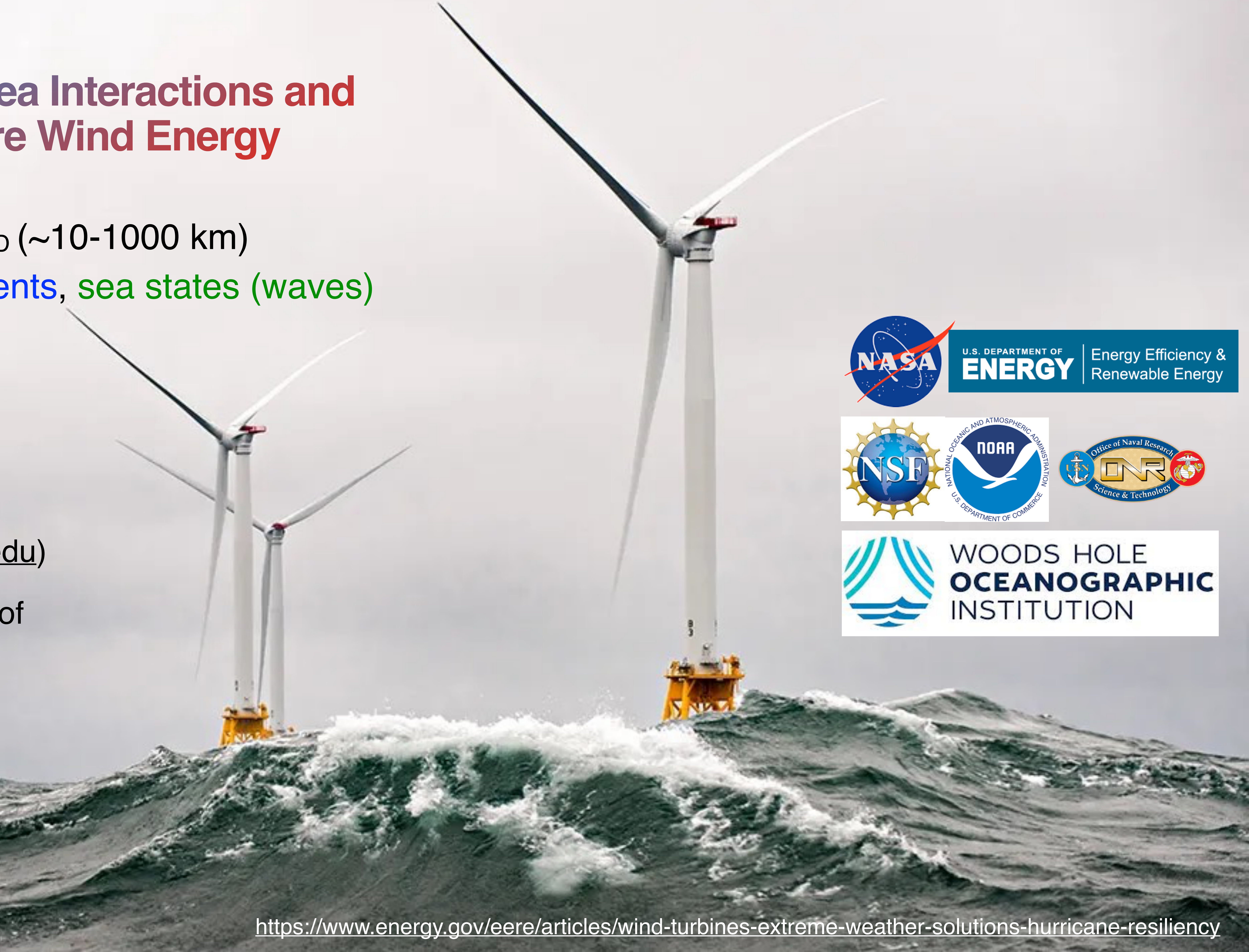
Ocean Mesoscale Air-Sea Interactions and Implications for Offshore Wind Energy

length-scale smaller than R_D (~10-1000 km)

mesoscale SST, ocean currents, sea states (waves)

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



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Gwangju Regional Office of Meteorology

January 27, 2023

NASA | U.S. DEPARTMENT OF ENERGY | Energy Efficiency & Renewable Energy

NSF | NOAA | Office of Naval Research Science & Technology

WOODS HOLE OCEANOGRAPHIC INSTITUTION

https://www.energy.gov/eere/articles/wind-turbines-extreme-weather-solutions-hurricane-resiliency

WOODS HOLE OCEANOGRAPHIC INSTITUTION

WHOI is the World's largest private ocean research institution

- Studying the ocean and related earth systems since 1930
- Major discoveries and advances in ocean science, marine technology and engineering
- 475 scientific and technical staff
- $200+ million annual research budget; ~800 active projects
- Fleet of nearly 100 vehicles, including three large ships, dozens of robotic and remotely operated submersibles, and the iconic human-occupied submersible *Alvin*
- 50+ years of world-class Ph.D. program with MIT; highly regarded post-doctoral program

Diversified Funding Sources

Government Funding

<u>Traditional</u>

- NSF
- ONR
- NOAA

<u>Other</u>

- NASA
- NIH
- Dept of Energy
- Dept of Interior
- DARPA
- Foreign Governments

WHOI Research

Industry Funding

- Sponsored Research
- IP Revenues
- OCIA

Private Funding

- Private Individuals
- Foundations
- Endowment

Developing a $300M horizontal offshore laboratory

Wind Forecast Improvement Project-3

U.S. DEPARTMENT OF ENERGY | Energy Efficiency & Renewable Energy

WOODS HOLE OCEANOGRAPHIC INSTITUTION

WHOI (lead) UC Boulder, NCAR, UT Dallas, Tufts, DNV, 4 DOE labs, 3 NOAA labs, & user advisory board

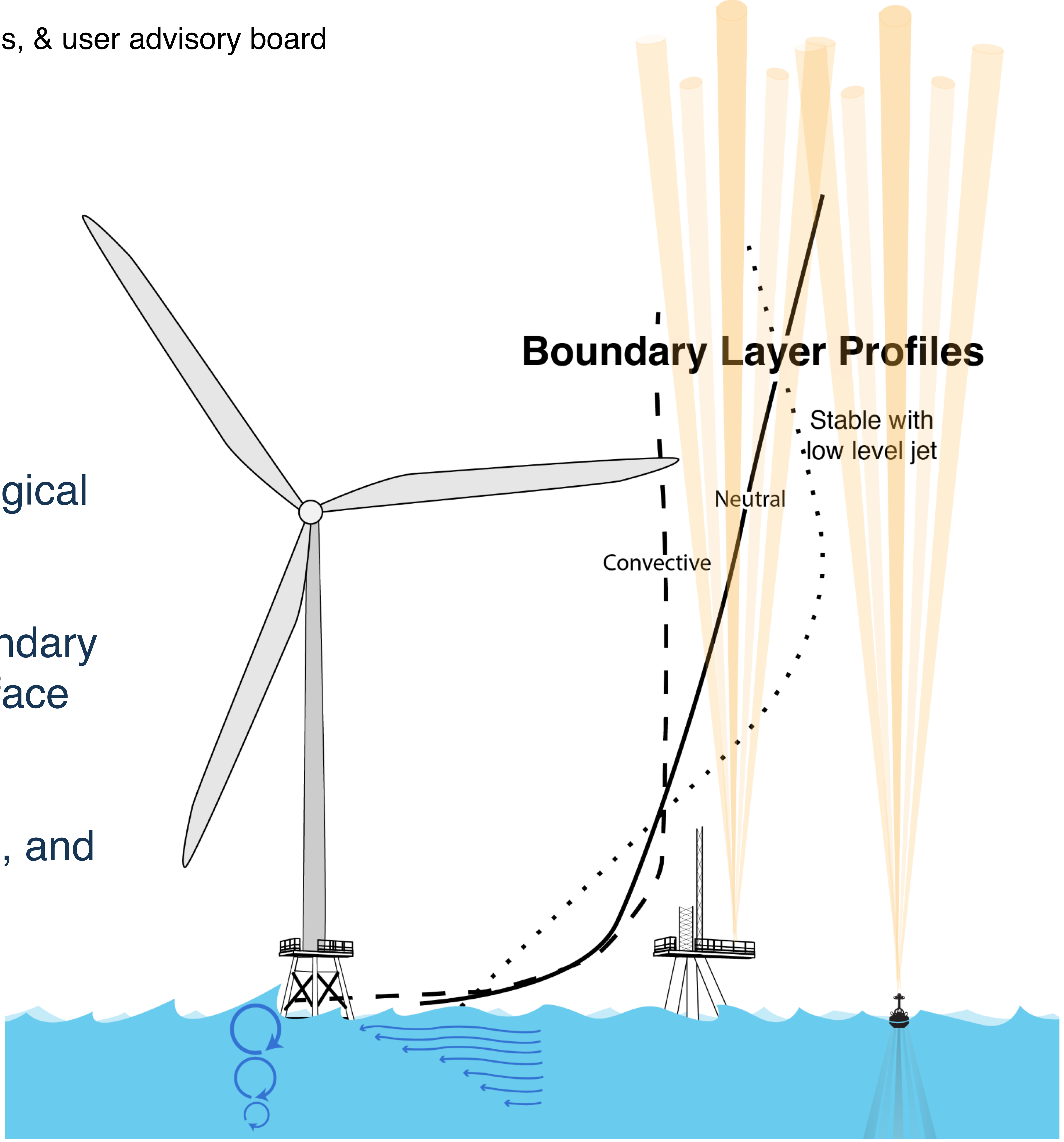
Offshore Wind requires accurate characterization of the resource and realistic, high resolution energy forecasts on time scales of minutes.

Goals:

Improve understanding of mesoscale and smaller meteorological and oceanographic processes that affect the wind resource.

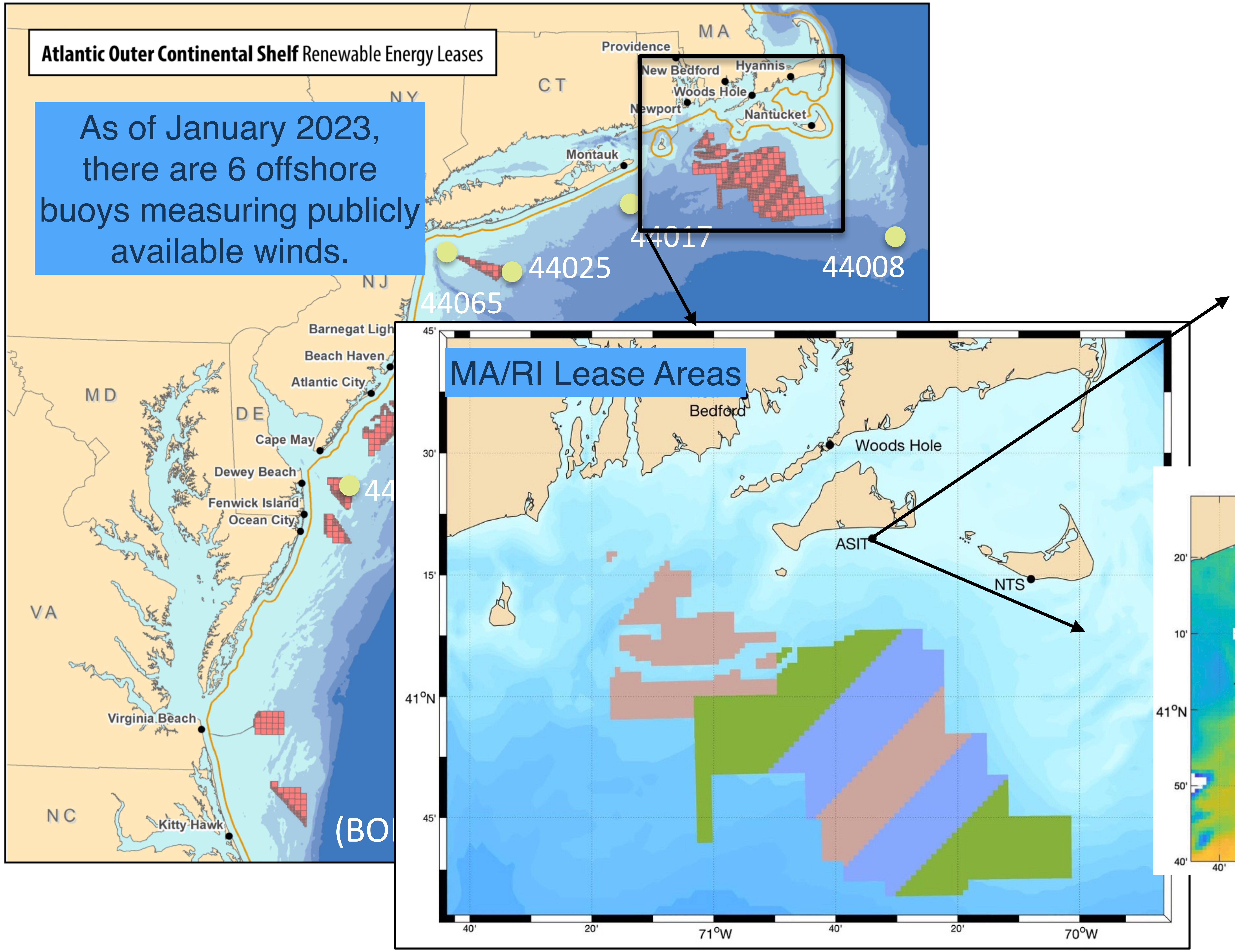
Improve understanding of the atmospheric and oceanic boundary layers and their interactions through the wave-mediated surface

Evaluate fully coupled wave, wind, and ocean models, and improved model parameterizations of small-scale processes, and industry-specific applications.

