



Advanced Summer School

Modelaciòn Aplicada del Océano



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

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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

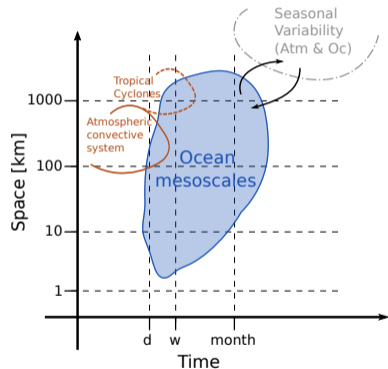
(i) How the atmosphere control **UPPER-OCEAN** variability and **thermodynamics** properties.

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

- Upscaling effect (reverse cascade of energy)

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

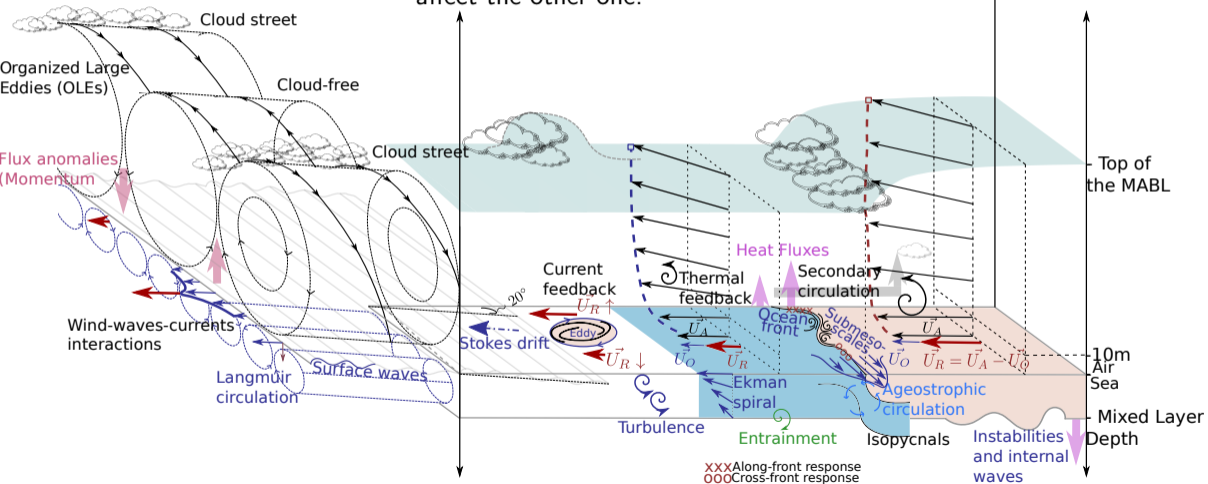
Mesoscale Range



AIR-SEA INTERACTIONS

Normal conditions

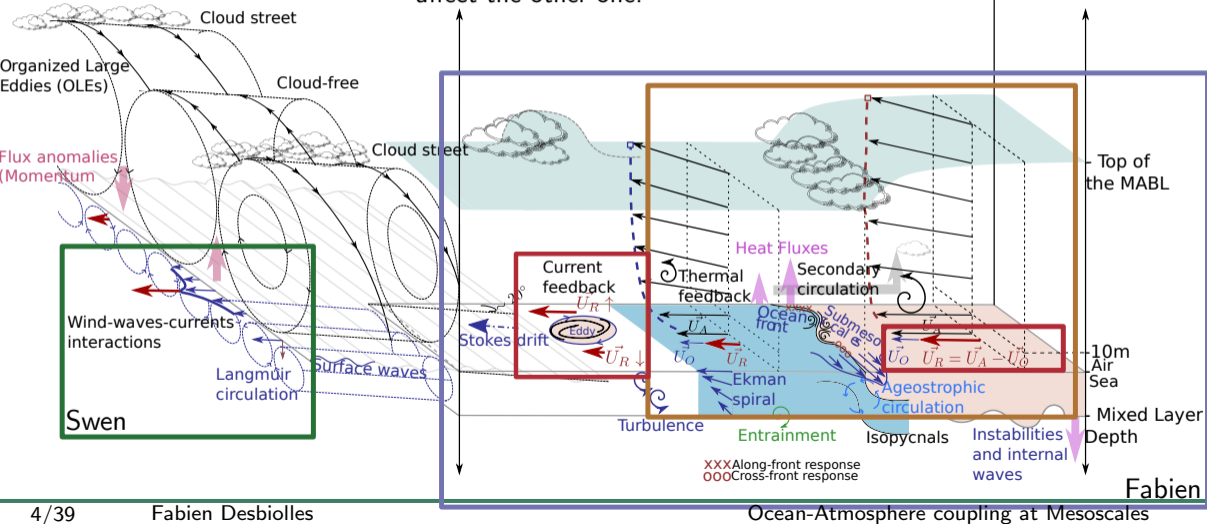
Processes of the upper-ocean and lower-atmosphere. Dynamical unbalanced at the interface, both fluids affect the other-one.



