

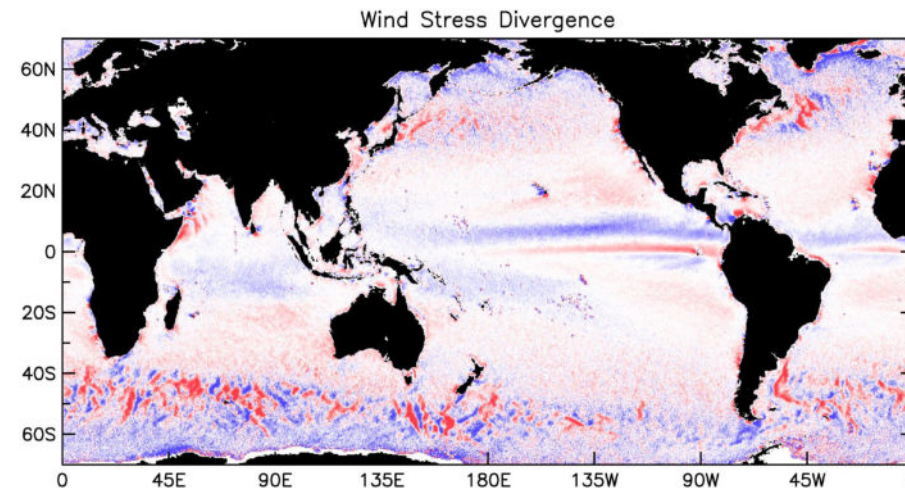
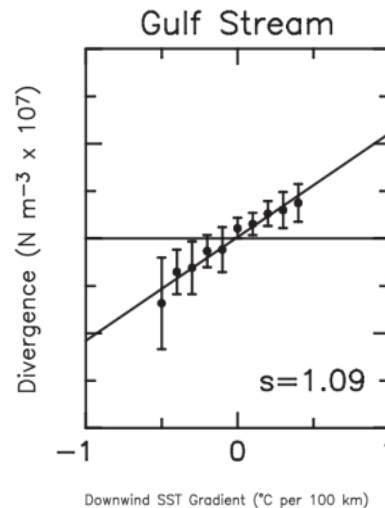
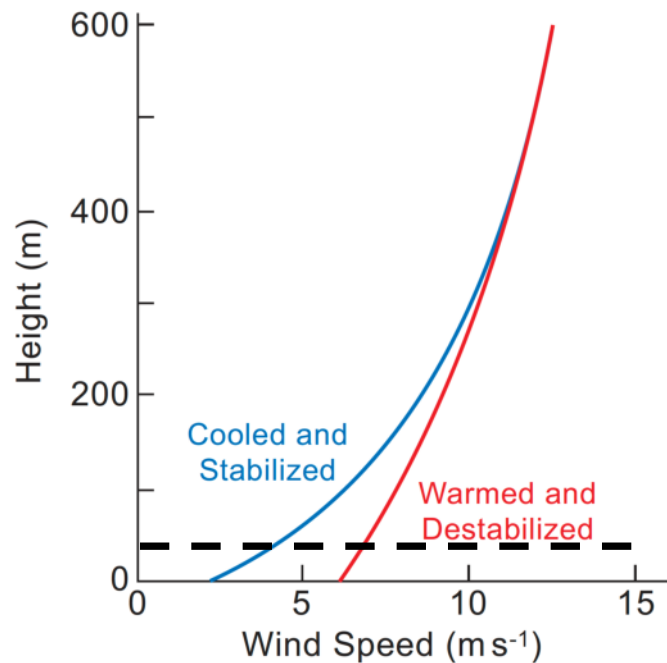
Observations of Finescale SST-Wind Coupling in High-Wind Conditions

Mingming Shao^{1,2}, Gregory Foltz¹, Jun Zhang^{1,2}, Matthieu Le Henaff¹

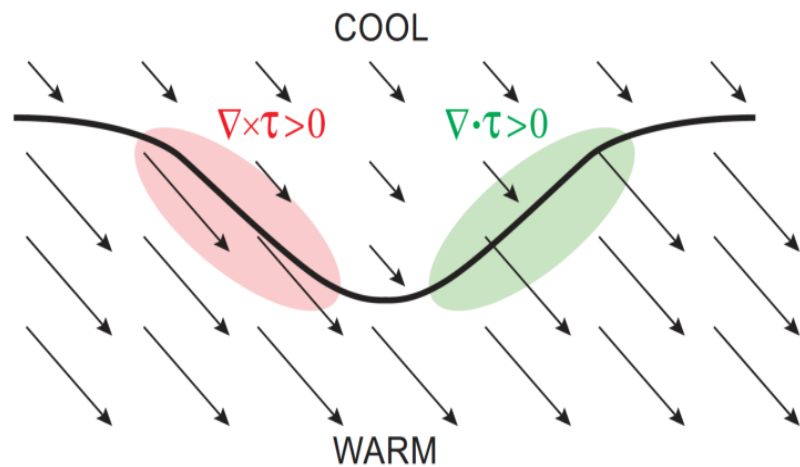
- 1. NOAA Atlantic Oceanographic and Meteorological Laboratory (AOML), Miami, FL**
- 2. Cooperative Institute for Marine and Atmospheric Studies, University of Miami, Miami, FL**

Background and motivation: Mesoscale SST-Wind Coupling

Chelton et al. 2004



Key processes of MABL adjustment

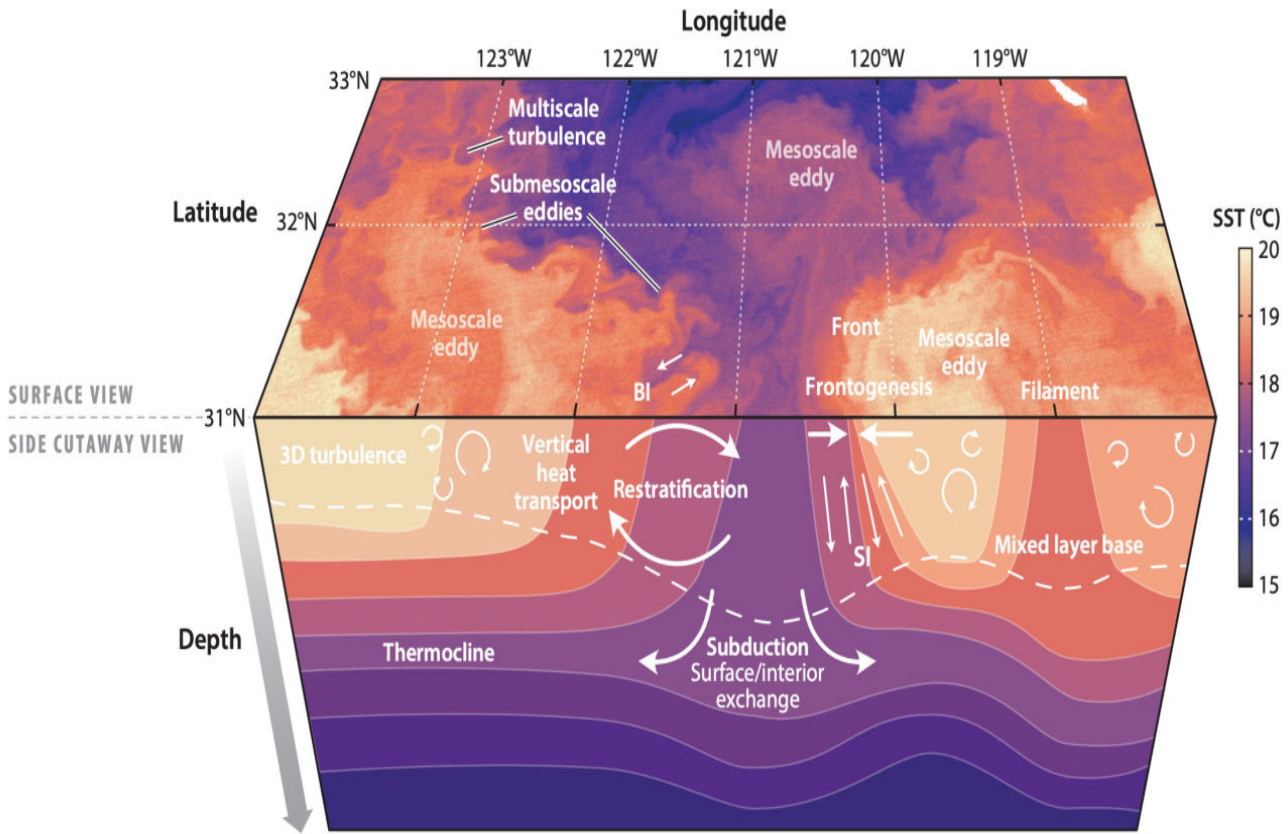


SST anomalies \rightarrow Heat flux variation

momentum mixing and pressure adjustment

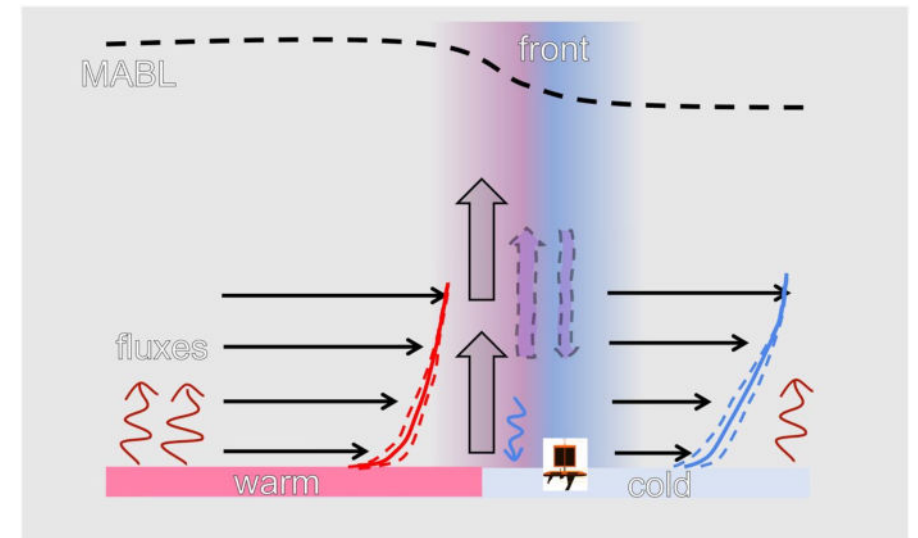
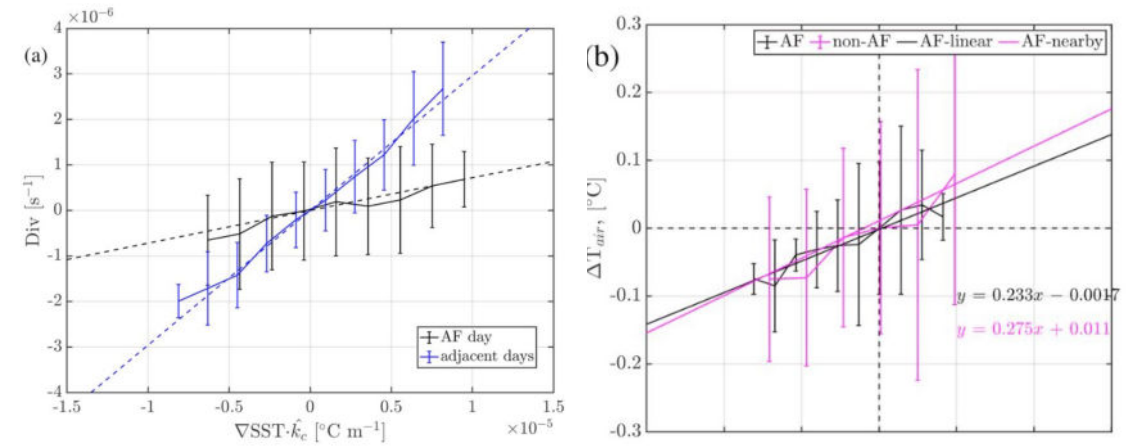
Variation of surface wind and momentum flux

Submesoscale SST-Wind Coupling



Taylor and Thompson, 2023

Synoptic events shaping SST-Wind coupling

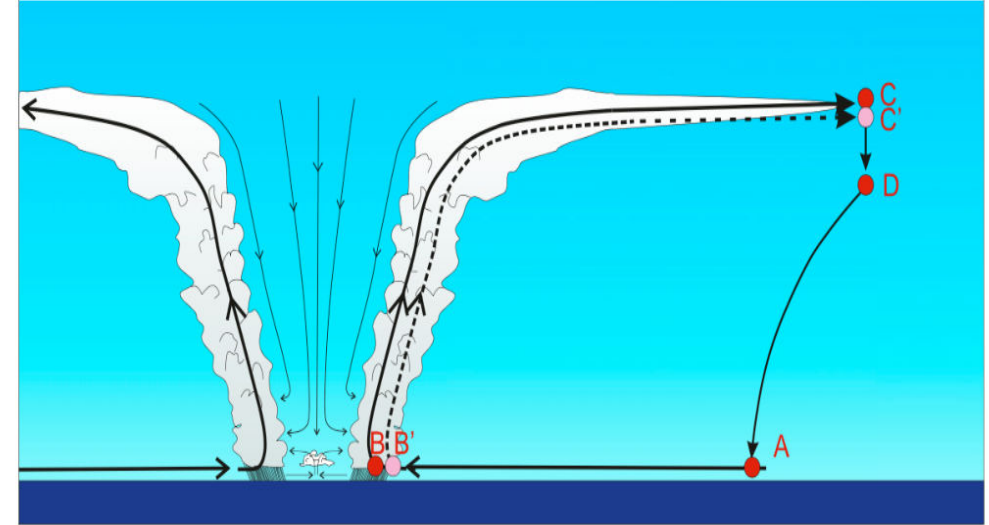


Shao et al 2024, 2019

Air-sea Interaction under TC Conditions

Tropical cyclone (TC) intensification related physical processes:

- **Surface enthalpy flux**
- Boundary layer process and eyewall turbulent mixing
- Microphysics and radiative impact
- TC structure
- Upper ocean structure
- ...