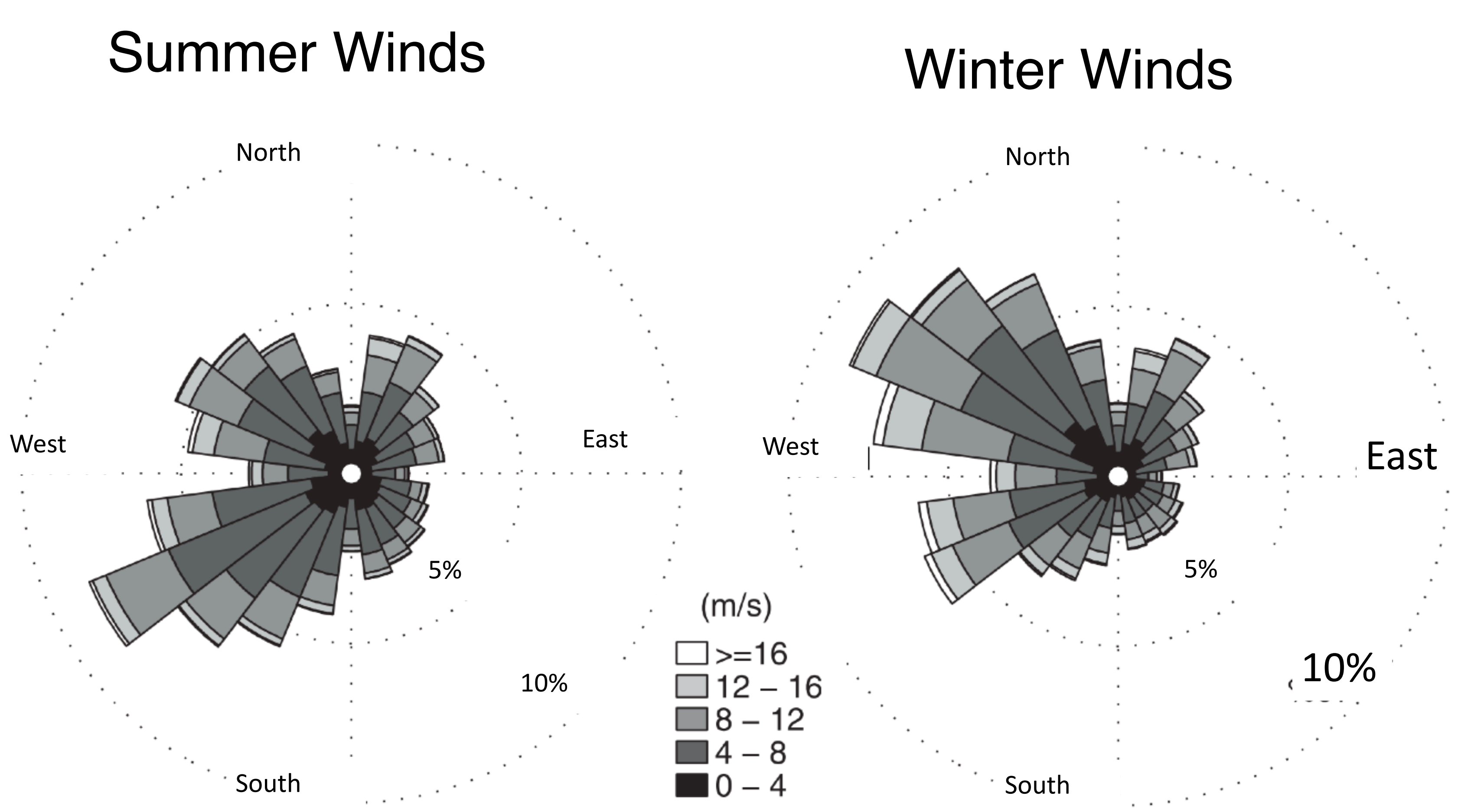


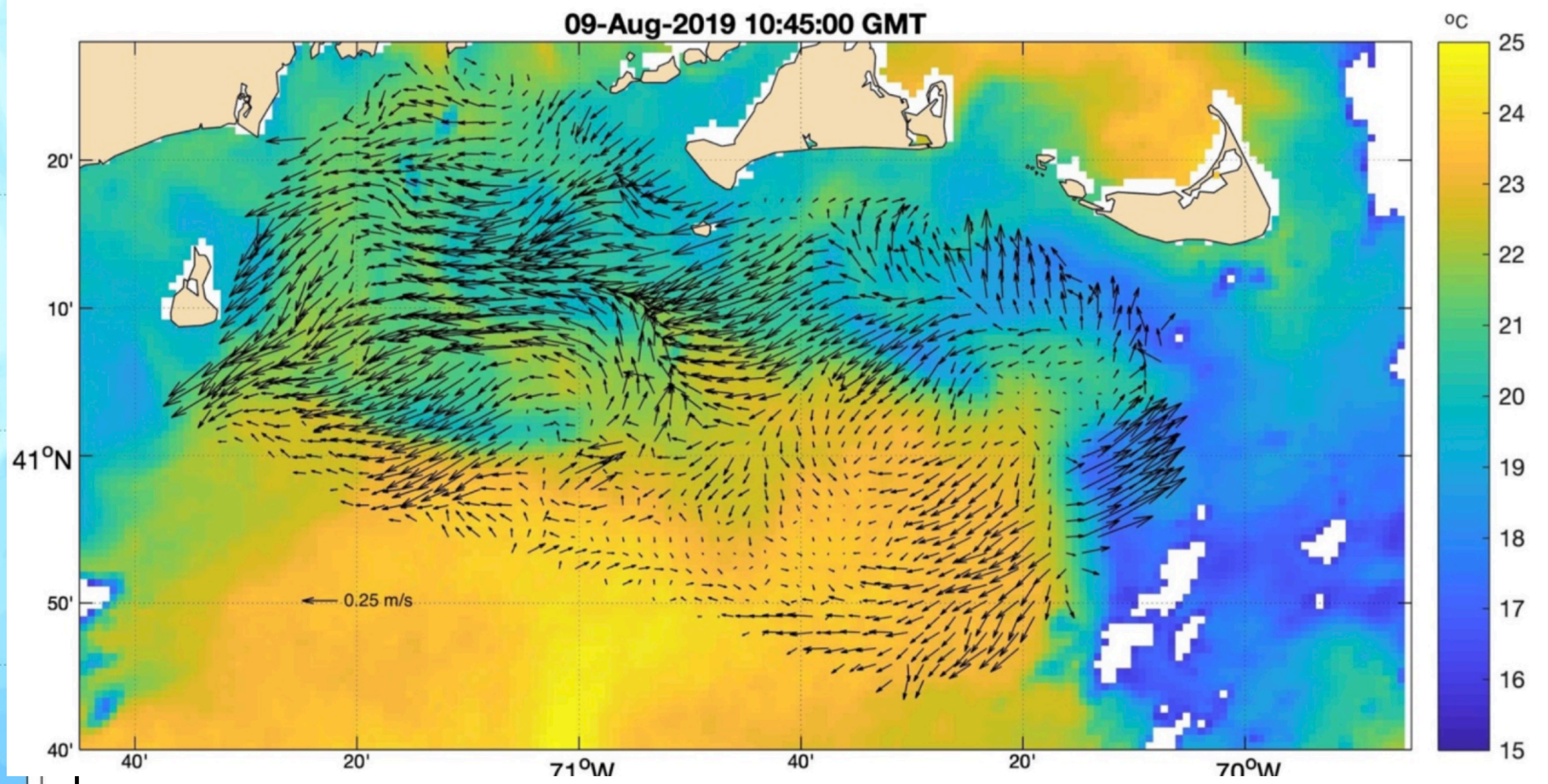
https://www2.whoi.edu/site/wfip3/

WFIP3 focus: The New England Shelf including MA/RI wind energy lease areas



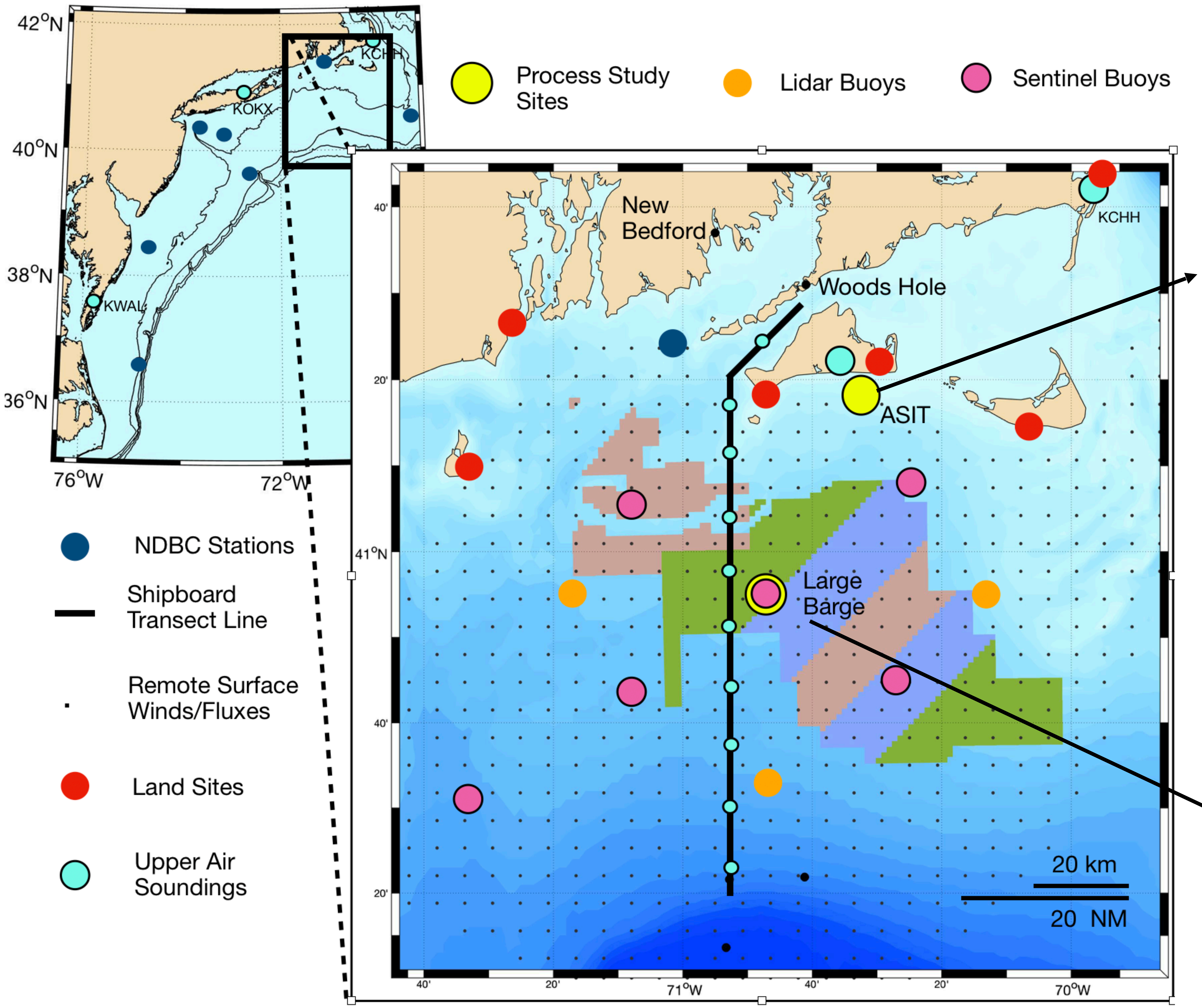
Strong seasonal changes in boundary layer winds and stability



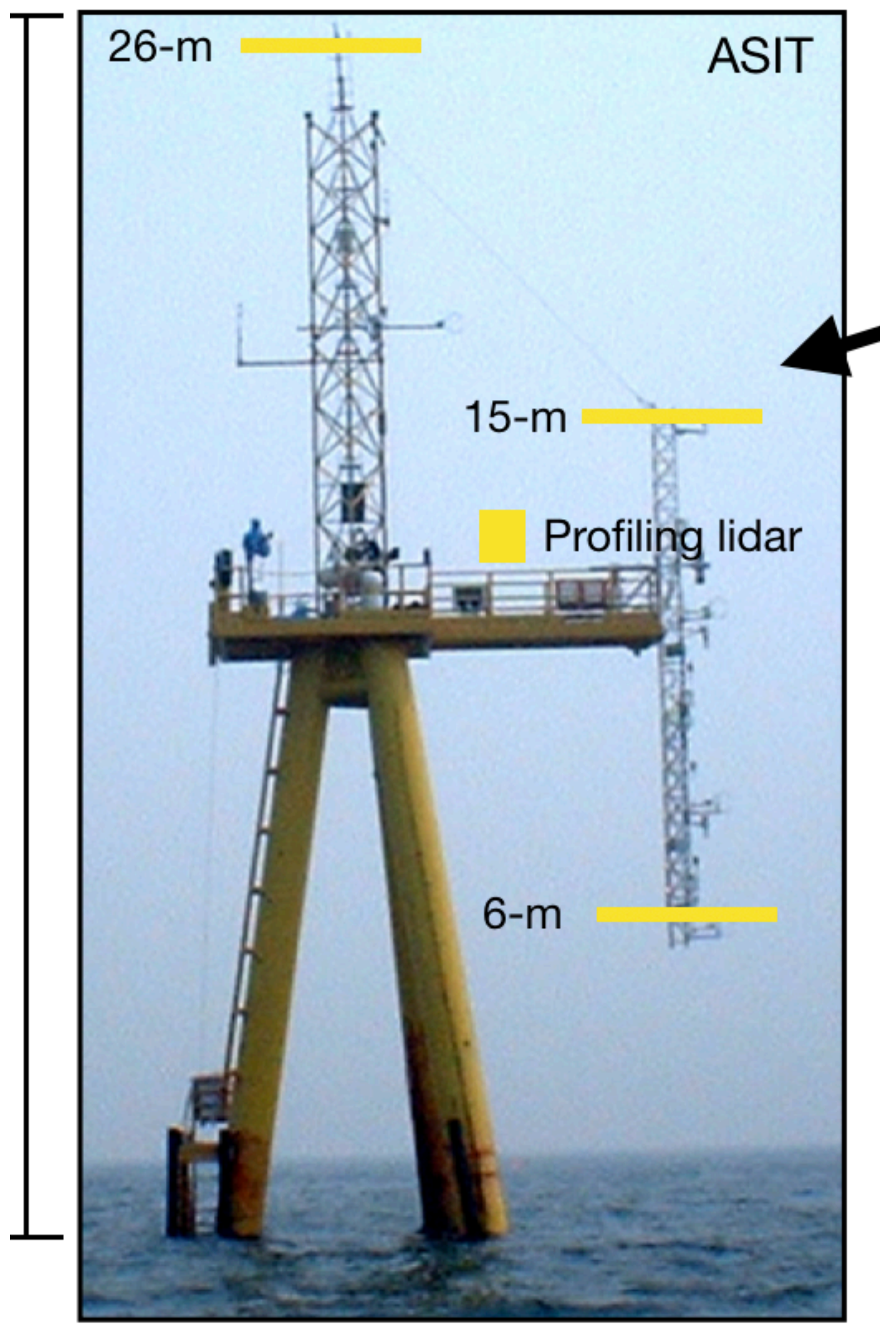


Strong spatial gradients in ocean properties and dynamics

WFIP3 Field Deployment Plan (2024)

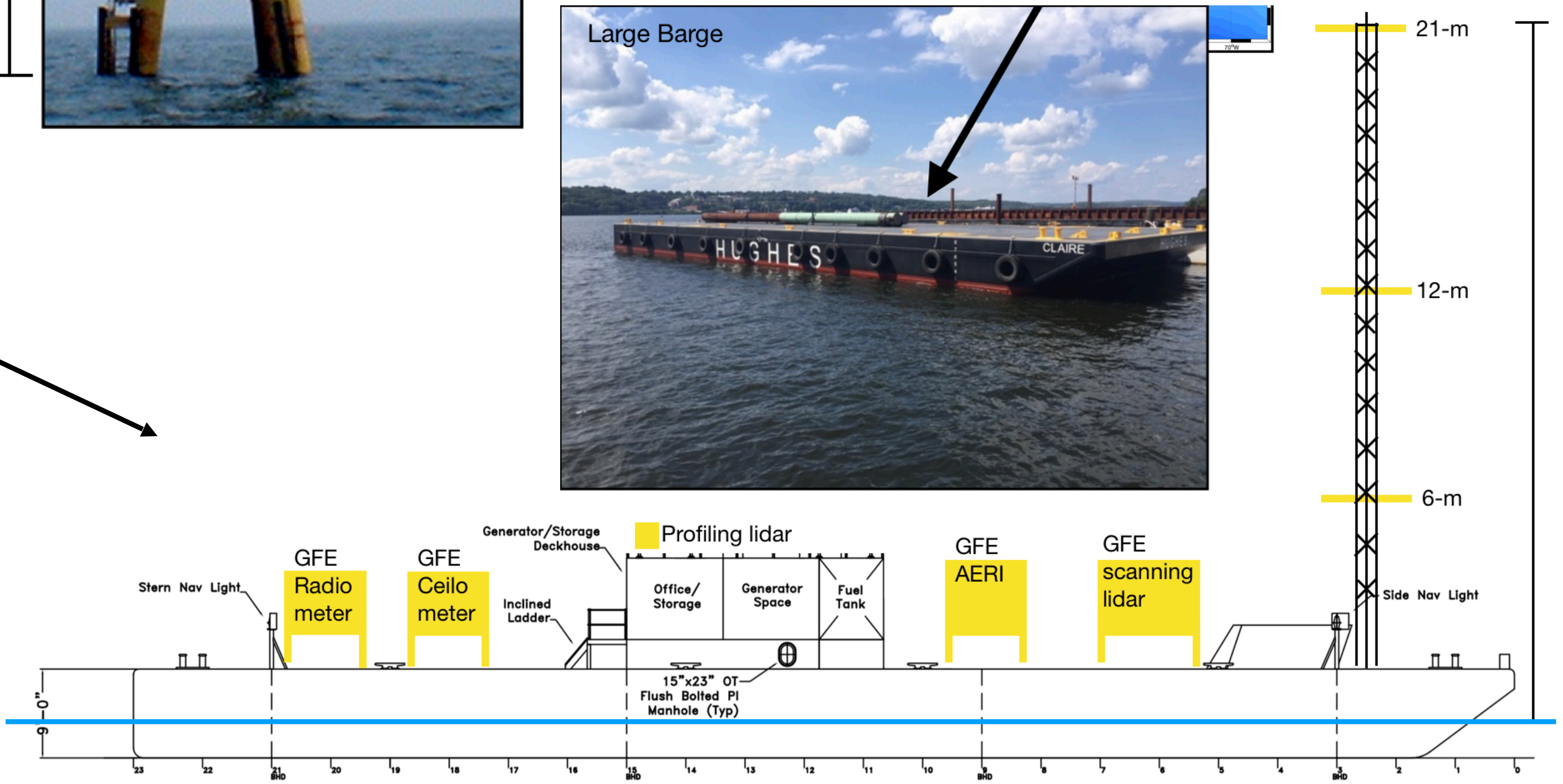


WHOI's Air-Sea Interaction Tower (ASIT)



DOE lidar buoy

purpose deployed large barge



WFIP3 Modeling Elements

Observations → Modeling Improvements → Industry Products

<u>Modeling goals:</u>

- Improve the planetary boundary layer (PBL) and surface-layer parameterizations used in mesoscale WRF and WRF-LES.
- **Incorporate ocean dynamics via a fully coupled atmospheric/wave/ocean modeling system**.
- Coupled mesoscale-microscale simulations, wind plant parameterizations, etc.

