A brief overview of the air-sea fluxes of heat, momentum, and gas tracers at oceanic mesoscales

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Introduction

- The surface fluxes are fundamental indicators of the coupling between the atmosphere and the ocean.
- In climate dynamics, a traditional view is that surface flux variability predominantly arises from the action of intrinsic atmospheric processes.
- However, mesoscale current and SST features can induce significant surface flux anomalies, with feedback to both oceanic and atmospheric circulations.
- Here, we'll revise the knowledge on the variability of air-sea fluxes of heat, momentum, and gas at the oceanic mesoscales.

Turbulent heat flux (THF) variability

- Sensible and latent heat flux bulk formulae:

$$Q_s = \rho c_p c_s w(t_o - t_a)$$

$$Q_l = \rho L_e c_l w(q_o - q_a)$$

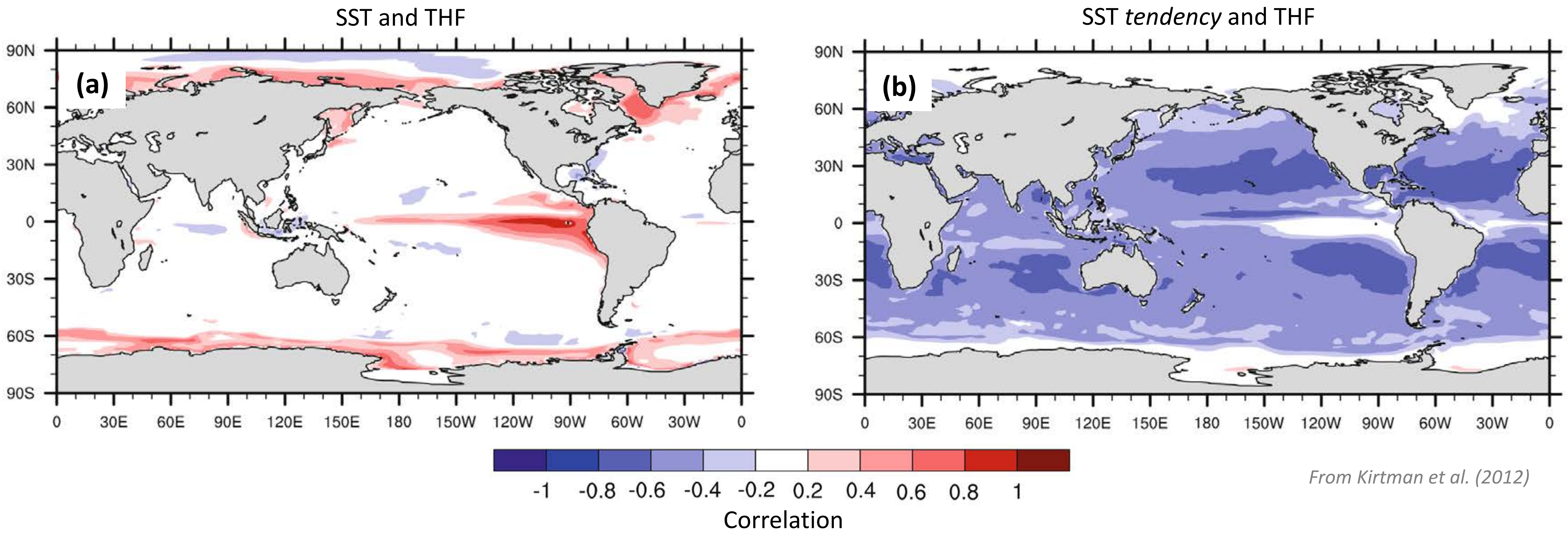
- Are proportional to the near-surface wind speed and the temperature and humidity contrast between the ocean and the atmosphere.

- Here, I'll define the heat fluxes as positive when out of the ocean.

Turbulent heat flux (THF) variability

- The stochastic climate model theory of Hasselmann (1976) successfully predicted the SST power spectrum and SST/THF lag-correlations at midlatitude oceanic regions away from strong currents.

CESM with 1° ocean (eddy-parameterized)



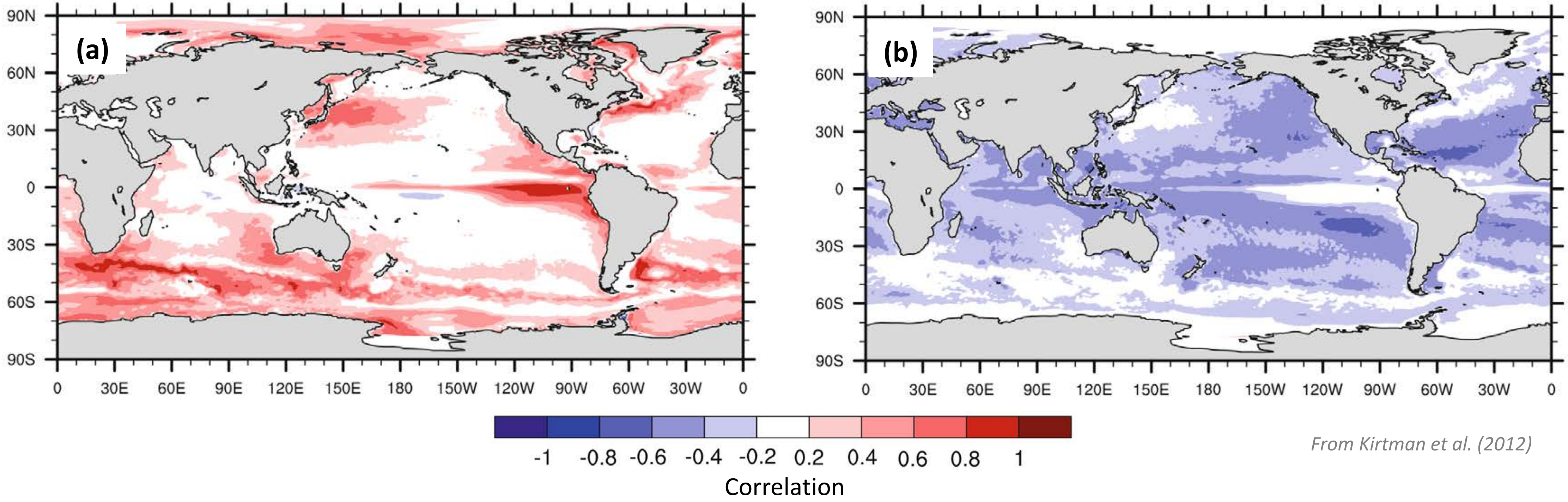
From Kirtman et al. (2012)

Influence of mesoscale ocean dynamics

- Observations and eddy-resolving coupled model simulations produce positive SST/THF correlations and near-zero SST tendency/THF correlations at energetic current systems, such as the Kuroshio Current and Gulf Stream.