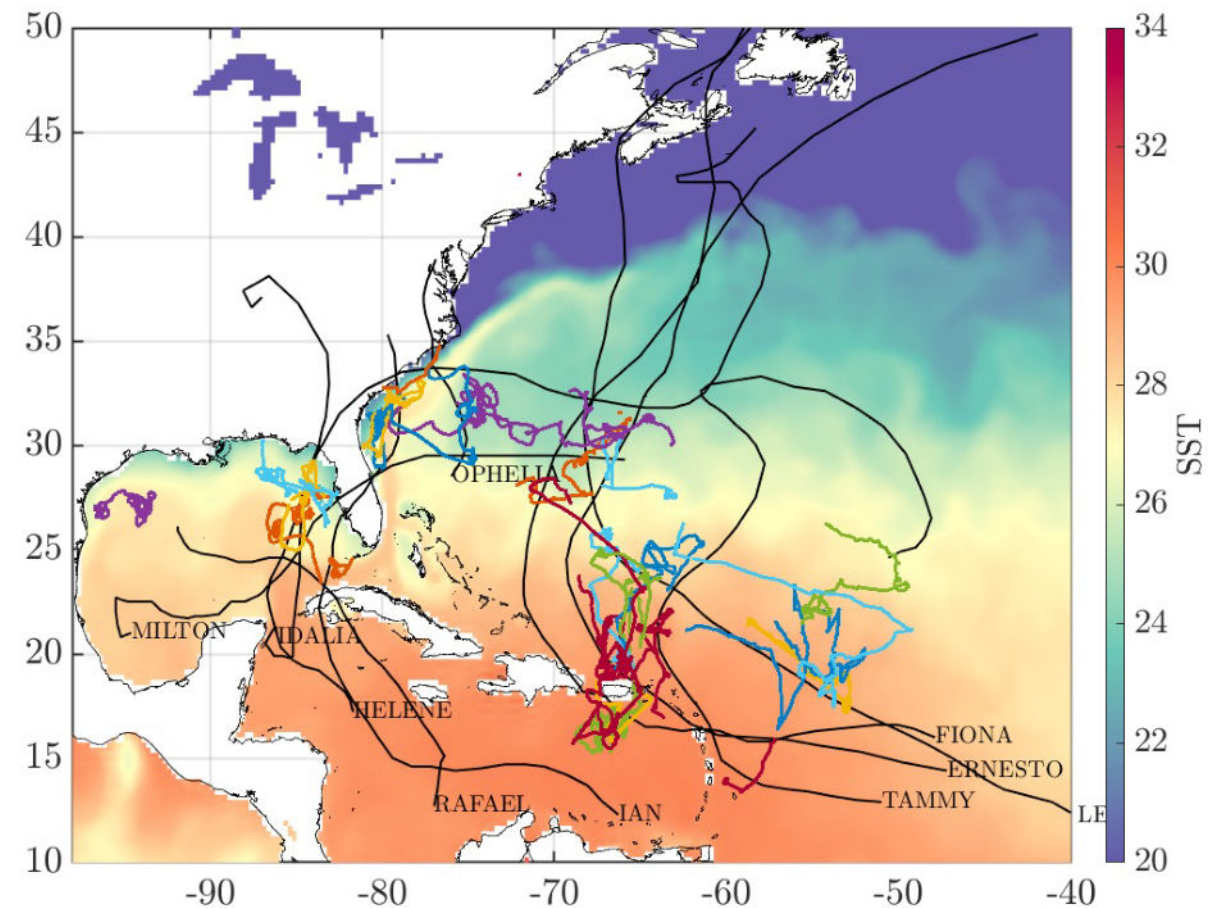
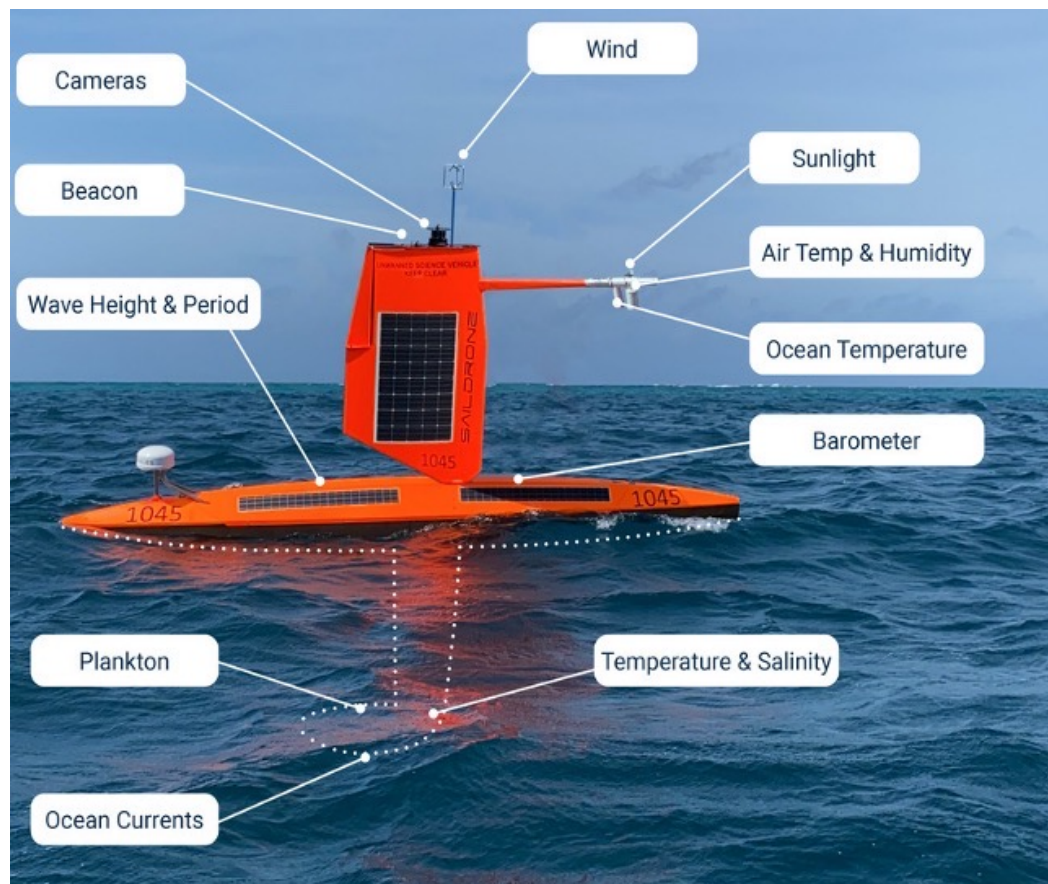
Emanuel 2021, TC review paper

- Wind induced surface heat exchange (**WISHE**) (*Emanuel et al 1986*): “...the intensification and maintenance of TC depend exclusively on self-induced heat transfer from the ocean ...”
- SST is assumed to be smoothed, or slowly evolved background, which may not be hold.
- The current operational model does not adequately resolve these processes

Research Questions:

- Q1, How do submesoscale SST-Wind Coupling in high-wind conditions?
 - Surface heat flux variation
 - Surface wind variation
- Q2, Does TC turbulence alter classical SST-Wind coupling pathways?
 - Strong convection
 - Enhance upper ocean boundary mixing
- Q3, Can finescale SST heterogeneity locally modulate TC boundary layer structure?

Data: Sairdrone Observation in Atlantic Hurricane Missions + ERA 5



Foltz et al 2026

Method: Isolating SST-Induced Flux Perturbations

Bulk formula

$$SHF = \rho C_p C_h (U - U_c) (\theta_s - \theta)$$

$$LHF = \rho L_e C_q (U - U_c) (q_s - q)$$

heat flux perturbation test

$$\Delta\theta = \theta - \bar{\theta}$$

$$SHF, LHF = COARE(\theta_A, \theta_O, \mathbf{u}_A, \mathbf{u}_O, q_A, p_A)$$

$$\overline{SHF}_{ocn}, \overline{LHF}_{ocn} = COARE(\theta_A, \bar{\theta}_O, \mathbf{u}_A, \mathbf{u}_O, q_A, p_A)$$

$$\overline{SHF}_{atm}, \overline{LHF}_{atm} = COARE(\bar{\theta}_A, \theta_O, \bar{\mathbf{u}}_A, \mathbf{u}_O, q_A, p_A)$$

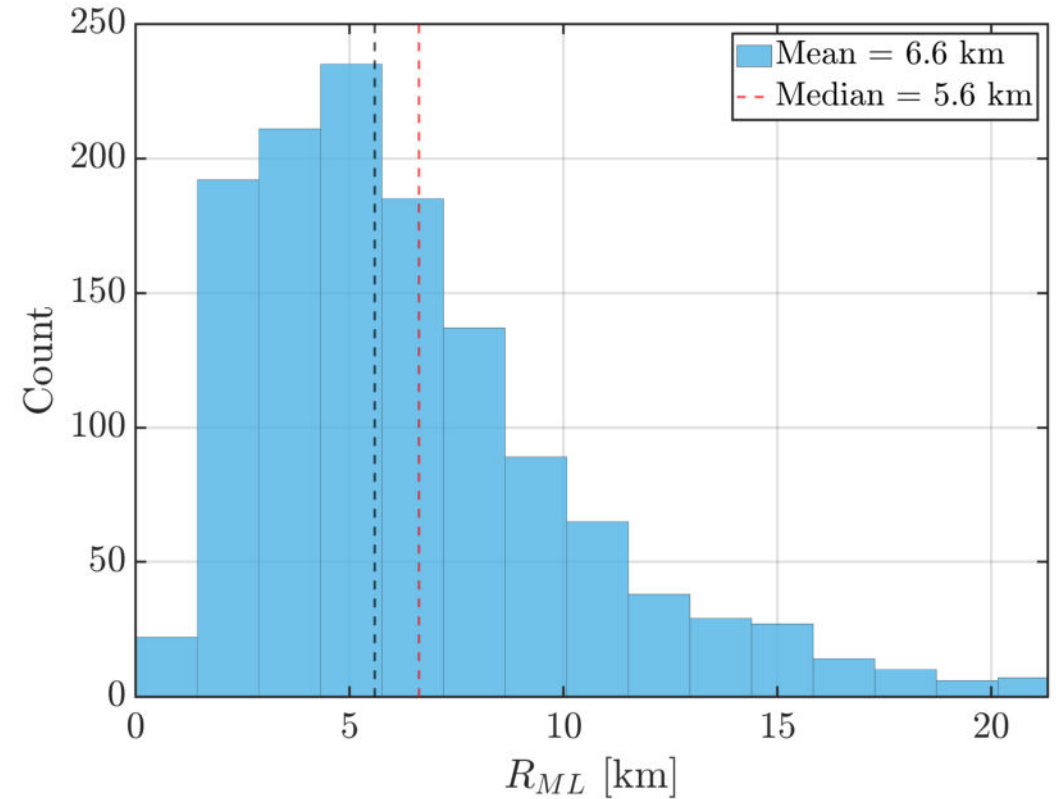
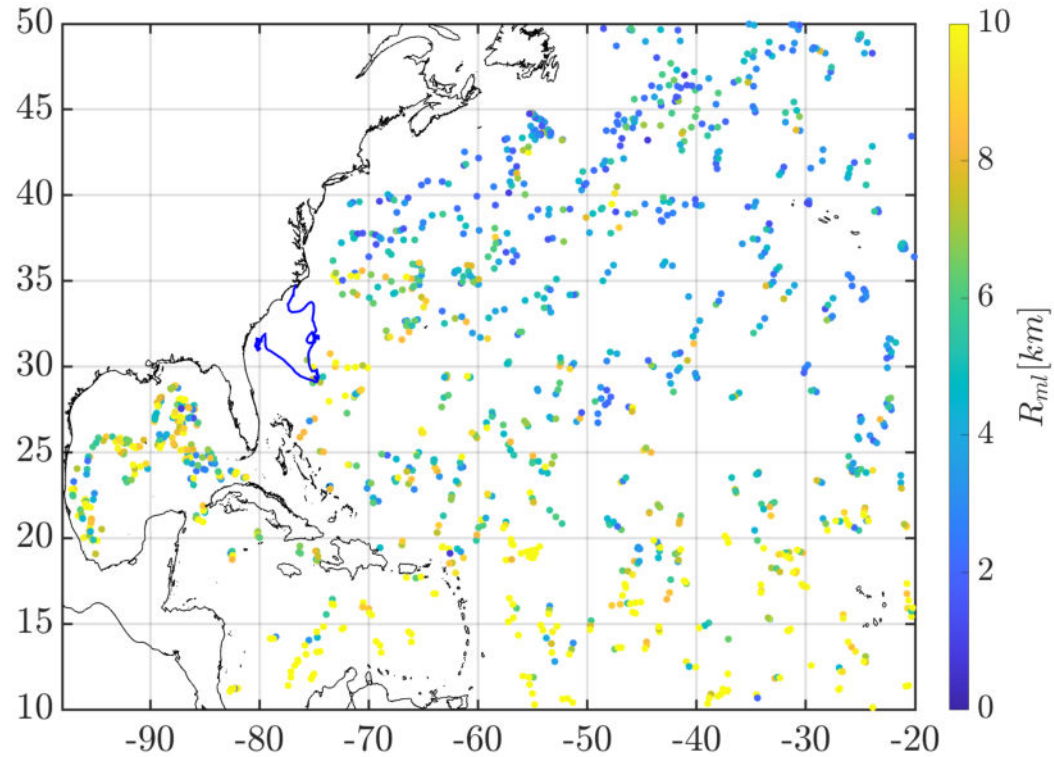
$$\Delta SHF = SHF - \overline{SHF}$$

$$\Delta LHF = LHF - \overline{LHF}$$

- Spatial filter length: local mixed layer deformation radius
- Limitation of COARE bulk algorithm in high wind condition

