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)

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

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Whither the Gulf Stream Workshop
June 15 2022

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

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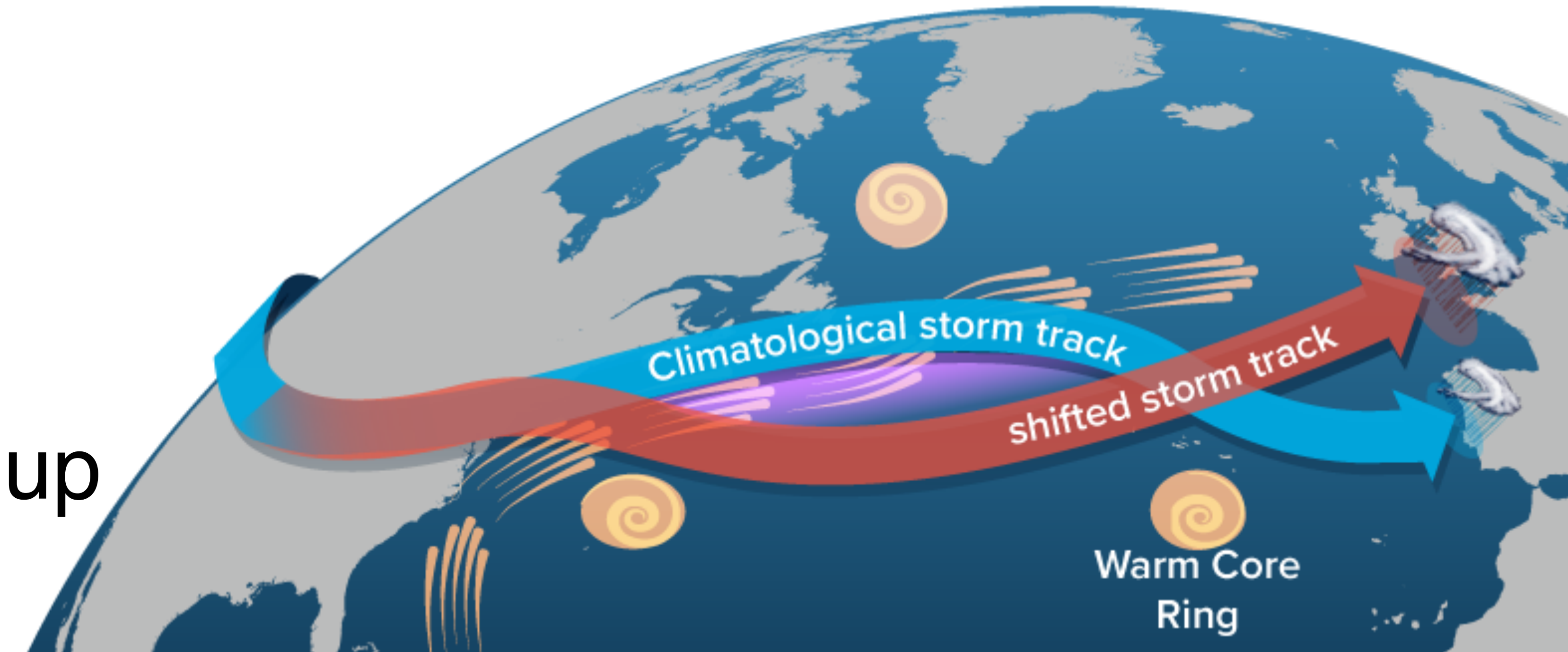
INSTITUTION



Air-sea interaction is spatial scale-dependent

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

$W = \overline{W} + W'$

SST

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

Corr(SST, W')
unfiltered

atmosphere
ocean

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

atmosphere
ocean

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

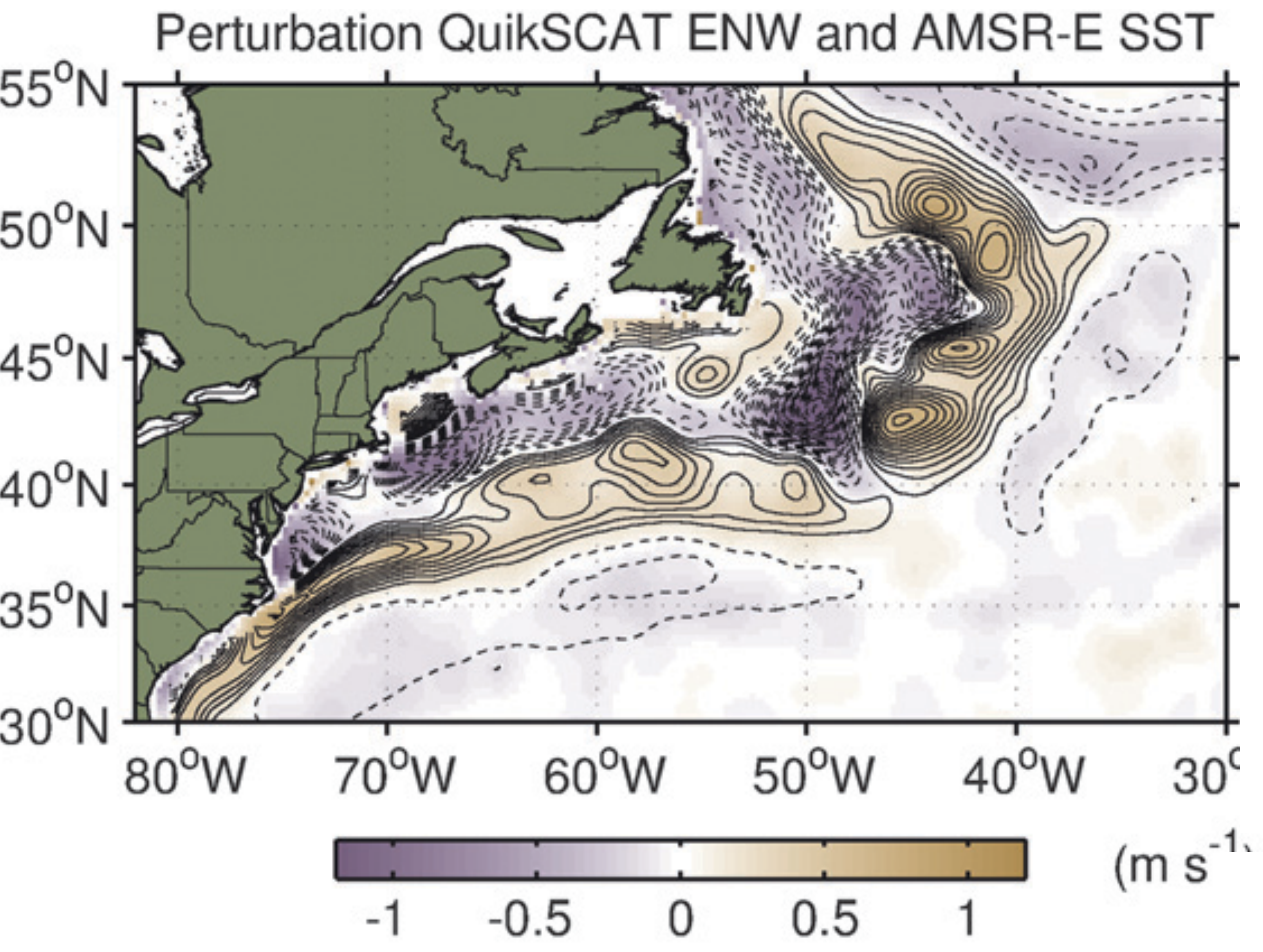
Correlation of SST(tendency) and heat flux or SST and precipitation are also used

(e.g., Wu et al. 2006; Bishop et al. 2017; Small et al. 2020)

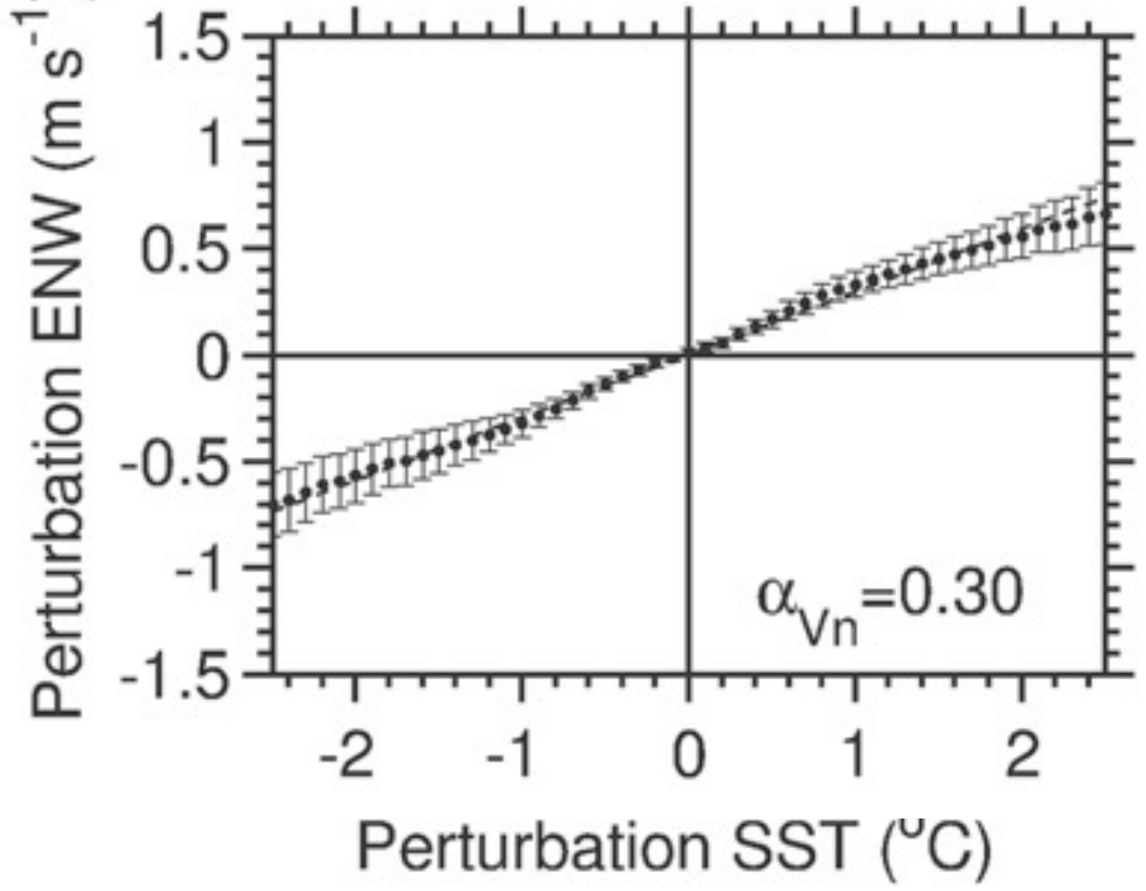
Small et al. (2008); Seo (2017)

Observed mesoscale SST impacts on surface wind

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



coupling coefficient

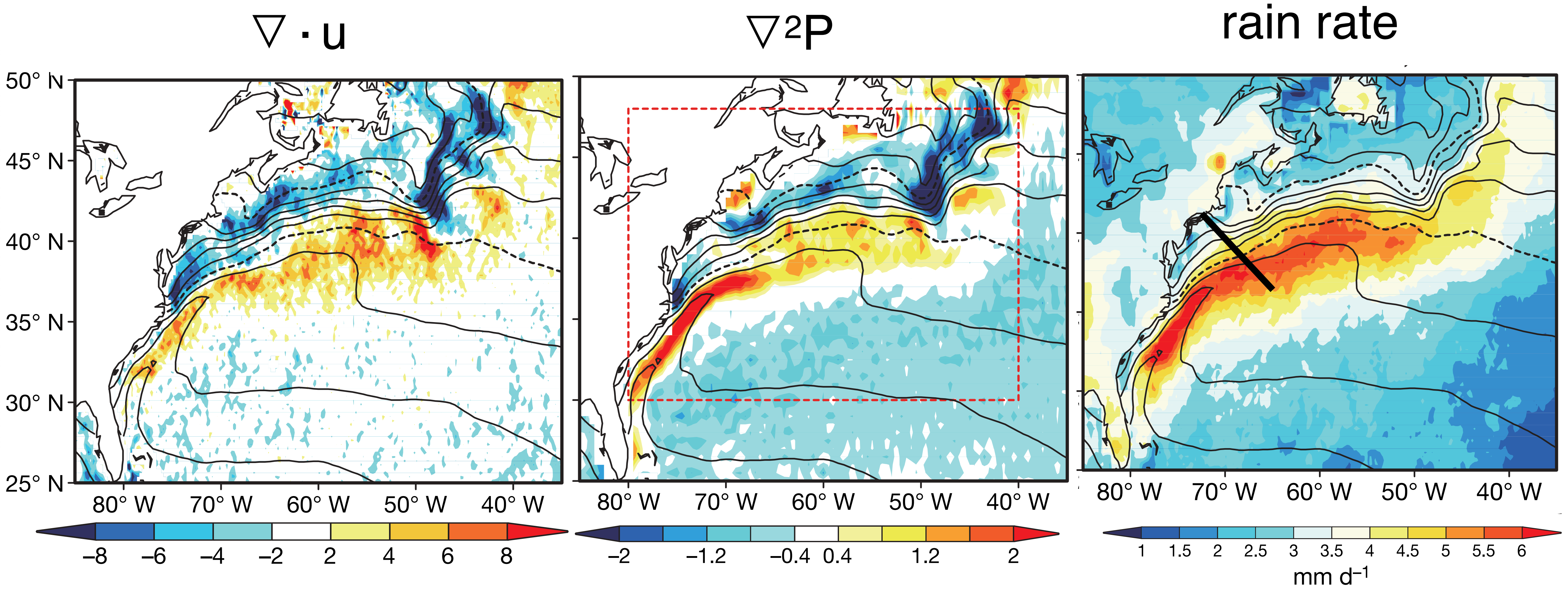


- The coupling coefficient is a widely-used diagnostic metric.
- Because of high-pass filtering, it is difficult to extract useful information on the scale dependence from such calculations.
  - Spectral method (Laurindo et al. 2018)
  - Analytical model by Schneider and Qiu (2018); Schneider (2020);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