AIR-SEA INTERACTIONS

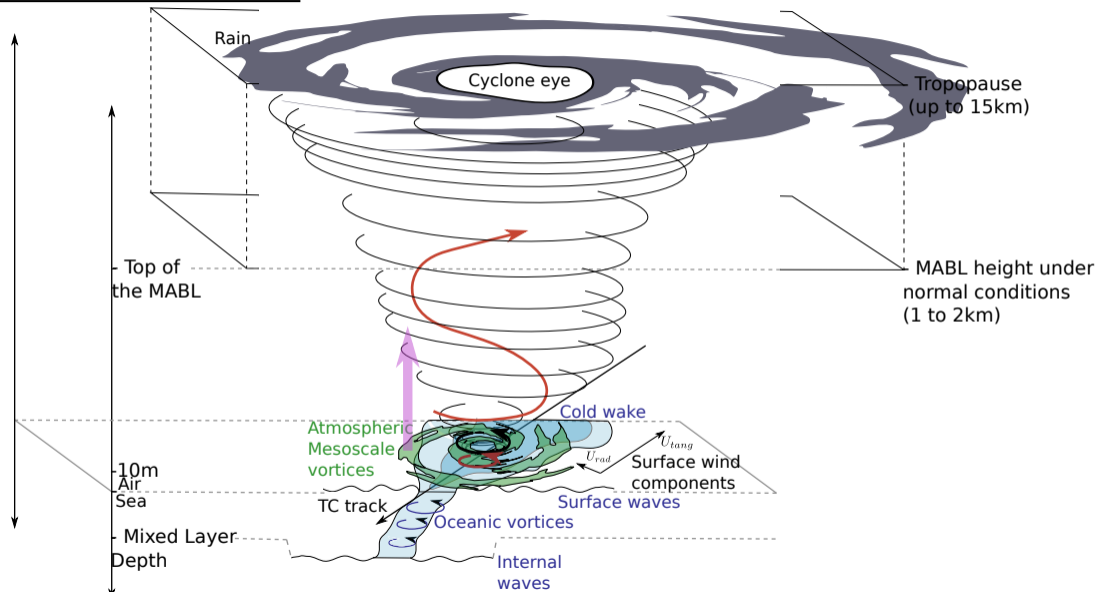
Normal conditions

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



- ① Forwards
- ② Thermal Feedback
 - 2.1 Introduction
 - 2.2 Downward Momentum Mechanism
 - Local effect over the full MABL
 - Atmospheric column, clouds and rain Responses
 - 2.3 Pressure Adjustment mechanism
 - Local effect over the full MABL
 - Temporal scales
 - 2.4 Implications for Atmosphere Dynamics
 - 2.5 Implications for Ocean Dynamics
 - 2.6 Take home messages
- ③ Current Feedback
 - 3.1 Basic concept
 - 3.2 Effect on Surface Stress
 - 3.3 Effects on Low-level Atmosphere
 - 3.4 Effect on Ocean Dynamics
 - 3.5 Take home messages
- ④ General Conclusion