CESM with 1/10° ocean (eddy-resolving)

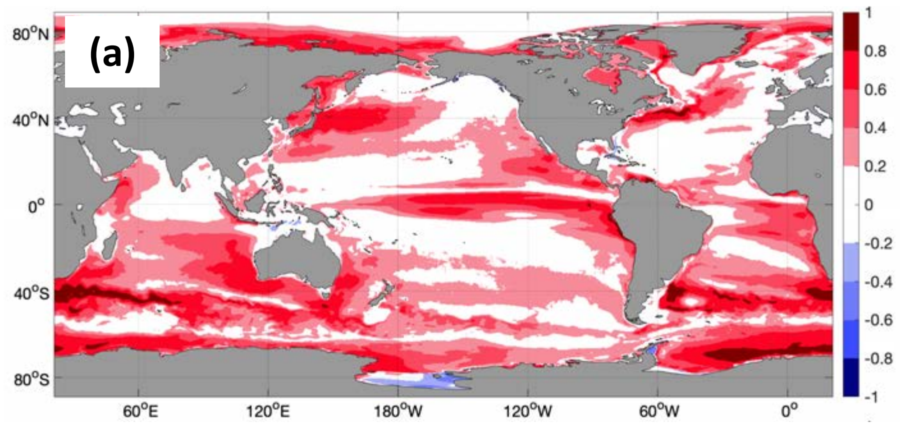
SST and THF | SST *tendency* and THF



From Kirtman et al. (2012)

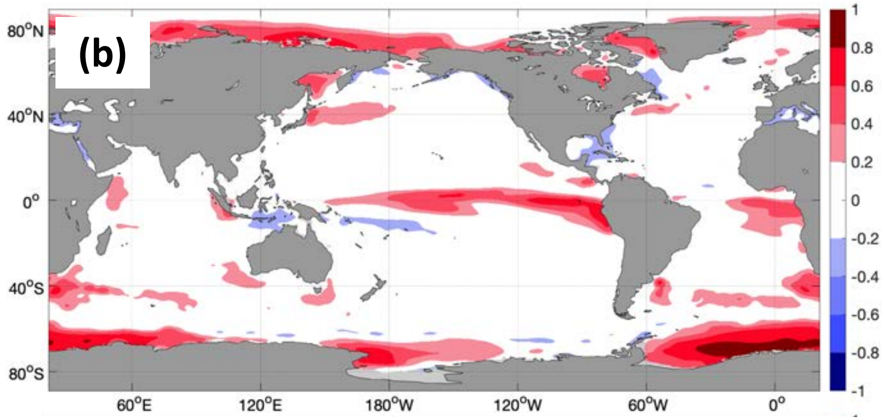
The correlations depend on the spatial scale

SST and THF correlation

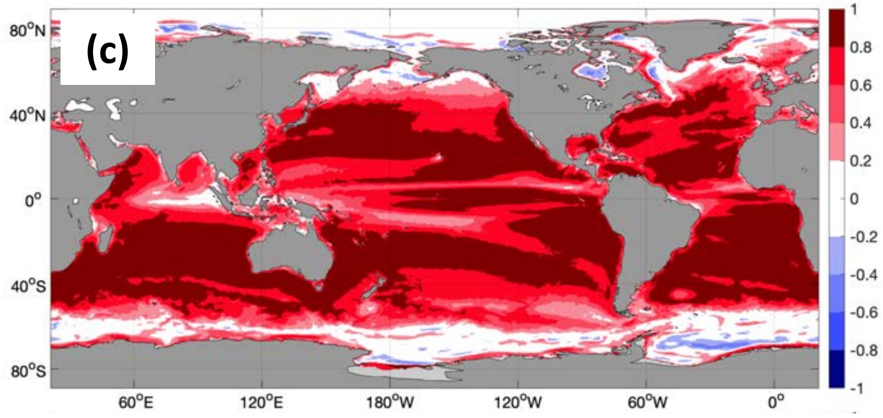


iHESP CESM HR preindustrial control run.

Large-scales (> 10º)



Oceanic mesoscales (< 10º)

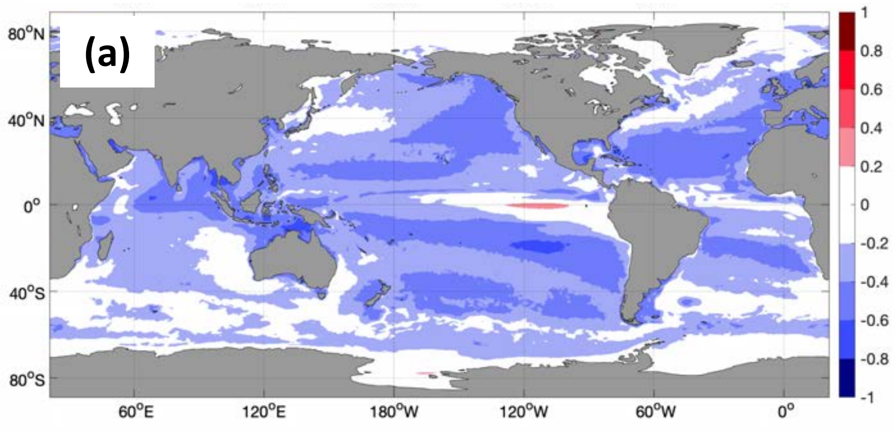


- The atmosphere drives the SST and THF variability at large spatial scales.
- The ocean processes dominate the variability at the mesoscales.

Based on Bishop et al. (2017) and Small et al. (2019, 2020).

