Fast thermal air-sea coupling: the instantaneous wind response and the role of environmental conditions

Agostino N Meroni, Fabien Desbiolles, Claudia Pasquero

Sea Surface Temperature mesoscale structures force the lower atmosphere, via, e.g. the Downward Momentum Mixing mechanism:

Data used:
- **ESA CCI SST** at Dx~0.05° (L3U: instantaneous, L4: daily);
- **Ascat** wind field (L2) at Dx~12.5 km;
- **ERA5** monthly at Dx~30 km.


Over all four major Western Boundary Currents we find that:

1) The daily/instantaneous response is found over a **wider range** of forcing and response fields.

2) The **instantaneous coupling is stronger** than the daily one.

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Over Northern Hemisphere WBCs, the minimum coupling is observed in winter.

In winter the NH has the strongest air-sea temp differences.

Five years of global daily ERA5 data are used to evaluate the modulation of background wind and air-sea temperature difference on the efficiency of the DMM [Desbiolles et al., 2023]: DMM is important for all wind speed in slightly unstable conditions.

The enhancement and the suppression of the vertical mixing for very unstable and stable conditions weakens the sensitivity to the surface gradients.

In the Northern Hemisphere, the winter-time unstable conditions (due to cold air outbreaks) reduce the DMM efficiency.

The cloud response is also being investigated. TBC…

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Mesoscale eddies are ubiquitous in the global ocean, have a critical role in the mixing and transporting of heat, salt, and biogeochemical properties across the global oceans, and thus, can regulate the regional and global climate.

However, it remains unclear how greenhouse warming will alter ocean eddies due to the shortage of observational long-term records and model simulations with high spatiotemporal resolutions.

Questions?
1. Will mesoscale eddy activity be enhanced or weakened under greenhouse warming?
2. What is the key process underlying it?

CESM-UHR revealed that CO2-induced global warming brings a complex EKE change across oceans.
Global warming effect on oceanic mesoscale eddy energetics

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Kuroshio current vs Gulf stream

\begin{itemize}
  \item KC: strong surface current \quad \Rightarrow \text{increase horizontal shear production} \quad \Rightarrow \text{enhancing EKE}
  \item GS: weak AMOC
  \begin{itemize}
    \item suppress vertical buoyancy flux
    \item reducing EKE
  \end{itemize}
\end{itemize}

How did the effect of current feedback change under global warming?

\begin{itemize}
  \item $\Delta$EKE vs $\Delta$EWWg: positive $\Delta$EKE $\Rightarrow$ enhanced eddy killing effects
  \item EWWg < 0: oceanic eddy killing by wind
  \begin{itemize}
    \item Reduced eddy killing effect
    \item Enhanced eddy killing effect
  \end{itemize}
\end{itemize}
Air-sea interactions and diabatic processes in the Gulf Stream region and their role in the life-cycle of a blocking anticyclone: a case study of European Blocking in Feb 2019.

Case Study (20.02.2019 - 27.02.2019)

Methods and results

Properties of the trajectories
Air-sea interactions and diabatic processes in the Gulf Stream region and their role in the life-cycle of a blocking anticyclone: a case study of European Blocking in Feb 2019.

Moisture sources

Mechanistic link: Gulf Stream → EuBl

Hand-over mechanism of moisture

Authors: Marta Wenta, Christian M. Grams, (Karlsruhe Institute of Technology), Lukas Papritz, Marc Federer (Institute for Atmospheric and Climate Science, ETH Zurich)
Latent heat flux coupling to the small-scale ocean

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Goals

1) How do ocean small-scale surface features (in SST and SSS) affect latent heat flux (LHF)?

2) Which are the surface ocean - MABL coupling mechanisms driving LHF changes?

Different data sets for different purposes

To evaluate the LHF coupling to the small-scale SST:

- ERA5 at Dx~25 km (daily averages).
- SeaFlux at Dx~25 km (daily averages).
- MUR-JPL daily at Dx~0.01°.
- WRF daily at Dx~0.03°.

Spatial domain: 5º-17ºN, 60º-51ºW.

To evaluate the effect of the pair SSS-SST on LHF: in-situ data:

- Saildrones
- CTDs, UCTDs, gliders, argo floats, RVs.
- Radiosoundings and lidar.

Time frame: During the EUREC4A-OA campaign, JFMA 2020.
Unprecedented high-resolution sampling of the air-sea interface in the north-west tropical Atlantic Ocean
Two mechanisms control LHF sensitivity to SST.

**Dynamic:** As a consequence of the thickening/shallowing of the MABL (~28% · K⁻¹). Only present when the small-scale coupling is considered.

**Thermodynamic:** As a result of the dependence of water vapour saturation pressure on SST (~5% · K⁻¹).

Lower SSSs imply a reduced water entrainment from the deep ocean and an increased heating rate of the ocean mixed layer.

These two ingredients increase LHF but a decrease is observed over the freshwater plume.
Research Questions

1) Do variations in the surface current direction and magnitude influence waves and momentum flux?

2) Do sea surface temperature (SST) variations influence air-sea heat and buoyancy flux?

Observations from the ATOMIC field campaign

- January-February 2020 in the NW tropical Atlantic

**Data:**

**Air:** T, humidity, wind, P, clouds

**Fluxes:** heat, vapor, buoyancy, momentum

**Ocean:** T, S, currents, wave parameters, wave spectra, TKE dissipation rate

*SWIFTs (WGs) deployed for 21 (30 and 34) days

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US CLIVAR Mesoscale and Frontal-Scale Air-Sea Interactions Workshop
March 6, 2023
Waves and momentum flux are modified by surface current variability

Momentum flux ($\tau$) derived from SWIFT wave spectra

$\tau$ is elevated (by 15%) when waves oppose currents and decreased when waves follow currents.