Ref: Iyer et al 2022; Busecke and Balwada 2025

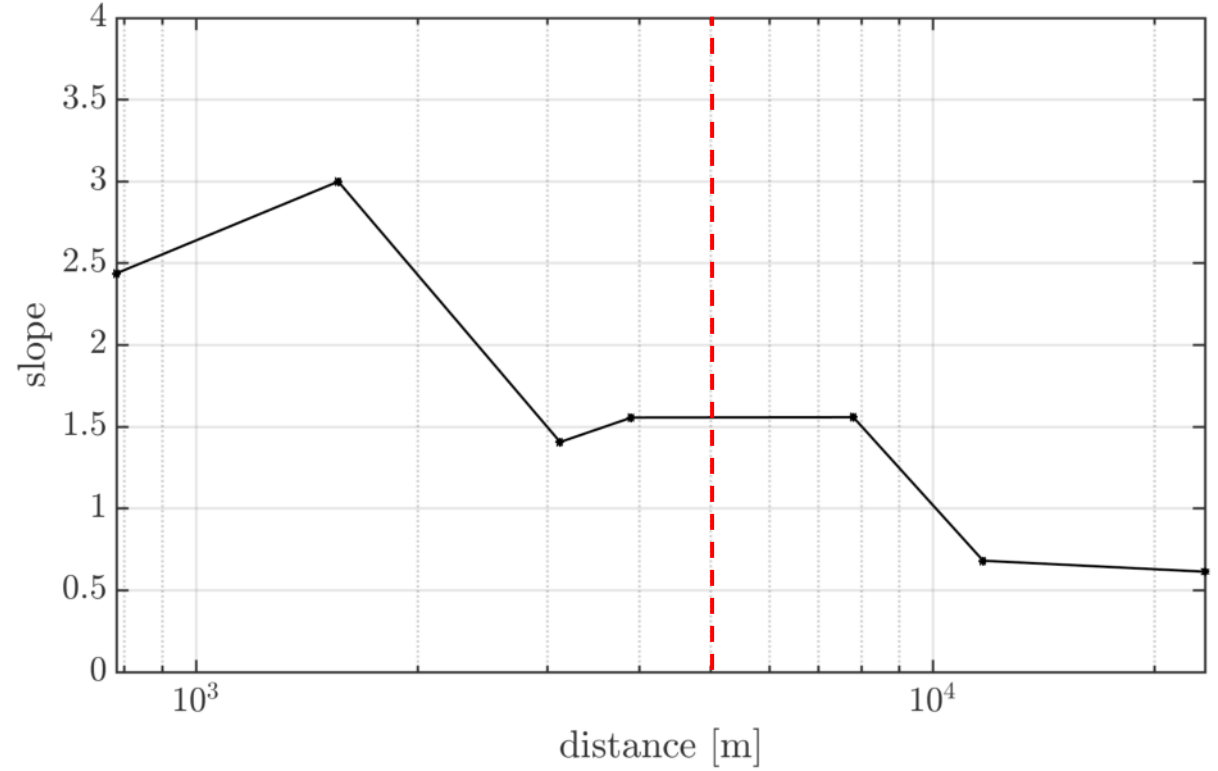
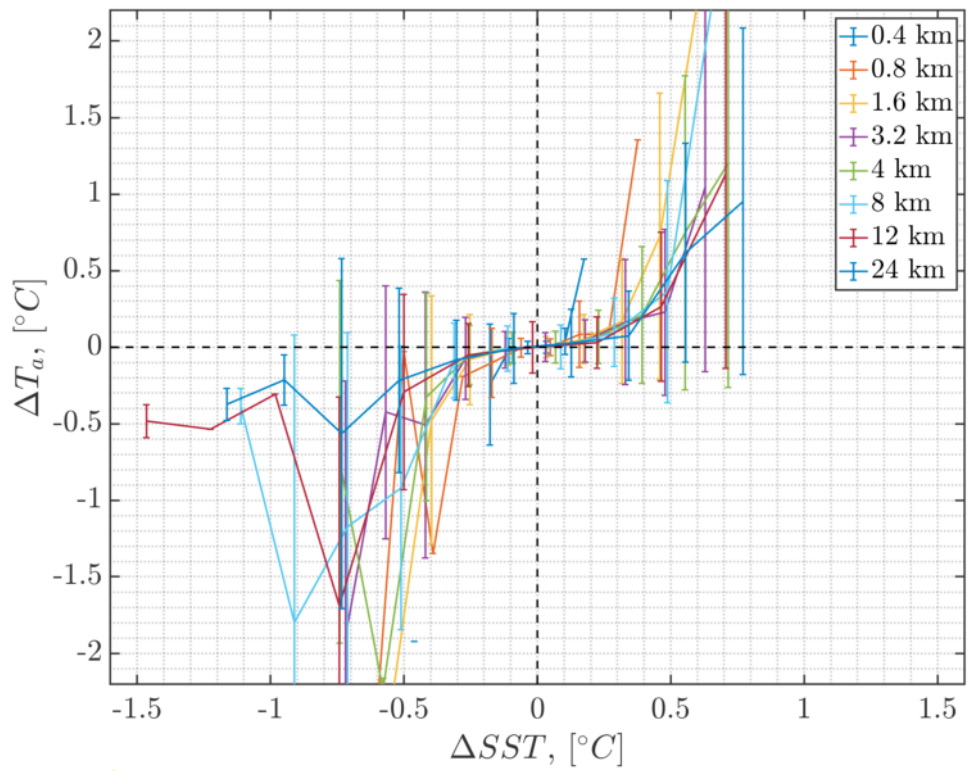
Mixed layer deformation radius



- Mixed layer deformation radius in Oct 2024
- Saildrone moving speed: 1 m/s \rightarrow 3.6 km/hr

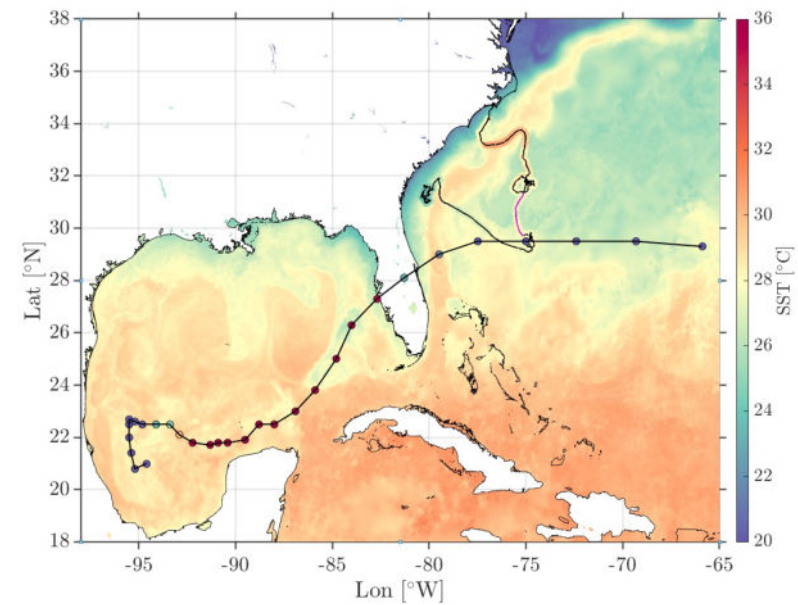
$$R_{ML} = \frac{N_{ML} H_{ML}}{f}$$

SST - Ta coupling strength vs smooth length scale

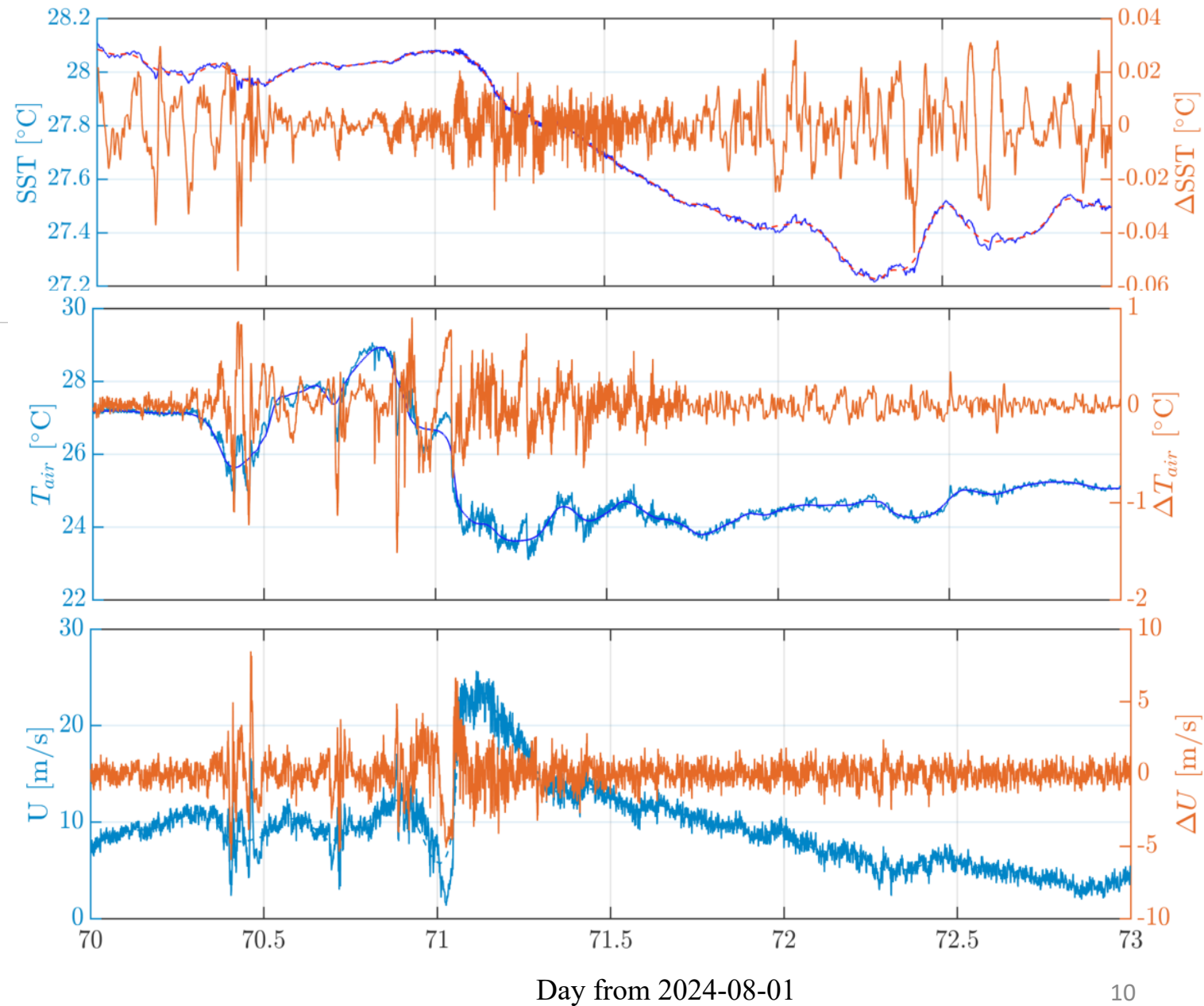
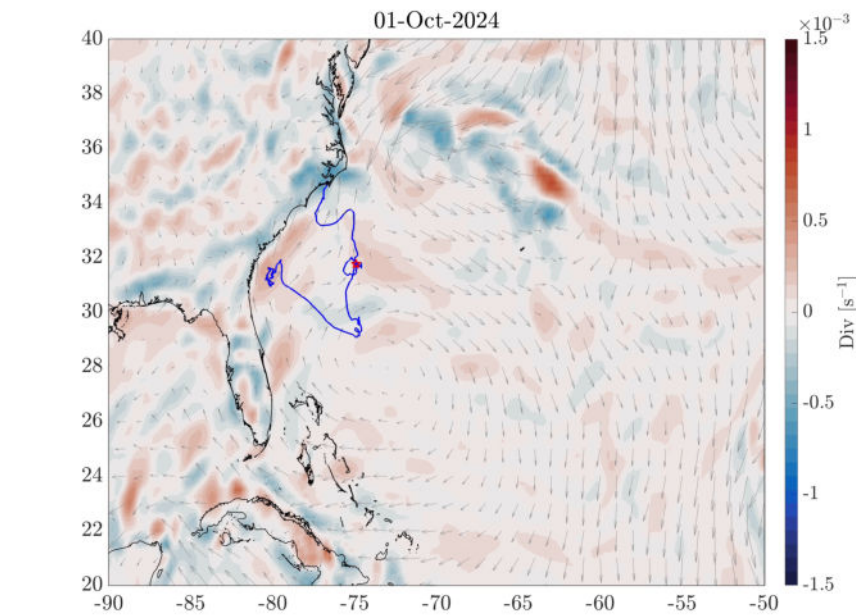


- Air-sea Coupling coupling between SST and Ta perturbation changes with filter length scale
 - The maximum coupling exists at about 1.2 km \rightarrow on the order of the mixed layer deformation radius
 - The coupling strength decreases with the increase in filter length scale