<u>Industry product goals:</u>

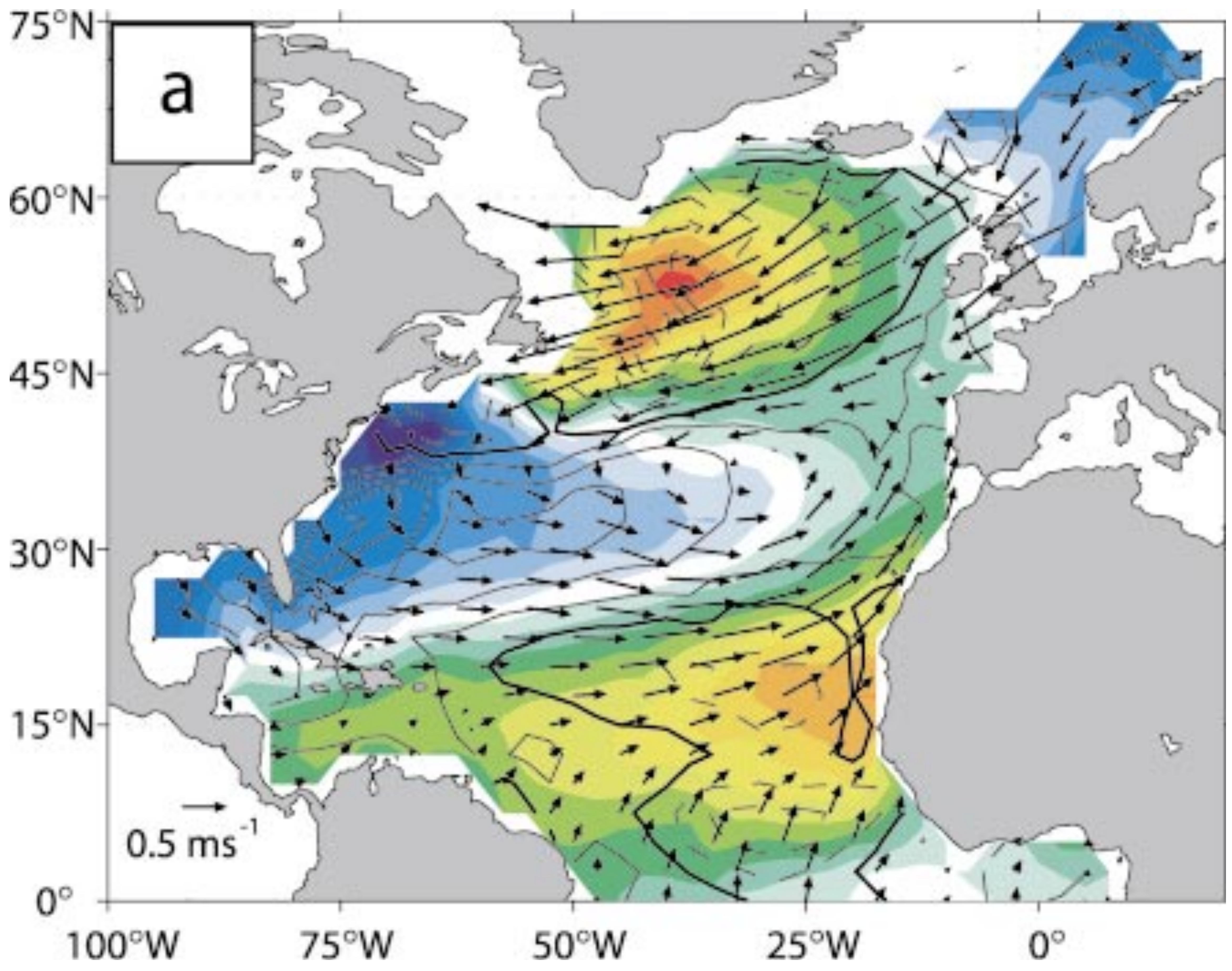
- Quantify which modeling developments (coupled modeling, improved PBL, improved surface layer, etc.) yield the largest impact on reducing the LCOE for offshore wind in the U.S.
- Use observational and modeling results to hone resource characterization efforts
- Industry application development and testing.

https://www2.whoi.edu/site/wfip3/

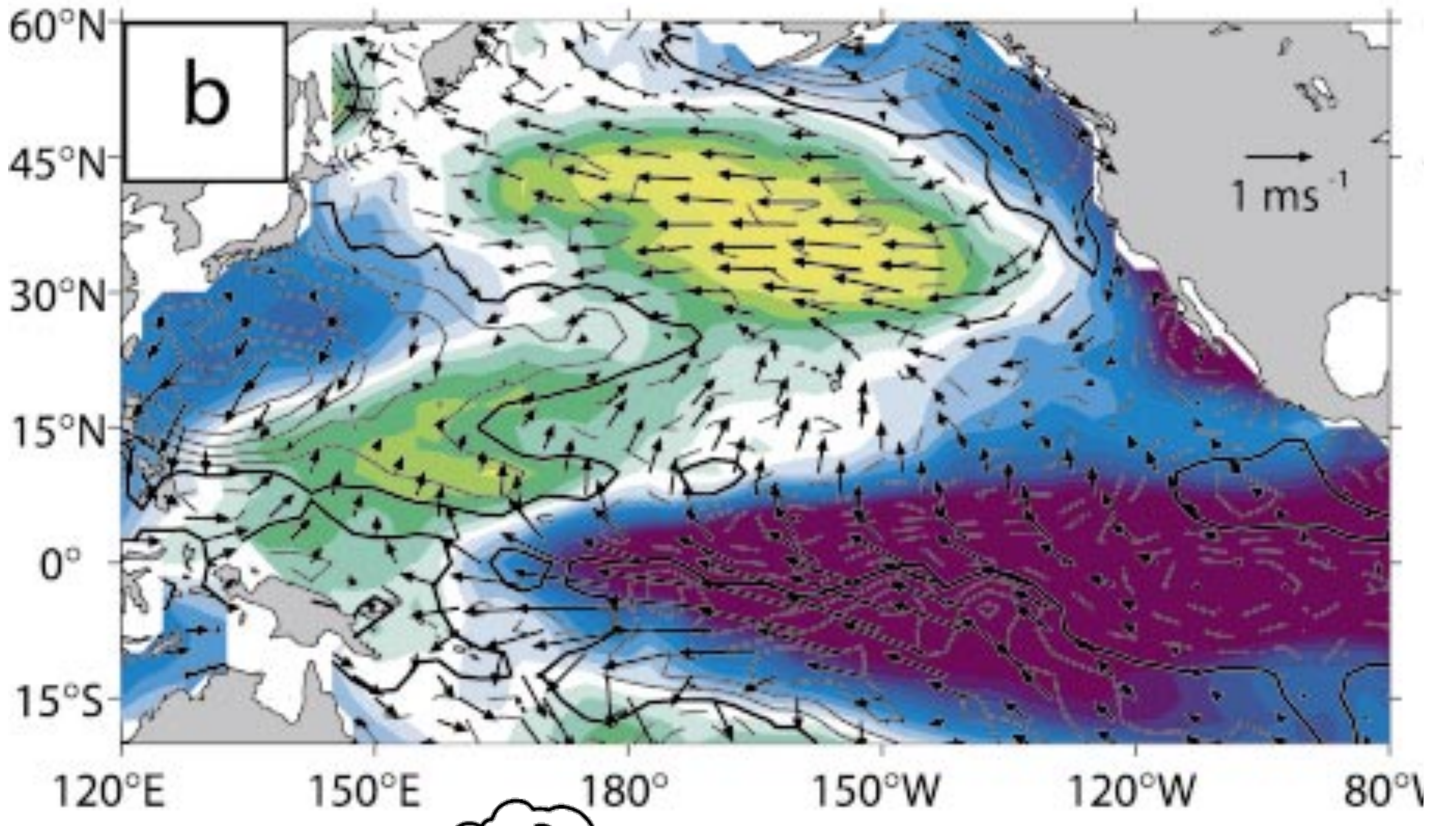
Ocean mesoscale air-sea-wave interactions