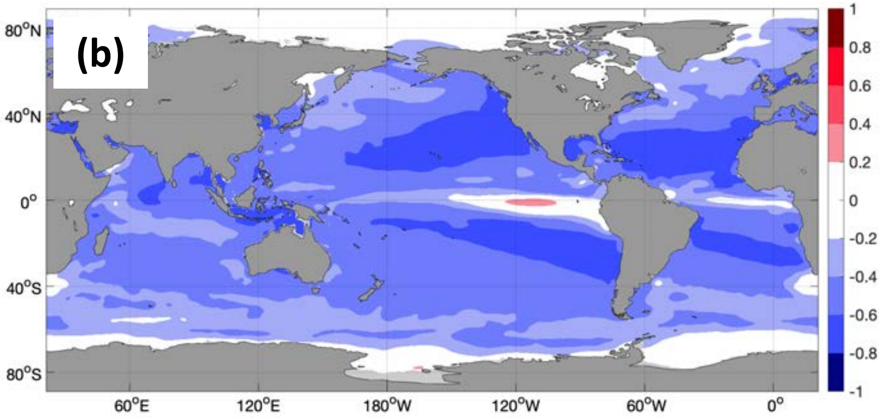
The correlations depend on the spatial scale

SST tendency and THF correlation

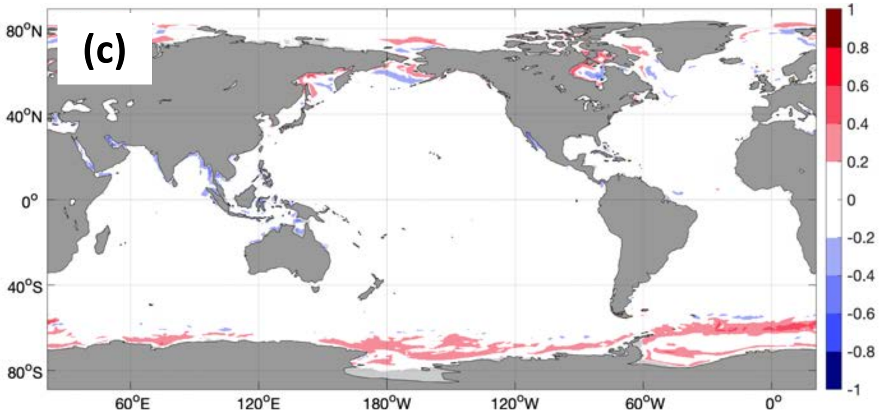


iHESP CESM HR preindustrial control run.

Large-scales (> 10º)



Oceanic mesoscales (< 10º)



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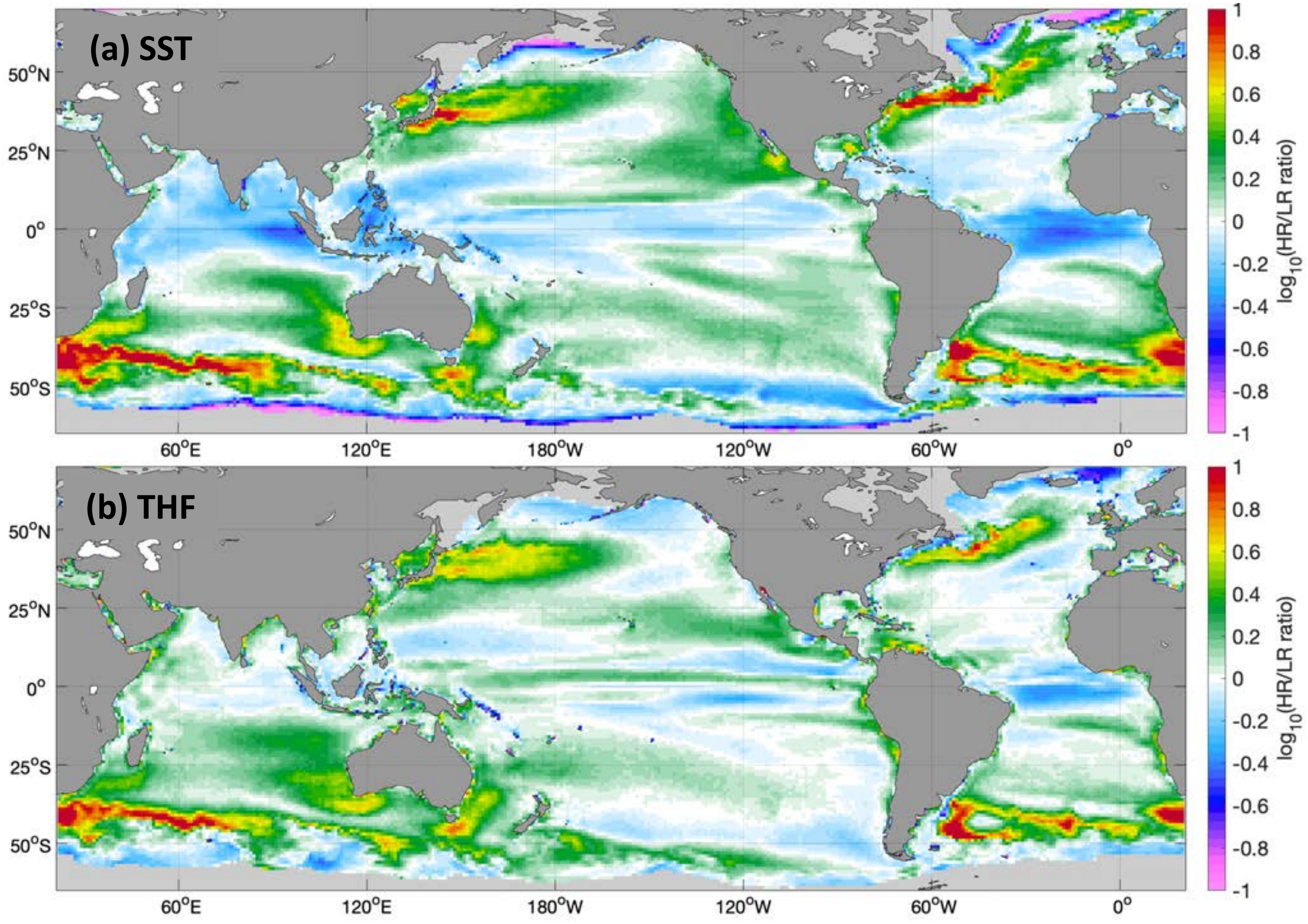
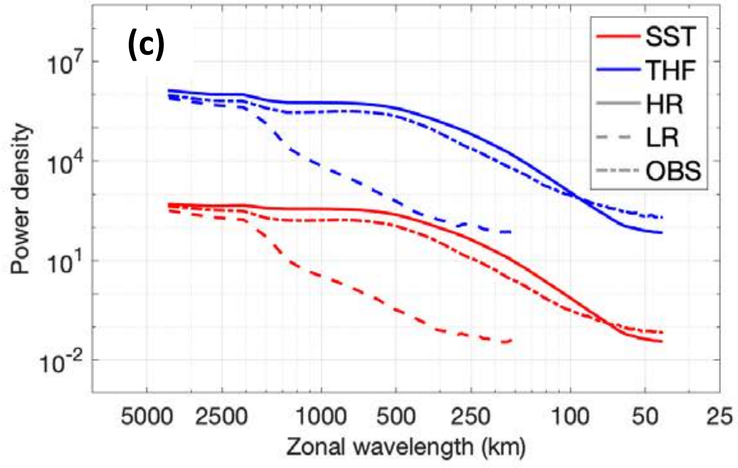
SST and turbulent heat flux variances