Thermal Feedback

Different behavior at different scales

Basin Scales

Atmosphere \Rightarrow **Wind and heat fluxes** \Rightarrow **Ocean**

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

Atmosphere drives Ocean

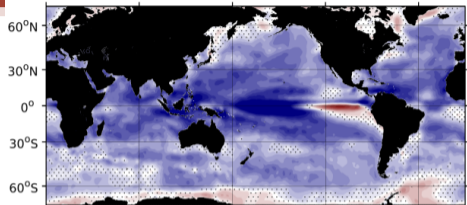
Mesoscale Scales

Atmosphere \Leftarrow **SST fronts** \Leftarrow **Ocean**

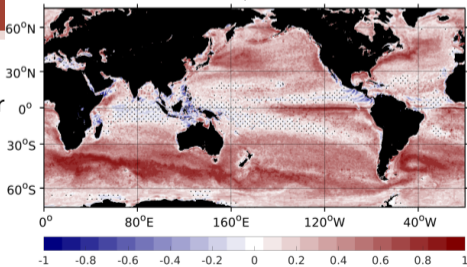
Ocean fronts \Rightarrow enhanced (reduced) wind speed over warmer (colder) SST. **POSITIVE CORRELATION** between SST and surface wind speed. **FEEDBACK LOOP**

Ocean drives Atmosphere

(a)
Correlation between wind speed and SST at large scales



(b)
Correlation between wind speed and SST at small scales



* From Pasquero et al. [2020]

Ocean-Atmosphere coupling at Mesoscales

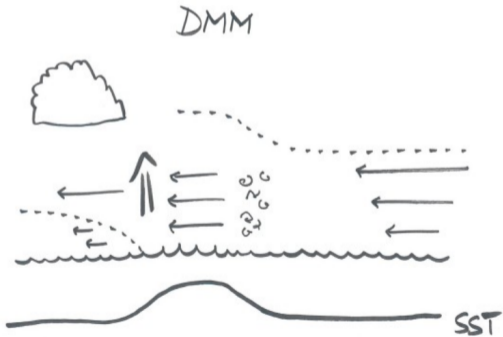
Thermal Feedback

Two main mechanisms: DMM and PA

Downward Momentum Mixing - DMM

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

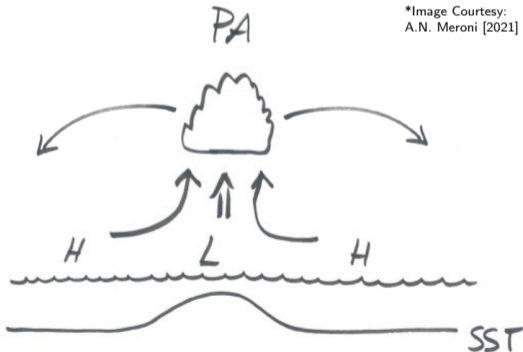
$$\nabla \cdot \vec{u} = \alpha_{DM} \nabla SST$$



Pressure Adjustment - PA

A secondary 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.

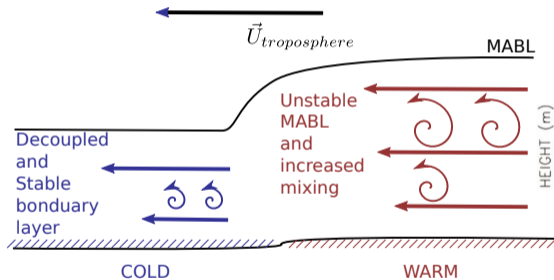
Thermal Feedback

Downward Momentum Mechanism: Local and Rapid effects

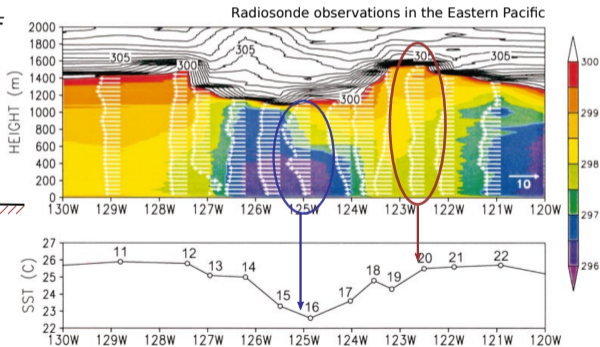
Eddies and **fronts** alter the stability of the Marine Atmospheric Boundary Layer (MABL).

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

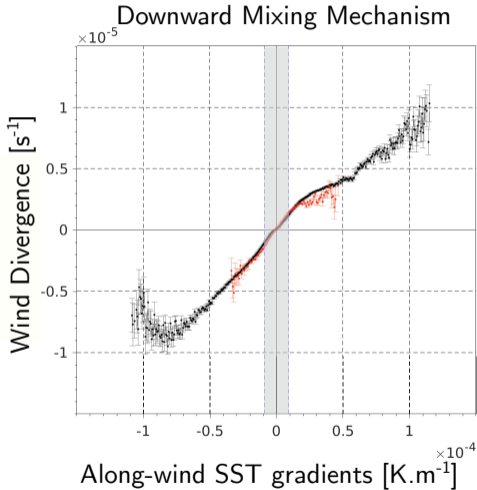
$$\nabla \cdot \vec{u} = \alpha_{DM} \nabla SST \quad (\text{at mesoscale})$$



** Adapted from Hyodae Seo [2014]



Hashizume et al. [2012]



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

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

⇒ The slope of this relationship is the coupling coefficient.