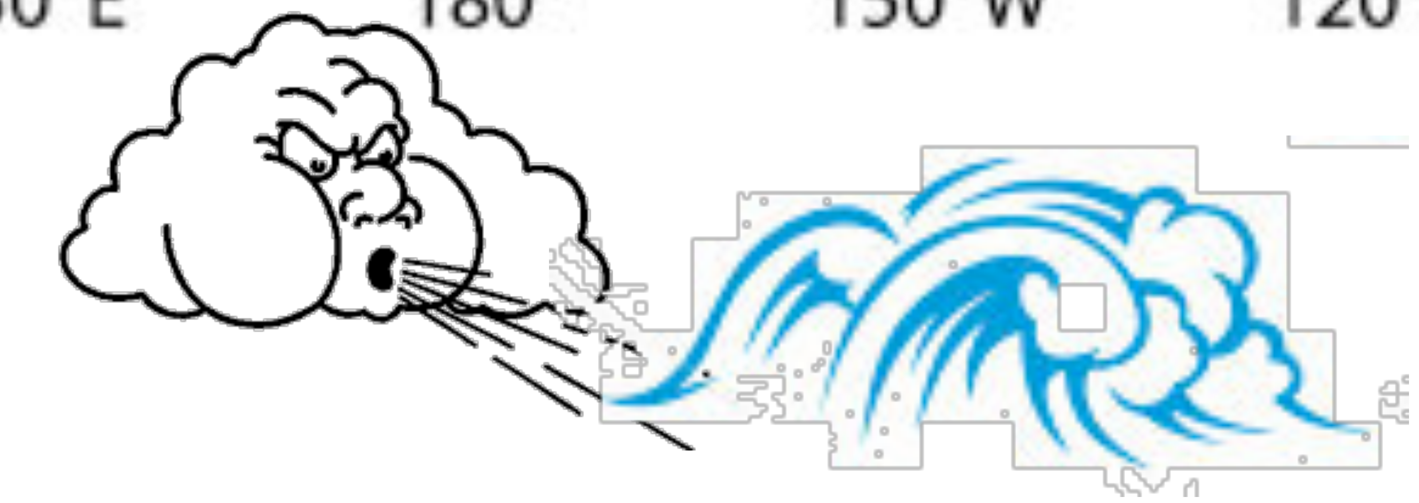
Wind-driven SST variability

North Atlantic Oscillation



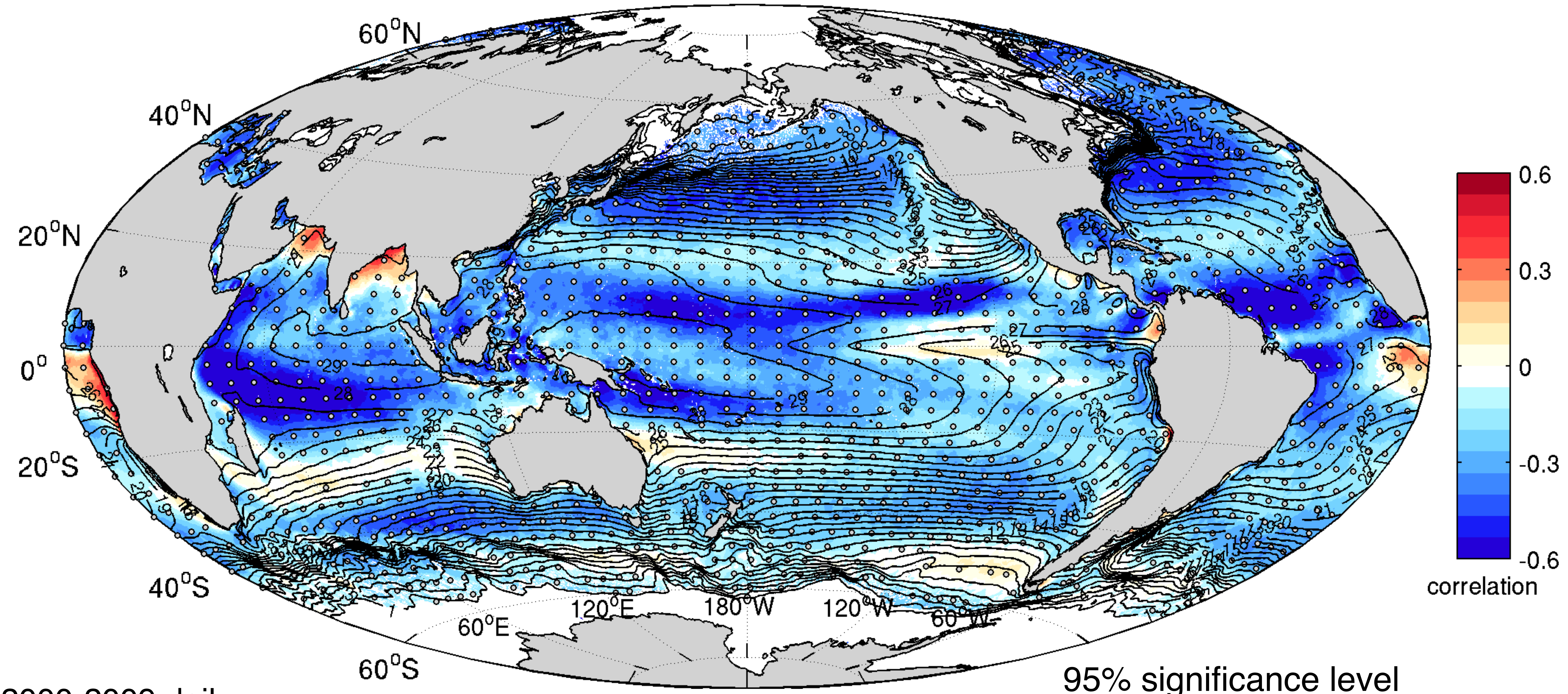
Pacific Decadal Oscillation





Kushnir et al. 2002. JCLI

Daily correlation between wind speed and SST

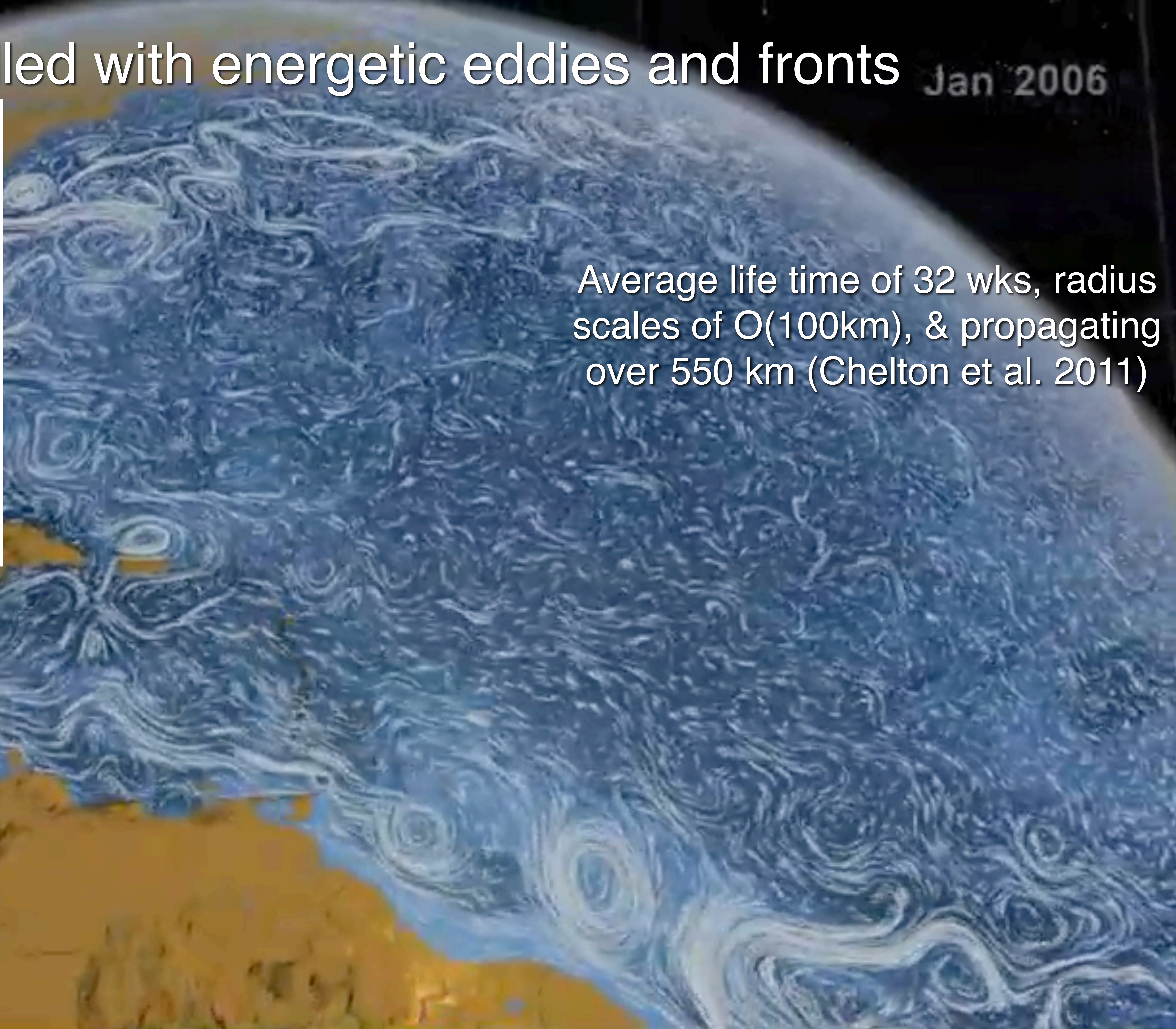


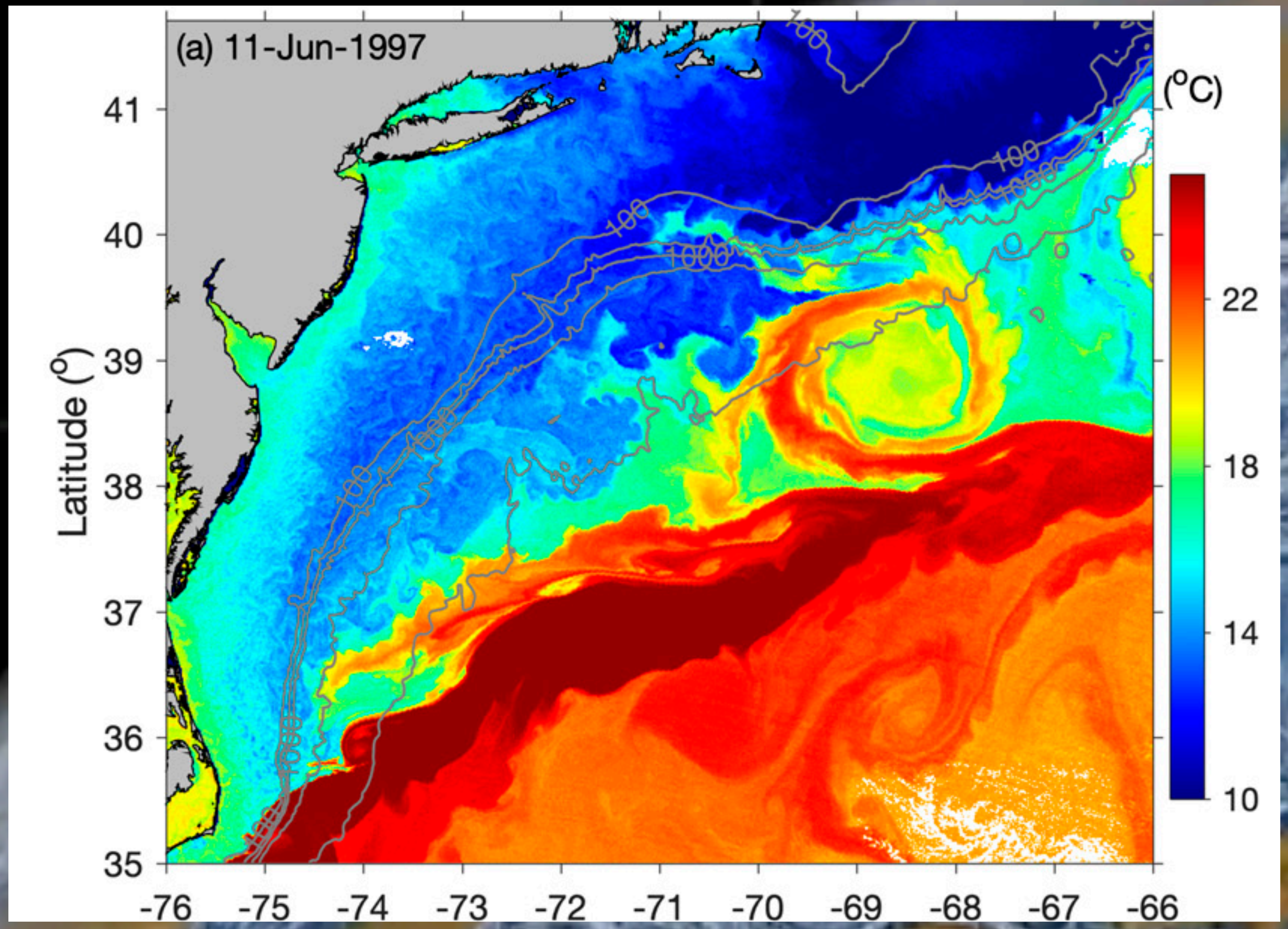
2000-2009 daily
QuikSCAT WS
NOAA-OI SST

Higher (lower) wind speed ➔ colder (warmer) SST

Negative correlation: Oceanic response to the atmosphere

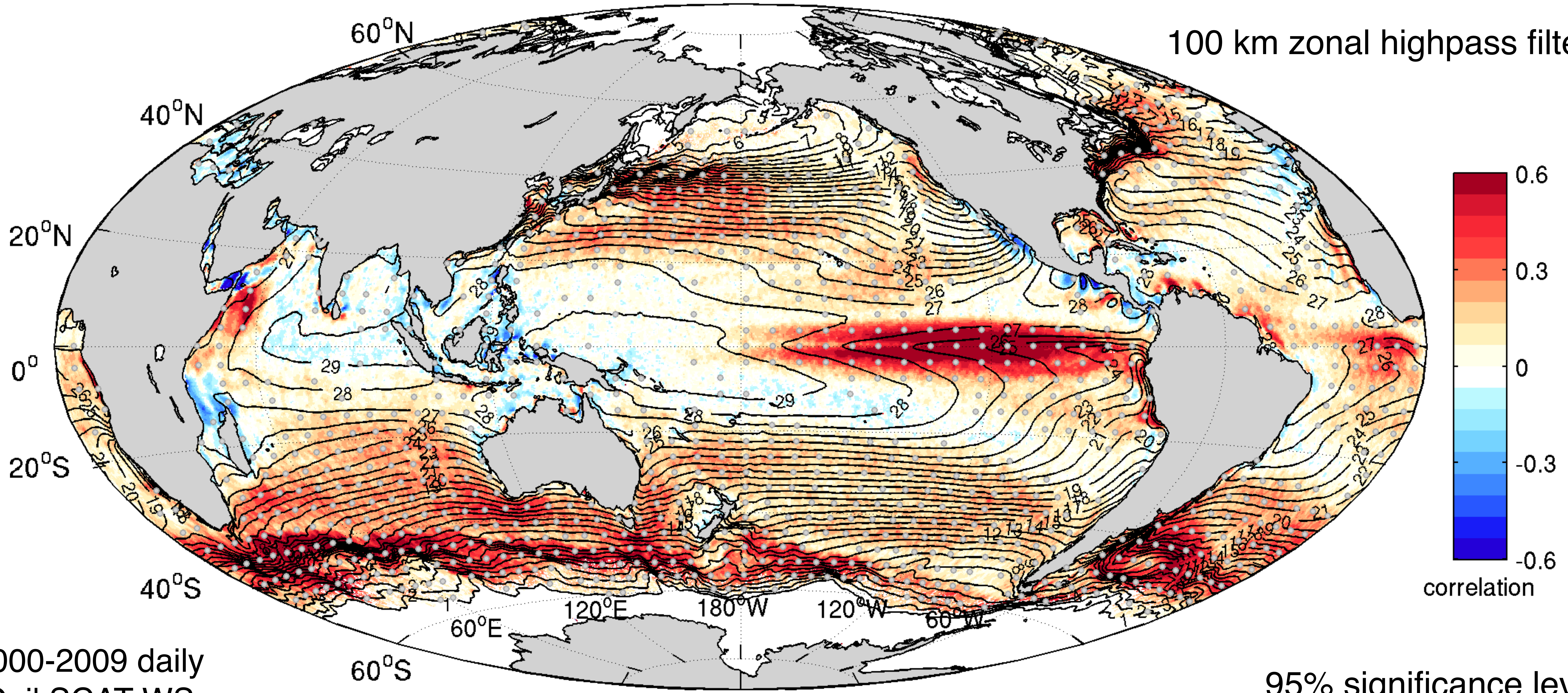
The ocean is filled with energetic eddies and fronts





Average life time of 32 wks, radius scales of O(100km), & propagating over 550 km (Chelton et al. 2011)

Daily correlation between high-pass filtered wind speeds and SSTs



100 km zonal highpass filter

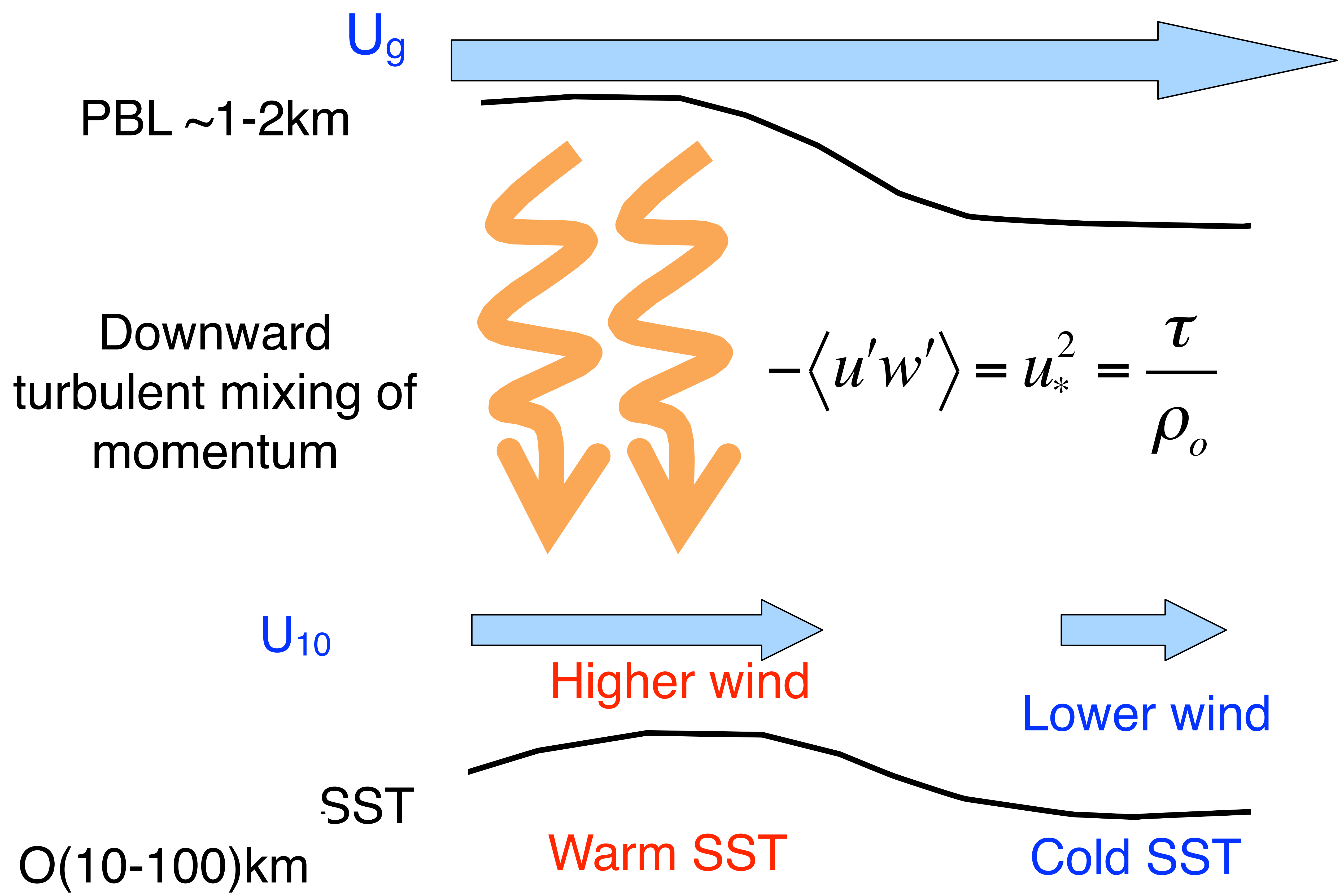
2000-2009 daily
QuikSCAT WS
NOAA-OI SST

95% significance level

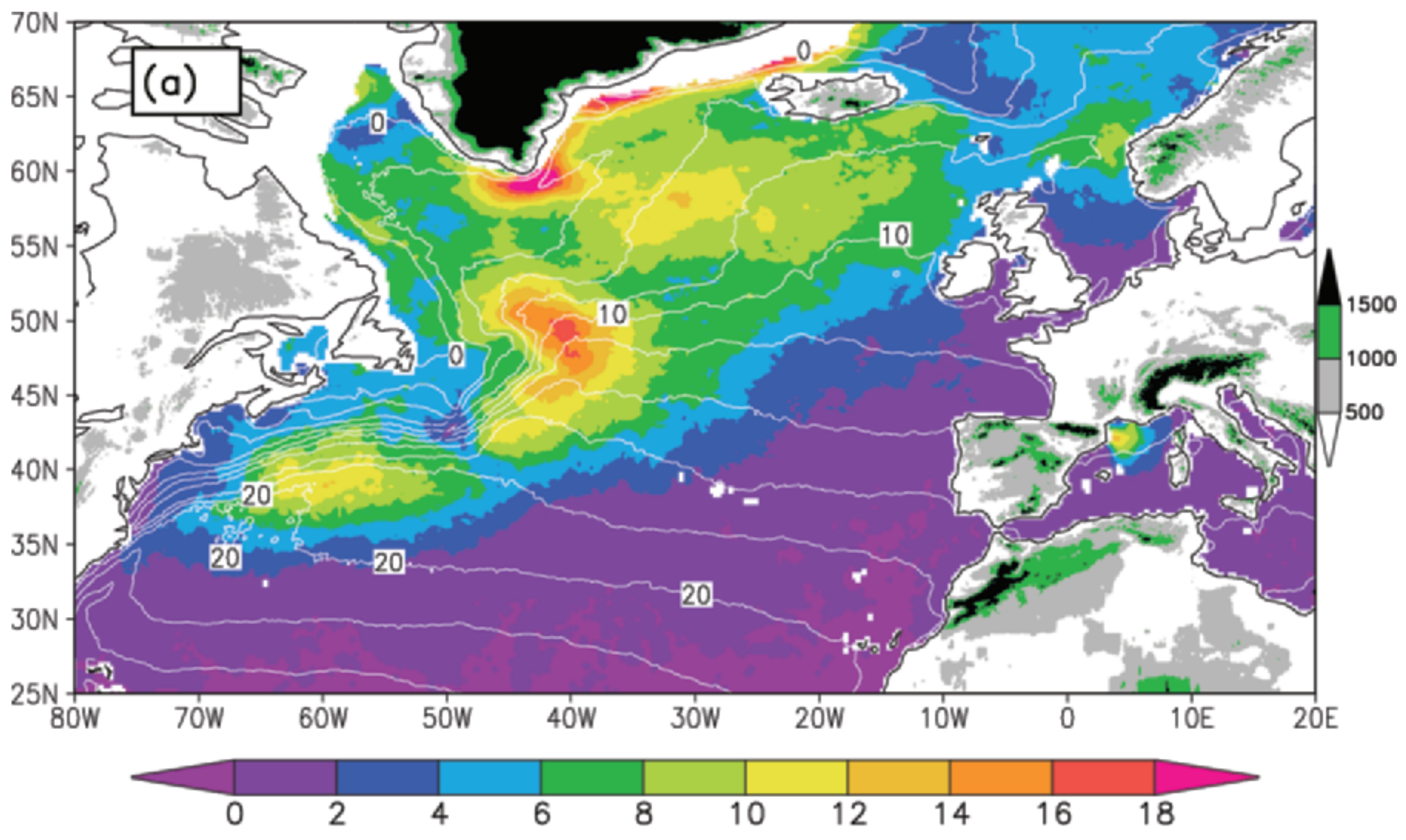
Oceanic forcing of the atmosphere on frontal and mesoscales.

