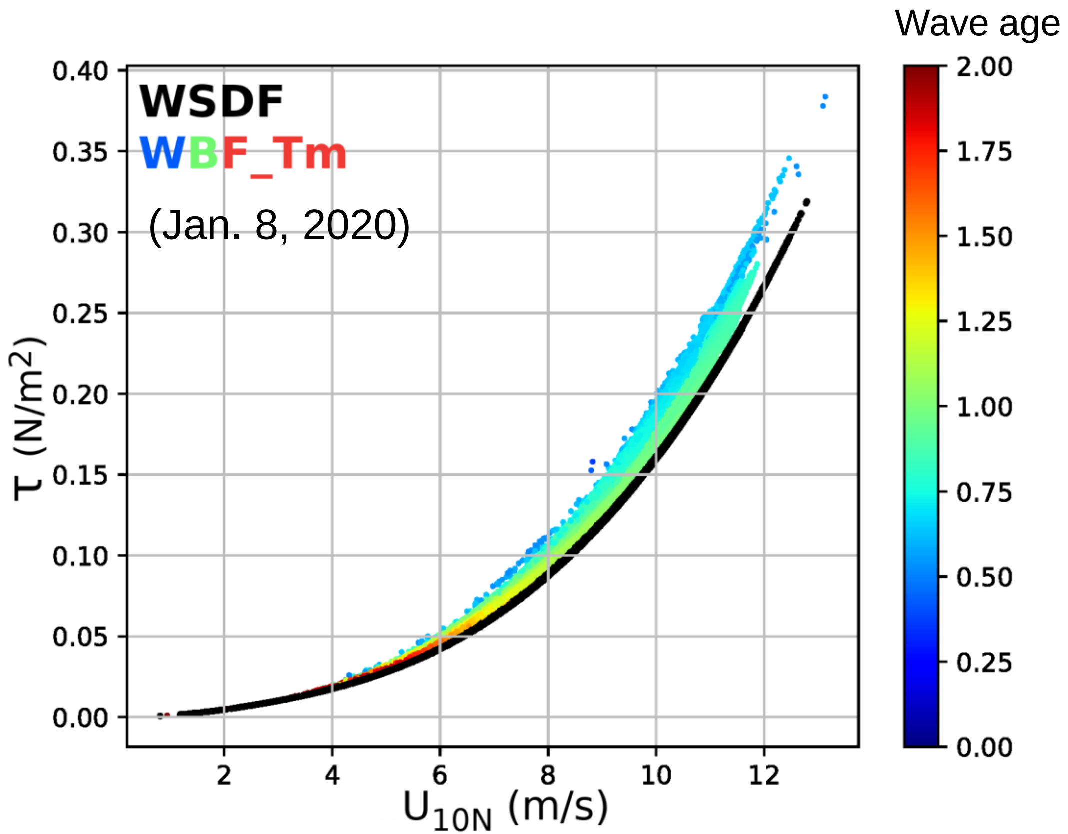
The mean period is more appropriate and shift the wave age distribution to younger waves.

$$z_{rough} = H_s \cdot 0.39 \cdot \left(\frac{u_*}{C_m}\right)^{2.6}$$

WBF_tm
(▬▬▬, Jan 8)

Ron Brown
(▬ ▬ ▬)



