Coupled Modeling of Mesoscale Air-Sea Interaction: Physics, Impacts, and Role of Surface Waves

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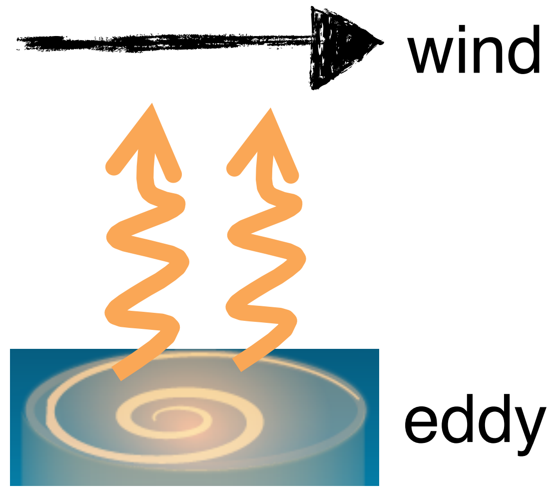
$$|\boldsymbol{\sigma}_{\mathrm{BI}}| = 0.31\left(\frac{g}{N\theta}\right)\left|-\frac{\partial\theta}{\partial y},\frac{\partial\theta}{\partial x}\right|$$

The growth rate of the extratropical cyclones **scales with low-level baroclinicity,** which is **enhanced over the WBC** regions.

Air-sea interaction is spatial scale-dependent

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

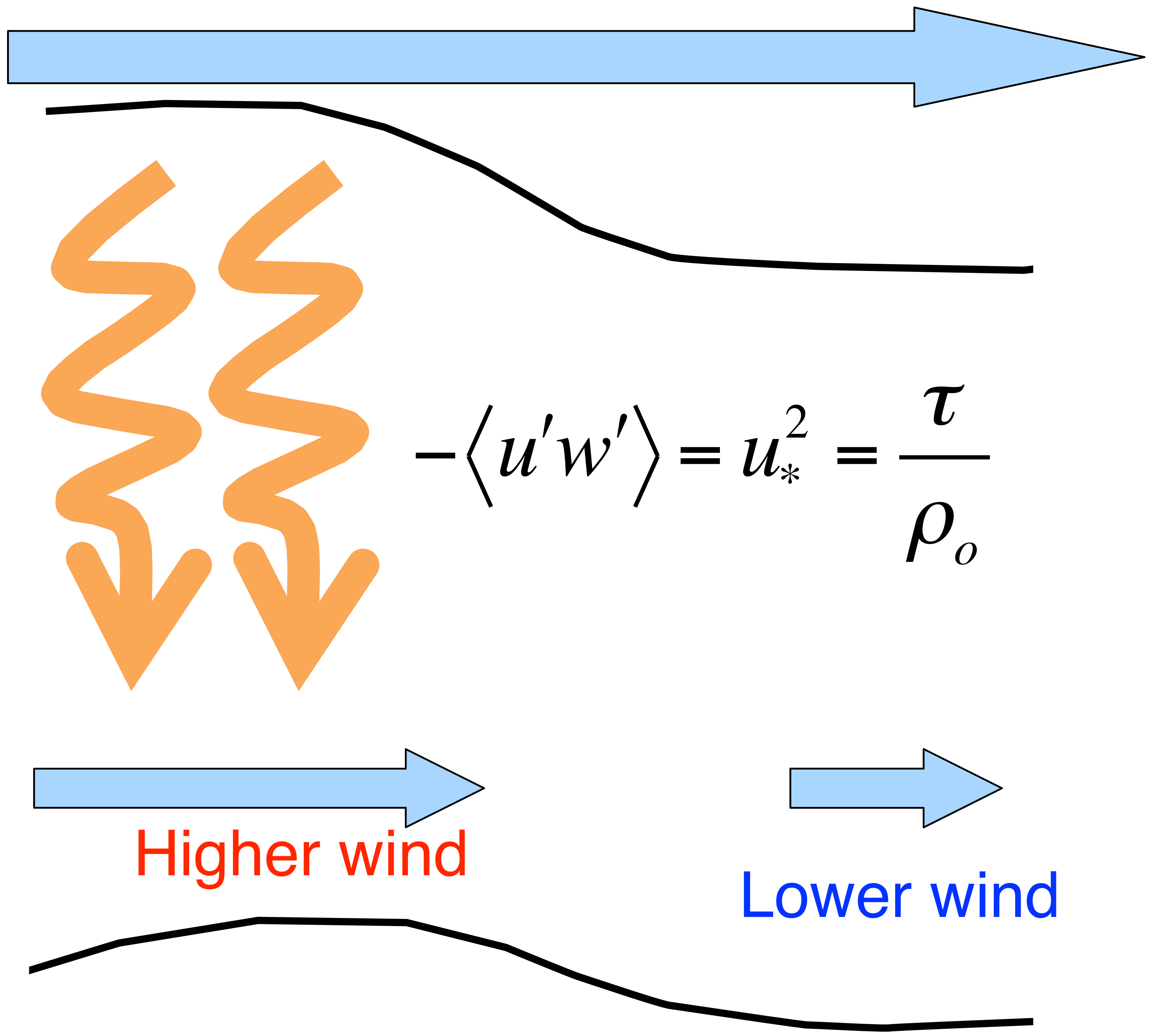
Positive correlation: SST forces the surface wind.

The sign and magnitude of the local SST-wind coupling provide a good indication of where and when the ocean influences the atmosphere.

Seo (2017) Gentemeann et al. (2020)

Atmospheric boundary layer responses

MABL stratification and turbulent mixing



U_g

PBL ~1-2km

Downward turbulent mixing of momentum

$$-\langle u'w' \rangle = u_*^2 = \frac{\tau}{\rho_o}$$

U_{10}

Higher wind

Lower wind

SST

O(10-100)km

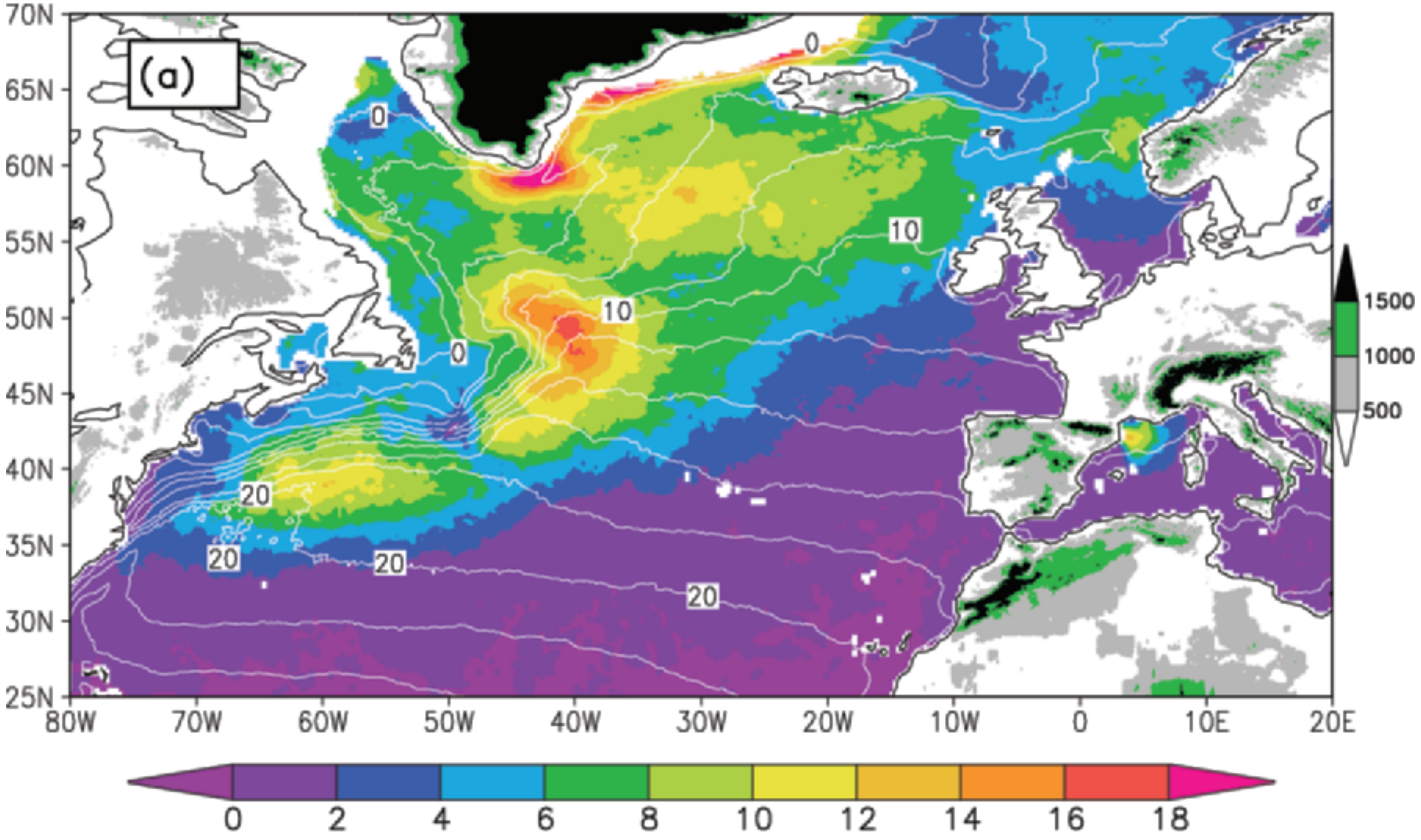
Warm SST

Cold SST

- 1-D turbulent boundary layer process
- A shallow and rapid adjustment (~hrs)

Wallace et al. (1998)

High-wind occurrence climatology



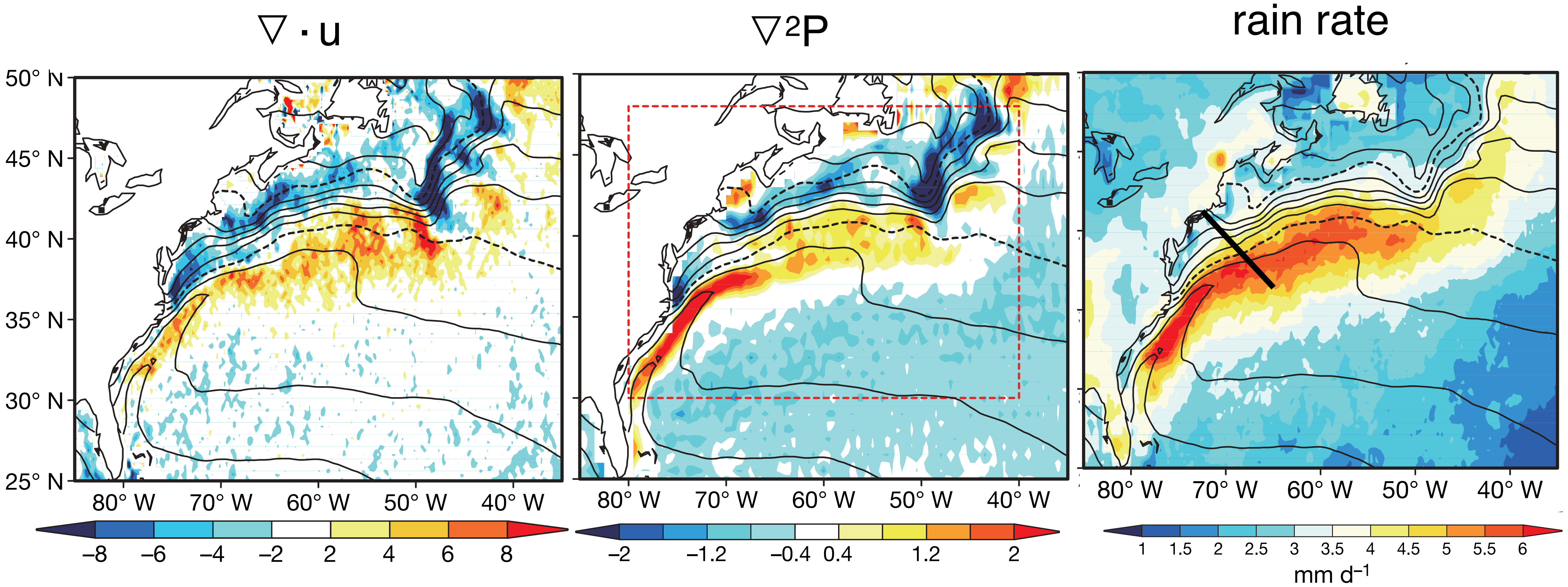
Imprints of warm SST in high wind frequency

Sampe and Xie (2007)

Wind convergence and vertical motion over the WBC SST front:

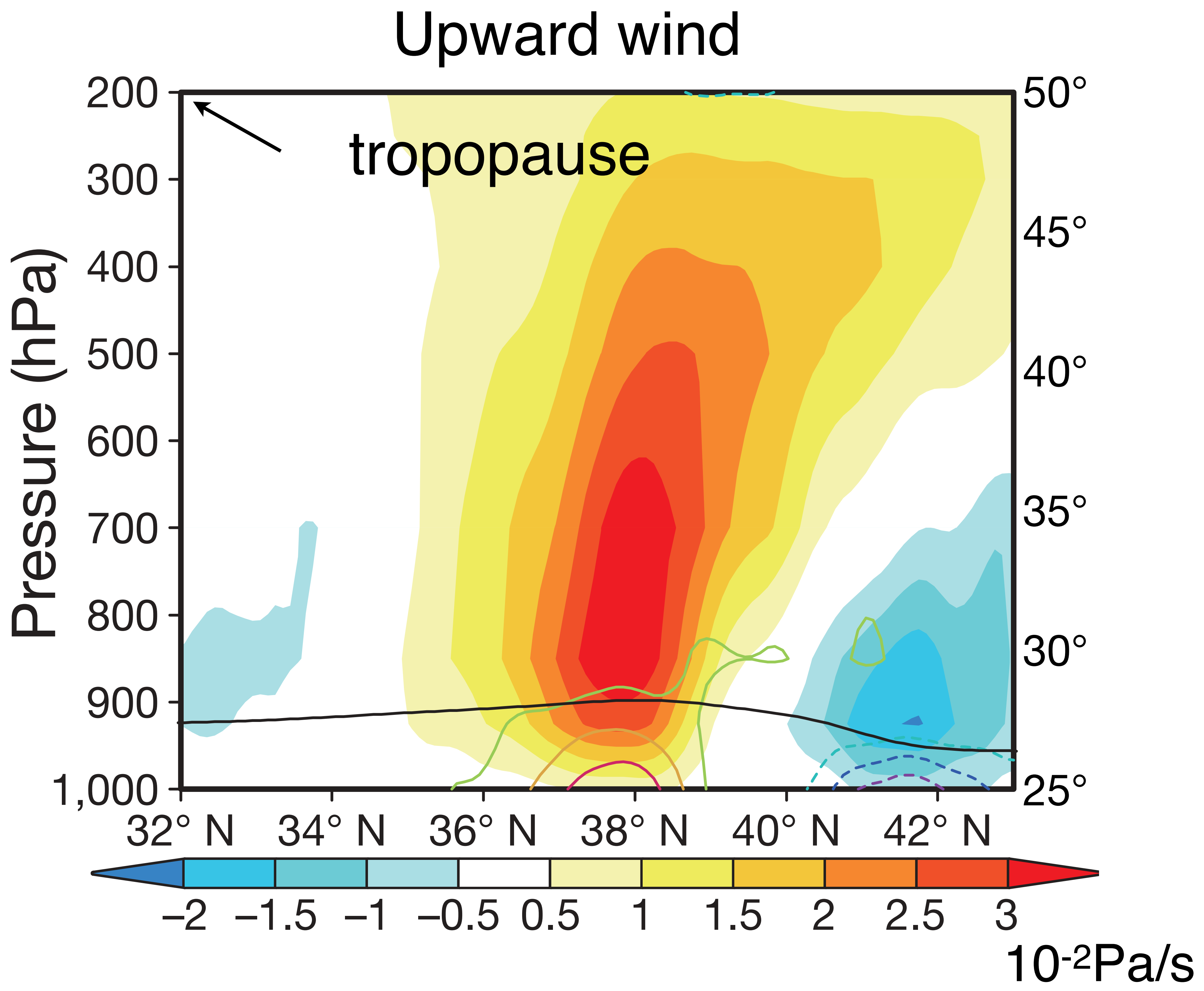
Steady-state linear Ekman-based boundary layer dynamics

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



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

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

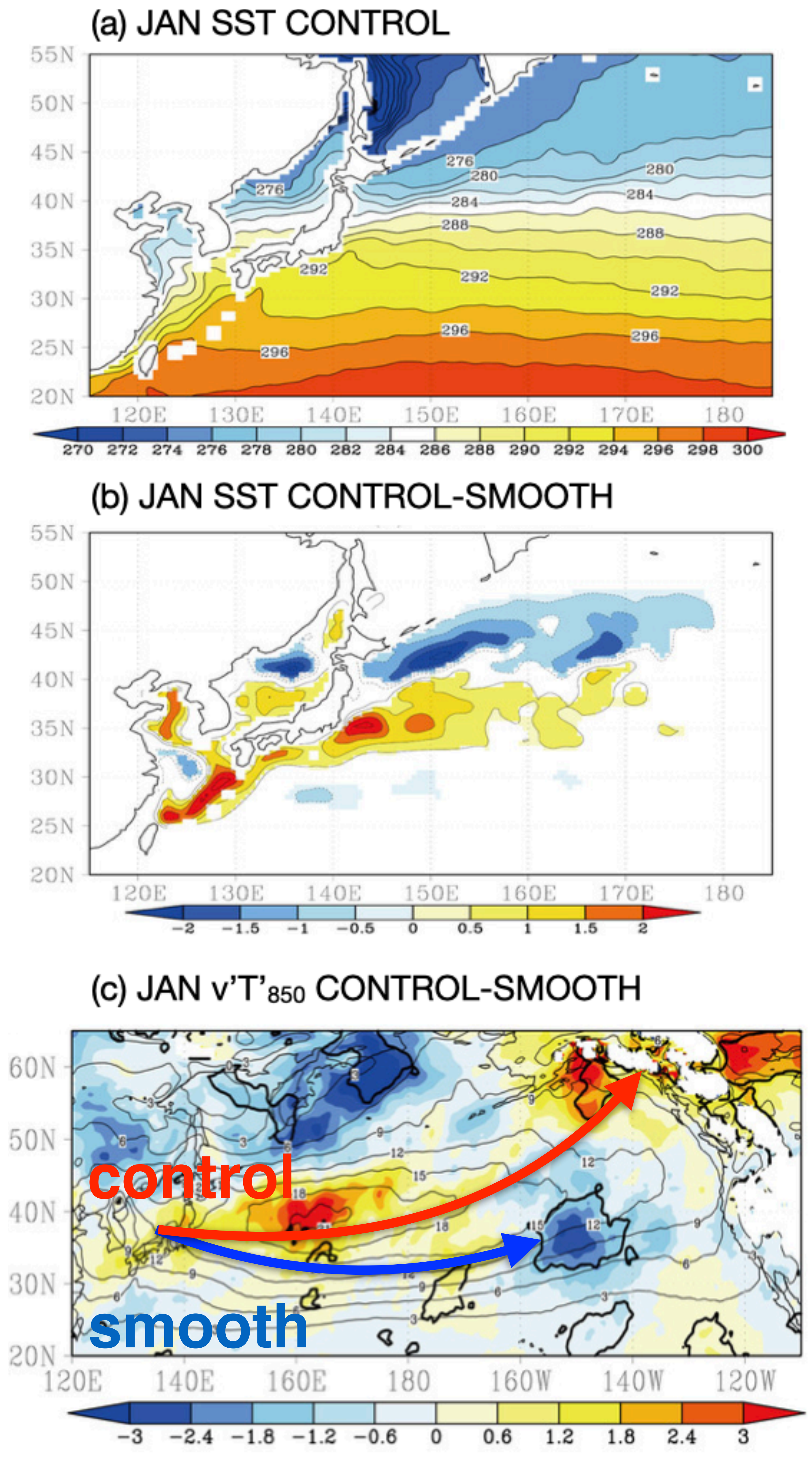


- The theory indicates a quasi-linear dependence of near-surface wind convergence and vertical motion to SST-driven ∇^2P.
- The model ignores the stochastic nature of the atmospheric processes in the region.