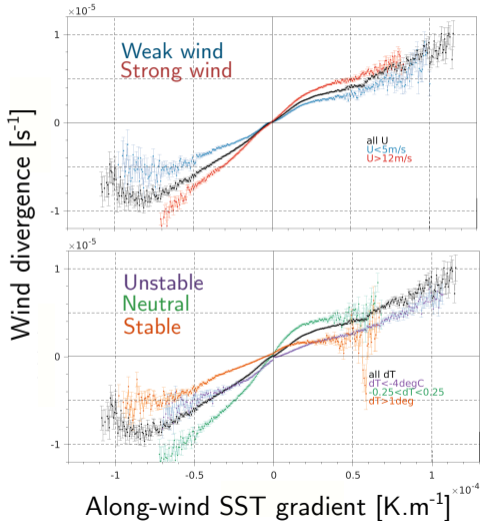
Environmental condition DMM depends upon ??

Thermal Feedback

Downward Momentum Mechanism: Local and Rapid effect

*From Desbiolles et al. [in

Downward Momentum Mixing



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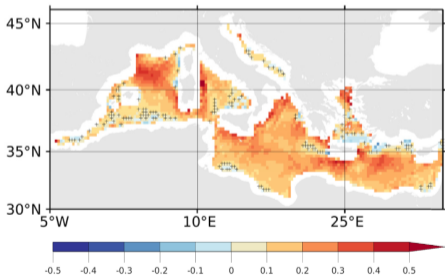
Environmental conditions DMM depend upon ??

Thermal Feedback

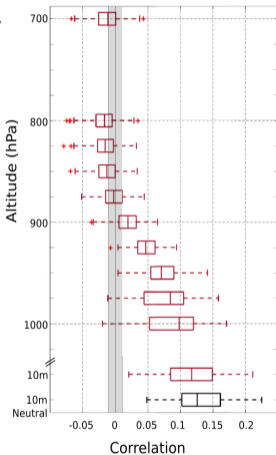
Downward Momentum Mechanism: MABL responses

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**

Thermal Feedback

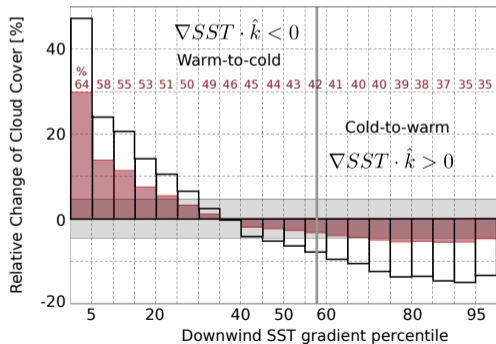
Downward Momentum Mechanism: Cloud and Rain responses

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

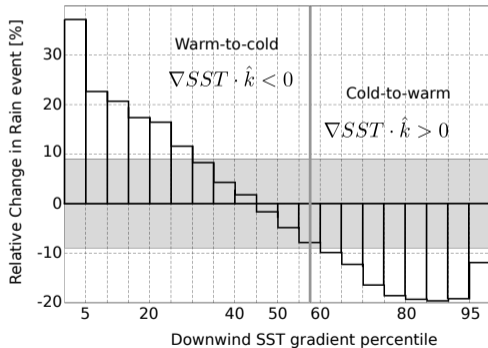
Winds is blowing from **warm to cold** patches $\implies \nabla SST \cdot \hat{k} < 0$