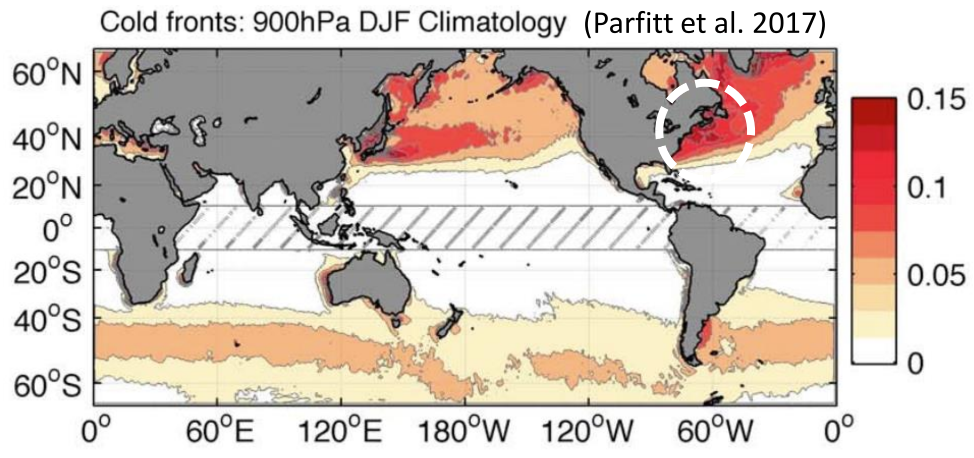


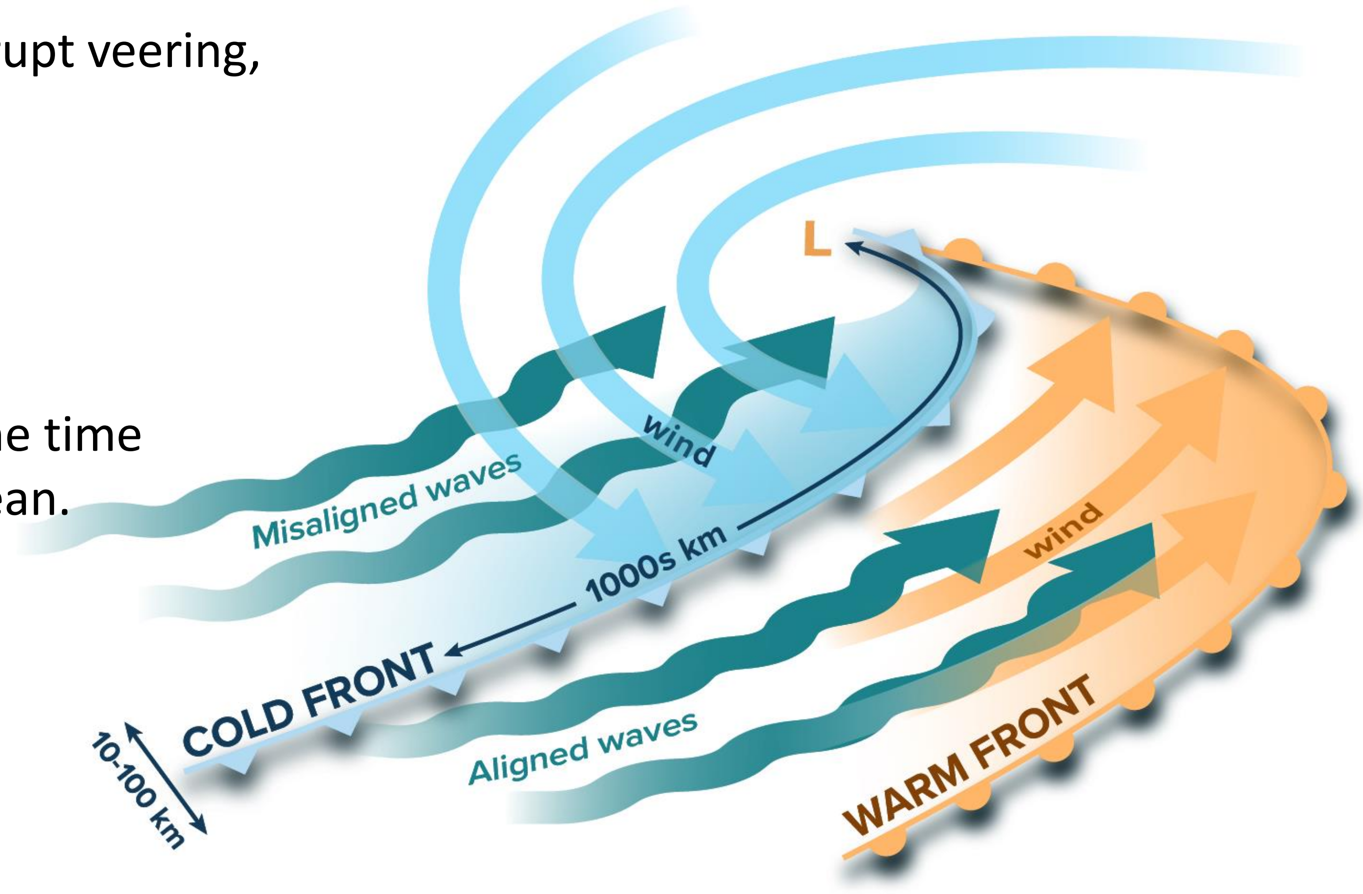
Misaligned Waves During Atmospheric Cold Fronts

They are characterized by high wind speed, abrupt veering, and rapid translation.

→ <u>Leads to strongly misaligned waves behind the cold front</u>

Atmospheric cold fronts account for ~15% of the time during winter months in the North Atlantic Ocean.





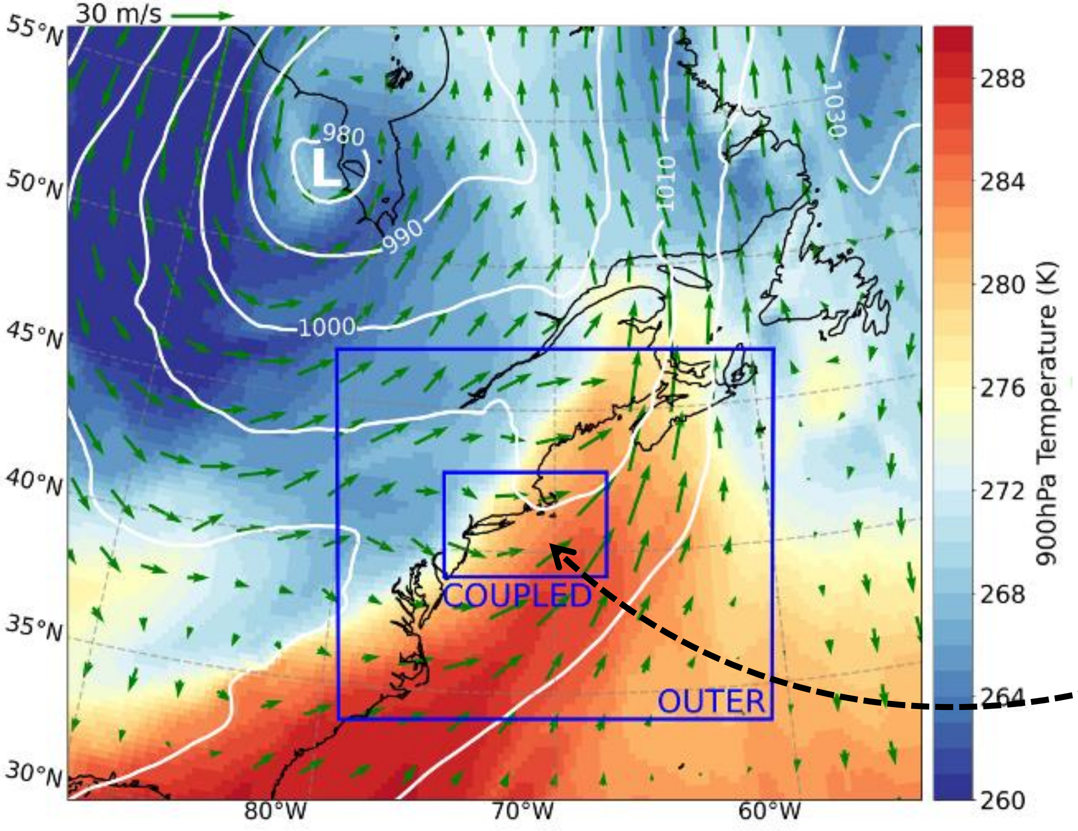
What are the resulting impacts on the surface drag and the air-sea momentum flux?