Sensitivity tests show that this is due to a combination of changes in the current-relative wind and wave-current interactions.

Sea surface temperature variability modifies air-sea heat fluxes

Sea surface temperature (SST) from Wave Gliders from 2-6 Feb.

Sensible heat flux (SHF) across the SST gradient observed on 2-6 Feb.

SST varies by 0.7°C across 25 km, typical of 10-100 km fronts in the region.

Sensible heat flux is on average 3.6 W m$^{-2}$ higher on the east (warm) side of the gradient. Because SST and SHF gradients were correlated throughout the campaign, SST likely modulates the spatial variability of sensible heat flux.

Read more at: Iyer et al. (2022), JGR Oceans, doi: 10.1029/2021JC018003 (waves, momentum flux)
Iyer et al. (2022), JGR Oceans, doi: 10.1029/2022JC018972 (heat flux)
1. Seasonal Variability

Winter Jet range at a minimum where SST gradients greatest

2. Decadal Trends

Jet Latitude

Jet Speed

Atlantic
+3°N, +4.5 ms⁻¹

Pacific
No changes

3. Interannual variability and the Pacific Decadal Oscillation (PDO)

The Pacific Decadal Oscillation (PDO) explains 50% of the winter variance in jet latitude since 1940. The direction of the arrows indicates the PDO and jet stream are anti correlated, and the PDO leads.
Global Warming Effect on Ocean Horizontal Stirring Characterized by Finite-Size Lyapunov Exponents

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Ocean Horizontal Stirring

- Stirring is a turbulent phenomenon that promotes mixing speed by deforming the fluid into an elongated shape.
- It is almost everywhere accompanied by other dynamical oceanic processes such as eddies, meandering, currents, and fronts.

“How will ocean horizontal stirring respond to greenhouse warming?”

Methods: Finite-Size Lyapunov Exponents (\(\lambda\))

- It is a Lagrangian metric that characterizes the dispersion rate of two infinitesimally separated particles as an exponential function in a chaotic system.

\[
\lambda(x, y, t) = \frac{1}{\tau} \ln \frac{\delta_f}{\delta_0}
\]

\(\delta_0\) at \(t = 0\)

\(\delta_f\) at \(t = \tau\)

FSLE 1-day snapshot

\(\sqrt{EKE}\) 1-day snapshot (on the same day)
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\(^1\) Pusan National University, Department of Climate System, Busan, South Korea, \(^2\) Center for Climate Physics, Institute for Basic Science, Busan, South Korea

**Model Experiments**
- High-resolution experiments based on the fully-coupled Community Earth System Model (CESM) version 1.2.2.
  - Present-day (367 ppm)
  - 2×CO\(_2\) (734 ppm)
  - 4×CO\(_2\) (1,468 ppm)
- Ocean model: POP2 (62 levels)
- Data: daily \(u\), \(v\) at 15 m depth (lev=2)
- Horizontal resolution: 25 km (atm), 10 km (ocean)
- Analysis period: 10 years for each condition

**Arctic Ocean Changes**
Here we present possible mechanisms for FSLE changes in the Arctic Ocean, where the change is most pronounced due to sea ice decline.
Using Ship-Deployed High-Endurance Uncrewed Aerial Vehicles for the Study of Ocean Surface and Atmospheric Boundary Layer Processes

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- Complete autonomous takeoff, flight and landing from ships
- Dual-UAV aircraft continuous flight operations.
  - 3 aircraft utilized
- High endurance flights for > 8-hours.

- Routine Flights (>40) with Payloads (242 hours)
  - MET, RAD, ATOM, VNIR payloads

- Long-range capability (50+ nm) with high bandwidth data link (100+ Mbps) for real-time mission control and tasking.
  - Primary UAV with squadron at further distance or lower altitude.... Coordinated with AUV and ASV.

- Demonstrated 24-hour operations.

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Eyes Over the Horizon

UAS Mission Control on R/V Falkor

Observing Cyanobacteria in Infrared and Hyper-Visible & BL Response

UAS Reconnaissance of Cyanobacteria Front

Putting It All Together...
By invoking Taylor’s frozen turbulence hypothesis, it is possible to remotely infer the mean advective velocity of a fluid through quantification of the spatiotemporal evolution of turbulent eddies at a single depth (Dugan et al., 2012).
Conceptual schematic of the constant stress and wave boundary layers above the ocean surface where surface waves break, create whitecaps, and induce flow separation. At the surface, the total turbulent stress is partitioned to the surface tangential viscous stress and the form drag.

\[ \rho u_s^2 = \tau_v + \tau_{\text{form}} \]

Our central hypothesis is that measurements of the velocity profile from thermal infrared (TIR) imagery within the top 100 \( \mu \text{m} \) of the water surface will provide a robust estimate of the surface ocean viscous stress. To test this hypothesis, we will conduct detailed measurements of the tangential stress structure beneath the air-water interface compared to form drag and the total stress in the wind tunnel using a recently developed infrared imaging technology under a range of wind-wave regimes.

The detailed structure of the tangential stress beneath the air-water interface was investigated using the recently-developed infrared imaging technology. The new multi-spectral TIR camera system (MultiIR) provides remotely sensed skin friction measurements within 10-100 \( \mu \text{m} \) of the water surface.