HR/LR monthly variance ratio



iHESP CESM preindustrial control simulations

SST and THF power spectra



Spectra for the Agulhas Return Current

From Chang et al. (2020)

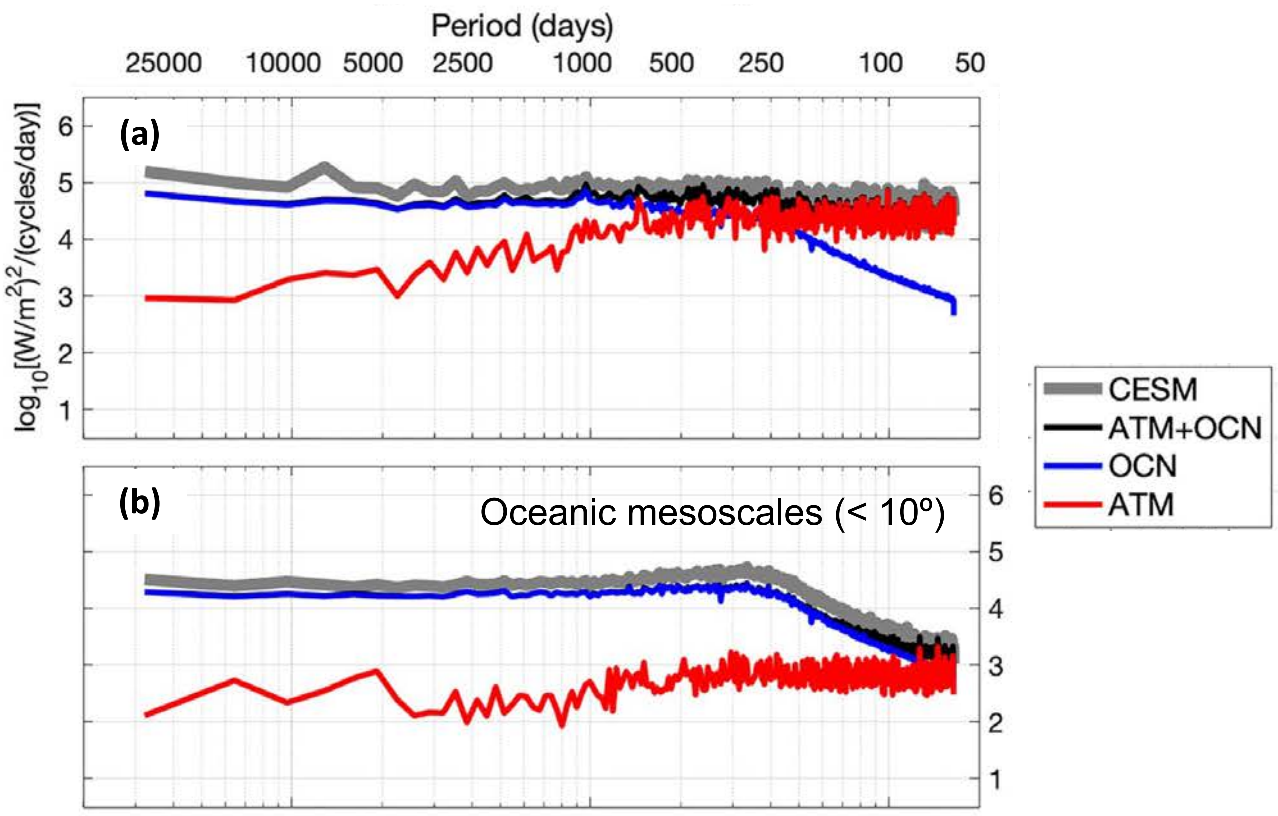
Role of the ocean and atmosphere across different timescales

- Turbulent heat flux variability at monthly timescales is driven by weather.

- At longer timescales, variability is forced by ocean dynamics.

(e.g., Bishop et al. 2017, Sun and Wu 2021, Laurindo et al. 2022)

THF power spectra in HR CESM



Spectra for 40ºS in the Pacific Ocean

From Laurindo et al. (2022)

Horizontal momentum flux (wind stress)

- Wind stress bulk formulation:

$$\boldsymbol{\tau} = \rho_{air} c_d |\mathbf{w} - \mathbf{u}| (\mathbf{w} - \mathbf{u})$$

