Advanced Summer School

Ocean and Atmosphere Modeling

Ocean-Atmosphere coupling at Mesoscales: Why does it matter ? Implications for upper-ocean and lower-atmosphere thermodynamical properties.

F. Desbiolles (Univ. Milan), L. Renault (IRD), Gildas Cambon (IRD), A. Sepulveda (Univ. Concepciòn), and J. Veitch (Saeon)

Contact: fabien.desbiolles@unimib.it

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FOREWORDS: INTERESTS AND QUESTIONS

Many coupling processes coexist over a large spectrum of temporal and spatial scales at the air–sea interface. Both one- and two-way interactions between the are key features in driving circulation in both fluids.

Air-sea interactions at mesoscales

Main processes which control the **local heat and momentum fluxes** at the interface and their consequences.

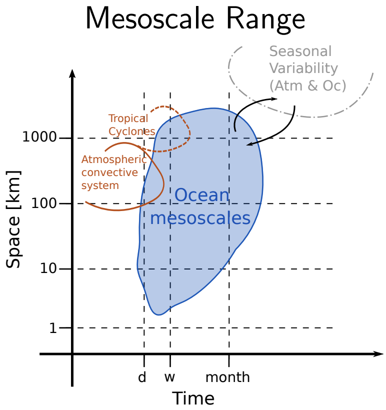
- Local and Remote effect

(i) How the atmosphere control UPPER-OCEAN variability and **thermodynamics** properties.

(ii) How ocean temporal and spatial scales induces LOWER-ATMOSPHERE **thermodynamics** properties.

- Upscalling effect (reverse cascade of energy)

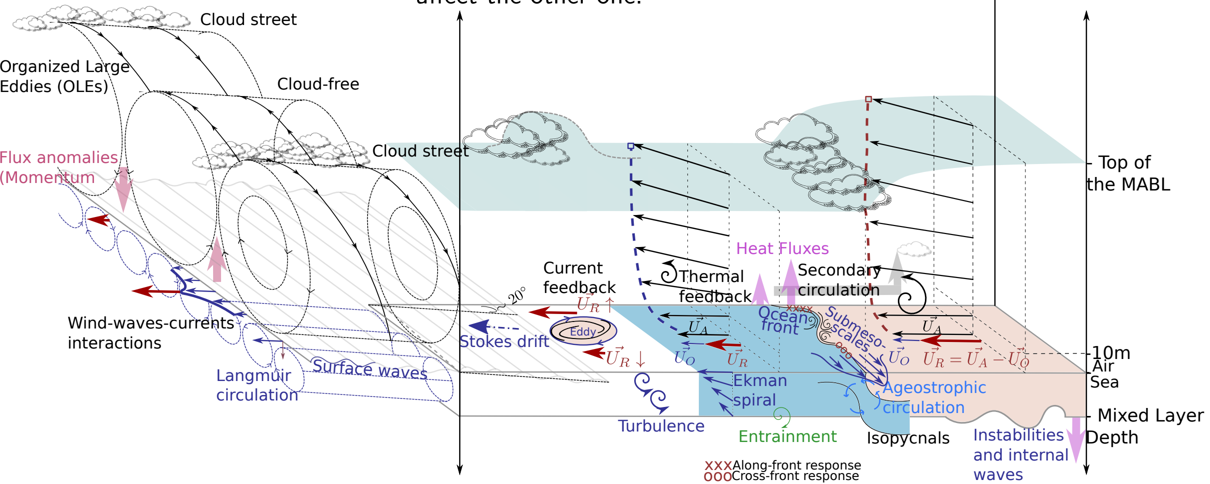
(iii) Impact of small-scale processes on larger scale variability



AIR-SEA INTERACTIONS

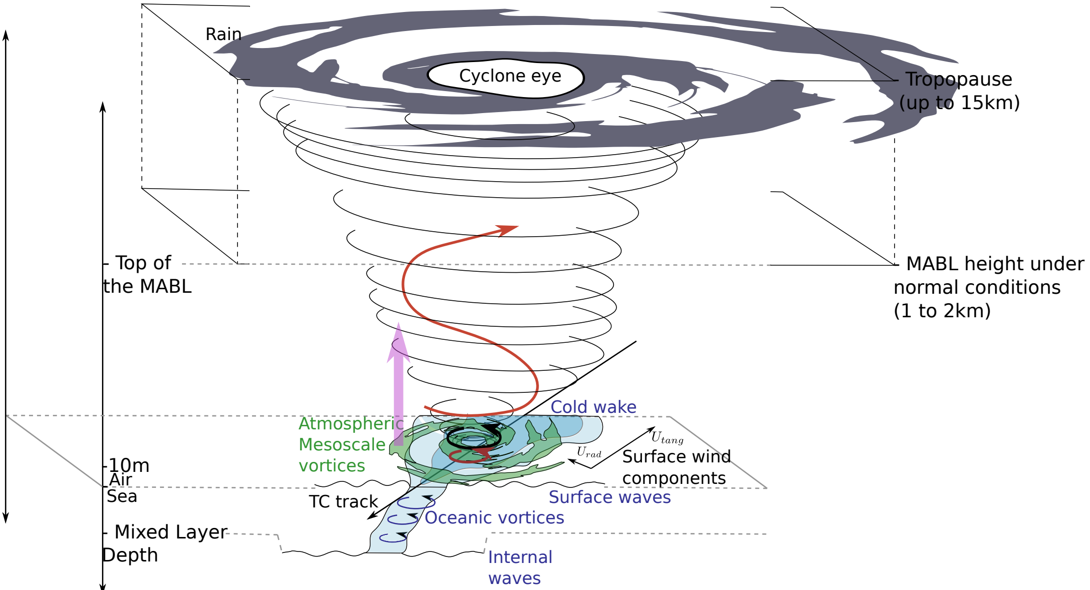
Normal conditions

Processes of the upper-ocean and lower-atmosphere. Dynamical unbalanced at the interface, both fluids affect the other-one.