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

Cloud Cover



Rainfall



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

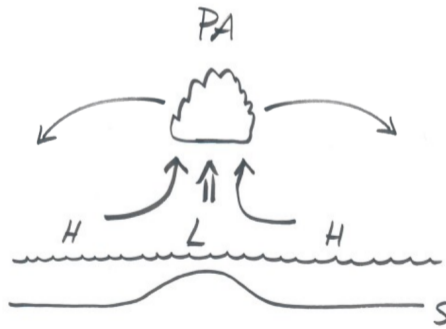
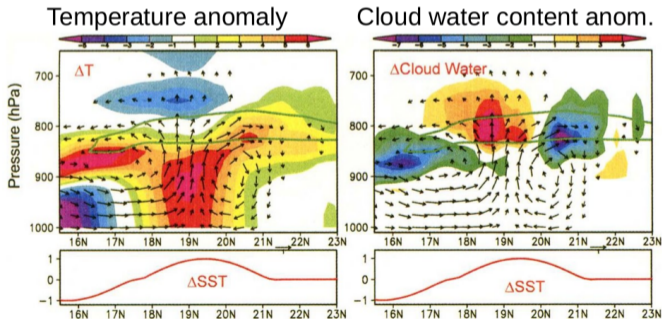
Thermal Feedback

Pressure Adjustment Mechanism

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.

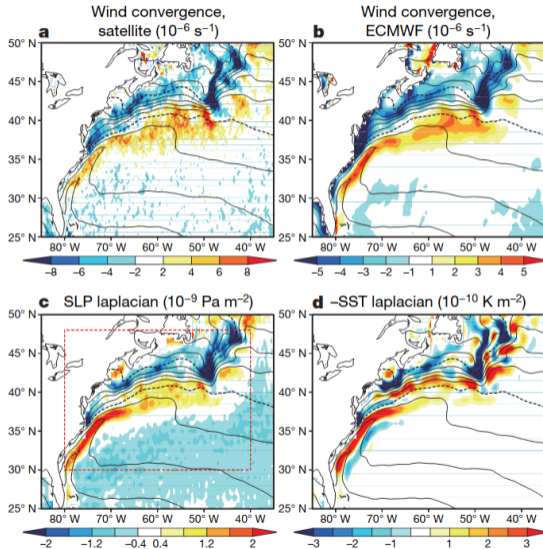
$$\nabla \cdot \vec{u} = \alpha_{PA} \nabla^2 SST \quad (\text{at mesoscale})$$

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.]



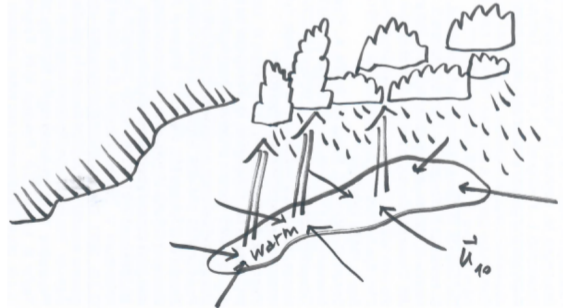
Thermal Feedback

Pressure Adjustment Mechanism: Temporal scales



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

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



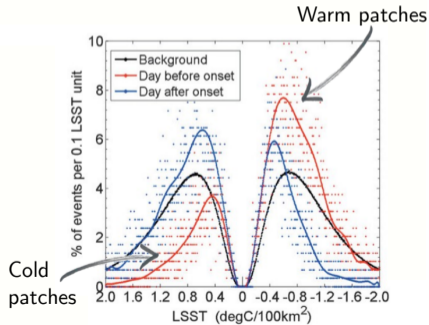
Ocean-Atmosphere coupling at Mesoscales

Thermal Feedback

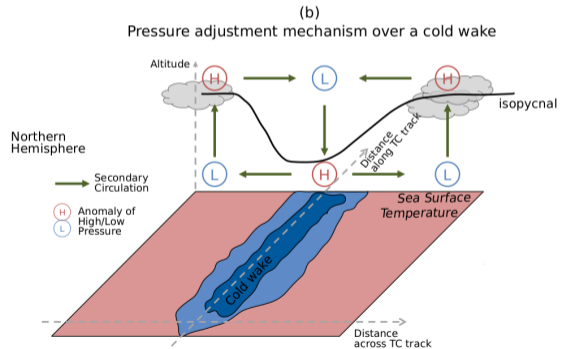
Pressure Adjustment Mechanism: Temporal scales

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.