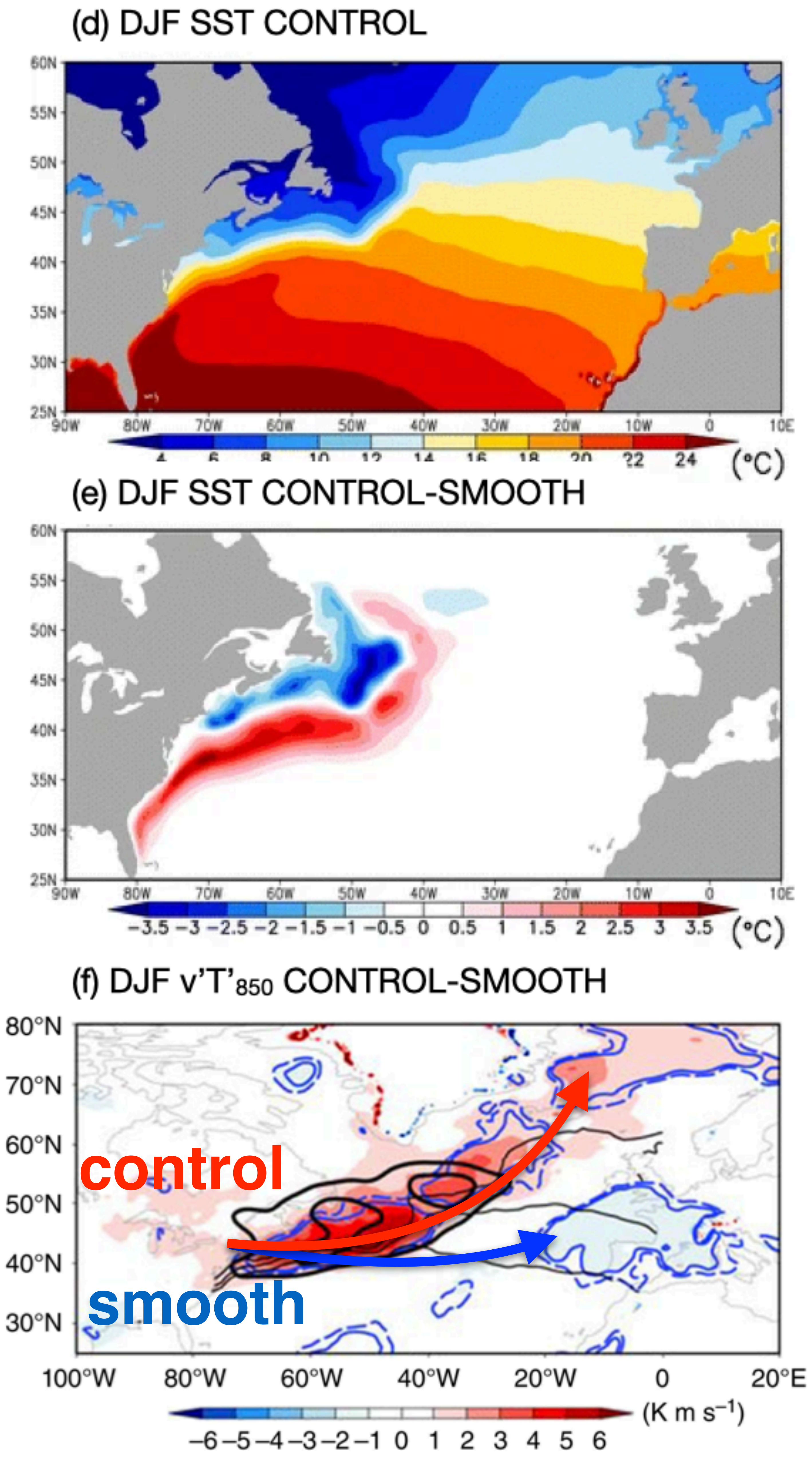
Minobe et al. (2008)
Lindzen and Nigam (1987)

Atmospheric Responses

WBC SST impacts on local and downstream storm track



Kuwano-Yoshida et al. (2017)



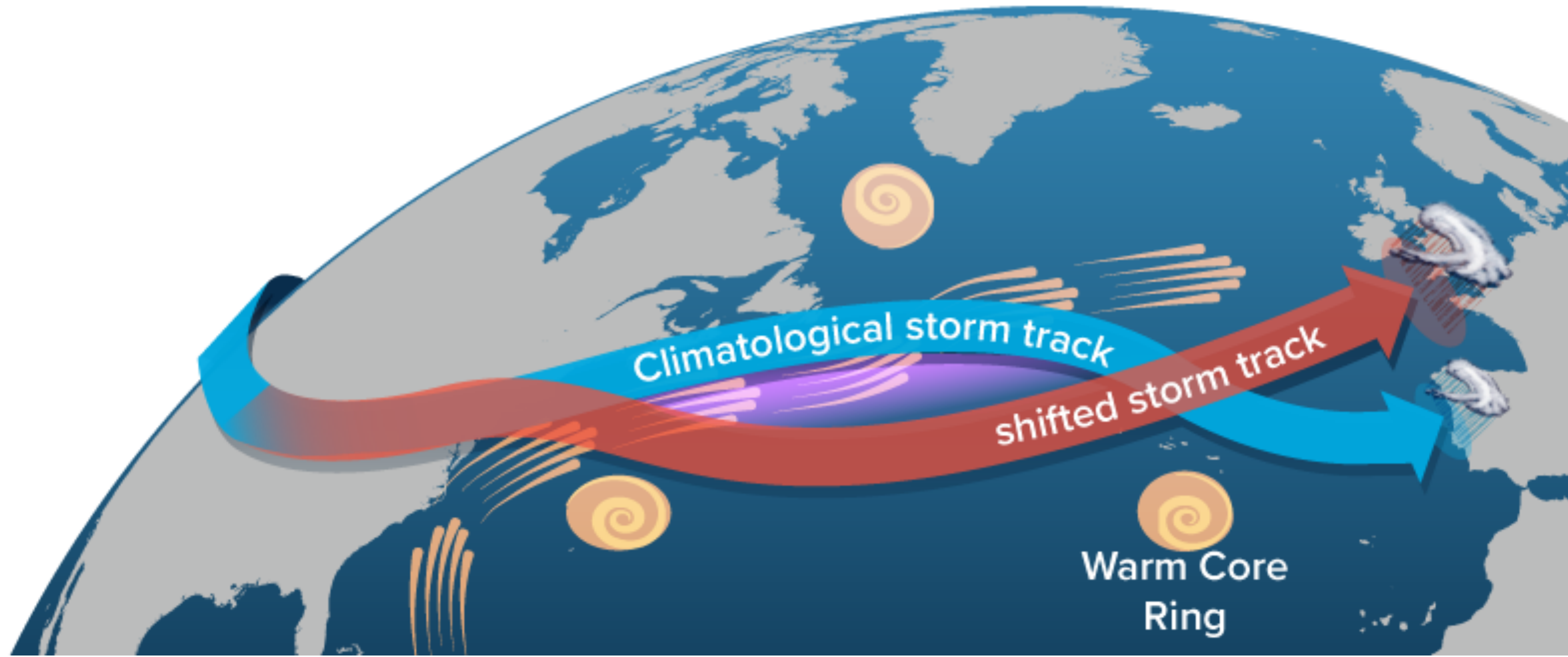
O'Reilly et al. (2017)

- WBC SSTs (e.g., front strength, meridional position, warm-core eddies)
  1. Locally, strengthen the storm activity locally,
  2. Downstream, modulate the intensity/path of the storm track.

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

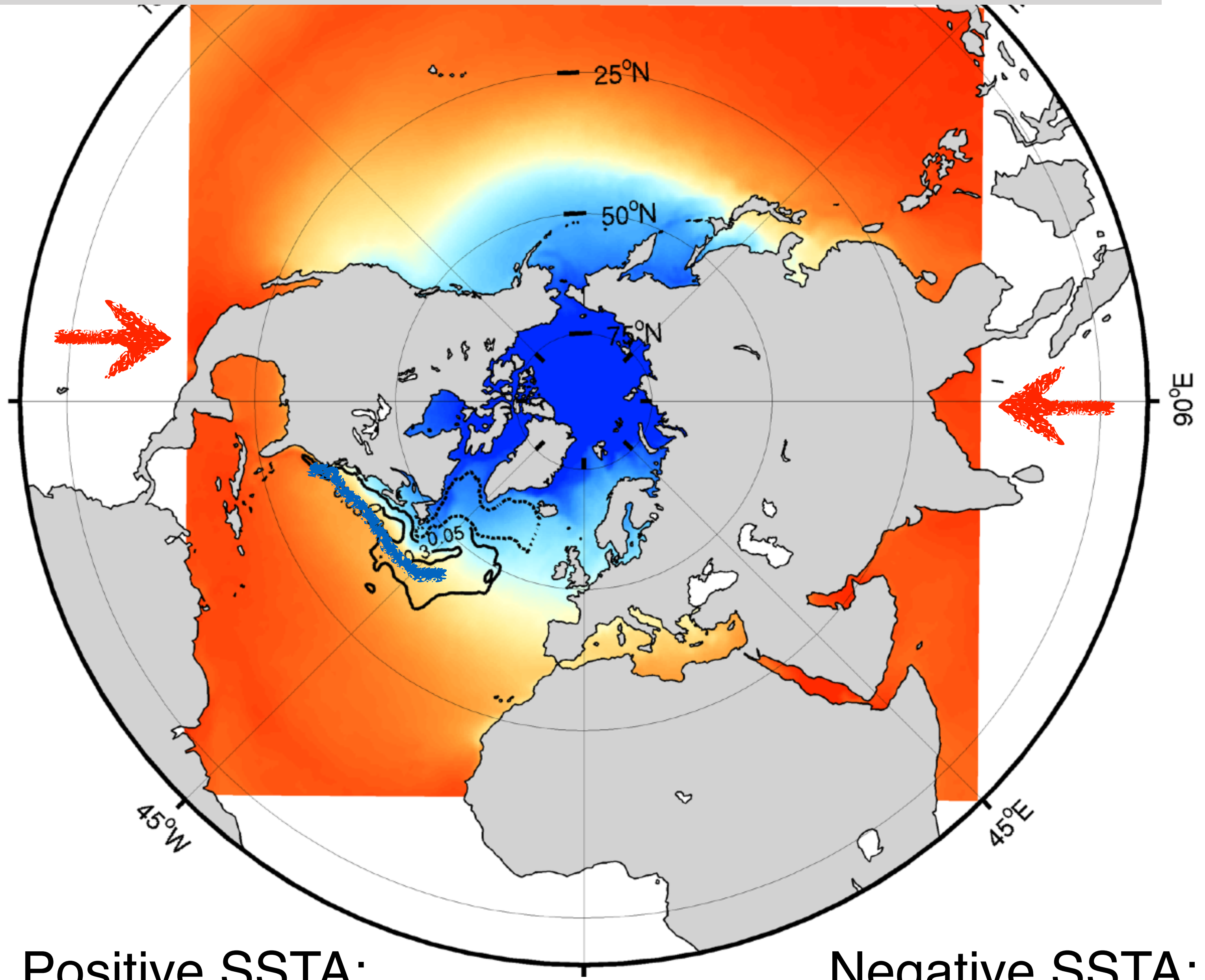
Hoskins and Valdes (1990); Nakamura and Shimpo (2004)

Enhanced baroclinicity MAINTAINED by the oceans near the WBCs

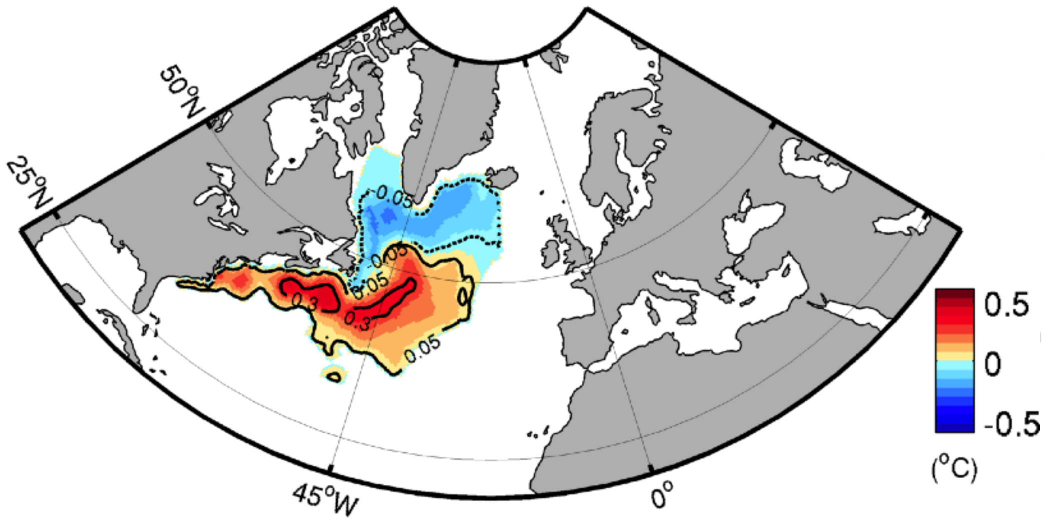


Linear vs. nonlinear extratropical atmospheric responses

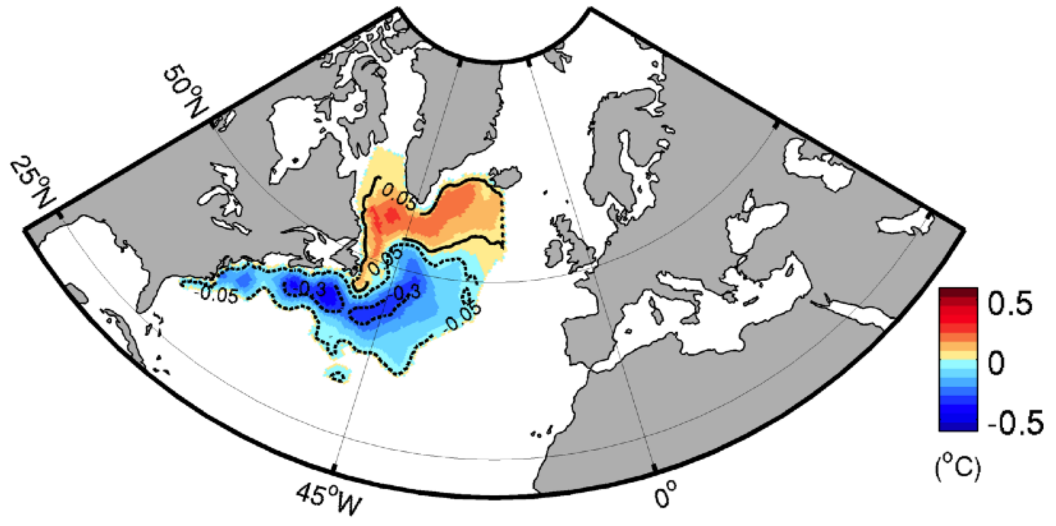
CTL: WRF forced with SSTA induced by the north/south shift in the GS position



Positive SSTA: Northward shifted GS



Negative SSTA: Northward shifted GS



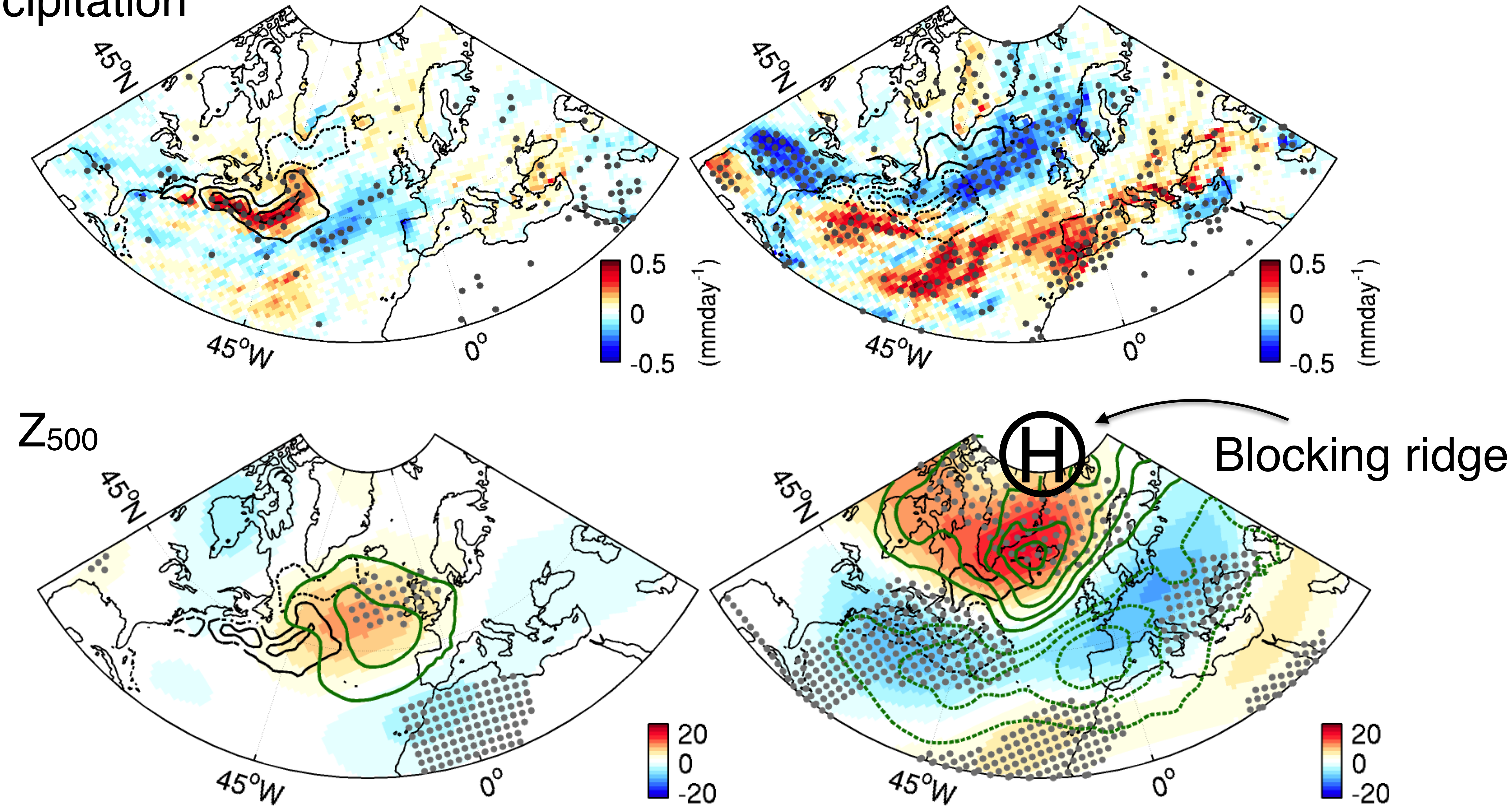
linear = ½ × (POS - NEG)
nonlinear = ½ × [(POS - CTL) + (NEG - CTL)]

Linear response

Nonlinear response

Precipitation

Z_{500}



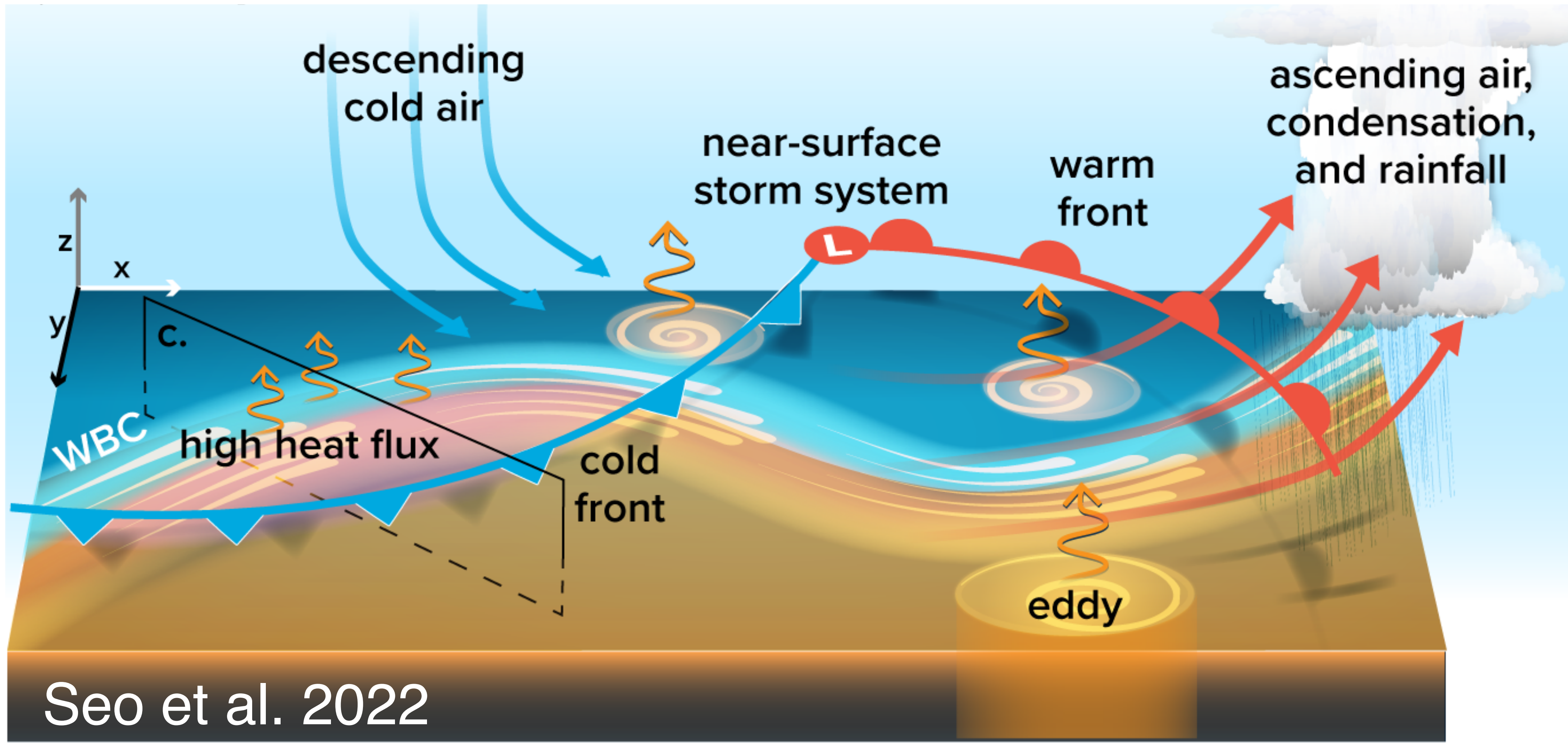
1) Linear response results from a *direct* diabatic forcing of the ocean confined in the vicinity of the forcing,