Seo 2017 JCLI

MABL stratification and turbulent mixing



High-wind occurrence climatology



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

Imprints of warm SST in high wind frequency

Wallace et al. (1998)

Sampe and Xie (2007)

Climatological impacts of SST fronts on extratropical storm tracks

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

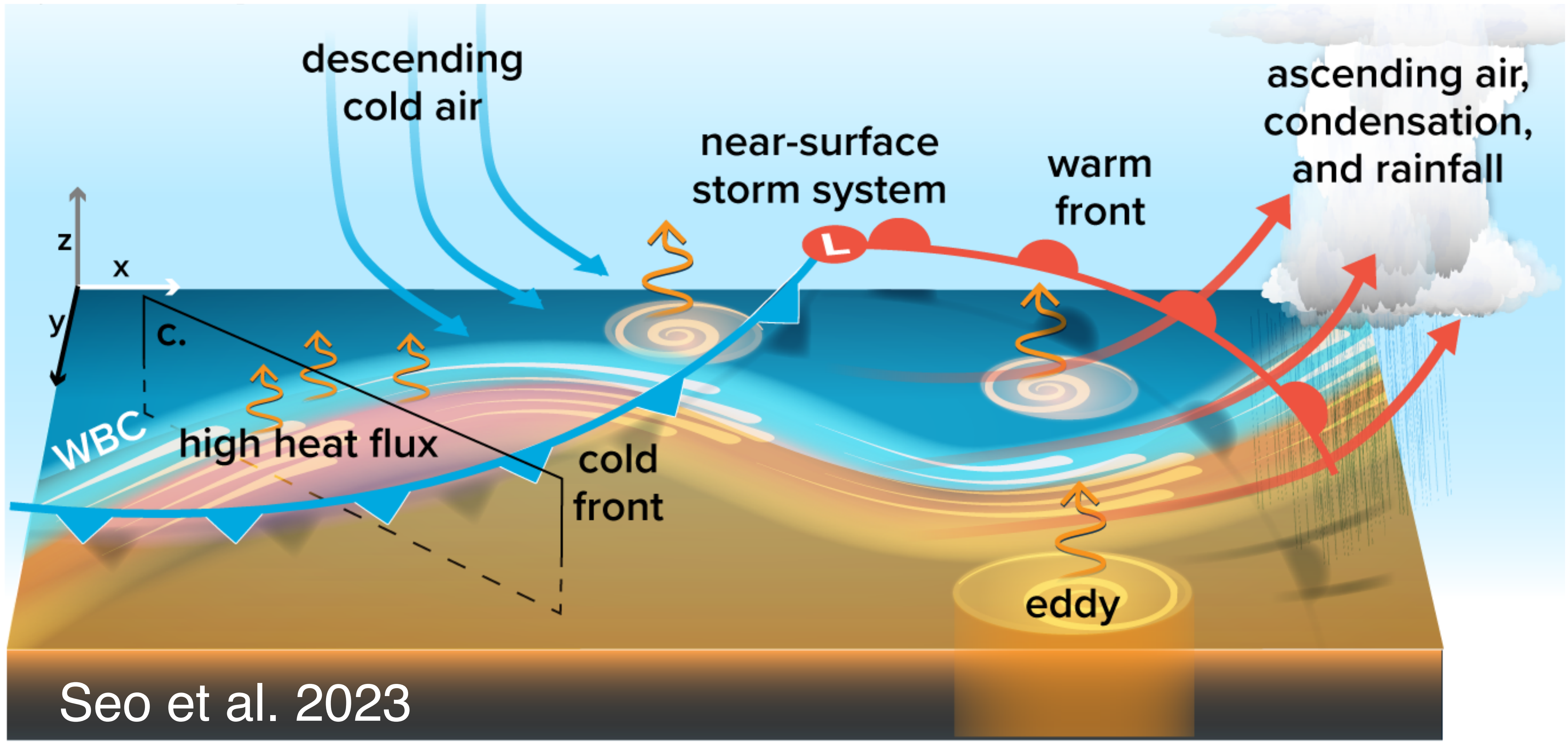
The growth rate of the extratropical cyclones scales with low-level baroclinicity

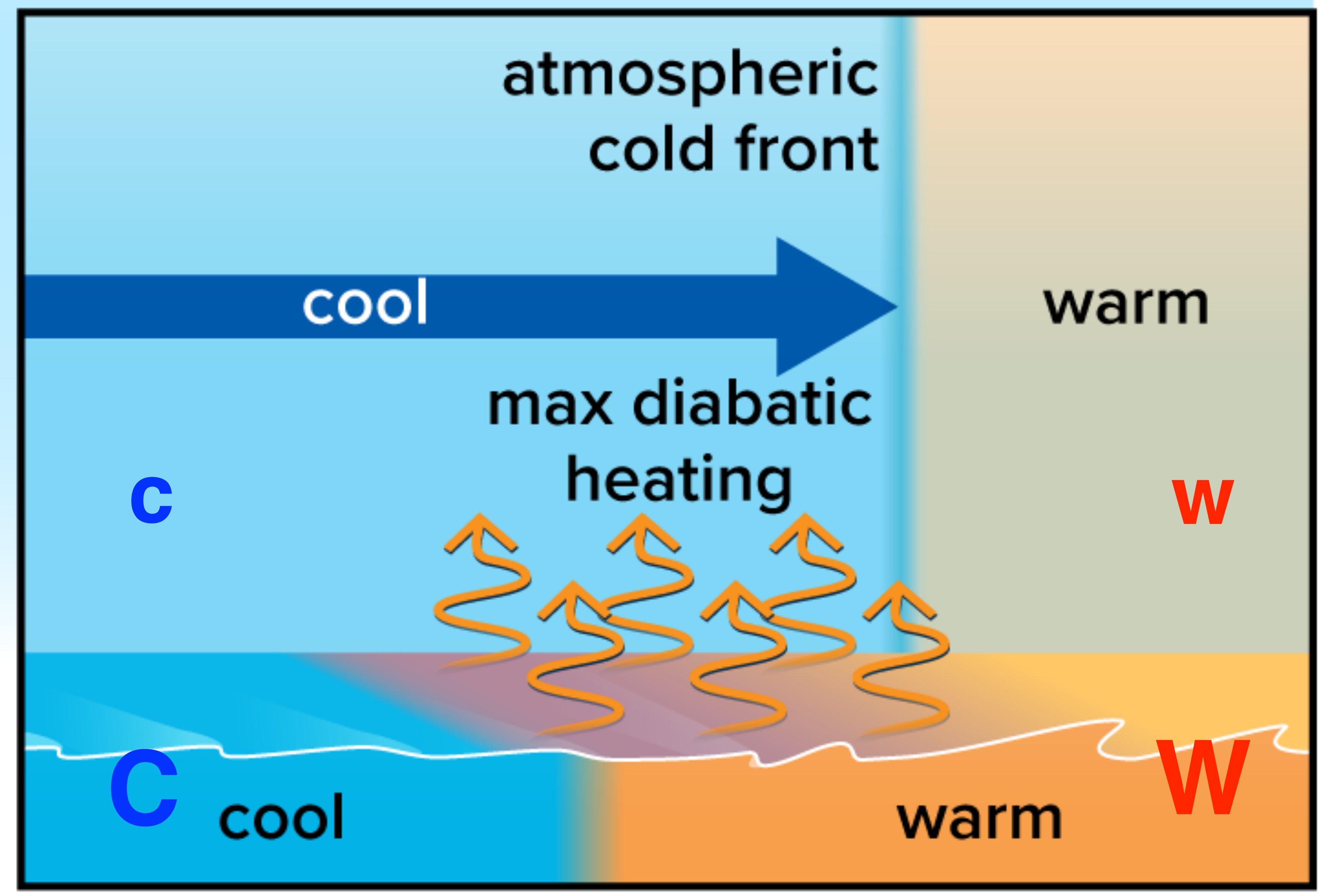
Atmospheric baroclinicity is maintained by the large-scale oceanic fronts near the WBCs

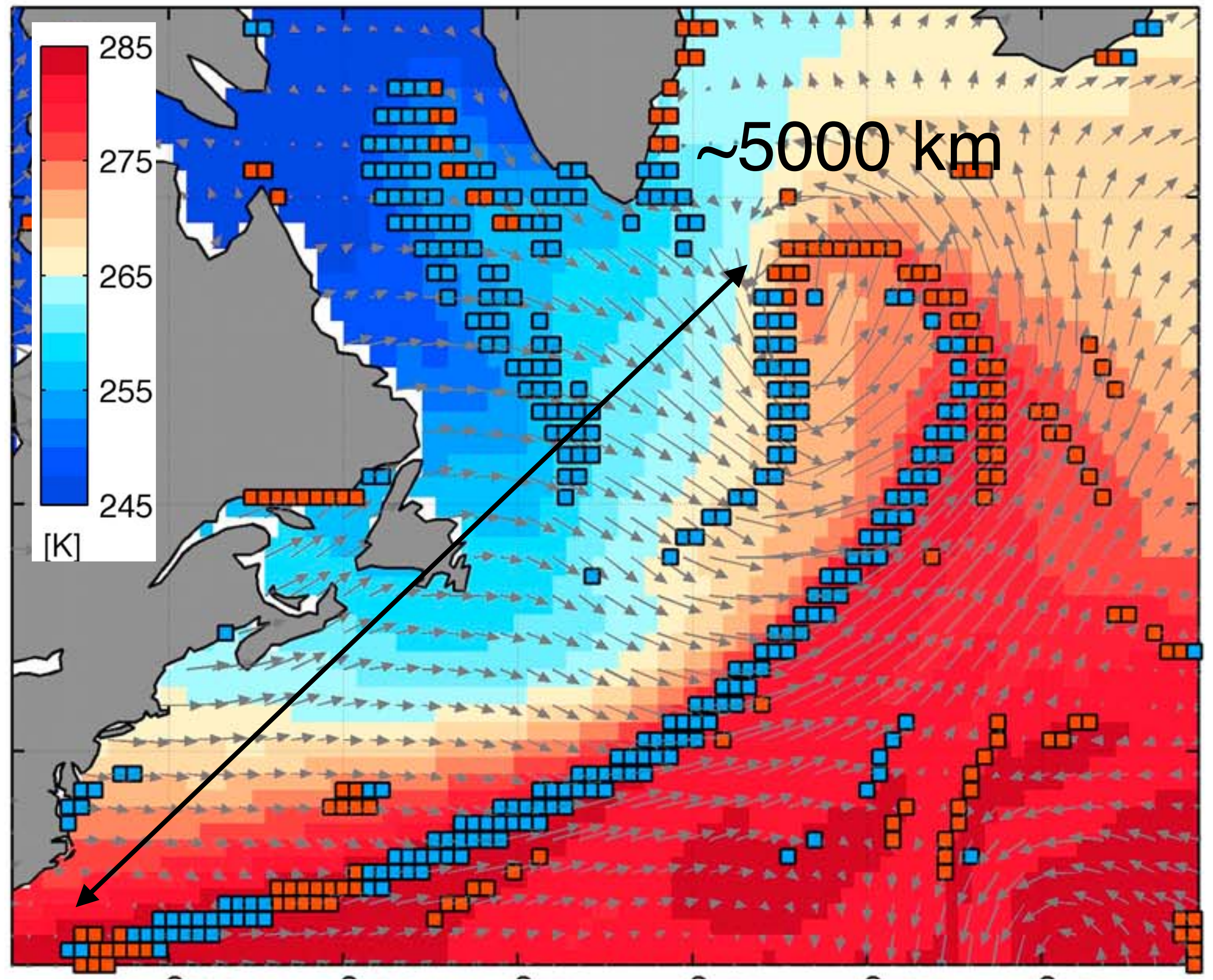
Synoptic-scale air-sea interactions: atmospheric fronts over SST fronts

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

many 1000 km scales





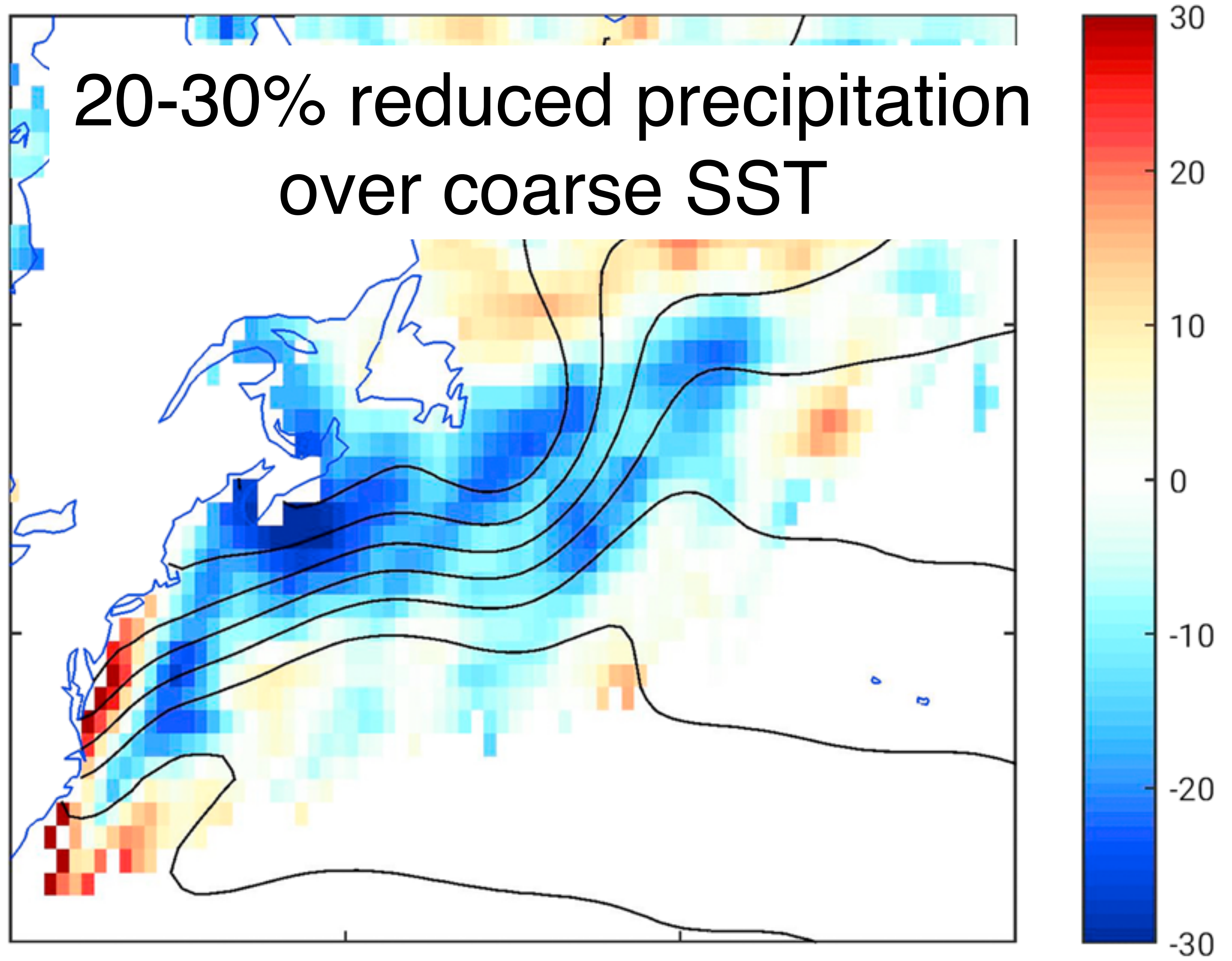


Atmospheric fronts account for ~90% of the wintertime precipitation

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

Precipitation difference between high vs low SST resolutions in ERA-Interim.

Parfitt et al. (2017)



Parameterizing surface wave impacts on wind stress

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

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

$$C_D \cong \left[\frac{\kappa}{\ln(z/z_0) - \psi_m(z/L)} \right]^2$$

$$z_0 = z_0^{smooth} + z_0^{rough}$$

1. Wind Speed Dependent Formulation (WSDF)

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

Charnock coefficient

2. Wave-Based Formulation (WBF)

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

inverse wave age

significant wave height

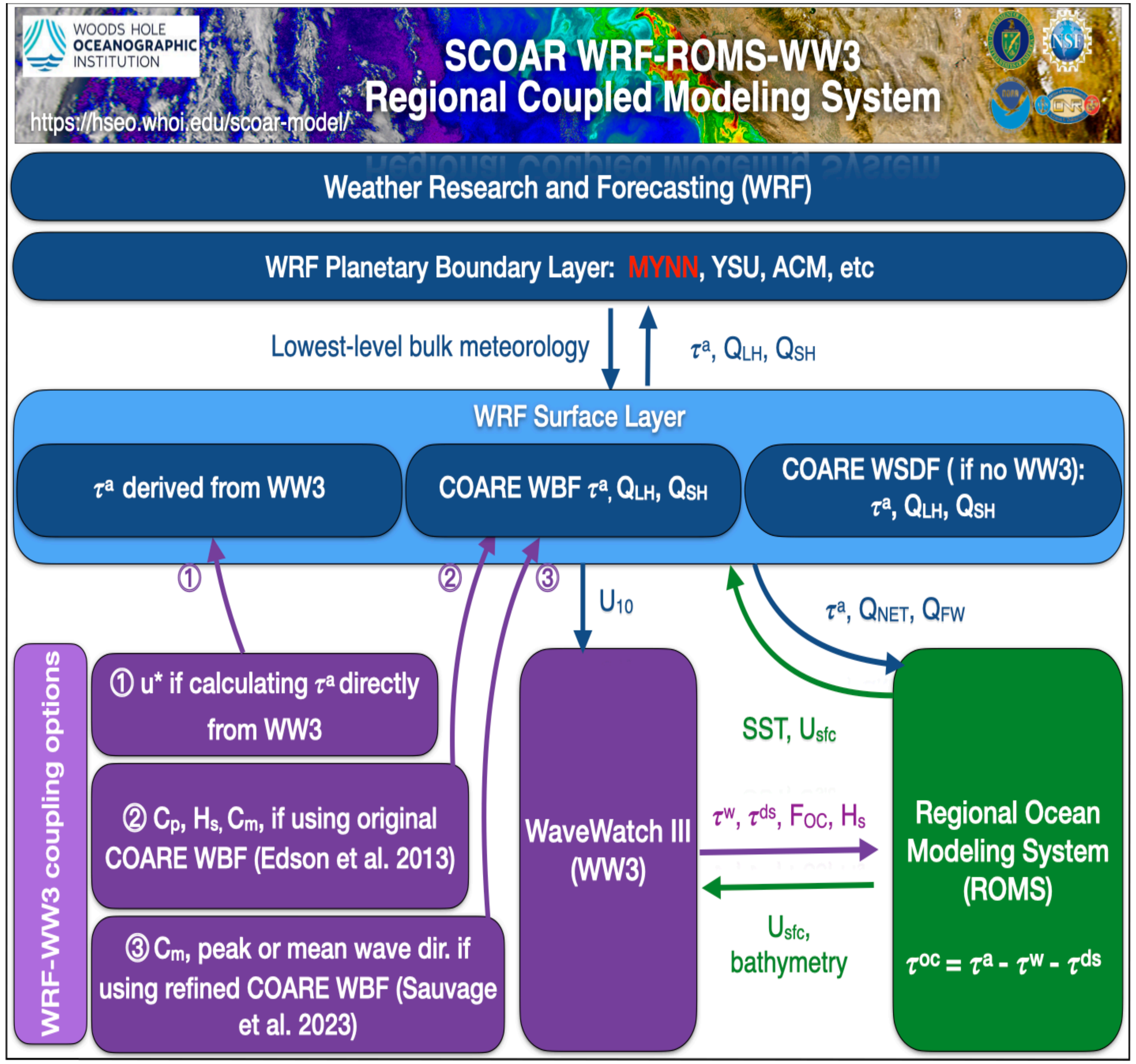
wave phase speed $C_p = g*(\mathbf{T_p}/2\pi)$

$\mathbf{T_p}$: 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.