Surface ocean currents

10-m winds

$$\mathbf{w} = \mathbf{w}_{LS} + \mathbf{w}_{SST}$$

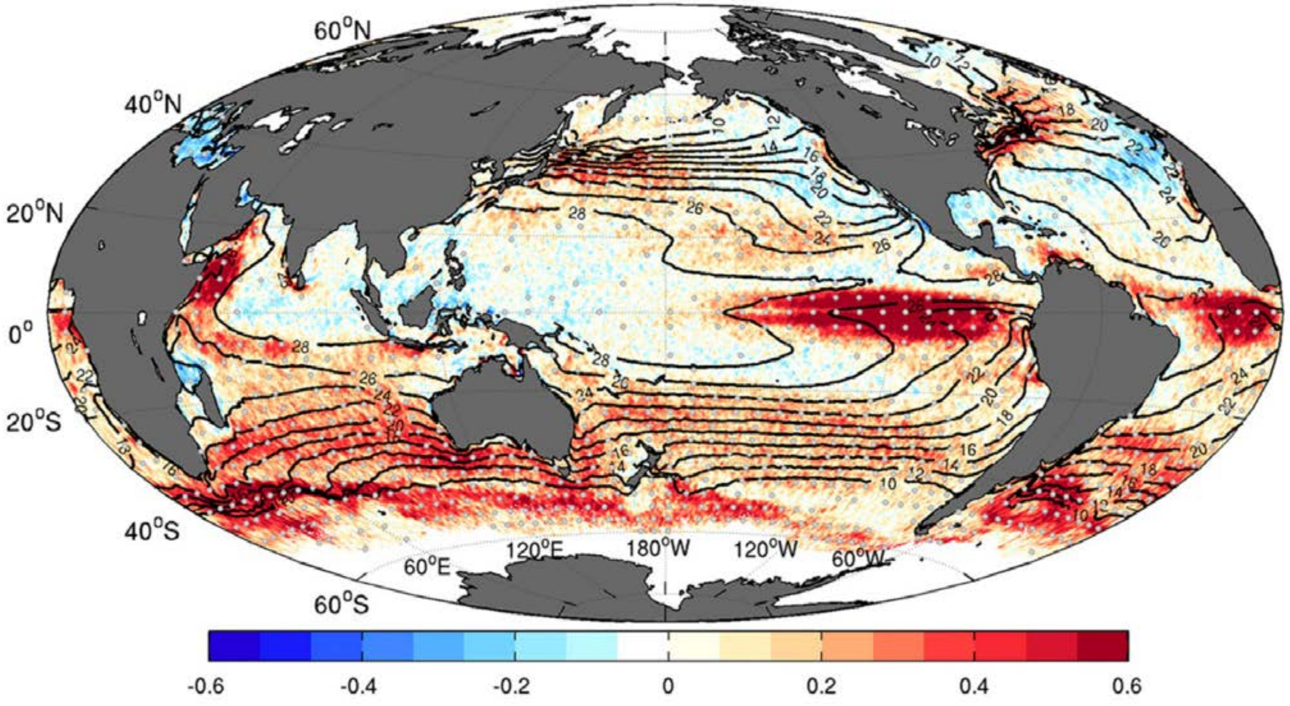
- Influence of SST:
  - *Modifies turbulent mixing, drag, and pressure gradients within the marine atmospheric boundary layer (MABL).*
  - *Ultimately accelerates the near-surface winds moving from cool to warm SST and decelerates winds moving from warm to cool SST.*

- Influence of surface ocean currents:
  - *Wind stress acts relative to the ocean surface, which is in motion.*

Characterizing the SST-induced response in MABL

- It is usually characterized by linear regressions between SST and 10-m wind speed/wind stress.
- Data needs to be high-pass filtered at scales of about 1000 km or smaller.
- Data is also frequently smoothed in time or averaged over a few weeks.

SST and wind stress correlation
oceanic mesoscales (< 10º)



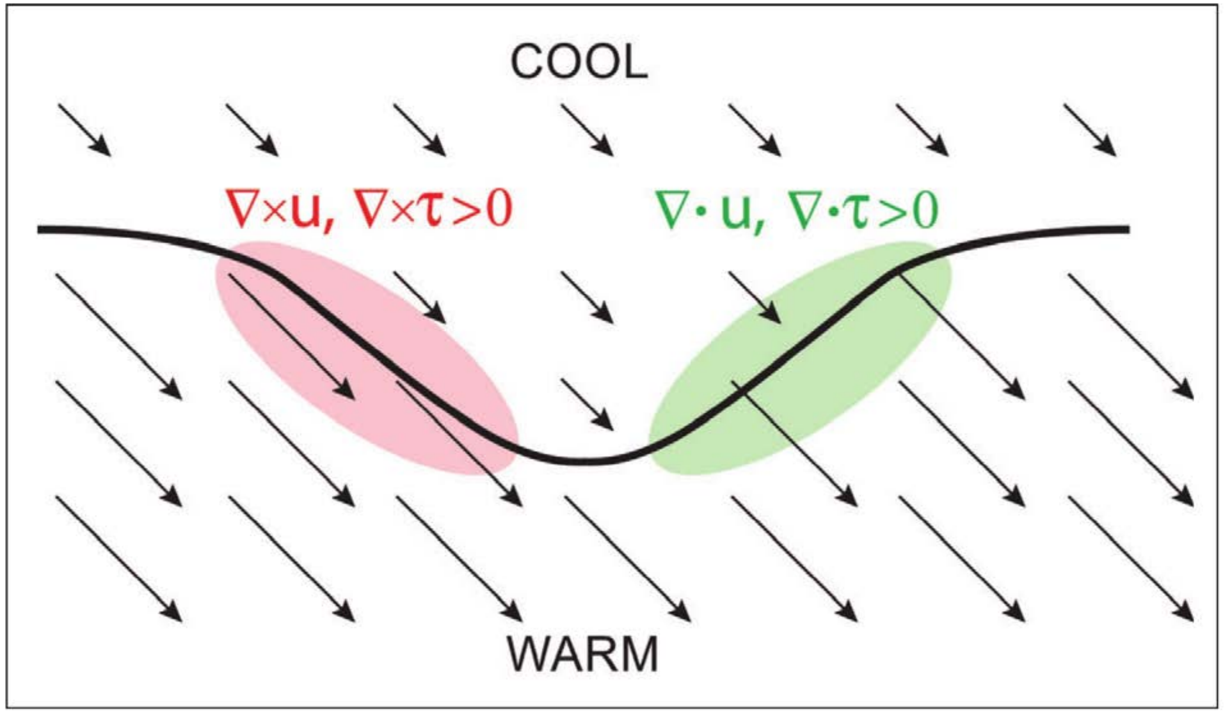
From Seo (2017)

Characterizing the SST-induced response

- Positive correlations also develop between:
  - The downwind component of the SST gradient and the wind curl/wind stress curl.
  - The cross-wind component of the SST gradient and the wind stress divergence.

