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)

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

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Thanks to Cesar Sauvage (WHOI)
US CLIVAR & Air-Sea Interaction Working Group
Air-sea interaction is spatial scale-dependent

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

Daily correlation between QuikSCAT wind speed and NOAA OI SST (2000-2009)

**Corr(SST, W')** unfiltered

**Corr(SST', W')** spatially high-pass filtered

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 high-pass filtered SST and (neutral) wind speed

- The coupling coefficient is a widely-used diagnostic 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)

Linear Ekman-based boundary layer dynamics

- 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

The growth rate of the extratropical cyclones is proportional to low-level baroclinicity

$$|\sigma_{BI}| = 0.31 \left( \frac{g}{N\theta} \right) \left| \frac{\partial \theta}{\partial y} \frac{\partial \theta}{\partial x} \right|$$

Enhanced baroclinicity supported by the oceans near the Kuroshio and Gulf Stream regions

Air temperature gradient

Static stability

Hoskins and Valdes (1990); Nakamura and Shimpo (2004)
SST impacts on local and downstream weather events

- WBC SST fronts and warm-core eddies
  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,
  → All these also affect the absolute SST.

See also O'Reilly et al. (2016) Liu et al. (2021) Siquera et al. (2021)
The atmospheric fronts “feel” the WBC SST fronts

Shared cross-frontal length scales: atmospheric fronts ≈ ocean fronts (10-100 km)

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

\[
\frac{\partial A_T}{\partial t} \approx c_{pa} \frac{\gamma}{T} \frac{\nabla H}{p} \cdot \nabla H + \frac{RT' \omega'}{p} + \frac{\gamma Q_T' T'}{\nabla Q} \nabla T
\]

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

Diabatic generation or dissipation of the atmospheric APE

\[
dQ_{SH}/dy < 0 \quad dQ_{SH}/dy > 0
\]

\[
dQ_{SH}/dy < 0 \quad dQ_{SH}/dy > 0
\]

Parfitt et al. (2016)
Convergence and vertical motion are determined by
1) quasi-steady linear boundary layer dynamics
2) storms/atmospheric fronts (related or unrelated to SST fronts)

Complications over the WBC regions

**diabatic contribution at the ocean frontal scales**

isentropic upglide and downglide that are canceled out

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Parfitt and Seo (2018)
Turbulent heat and momentum fluxes over Gulf Stream

\[ Q_{LH} = \rho_a L_e C_E \Delta q W - U \]

Turbulent heat flux

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

Wind stress curl

Air-sea flux anomalies exert thermal and mechanical feedback on the oceans.

Weller et al. 2012

Chelton et al. 2004
Diabatic and mechanical feedbacks to ocean

Mean diabatic dissipation \( G_m = \int_A \frac{\alpha^2 \theta^2}{c_p N_f^2} \theta^m Q_0^m dA \).

Eddy diabatic dissipation \( G_e = \int_A \frac{\alpha^2 \theta^2}{c_p N_f^2} \theta^r Q_0^r dA \).

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

Bishop et al. 2020

Total mean wind work \( \frac{1}{\rho_0} (\overline{\nu} \tau_x + \overline{\nu} \tau_y) \).

Geostrophic eddy wind work \( \frac{1}{\rho_0} \left( \nu^r \tau_x + \nu^r \tau_y \right) \).

Ocean EKE reduction by ocean eddies via the negative \( \tau-u_s \) covariance → an ocean EKE sink

Renault et al. 2017
Damping of eddy energy by the RW effect

\[ \tau = \rho a C_D (W - U)^2 \]

\[ \tau = \rho a C_D (W)^2 \]

- With the RW effect, the Gulf Stream becomes more stable and eddy activity is attenuated by 30-40%.

Renault et al. 2016

RW effect also influences the turbulent heat flux

\[ \tau = \rho a C_D (W - U)^2 \]

\[ Q_{LH} = \rho a L_a C_E \Delta q |W - U| \]

6 km WRF-ROMS coupled model simulation: 2016-2018 annual averages

\[ G_e = \int_{A} \frac{\alpha g^2}{c_p N_c^2} \theta |Q_e| dA \]

- The RW effect on Q is not negligible.
- Induces distinct responses in SST and the storm track.