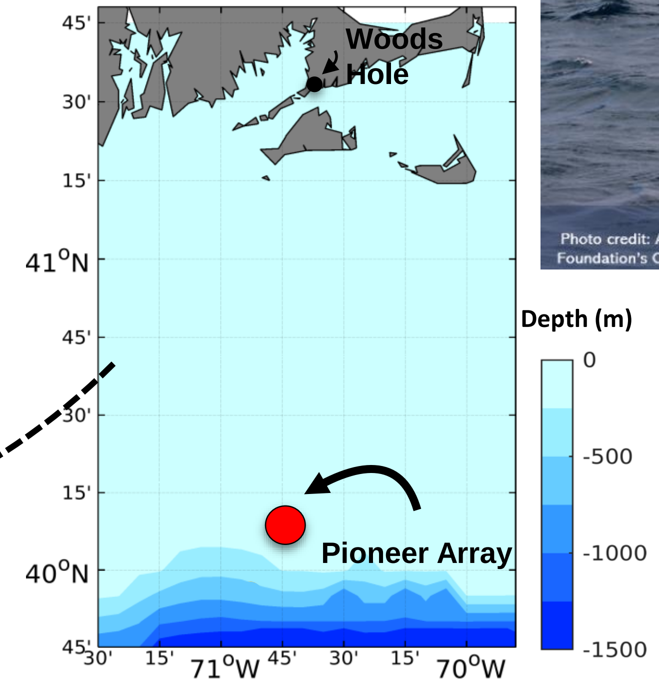
Coupled Modeling and Observation

SCOAR Regional Coupled Modeling (Seo et al. 2007)
WRF nested configuration, with an OUTER domain at 7.5 km
WRF-ROMS-WW3 COUPLED domain at 1.5 km

Ocean Observatories Initiative
Pioneer Array (2014-2022)

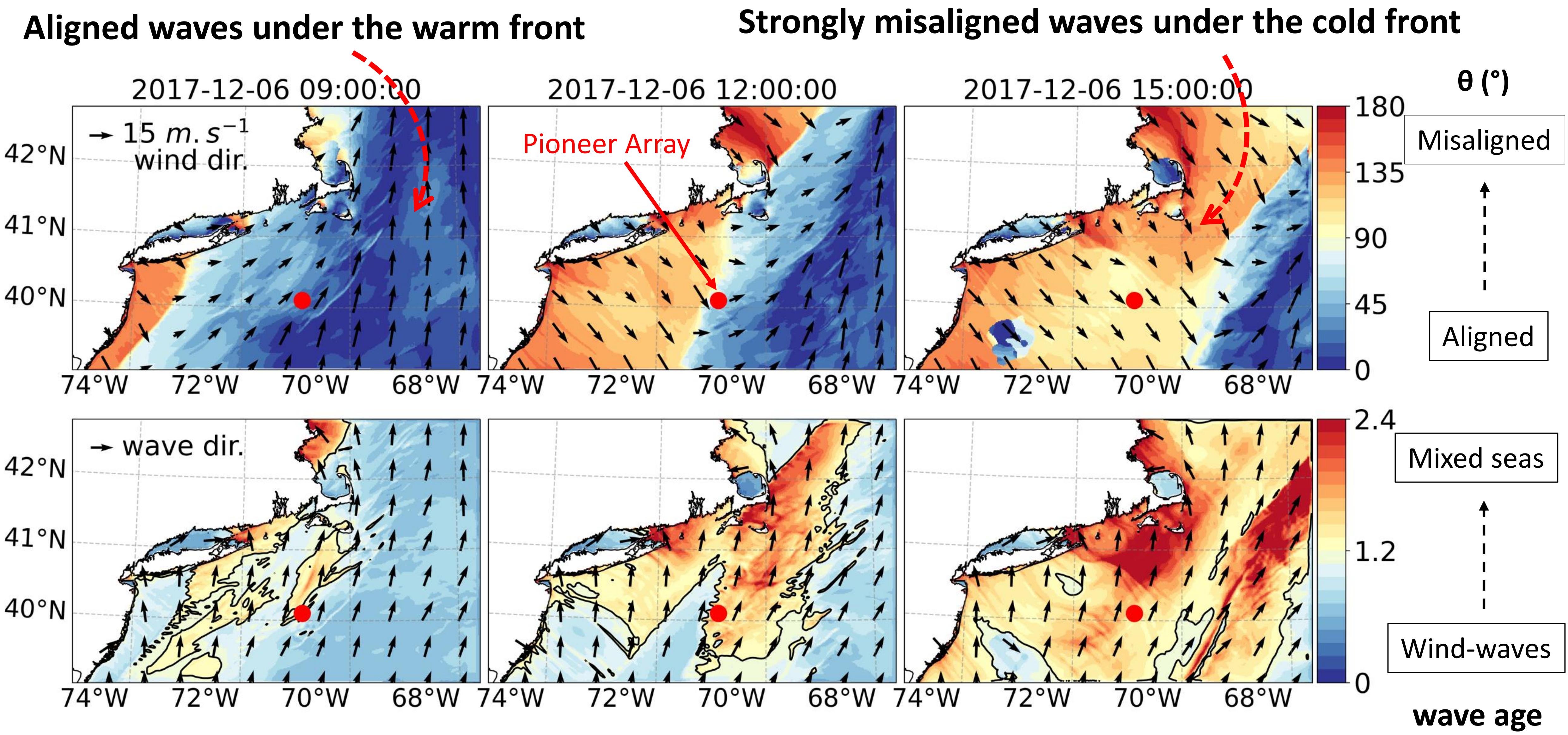
Wave based formulation + wave directionality (**WBFθ**)
Wave based formulation (**WBF**)