- Correlations between the Laplacian of SST and the Laplacian of sea-level pressure are also frequently used.

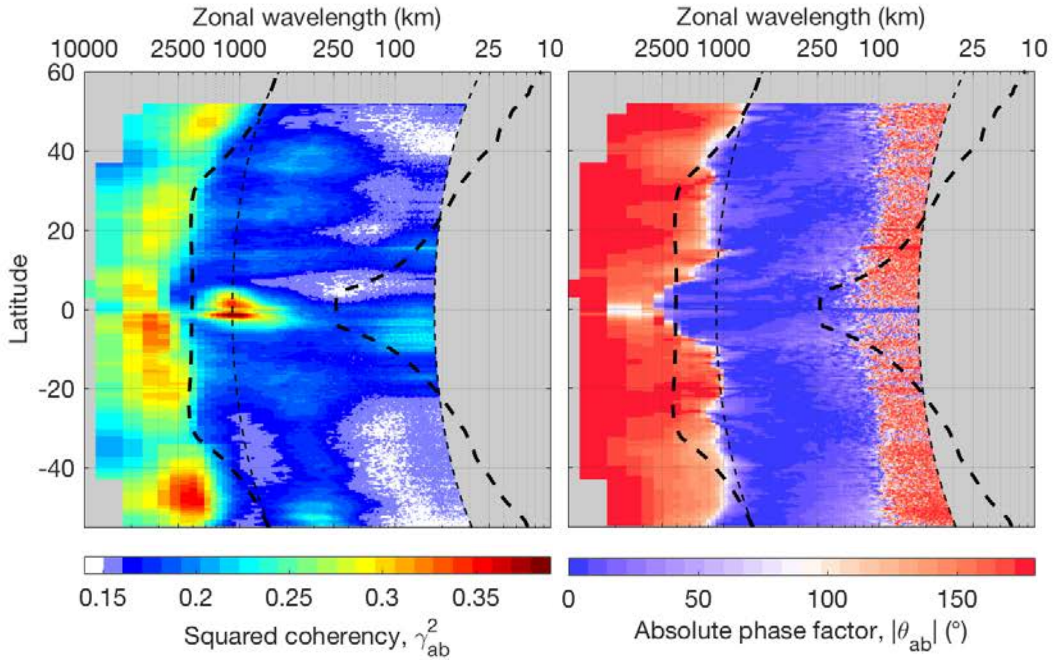
Schematic illustration of winds blowing across a meandering SST front



From Chelton et al. (2010)

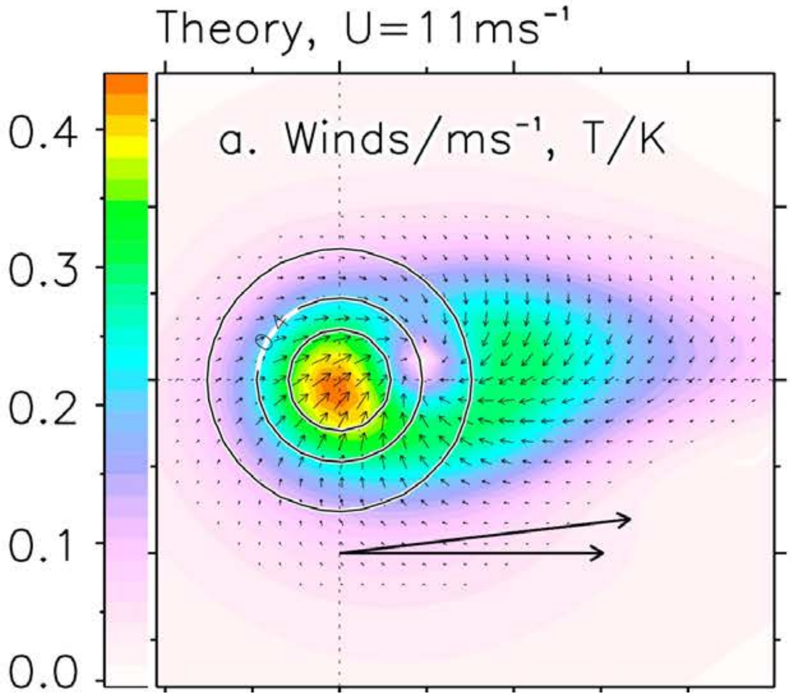
Spectral methods

- *Zonal wavenumber coherence and phase factor between SST and 10-m wind speed, Pacific Ocean.*



From Laurindo et al. (2019)

- *Surface wind response to a Gaussian monopole SST anomaly of 1 K.*
- *Computed using spectral transfer functions derived from the linear MABL model of Schneider and Qiu (2015).*