AIR-SEA INTERACTIONS

Extreme events Fluxes change of an order of magnitude



Contents

Thermal Feedback

Different behavior at different scales

Basin Scales

Atmosphere ⇒ Wind and heat fluxes ⇒ Ocean

Stronger wind speed ⇒ lower Sea Surface Temperature (SST) via mixing and turbulent heat fluxes. *NEGATIVE CORRELATION* between SST and surface wind speed

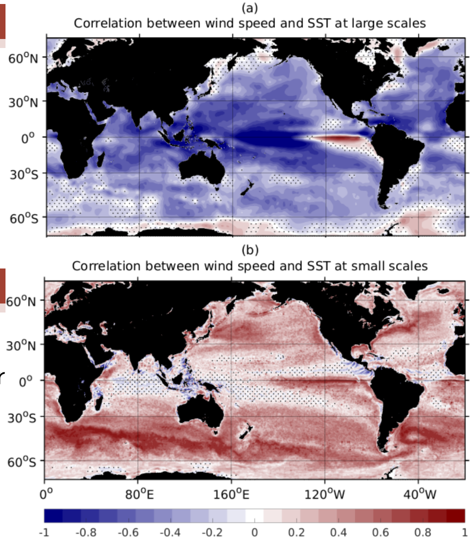
Atmosphere drives Ocean

Mesoscale Scales

Atmosphere ⇐ SST fronts ⇐ Ocean

Ocean fronts ⇒ enhanced (reduced) wind speed over warmer (colder) SST. *POSITIVE CORRELATION* between SST and surface wind speed. **FEEDBACK LOOP**

Ocean drives Atmosphere



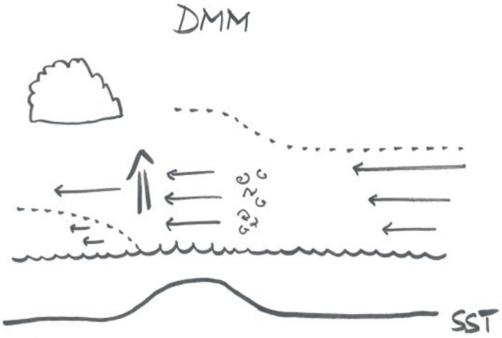
* From Pasquero et al. [2020]

Thermal Feedback
Two main mechanisms: DMM and PA

Donward Momentum Mixing - DMM

Involves the large eddies with the MABL, acting on the turbulent fluctuations of momemtum from the top of the MABL towards the surface

$\nabla \cdot \vec{u} = \alpha_{DM} \nabla SST$

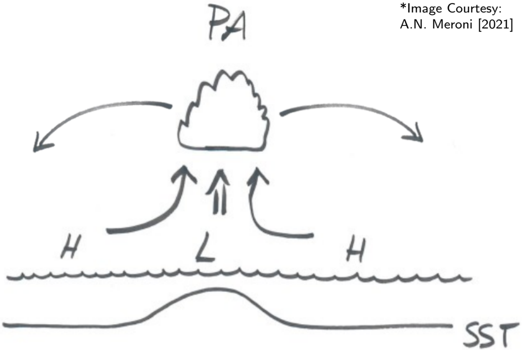


Pressure Adjustment - PA

A secondduary circulation is forced by the divergence of the air-temperature gradient, itself driven by Sea Surface Temperature (SST)

$\nabla \cdot \vec{u} = \alpha_{PA} \nabla^2 SST$

*Image Courtesy: A.N. Meroni [2021]

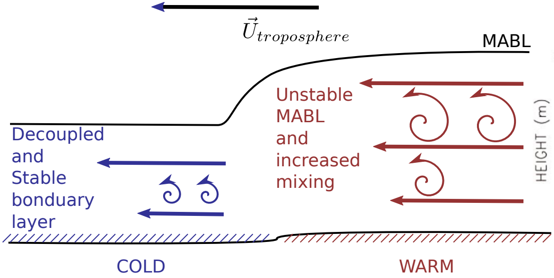


Thermal Feedback

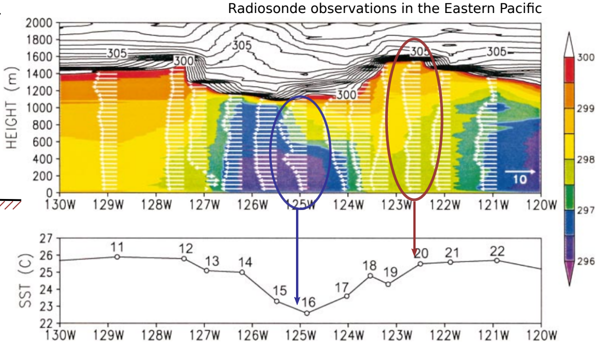
Downward Momentum Mixing: modifies MABL stability and consequently its thermodynamical properties.

Eddies and **fronts** alter the stability of the Marine Atmospheric Boundary Layer (MABL).
Involves the large eddies with the MABL, acting on the turbulent fluctuations of momemtum from the top of the MABL towards the surface

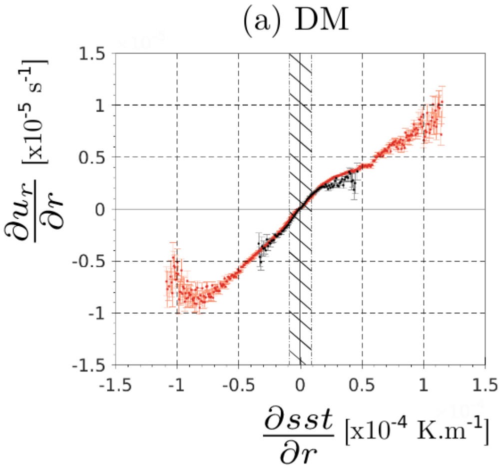
$\nabla \cdot \vec{u} = \alpha_{DM} \nabla SST$ (at mesoscale)



** Adapted from Hyodae Seo [2014]



Hashizume et al. [2012]



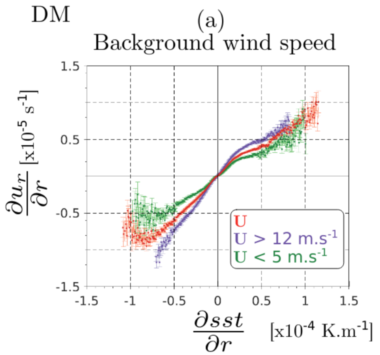
$\Longrightarrow$ DM mechism: as a first guess, linear relationship (significant correlation) between Along-wind SST gradients and wind divergence structures.