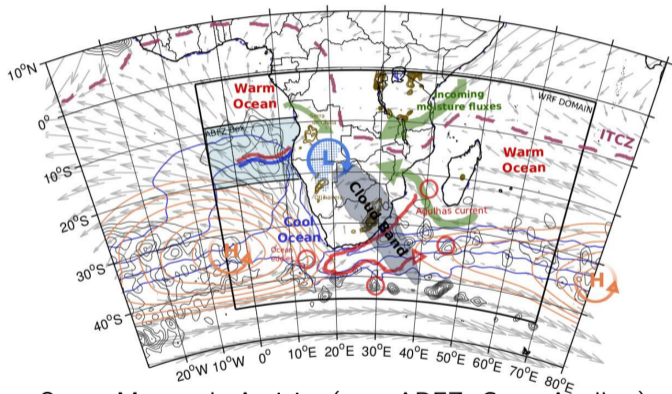
Thermal Feedback

Implications for Atmospheric Dynamics

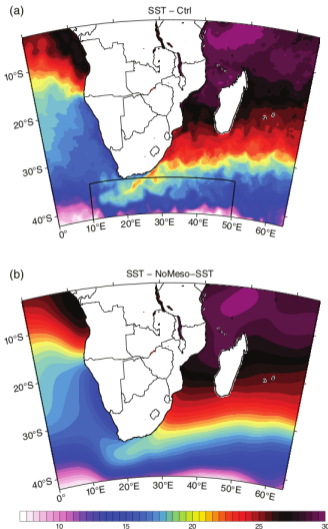
Thermal Feedback

Implication for Atmosphere Dynamics

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



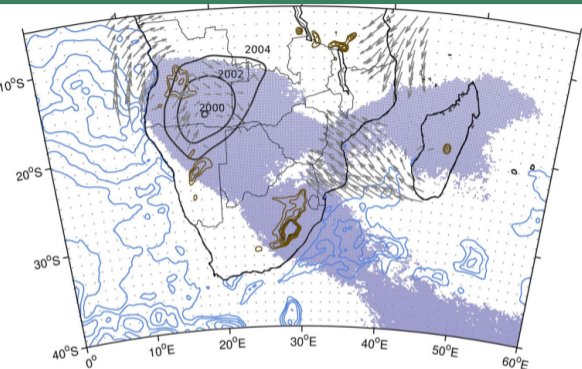
Ocean Mesoscale Activity (e.g., ABFZ, Great Agulhas), Incoming moisture fluxes, Low-pressure system which leads to Cloud band and Rainfall



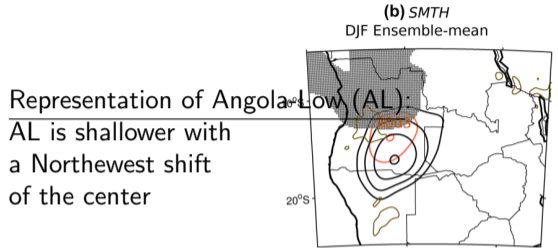
* From Desbiolles et al. [2018,2020]

Thermal Feedback

Implication for Atmosphere Dynamics

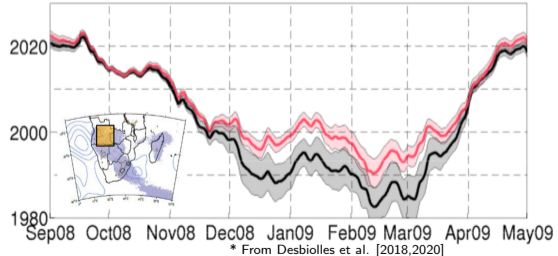


Underlying mechanism: Mesoscale activity increase the **near-surface baroclinicity** of the atmosphere and significantly impact the basin-scale circulation:
 → increase of the incoming Moisture fluxes and consequently the tropical-low activity



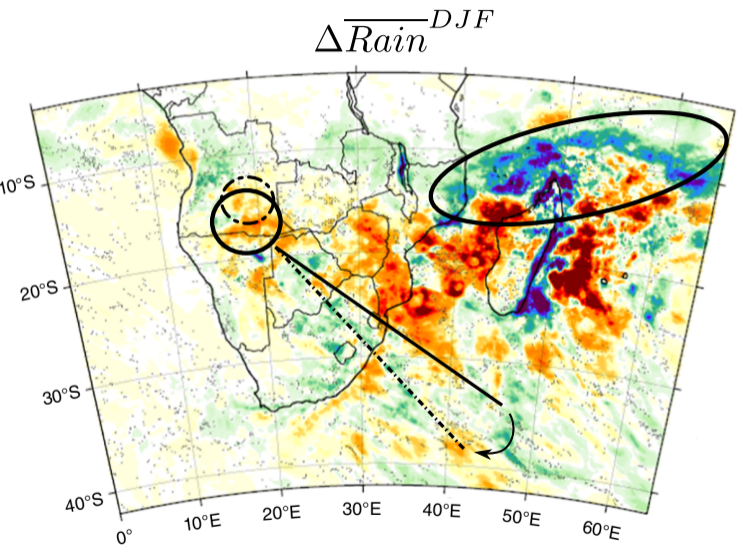
Representation of Angola Low (AL):
 AL is shallower with a Northwest shift of the center