O'Neill et al. (2012)

Linear Ekman-based boundary layer dynamics

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



$$\rho_o\left(\nabla\cdot\vec{u}\right) = -\left(\nabla^2 P\right)\varepsilon/\left(\varepsilon^2+f^2\right)$$

$$w(z) = \frac{1}{\rho_o}\left(\frac{\varepsilon z}{\varepsilon^2+f^2}\right)\nabla^2 P$$

- The linear model indicates a quasi-linear dependence of near-surface wind convergence and vertical motion to SST-driven ∇²P.
- 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 ($\overline{v'T'}$@ 850hPa)

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

$$|\boldsymbol{\sigma}_{\mathrm{BI}}| = 0.31\left(\frac{g}{N\theta}\right)\left|-\frac{\partial\theta}{\partial y},\frac{\partial\theta}{\partial x}\right|$$

Static stability

Air temperature gradient

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

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

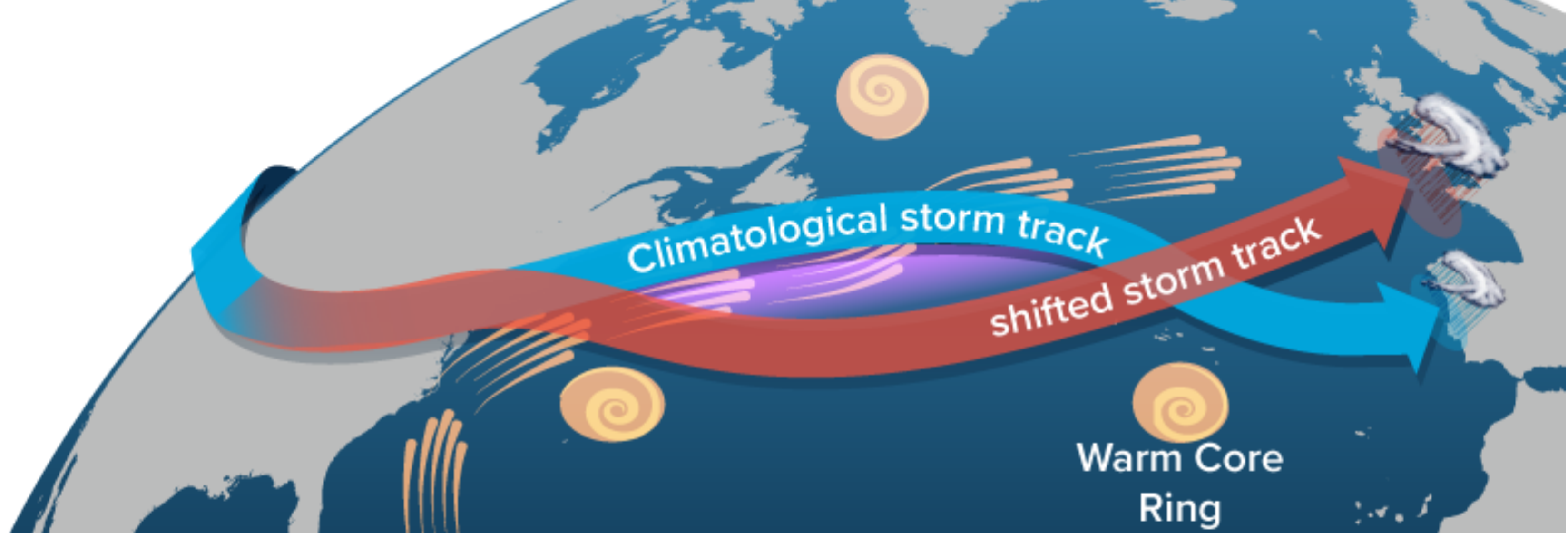
SST impacts on local and downstream weather events

- 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

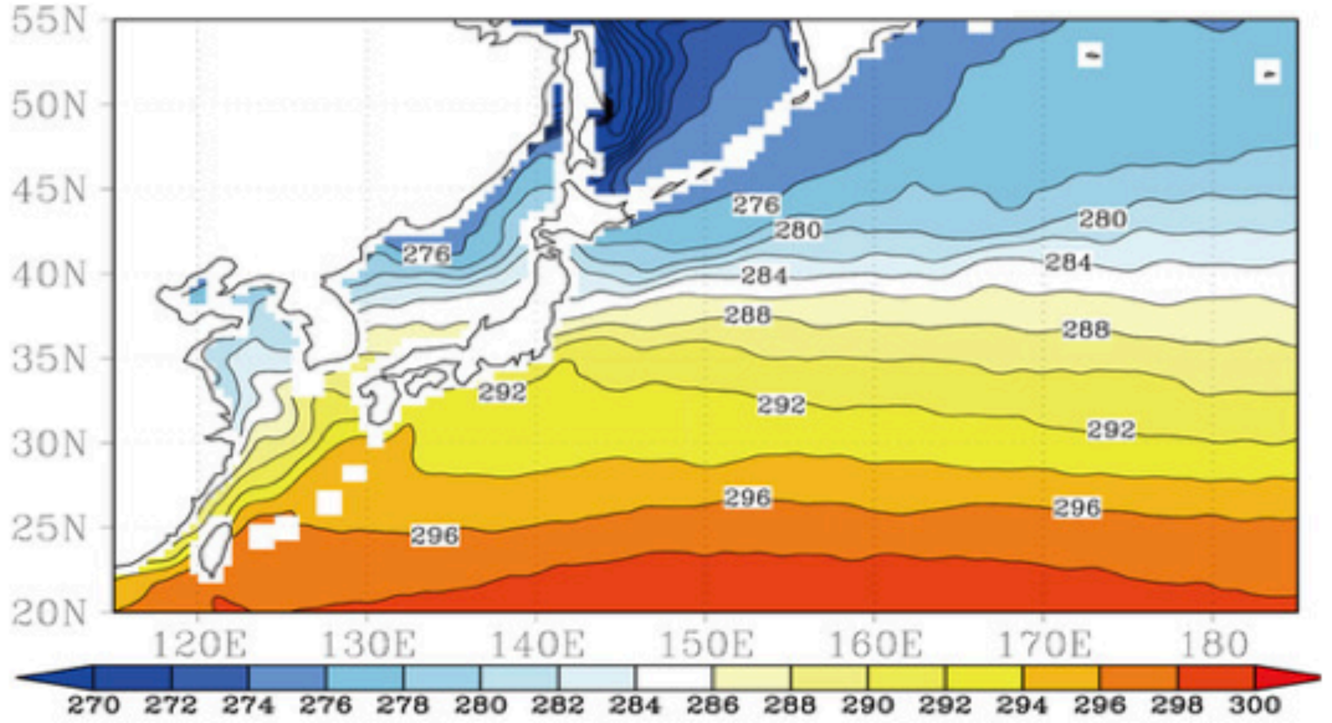
- Robust characterization of the downstream circulation responses remains difficult
  - due to different methods to define SST impacts
  - different model climatologies

- 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,

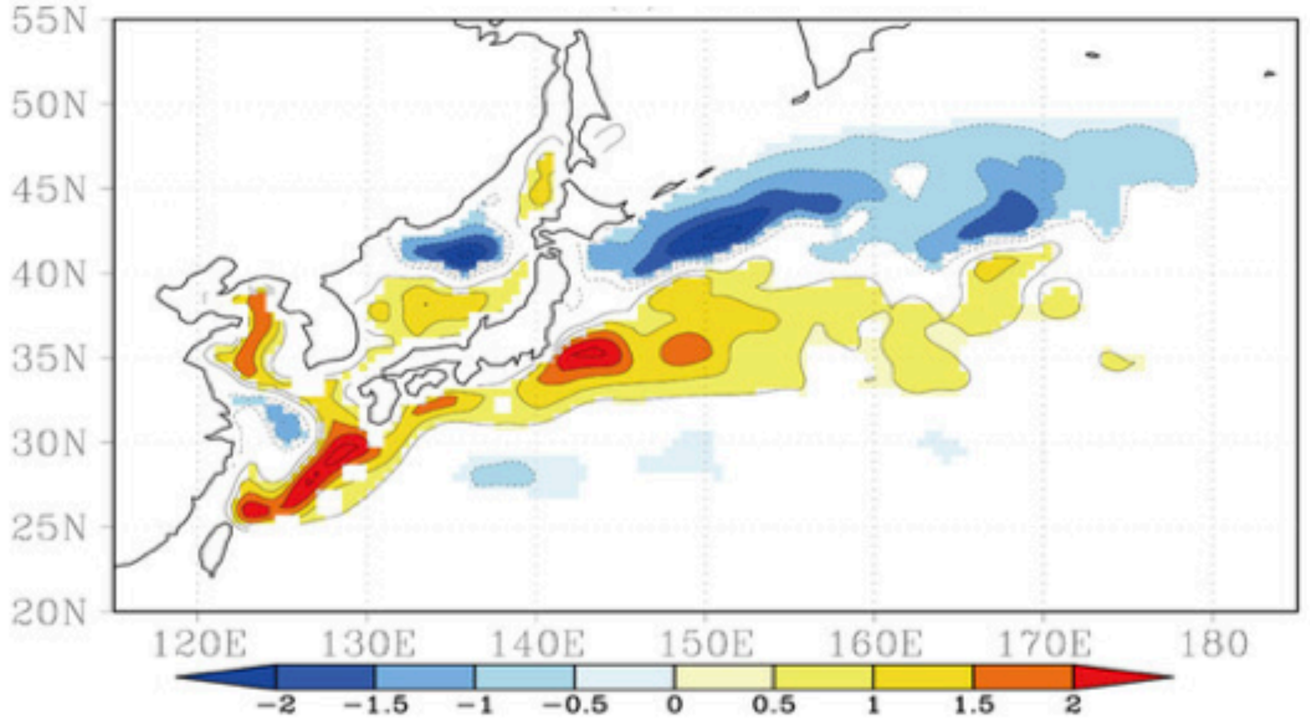
  → All these also affect the absolute SST.