2) Nonlinear response represents eddy-mean flow interactions, involve the response pattern who area much greater than that of the forcing

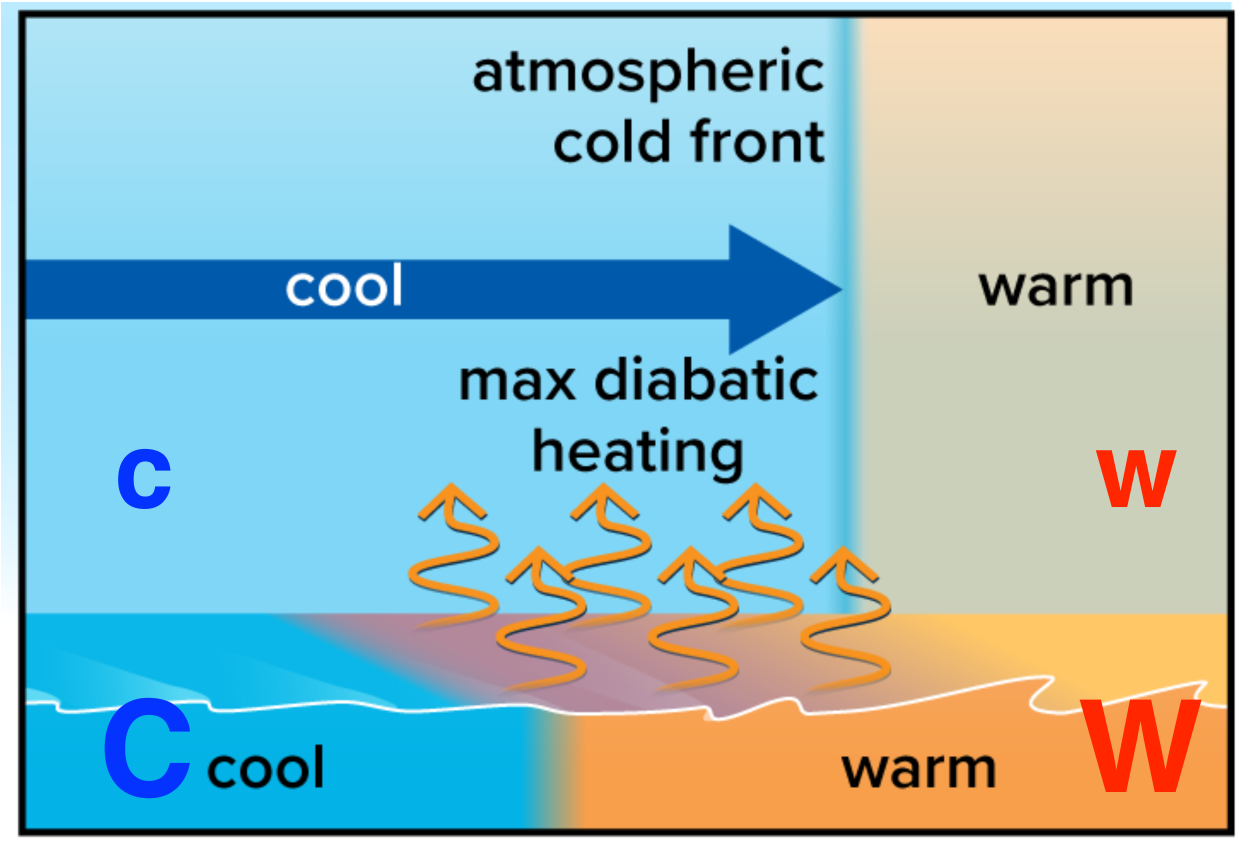
Seo et al. (2017)

The linear response: The atmospheric fronts “feel” (diabatically) the WBC SST front

Length scale: atmospheric fronts ≈ ocean fronts (10-100 km)



Seo et al. 2022

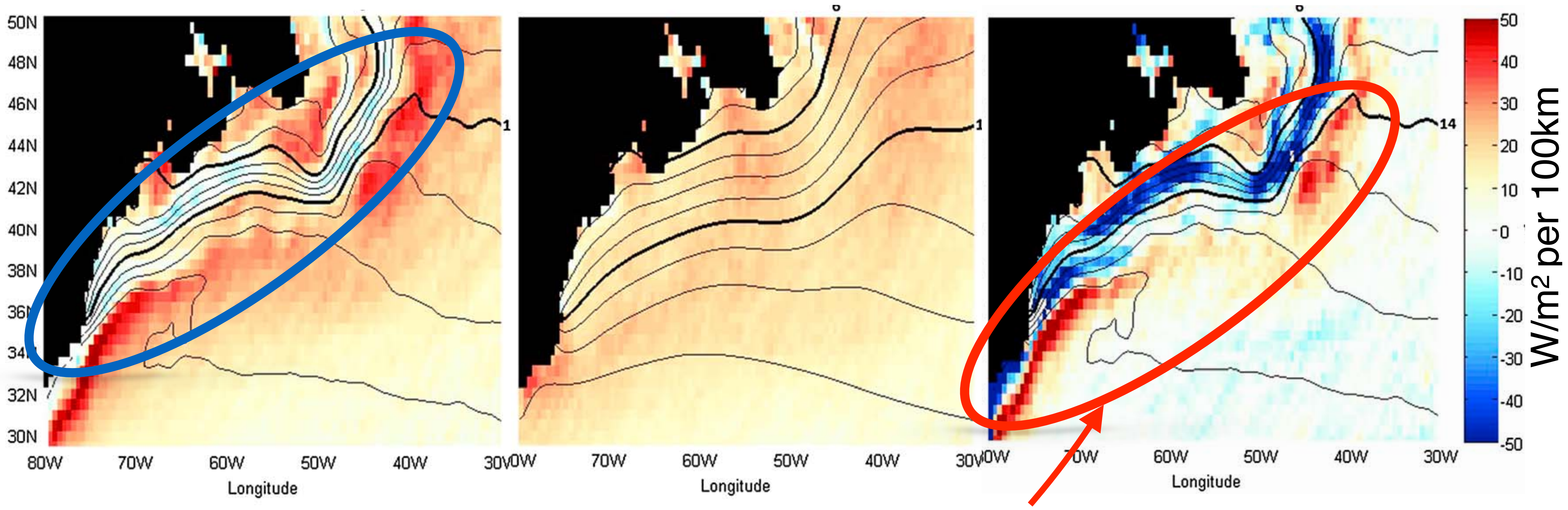


The sign of the dQ_{SH}/dy indicates the diabatic frontogenesis or frontolysis

dQ_{SH}/dy in CONTROL

dQ_{SH}/dy SMOOTH

dQ_{SH}/dy CONTROL-SMOOTH



$dQ_{SH}/dy < 0$ → Strengthening of the atmospheric front

$dQ_{SH}/dy < 0$ → Weakening of the atmospheric front

diabatic frontogensis and generation of APE

Parfitt et al. (2016) Parfitt and Seo (2018)

The nonlinear response is maintained by LF rectifying effects of HF eddy vorticity flux convergence

$$\left(\frac{\partial Z_{250}}{\partial t}\right)_{\mathrm{HFT}} = \frac{f_0}{g}\nabla^{-2}[-\boldsymbol{\nabla}\cdot(\overline{\boldsymbol{v}'\zeta'})]$$

Z tendency solely due to anomalous
edgy vorticity flux convergence

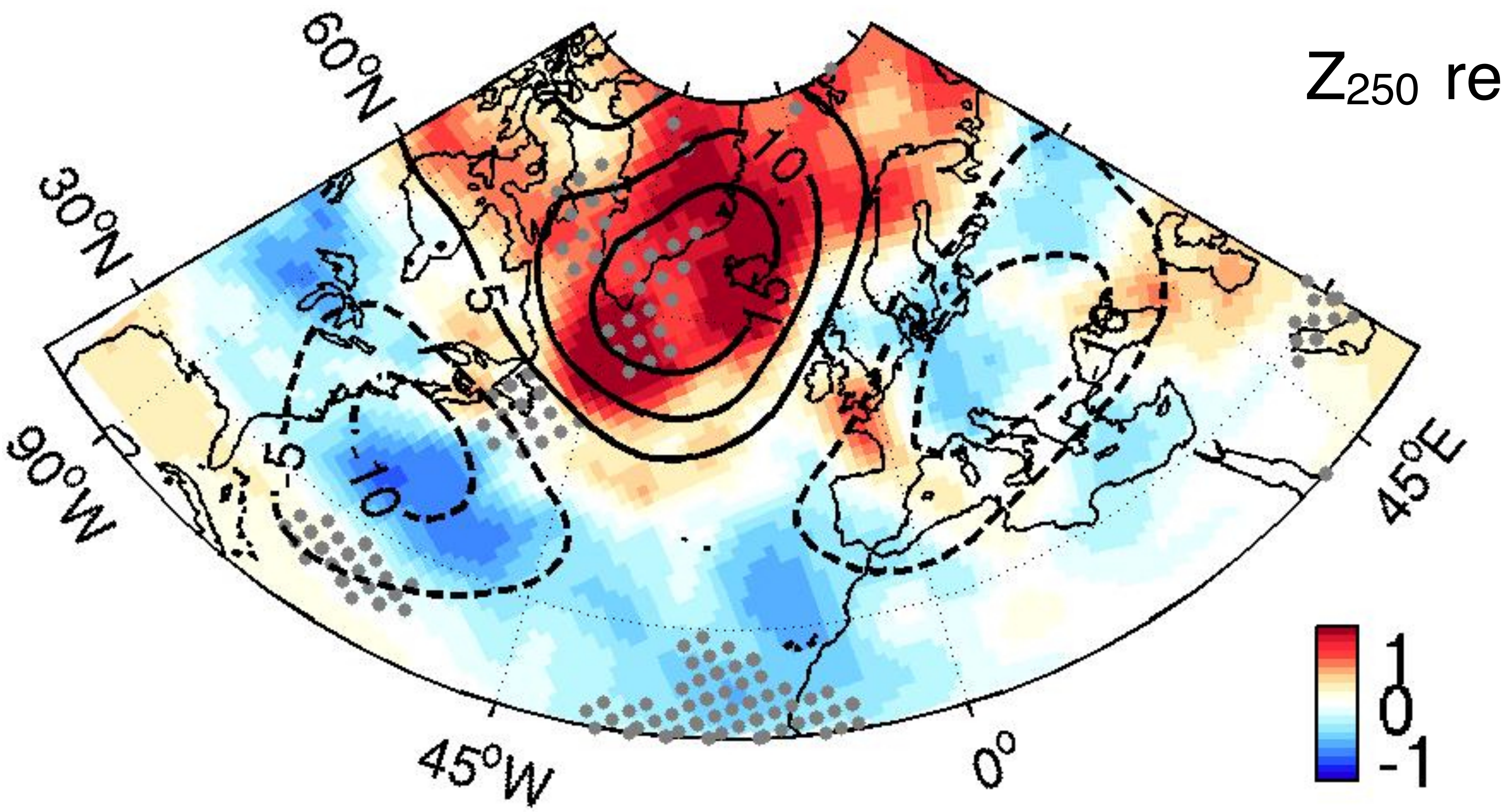
Nakamura et al. (1997)

POS minus CTL

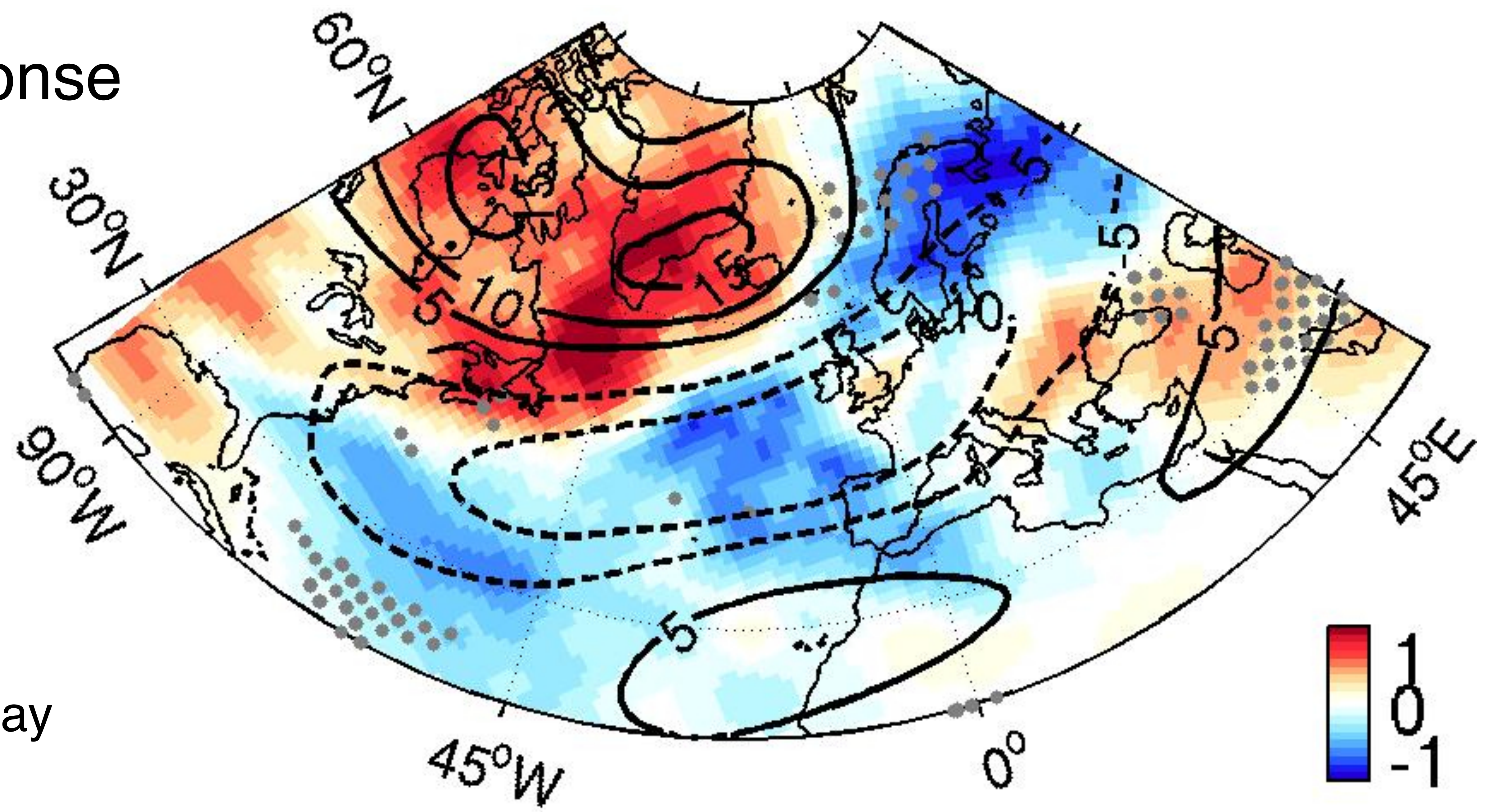
$(\partial Z_{250}/\partial t)_{HF}$ response

NEG minus CTL

Z_{250} response



m/day



Seo et al. (2014; 2017)

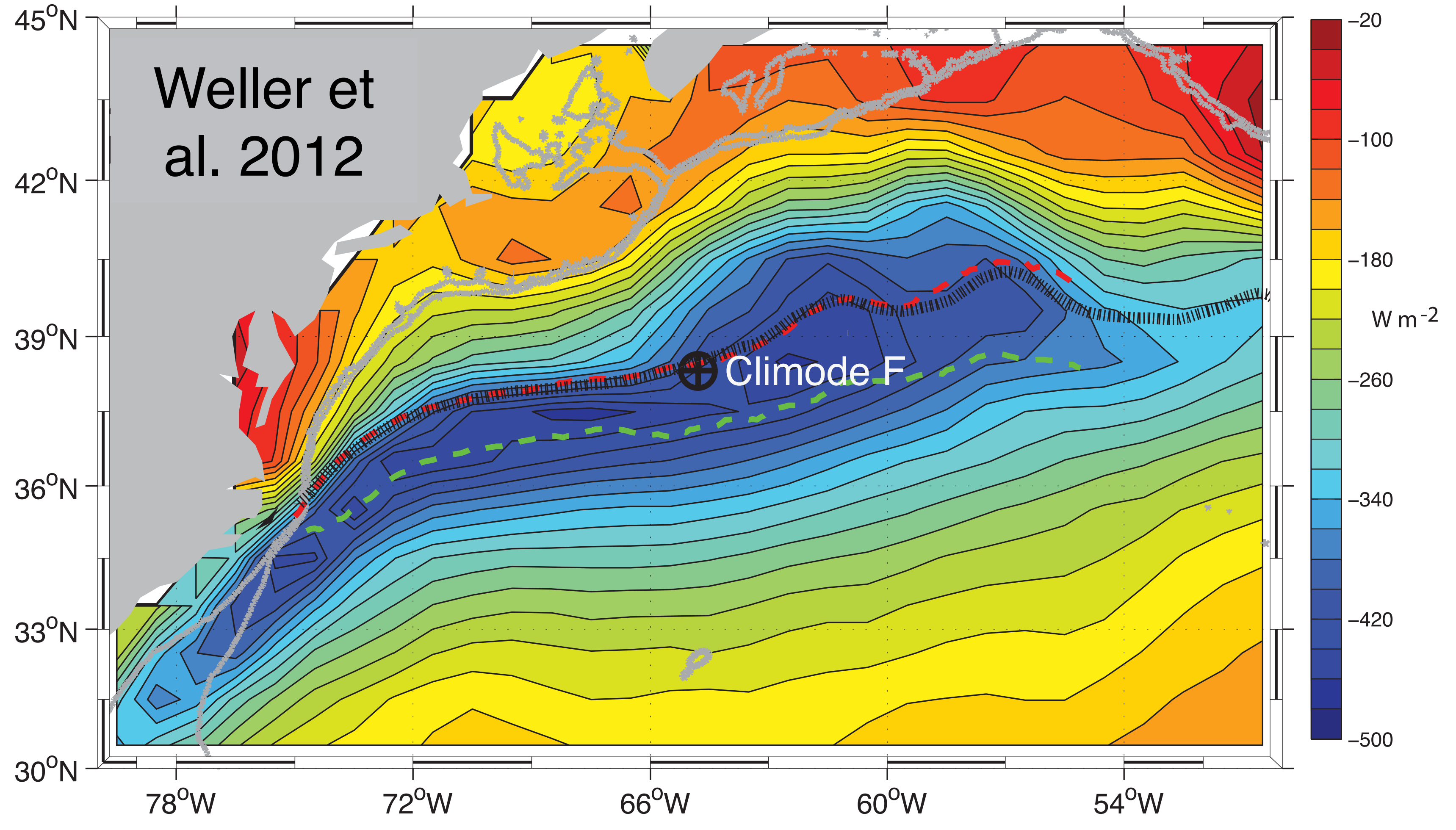
The transient eddy effect explains a substantial portion of the low-frequency total Z250 increase

Feedback to oceans

How do the turbulent flux responses influence the ocean?