Seo et al. in prep.
Wave-current interaction and sea state

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

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

The spatial variability in ocean currents affects the wave properties, leading to congruent patterns of wave energy and ocean currents.

- **Wind stress**
- **Surface current**

<table>
<thead>
<tr>
<th>Current direction</th>
<th>Wave direction</th>
<th>Significant wave height ( H_s )</th>
</tr>
</thead>
<tbody>
<tr>
<td>( \Delta z_0 )</td>
<td>( \Delta C_D )</td>
<td>( \Delta \tau )</td>
</tr>
</tbody>
</table>

- \( \Delta z_0 \) up to 10%
- \( \Delta C_D \) up to 10%
- \( \Delta \tau \) ~1%

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

• Satellite remote sensing plays a crucial role in mesoscale air-sea interaction studies.
  - Mostly in identifying and understanding neutral wind response to mesoscale SSTs
  - A critical gap remains to provide accurate global estimates of turbulent heat and moisture fluxes at high-resolution (10-25 km) (Butterfly addresses this).
  - 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).

• Models have been LEADING the research on weather-ocean-climate interactions
  - Air-sea fluxes and MABL processes are not well validated.
  - Bulk formulas do not represent the recent observations of wave-wind-current 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.
Helpful reading

- Satellite observations of surface wind response to mesoscale SSTs: Chelton et al. (2004); Xie (2004)
- Comprehensive reviews on mesoscale air-sea interaction: Small et al. (2008)
- WBCs, air-sea interaction, and climate implications: Kelly et al. (2010); Kwon et al. (2010)
- Extratropical atmospheric responses and modeling: Kushir et al. (2002); Czaja et al. (2019)

- Special Collection:
  - Climate Implications of Frontal Scale Air-Sea Interaction, J. Climate, 2013-Present
  - "Hot Spots” in the climate system, J. Oceanography, 2015

- An updated review by the US CLIVAR Air-Sea Interaction Working Group
  - Preprint available here

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Thanks, US CLIVAR!
The parameterized wave and sea-state impacts on momentum and heat flux influence the kinematic and thermodynamic profiles of the PBL.

Cesar Sauvage’s poster: “Impacts of surface waves on air-sea flux and marine boundary layer processes in the North Atlantic Oceans”
Extra
Wave-wind interaction near the Gulf Stream
See Cesar’s poster for more detail!

Wave age ($C_p/W_{10}$)

Surface wind, WBF-WSDF

Wave slope

Waves have a slope of:

- Rough
- Rough and aligned
- Smooth
- Misaligned

Abs(θ) between wave and wind

Wind speeds

-Wave age = 1.2: wind-wave equilibrium

- Young swell (mixed sea)

- Young seas

- Young swell leads to higher wind

- Wind seas leads to lower wind

See Cesar’s poster for more detail!
Significance?

Kushnir et al. 2002

Atmospheric GCM Response to Extratropical SST Anomalies: Synthesis and Evaluation

Y. Kushnir, W. A. Robinson, I. Blade, N. M. J. Hall, and 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 at 500 hPa. These values are in agreement with the-

Czaja et al. 2019

Simulating the Midlatitude Atmospheric Circulation: What Might We Gain From High-Resolution Modeling of Air-Sea Interactions?

A. Czaja, C. Frankignoul, S. Minobe, and B. Vannière

The prescribed SST anomalies are stripped of details and by the desire to remain close to the setting in the-

Early GCM experiments exploring the atmospheric response to extratropical SST anomalies were designed to (a) test the response to stationary and simplified SST forcing, and (b) test the response to simplified SST forcing.

Seo et al. 2017 using ~40km atmosphere

Over KOE: “observed” Z300 response >> modeled. But high-resolution models yield a greater response.