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

Whither the Gulf Stream Workshop June 15 2022

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



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



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

atological storm tract

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Ring



- - -

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 to middle and high latitudes, and the set of IT imnacte on curface wind nearly non-divergent, substantial divergence occurs in the MABL Observed mesoscale SST impacts of precipitation along the Gulf Stream. In this rain band, upward enzed mesoscale SST imnacts on su pressure adjustments to sharp sea surface the sea surface temperature gradients of  $\overline{1}$   $\overline{1}$

### pass filtered SST and (neutral) wind speed Quasi-linear relationship between spatially high-<br>
Linea poor in particular, it is unclear the warm current warm current warm current warm current warm current warm cu<br>The warm current wa as corroborated by the frequent occurrence of very low cloud-top temperatures. The mechanisms provide a pathway by the set of the s the Gulf Stream can affect the atmosphere local development of a stream can be a stream of the atmosphere local<br>Strengthende localized the atmosphere local local development of the strength of the strength of the strength Quasi-linear relationship between spatially high-<br>
Guasi-linear relationship between spatially high-<br> pass filtered SST and (neutral) wind speed source of layer dyn





- metric.  $t=0$  turning circulation, which has varied in strength in strength in strength in the past $7$  and  $\mu$
- from the 208 longitude by 108 longitude by 108 longitude used the 208 longitude used to 208 longitude used thr<br>Analysis of the 200 longitude used throughout used through the 200 long to 200 long through the 200 long throug the conduction on the set of the <br>This is a latitude on the set of t by the black dashed lines in Fig. 3 (middle row). Second, which dashed lines in Fig. 3 (middle row). Second, w<br>Second, which dashed lines in Fig. 3 (middle row). Second, which dashed lines in Fig. 3 (middle row). Second,  $\frac{1}{2}$  expected from a the shock and  $\frac{1}{2}$ • Because of high-pass filtering, it is difficult to extract useful information on the scale dependence from such calculations. information on the It is a challenging the country to produce the climatic order  $\lim_{n \to \infty}$  it in difficult to owtroot ring, it is alliicuit to extract ale dependence from such and the meaning is difficult to extract nondonce from quah van The linear m period to know parameters not available from satellite fr
- **the available settimate**  $\Box$ communique datasets, including the satellite datasets, including the satellite data sets  $\Box$ • Spectral method (Laurindo et al. 2018) resolutions satellite or all  $2010$ operational and European Centre for Medium-Range of Allian Sections (ECMWF).
- Analytical model by Schneider and Qiu (2018); The sea surface of the Stream 9, the Constant Stream 9, the Schneider (2020); Masunaga et al. (2022)  $\sim$  ( $\sim$   $(2020)$  Masunaga et al. (2022)  $\sum_{i=1}^{n}$  $\mathsf{B}^{\mathsf{a}}$  and  $\mathsf{O}^{\mathsf{b}}$  (2018). The mode  $\frac{1}{2}$ haga et al. (2022) ette convergence convergence convergence at the pattern of the laplacian of the laplace str sea-level pressure (=<sup>2</sup>  $\mathsf{c}_1$ and win (2010), and the pattern of the pattern of with an immediate consequence of a marine atmospheric boundary  $\mathcal{C}$  matrix boundary  $\mathcal{C}$

O'Neill et al. (2012)  $\angle$ )  $S<sup>y</sup>$  of all  $(2012)$ while ay<sup>n</sup> is relatively insensitive to the full range of  $\mathsf{et} \ \mathsf{al.} \ (2012)$ 







Linear Ekman-based boundary  
layer dynamics 
$$
\hat{f} \times u = -\frac{1}{\rho_0} \nabla p - \varepsilon u
$$