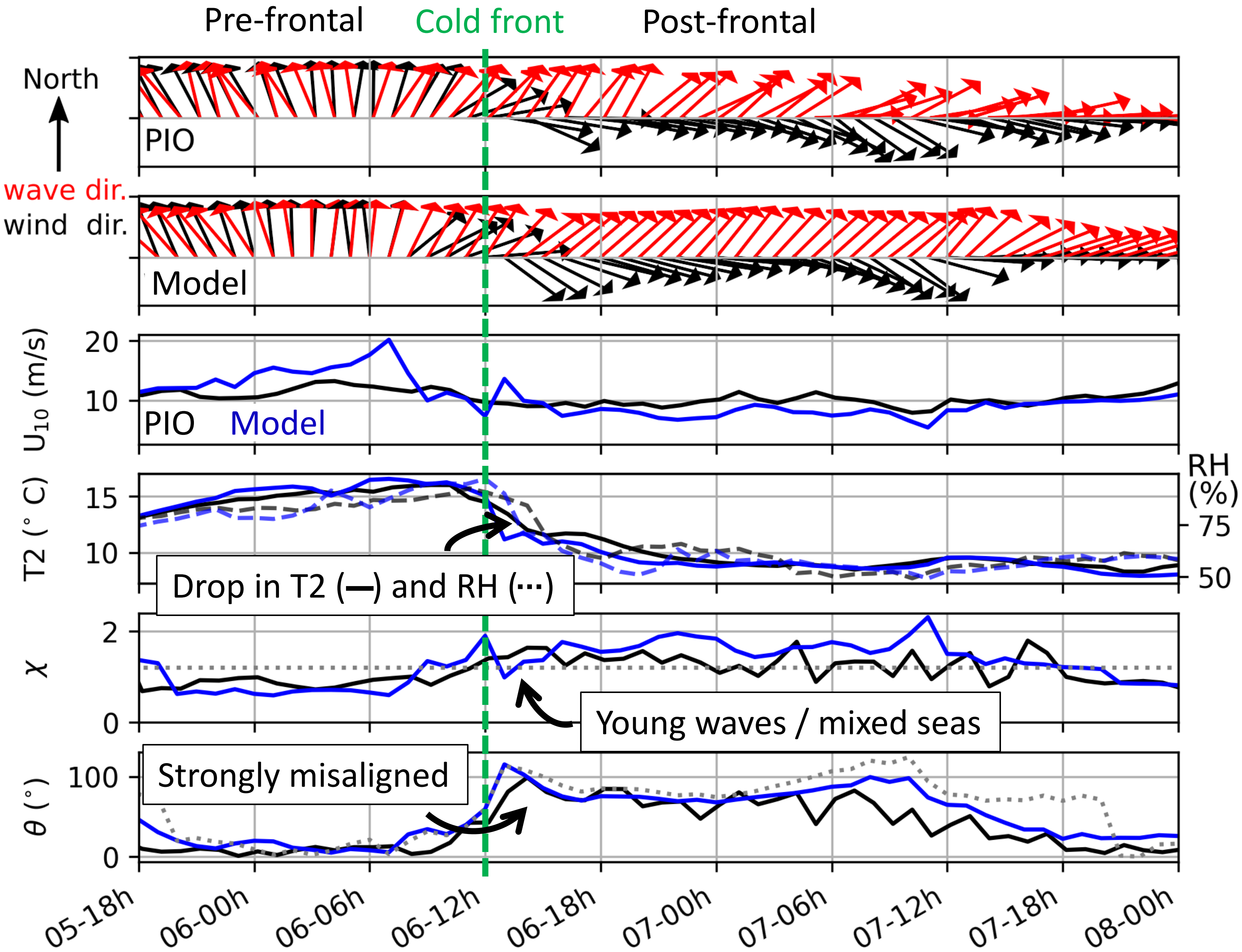


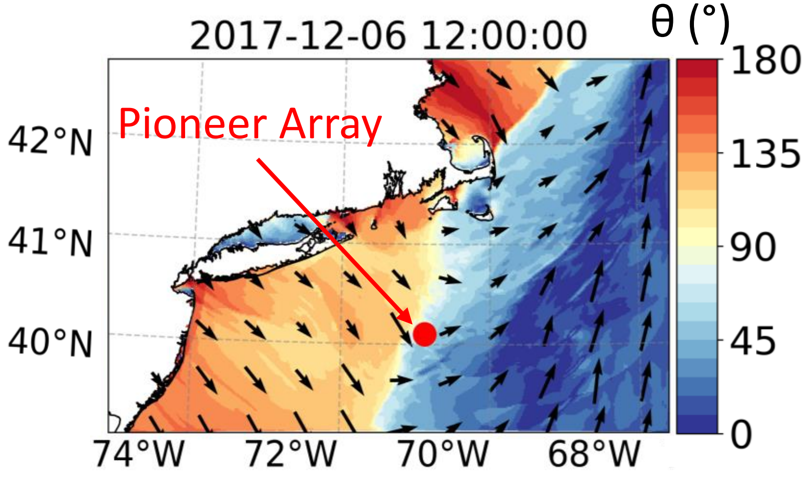

Pioneer Array Inshore Surface Mooring.
Photo credit: Al Plueddemann. Image from work supported by the National Science Foundation's Ocean Observatories Initiative, a major facility fully funded by the NSF.