(a) Minimum of 800 hPa gph
 CTRL vs SMTH

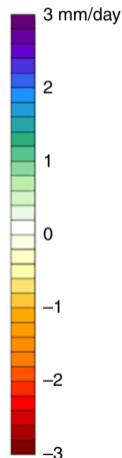


Thermal Feedback

Implication for Atmosphere Dynamics



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



Mesoscale Ocean

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

* From Desbiolles et al. [2018,2020]

Thermal Feedback

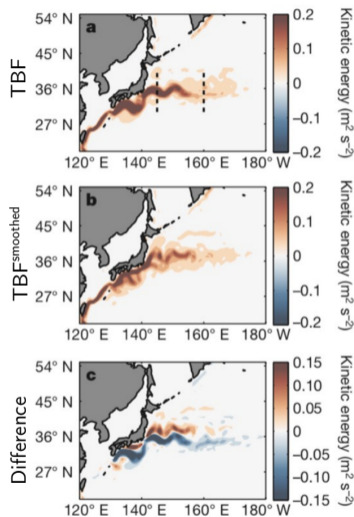
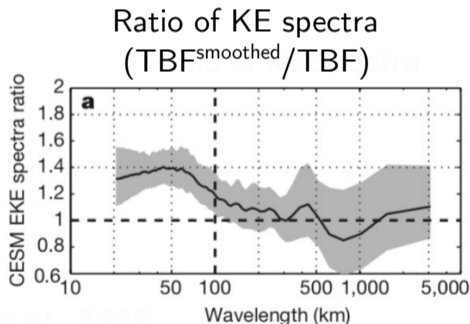
Implications for Ocean Dynamics

Thermal Feedback

Implication 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 extension



Exchange of Mechanical Energy by the Windwork: Weak direct impact

(i) the mean geostrophic mean wind work:

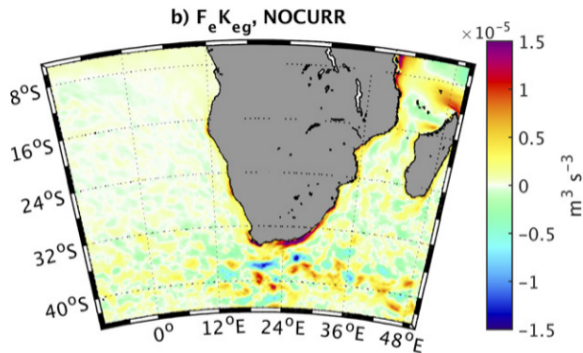
$$F_m K_{mg} = \frac{1}{\rho_0} (\bar{\tau}_x \bar{u}_{og} + \bar{\tau}_y \bar{v}_{og})$$

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]

Thermal Feedback

Take home messages

Mesoscale SST variability 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 \implies converging winds \implies excites upward motion \implies enhanced cloud formation \implies increased chance of Rainfall

COLD-TO-WARM \implies diverging cells \implies downward motion \implies cloud-free sky \implies 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:

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

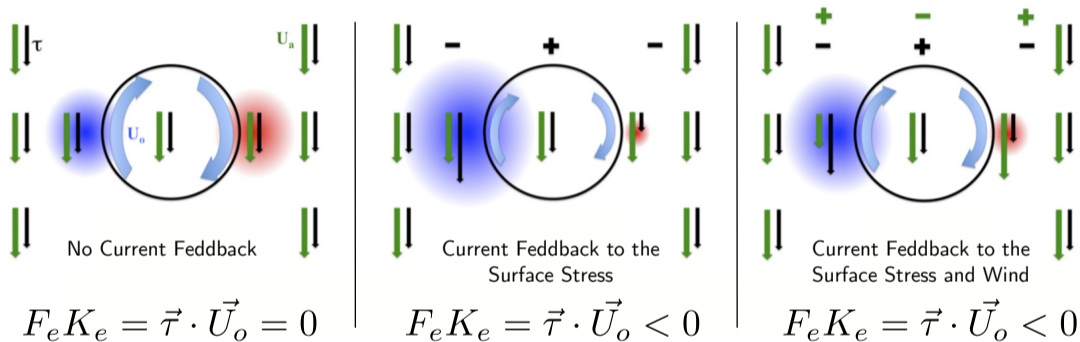
Note that C_d is highly non-linear with \vec{U}_{rel}