$\Longrightarrow$ This is true for daily to monthly values (cf. Chelton et al. [2007,2010], Small et al. [2008] and ref. within)

$\Longrightarrow$ The slope of this relationship is the coupling coefficient.

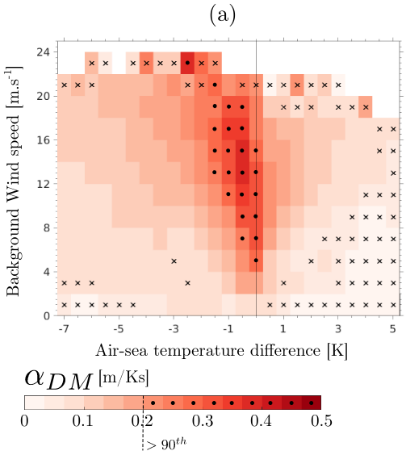
Environmental condition DMM depends upon ??

*From Desbiolles et al. [in prep.]



$\Longrightarrow$ DM mechism: Effective for near-neutral stability from moderate to strong winds.

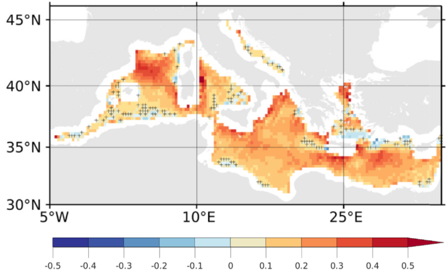
Generalization:

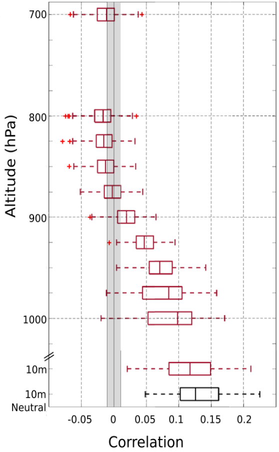


*From Desbiolles et al. [in rev.]

25 yrs of ERA5 Reanalysis, 00UTC, daily frequency
Temporal correlation between Downwind SST Gradients and Wind Divergence

10 m Wind Divergence





* From Desbiolles et al. [2021]

⟹ DM mechism is the leading process which shapes the surface wind divergence over the Mediterranean at **daily time scale**

⟹ Significant correlation between wind divergence and SST gradients up to 925 hPa, which corresponds to the top of the boundary layer.

Agreement with the theory

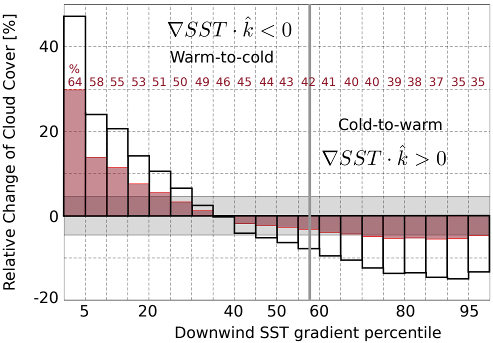
⟹ DM mechanism modifies wind variability throughout the whole MABL

Cloud Cover (integrated over the MABL) and Rain responses to SST gradients:

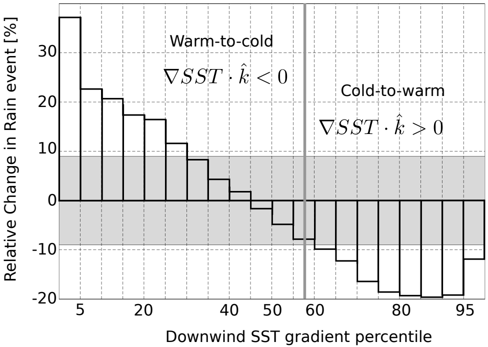
Winds is blowing from warm to cold patches $\Longrightarrow \nabla SST \cdot \hat{k} < 0$