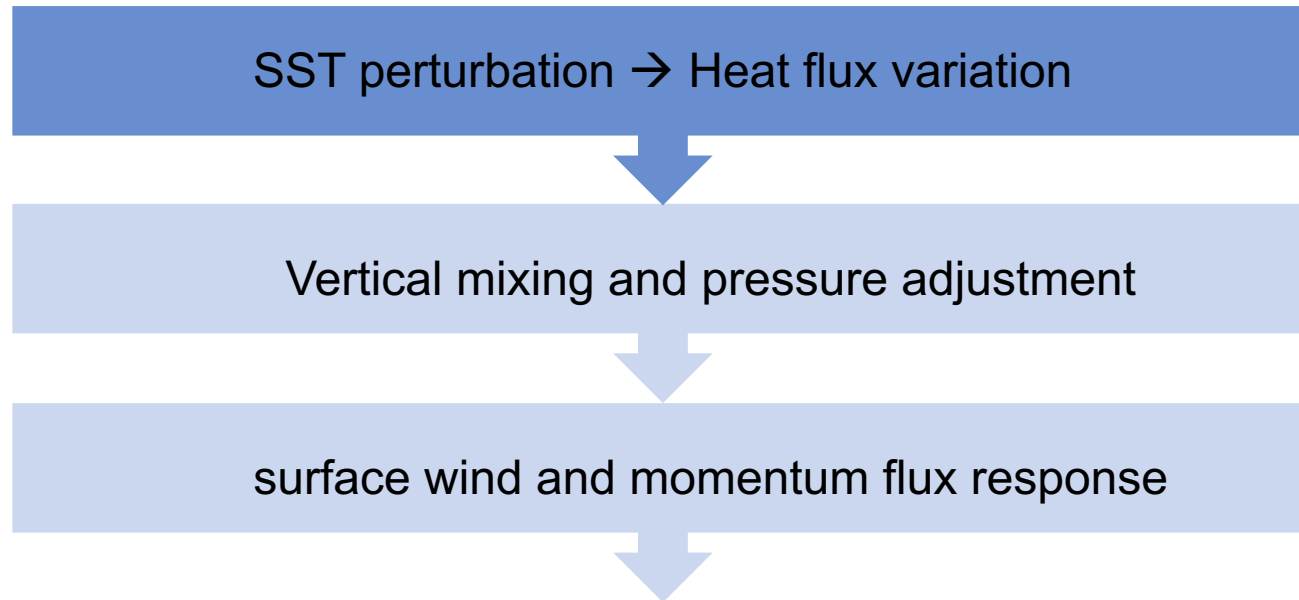
Saildrone observation in Milton (2024)



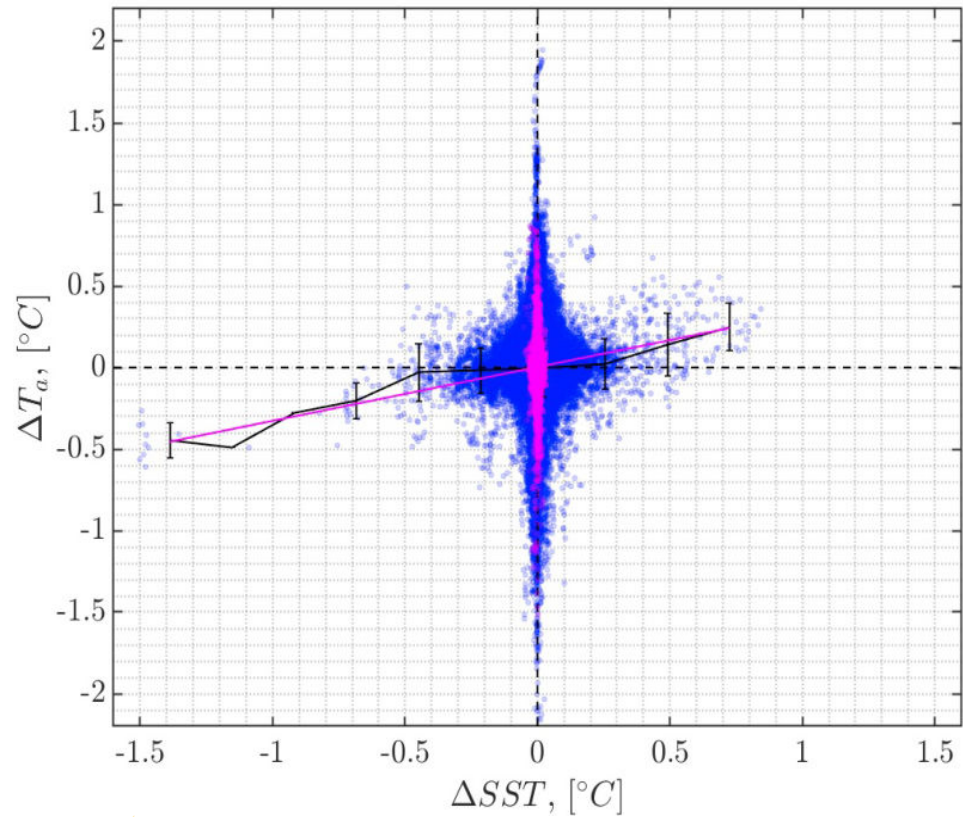
01-Oct-2024



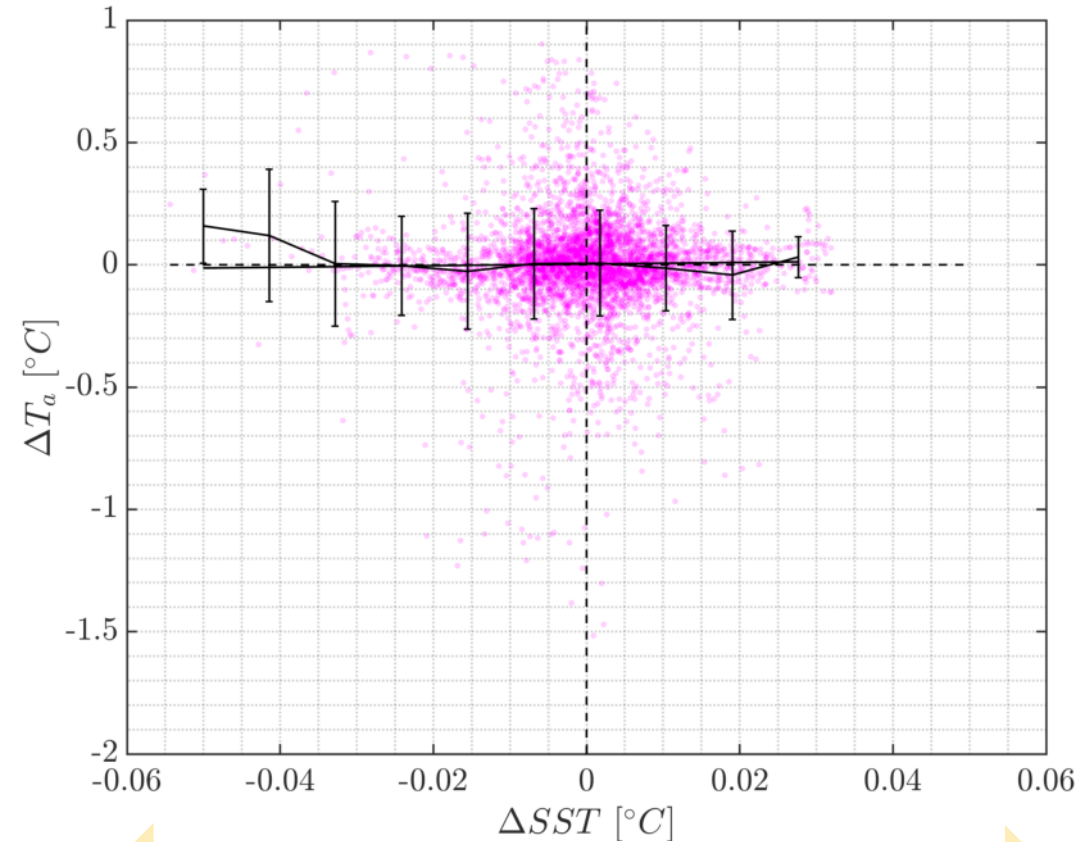
Key processes of MABL Thermal adjustment



SST-heat flux coupling strength for Milton (2024)



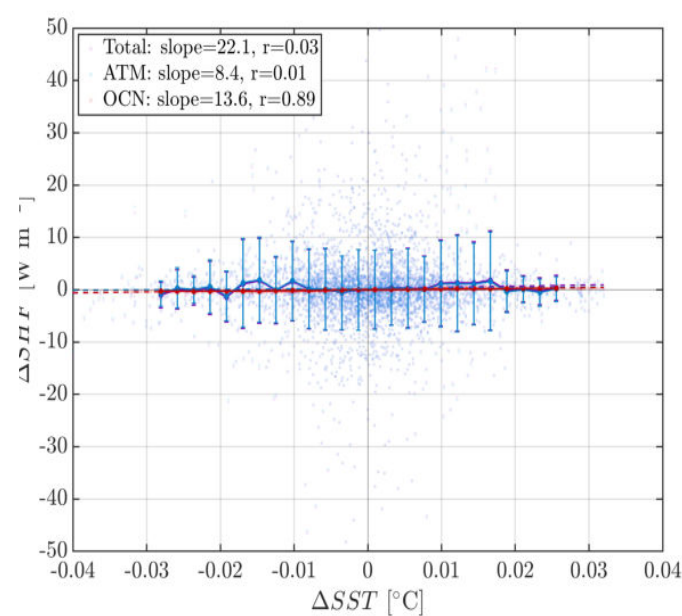
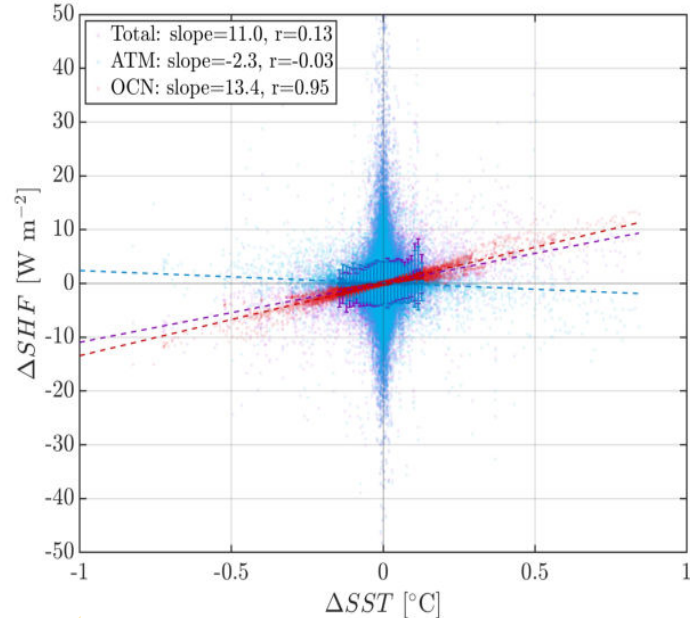
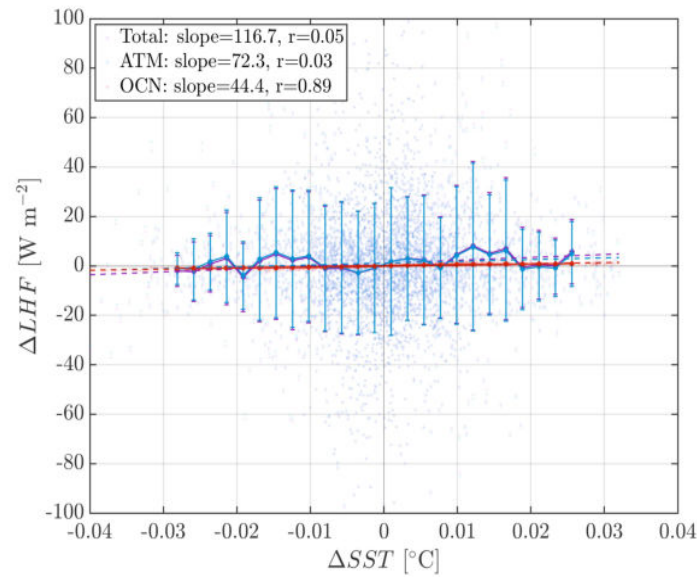
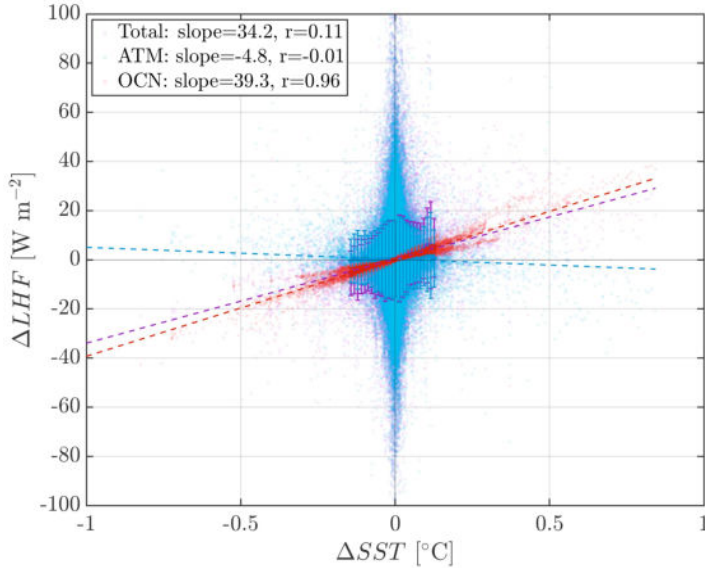
warm to cold cold to warm



warm to cold cold to warm

- TC winds suppress surface T_a thermal adjustment

SST-heat flux coupling strength for Milton (2024)



Non-TC condition:

- Ocn forcing \rightarrow positive heat flux
- Atm forcing \rightarrow negative heat flux
- Total forcing \rightarrow positive heat flux

TC condition:

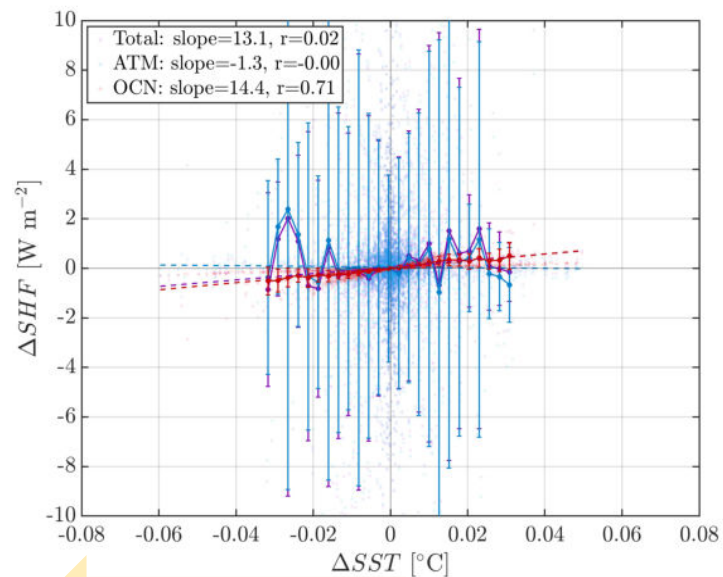
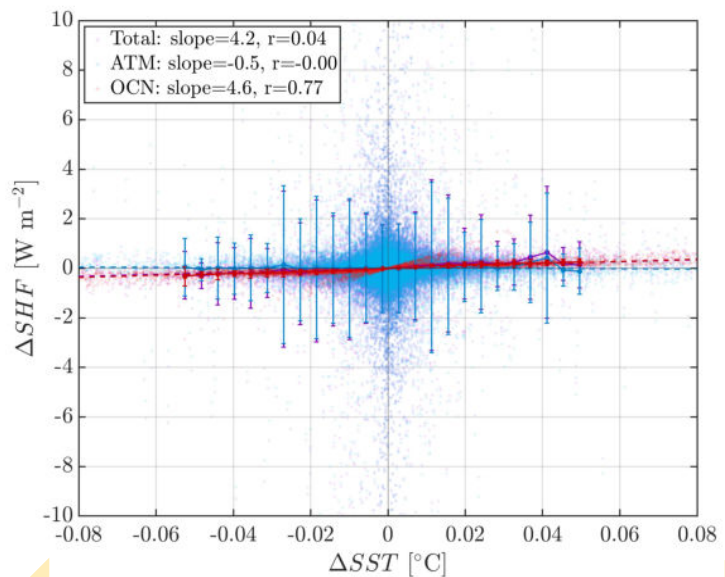
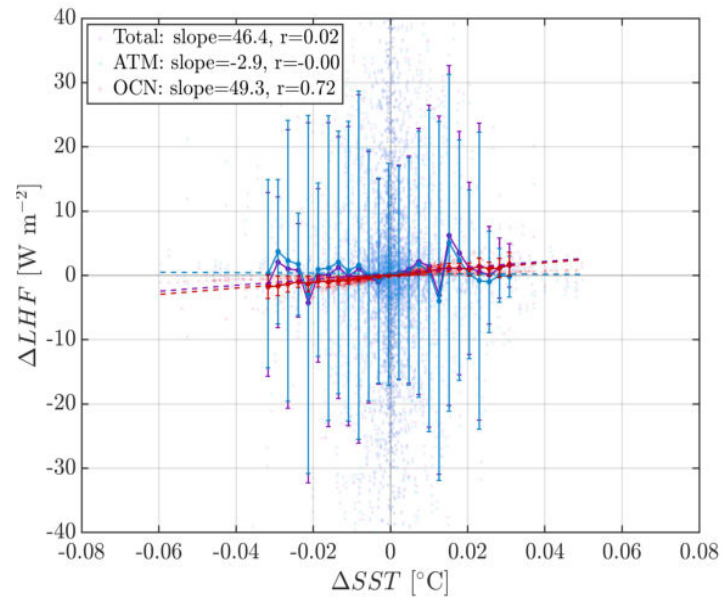
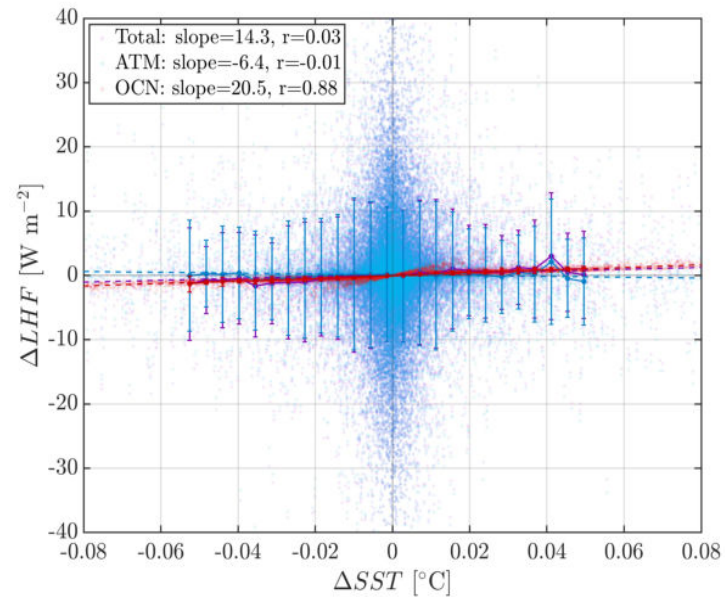
- SST-heat flux weakened substantially
- Ocn forcing persist
- Atm forcing is strongly suppressed
- Consistent with vertically saturated turbulent mixing

SHF varies consistently with LHF

warm to cold cold to warm

warm to cold cold to warm

SST-heat flux coupling strength for Ernesto (2024)

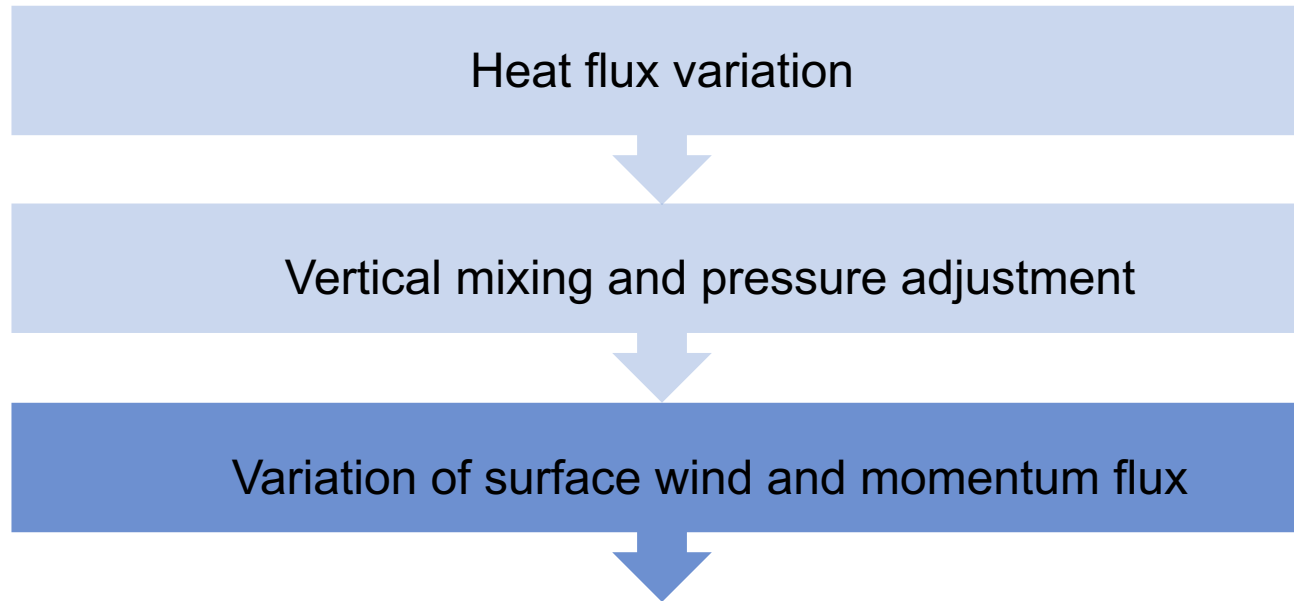


- Independent validation in Ernesto (2024)
- And many other TCs ...