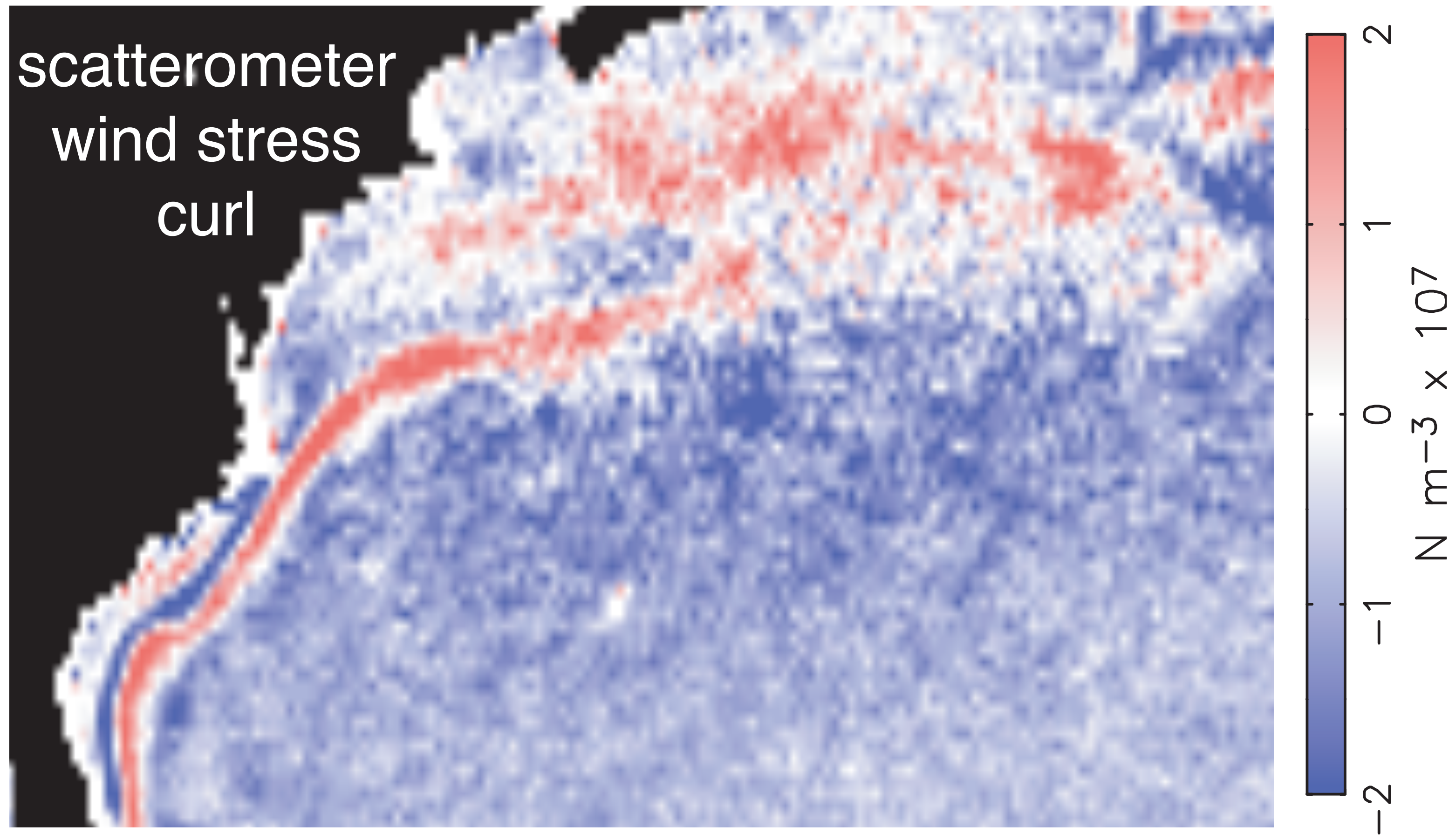
Mean turbulent heat flux

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

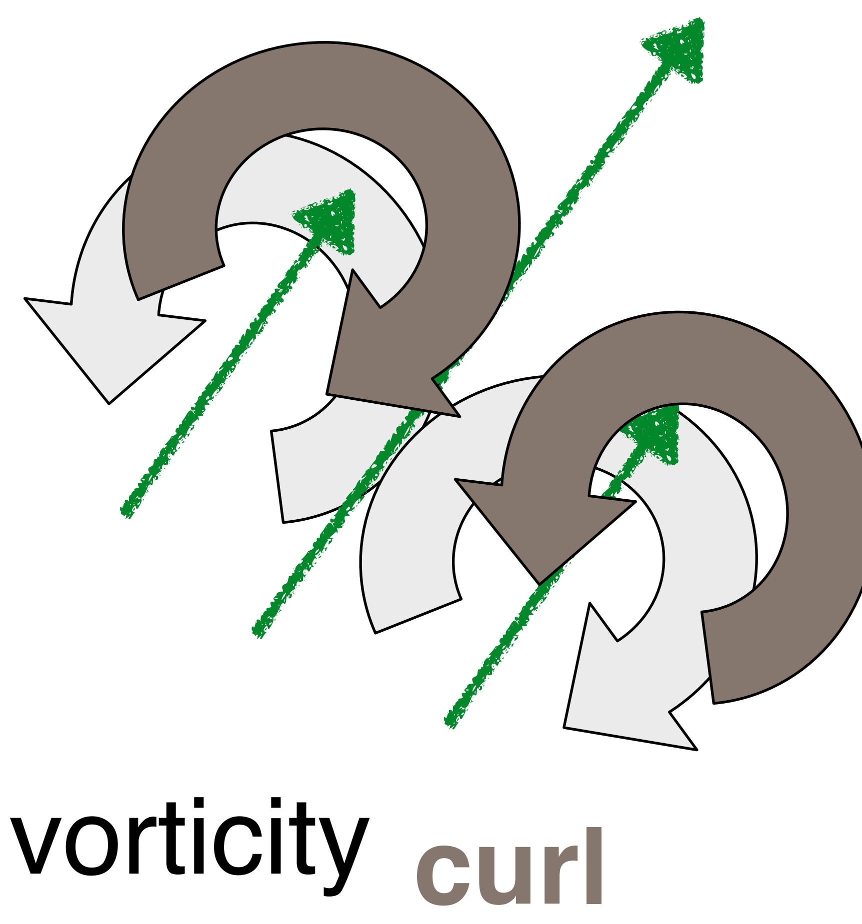


HF wind stress curl

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

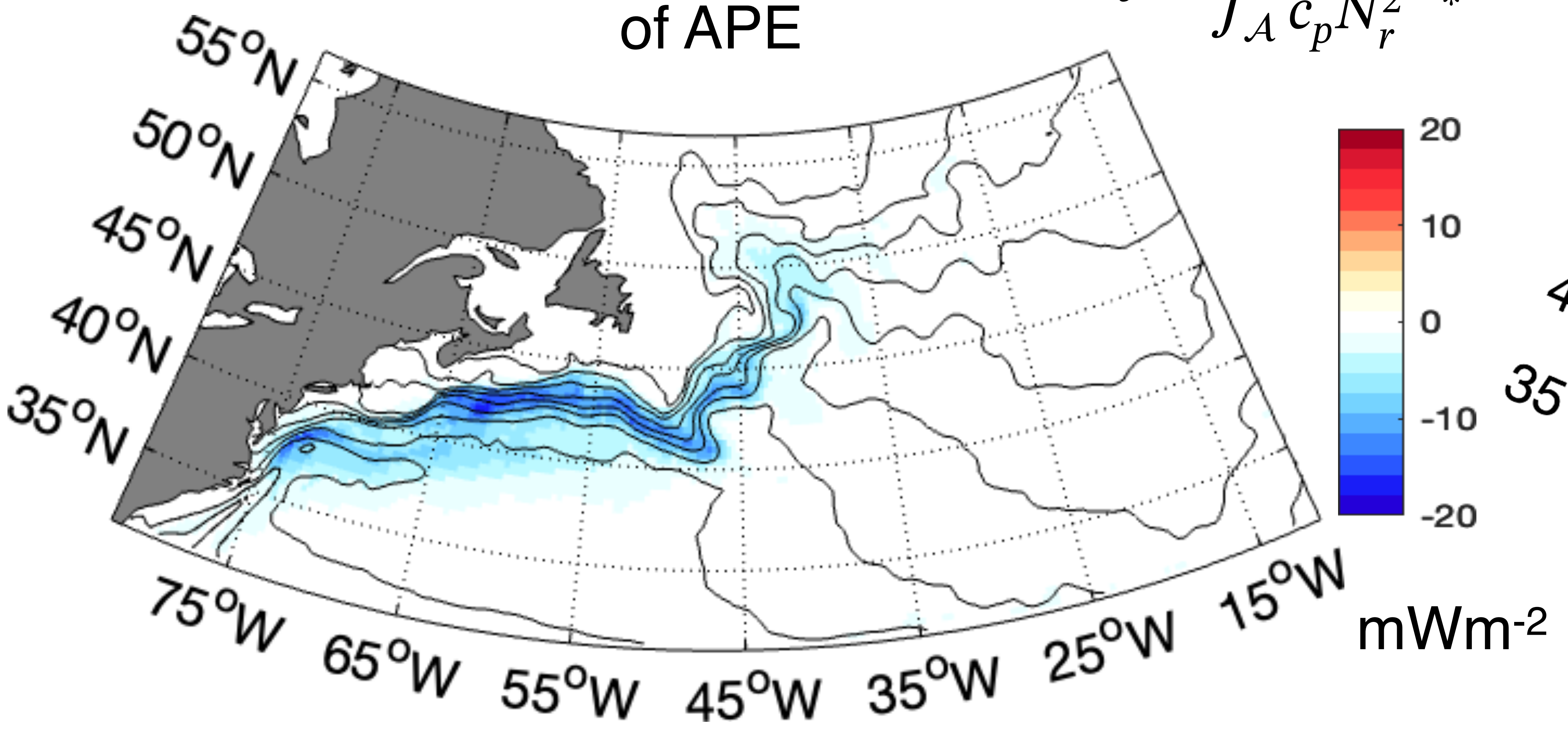


relative wind effect



Eddy diabatic dissipation of APE

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

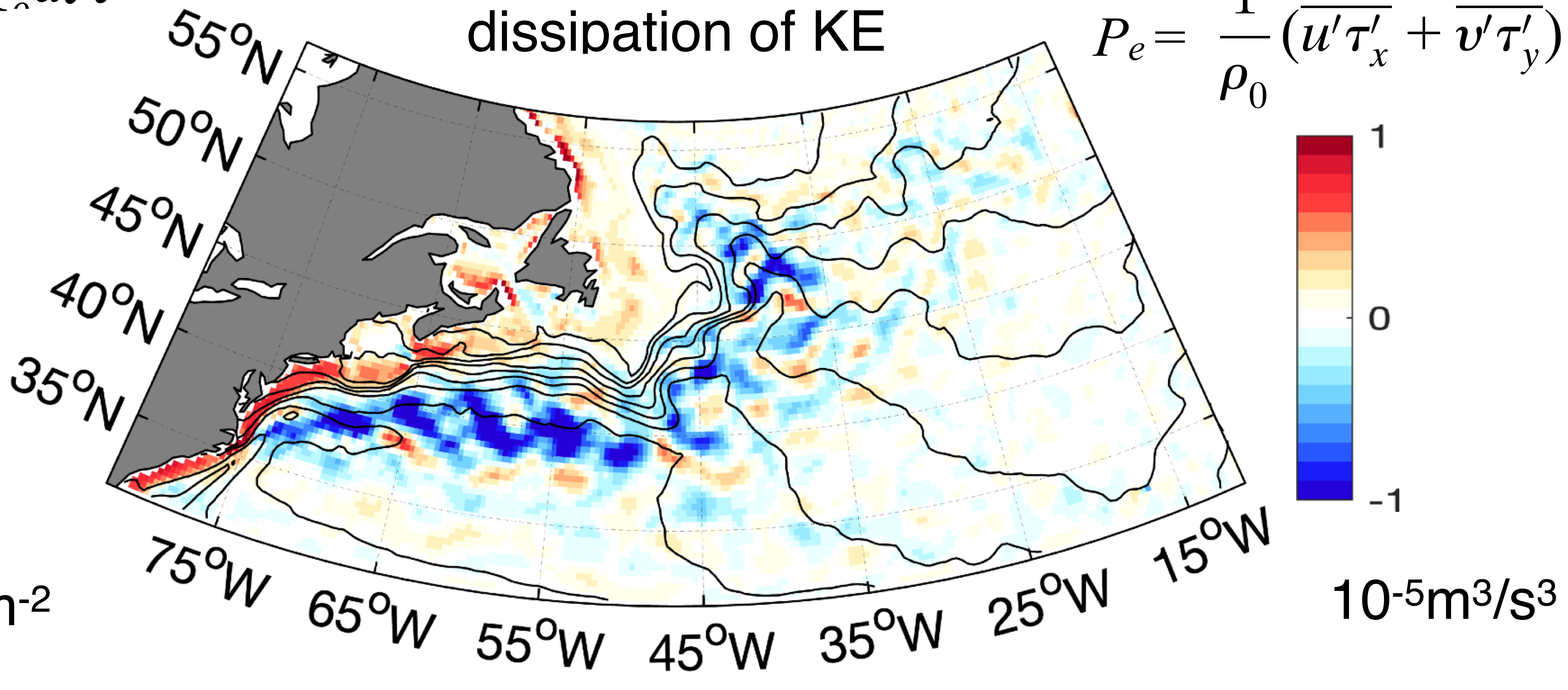


Negative eddy-induced SST-Q_{turb} covariance
→ EPE destruction (sink)

Eddy mechanical dissipation of KE

Geostrophic eddy wind work

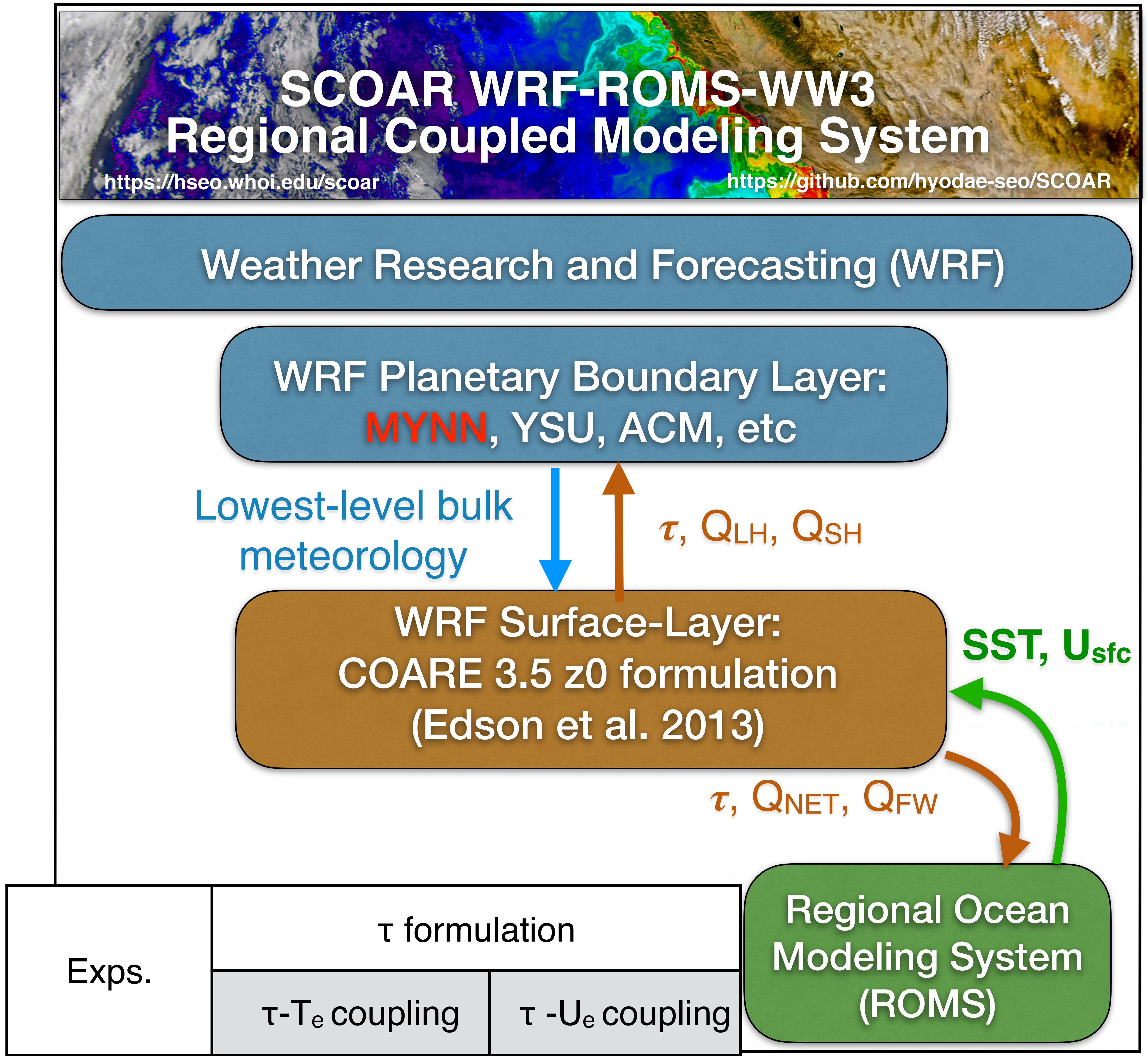
$$P_e = \frac{1}{\rho_0}\left(\overline{u'\tau'_x} + \overline{v'\tau'_y}\right),$$



Negative eddy-induced τ-u_s covariance
→ EKE destruction (sink)

Seo et al. (in prep)

Coupled ocean-atmosphere model simulations



SCOAR WRF-ROMS-WW3
Regional Coupled Modeling System

https://hseo.whoi.edu/scoar https://github.com/hyodae-seo/SCOAR

Weather Research and Forecasting (WRF)

WRF Planetary Boundary Layer:
MYNN, YSU, ACM, etc

Lowest-level bulk meteorology

τ, Q_{LH}, Q_{SH}

WRF Surface-Layer:
COARE 3.5 z0 formulation
(Edson et al. 2013)

SST, U_{sfc}

τ, Q_{NET}, Q_{FW}

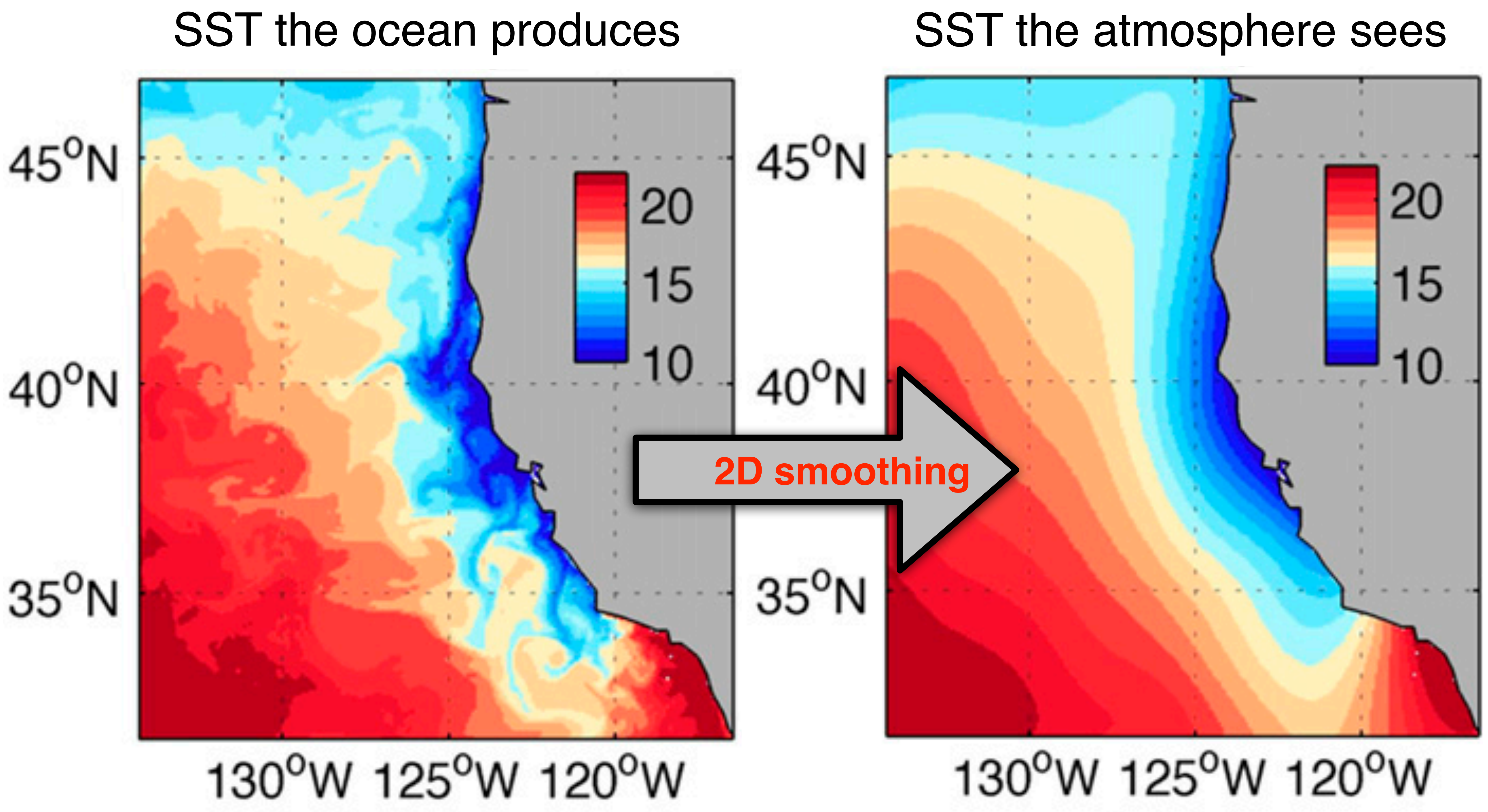
Regional Ocean Modeling System (ROMS)

