Misaligned Wind-Waves Behind Atmospheric Cold Fronts

César Sauvage[1], Hyodae Seo[1], Benjamin W. Barr[1], Carol Anne Clayson[2], James B. Edson[2]

1-University of Hawai'i at Manoa, HI,USA | 2-Woods Hole Oceanographic Institution, MA, USA

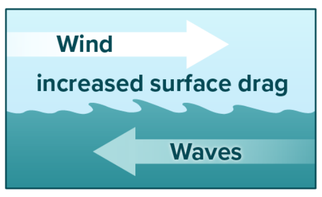
Sauvage et al. 2024
DOI: 10.1029/2024JC021162

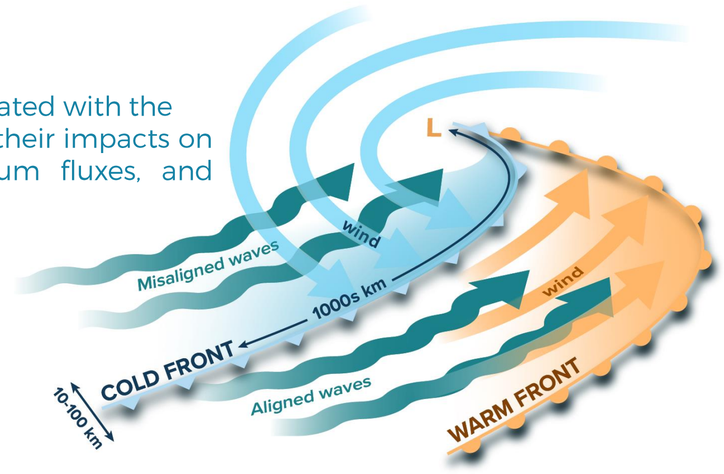
Introduction

Atmospheric cold fronts have along-frontal scales of many 1000s km, but much shorter cross-frontal scales of 10-100s km. At the sea surface, the high winds near the fronts generate strongly coupled short wind-waves, while the abrupt shift in wind direction across the front, combined with the rapid translation of the frontal system, produces a large area of misaligned surface waves behind the cold fronts.

Objectives:

Characterize the sea state associated with the misaligned waves and evaluate their impacts on surface drag, air-sea momentum fluxes, and wind profiles.





Regional Coupled Modeling

The surface fluxes are parameterized via COARE3.5

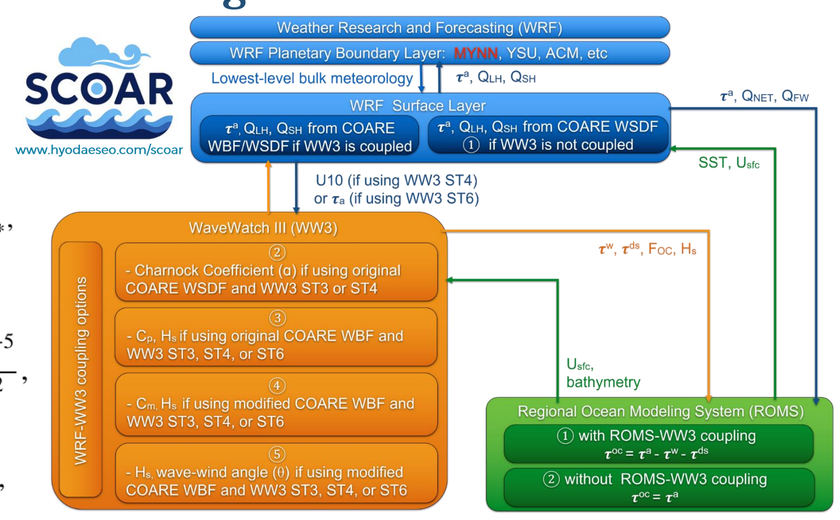
$$\tau = \rho_a C_D S_r U_r = \rho_a u_*^2,$$

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

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

Scalar roughness length for temperature $z_{0t} = \frac{5.8e^{-5}}{R_r^{0.72}}$,

Roughness Reynolds number $R_r = \frac{u_* z_0}{\nu}$,



Case study simulations using the SCOAR coupled model with different wave-based roughness length (z_0) formulations:

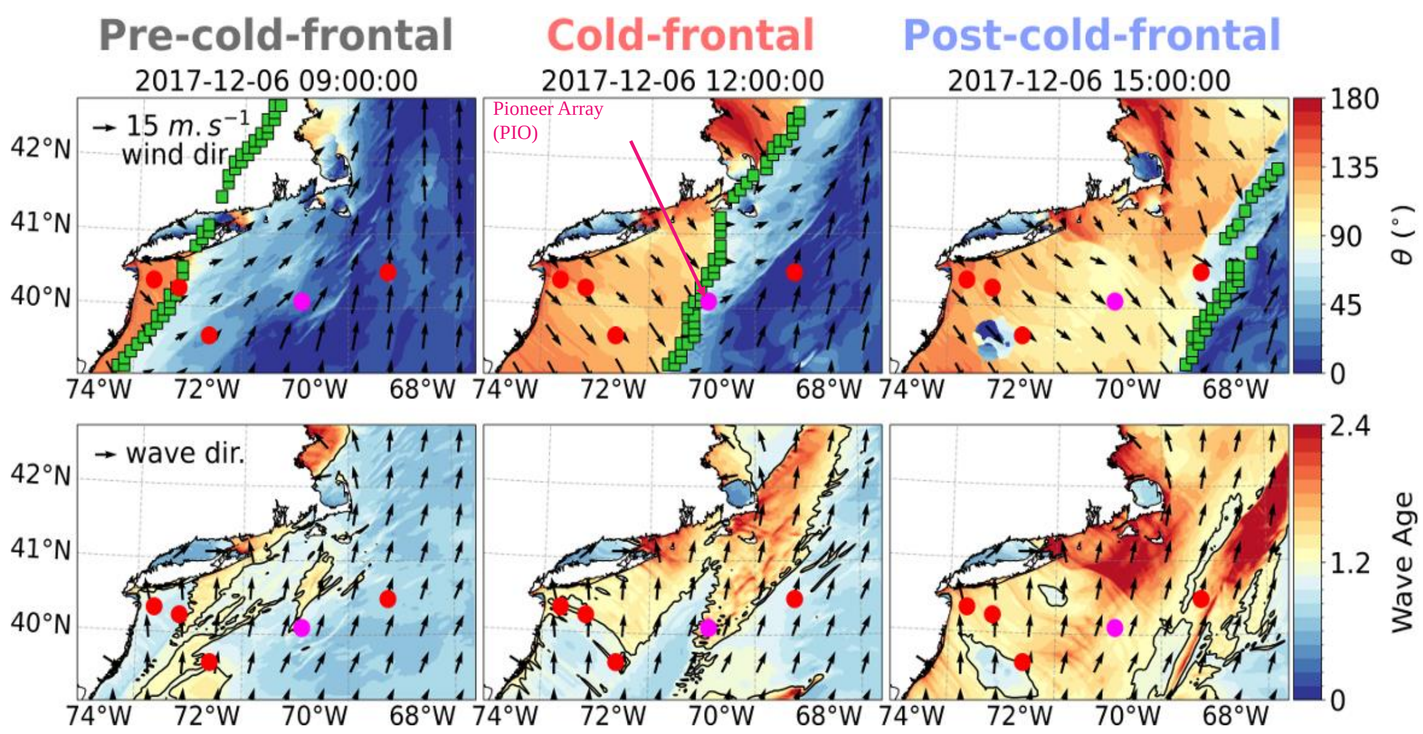
WBF: $z_0 = H_s D \left(\frac{u_*}{c_p}\right)^B$, D=0.09 ; B=2

Wind and waves are assumed to be aligned, θ = 0.
Reference: Edson et al. 2013

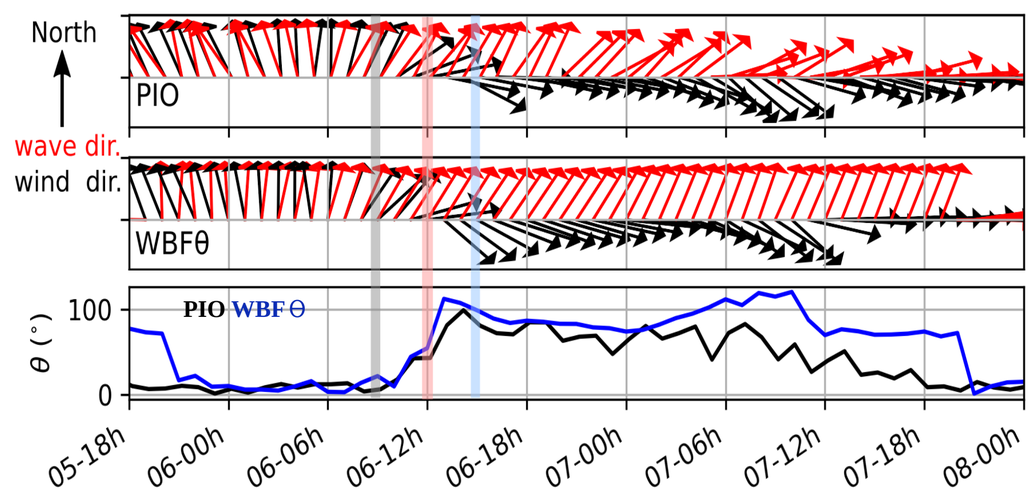
WBFΘ: $z_0 = H_s D \cos(a\theta) \left(\frac{u_*}{c_p}\right)^{B\cos(b\theta)}$, a=0.4; b=-0.32