SCOAR ocean-wave-atmosphere coupled modeling system



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

Seo et al. 2007, 2014; Sauvage et al. 2023

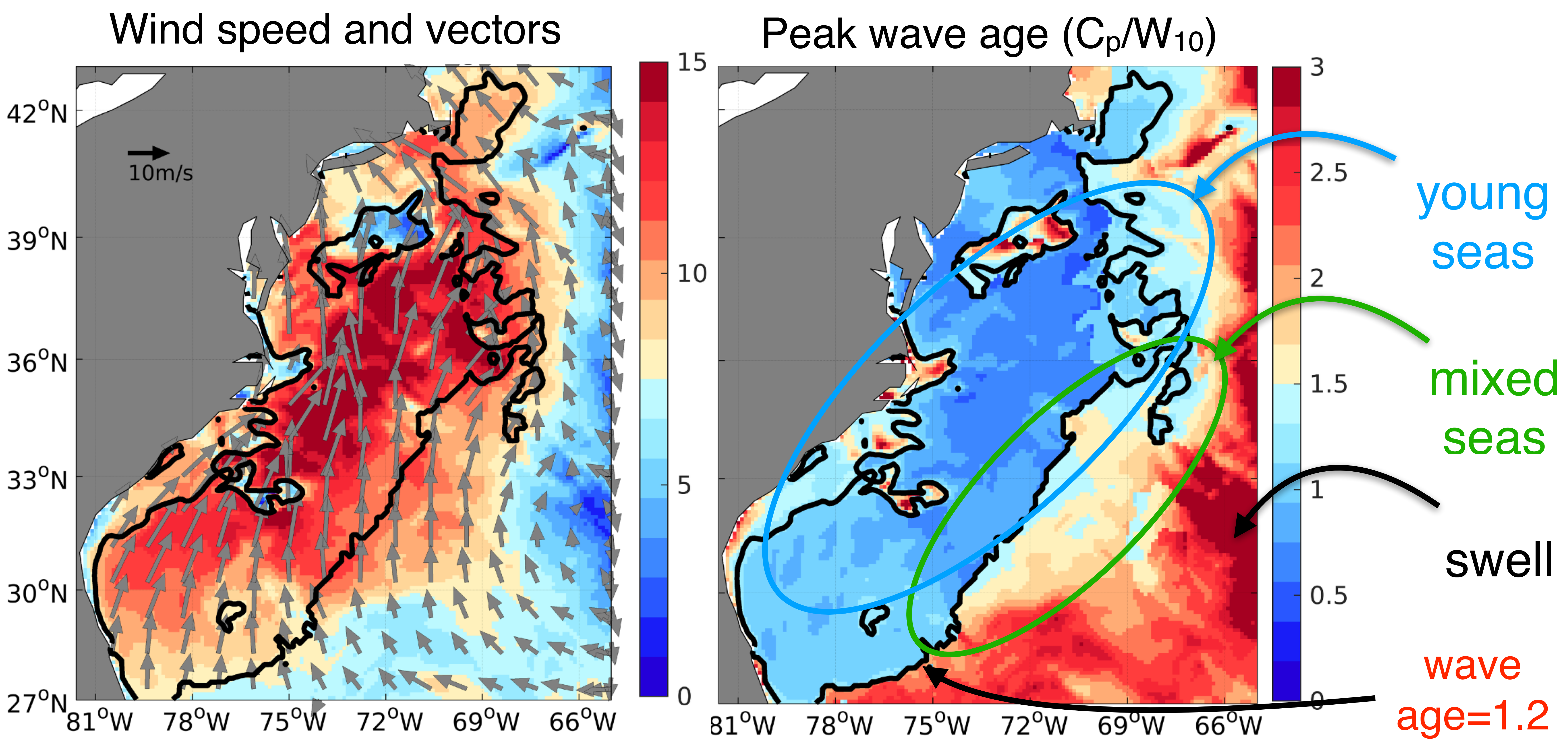
- A modeling tool to study the multi-scale nature of the ocean-atmosphere interactions and their climate implications
- The wave-coupling procedure is documented in Sauvage et al. (2023)

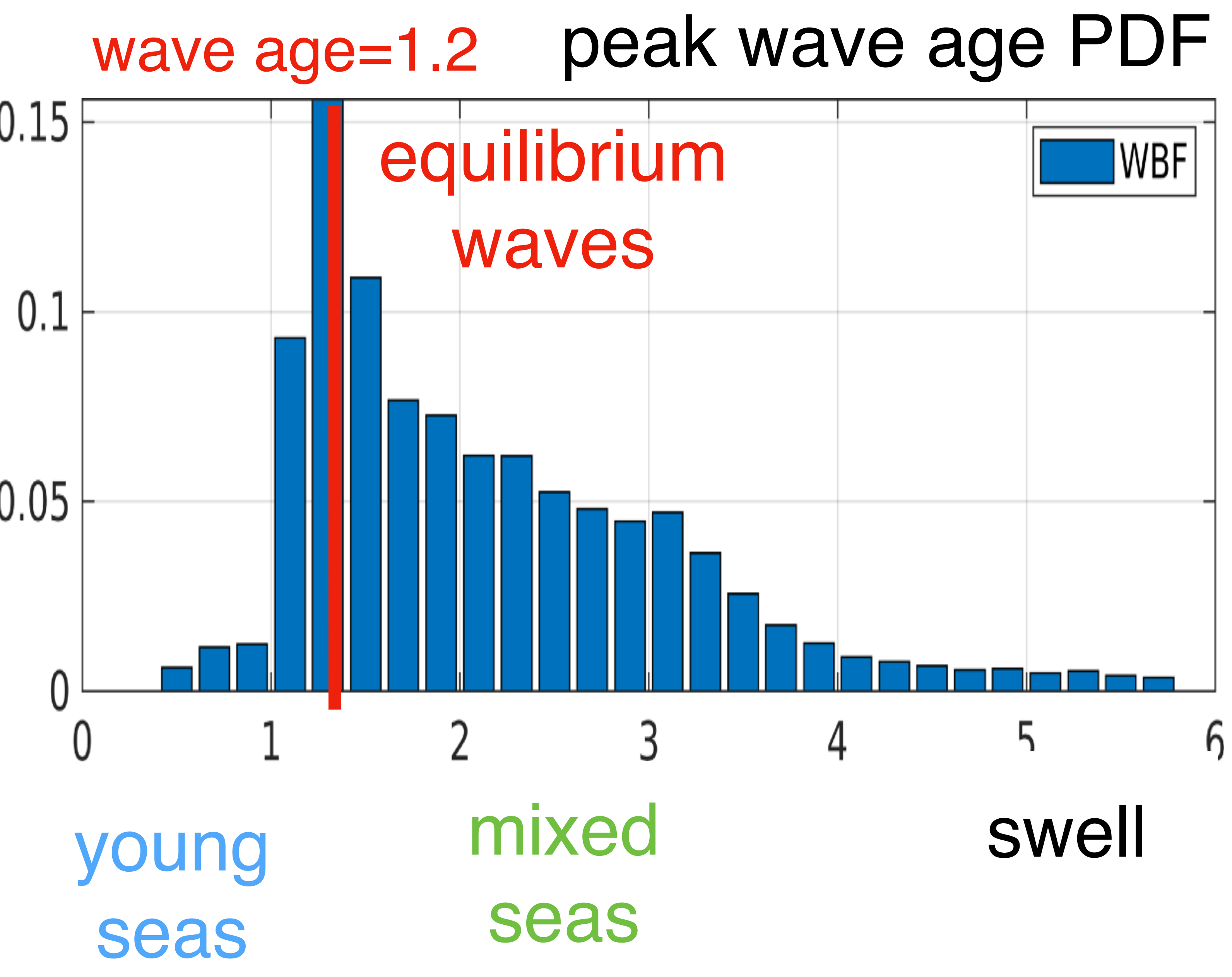
Experiments	Coupling	z0 in COARE3.5
WSDF	WRF-ROMS	wind speed only
WBF	WRF-ROMS-WW3 with default WBF	wave-based (T_p, H_s)
WBF_θ	WRF-ROMS-WW3 with *modified* WBF	vector wave stress (θ≠0)
WBF_T_m		with T_m instead of T_p

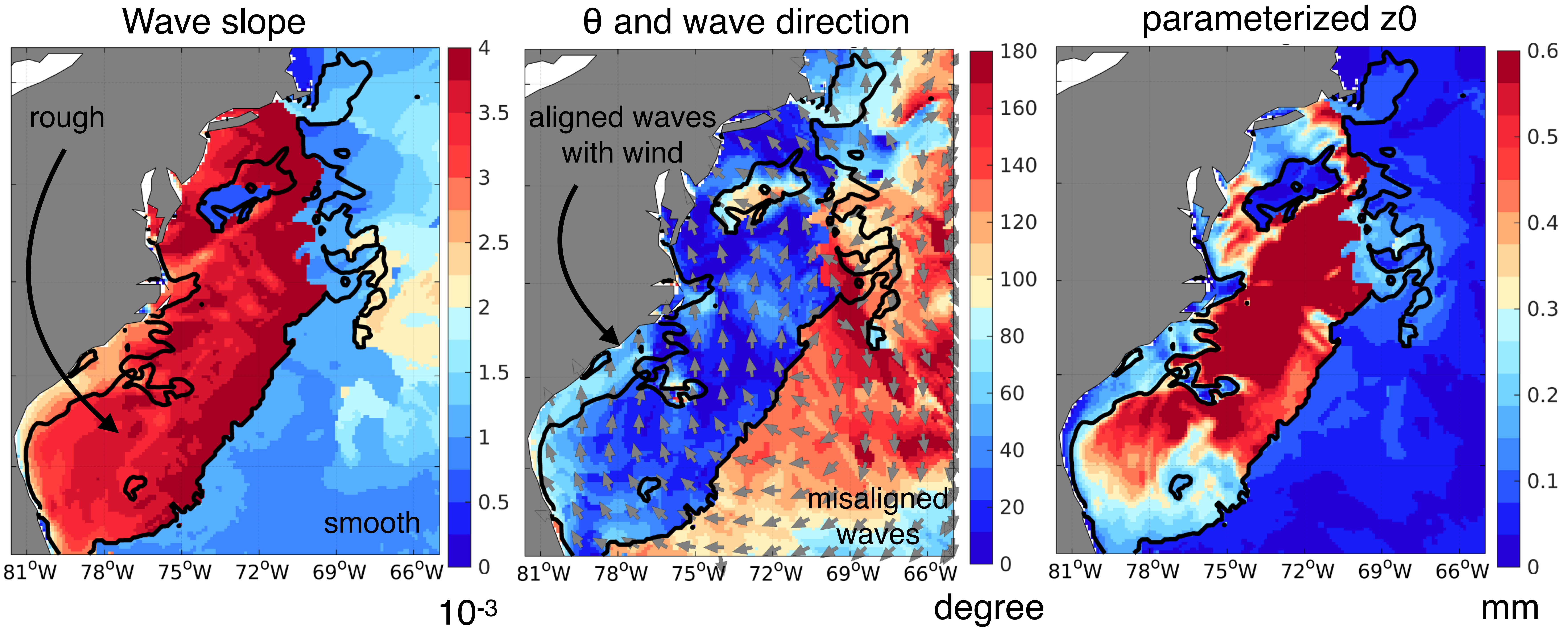
- 10 km resolutions with matching grids. All runs include tides, current-wind and SST-wind interactions, and breaking wave induced vertical mixing.