cold-to-warm $\Longrightarrow \nabla SST \cdot \hat{k} > 0$

Cloud Cover



Rainfall

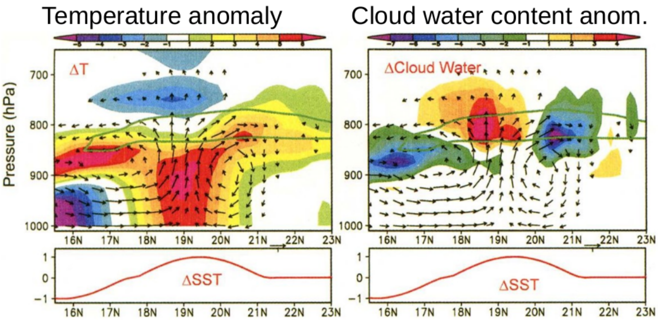


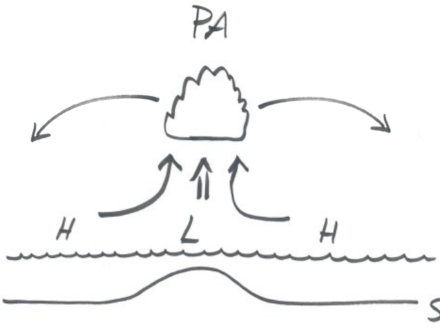
Thermal Feedback

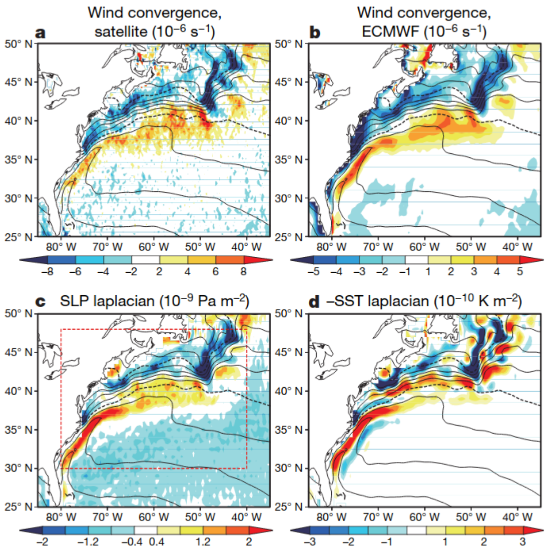
Pressure Adjustment: Secondary circulation driven by SLP anomalies (themselves forced by the local SST)

A secondary circulation is forced by the divergence of the air-temperature gradient, itself driven by Sea Surface Temperature (SST) and the resulting sensible heat flux.
$\nabla \cdot \vec{u} = \alpha_{PA} \nabla^2 SST$ (at mesoscale)

Latitude-pressure section of temperature and cloud water content, together with the zonally-averaged meridional circulation anomalies simulated in a regional atmospheric model near Hawaii. *From Xie et al. [2004.]

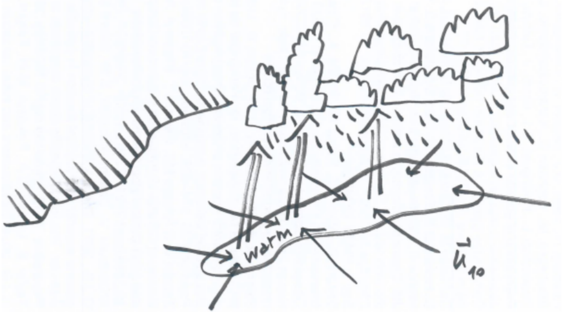






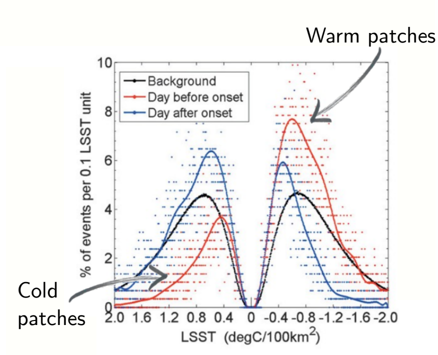
PA is detectable on long time scale over the Western Bonduary Currents:

Multi-annual averages of QuickSCAT wind observations and ECMWF model data. Takatama et al. [2015] theoretically show thatPA controls the wind divergence response toSST structures in long-term

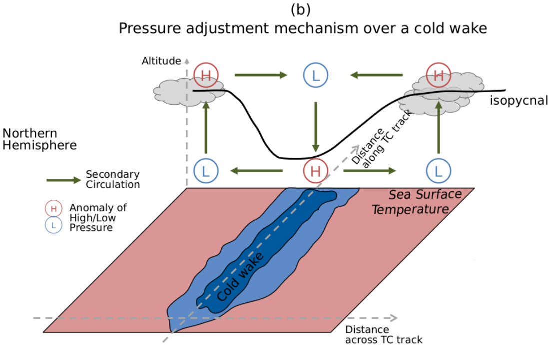


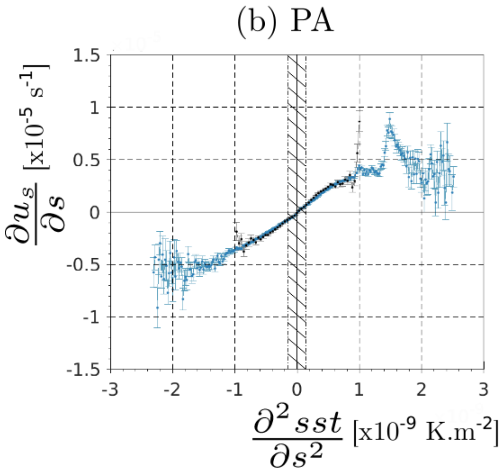
PA is also acting on shorter time-scale

(i) **Convective events:** Li and Carbone [2012] find that the probability of convective events triggered over warm SST patches is much higher than those over cool ones.



(ii) **Over a cold wake of a tropical cyclone:** Ma et al. [2020] show that the cold wakes of tropical cyclones reduce cloud cover and rainfall by setting a secondary circulation.





$\Longrightarrow$ PA mechism: as a first guess, linear relationship (significant correlation) between SST Laplacian and wind divergence structures.