Atmospheric cold front passing on December 6th 2017



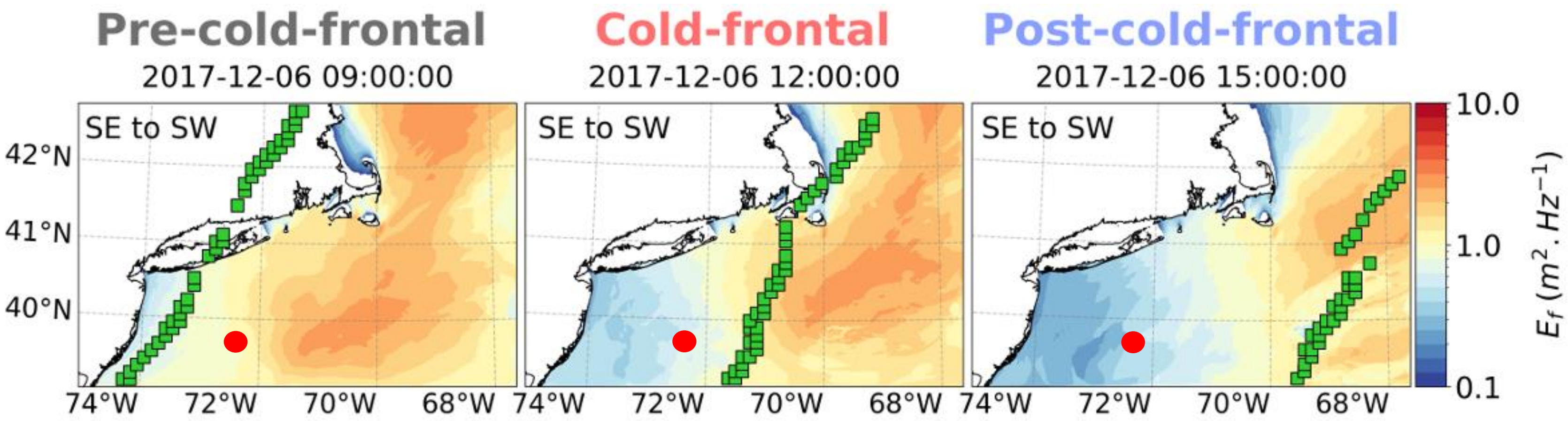
Ocean Observatories Initiative: Pioneer Array (PIO)





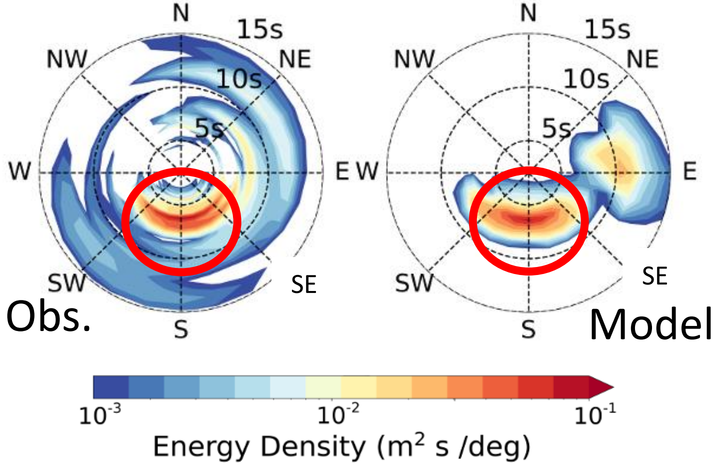
Waves stayed strongly misaligned more than 12h hours after the passage of the cold front ..!

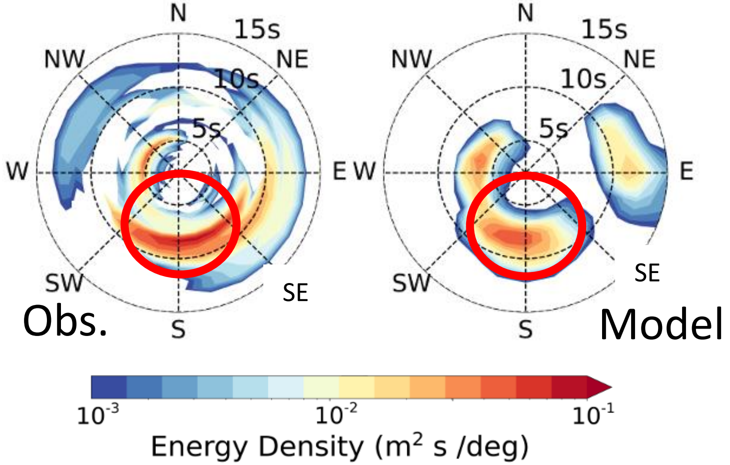
Wave energy spectrum



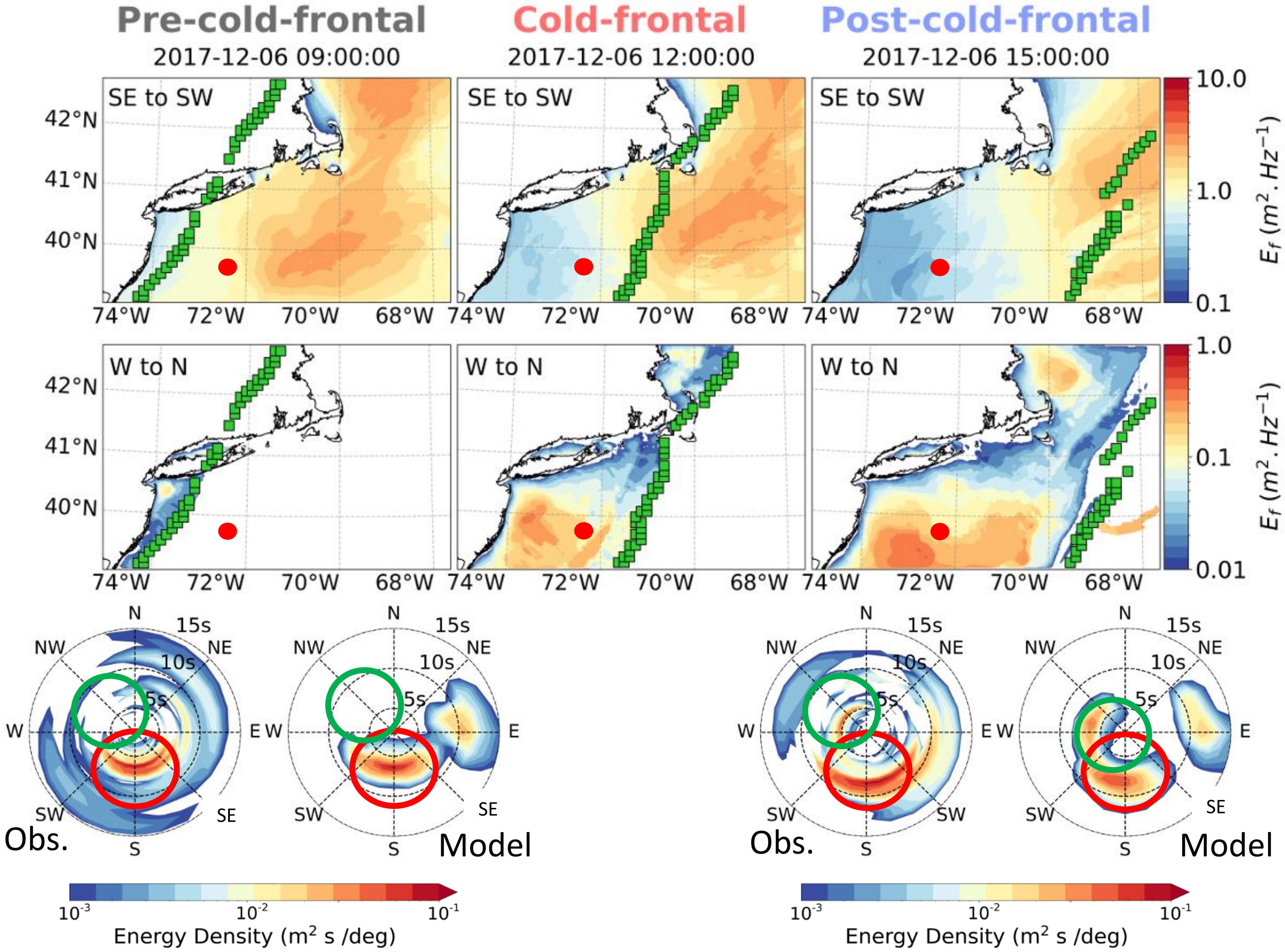
Strong southerly waves aligned with the wind in the pre-cold-frontal conditions.