Case study: mixed sea states under a storm

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

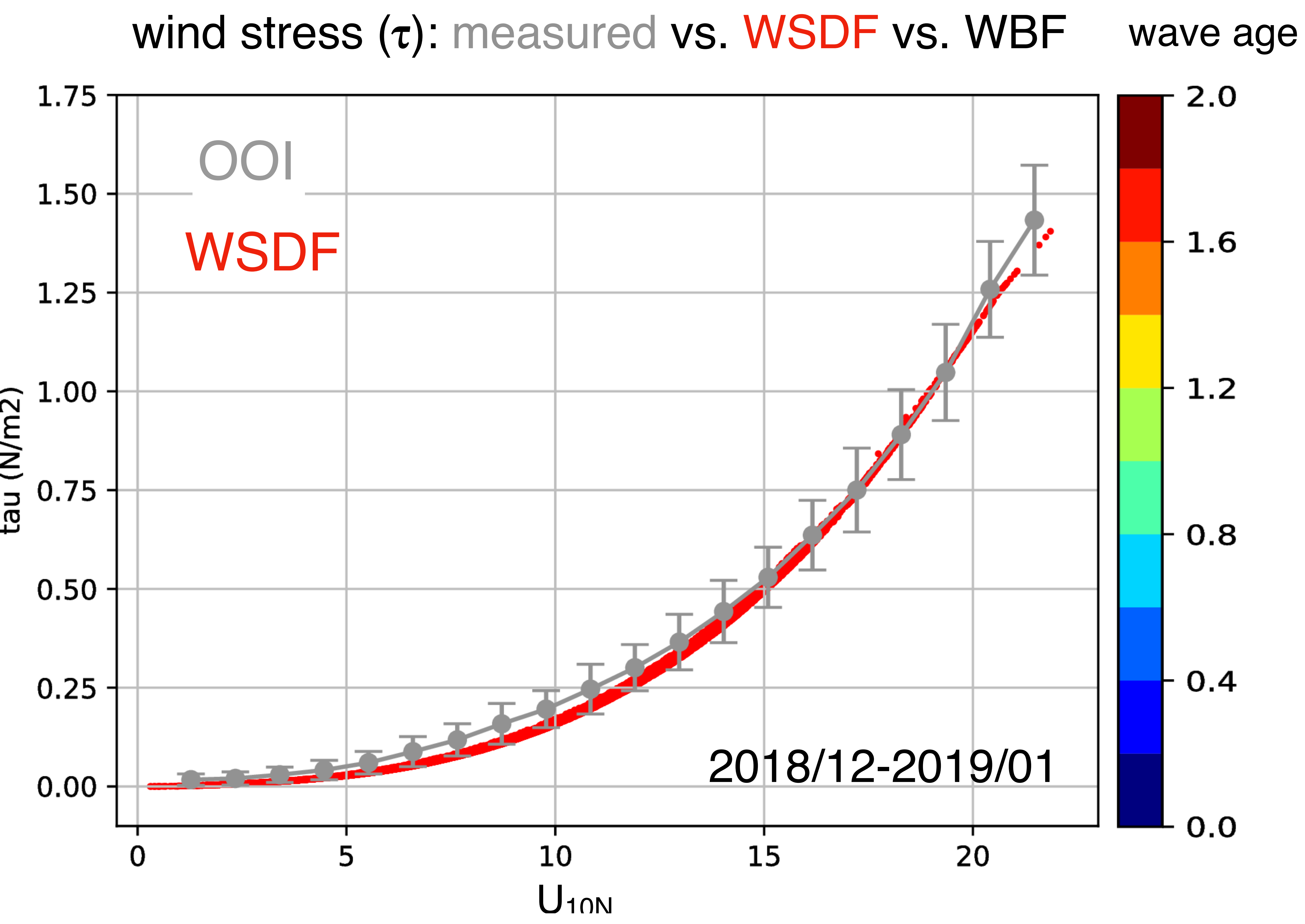


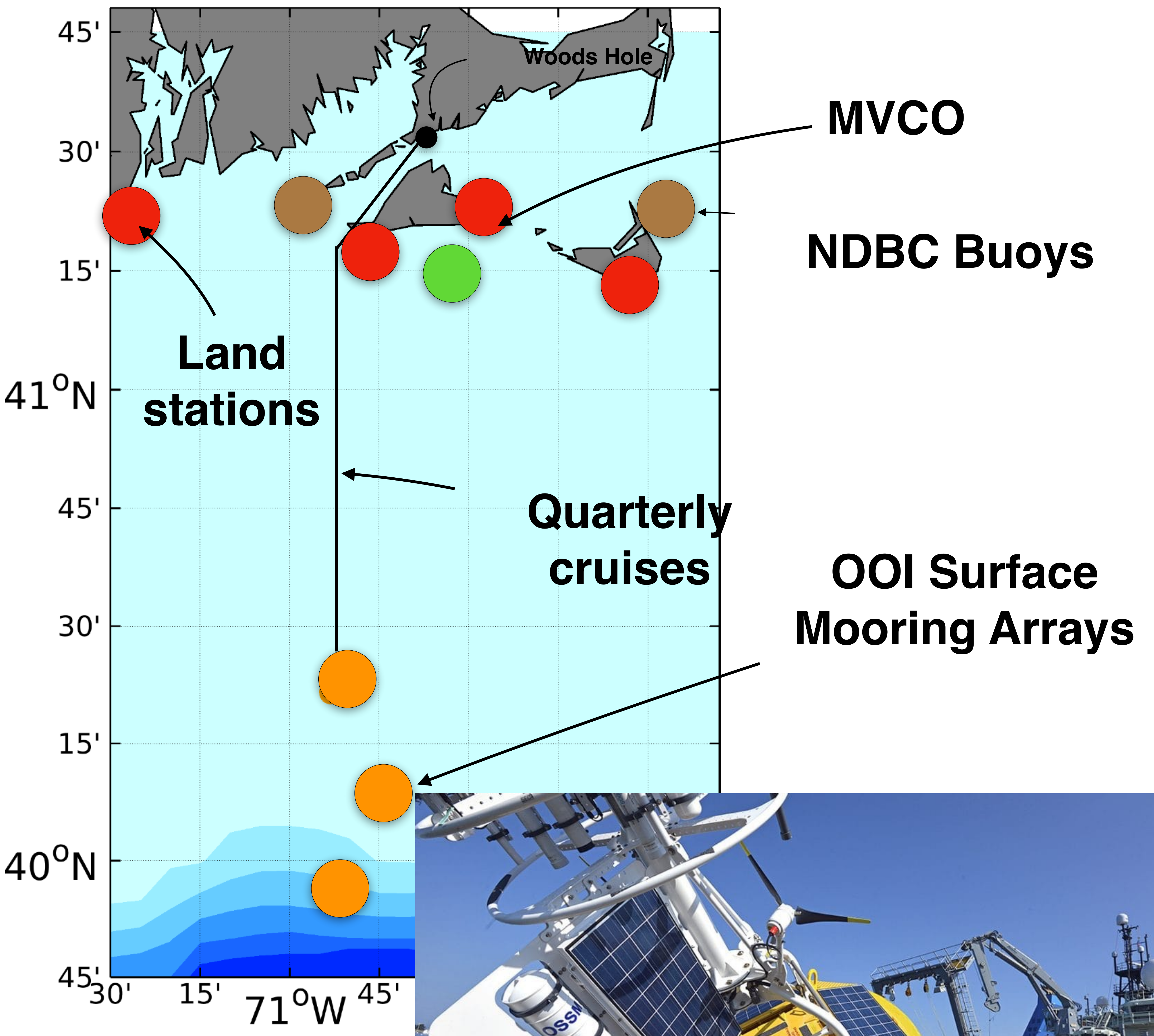




z0 and τ responses to surface waves and sea state in COARE3.5

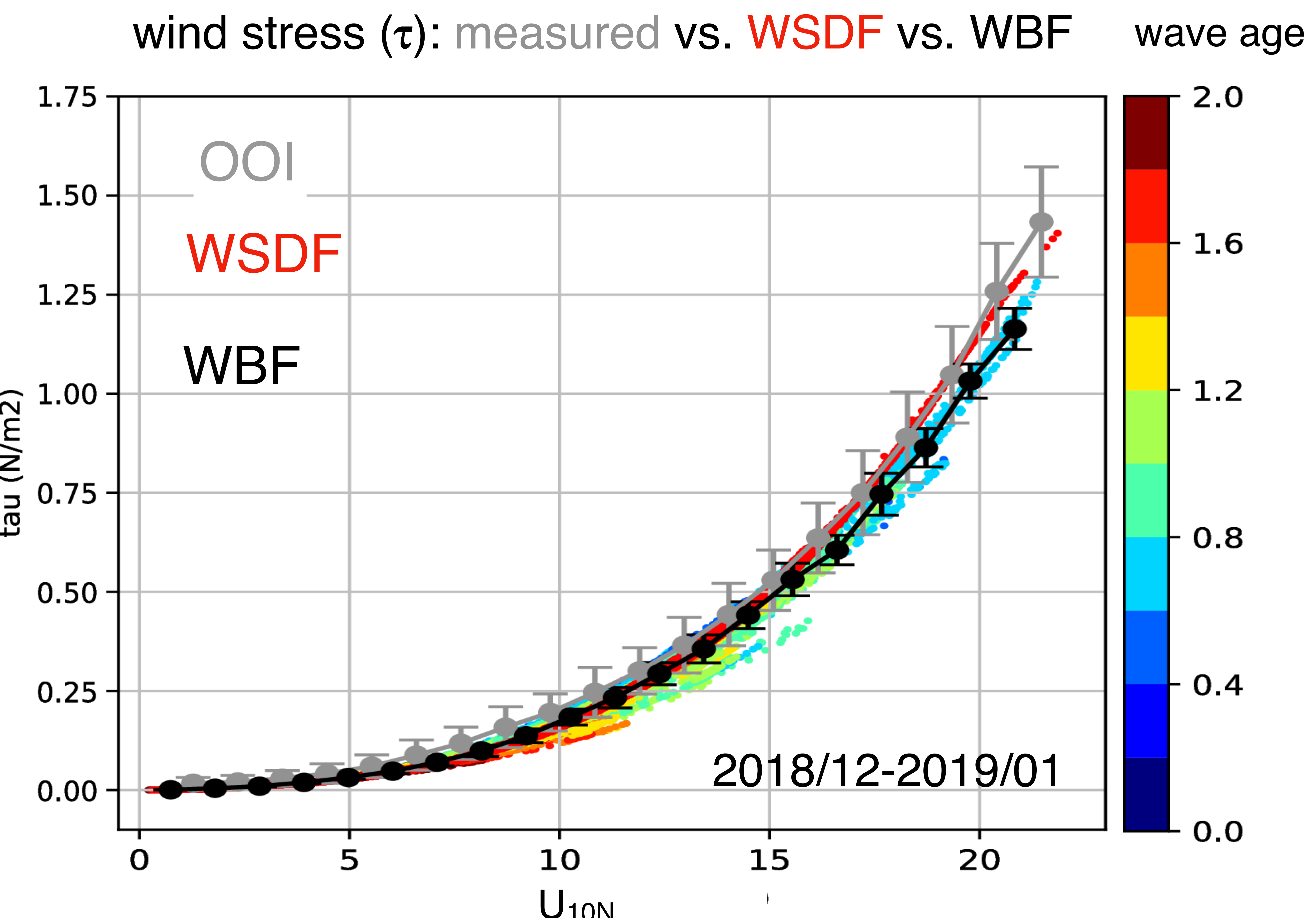
Comparison to the directly measured wind stress

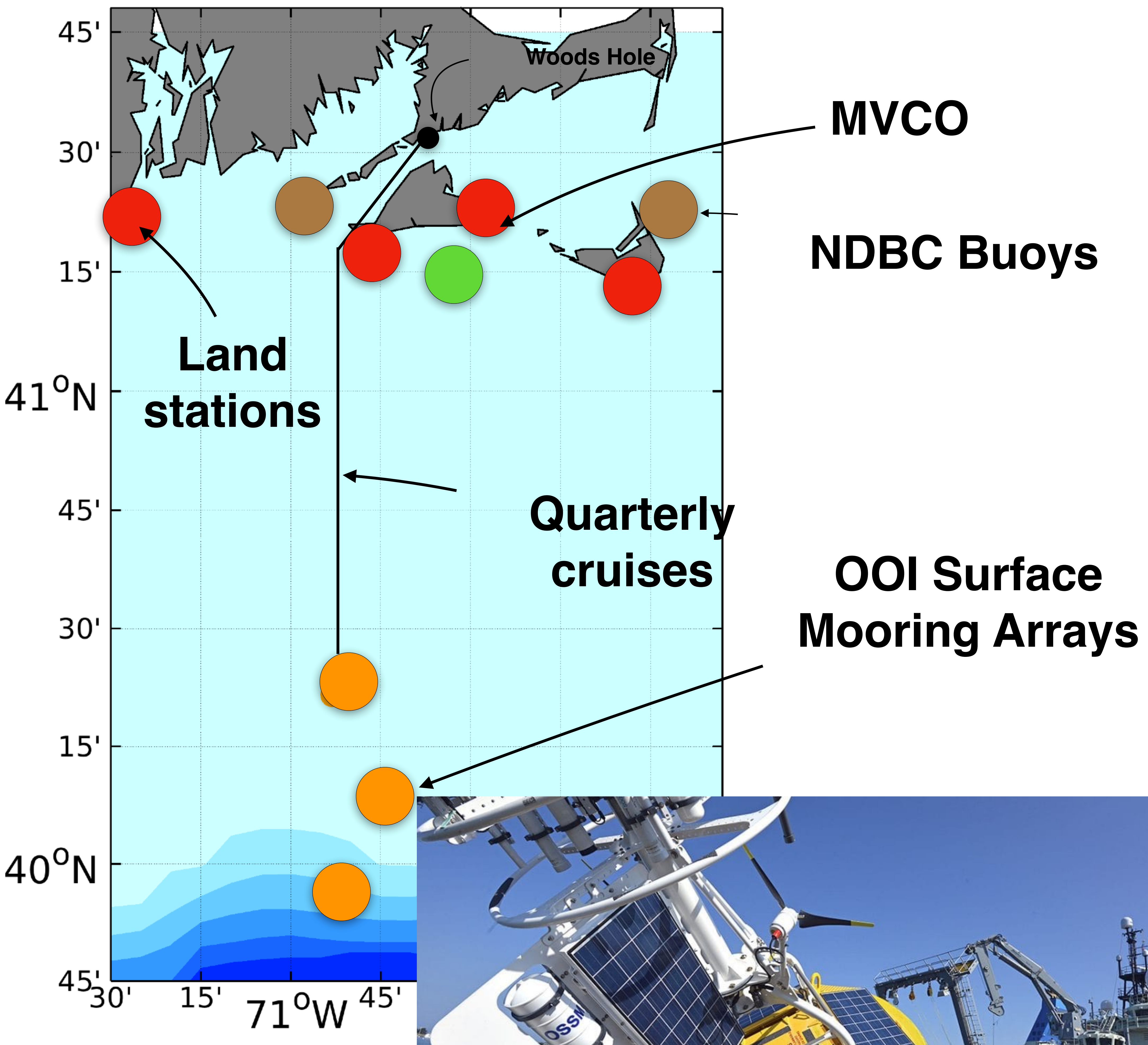




- WSDF underestimates stress over young sea, but shows a good agreement with the measurements in high winds.

Comparison to the directly measured wind stress

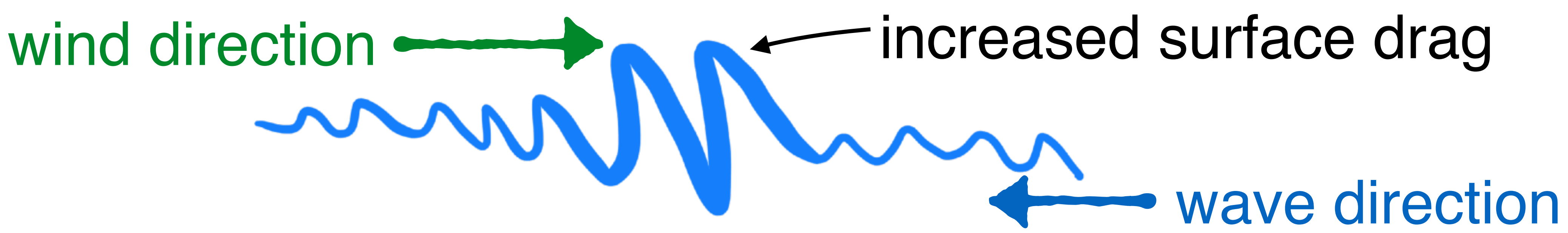




- WBF alleviates the low-stress bias over young sea
- But it underestimates the stress in mixed sea

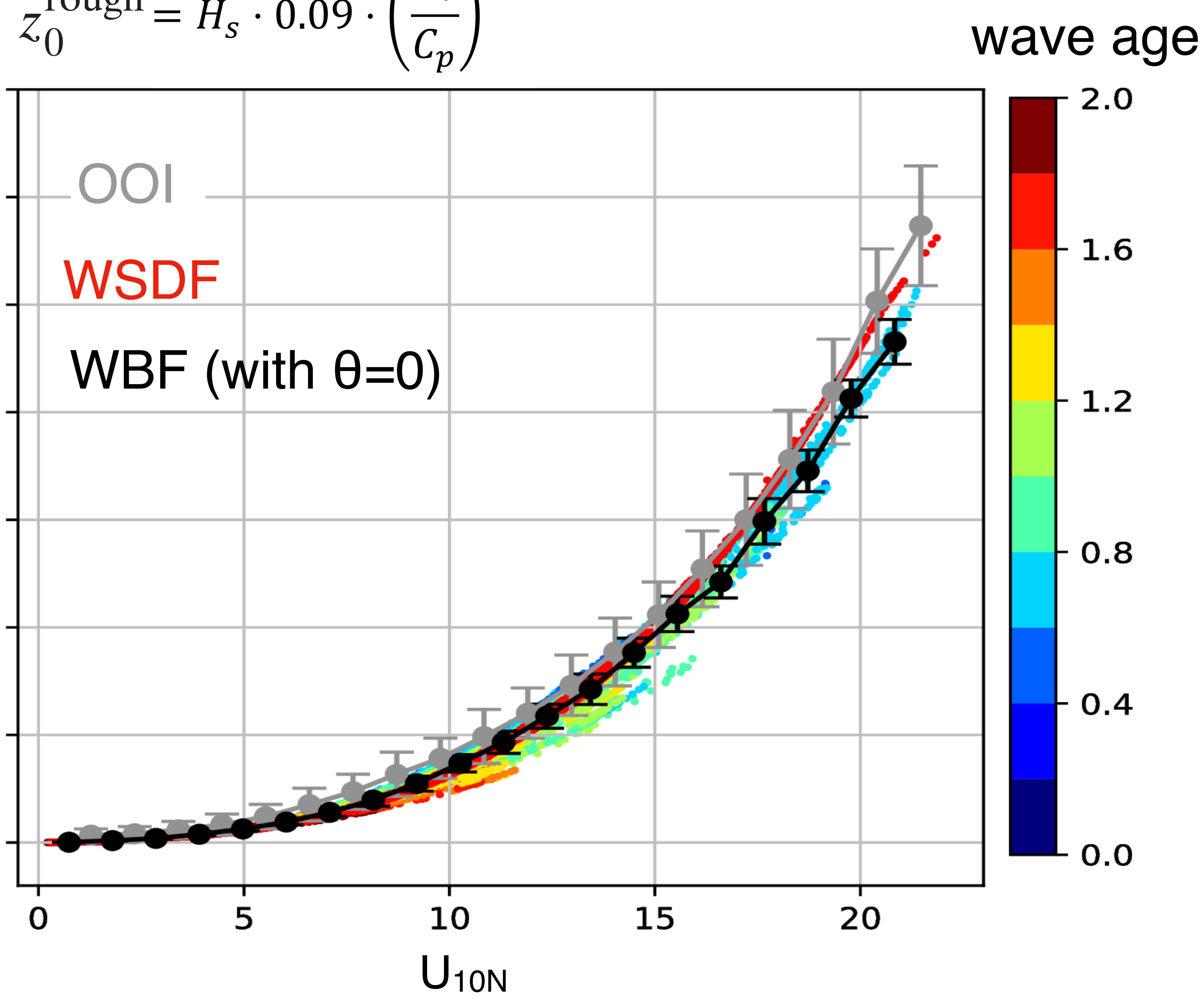
Improving the wave-based formulation for the mixed sea conditions