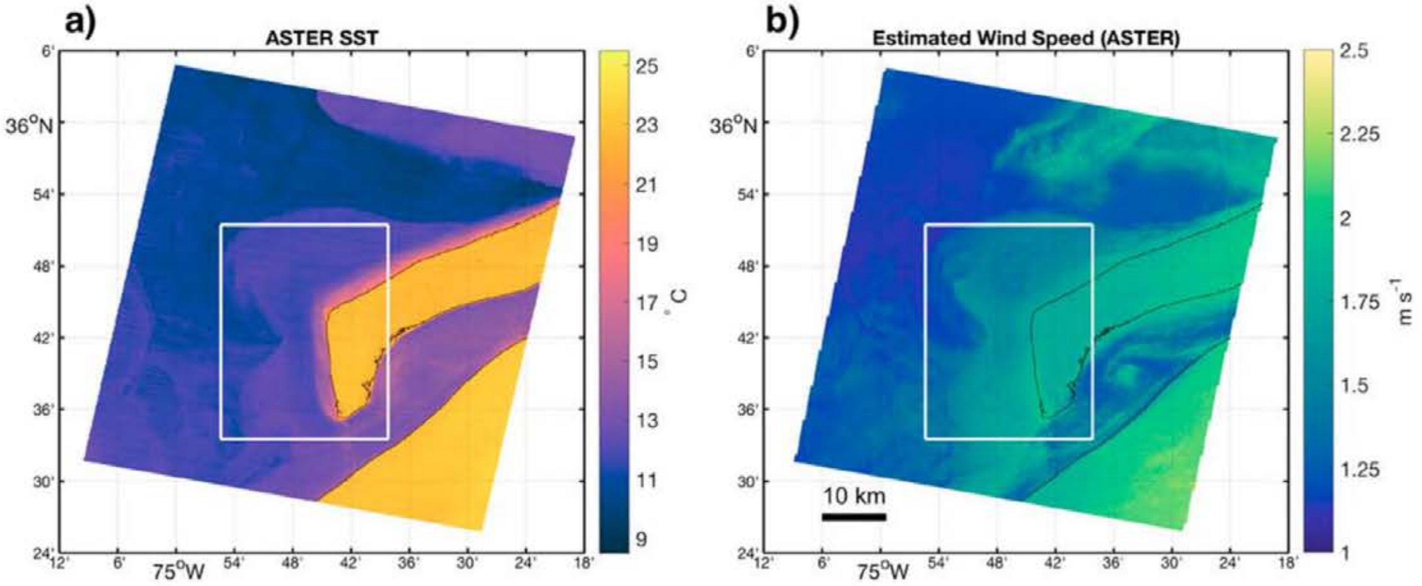


From Schneider (2020)

Submesoscale SST-driven response

- Papers on the influence of SST in the MABL over submesoscale ranges (1-10 km) are beginning to appear in literature.
- Meroni et al. (2022): standard metrics may be insensitive to the atmospheric response to SST forcing due to the influence of advection.
  - *Suggests using the linear relationship between wind divergence and the SST second derivative.*

- *SST and wind speed fields over a submesoscale filament associated with the Gulf Stream from the* Advanced Spaceborne Thermal Emission and Reflection Radiometer *(ASTER)*



From Gaube et al. (2019)

Influence of surface ocean currents

- Wind stress bulk formulation:

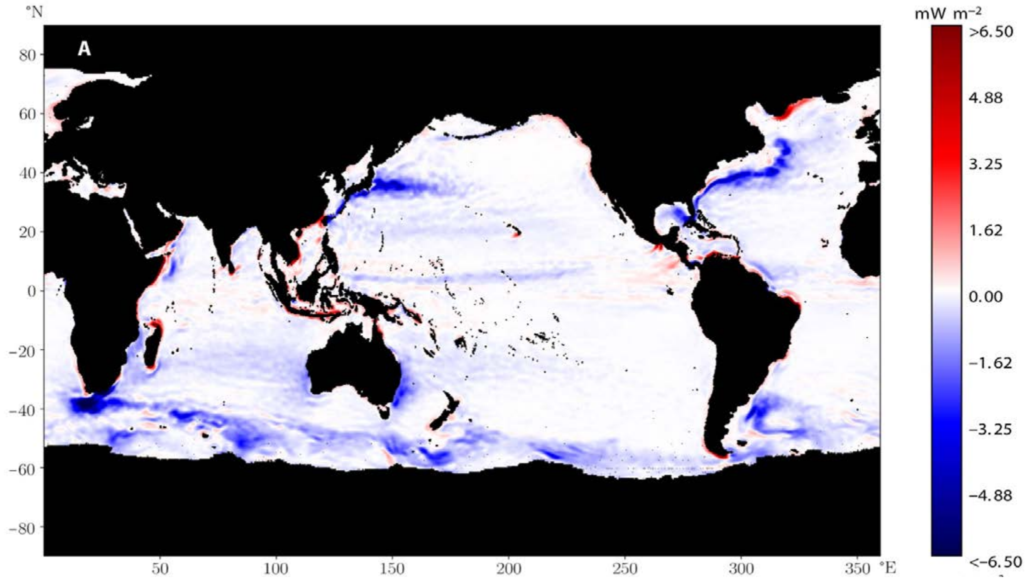
$$\boldsymbol{\tau} = \rho_{air} c_d |\mathbf{w} - \mathbf{u}|(\mathbf{w} - \mathbf{u})$$

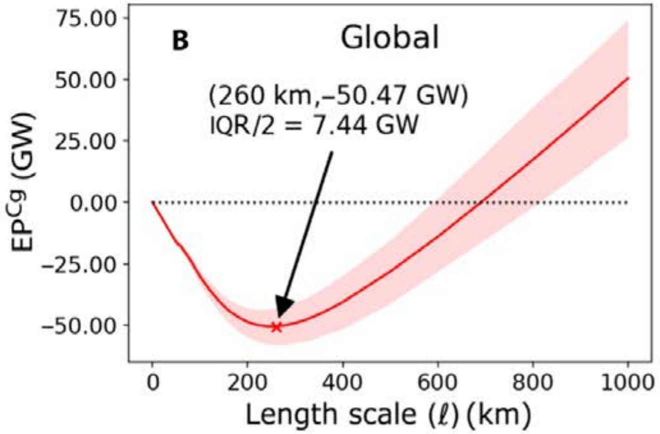
- Accounting for the influence of surface currents ($\mathbf{u}$) is usually a small correction to wind stress.

- However, it greatly impacts wind stress curl and eddy energetics.

- It also affects the low-level wind shear.

Covariance btw geostrophic currents and wind stress
oceanic mesoscales (< 250 km)