Account for wind wave misalignment, , θ ≠ 0.
Reference: Sauvage et al. 2023, 2024

Atmospheric cold front passing on December 6th 2017

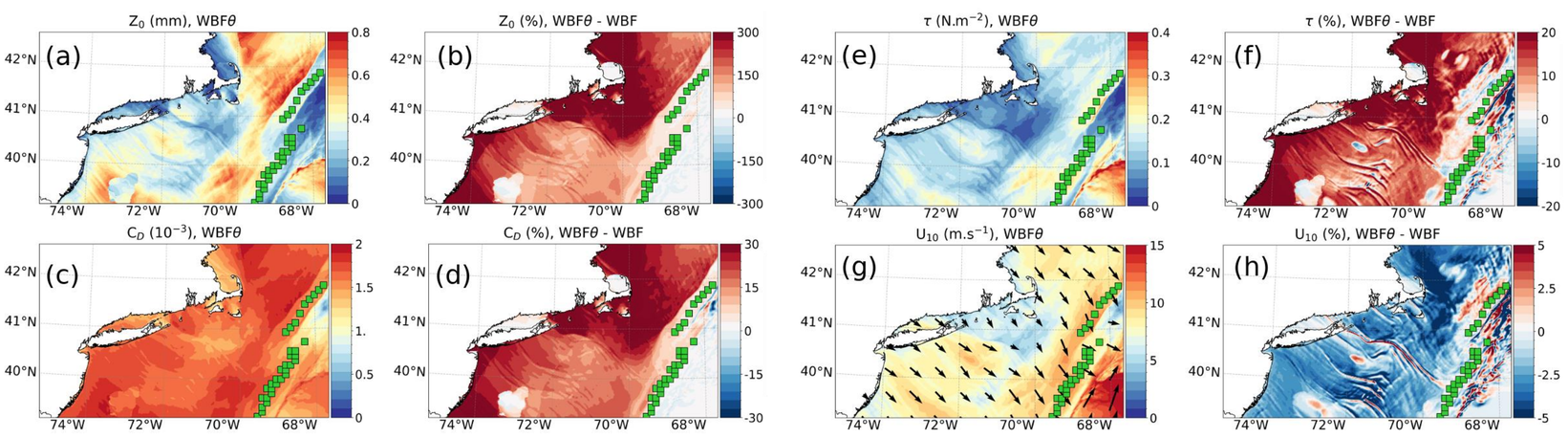


Cold front location



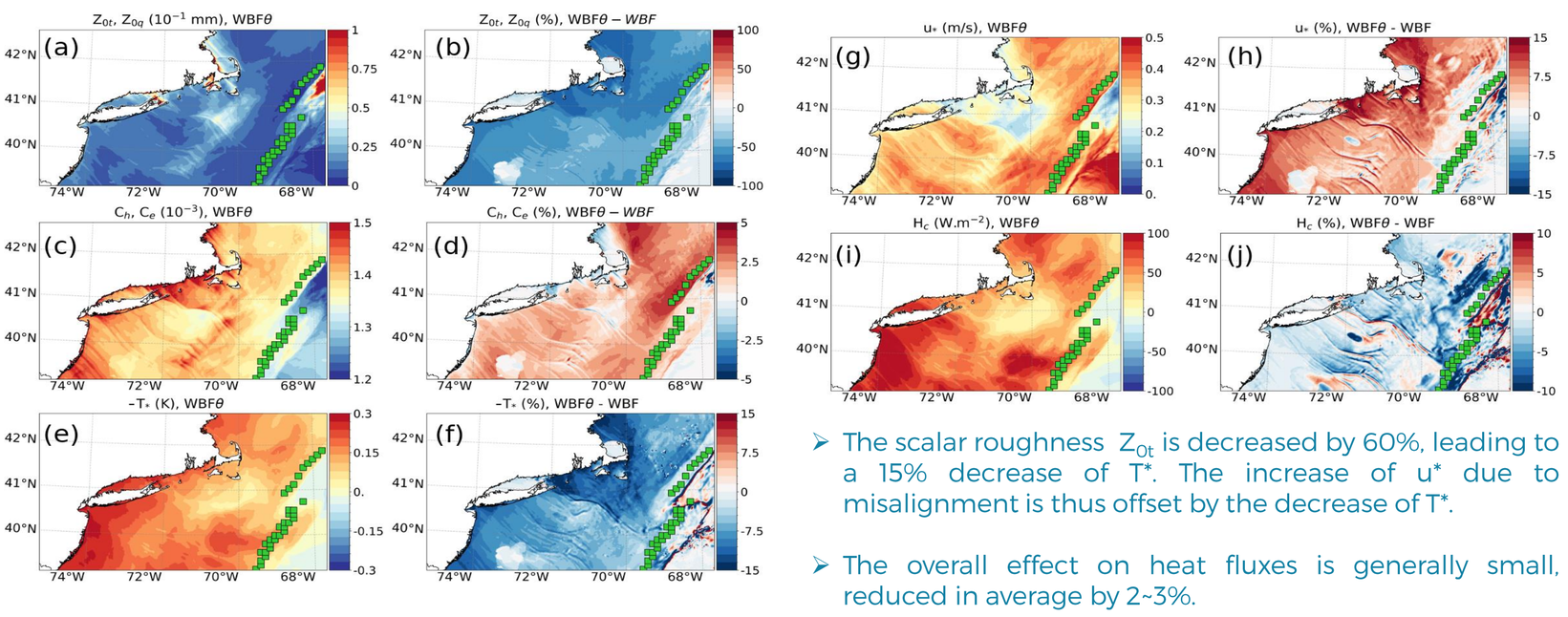
- Strong southerly waves aligned with the wind in the pre-cold-frontal conditions.
- While the wind shifted to northerly, strong southerly waves were still present leading to strongly misaligned waves during more than 12h hours after the passage of the cold front ..!