Exps.	τ formulation	
	τ-T_e coupling	τ-U_e coupling
CTL	Y	Y
noT_e	N	Y
noU_e	Y	N

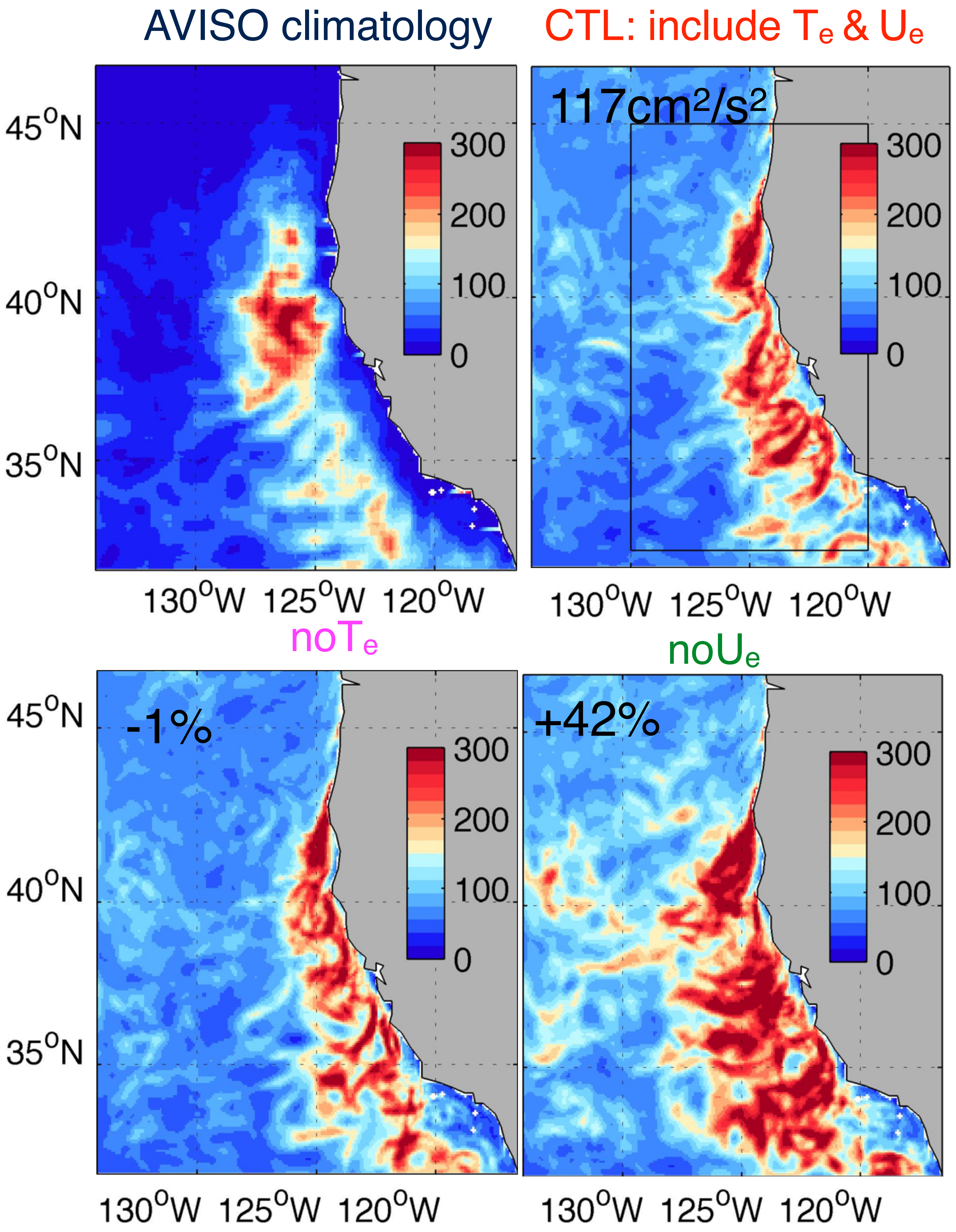
- SCOAR (WRF-ROMS) model was developed to study mesoscale air-sea interaction and regional climate processes (Seo et al. 2007~2021). https://hseo.whoi.edu/scoar-model, https://github.com/hyodae-seo/SCOAR.

- For scale dependence of air-sea coupling, an online 2-D Loess smoothing is applied to SST/currents or air-sea fluxes
  - Putrasahan et al. (2013); Seo et al. (2016); Seo (2017)

Online 2D spatial smoother



SST-wind and current-wind coupling effects on geostrophic EKE



alongshore and depth-averaged EKE

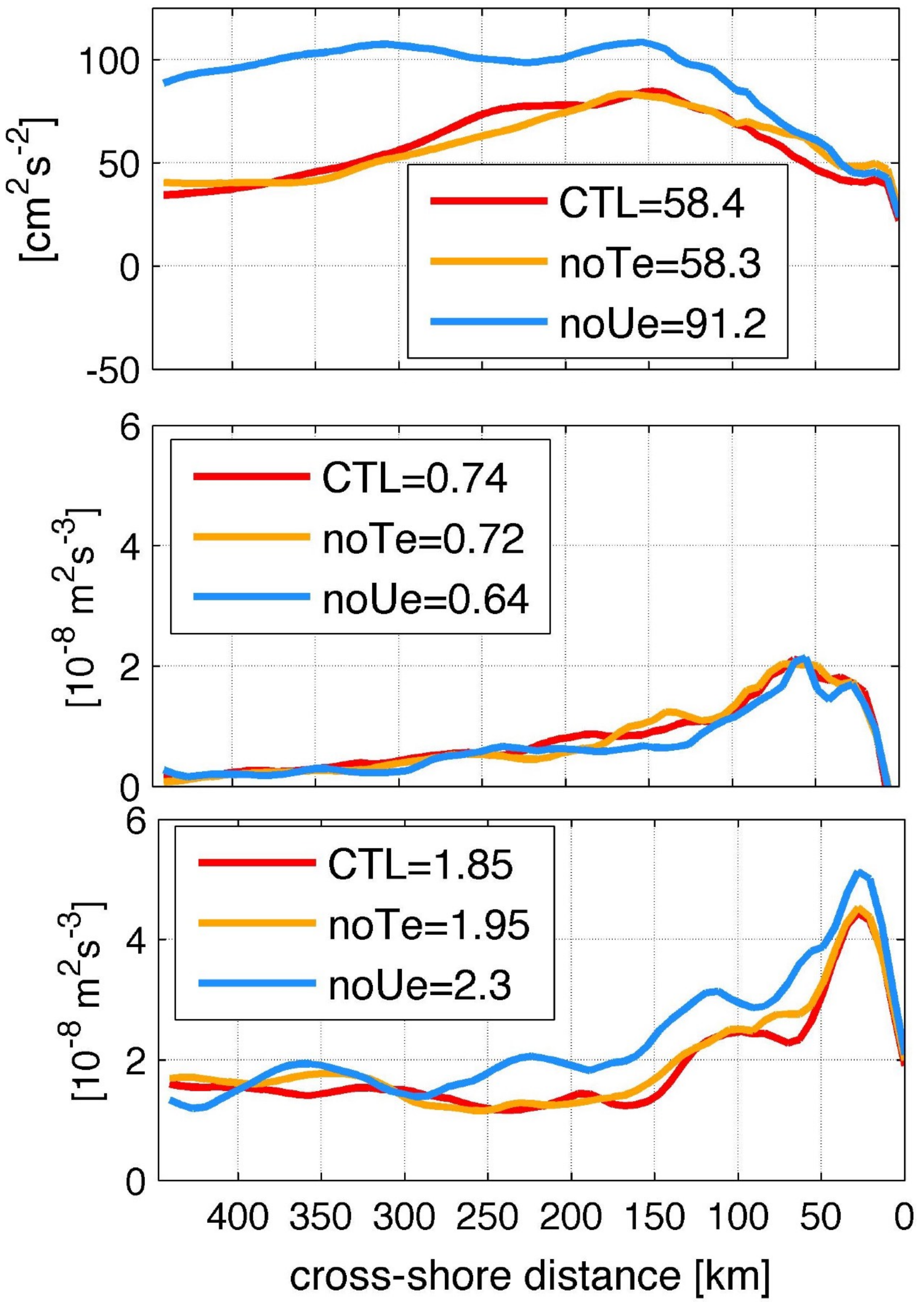
$$dEKE/dt = BC + P_e + \ldots$$

baroclinic conversion

$$\boxed{BC = -\frac{g}{\rho_0}\overline{\rho' w'},}$$

geostrophic eddy wind work

$$\boxed{P_e = \frac{1}{\rho_0}\left(\overline{u'\tau_x'} + \overline{v'\tau_y'}\right).}$$

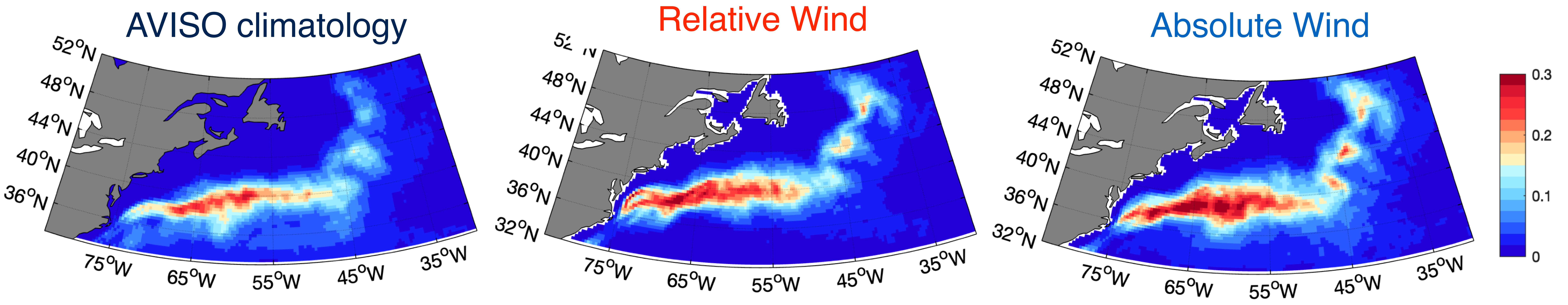


- T_e-τ has small impact
- U_e-τ is a significant damping effect (40%)

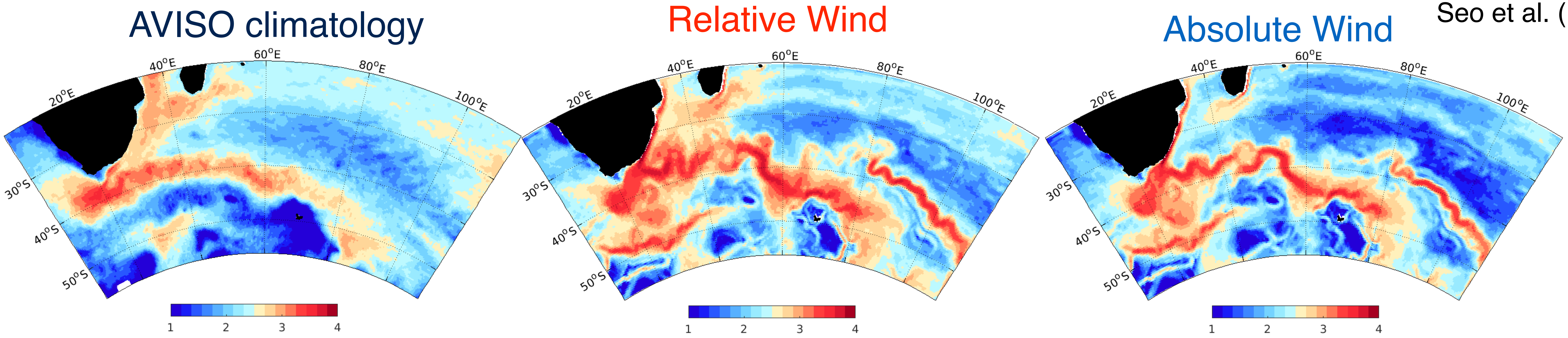
The EKE reduction is largely due to reduced wind work

Seo et al. (2016);

Current-wind coupling effects in the WBCs



Seo et al. (in prep)



Seo et al. (2021)

- With the relative wind effect, the Gulf Stream and Agulhas Current are stabilized and eddy activity attenuated (30-40%).

Role of Surface Waves

Parameterizing surface wave impacts on wind stress

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

Wave roughness length (z0) parameterization in COARE3.5 (Edson et al. 2013)

$$C_D \cong \left[\frac{\kappa}{\ln(z/z_0) - \psi_m(z/L)}\right]^2 \qquad z_0 = z_0^{\text{smooth}} + z_0^{\text{rough}}$$

1. Wind Speed Dependent Formulation (WSDF)

$$z_0^{\text{rough}} = \alpha \frac{u_*^2}{g} \qquad \alpha = f_1(U_{10N})$$

Charnock coefficient

2. Wave-Based Formulation (WBF)

$$z_0^{\text{rough}} = H_s \cdot 0.09 \cdot \left(\frac{u_*}{C_p}\right)^2$$

inverse wave age

significant wave height

wave phase speed $C_p = g^*(\mathbf{T_p}/2\pi)$

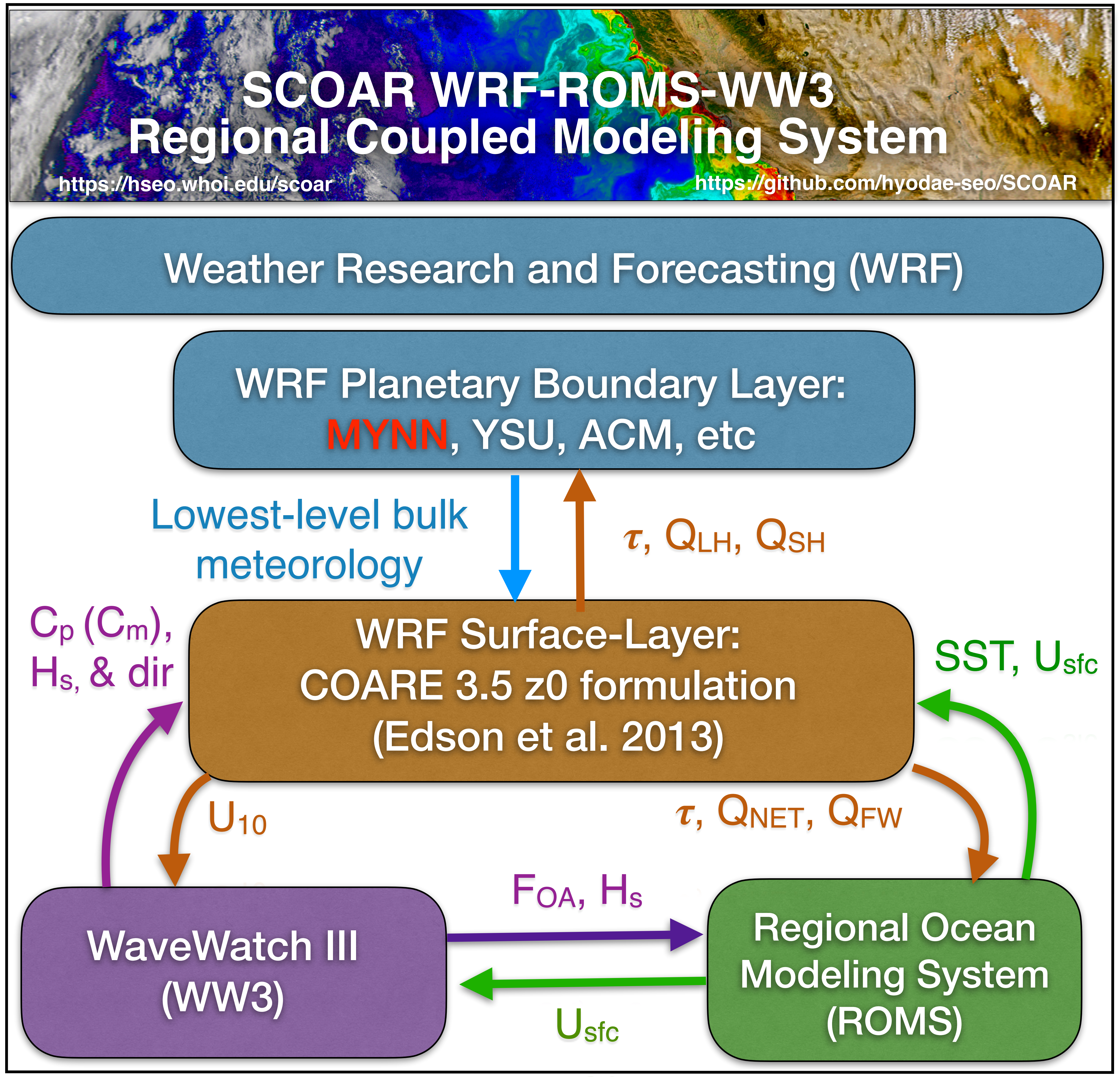
$\mathbf{T_p}$: wave period at the spectral peak

- **Assumption #1**: Wind-wave equilibrium (wave age~1.2):
  - Wind seas under high wind and swell under low wind.
- **Assumption #2:** Waves aligned with winds (θ=0)
- Violated near strong density fronts, shallow, fetch-limited oceans, under rapidly translating cyclones.

- Still assumes θ=0.
- WBF often DOES NOT yield better fluxes.
- Does that mean waves aren't important?
- No, parameterizations are imperfect.

Ocean-WAVE-atmosphere coupled modeling

for wave-wind and wave-current interactions:



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WRF Planetary Boundary Layer:
MYNN, YSU, ACM, etc

Lowest-level bulk meteorology

τ, Q_{LH}, Q_{SH}

C_p (C_m), H_s, & dir

WRF Surface-Layer:
COARE 3.5 z0 formulation
(Edson et al. 2013)

SST, U_{sfc}

U_{10}

τ, Q_{NET}, Q_{FW}

F_{OA}, H_s

WaveWatch III
(WW3)

Regional Ocean
Modeling System
(ROMS)

U_{sfc}

https://hseo.whoi.edu/scoar-model

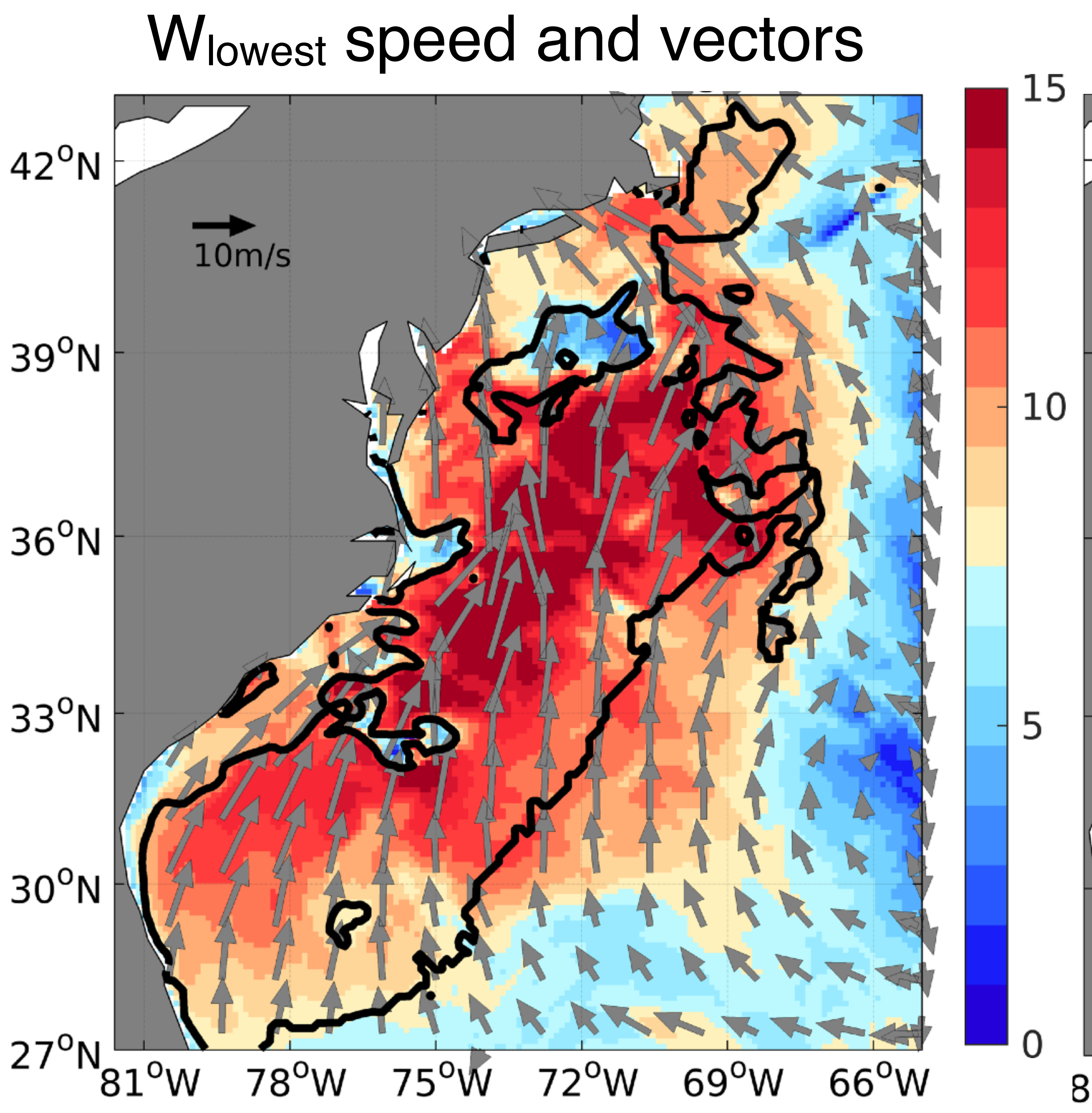
- COARE3.5 WBF as the cornerstone of the OAW coupling
- Goal to improve WBF over a range of wind/wave regimes
- Wave-coupling procedure is documented in Sauvage et al. (*Submitted to JGR Oceans*)