- The linear model indicates a quasi-linear dependence of near-surface wind convergence and vertical motion to  $\log$  of all 2018)  $SST$ -driven  $\nabla^2 P$ . del indicates e quesi linear denondence of wind convergence and vertical metion to  $\frac{1}{\sqrt{6}}$ alto a quasi-ilitoal doportuorico vi pressure warm for the warmer from the warmer from the warmer from the component of the component of the component o i-linear dependence of similar to laplacian to laplacian to laplacitude to laplacitude the substantial concrete to the substantial con<br>Substantial convergences (Fig. 10). The set of the substantial convergence of the substantial convergence of t results indicate the Magnetic SST gradients to SST gradients to SST gradients to SST gradients to SST gradients near-surtace wind convergence and vei  $\mathbf{v}$ <sup>1</sup> 30° N | =<br>|
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	- The model ignores the stochastic nature of the atmospheric processes in the region. a Tho model ignores the stochastic pot nesos in the region es the stochastic hature of the  $\sim$ Previous studies suggested that warmer SSTs induce stronger verstochastic hature or the atmospheric processes in the region. adjustments17. Our observation indicates the importance of the importance of the importance of the importance o  $R_{\text{e}}$  high pressure on the colder flags on the colder flags  $R_{\text{e}}$ on.  $s$  the stochastic nature of the convergence (colour) in  $\mathcal{S}_1$  satellite observations (a) and in the integrations (a) and in the integration

Minobe et al. (2008) mentary Fig. 1). Principe et al. (2000) ECMWF and the equation of all  $(2008)$  $\dots \dots \dots$ 





NH storm track climatology (v'T'@ 850hPa)  $\overline{\phantom{a}}$ 



# Climatological impacts of WBC SST fronts on storm track

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

Air temperature gradient







- 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,
		- $\rightarrow$  All these also affect the absolute SST.







Ring

# SST impacts on local and downstream weather events

matological storm track

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

(d) DJF SST CONTROL



(e) DJF SST CONTROL-SMOOTH



(f) DJF v'T'850 CONTROL-SMOOTH







PI

KP

### The atmospheric fronts "feel" the WBC SST fronts  $F_{\text{max}}$  and a straight gradient and atmospheric cold from the ocean temperature is equal to the atmospheric temperature is equal to the atmospheric temperature is equal to the atmospheric temperature is equal to the atm and spirent along  $\approx$  ocean nong  $(10-100$  and  $)$

at each  $\alpha$  see the set of rough  $\sum_{i=1}^{N}$ diabatic frontogenesis or frontolysis (Parfitt et al. 2016) direction of surface sensible heat fluxes, while the cross-frontal direction vector (y) is shown as <sup>a</sup> thin black arrow (positive toward the cold sector).  $\longrightarrow$  The sign of the cross-frontal sensible heat flux gradient indicates the 1000km (The sign of the cross-frontal sensible heat flux gradient indicates the<br>dishetic frontogenesis or frontologic (Perfitt et al. 2016)

PQ

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

Diabatic generation or dissipation of the atmospheric APE

## Complications over the WBC regions

Figure 4. (a) The product of the atmospheric frontal frequency (as a fraction of the total period December–February 1979– Figure 4. (a) The product of the atmospheric frontal frequency (as a fraction of the total period December–February 1979– The time-mean convergence is induced by the atmospheric (cold) fronts. matmorphoric (cold) fronte  $\frac{1}{2}$ Guifouphond (sold) monton

weighted convergence in AFs: (q<sub>n</sub>C<sub>n</sub>) the parameter in Figure in Figure 11, 110 and 11 december 11 fields essentially leaves a large-scale residual conversion  $AFS$ . I OnCr gence pattern in the time-mean divergence fields. The time-mean divergence fields. anog in stream. Finally, it is not the techniques perfection  $\mathbf{v}$ remove all traces of storms from the instantaneous divergence, so the divergence minima along the Gulf Stream

weighted convergence in non-AF: (1-q<sub>n</sub>)d<sub>n</sub> the parameter  $\frac{1}{2}$ fields essentially leaves a large-scale residual converuprannon motion over the Gulf Stream. reference that  $\sim$ remove all traces of storms from the instantaneous divergence, so the divergence minima along the divergence minima along the Gulf Stream and the Gulf Stream of the Gulf Stream and the Gulf Stream of the Gulf Stream and the Gulf Stream and the Gulf Stream and the Gulf Stream