$\Longrightarrow$ This is true from daily to monthly timescale

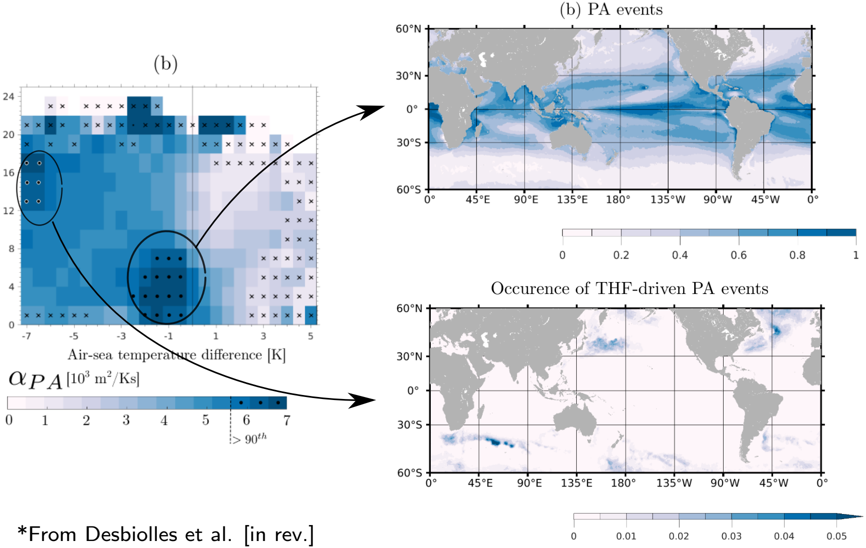
$\Longrightarrow$ The slope of this relationship is the coupling coefficient.

Environmental condition PA depends upon ??

*From Desbiolles et al. [in rev.]

Thermal Feedback

Pressure adjustment Mechanism: Local and Rapid effect

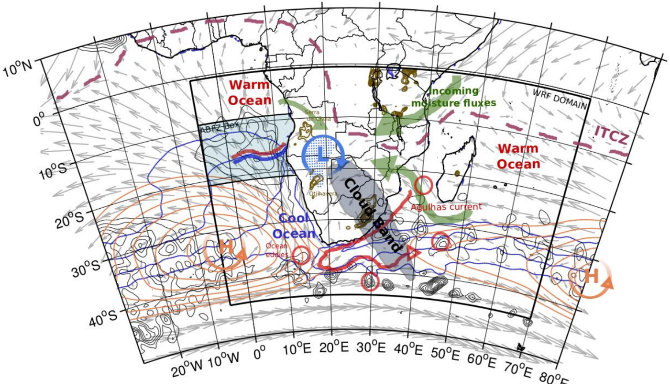


*From Desbiolles et al. [in rev.]

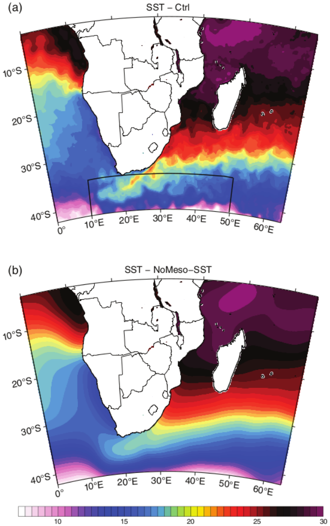
Thermal Feedback

Implications for Atmospheric Dynamics

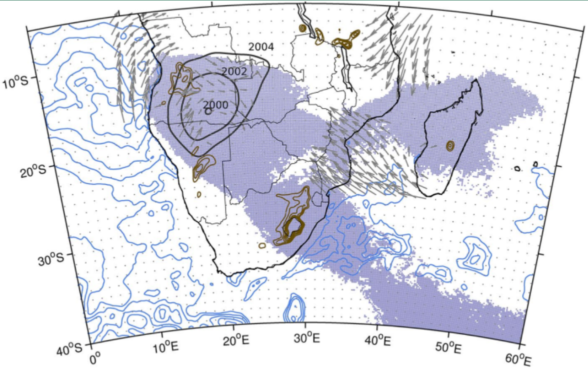
Remote and Uscaling effect: Example of the Southern Africa summer climate



Ocean Mesoscale Activity (e.g., ABFZ, Great Agulhas), Incoming moisture fluxes, Low-pressure system which leads to Cloud band and Rainfall

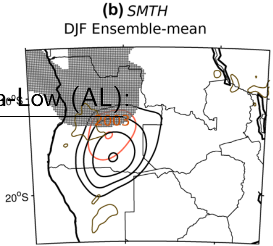


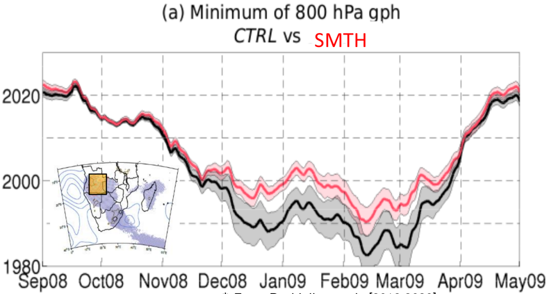
* From Desbiolles et al. [2018,2020]



Representation of Angola-Low (AL):

AL is shallower with a Northewest shift of the center



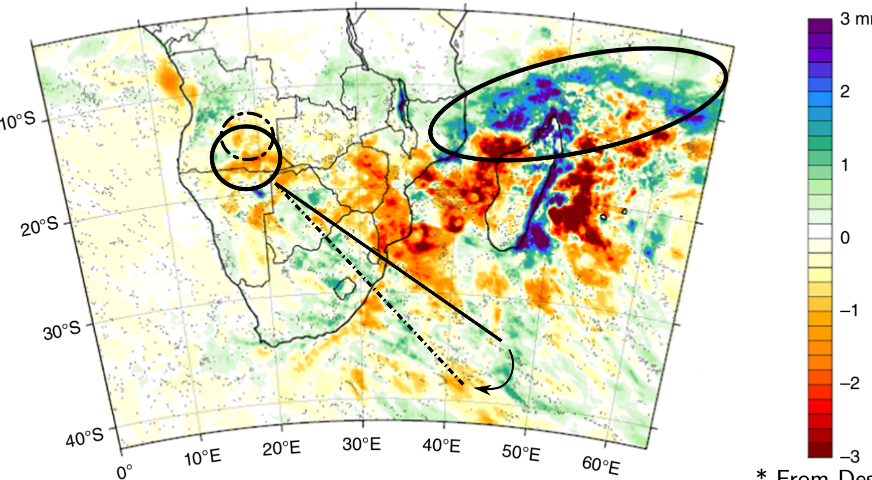


* From Desbiolles et al. [2018,2020]