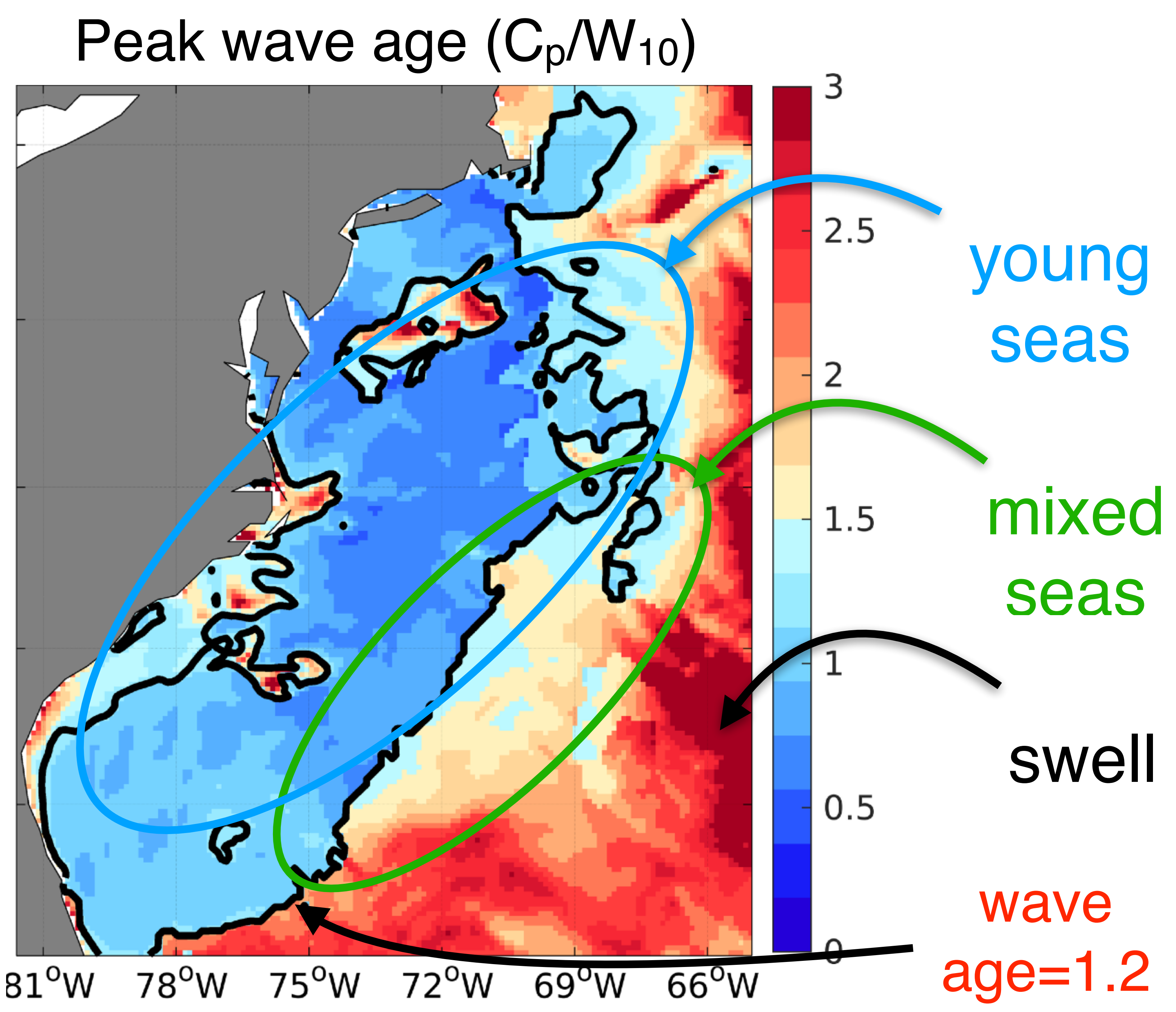
Experiments	**Coupling**	**z0 in COARE3.5**
WSDF	WRF-ROMS	wind speed only
WBF	WRF-ROMS-WW3 with default WBF	wave-based (T_p, H_s)
WBF_θ	WRF-ROMS-WW3 with *modified* WBF	vector wave stress (θ≠0)
WBF_T_m		with T_m instead of T_p

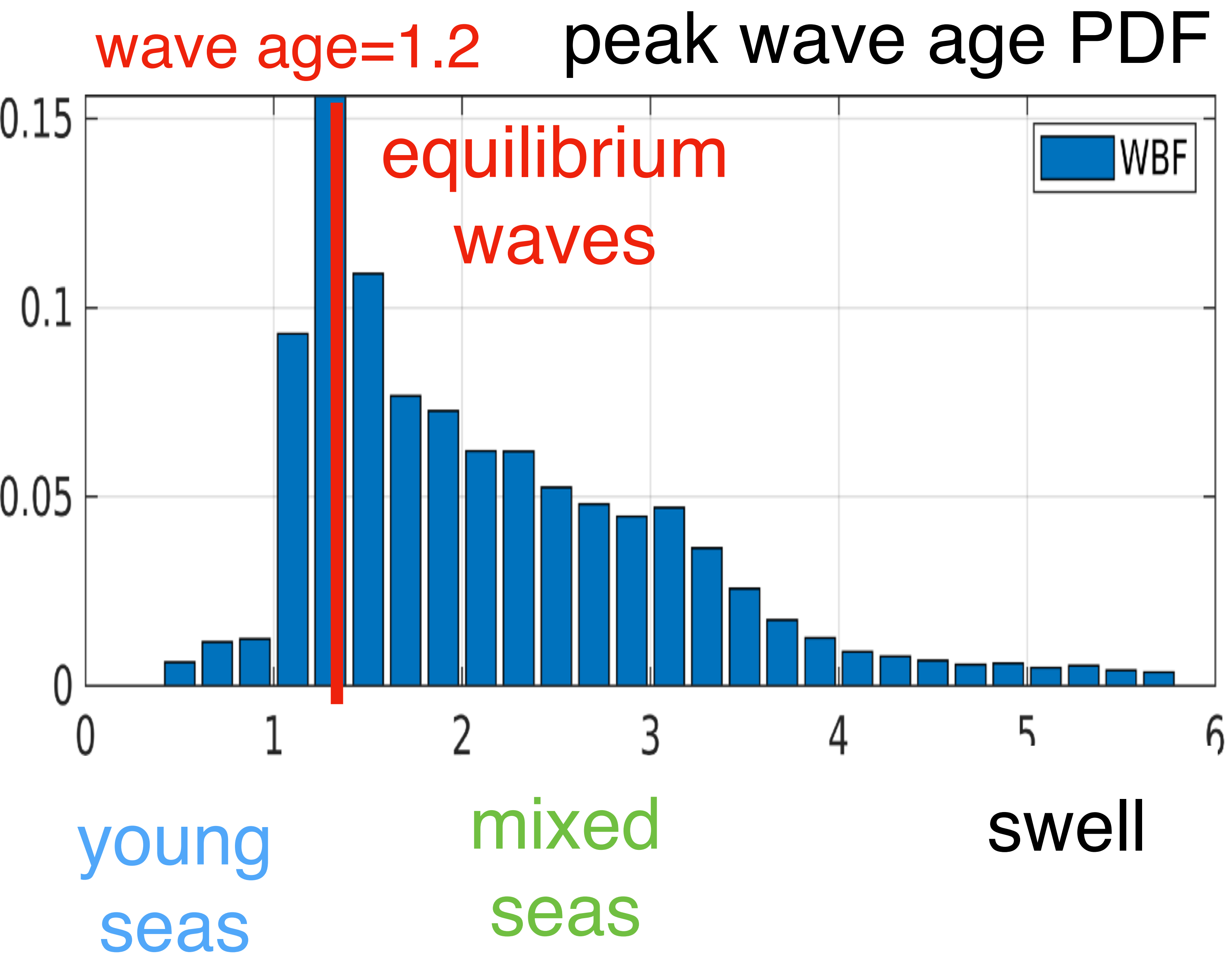
- 10 km resolutions with matching grids. All runs include tides, current-wind and SST-wind interactions, and breaking wave induced vertical mixing.

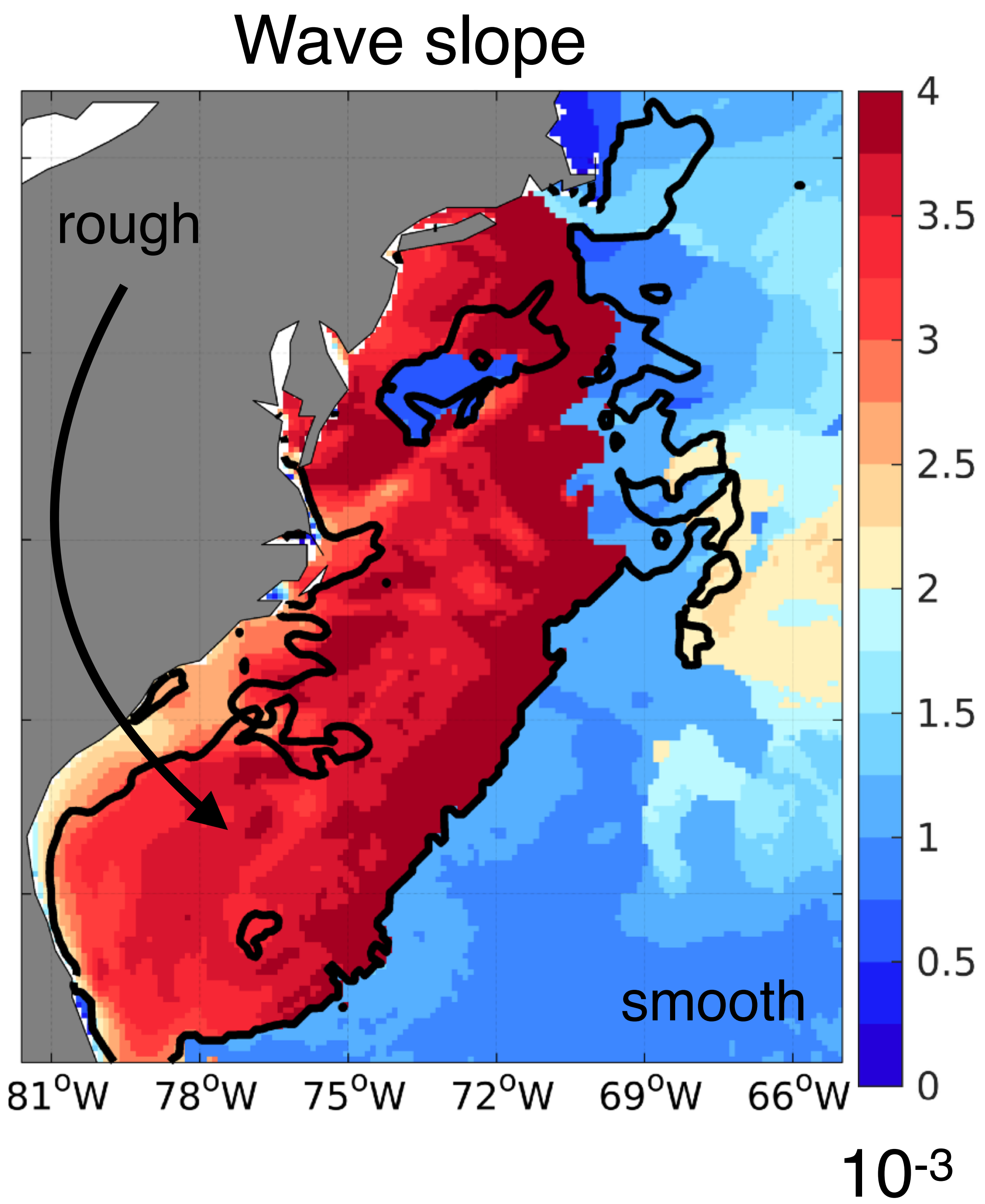
Case study: mixed sea states under a storm

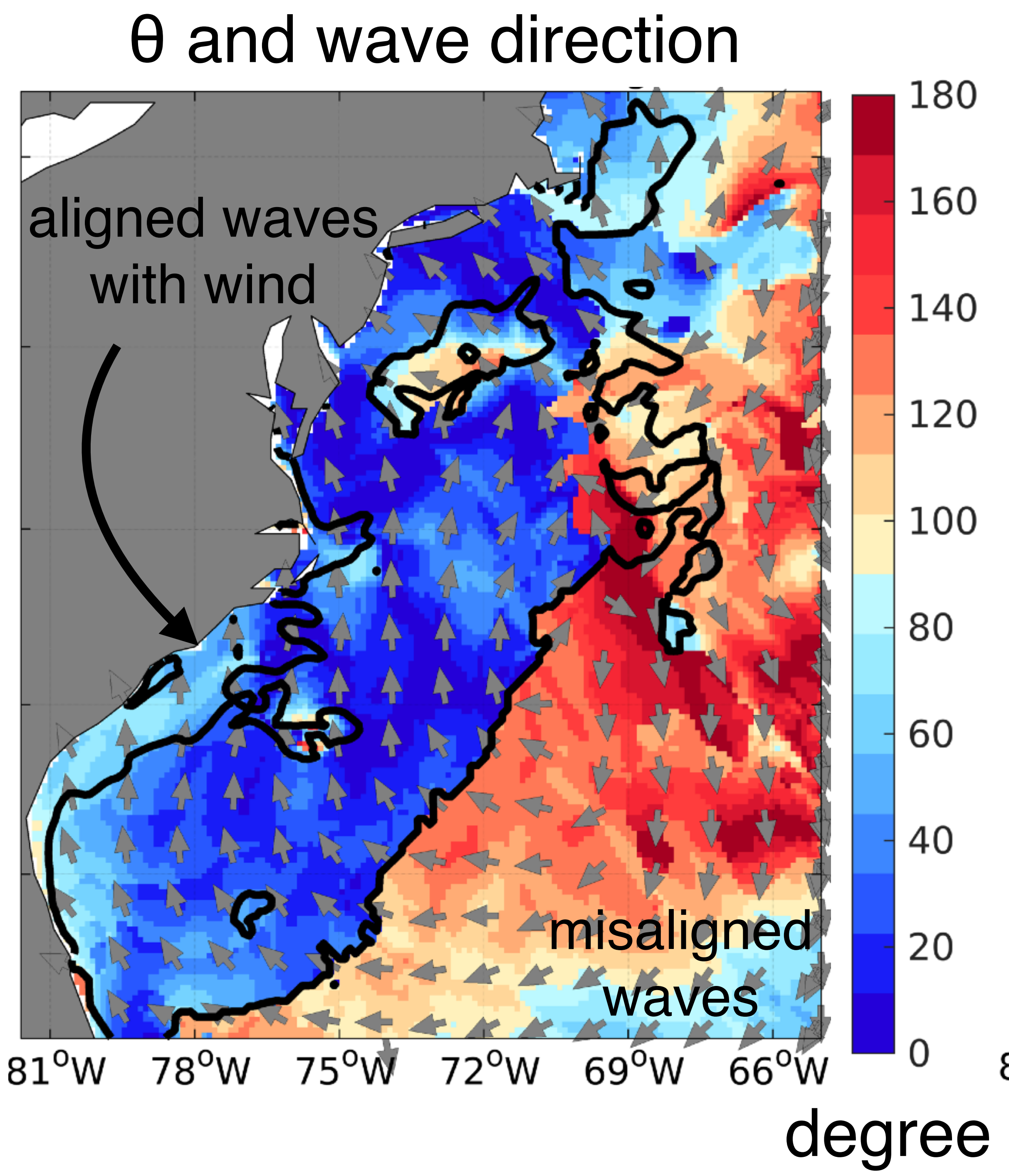
Snapshots 36 hours after the initial condition (12Z Dec 2 2018)