While the wind shifted to northerly, strong southerly waves were still present leading to strong misalignment during the post-cold-front conditions.





Wave energy spectrum



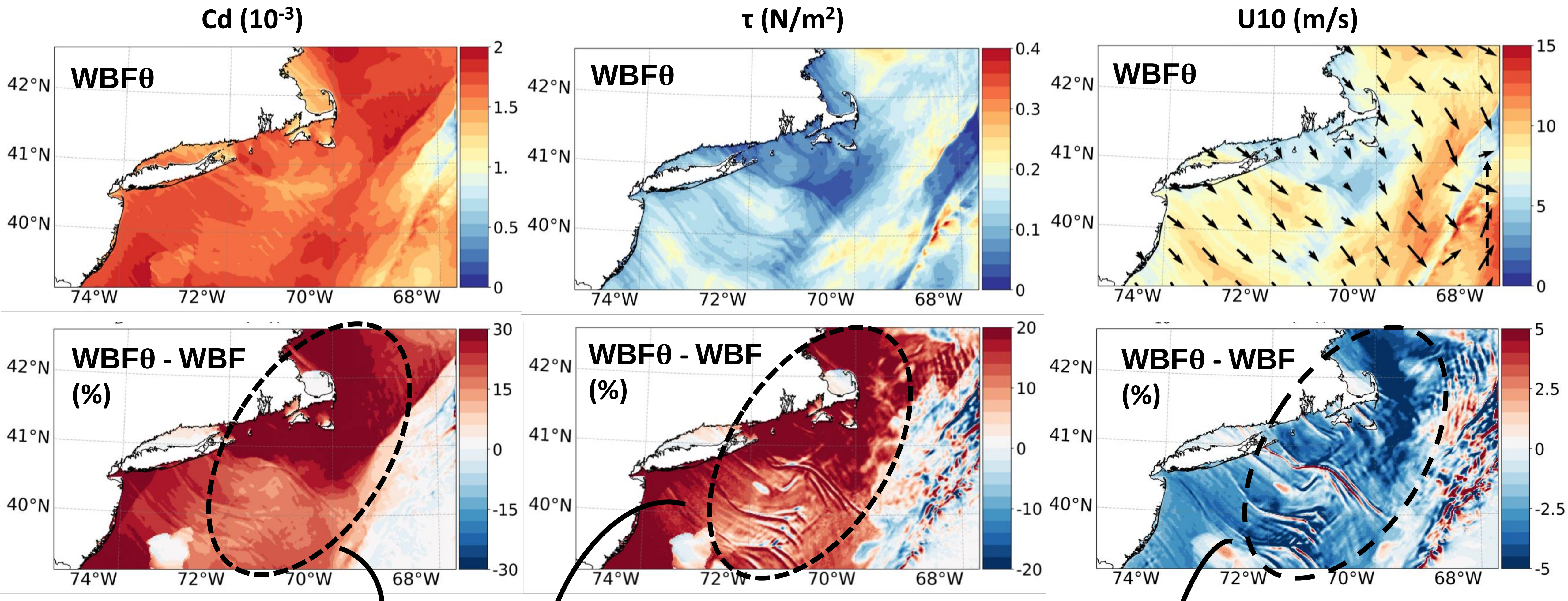
Strong southerly waves aligned with the wind in the pre-cold-frontal conditions.

While the wind shifted to northerly, strong southerly waves were still present leading to strong misalignment during the post-cold-front conditions.

After the cold front, younger waves are generated following the northwesterly wind, contributing to the mixed sea state conditions.