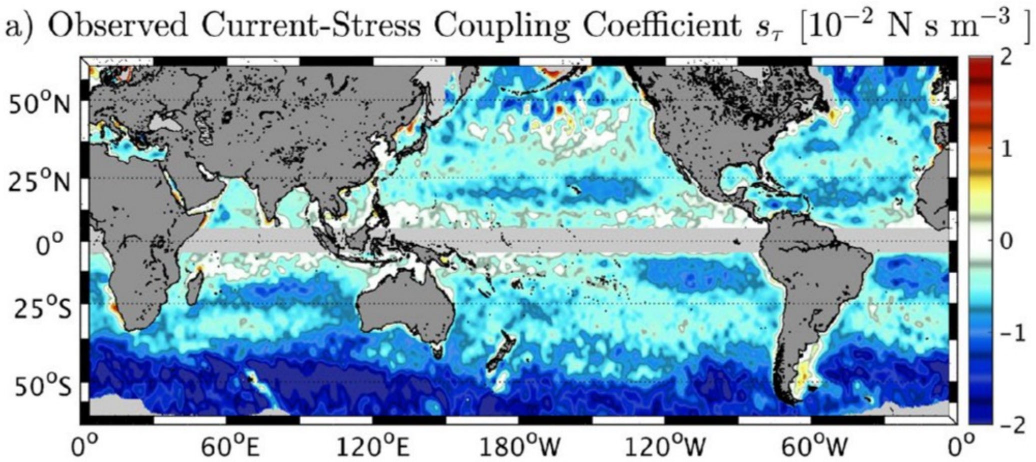


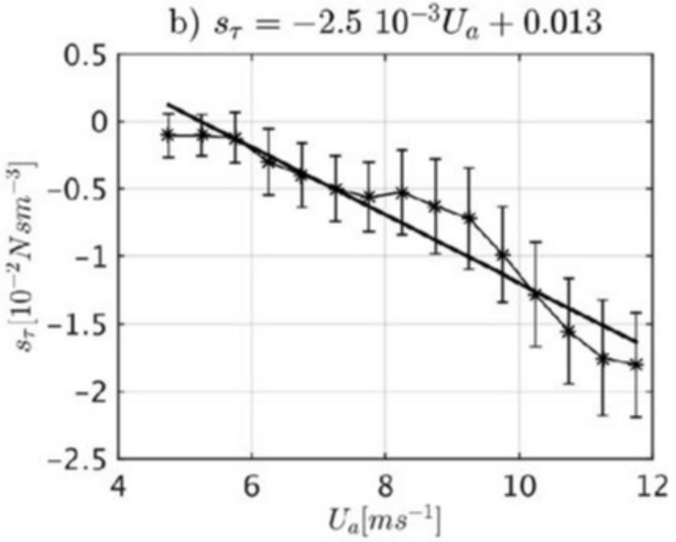
From Rai et al. (2021)

Characterizing the current-induced response

- Separating the SST-driven modifications of the wind stress and derived quantities from those induced by surface currents is not trivial.

- Renault et al. (2017): the current-driven response can be characterized via the linear regression coefficient between the wind stress curl and surface current curl (s_τ).





From Renault et al. (2017)

Air-sea flux of gas tracers

- The air-sea flux of a gas x can be given by:

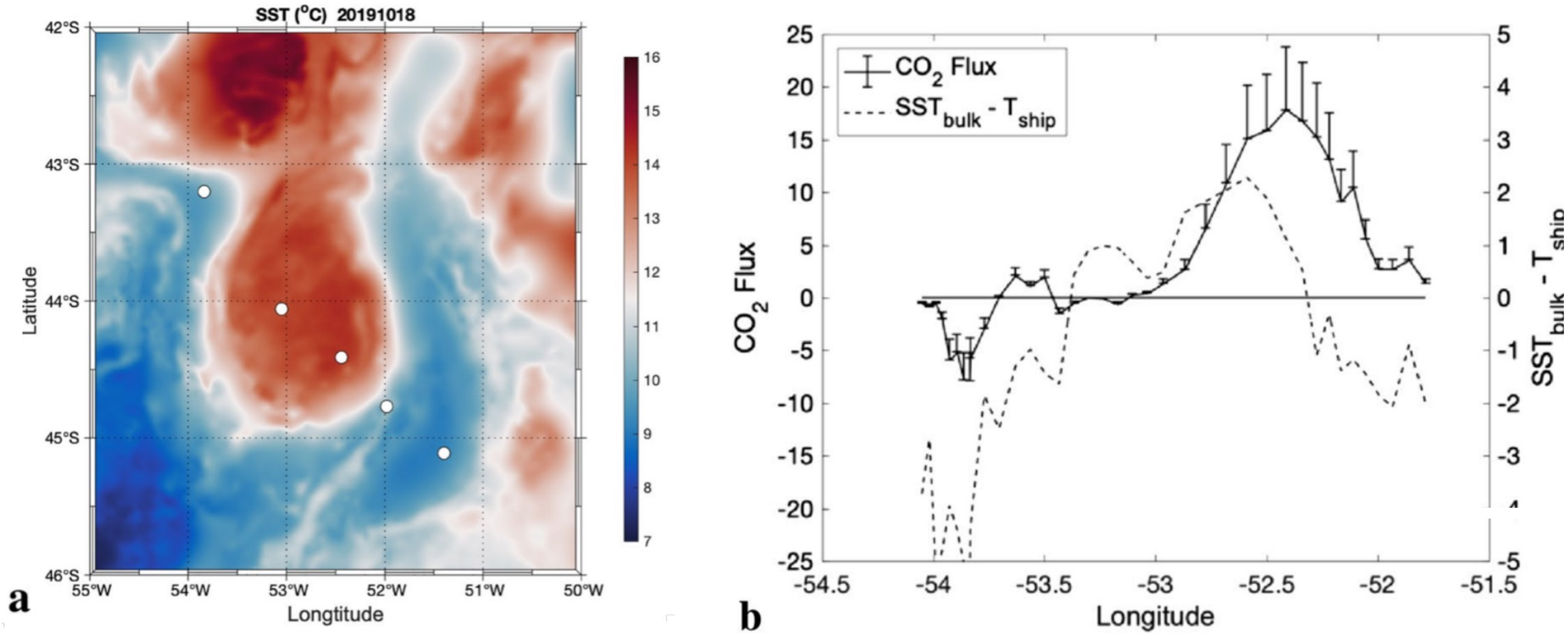
$$F_x = k\left(C - C_{eq}\right)$$

- where:
  - *k: gas transfer velocity.*
  - *C: gas concentration at seawater.*
  - *C_{eq}: gas concentration in equilibrium with the atmosphere*

- Mesoscales can impact F_x via k or C_{eq}:
  - *Parameters vary nonlinearly with wind speed and depend on sea state*

- Mesoscales can also impact C:
  - *Influence on biological sources and sinks of gas tracers.*

Air-sea flux of gas tracers



From Seo et al. (2023), reproduced from Pezzi et al. (2013)

Thank you!

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