Misaligned waves impact on momentum flux



- East of the cold front, where the wave and wind are largely aligned, little difference are found.
- Sizable increases are found in z_0, C_D, and τ west of the cold front. The increase can be as high as 300% for z_0, 30% for C_D, and 20% for τ, respectively. Because of the increase in the surface drag, U_{10} is reduced in WBFΘ by up to 5%.

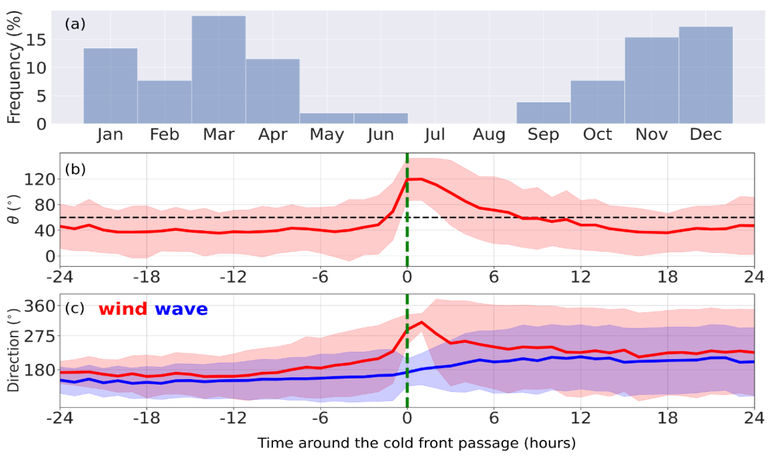
Misaligned waves impact on heat flux

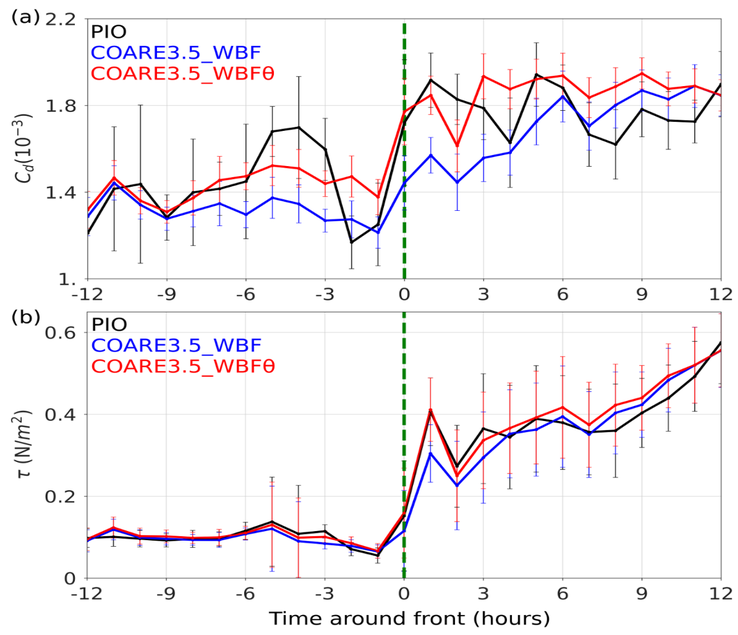


- The scalar roughness Z_{0t} is decreased by 60%, leading to a 15% decrease of T*. The increase of u* due to misalignment is thus offset by the decrease of T*.
- The overall effect on heat fluxes is generally small, reduced in average by 2~3%.

Direct covariance flux system measurements at Pioneer Array

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





- Using WBFΘ 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 -7.6% in WBF to 3.5% in WBFΘ.