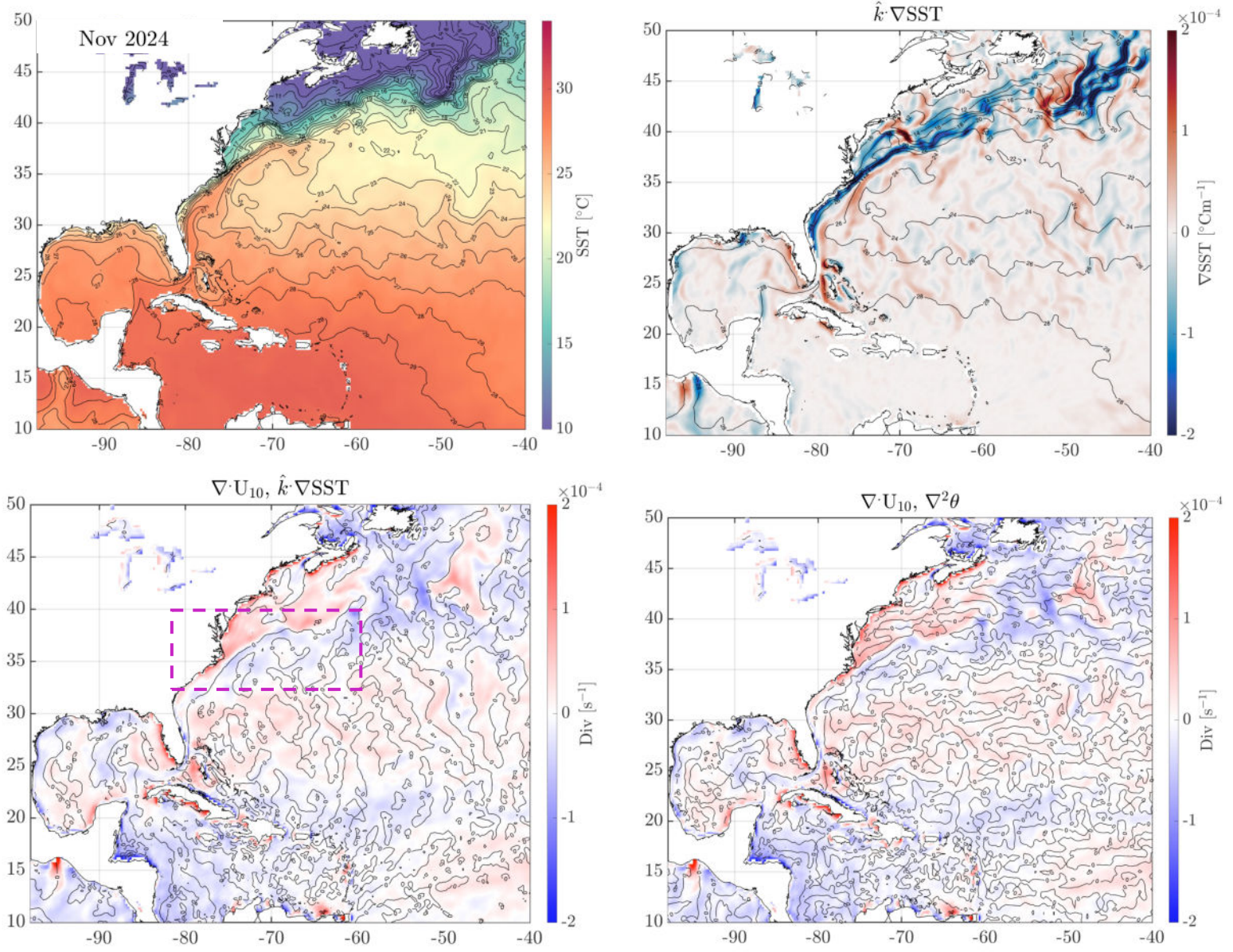
warm to cold cold to warm

warm to cold cold to warm

Key processes of MABL adjustment

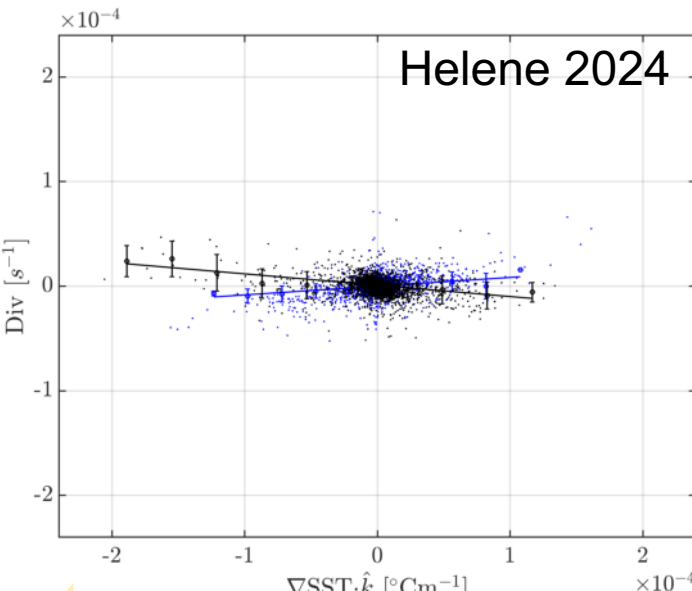
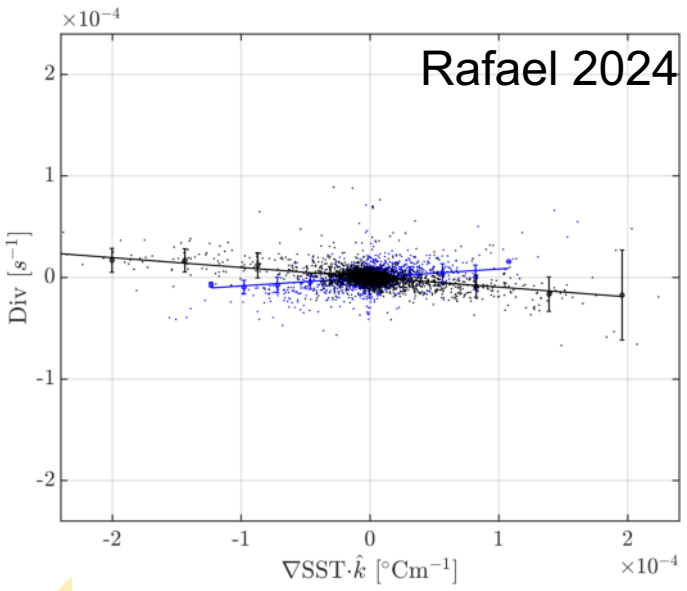
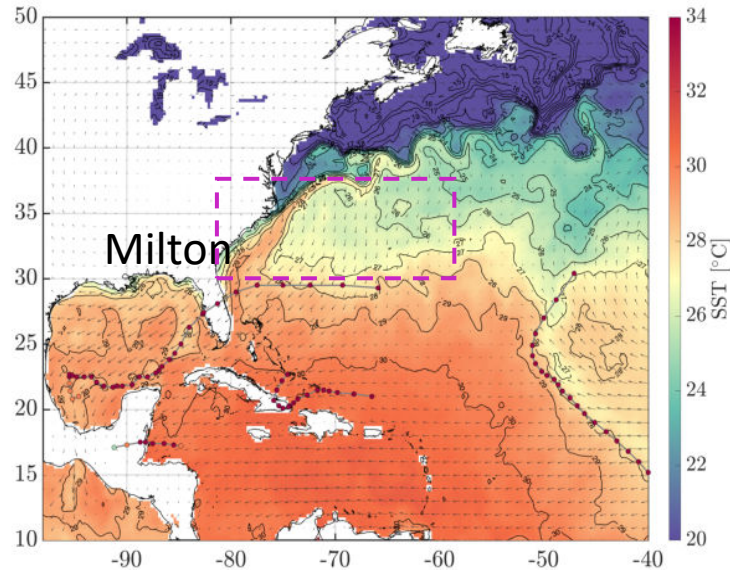
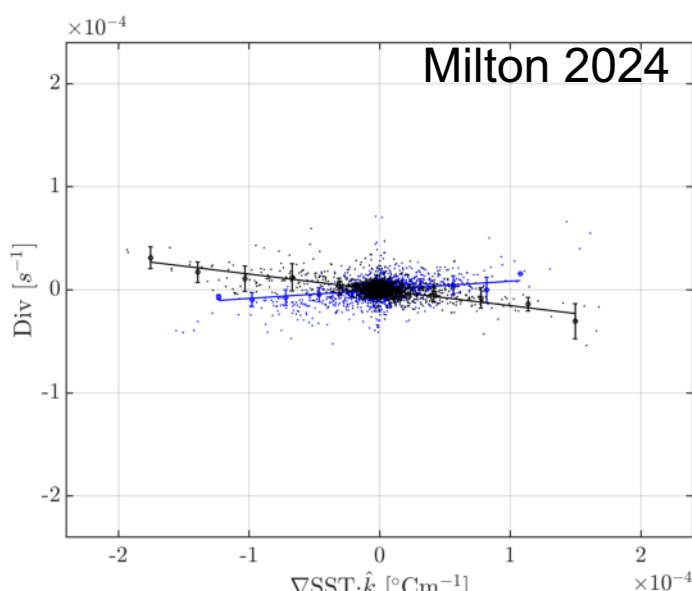
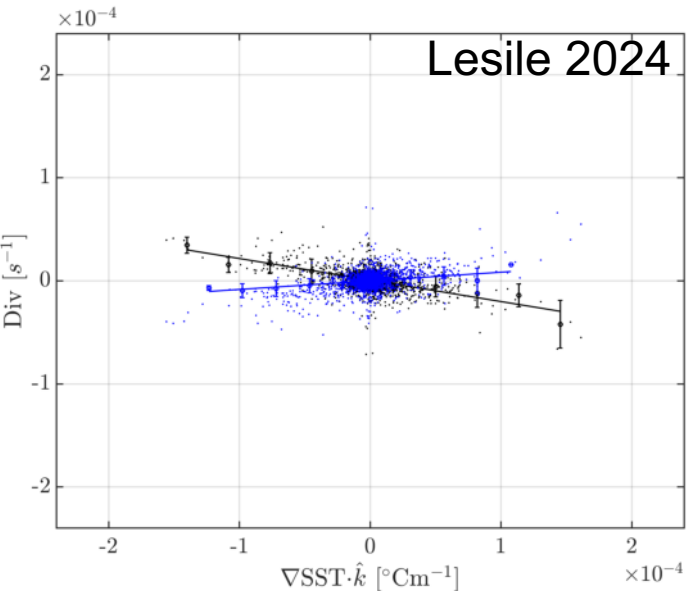


Mesoscale SST-Wind Coupling



- Monthly-mean SST, downwind SST gradient, surface wind divergence, Laplacian of air temperature

Mesoscale SST-Wind Coupling Under TC Condition



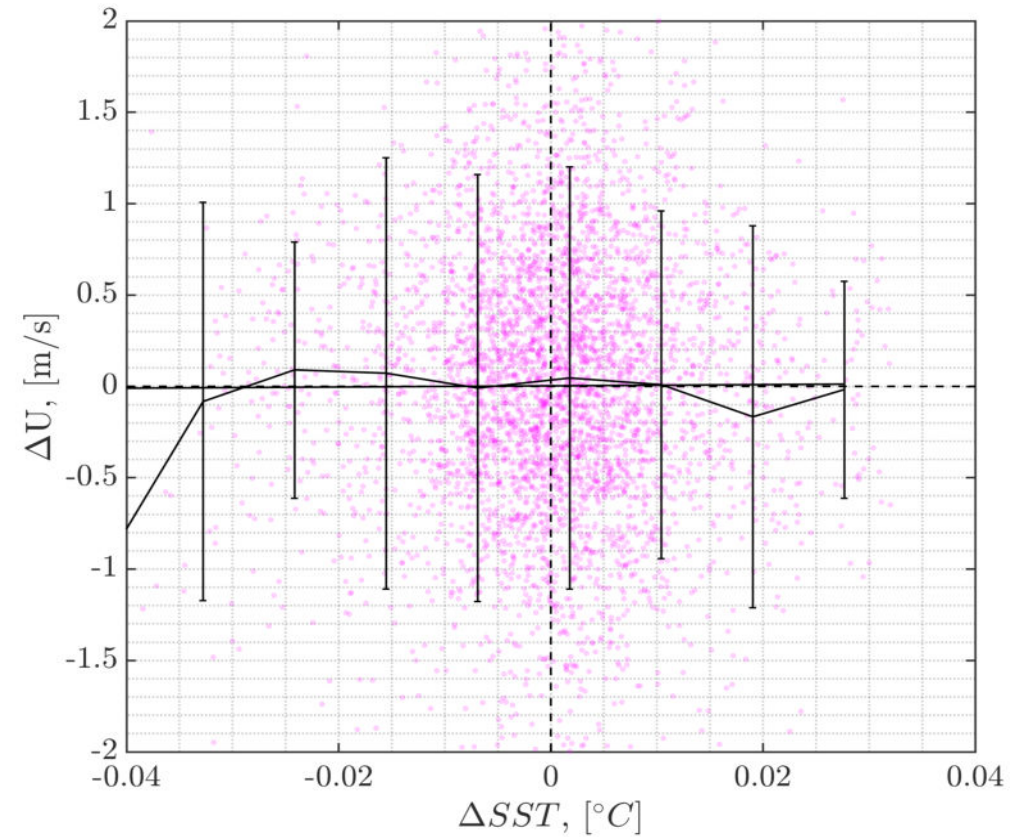
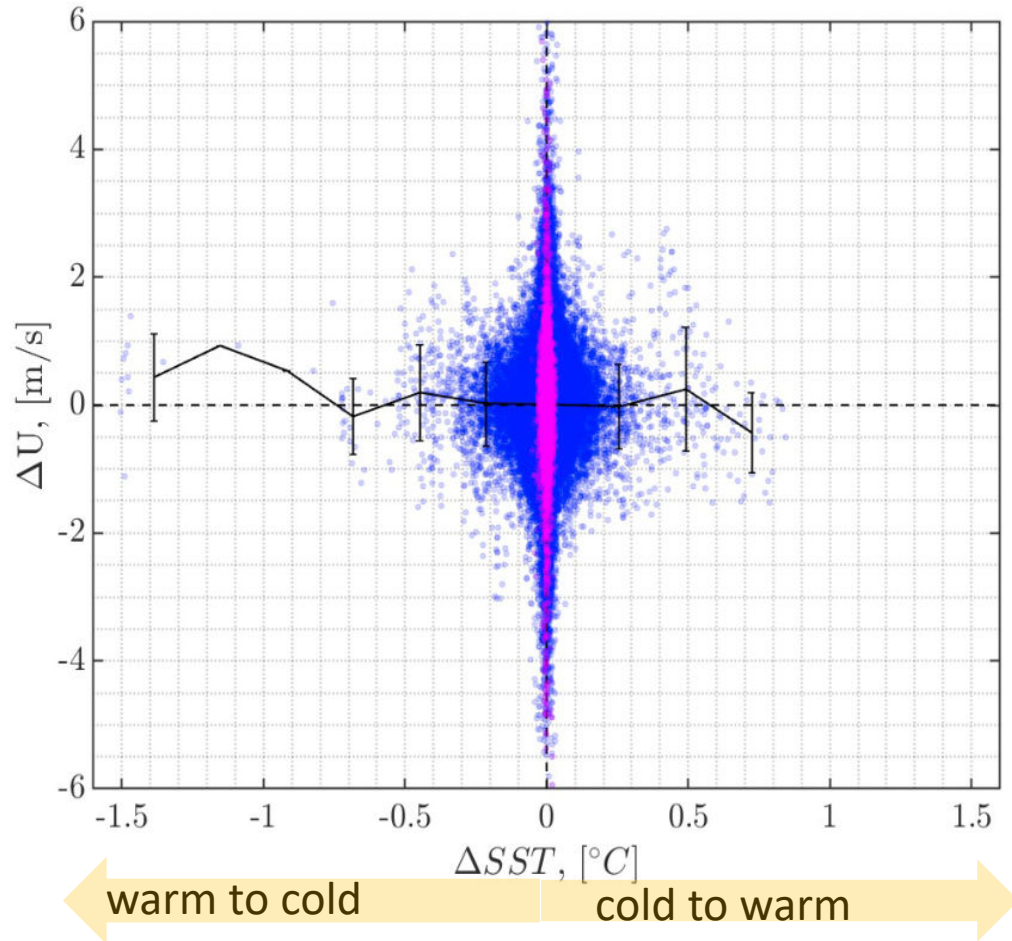
surface wind divergence vs downwind sst gradient

- blue dot: monthly-mean
- black dot: TC condition → negative value
 - Intense mixing?
 - Atm force SST gradient?

warm to cold cold to warm

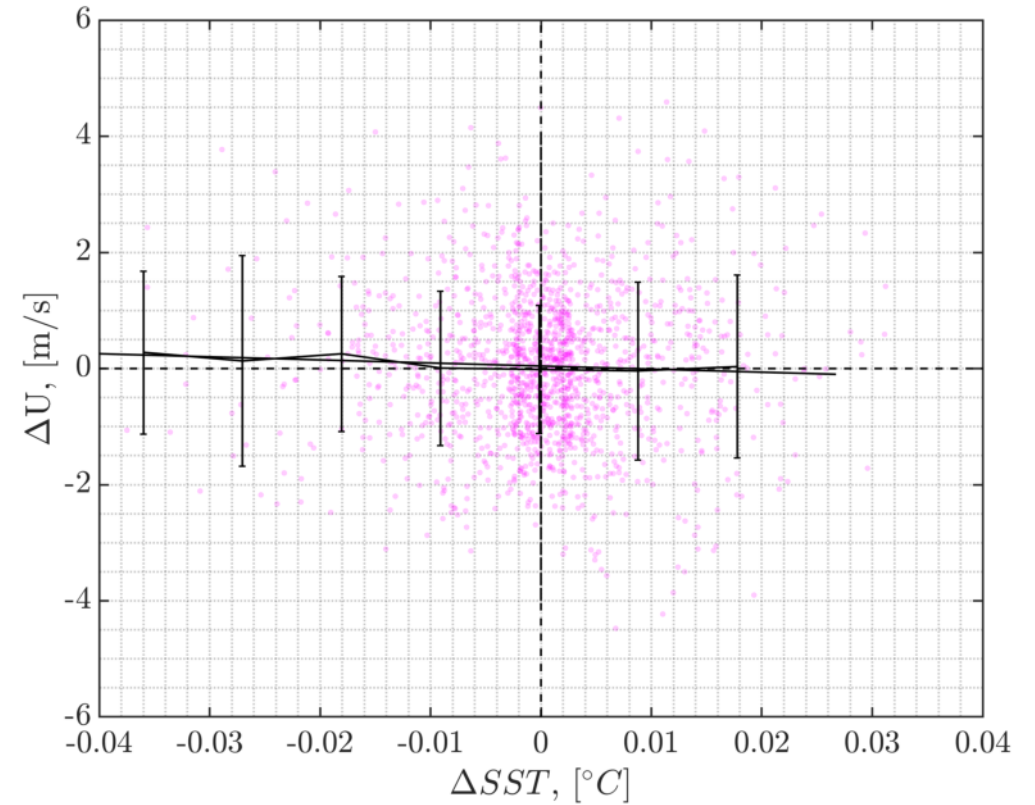
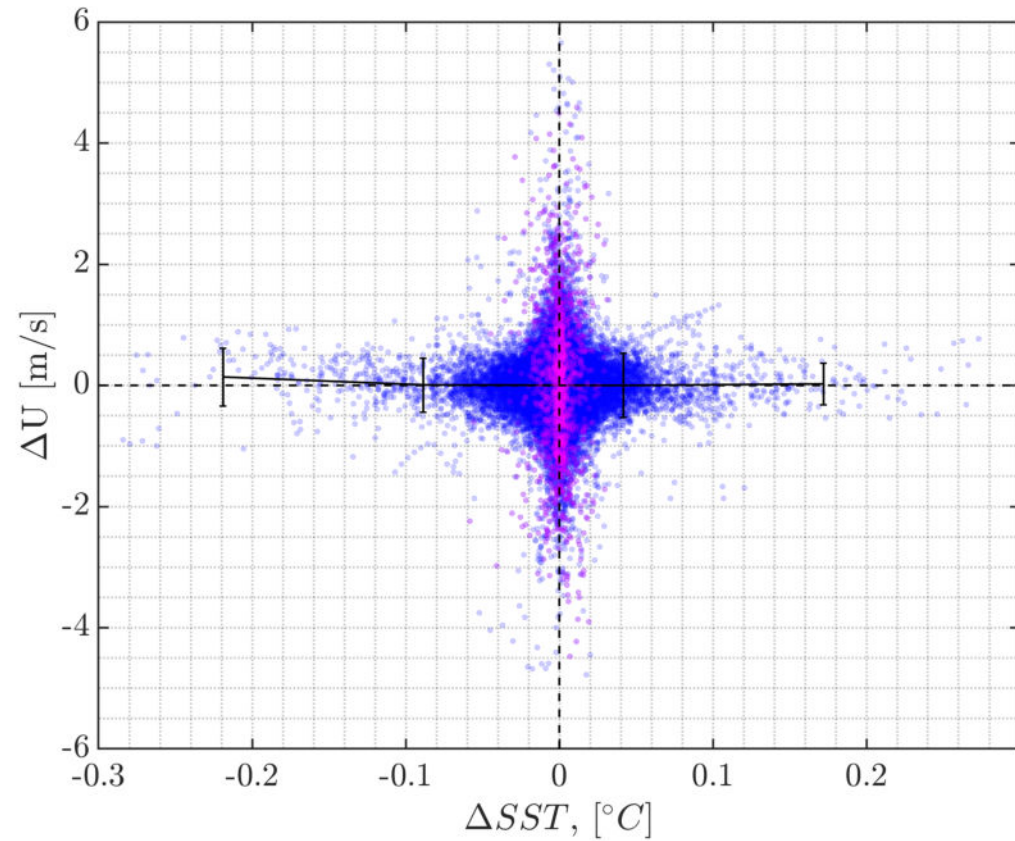
warm to cold cold to warm