2σ filtering (storms and atmospheric <sub>o</sub><sub>misil</sub> fronts) removes the convergence the spatial fields are nearly in the spatial fields are nearly in the spatial fields are near  $\sim$  $\frac{1}{2}$  for the  $\frac{1}{2}$  s-filter sary forcing to achieve a deep atmospheric response. In this AS THA CONVALUANCA forcing by storms and small-scale SST, then storms are still and 11d. Perhaps the most significant result here is that  $n$  $n$  $n$  $n$  $n$  $n$  $n$  $n$ for the temporally unfiltered and 2s-filtered fields. The

 $\overline{a}$  surface does not by its line  $\overline{a}$ sary forcing to achieve a deep atmospheric response. In this O'Neill et al. (2017)

Convergence and vertical motion are determined by

1) quasi-steady linear boundary layer dynamics

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

DJF Climatological convergence DJF  $2\sigma$  filtered convergence













 $\overline{\phantom{a}}$ 

out of the two primary sensors had a data return of the two primary sensors had a data return of the two primary sensors in the two primary s

are also prominent in the lee of extratropi-

cal islands but are less evident in the 4-year

rection is much more variable outside of

the trade wind regimes. The existence of

such features becomes clear when the

QuikSCAT data are segregated by averag-

ing the data only during the periods of the

prevailing wind direction. The prevailing



### doing an eddy-mean decomposition when using surface data and or long temporal records that can record that can record Diabatic and mechanical feedbacks to ocean Diabatic and mechanical feedbacks to ocean **Juabatic and mechanical teedbacks to ocean**  $\overline{c}$  $\frac{1}{\sqrt{1-\frac{1}{\sqrt{1+\frac{1$ 1  $\mathbf{z}$  $\left(\overline{u}\overline{\tau}\right)$  $+\,\overline{v\tau}_{_{\cal Y}})$  $=\int_{c}^{\infty} \frac{\omega_{\theta} s}{c N^2} \theta_{*}^{m} Q_{o}^{m} dA$ , *d,* (5) Total mean wind work  $\mathcal{X}$  $\rho_{0}^{\phantom{\dag}}$  $\int A^c p^1 r$ (*Gm*), seasonal (*Gs*), and transient (*Ge*) SST and net air-sea heat flux can be written by integrating (4) over  $\times10^{-4}$  $\mathcal{F}^{\circ}$ g and much of the GW; Fig. 3), rather than on small scales,  $\sqrt{2}$ 5 2  $\alpha$  $\overline{\phantom{0}}$ ) dz, and (3)  $\frac{360}{\sqrt{2}}$  and  $\frac{360}{\sqrt{2}}$  mWm<sup>-2</sup>  $\frac{1}{\alpha}$  $\frac{1}{2}$  ( $\frac{1}{2}$  co mWm<sup>-2</sup> *𝜃s* ∗*Qs* mWm-2 S.  $\geq$ <sup>∗</sup> *<sup>Q</sup><sup>m</sup>*  $\overline{\phantom{a}}$  (50)  $\overline{\phantom{a}}$  ( $\overline{\phantom{a}}$  ( $\overline{\phantom{a}}$ )  $\overline{\phantom{a$  $p_{\text{max}}$  on the chosen filtering second secon *r o*  $\ddot{\varepsilon}$ " ›U ) ທີ່ *r* tions look into each process in greater detail.  $\overline{1}$ <u>Company</u>  $\ddot{\cdot}$ 2  $1000$  $\mathbf{y}$ ›y  $\omega$  $I$   $-25$   $\frac{5}{5}$   $\frac{3}{5}$   $\frac{3}{5}$ *𝜃*′ ∗*Q*′  $\sum$   $\frac{1}{25}$   $\frac{1}{25}$   $\frac{1}{25}$   $\frac{1}{25}$  $0.1$  N.m<sup>-</sup> 8070 JOURNAL OF CLIMATE VOLUME 30 ›U  $\frac{1}{\sqrt{2\pi}}$  the GW, the CTL and the CT *𝜃s* ∗*Qs*  $\frac{1}{2}$  (6)  $\frac{1}{2}$  = 50  $\frac{1}{2}$  (6)  $\frac{1}{2}$  $\langle f_1 \rangle$  $\overline{\phantom{0}}$  $\frac{1}{2}$  $\mathbf{1}$ *r*  $\frac{1}{24}$  and  $\frac{1}{24}$  narrow and  $\frac{1}{24}$  $\dot{\mathcal{L}}$ ›z  $\sum_{i=1}^n$  $\sim$  $35\%$  Journal of Physical Order of Physi  $\sim$  stress curl extending southwestward southwestern southwest southwest southwestern southwest southwest southwestern southwestern southwestern southwestern southwestern southwestern southwestern southwestern southweste e  $50^{\circ}$ W  $\int \frac{a_{\theta}g}{\sqrt{S}} \overline{\theta'_{s}Q'_{s}} d\mathcal{A}$  $\frac{3}{4}$ 1  $\mathbf{I}$ *d.* (7) Geostrophic eddy wind work lv w nd work  $(\overline{u^{\prime}\tau_{_{\chi}}^{\prime}}+\overline{v^{\prime}\tau_{_{\rm Y}}^{\prime}})$  ,  $J_A c_p r_r$  Geostro  $\mathbf{I}$ rul<br>...  $\rho_{0}^{\phantom{\dag}}$  $\varphi_0$  is the density of  $\rho_0$  is the  $\varphi_1$ <sup>5</sup>  $\sim$   $\frac{1}{3}$ ,  $\sim$   $\frac{1}{3}$ , suggesting the 3 cm  $\frac{1}{3}$  $\blacksquare$ g  $\sqrt[10]{\frac{10}{250}}$  $\overline{\phantom{a}}$  $\mathbb{R}$ 5 2 2 2  $\mathcal{E}$  .  $\sum_{i=1}^n$  $\mathbb{Z}$  and the deviation from it.  $\frac{1}{2}$  $\begin{array}{ccc} \hline \text{16} & \text{16} & \text{16} \\ \hline \end{array}$   $\begin{array}{ccc} \text{16} & \text{16} & \text{16} \\ \text{17} & \text{18} & \text{17} \\ \text{18} & \text{18} & \text{18} \\ \hline \end{array}$  $\mathcal{L} = \mathcal{L} = \mathcal$  $t_{\text{max}}$  and  $t_{\text{max}}$  a **I**  $\frac{1}{2}$  is the correlation between  $\frac{1}{2}$  is the correlation between  $\frac{1}{2}$  is the correlation between  $\frac{1}{2}$ **CMARK** 5 2  $\ddot{\phantom{0}}$  $\overline{\phantom{a}}$  $\mathcal{N}$  $\frac{1}{\sqrt{1-\frac{1$ **r** current and wind stress (i.e., which is a stress of wind on by the wind  $\sim$  coupling, in particular on the oceanic mesoscale. This is in particular on the oceanic mesoscale. The oceanic mesoscale is in particular on the oceanic mesoscale is in the oceanic mesoscale in the oceanic mesoscale i  $\begin{array}{ccc} \hline \text{t} & \text{t} & \text{t} & \text{t} \end{array}$ #  $\geq$  $l_{-1.5}$  $\frac{1}{2}$  and  $\frac{1}{2}$  and  $\frac{1}{2}$  in  $\frac{1}{2}$  and  $\frac{1}{2}$  in  $\frac{1}{2}$  in  $\frac{1}{2}$ <u>1 ya Jo</u> 1 1u0  $\overline{r}$  $\overline{\phantom{a}}$  $\blacktriangledown$ mean wind work (Pm) affecting the MKE, and eddy wind ›z  $r_{\text{F}}$  and  $r_{\text{F}}$  is weakened not the top that is very set of  $\frac{1}{25}$  or  $\frac{1}{2}$  (Pe), which enters the ERE budget. If  $p$  is positive, window is positive, window in the ERE budget. If  $p$  $85°W$  /5°W 65°W 55°W 45°W 35°W 25°W 15°W  $\frac{1}{2}$  $e^{i\theta}$  is supplying the ocean, and an extending the ocean, and an extending the  $E$