Underlying mechanism: Mesoscale activity increase the **near-surface baroclinicity** of the atmosphere and significatively impact the basin-scale circulation:

➔ increase of the incoming Moisture fluxes and consequently the tropical-low activity

$$\Delta\overline{Rain}^{DJF}$$



Mesoscale Ocean

→ possible shift in the ITCZ in the Indian OCean
→ More Tropical Temperate Troughs (TTTs)
→ shitfted in the Cloud bands inclination
→ More intense Tropical-Low events

* From Desbiolles et al. [2018,2020]

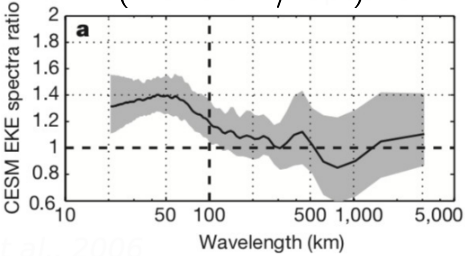
Thermal Feedback

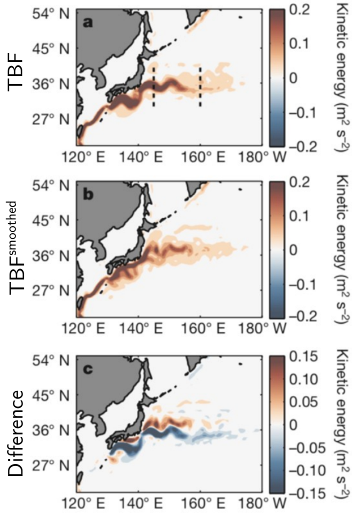
Implications for Ocean Dynamics

A partial Control of the Kuroshio by Alteration of Heat Fluxes

Ma et al. [2006]: By altering the heat fluxes and then the baroclinic instability, mesoscale TFB can induce in some regions a damping of the fine mesoscale ($< 100km$). Impact on the Kuroshio extention

Ratio of KE spectra
($TBF^{smoothed}/TBF$)





Exchange of Mechanical Energy by the Windwork: Weak direct impact

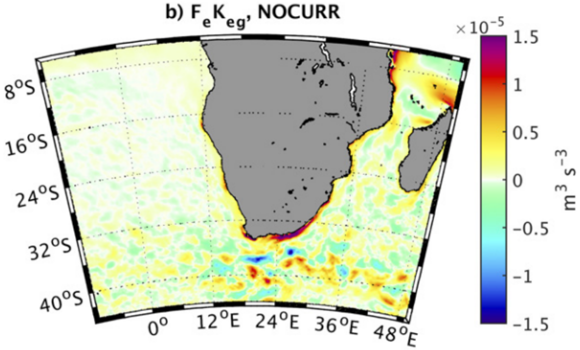
(i) the mean geostrophic mean wind work:

$$F_m K_{mg} = \frac{1}{\rho_0}(\bar{\tau_x}\bar{u_{og}} + \bar{\tau_y}\bar{v_{og}})$$

Represents the transfer of energy mean surface wind to the mean oceanic KE
Main source of energy of the ocean at basin scale

(ii) the mean geostrophic eddy wind work:

$$F_e K_{eg} = \frac{1}{\rho_0}(\tau_x' u_{og}' + \tau_y' v_{og}')$$



While TFB has a impact on the surface stress, but it only weakly alters the windwork.
Renault et al. [2017]

Mesoscale SST varibility acts on the atmospheric dynamics over the MABL.

2 main mechanisms: Donward Momentum Mixing (DMM) and Pressure Adjustment (PA)

Top-Bottom Effect: TFB first affects the entire MABL and the surface wind via the mixing and, then, the surface stress **Local and Rapid effect :**

WARM-TO-COLD $\Longrightarrow$ converging winds $\Longrightarrow$ excites upward motion $\Longrightarrow$ enhanced cloud formation $\Longrightarrow$ increased chance of Rainfall

COLD-TO-WARM $\Longrightarrow$ diverging cells $\Longrightarrow$ downward motion $\Longrightarrow$ cloud-free sky $\Longrightarrow$ decreased chance of Rainfall

Larger-scale atmospheric responses:

Oceanic mesoscale structures increase the near-surface baroclinicity of the lower atmosphere. The latter has an import impact on the regional/basin scale atmo. circulation: Alteration of extra-tropical low pressure system over the continent and the subsequent tropical-extra-tropical interactions and the development of cloudbands (a key local rainfall producer) - e.g. Southern Africa summer climate

Ocean Responses:

- Impact on heat fluxes (weak impact of momentum fluxes)
- Partial Control on some large scale Current by altering heat fluxes Important impact on Upwelling dynamics

Submesoscale effect poorly known !

Part II: Current Feedback

The **transfer of momentum** between the atmosphere and the Ocean is given by the **stress** $\vec{\tau}$

$$\vec{\tau} = \rho_a C_d (\vec{U}_{rel} \cdot |\vec{U}_{rel}|)$$

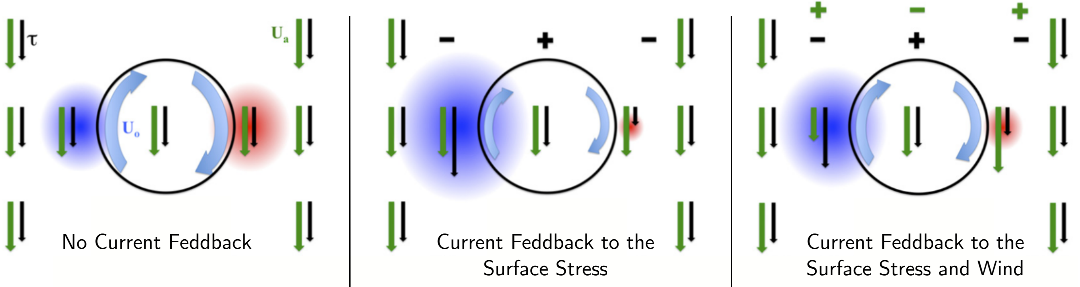
Relative motion between the two fluids, then:

$$\vec{U}_{rel} = \vec{U}_a - \vec{U}_o$$

Note that C_d is highly non-linear with $\vec{U}_{rel}$

* Duhaut and Straub 2006; Dewar and Flierl 1987; Dawe and Thompson 2006; Hughes and Wilson 2008; Eden and Dietze 2009; Seo et al., 2015,2017; Renault et al., 2016cd; Renault et al., 2017ab; Oerder et al. 2018;Renault2019abc, Renault2020ab; Jullien et al. 2020