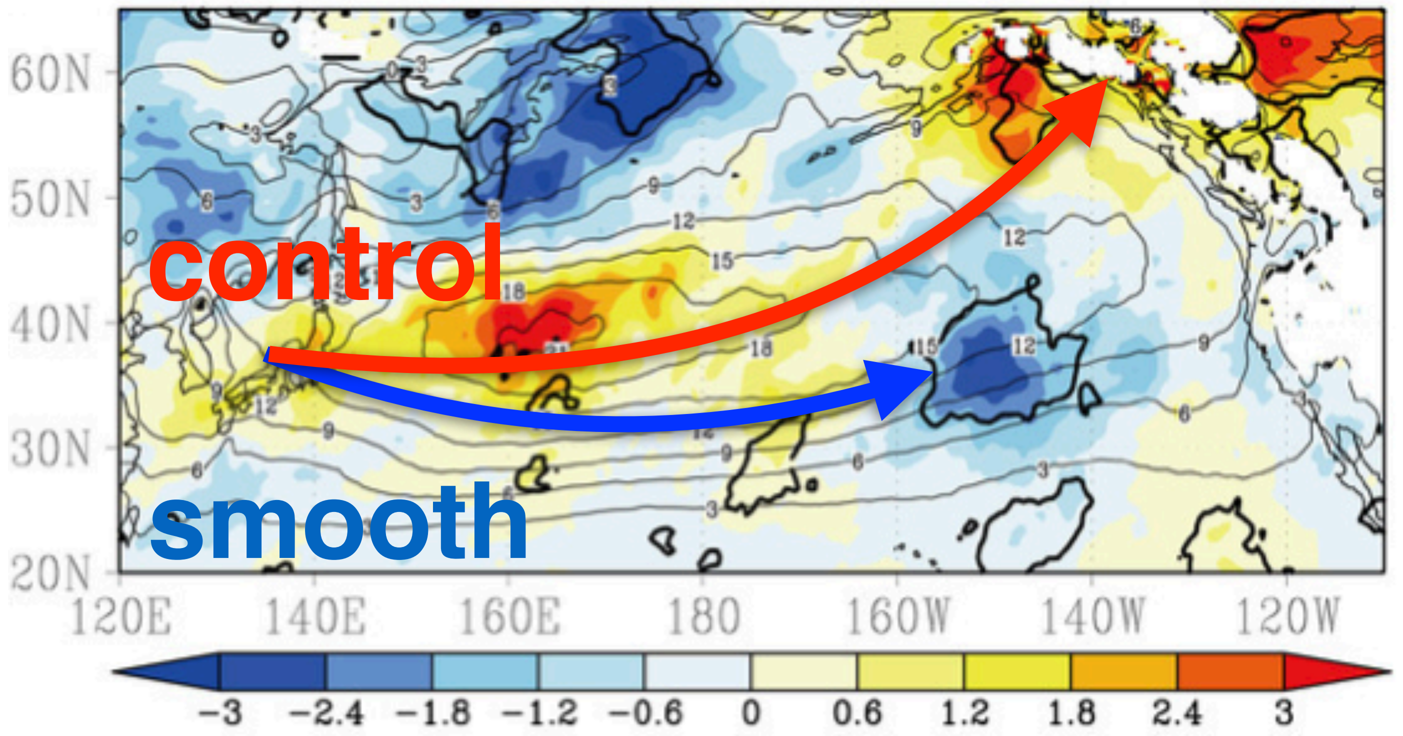
(a) JAN SST CONTROL



(b) JAN SST CONTROL-SMOOTH

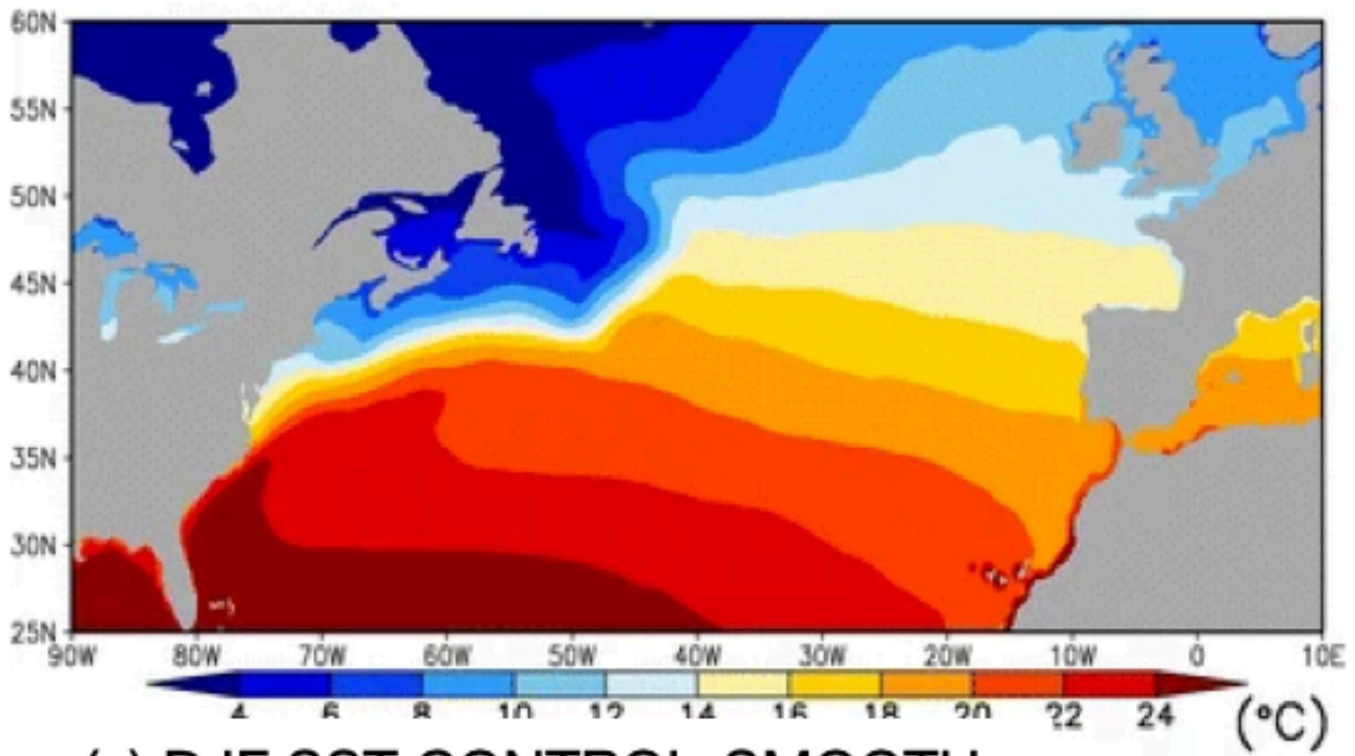


(c) JAN v'T'$_{850}$ CONTROL-SMOOTH

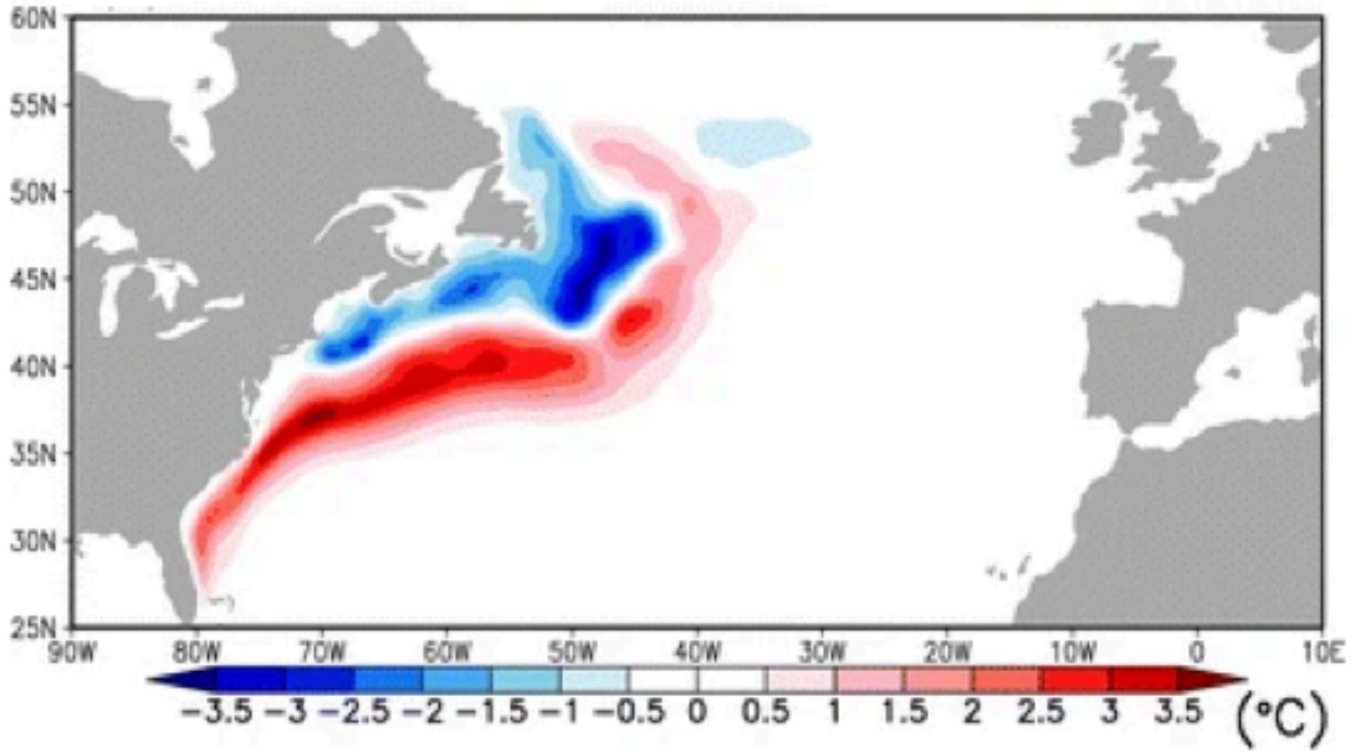


Kuwano-Yoshida et al. (2017)

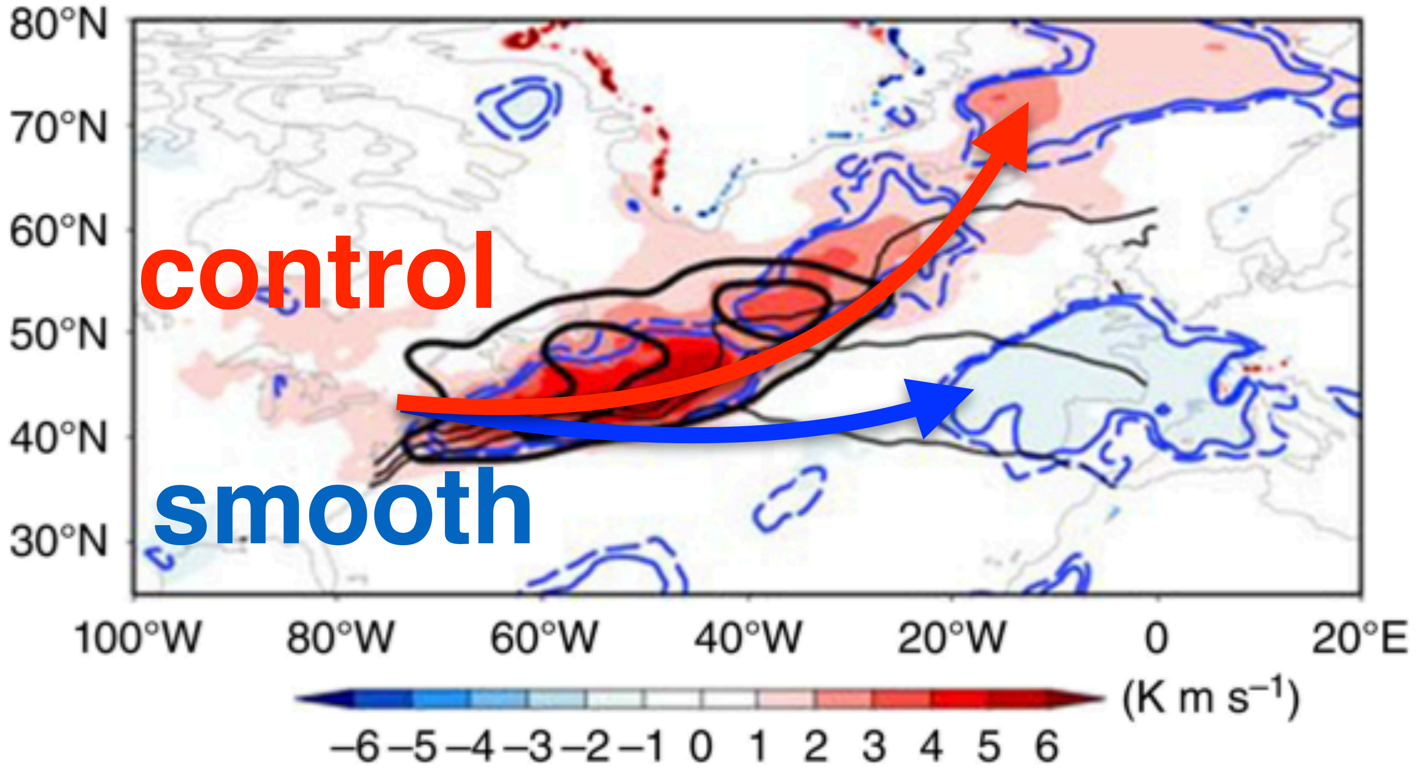
(d) DJF SST CONTROL



(e) DJF SST CONTROL-SMOOTH



(f) DJF v'T'$_{850}$ CONTROL-SMOOTH

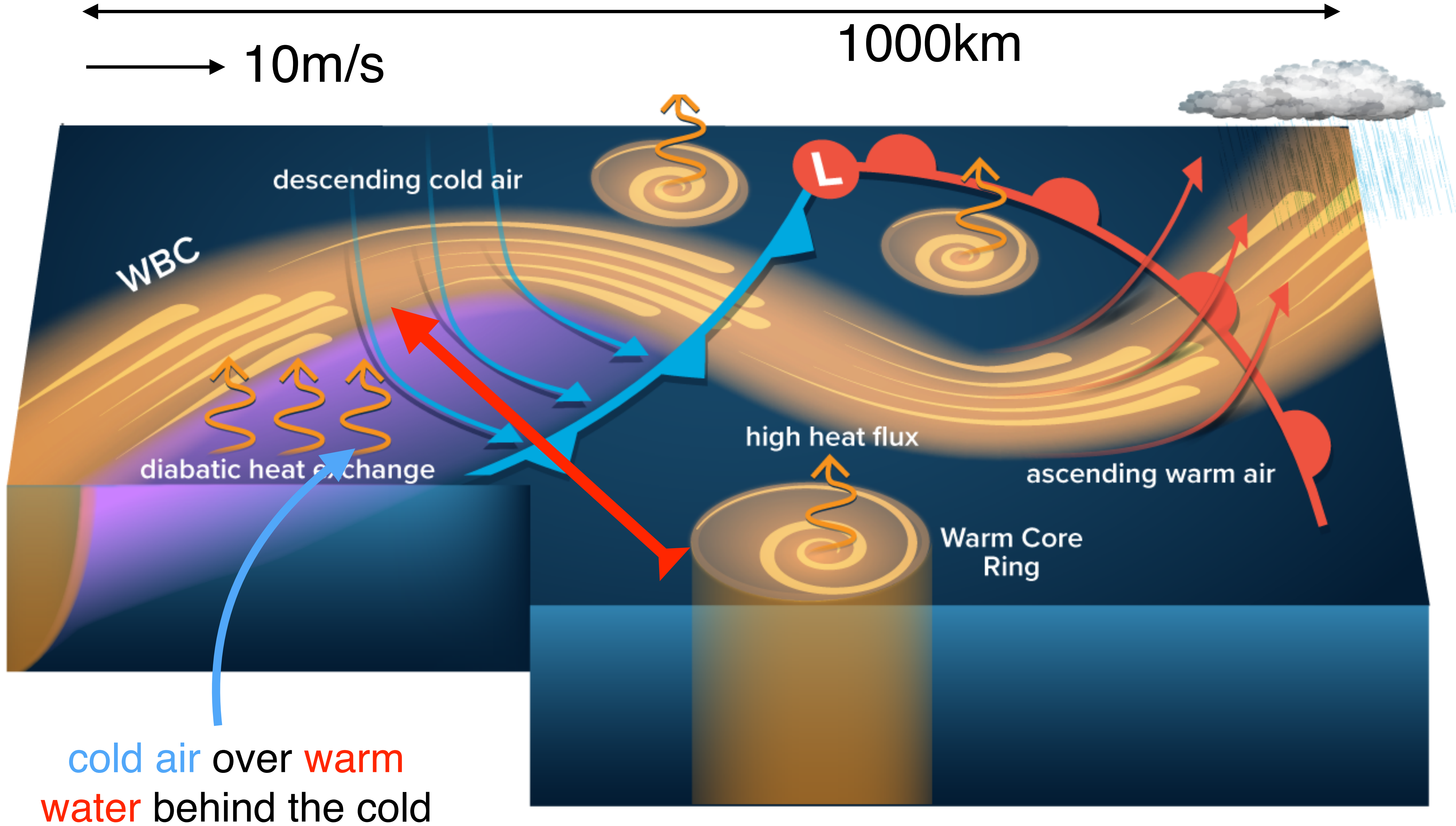


O'Reilly et al. (2017)