 $\int a_{\theta}^2 g^2$  will be right-hand side of  $\alpha_{\theta}^2$  will be referred to as the local means of  $\alpha_{\theta}^2$ Mean diabatic dissipation  $G_m = \int_{\mathcal{A}} \frac{\partial^{\infty}}{c_p N_r^2} \theta_*^m Q_o^m d\mathcal{A}$ ,  $\alpha_\theta^2 g^2$  $c_p N_r^2$ 



et al., 2002; Domitia et al., 2010). The new version is available for the new version is available for the new version is available for  $\alpha$ temporal resolution and 0.25◦ spatial resolution. The focus of this study is on the monthly mean product, Via the negative SS1-Q covariance  $\rightarrow$  an ocean EPE sink<br>T-II, covariance  $\rightarrow$  an ocean Ek **Stream EPE destruction by mean and eddies** and column and column and column and column and column and and observations of the GM (Figs. 4g, f). *GM (Figs. 4g,f)* ocean Er E destigueud by fileari and equies<br>Cean EKE reduction by ocean eddies v via the negative SST-O covariance  $\rightarrow$  an ocean FPF sink  $\overline{C}$  $r$  an ocean EPE sink and  $r$ -ile  $\alpha$ Ocean EPE destruction by mean and eddies via the negative SST-Q covariance $\rightarrow$  an ocean EPE sink



 $\mathsf{Bishen}$  at al.  $\mathsf{OQQQ}$ reanalysis (Kanamitsu et al., 2002). Daily averaged SST is an ensemble median of multiple satellite data Bishop et al. 2020

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 $c_pN_r^2$ *r*

). The current

• The RW effect on Q is not negligible.

 $G_e = \int_{\mathcal{A}}$ 



### Damping of eddy energy by the RW effect  $\sim$  to as the traditional approach. Many of the pioneering works on ocean energy short used relatively short u



 $\frac{1}{\sqrt{2}}$ 6 km WRF-ROMS coupled model simulation: 2016-2018 annual averages







# 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"





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

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

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

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

### Synthesis and discussion

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

- 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

- mesoscale SSTs
- addresses this).
- 

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











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	-

### **• 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-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.

### **•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).

![](_page_12_Figure_0.jpeg)

![](_page_12_Figure_1.jpeg)

## Synthesis and discussion

# Helpful reading

- 
- Comprehensive reviews on mesoscale air-sea interaction: **[Small et al. \(2008\)](https://doi.org/10.1016/j.dynatmoce.2008.01.001)**
- WBCs, air-sea interaction, and climate implications: [Kelly et al. \(2010\);](https://journals.ametsoc.org/view/journals/clim/23/21/2010jcli3346.1.xml) [Kwon et al. \(2010\)](https://journals.ametsoc.org/view/journals/clim/23/12/2010jcli3343.1.xml)
- Extratropical atmospheric responses and modeling: [Kushir et al. \(2002\);](https://journals.ametsoc.org/view/journals/clim/15/16/1520-0442_2002_015_2233_agrtes_2.0.co_2.xml) [Czaja et al. \(2019\)](https://link.springer.com/article/10.1007/s40641-019-00148-5)
- US CLIVAR Workshop report by Robinson et al. [\(2018,](https://opensky.ucar.edu/islandora/object/usclivar:123) [2020](https://doi.org/10.1029/2018EO100609))
- Special Collection:
	-
	- "[Hot Spots" in the climate system,](https://link.springer.com/book/10.1007/978-4-431-56053-1) *J. Oceanography,* 2015
- An updated review by the US CLIVAR Air-Sea Interaction Working Group
	- Preprint available [here](https://hseo.whoi.edu/wp-content/uploads/sites/41/2022/02/ASI_Review_JCLI.pdf)

• Satellite observations of surface wind response to mesoscale SSTs: Chelton et al. (2004); Xie (2004)

![](_page_13_Picture_15.jpeg)

![](_page_13_Picture_16.jpeg)

![](_page_13_Picture_17.jpeg)

• [Climate Implications of Frontal Scale Air-Sea Interaction](https://journals.ametsoc.org/collection/climate-implications), *J. Climate*, 2013-Present

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