Renault et al. [2017]

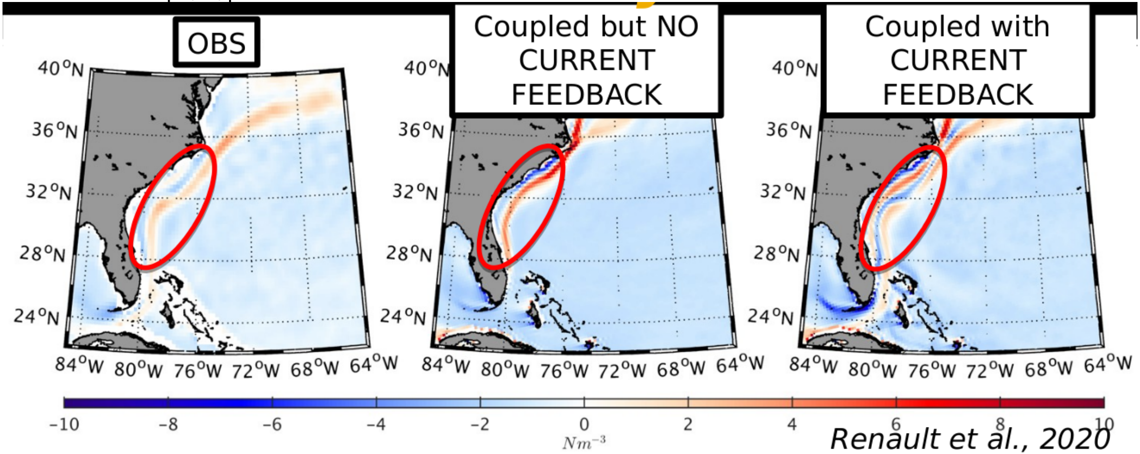


$$F_eK_e = \vec{\tau} \cdot \vec{U_o} = 0 \qquad F_eK_e = \vec{\tau} \cdot \vec{U_o} < 0 \qquad F_eK_e = \vec{\tau} \cdot \vec{U_o} < 0$$

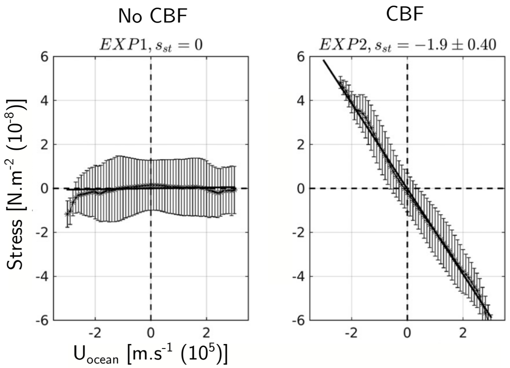
Schematic representation of the current feedback effects over an anticyclonic eddy, considering a uniform southward wind. The arrows represent the wind (green), surface stress (black), and surface current (blue). The red (blue) shade indicates a positive (negative) F_eK_e.

Not only reduction of F_eK_e but **negative** F_eK_e (Deflection of energy ocean $\Longrightarrow$ atmosphere). Partial reenergization by the atmospheric response.

Renault et al. [2020]



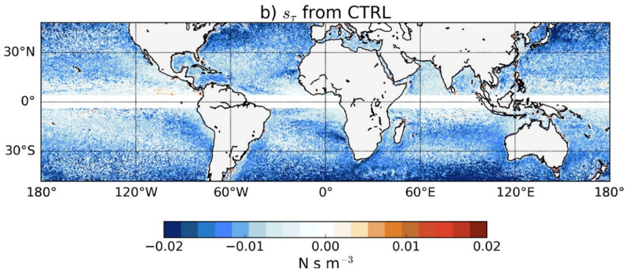
The mean currents induce a large imprint on the mean surface stress Negative correlation: positive current vorticity $\Longrightarrow$ negative stress curl



CFB Drives Mesoscale Stress: Coupling Coefficients.

Correlations between surface Current and surface stress

Definition of Coupling Coefficients s_τ : Efficiency of transfer of energy.



The more negative, the more efficient the transfer of energy from the ocean to the Atmosphere [Renault et al., 2016b;2019]