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)



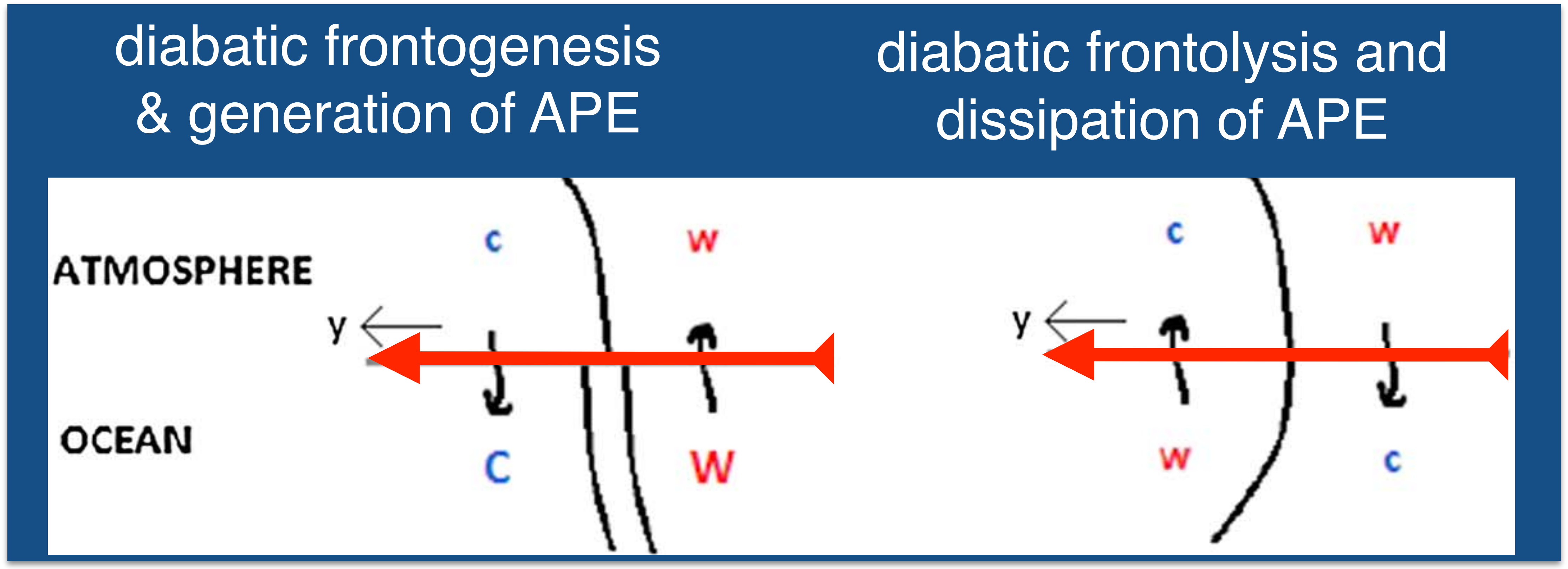
cold air over warm water behind the cold front

$$\frac{\partial A_T}{\partial t} \approx \underbrace{\frac{c_{pa}\gamma}{\overline{T}}\overline{\mathbf{V}'_H T'}\cdot\nabla_H\overline{T}}_{\text{PI}} + \underbrace{\frac{R\overline{T'\omega'}}{p}}_{\text{KP}} + \underbrace{\frac{\gamma\overline{Q'_1 T'}}{\overline{T}}}_{\text{PQ}}$$

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

Diabatic generation or dissipation of the atmospheric APE

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


diabatic frontogenesis & generation of APE

diabatic frontolysis and dissipation of APE

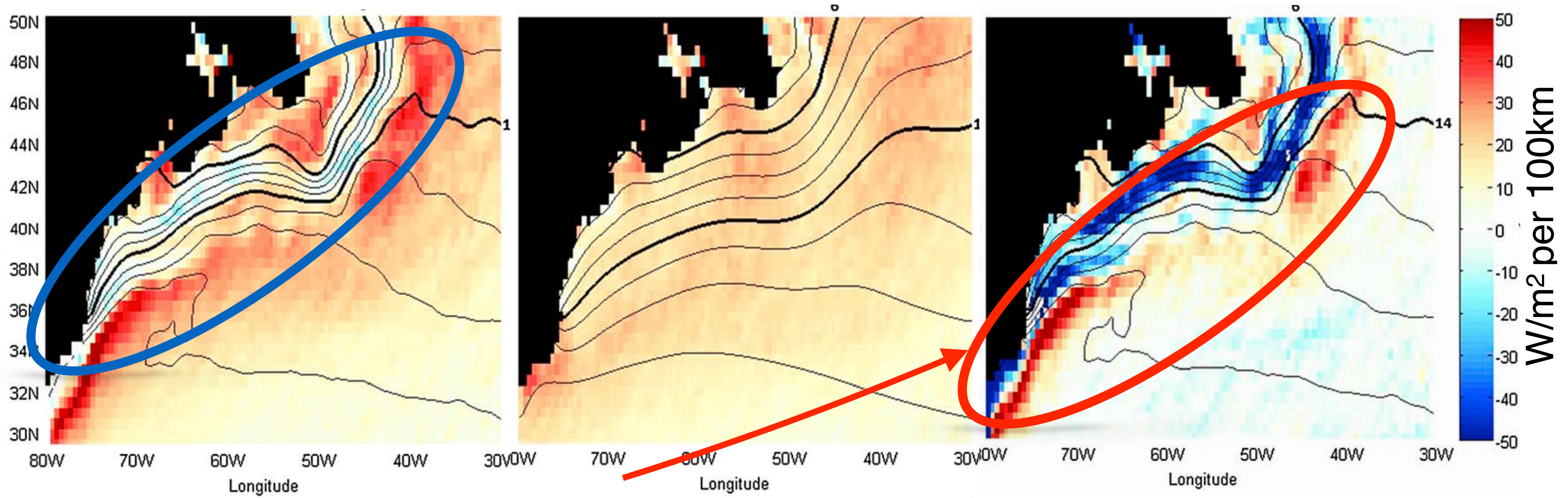
$dQ_{SH}/dy < 0$

$dQ_{SH}/dy > 0$

dQ_{SH}/dy in AGCM CONTROL

dQ_{SH}/dy SMOOTH

dQ_{SH}/dy CONTROL-SMOOTH

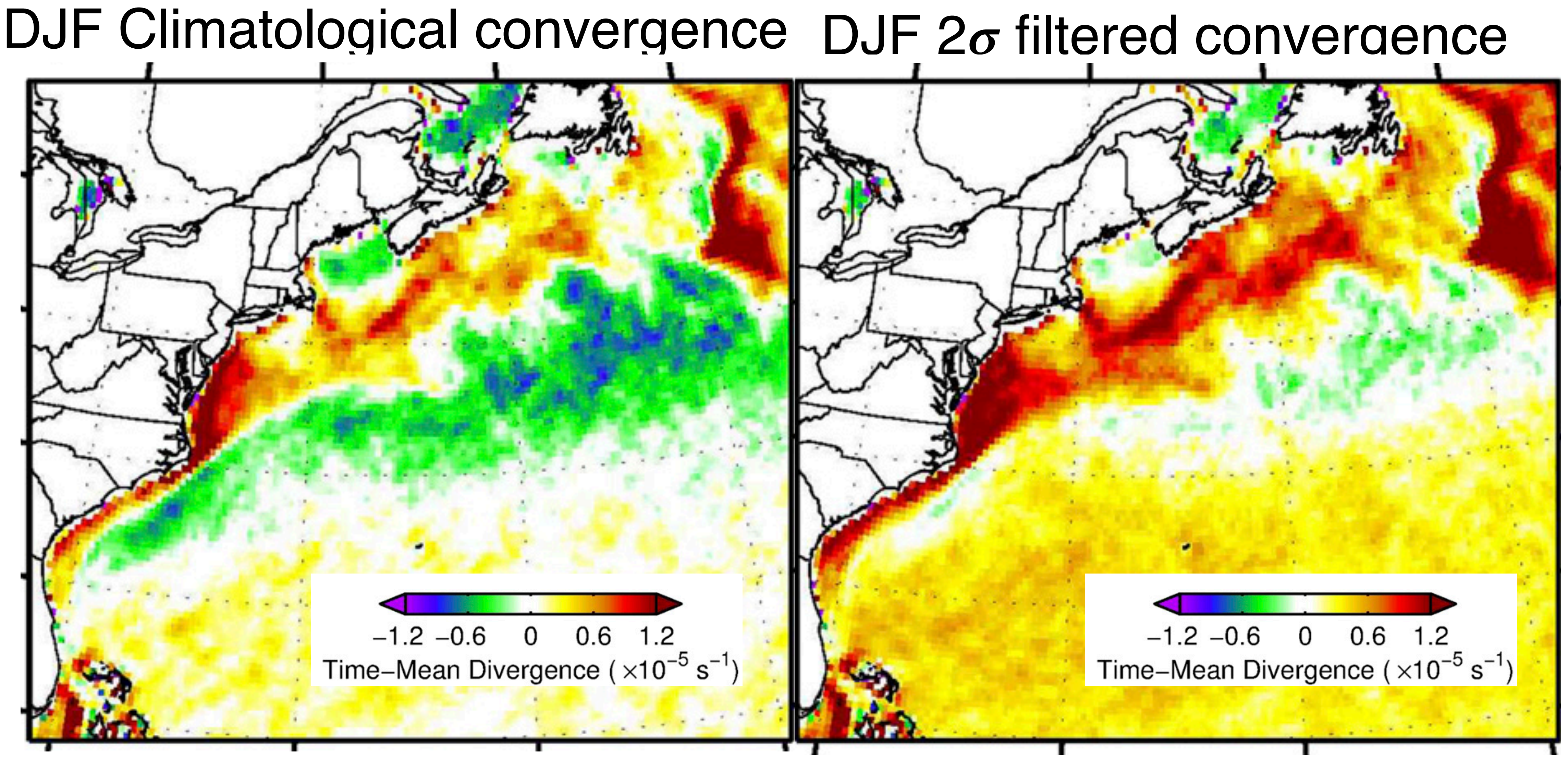


diabatic frontogensis and generation of APE over the GS front

Parfitt et al. (2016)

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)

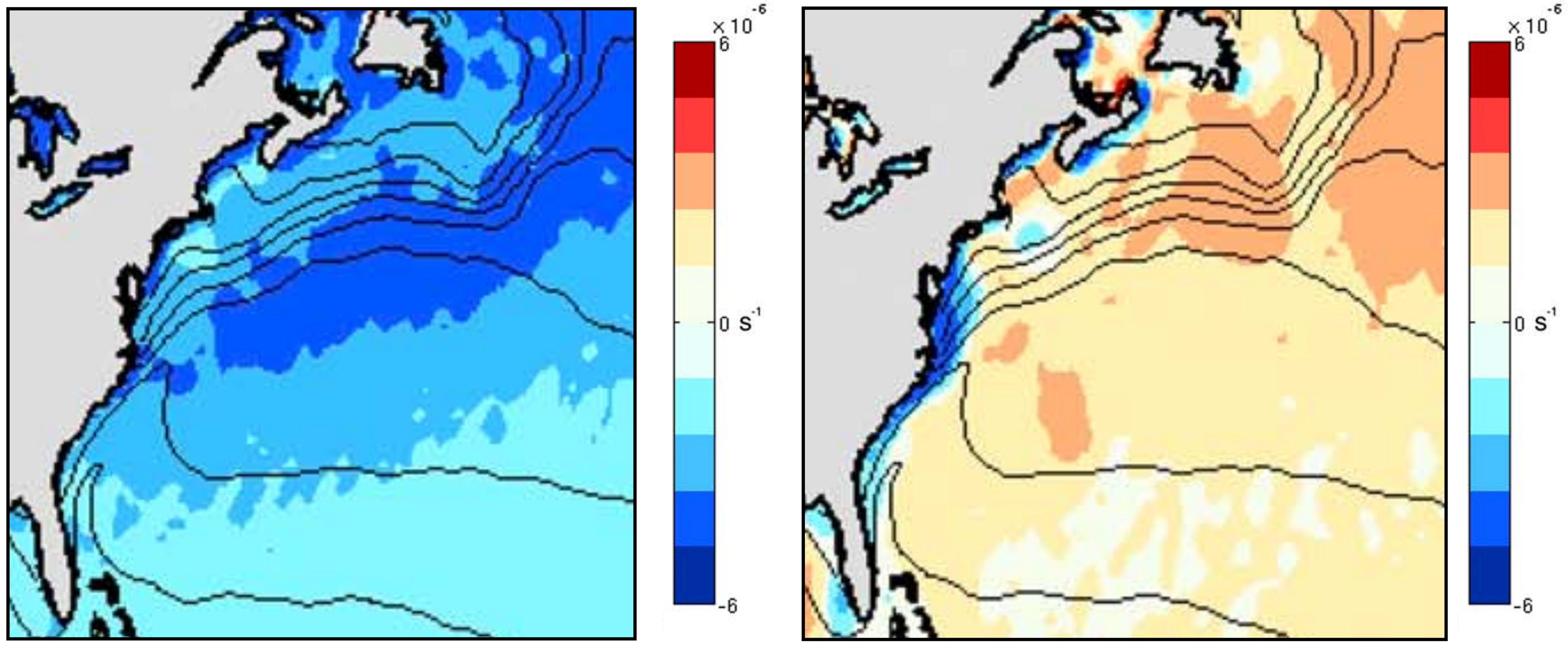


2σ filtering (storms and atmospheric fronts) removes the convergence

O'Neill et al. (2017)