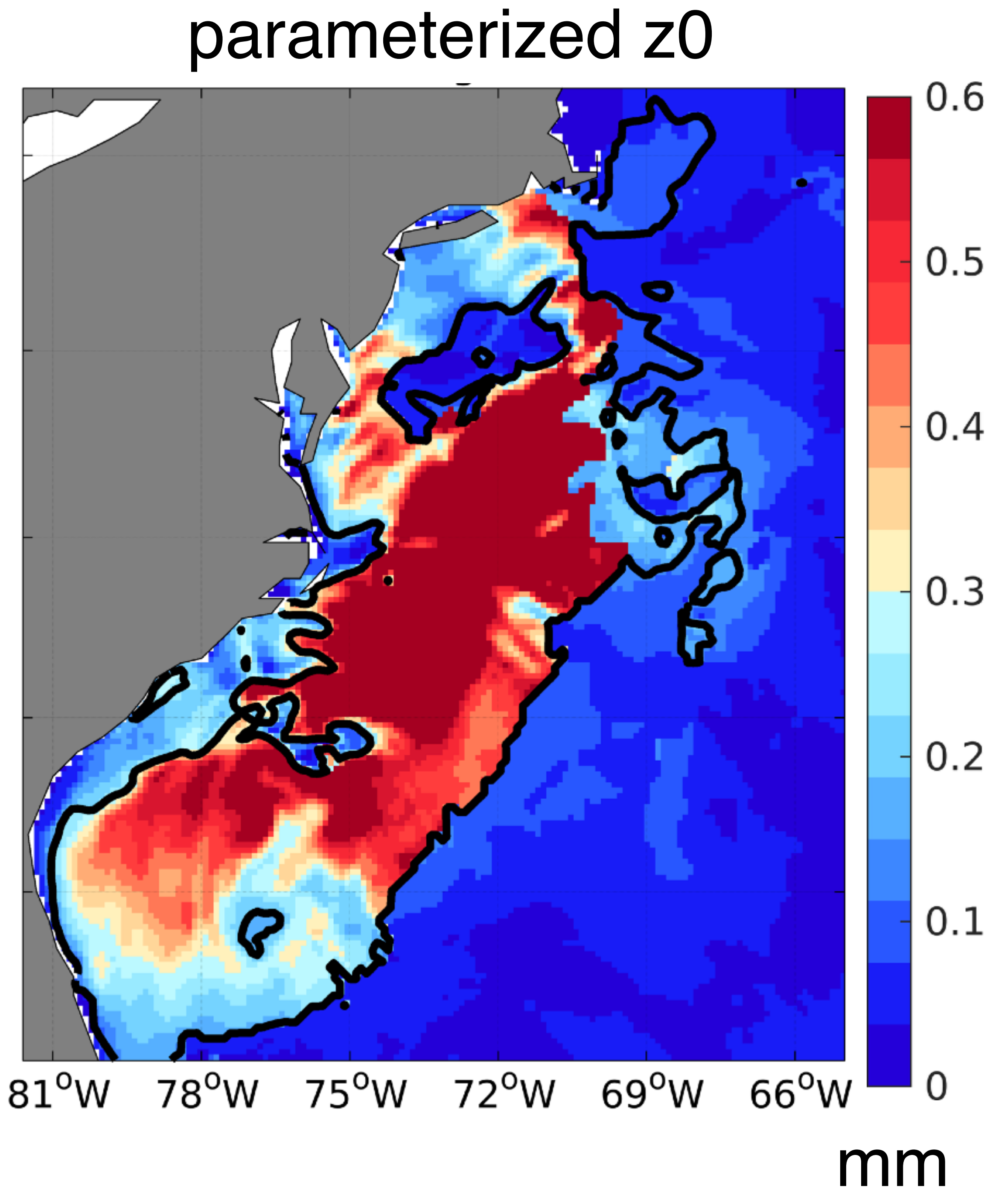




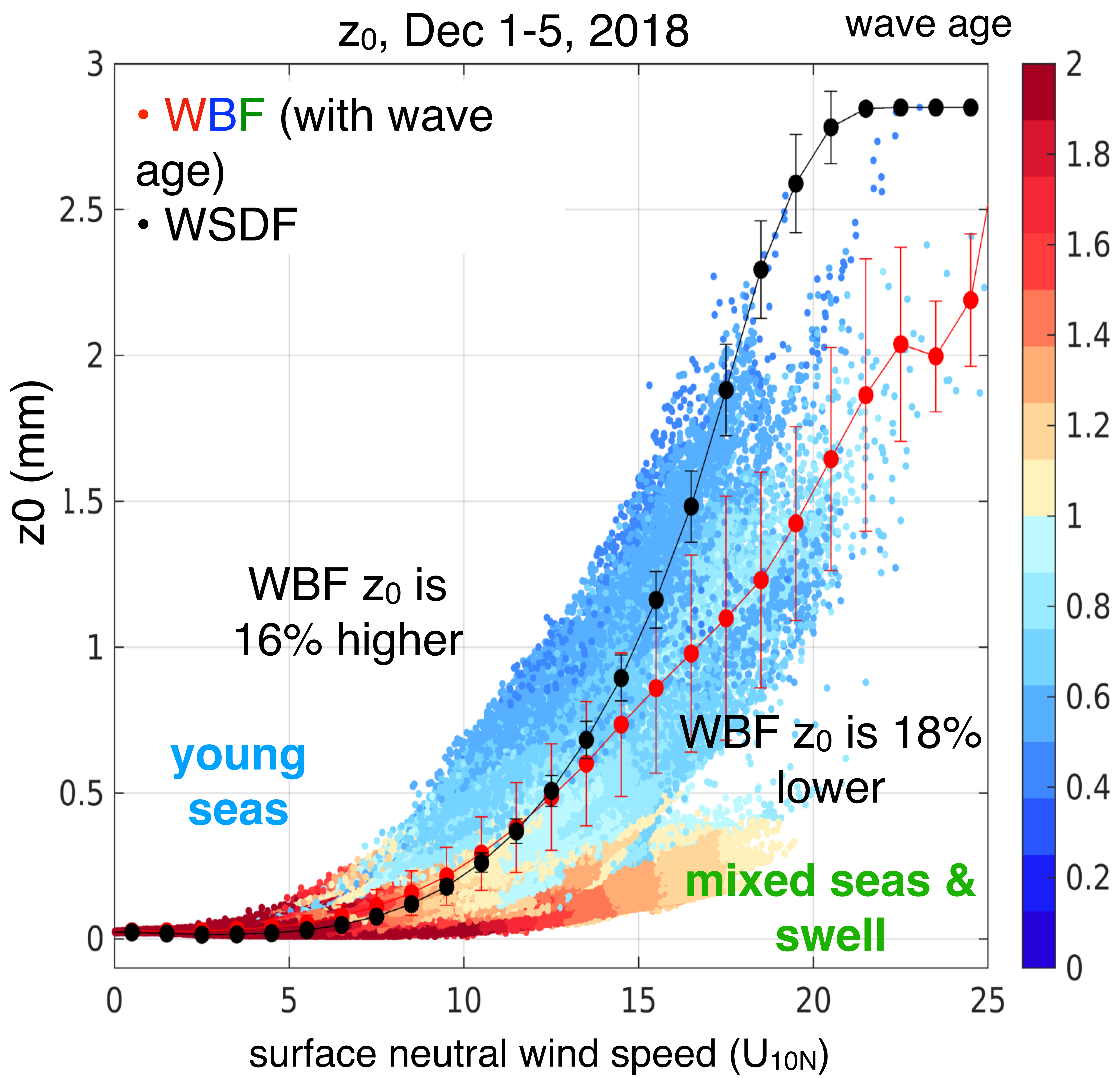


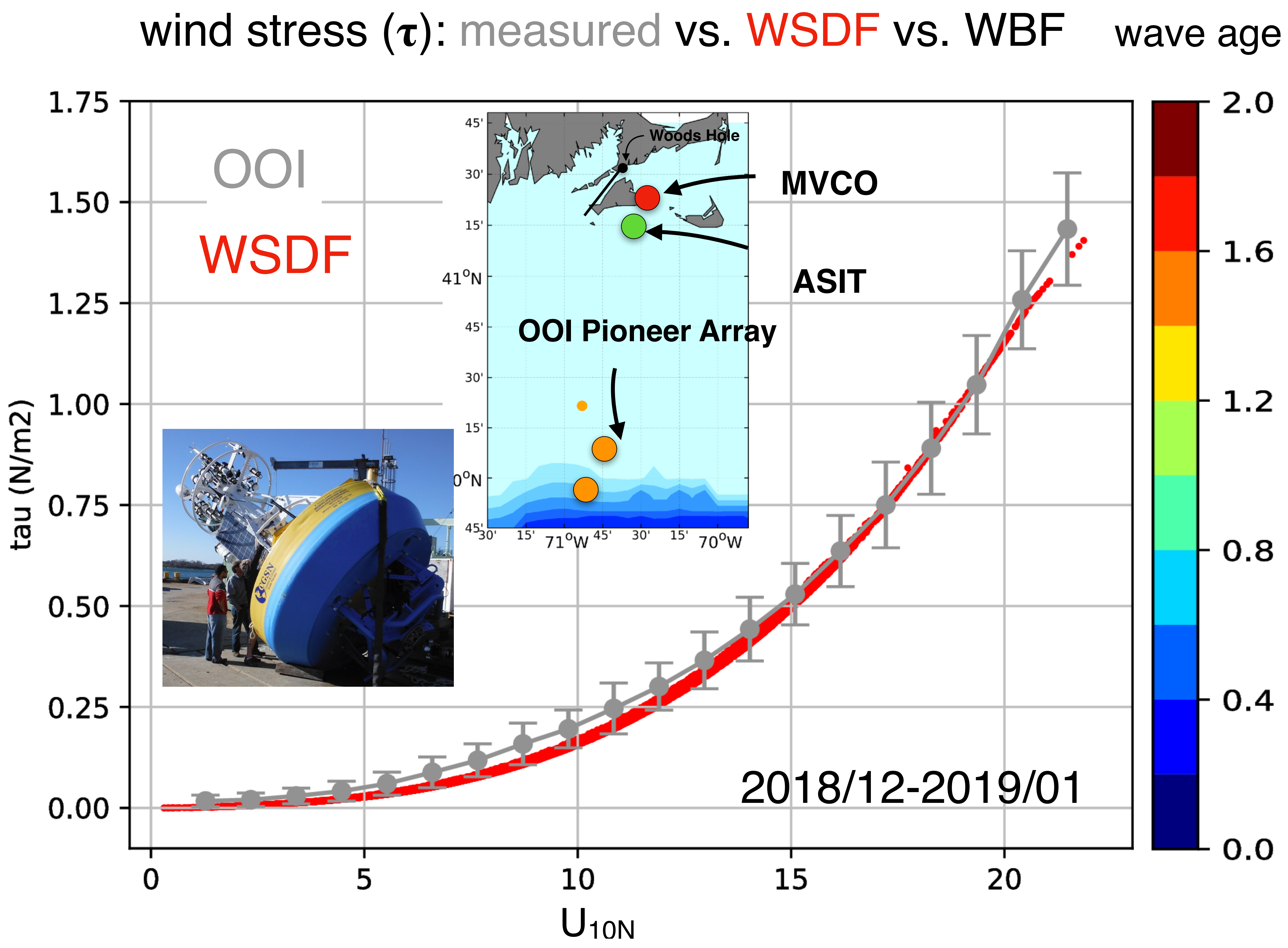






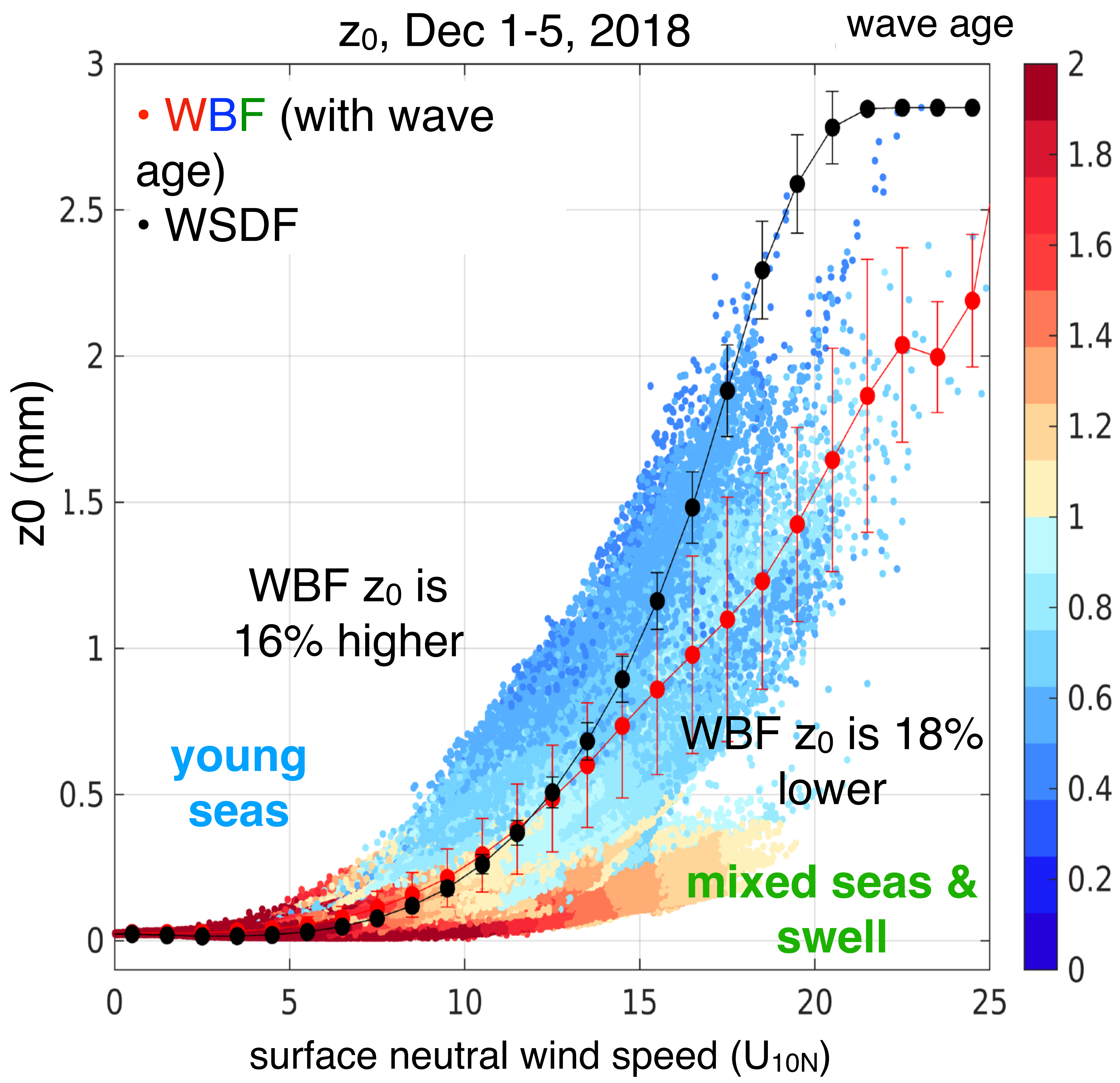
z0 and τ responses to inclusion of waves and sea state in COARE3.5

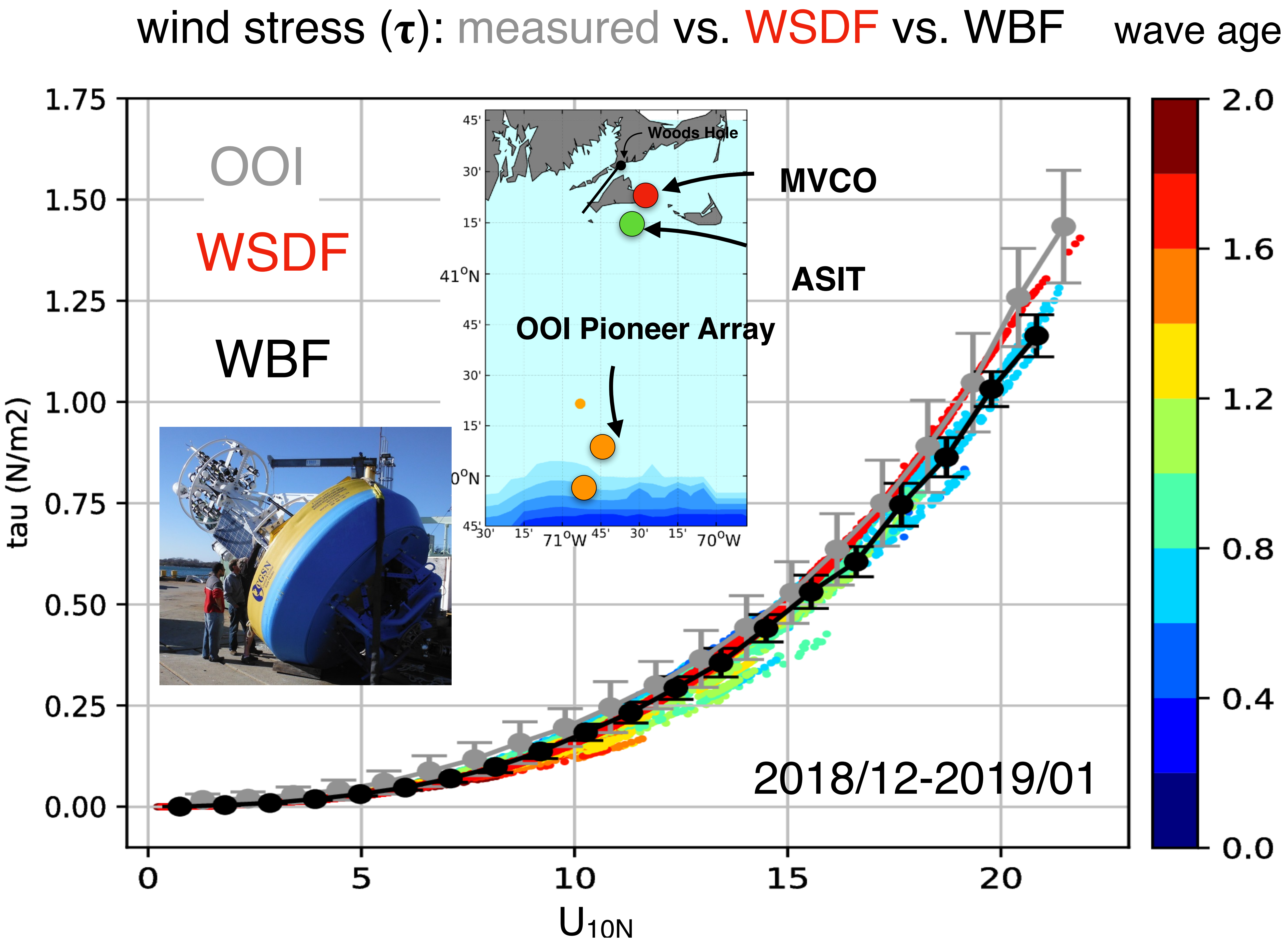




- WSDF underestimates stress over young seas, but shows a good agreement with the measurements in high winds.

z0 and τ responses to inclusion of waves and sea state in COARE3.5

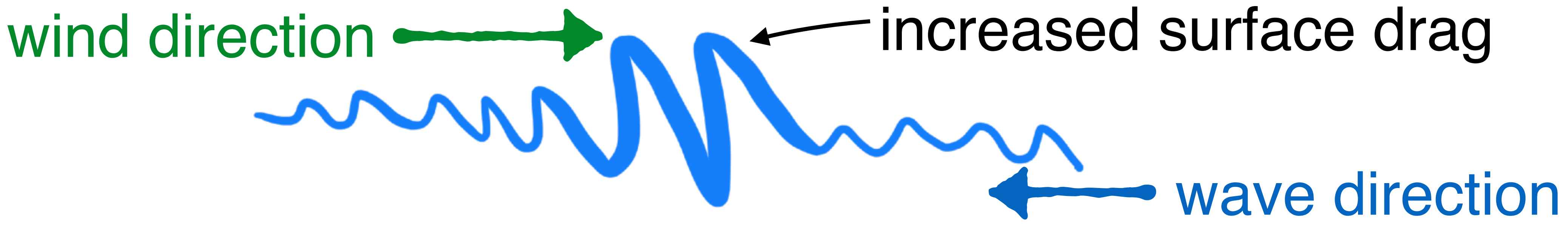




- WBF alleviates the low-stress bias over young seas
- But it underestimates the stress in mixed sea conditions

Re-engineering the wave-based formulation in bulk flux algorithm

Waves are not aligned (θ≠0) with local winds in mixed seas:



