Ocean Mesoscale Air-Sea Interaction over Gulf Stream: Drivers, Physics, and Influence

10-1000 km: Semi-permanent SST fronts, transient eddies, & filaments SST, ocean currents, and sea states (waves)



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Thanks to Cesar Sauvage (WHOI) US CLIVAR & Air-Sea Interaction Working Group



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

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Negative correlation: Wind drives SST responses

Positive correlation: SST forces the surface wind.

The sign and magnitude of the local SST-wind coupling provide a good indication of where and when the ocean influences the atmosphere Correlation of SST(tendency) and heat flux or SST and precipitation are also used (e.g., Wu et al. 2006; Bishop et al. 2017; Small et al. 2020) Small et al. (2008); Seo (2017)







Observed mesoscale SST impacts on surface wind

Quasi-linear relationship between spatially highpass filtered SST and (neutral) wind speed



- metric.
- Because of high-pass filtering, it is difficult to extract useful information on the scale dependence from such calculations.
- Spectral method (Laurindo et al. 2018)
- Analytical model by Schneider and Qiu (2018); Schneider (2020); Masunaga et al. (2022)

O'Neill et al. (2012)



$$\hat{fk} \times u = -\frac{1}{\rho_0} \nabla p - \varepsilon u$$

- The linear model indicates a quasi-linear dependence of near-surface wind convergence and vertical motion to SST-driven $\nabla^2 P$.
- The model ignores the stochastic nature of the atmospheric processes in the region.

Minobe et al. (2008)













Climatological impacts of WBC SST fronts on storm track

NH storm track climatology (v'T'@ 850hPa)



Hoskins and Valdes (1990); Nakamura and Shimpo (2004)



O'Reilly et al. (2017)

See also O'Reilly et al. (2016) Liu et al. (2021) Siquera et al. (2021)

(d) DJF SST CONTROL







SST impacts on local and downstream weather events

- WBC SST fronts and warm-core eddies ullet
 - 1. strengthen the storm activity locally,
 - 2. modulate the intensity/path of the storm track,
 - 3. alters the quasi-stationary circulation, leading to downstream rainfall and temperature anomalies
- Robust characterization of the downstream circulation responses remains difficult
 - due to different methods to define SST impacts
 - different model climatologies
- Coordinated studies to quantify relative impacts of sharpness of the SST front,
 - meridional position of the SST front, and
 - activity of warm or cold-core eddies,
 - \rightarrow All these also affect the absolute SST.







atological storm trac

shifted storm

Ring

The atmospheric fronts "feel" the WBC SST fronts Shared cross-frontal length scales: atmospheric fronts \approx ocean fronts (10-100 km) 1000km → 10m/s descending cold air diabatic frontogenesis WBC & generation of APE ATMOSPHERE high heat flux diabatic heat *c*, change ascending warm air Warm Core OCEAN Ring dQ_{SH}/dy <0 cold air over warm water behind the cold



APE budget modulated by anomalous SST near the WBC (Seo et al. 2021)

front

Diabatic generation or dissipation of the atmospheric APE

PO

46N 44N

The sign of the cross-frontal sensible heat flux gradient indicates the diabatic frontogenesis or frontolysis (Parfitt et al. 2016)









DJF Climatological convergence DJF 2σ filtered convergence



2σ filtering (storms and atmospheric fronts) removes the convergence

O'Neill et al. (2017)

weighted convergence in AFs: $(q_n C_n)$

weighted convergence in non-AF: $(1-q_n)d_n$





The time-mean convergence is induced by the atmospheric (cold) fronts.

Complications over the WBC regions

Convergence and vertical motion are determined by

1) quasi-steady linear boundary layer dynamics

2) storms/atmospheric fronts (related or unrelated to SST fronts)





Turbulent heat and momentum fluxes over Gulf Stream





ton et al. 2004



Diabatic and mechanical feedbacks to ocean

Mean diabatic dissipation $G_m = \int_{\mathcal{A}} \frac{\alpha_{\theta}^2 g^2}{c_p N_r^2} \theta_*^m Q_o^m d\mathcal{A}$



Ocean EPE destruction by mean and eddies via the negative SST-Q covariance \rightarrow an ocean EPE sink

Bishop et al. 2020



Ocean EKE reduction by ocean eddies via the negative τ -u_s covariance \rightarrow an ocean EKE sink Renault et al. 2017







Damping of eddy energy by the RW effect





Seo et al. in prep.