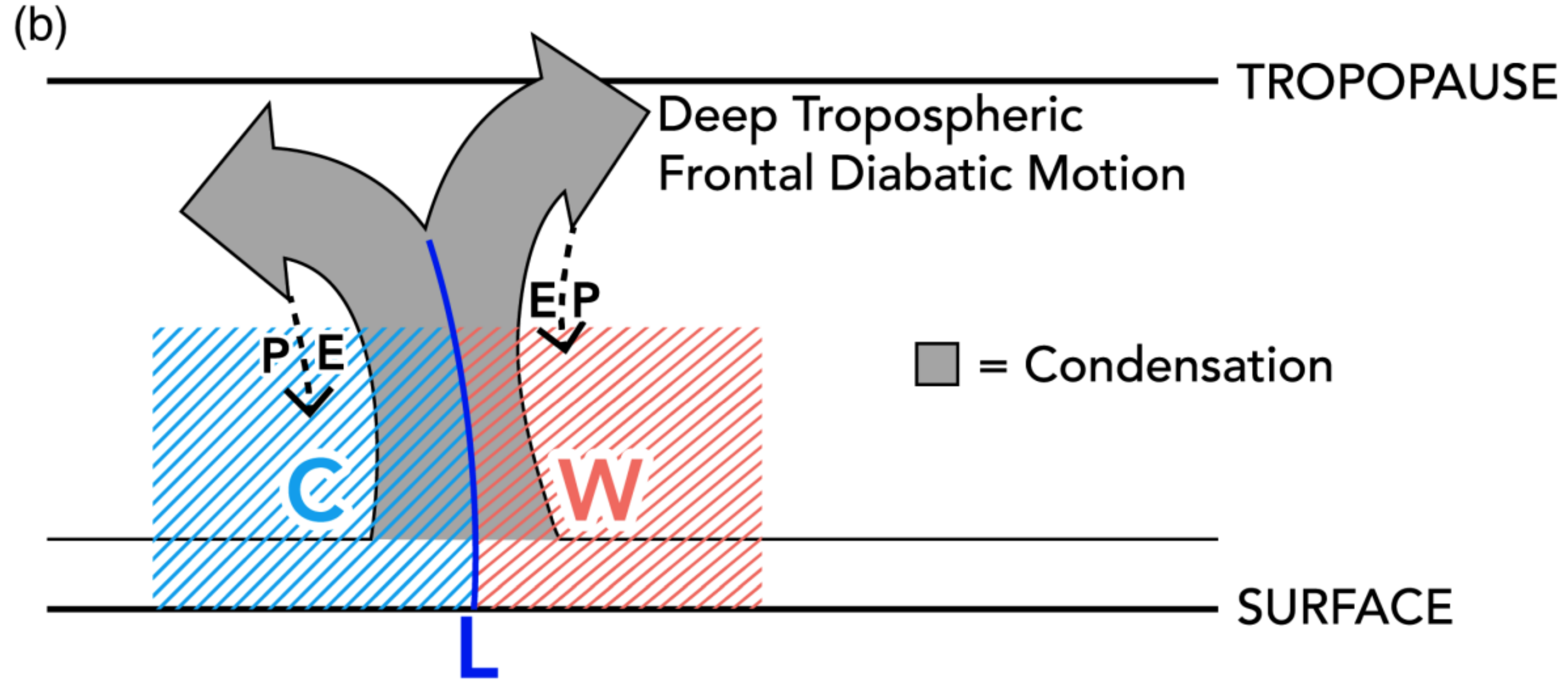
weighted convergence in AFs: ($q_n c_n$)

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

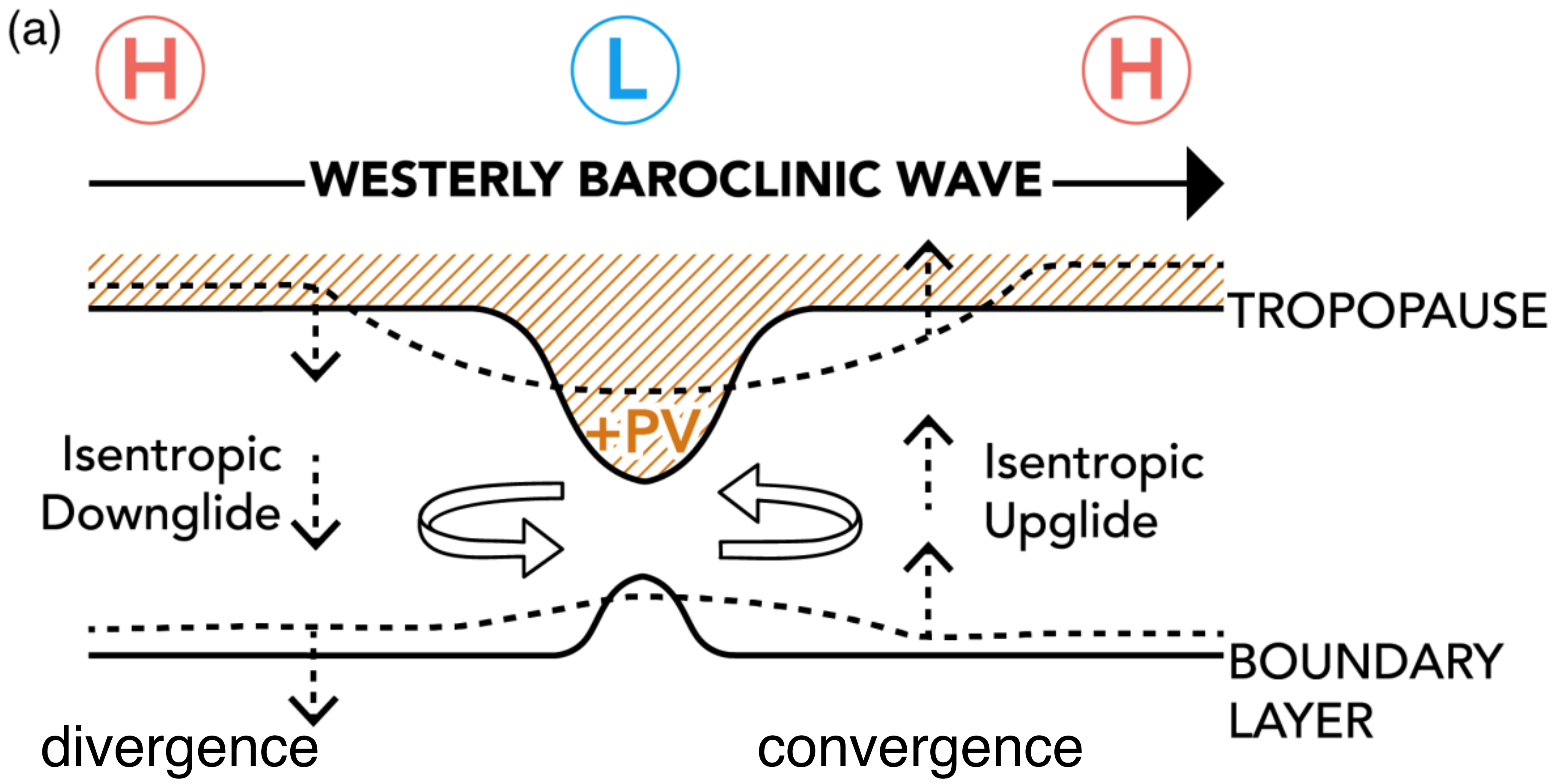


The time-mean convergence is induced by the atmospheric (cold) fronts.

diabatic contribution at the ocean frontal scales



isentropic upglide and downglide that are canceled out



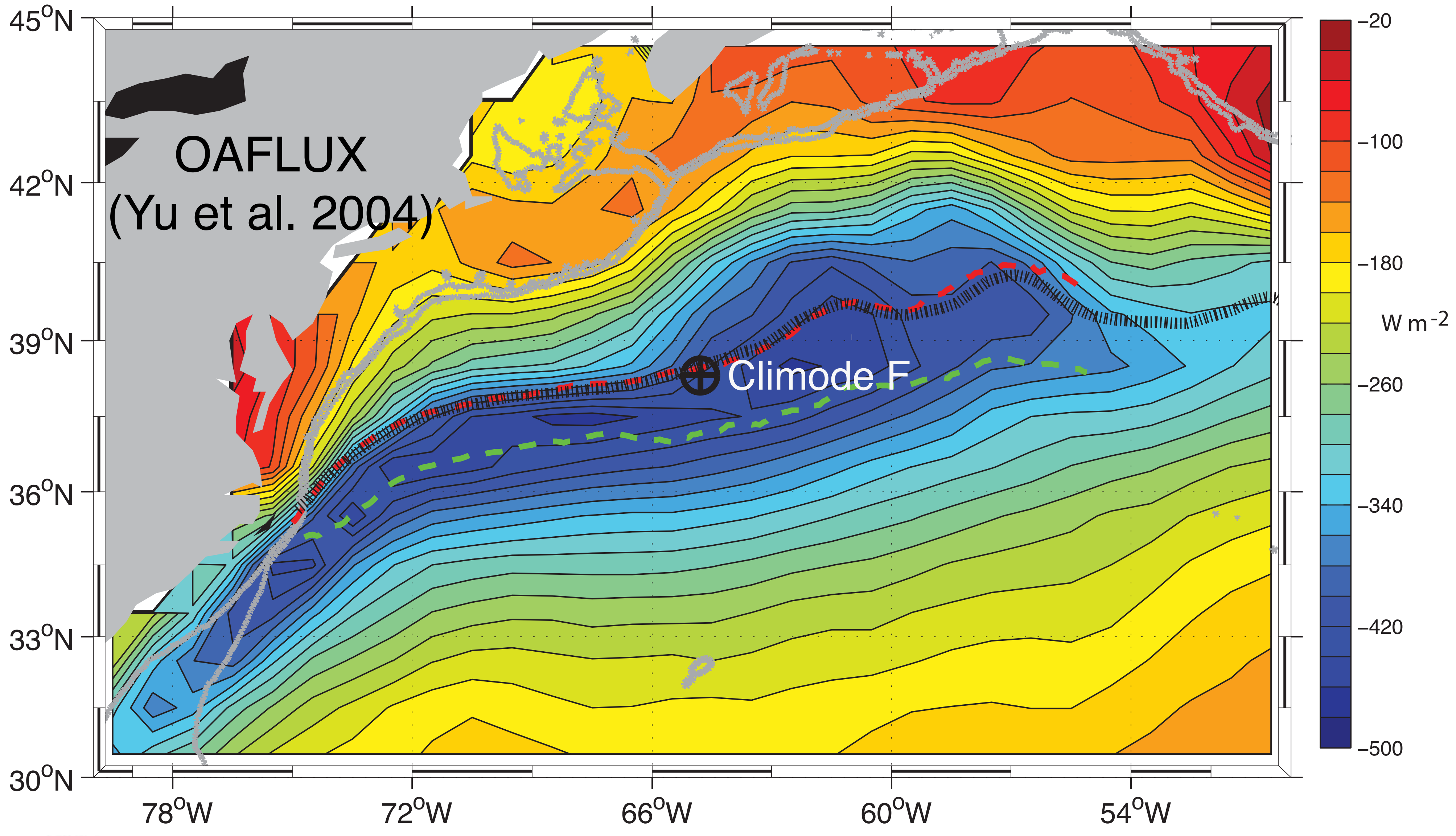
Parfitt and Seo (2018)

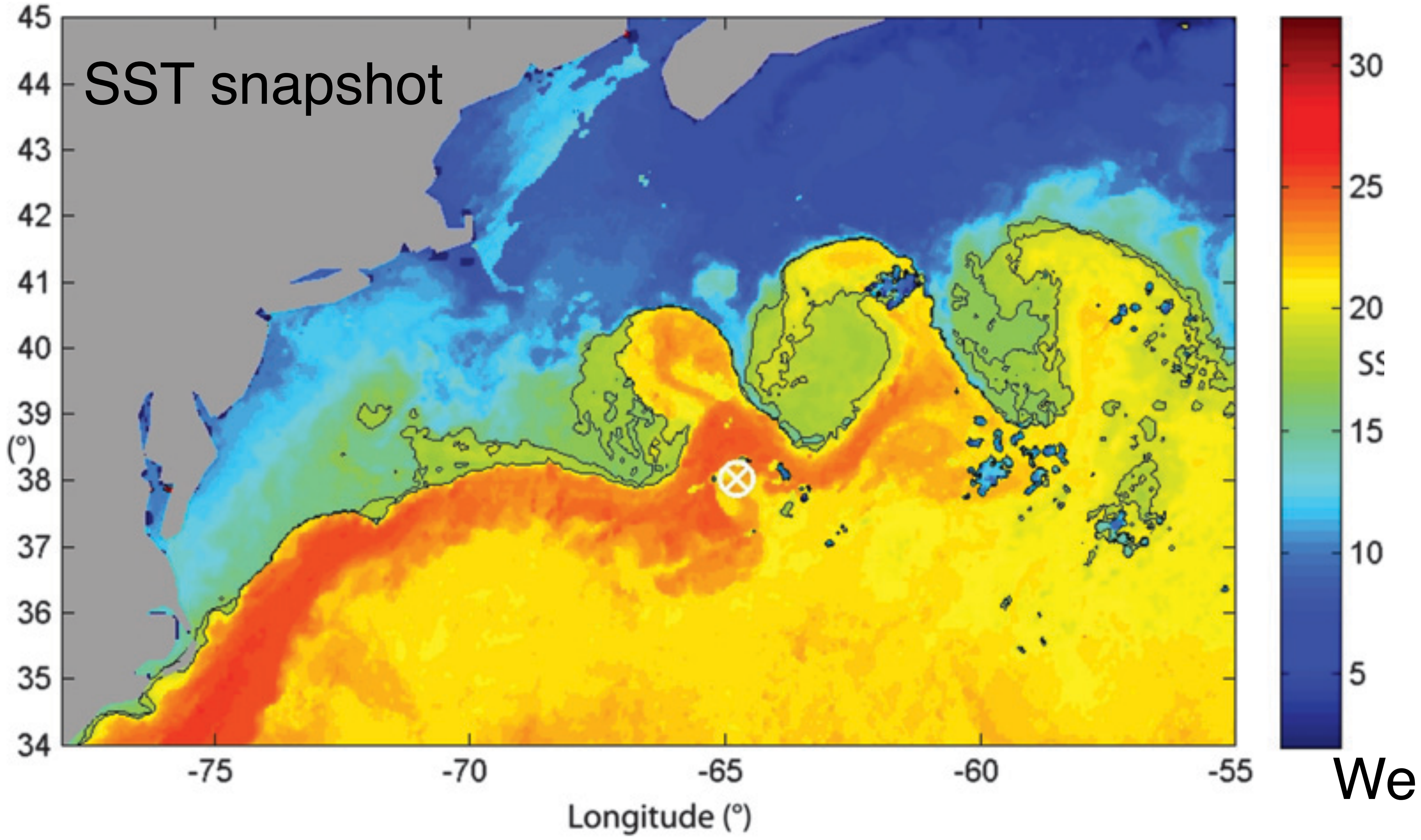
Turbulent heat and momentum fluxes over Gulf Stream