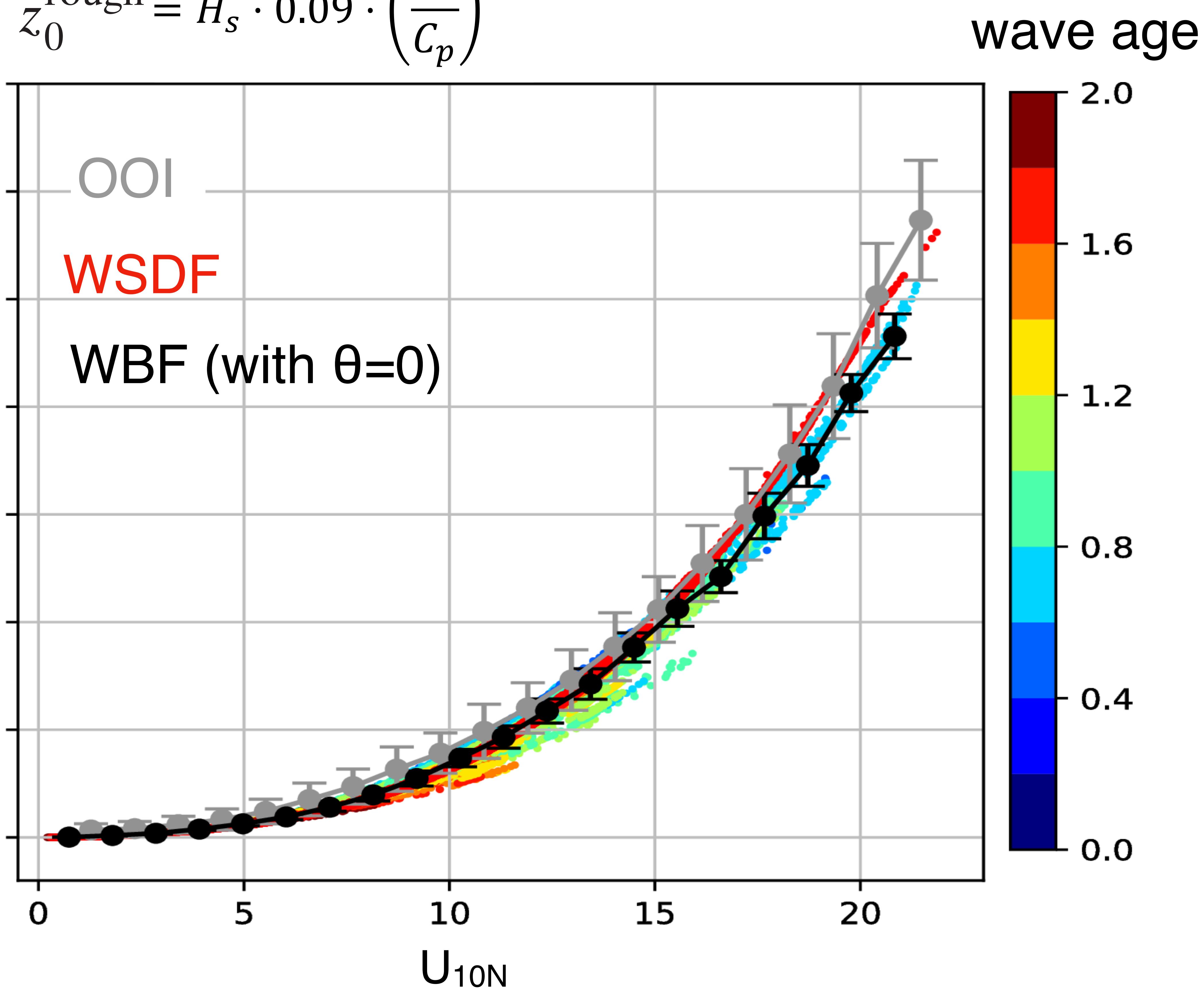
wind direction

increased surface drag

wave direction

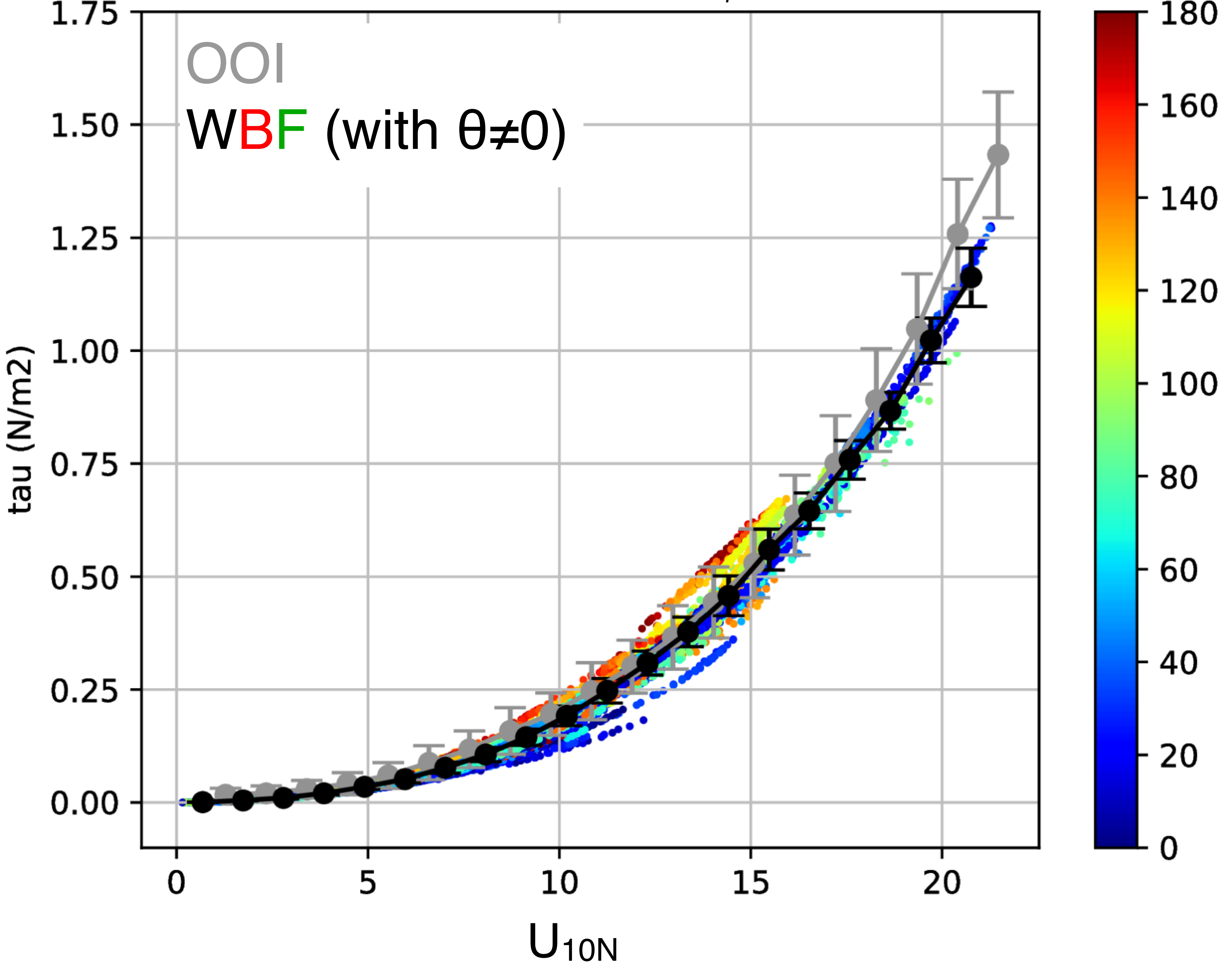
Edson et al. (2013) COARE3.5

$$z_0^{\text{rough}} = H_s \cdot 0.09 \cdot \left(\frac{u_*}{C_p}\right)^2$$



Sauvage, Seo, Edson et al. (submitted)

$$z_{rough} = H_s \cdot 0.09 \cdot \cos(0.45\,\theta) \cdot \left(\frac{u_*}{C_p}\right)^{2\cdot\cos(-0.32\,\theta)}$$

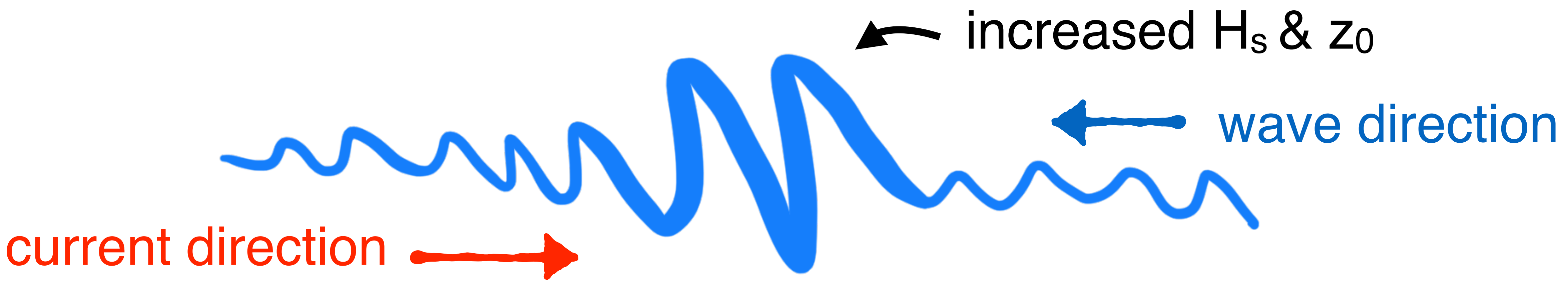


- The next-generation COARE (v4.0) will continue to assume θ=0.
- Our model provides various revised formulations to represent the wave effects.

Sauvage et al. (in prep)

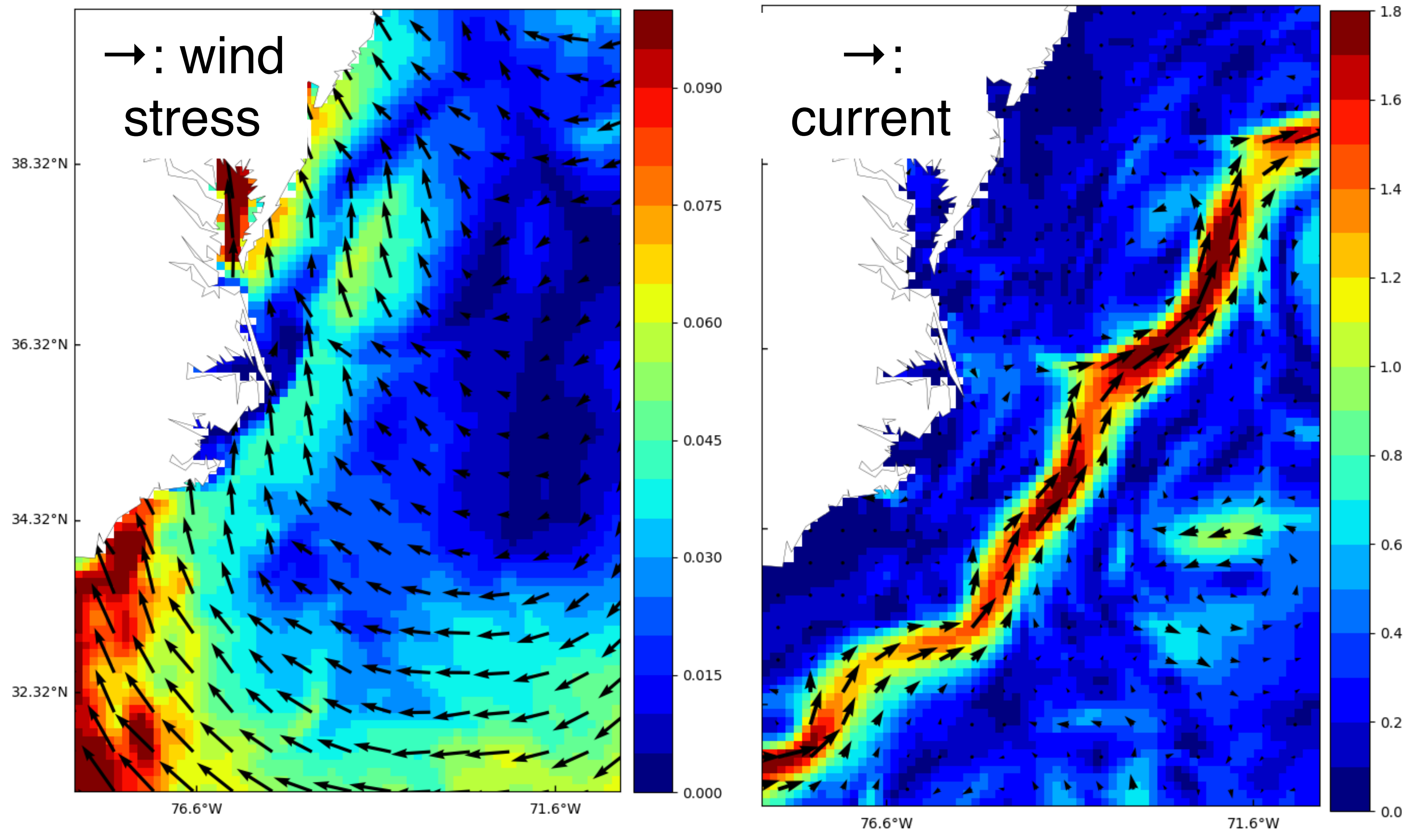
Wave-current interaction

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



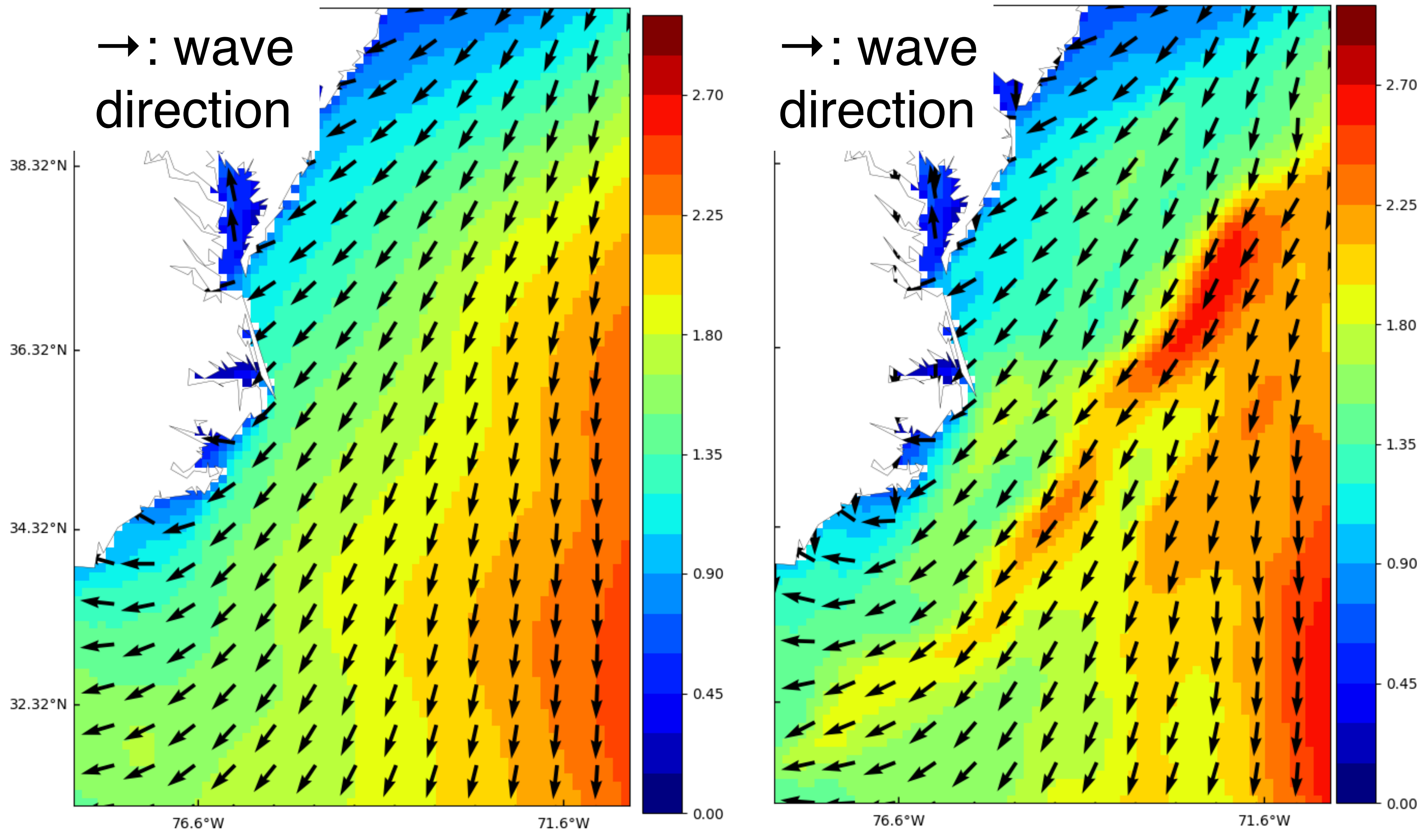
wind stress

surface current



H_s without current

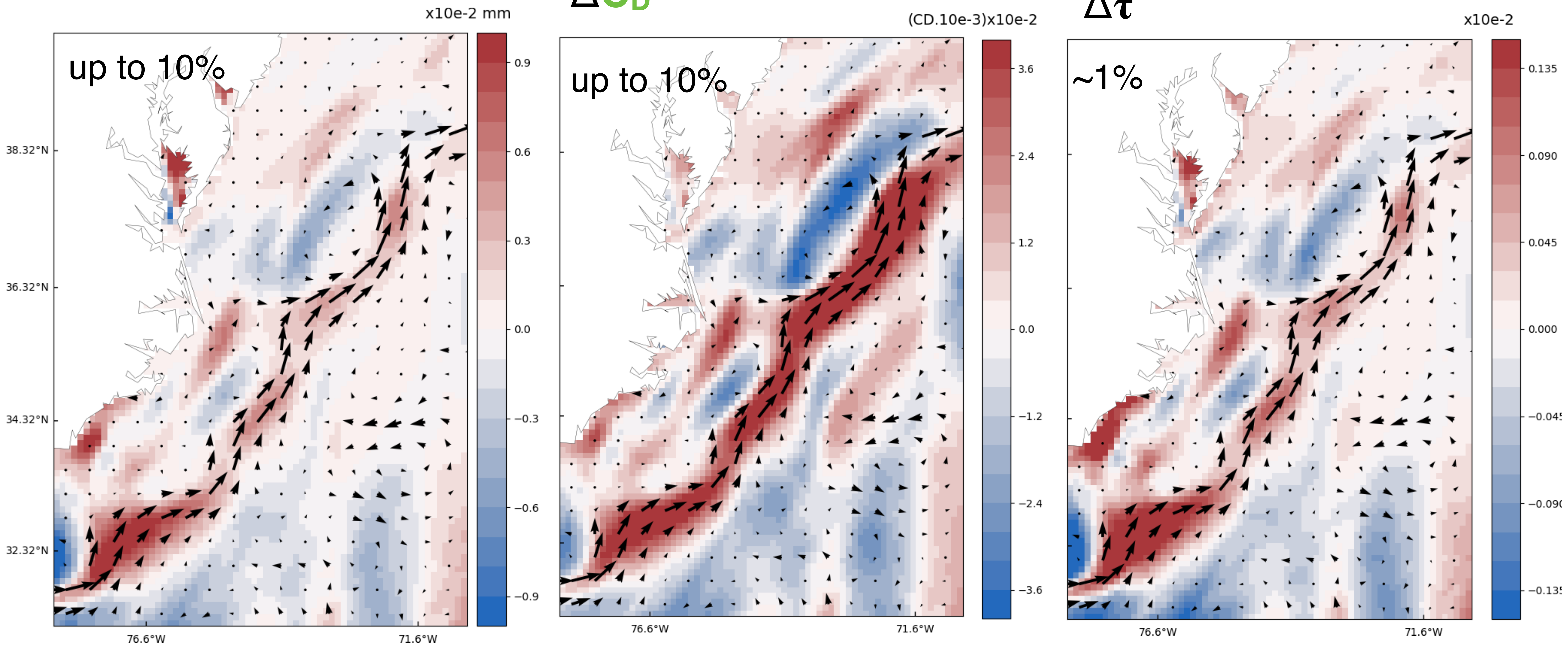
H_s with current



Δz_0

ΔC_D

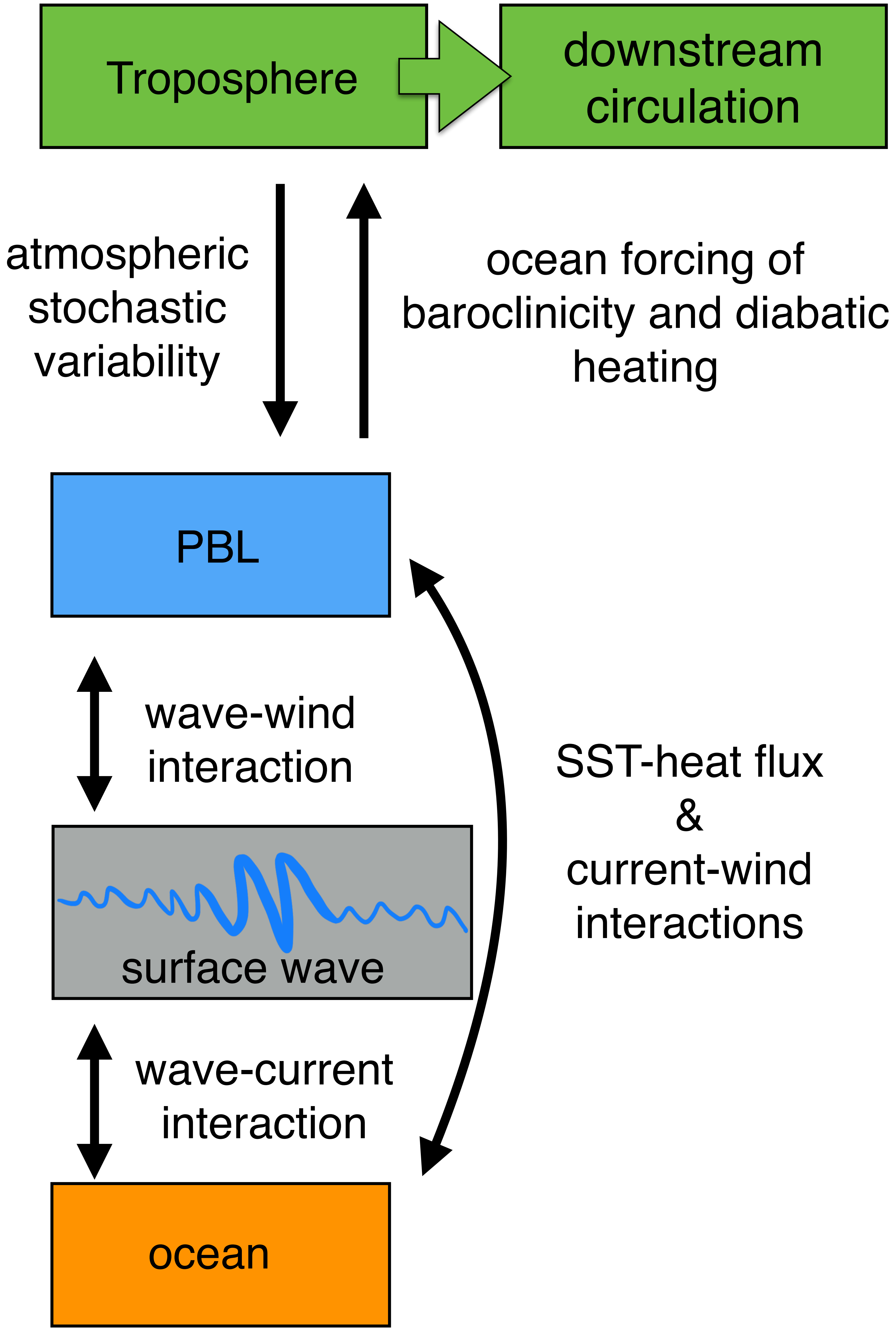
$\Delta \tau$



The spatial variability in ocean currents affects the wave properties and thus air-sea flux (Ardhuin et al. 2017)
Even the most advanced bulk formula do not take into account this effect.

Synthesis and discussion

O-W-A coupling across scales



Troposphere

downstream circulation

atmospheric stochastic variability

ocean forcing of baroclinicity and diabatic heating

PBL

wave-wind interaction

SST-heat flux & current-wind interactions

surface wave

wave-current interaction

ocean

- Mesoscale air-sea interaction is important for simulations of ocean circulation, boundary layer dynamics, and high-impact weather events.
  - Challenges for developing observational strategies and improving model physics.
  - In-situ measurements of PBL, air-sea flux, and sea states are extremely sparse.
  - Bulk formula is imperfect. Need distributed arrays of DCF systems, bulk met. sensors, sea-state, and PBL.

- High-resolution models are leading the ocean-weather-climate research
  - Air-sea fluxes and MABL processes are not well validated.
  - Some coupled effects of ocean eddy (on EPE/EKE) are not parameterized.
  - Regional modeling can guide effective sampling strategies and refine the physics.

- Strong interests exist in coordinated air-sea interaction observations
  - A critical gap remains in remote sensing capability to provide accurate global estimates of turbulent heat/moisture fluxes at high-resolution (10-25 km)