Ardhuin et al. (2017): The spatial variability in ocean currents affects the wave properties, leading to congruent patterns of wave energy and ocean currents

wind stress

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

S ↔ N



surface current

71.6°W

Wave-current interaction and sea state



• The waves misaligned with the currents increase H_s , surface drag, and stress. • Wave-wind interactions: Cesar's poster: "Impacts of surface waves on air-sea flux and marine boundary layer processes in the North Atlantic Oceans"







Mesoscale air-sea interaction is important for accurate simulations of ocean circulation, boundary layer process, and some highimpact weather events.

• Satellite remote sensing plays a crucial role in mesoscale air-sea interaction studies.

- mesoscale SSTs
- addresses this).

Synthesis and discussion

- This represents challenges for developing observational strategies, model physics, and diagnostics approaches, important for Earth System predictability across scales.

- Mostly in identifying and understanding neutral wind response to

- A critical gap remains to provide accurate global estimates of turbulent heat and moisture fluxes at high-resolution (10-25 km) (Butterfly

- Synchronous measurements of surface winds & currents and surface winds & waves are forthcoming or ongoing (S-MODE, Odysea, Harmony, & CFOSAT).











In-situ measurements of PBL, air-sea flux, and sea-states are extremely sparse.

- Need distributed arrays of DCF systems, bulk met. sensors, sea-state, and PBL to refine the bulk formula (e.g., DOE WFIP3)
- Novel technologies enable detailed characterization of the air-sea processes
- Strong interests exist in coordinated air-sea interaction studies (OASIS, US CLIVAR).

interactions

- Air-sea fluxes and MABL processes are not well validated.
- Bulk formulas do not represent the recent observations of wave-windcurrent interactions.
- (Rectified) coupled effects of ocean eddy coupling (on EPE and EKE) should be parameterized.
- Coordinated global modeling and diagnostic efforts are increasing (e.g., HighresMIPs)
- Regional-scale or LES modeling could guide sampling strategies and refine the physics.

Synthesis and discussion

Models have been LEADING the research on weather-ocean-climate

Helpful reading

- \bullet
- Comprehensive reviews on mesoscale air-sea interaction: Small et al. (2008)
- WBCs, air-sea interaction, and climate implications: <u>Kelly et al. (2010)</u>; <u>Kwon et al. (2010)</u> \bullet
- \bullet
- US CLIVAR Workshop report by Robinson et al. (2018, 2020) ullet
- **Special Collection:**

 - "Hot Spots" in the climate system, J. Oceanography, 2015
- An updated review by the US CLIVAR Air-Sea Interaction Working Group \bullet
 - Preprint available <u>here</u>

Satellite observations of surface wind response to mesoscale SSTs: Chelton et al. (2004); Xie (2004) Extratropical atmospheric responses and modeling: Kushir et al. (2002); Czaja et al. (2019)

Climate Implications of Frontal Scale Air-Sea Interaction, J. Climate, 2013-Present

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Extra



Significance?

Kushnir et al. 2002

Atmospheric GCM Response to Extratropical SST Anomalies: Synthesis and Evaluation^{*}

Y. KUSHNIR,⁺ W. A. ROBINSON,[#] I. BLADÉ,[@] N. M. J. HALL,[&] S. PENG,^{**} AND R. SUTTON⁺⁺

The observed standard deviation of 500-hPa heights on monthly to interannual timescales is of the order of 50– 100 m. Thus, while it is possible for the response to an SST anomaly to provide a significant signal at the 500-

GCM responses to extratropical SST anomalies with realistic spatial sizes and amplitudes of up to a few degrees are on the order of 10–20 gpm K⁻¹ anomaly A. Czaja¹ \bigcirc · C. Frankignoul² · S. Minobe³ · B. Vannière⁴ at 500 hPa. These values are in agreement with the-

Typical SSTA of ±1K due to GS shift

Z₅₀₀ response of ±20m/K



Seo et al. 2017 using ~40km atmosphere

Czaja et al. 2019

Current Climate Change Reports https://doi.org/10.1007/s40641-019-00148-5

MID-LATITUDE PROCESSES AND CLIMATE CHANGE (I SIMPSON, SECTION EDITOR)