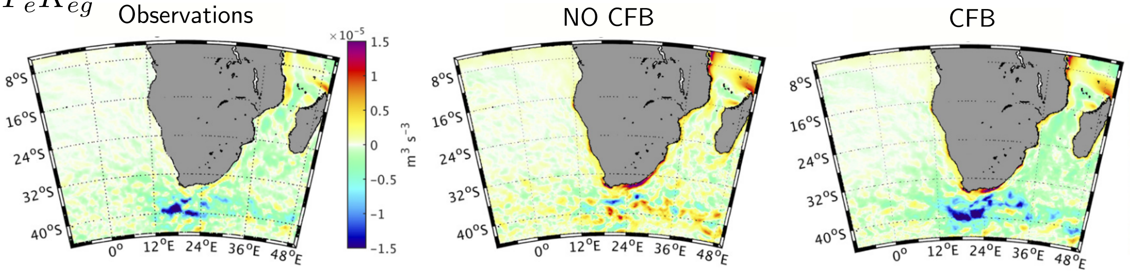
Current Feedback

Implications for Atmospheric Dynamics

Transfer of Energy from Mesoscale Eddies to the Atmosphere

Mean Eddy Windwork

$F_e K_{eg}$

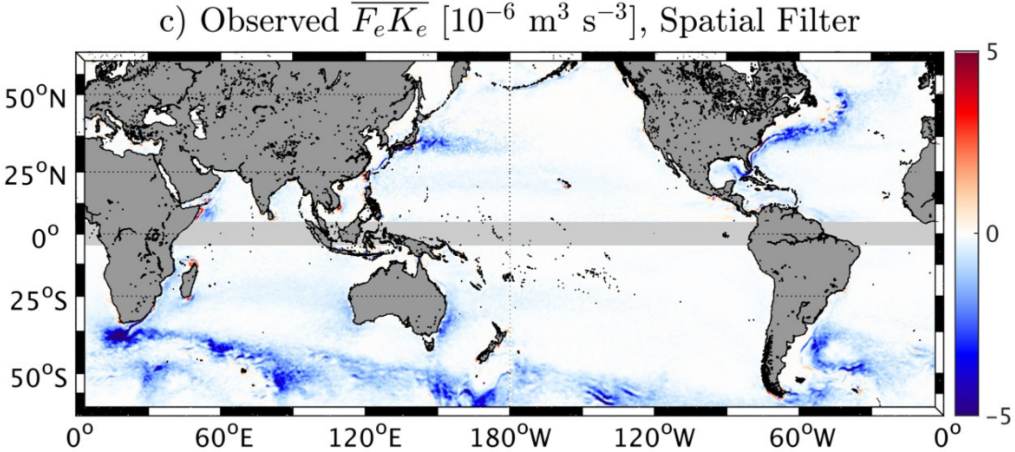


$$F_e K_{eg} = \frac{1}{\rho_0}(\tau_x' u_{og}' + \tau_y' v_{og}')$$

Negative mean eddy windwork (blue) $\Longrightarrow$ Transfer form Ocean to Atmosphere $\Longrightarrow$ partial reenergization of low-level wind !

[Renault et al., 2017a]

Globalisation of that Result:



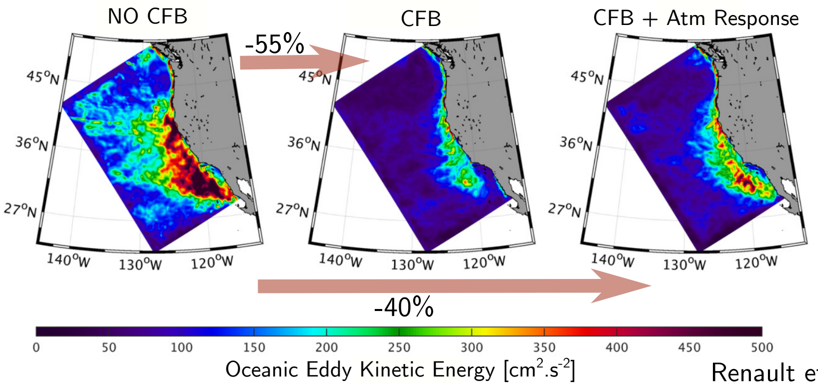
Renault et al. [2017b]

Current Feedback

Implications for Ocean Dynamics

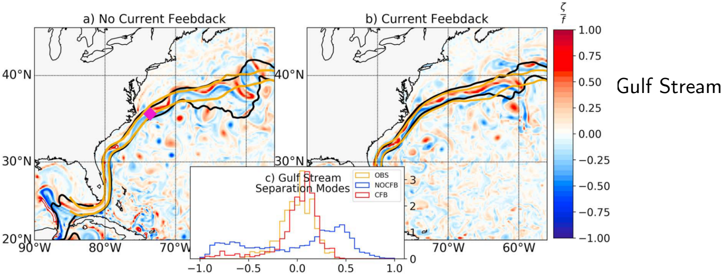
Large Effect on Mesoscale Activity: Eddy Killig

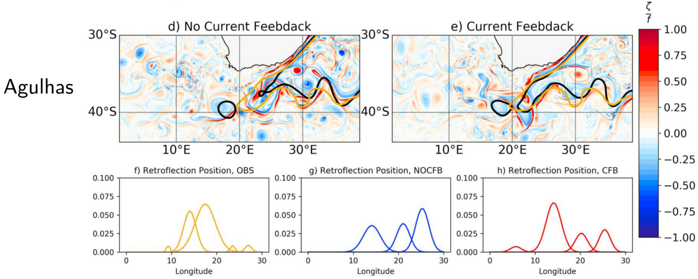
- Slow Down the mean circulation
- Sinks of Energy from Mesoscale Current to the Atmosphere
- Dampening of the EKE.. but with a partial **re-energization** by taking account the wind response



Renault et al. [2016c]

Control of the Western Boundary





Renault et al. [2019b]

- CFB has a bottom-top effect: modify the stress and then the wind
- Current feedback to the Atmosphere has a crucial role in determining the energy exchange and oceanic circulation
- Induces sink of energy from the Ocean to the Atmosphere
- Large Dampening of the Mesoscale Activity (submesoscale too)
- Control of Western Boundary Current by reducing the eddy-mean flow interactions

Some Refs

Non exhaustive list:

Jullien et al. [2020]
Renault et al. [2016ab;2017ab;2018;2019abc;2020ab]
Desbiolles et al. [2018;2020;2021;2022]
Seo et al. [2016; 2017]
Pasquero et al. [2021]
Meroni et al [2020;in press]
Chelton et al. [2007]
Small et al. [2008]

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CONTACT:
fabien.desbiolles@unimib.it