Misaligned waves impact on momentum flux

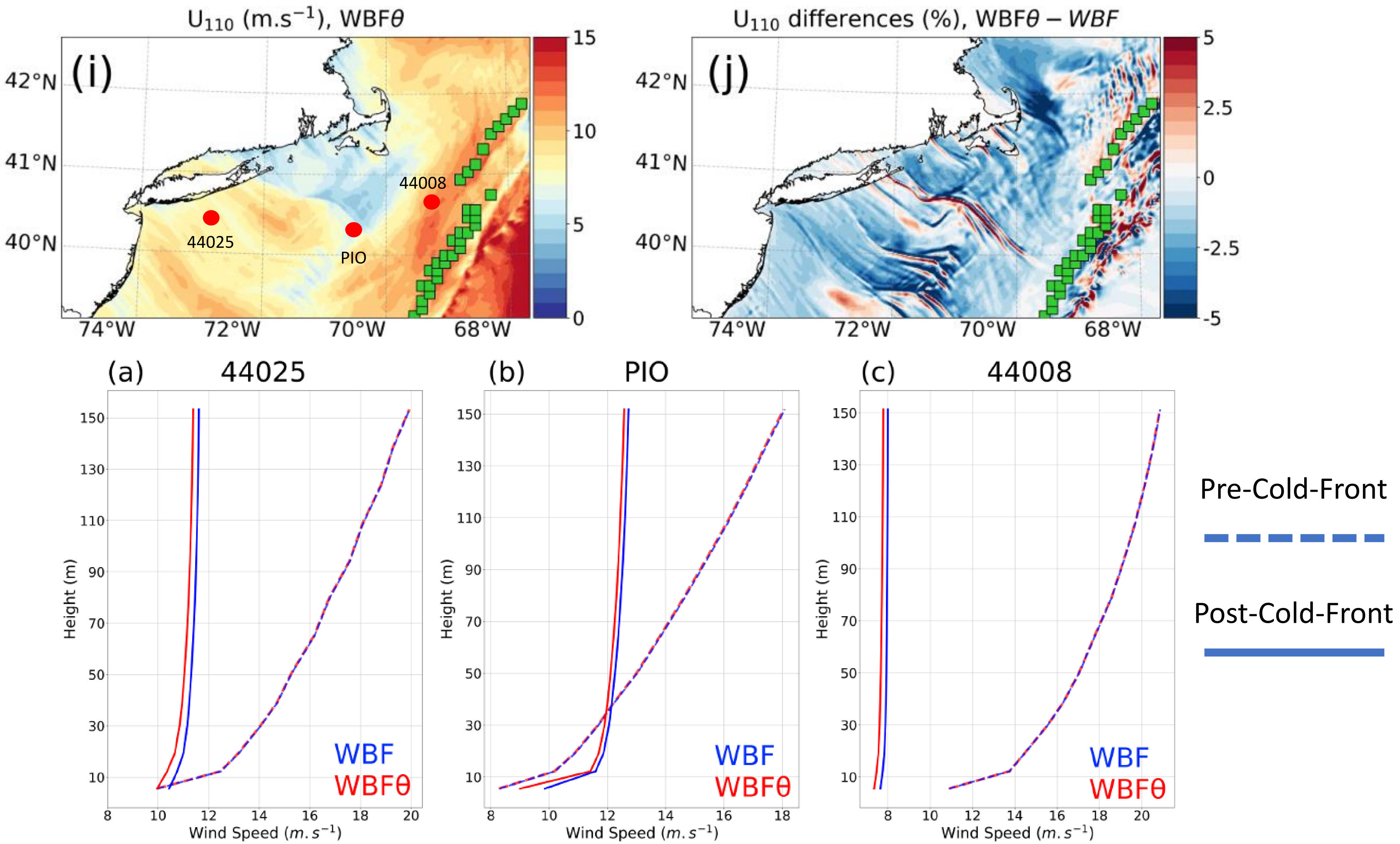
2017-12-06-15:00



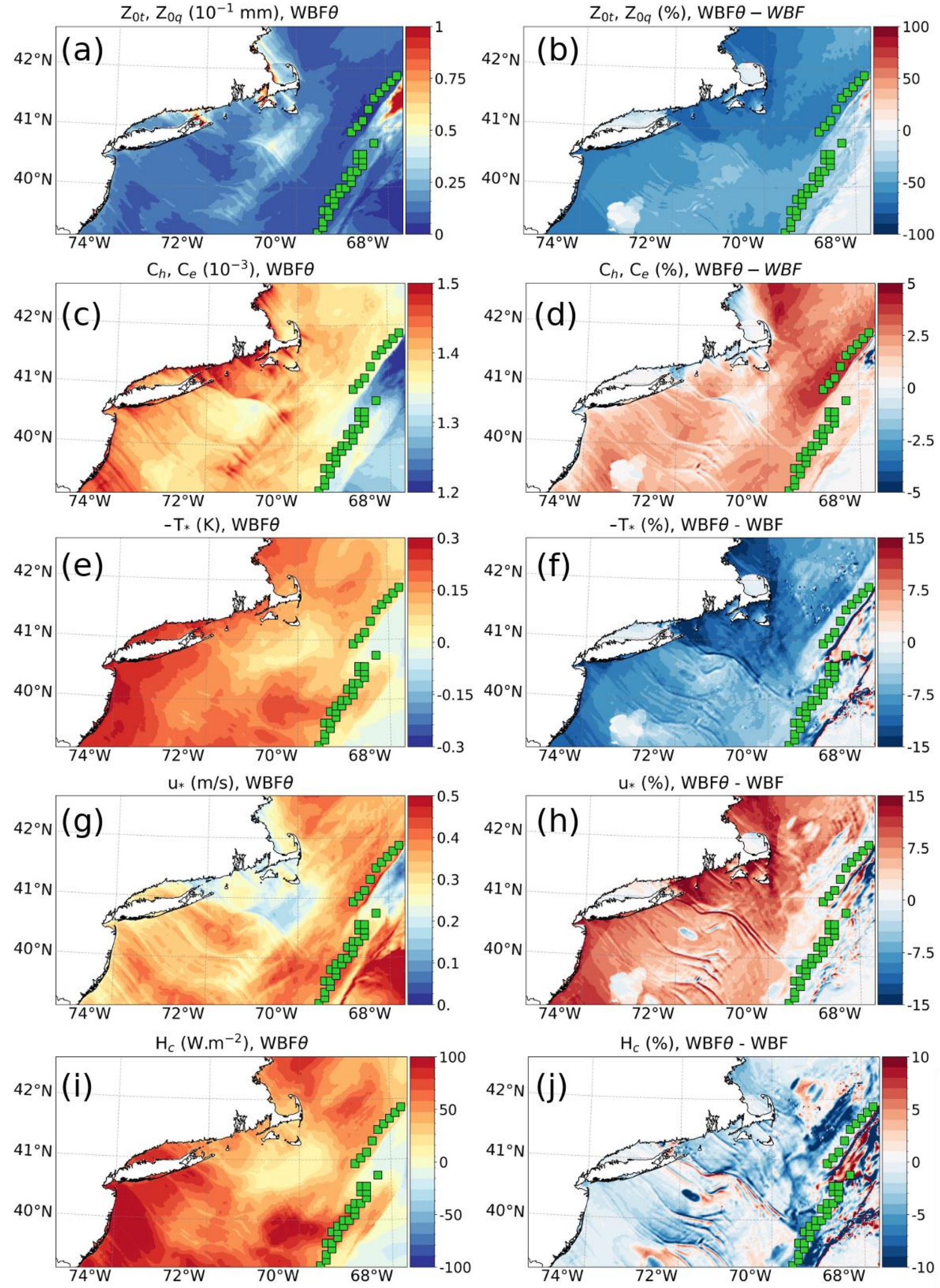
Surface drag coefficient and momentum stress increase by 20% and 11% on average behind the cold front