Submesoscale SST-Wind coupling strength for Milton (2024): SD1042



- SST-induced perturbations become overwhelmed by TC turbulence

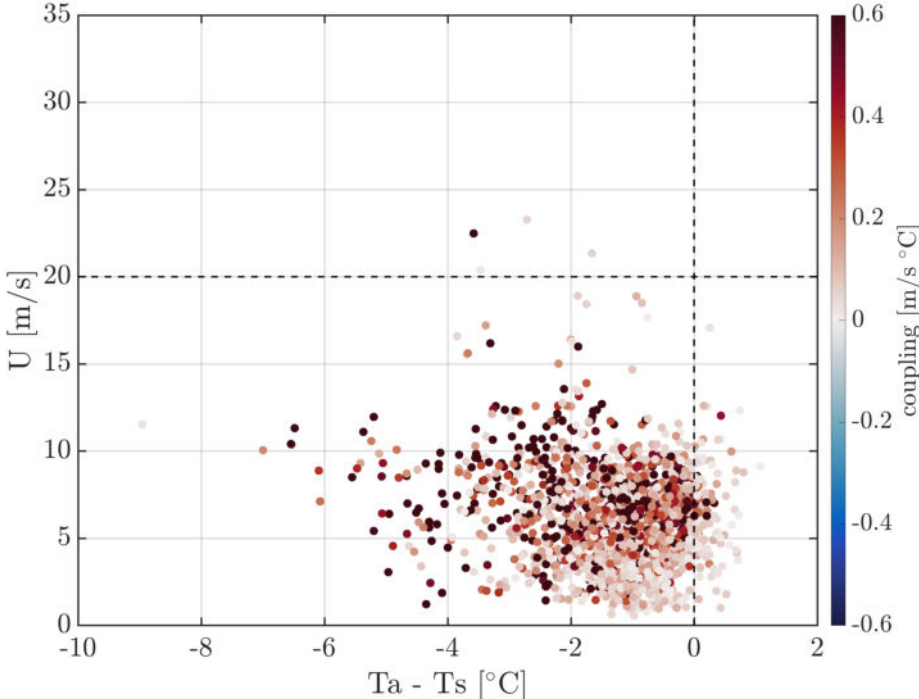
Submesoscale SST-Wind coupling strength for Ernesto (2024): SD1068



- SST-induced perturbations in TC even showed negative trend

Following: Saildrone Observations vs Previous Coupling Regime Studies

Saildrone 2024



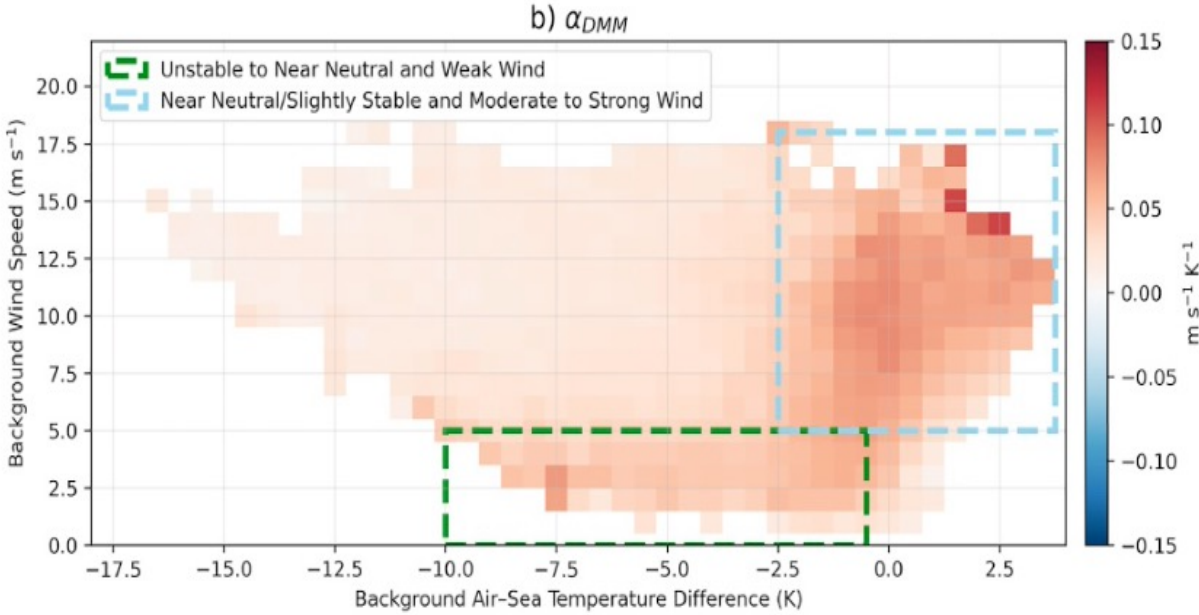
Geophysical Research Letters*

RESEARCH LETTER
10.1029/2025GL120700

Environmental Controls on the Seasonal and Spatial Variability of Submesoscale Thermal Air-Sea Coupling Over the Gulf Stream

Key Points:
• The Downward Momentum Mixing mechanism drives submesoscale wind-SST coupling, with stronger responses

Lionel Renault¹, Carlos Conejero^{1,2}, and Fabien Desbiolles¹



- Saildrone observations suggest coupling behavior beyond regimes in previous simulation studies
- TC may modify the thermal coupling to a turbulence-dominated regime

Preliminary Summary

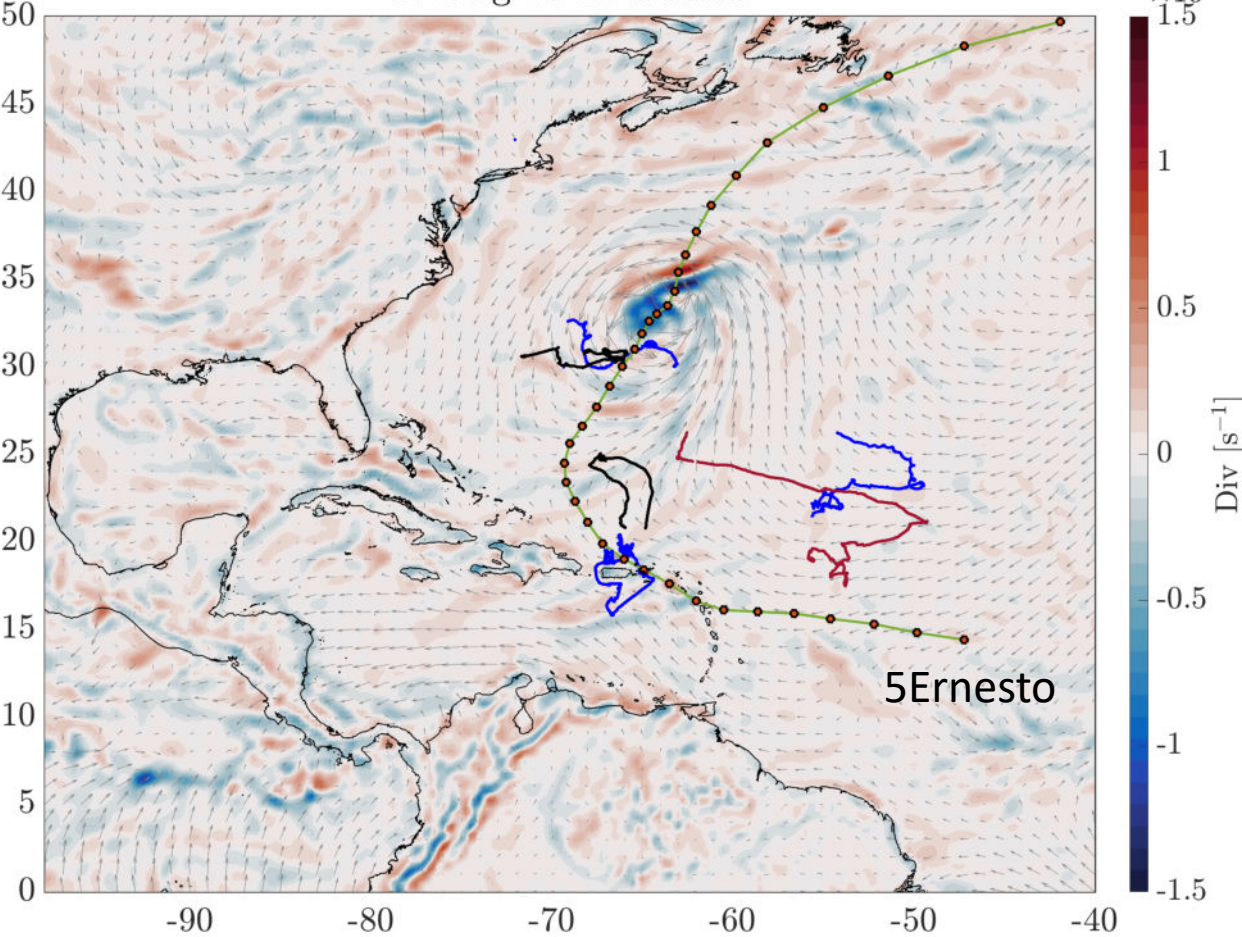
- The USV (Saildrone) resolve the fine scale (100 m) air-sea interaction processes.
- Classical thermal coupling exists under non-TC conditions
 - SST perturbation induce coherent air temperature and turbulent heat flux response
 - Oceanic and atmospheric forcing jointly modulate surface heat flux variability
- TC turbulence fundamentally alters coupling pathways
 - Under TC conditions, atmospheric thermal adjustment becomes weakened
 - SST-induced wind responses collapse
 - A possible transition toward a mixing-saturated coupling regime
 - Mesoscale regional SST-wind coupling showed negative value