$$Q_{LH} = \rho_a L_e C_E \Delta q |W - U|$$

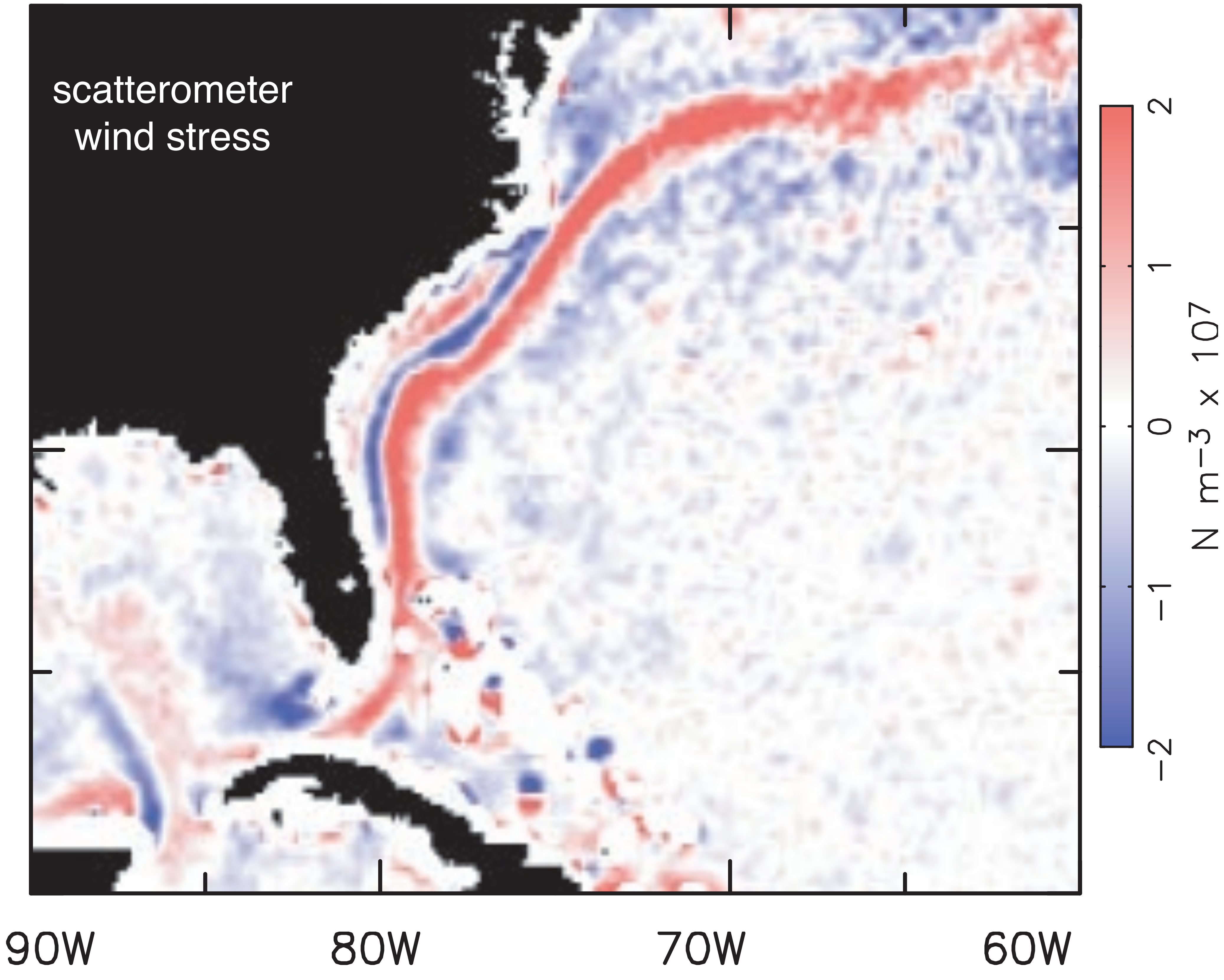
$$\tau = \rho_a C_D (W - U)^2$$

Turbulent heat flux





Wind stress curl



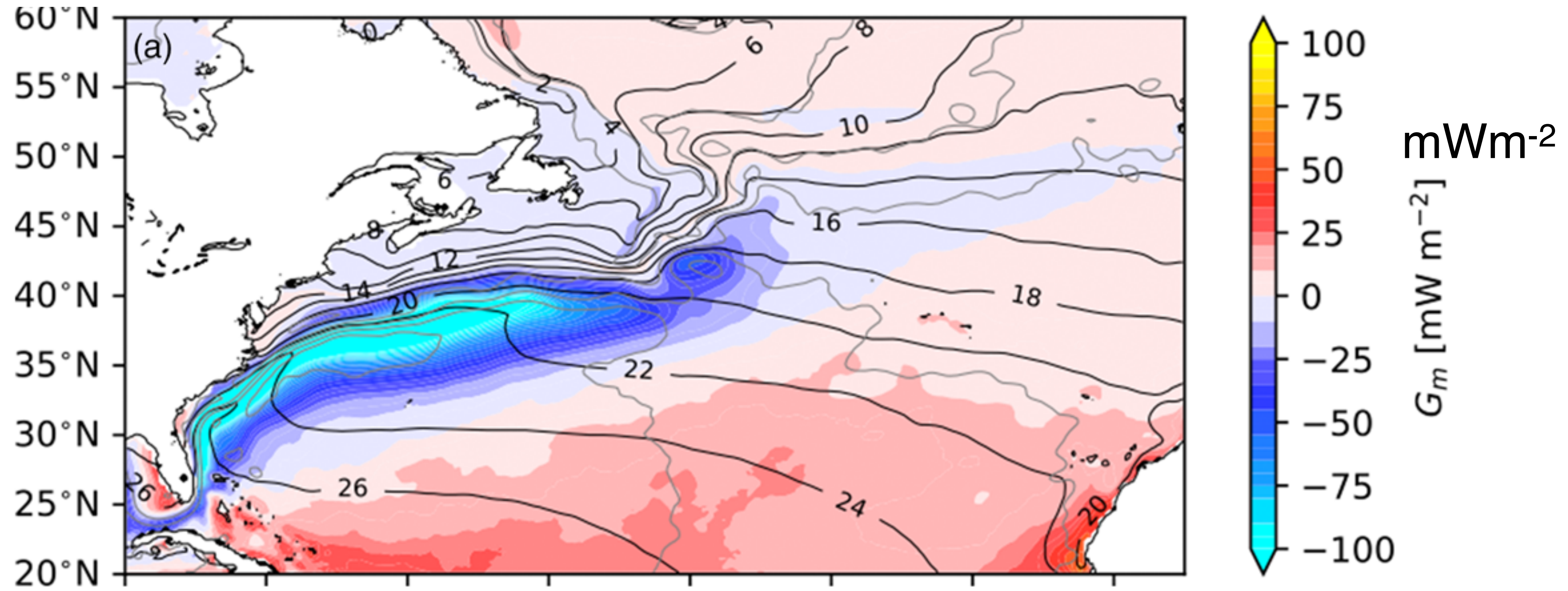
Weller et al. 2012

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

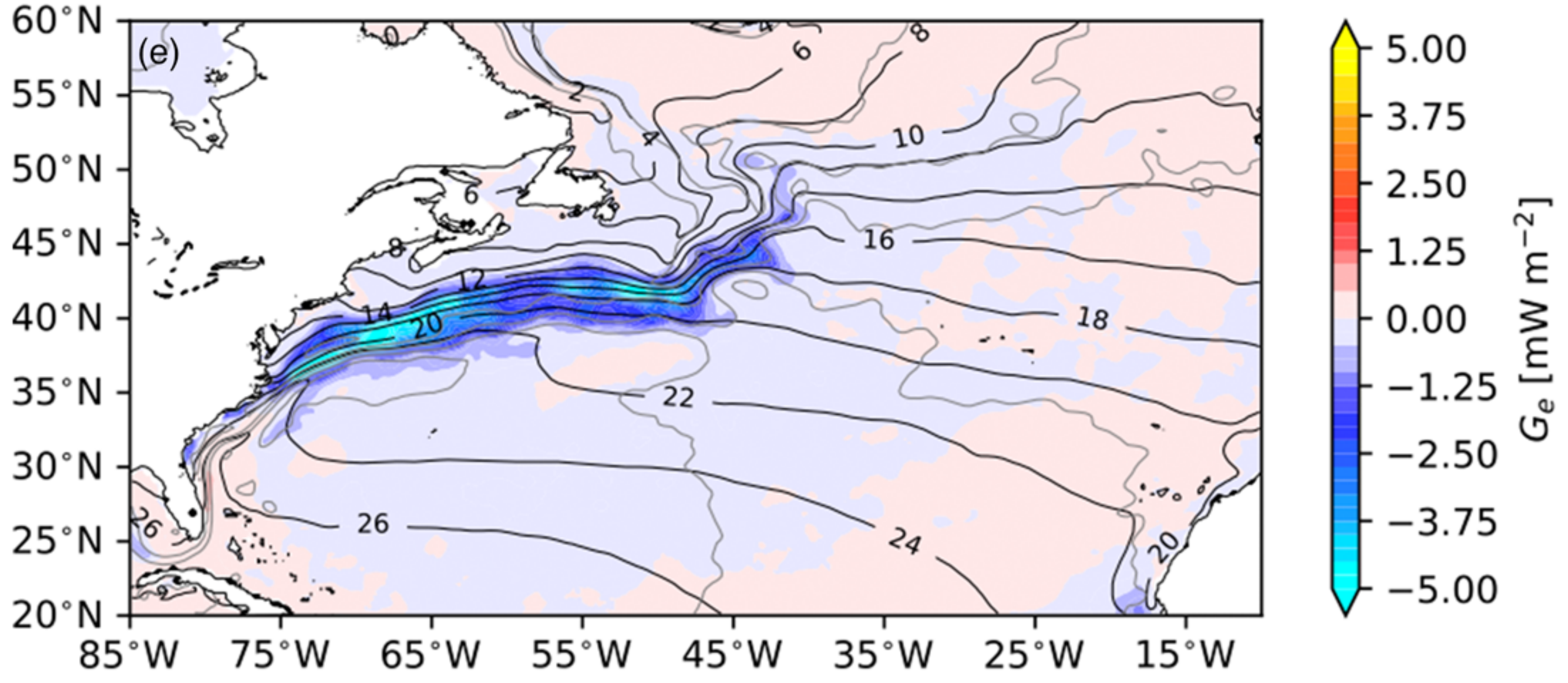
Chelton et al. 2004

Diabatic and mechanical feedbacks to ocean

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



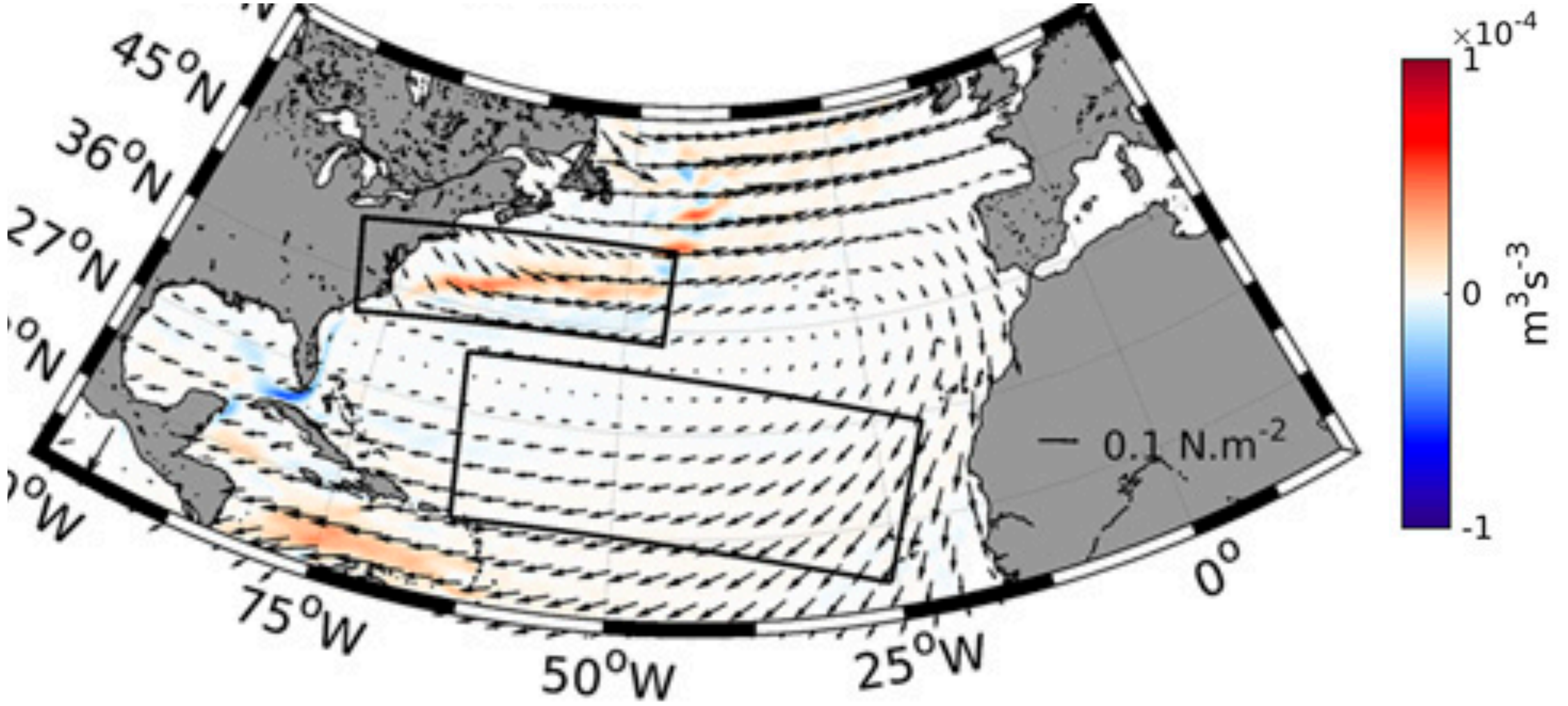
Eddy diabatic dissipation $G_e = \int_{\mathcal{A}} \frac{\alpha_\theta^2 g^2}{c_p N_r^2} \overline{\theta_*' Q_o'} \, d\mathcal{A}$