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



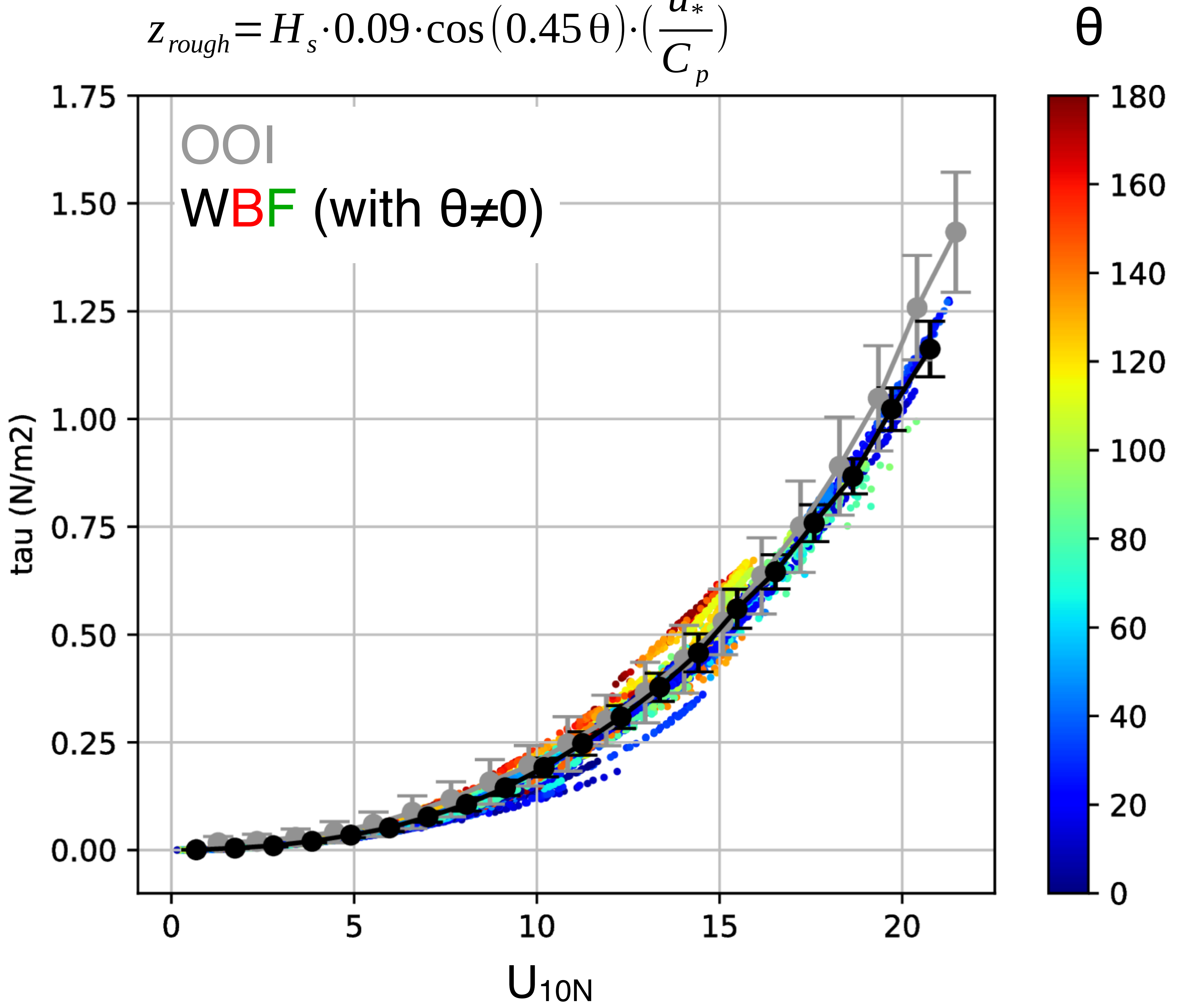
Edson et al. (2013) COARE3.5

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



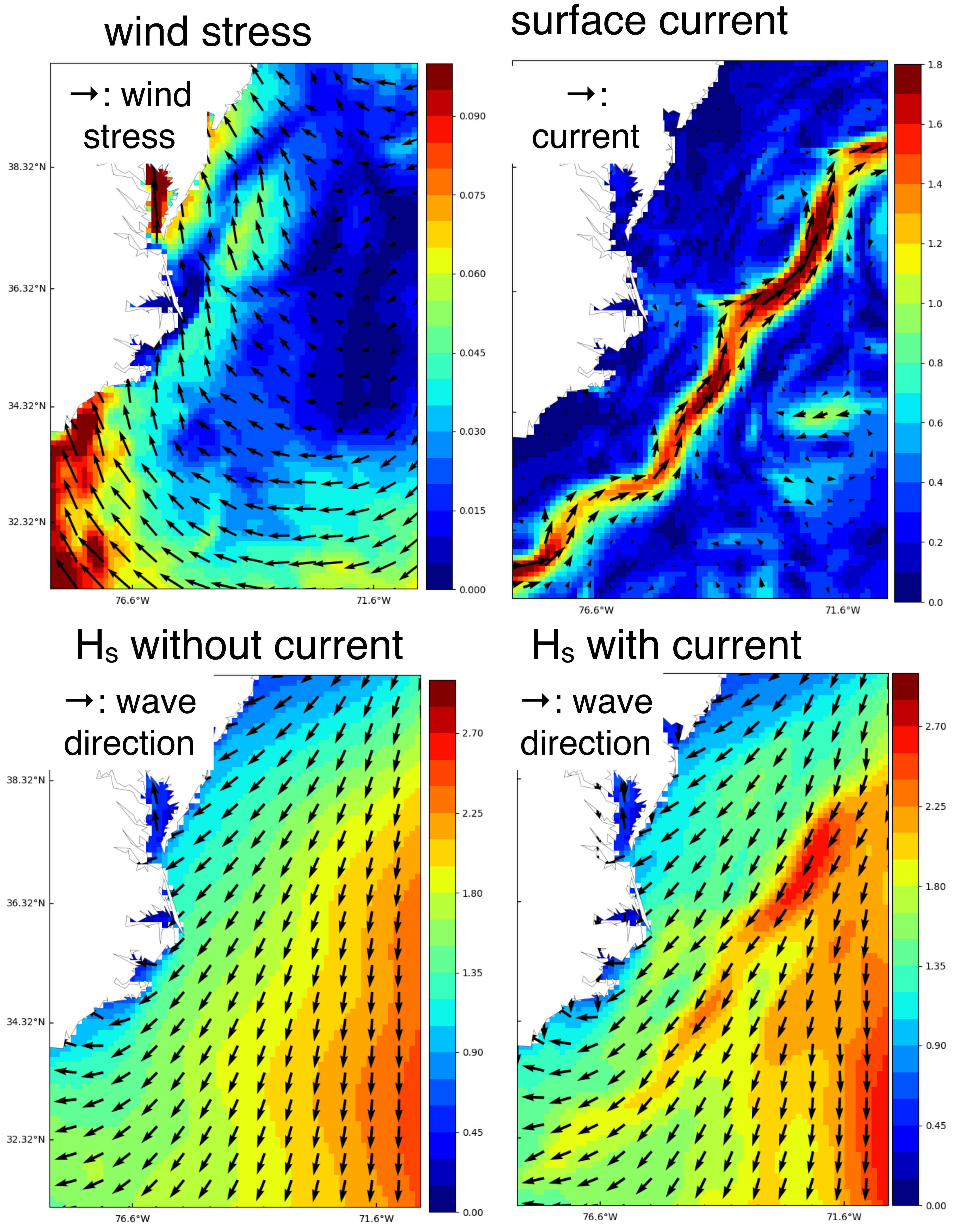
Sauvage, et al. (2023)

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

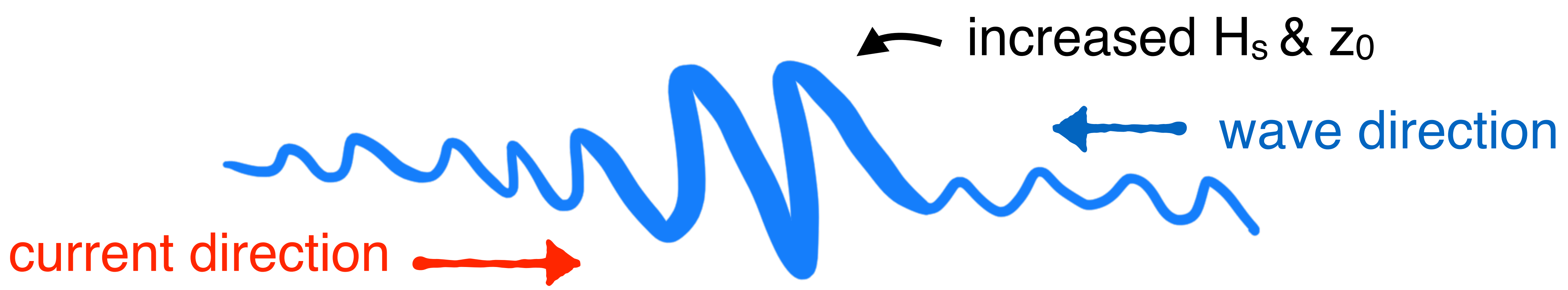


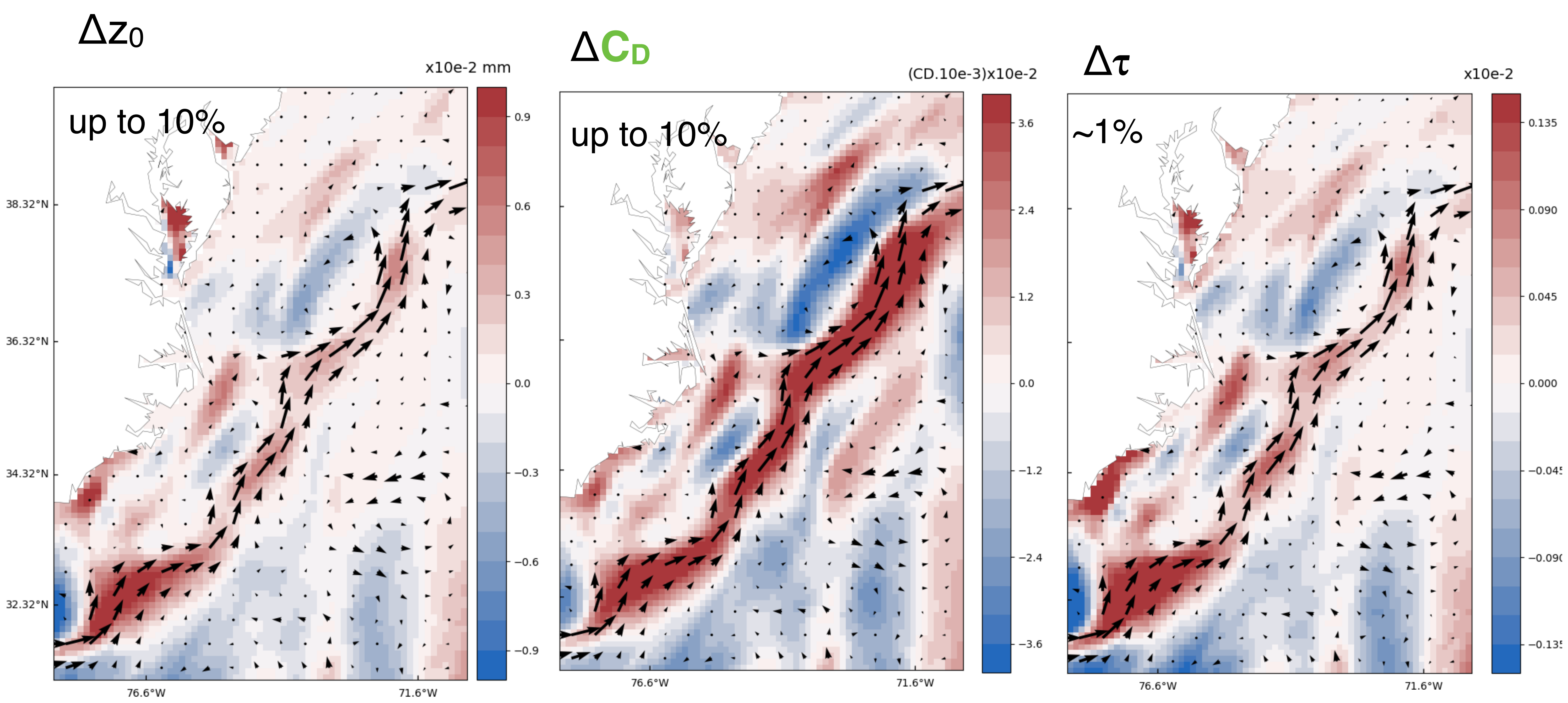
- The next-generation COARE (v4.0) will continue to assume θ=0.
- Our model provides various revised formulations to represent the wave effects.

Wave-current interaction



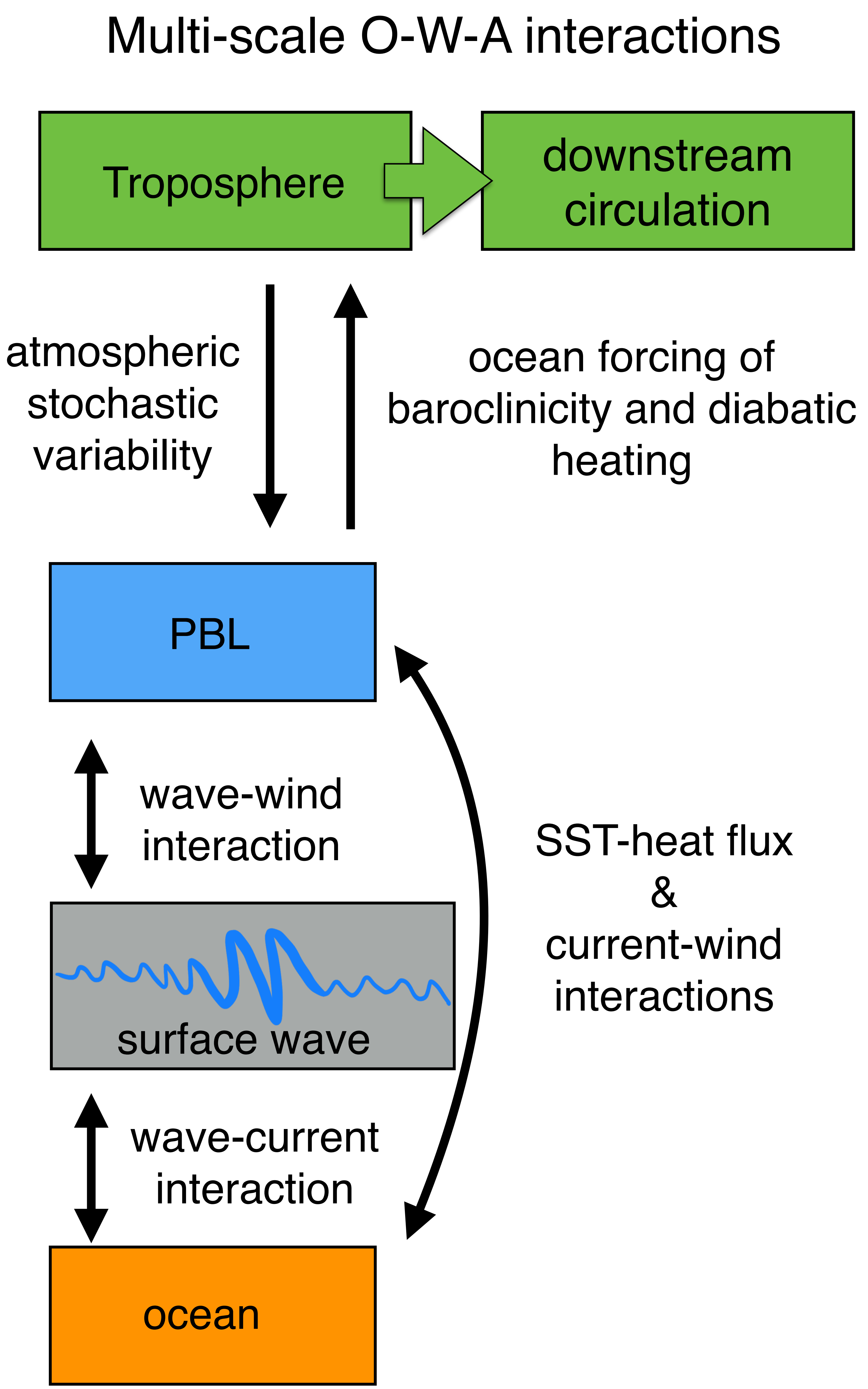
WRF-ROMS-WW3 simulations with and without surface current effects on waves





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.



Air-sea interaction research and the of WHOI

- Ocean mesoscale air-sea interaction is a multi-scale phenomenon, and is important for determining the air-sea flux impacts on boundary layer processes, ocean circulation, and high-impact weather events.
- Because of the multi-scale nature, there are many challenges in developing observing and modeling strategies
- In-situ measurements are extremely sparse. But there are many emerging technologies that enable fine-scale sampling of the ocean and air-sea interaction. WHOI is the leading institution in many efforts.
- Efforts like WFIP-3 will develop the RI/MA lease areas into **an ocean test bed** for energy and climate research and development.
- An ambitious ($100M) project is being developed led by WHOI scientists to provide better global observations of mesoscale air-sea coupling.

A NASA Earth Venture Mission - EVM3 - Proposed Mission

EVMs are science driven, competitively selected, low cost satellite missions

BUTTERFLY

a satellite mission to reveal the oceans' impact on our weather and climate.

https://nasa-butterfly.github.io/

Principal Investigator: Dr. Chelle Gentemann
Deputy Principal Investigator: Dr. Carol Anne Clayson
Project Scientist: Dr. Tony Lee
Deputy Project Scientist: Dr. Shannon Brown

Science Team: Aneesh Subramanian, Mark Bourassa, Hyodae Seo, Kelly Lombardo, Sarah Gille, Tom Farrar, Rhys Parfitt, Brian Argrow

Helpful reading:

Offshore wind energy

Shaw et al. 2022: Scientific challenges to characterizing the wind resource in the marine atmospheric boundary layer. *Wind Energ. Sci*., https://doi.org/10.5194/wes-7-2307-2022.

Veers et al. 2019: Grand challenges in the science of wind energy, *Science*, https://doi.org/10.1126/science.aau2027

Air-sea interaction

Seo et al. 2023: Ocean Mesoscale and Frontal-scale Ocean-Atmosphere Interactions and Influence on Large-scale Climate: A Review. *J. Climate*, https://doi.org/10.1175/JCLI-D-21-0982.

Small et al. 2008: Air-Sea Interaction over Ocean Fronts and Eddies. *Dyn. Atmos. Oceans*., https://doi.org/10.1016/j.dynatmoce.2008.01.001