Thank you! mshao@rsmas.miami.edu

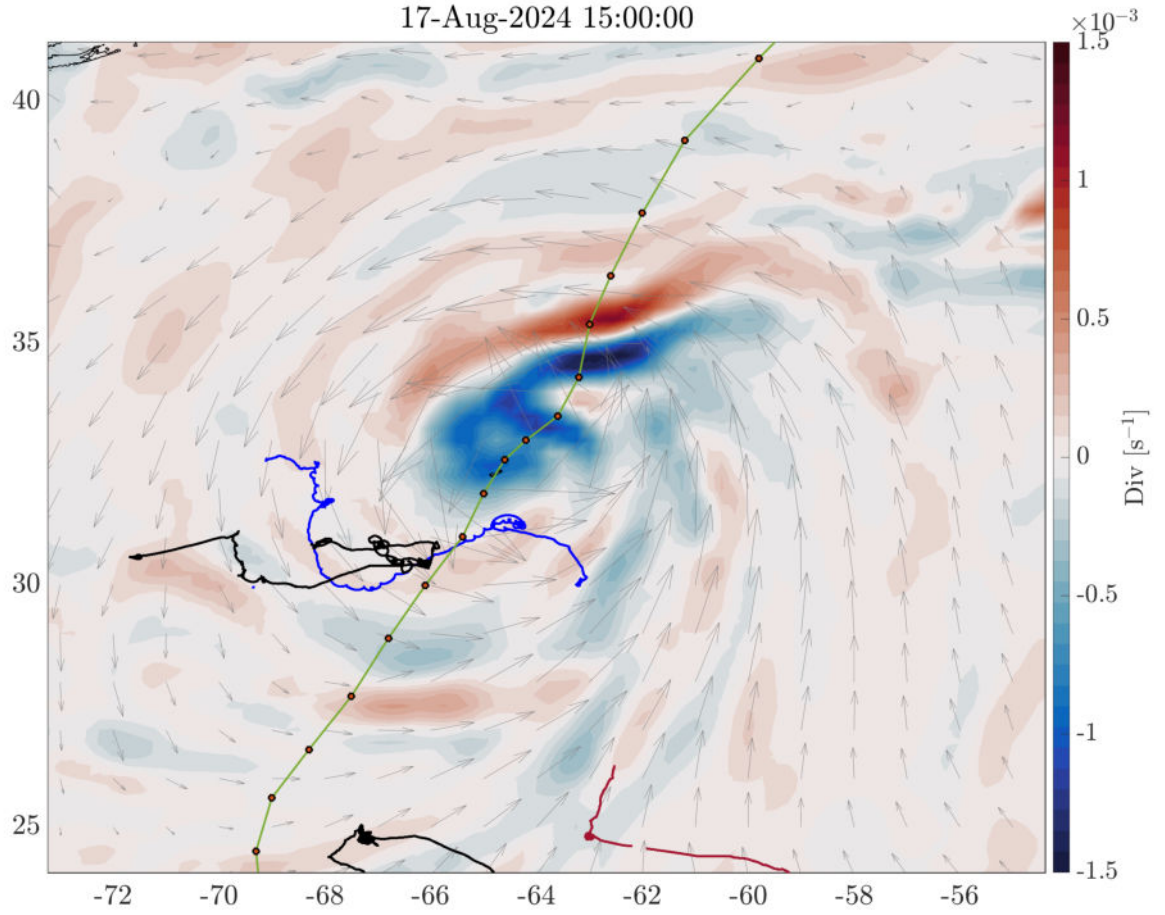
Backup Slides

Hurricane Ernesto

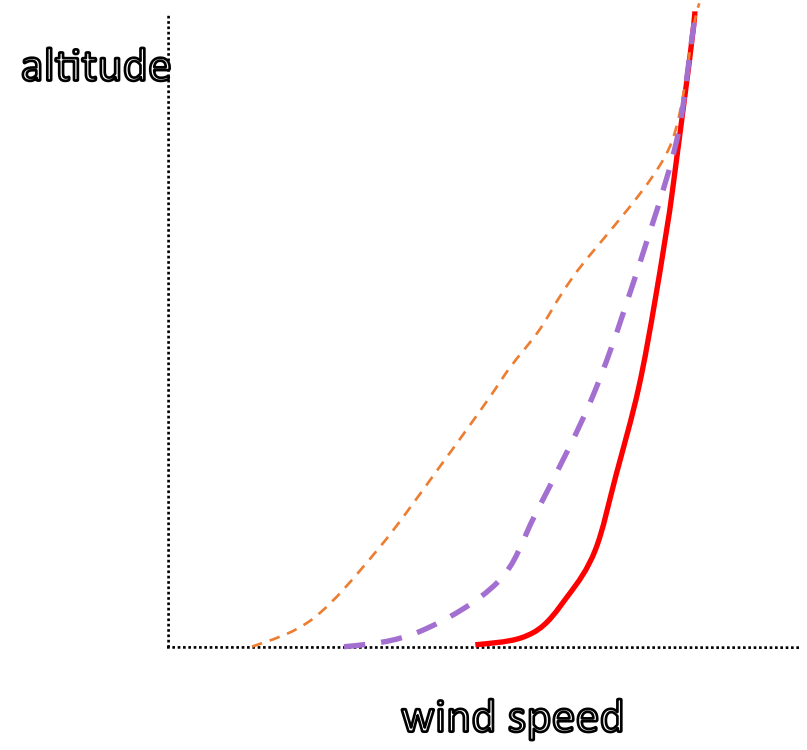
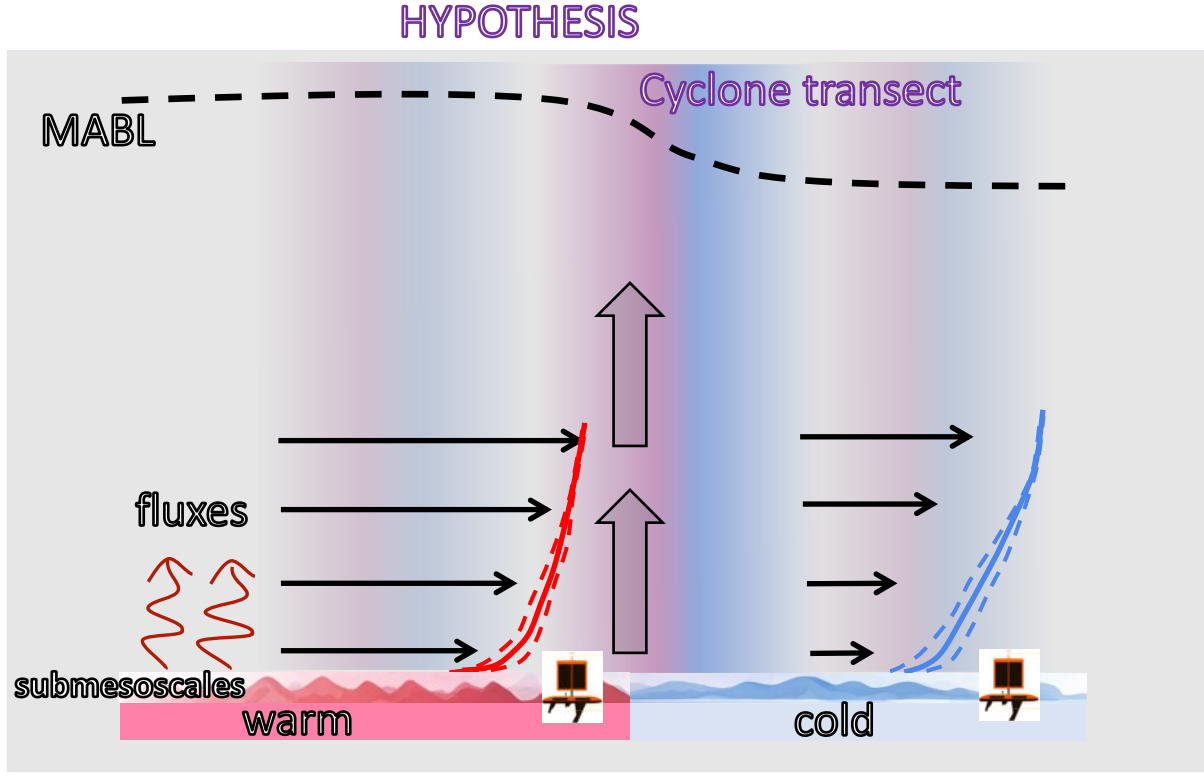
17-Aug-2024 15:00:00



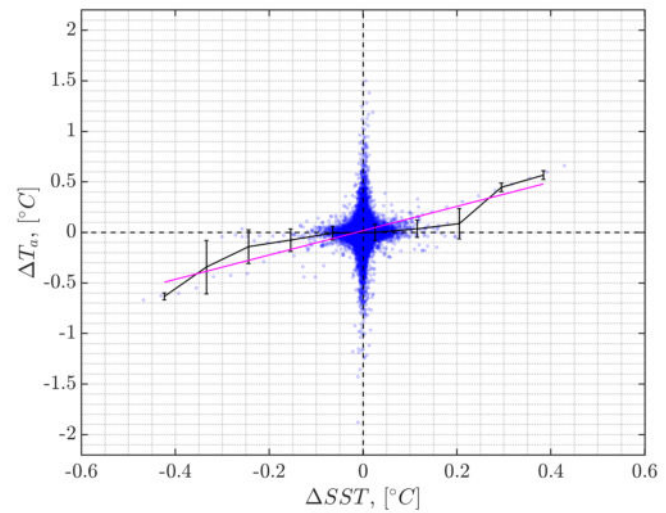
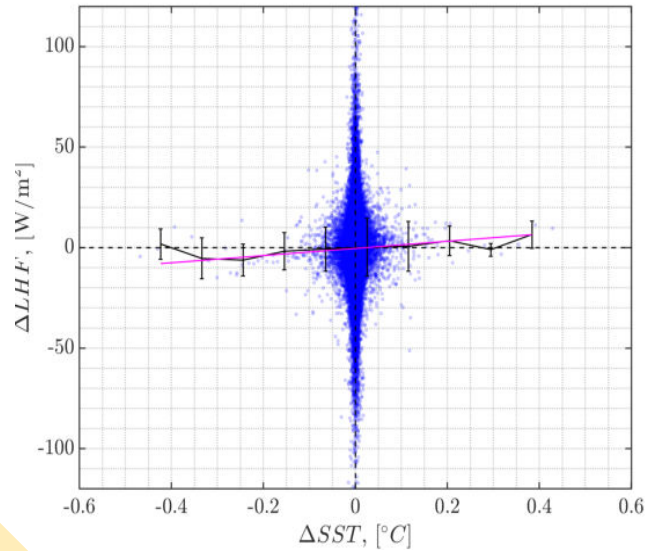
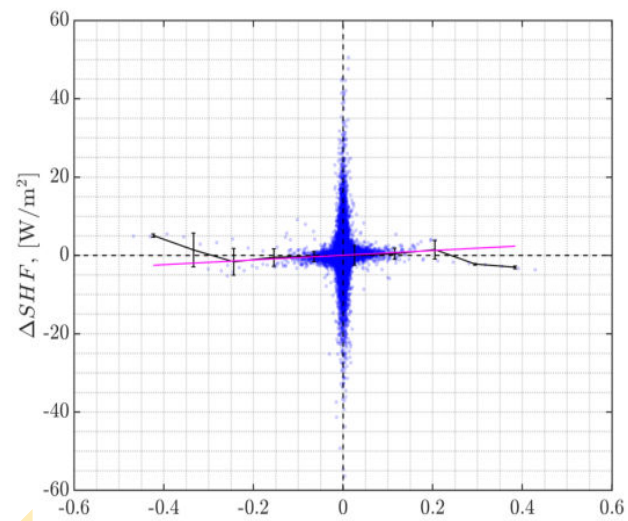
17-Aug-2024 15:00:00



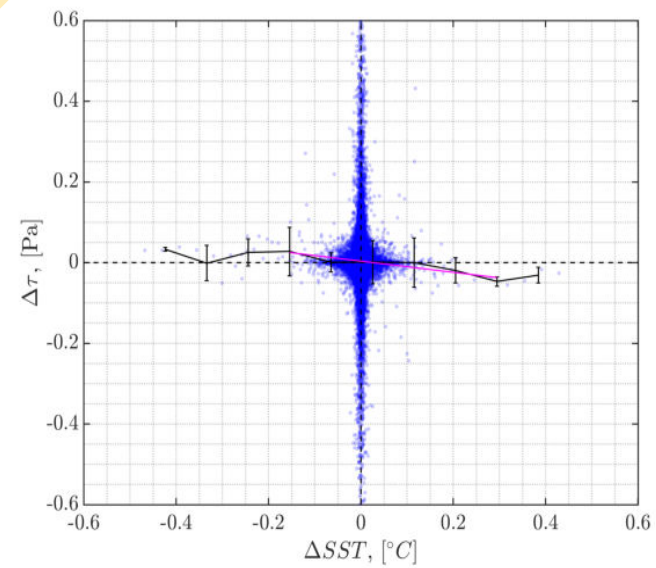
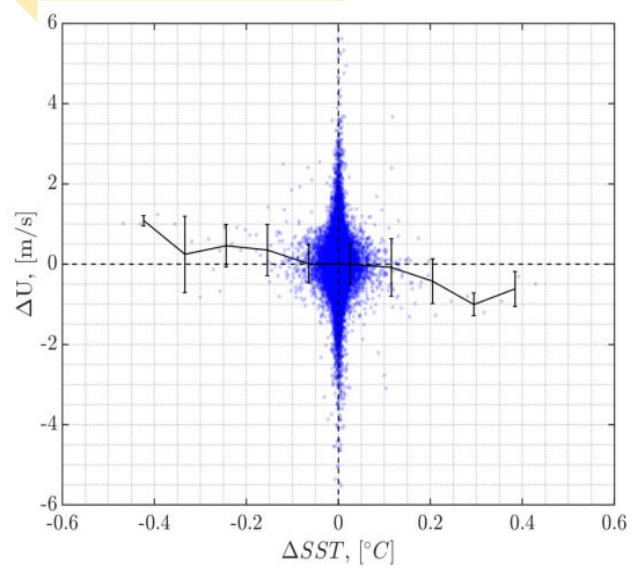
Schematic plot



Submesoscale SST-Wind coupling from Saildrone



warm to cold $\Delta SST, [^{\circ}C]$ cold to warm



Two mechanisms controlling the surface wind variation

Vertical mixing mechanism (Wallace et al. 1989, Skillingstad et al. 2007, Kilpatrick et al. 2013, Sullivan et al. 2020, 2021)

Linear relationship: divergence of the wind stress perturbation ($\nabla \cdot \tau$) and downwind SST gradient field ($\hat{\tau} \cdot \nabla SST$)

Pressure gradient adjustment (Lindenze et al. 1987, Lambaerts et al. 2013, Foussard et al. 2019), weak wind conditions,

$$f \hat{z} \times V = -\nabla \Phi - \epsilon V$$

V and Φ are the weight averaged velocity and pressure in the boundary layer, and ϵ the drag coefficient,

Assuming the hydrostatic equation and mean air temperature adjusts to the SST,

$$-\nabla \Phi \approx \kappa \nabla SST \quad \kappa = R \log(P_0/P_h)$$

The momentum balance leads to a linear relationship between wind divergence and the SST Laplacian

$$\nabla \cdot V = \frac{\kappa \epsilon}{f^2 + \epsilon^2} \nabla^2 SST$$