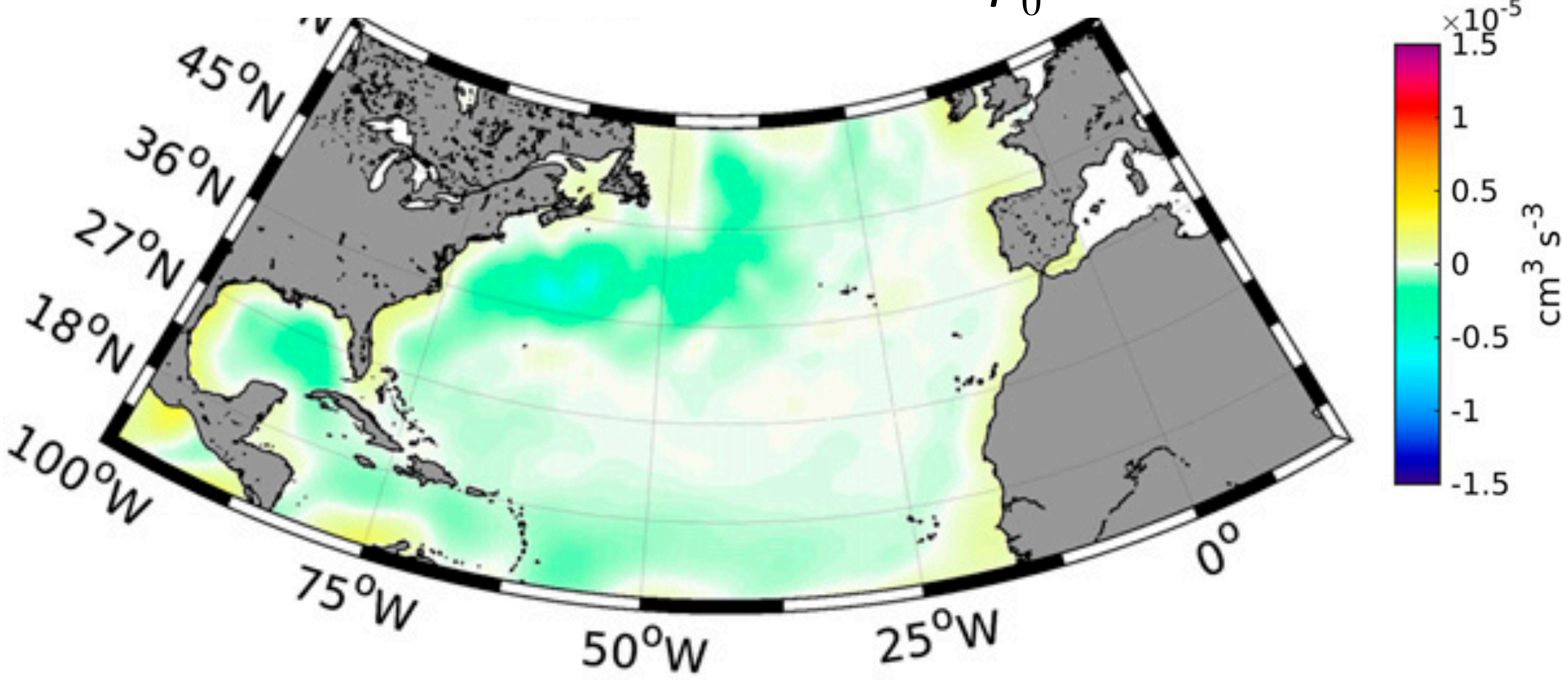
Ocean EPE destruction by mean and eddies
via the negative SST-Q covariance→ an ocean EPE sink

Bishop et al. 2020

Total mean wind work $\frac{1}{\rho_0}(\overline{u}\overline{\tau}_x + \overline{v}\overline{\tau}_y)$



Geostrophic eddy wind work $\frac{1}{\rho_0}(\overline{u'\tau_x'} + \overline{v'\tau_y'}),$



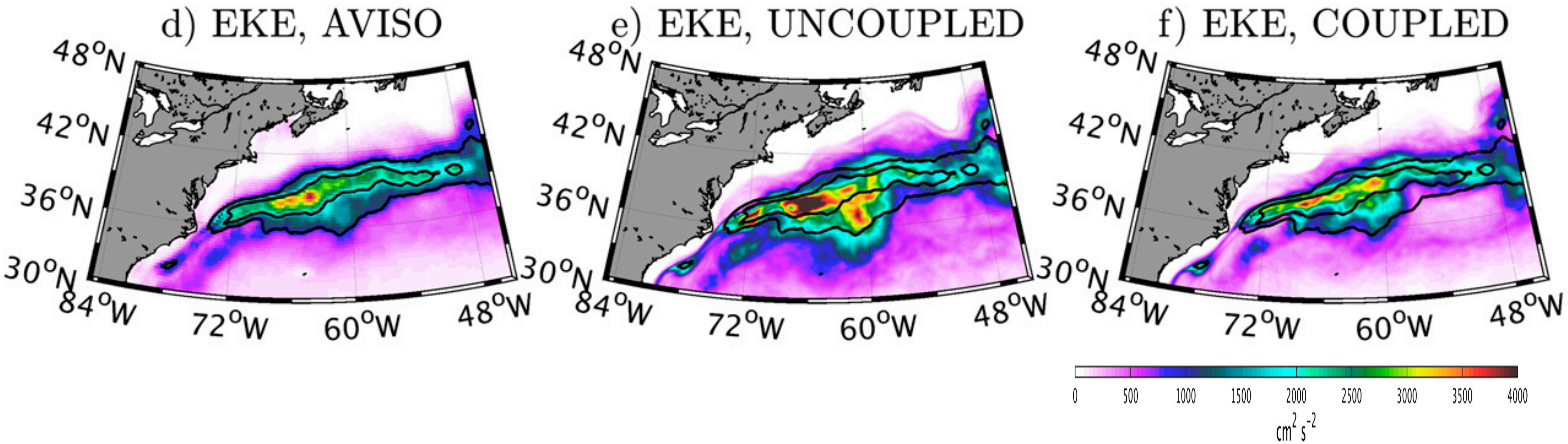
Ocean EKE reduction by ocean eddies via the negative
τ-u_s covariance → an ocean EKE sink

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

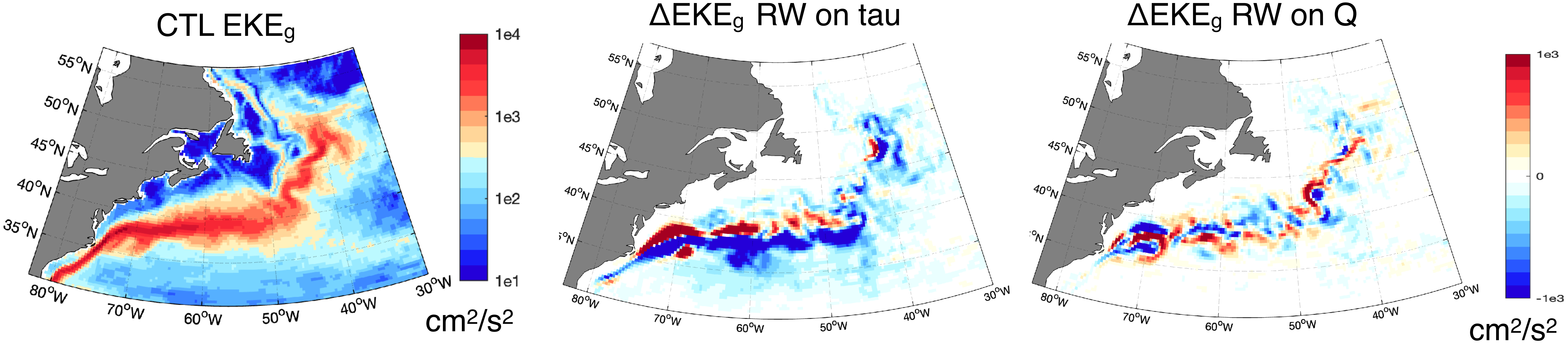
RW effect also influences the turbulent heat flux

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

$Q_{LH} = \rho_a L_e C_E \Delta q |\underline{W} - \underline{U}|$

$$G_e = \int_{\mathcal{A}} \frac{\alpha_\theta^2 g^2}{c_p N_r^2} \overline{\theta'_* Q'_o} \, d\mathcal{A}$$

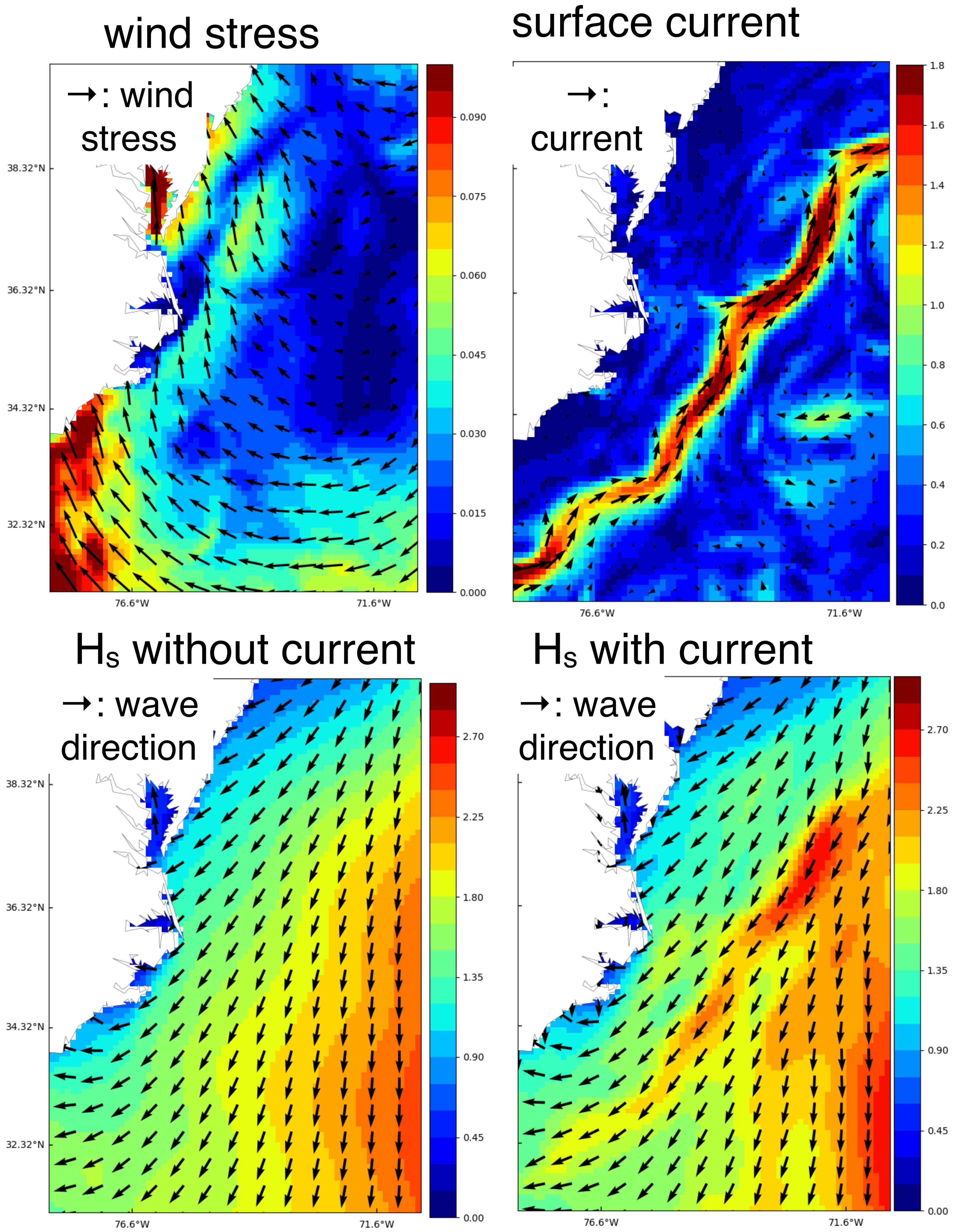
6 km WRF-ROMS coupled model simulation: 2016-2018 annual averages



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

Seo et al. in prep.