Direct impact on the surface wind speed which decreases by 2% on average

Misaligned waves impact on wind profile



Misaligned waves impact on heat flux



$$\tau = \rho_a C_D \Delta U_r^2 = \rho_a u_*^2,$$

$$H_s = \rho_a C_{pa} C_h \Delta U_r \Delta T = -\rho_a C_{pa} u_* T_*,$$

$$H_l = \rho_a L_e C_e \Delta U_r \Delta Q = -\rho_a L_e u_* q_*,$$

$$z_{0t} = \frac{5.8e^{-5}}{R_r^{0.72}}, \qquad R_r = \frac{u_* z_0}{\nu},$$

The increase in z0 due to wave misalignment decreases z0t (60%) and the turbulent flux scale for temperature, T* by up to 15% (5% on average).

The increase in u* (4% on average) due to misalignment is more than offset by the decrease in − T*, resulting in a 1.5% decrease on average in heat fluxes.

Supplementary figures

$$\tau = \rho_a C_D \Delta U_r^2 = \rho_a u_*^2,$$

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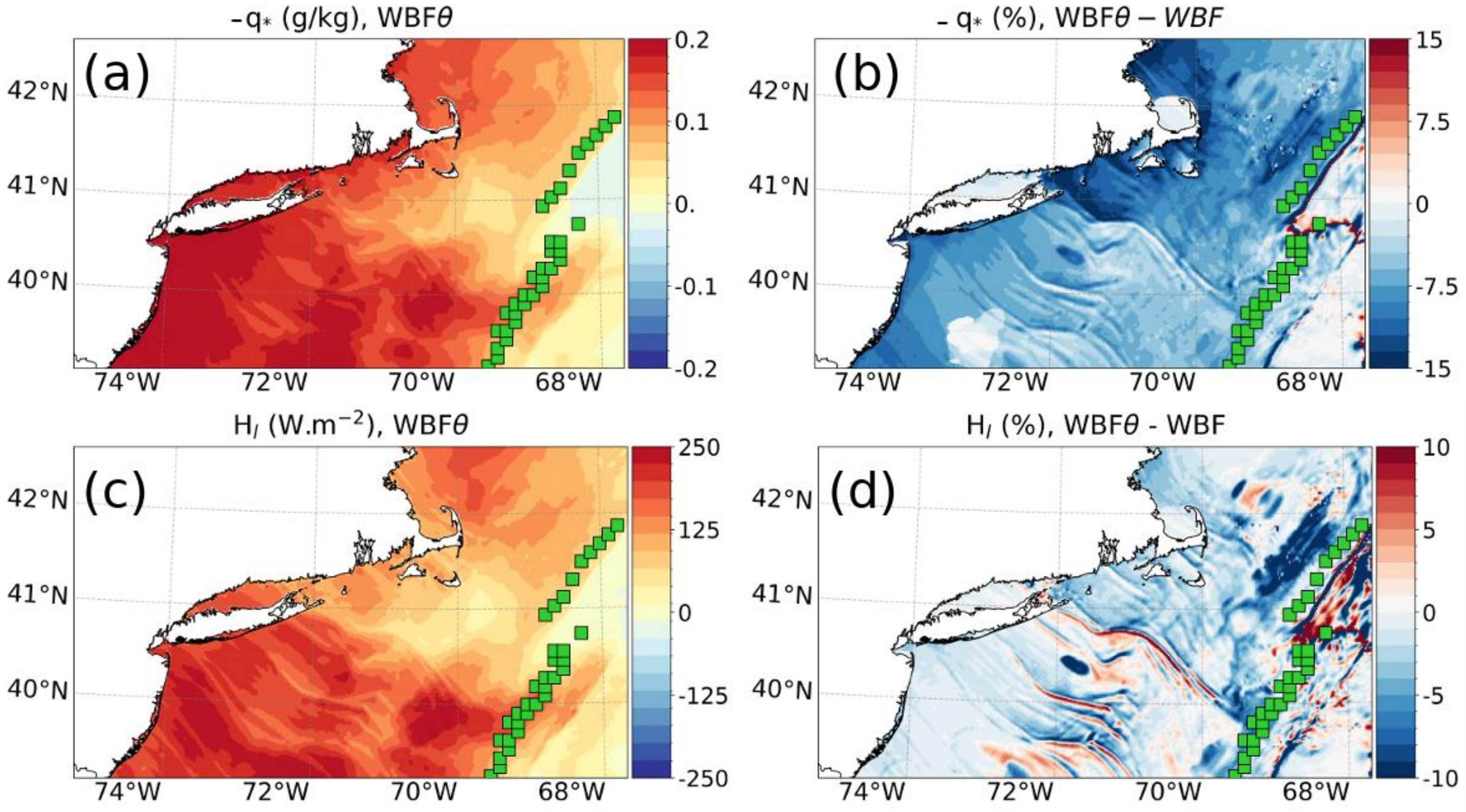

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