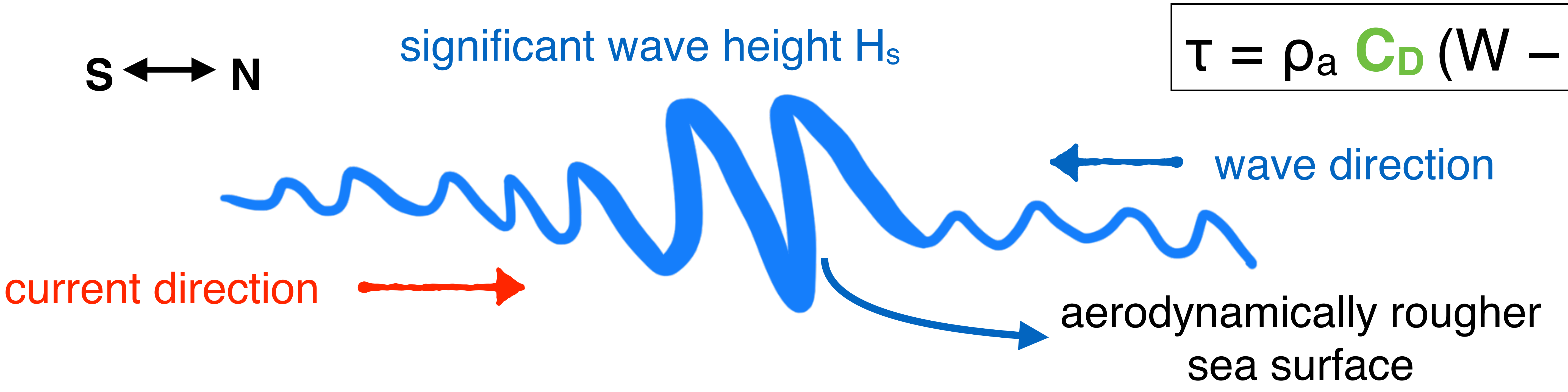
Ardhuin et al. (2017): The spatial variability in ocean currents affects the wave properties, leading to congruent patterns of wave energy and ocean currents

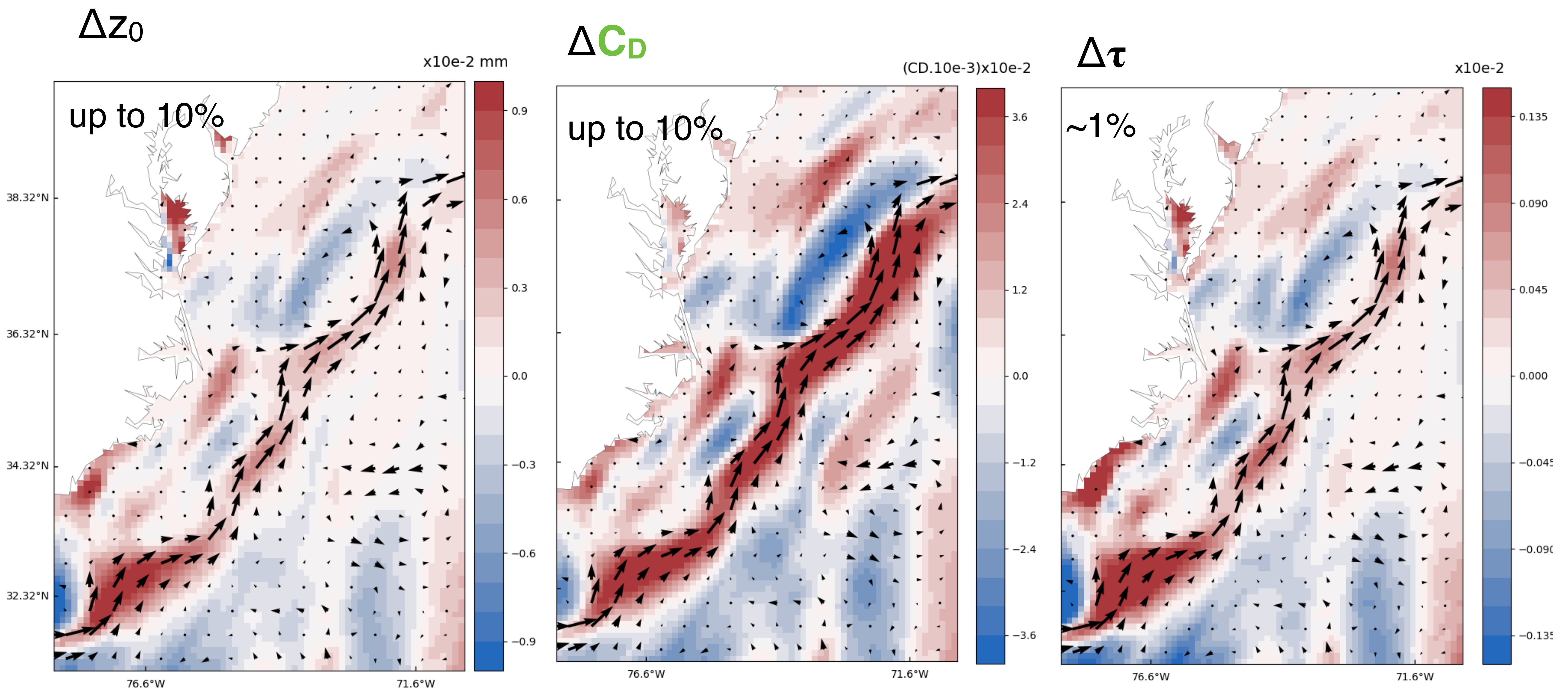


Wave-current interaction and sea state

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

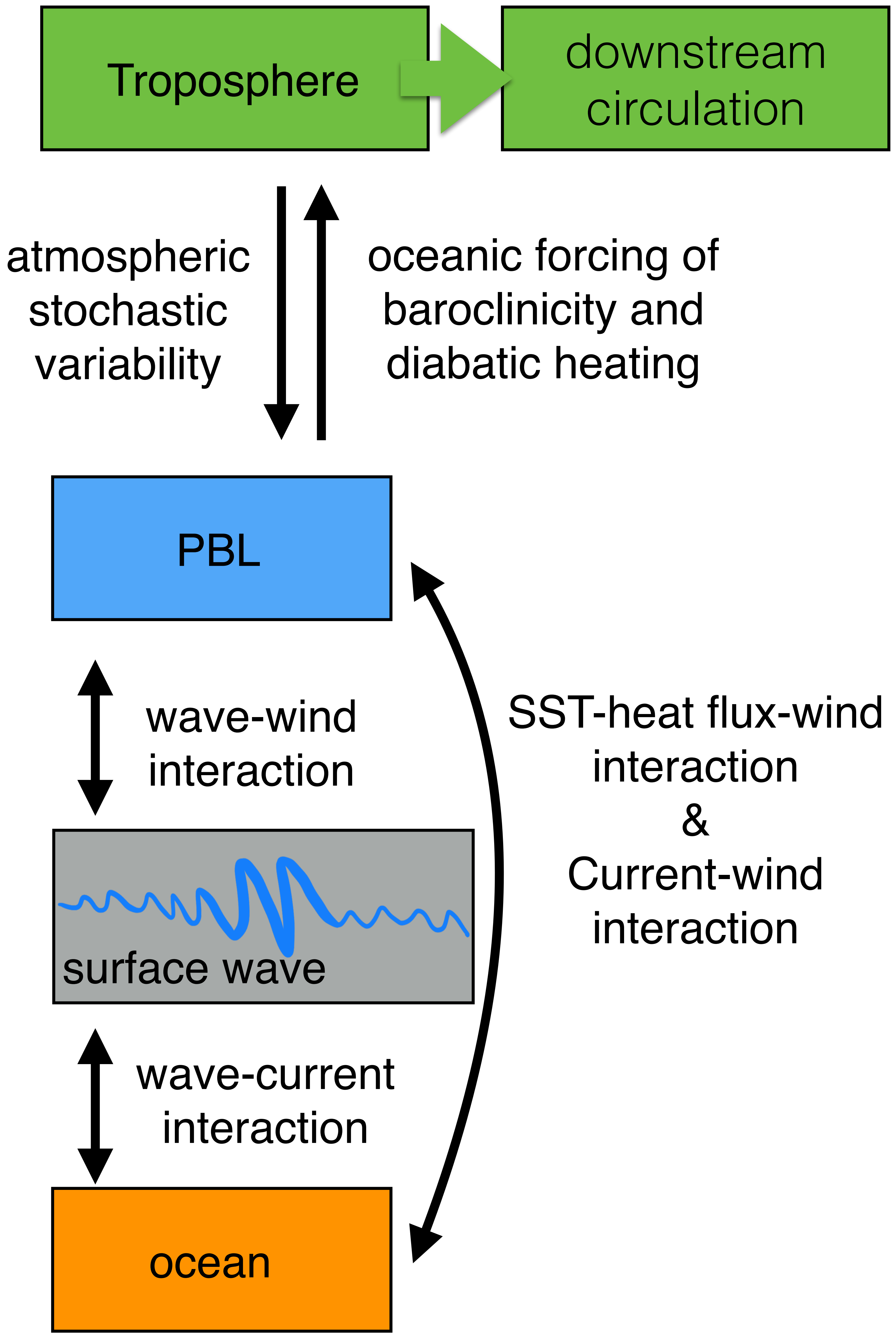
$\tau = \rho_a C_D (W - U)^2$





- The 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”

Synthesis and discussion



Troposphere

downstream circulation

atmospheric stochastic variability

oceanic forcing of baroclinicity and diabatic heating

PBL

wave-wind interaction

SST-heat flux-wind interaction & Current-wind interaction

surface wave

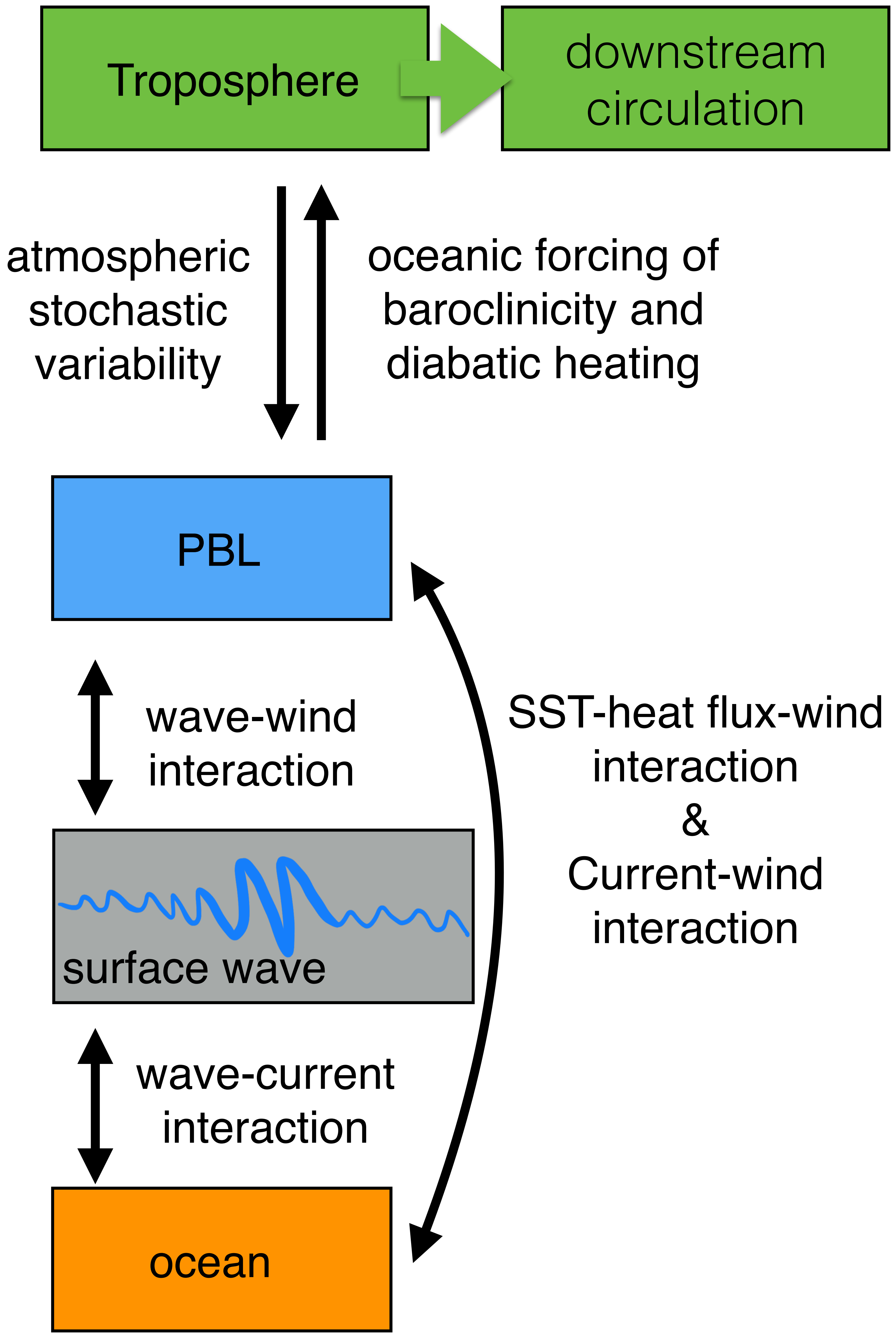
wave-current interaction

ocean

- **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).

Synthesis and discussion



- **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)
- US CLIVAR Workshop report by Robinson et al. (2018, 2020)

- 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!