* 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

Current Feedback

Basic concepts

Renault et al. [2017]



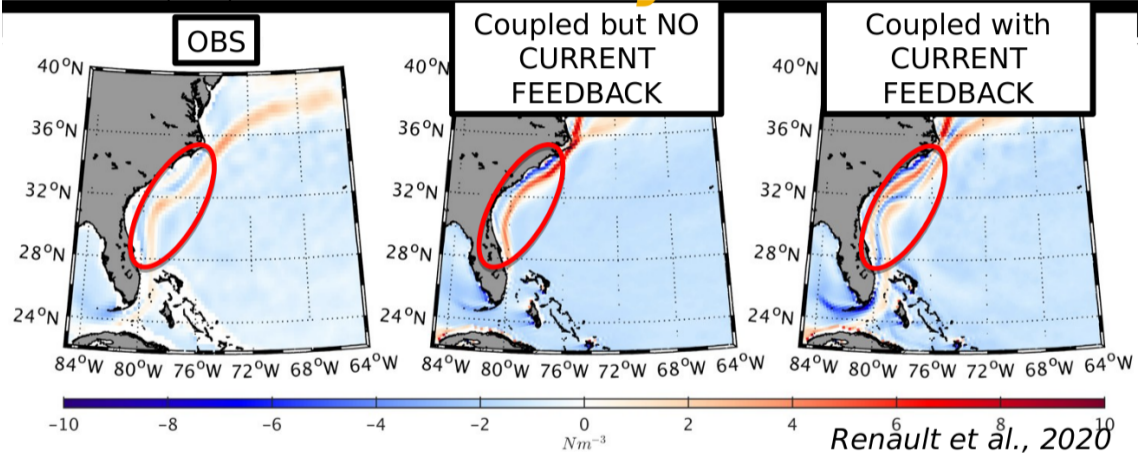
Schematic representation of the current feedback effects over an anticyclonic eddy, considering a uniform southward wind. The arrows represent the wind (green), surface stress (black), and surface current (blue). The red (blue) shade indicates a positive (negative) $F_e K_e$.

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

Current Feedback

Effect on Surface Stress

Renault et al. [2020]

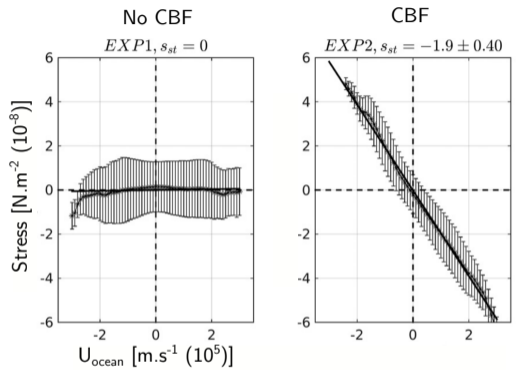


Renault et al., 2020

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

Current Feedback

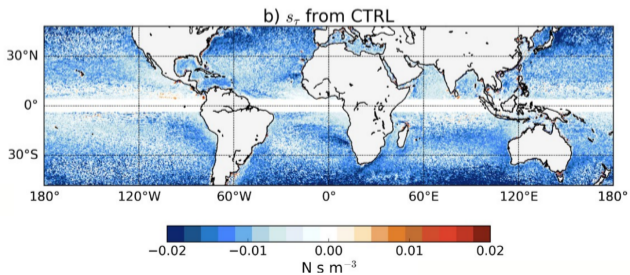
Effect on Surface Stress



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

CBF Drives Mesoscale Stress: Coupling Coefficients. Correlations between surface Current and surface stress

Definition of Coupling Coefficients s_{τ} : Efficiency of transfer of energy.



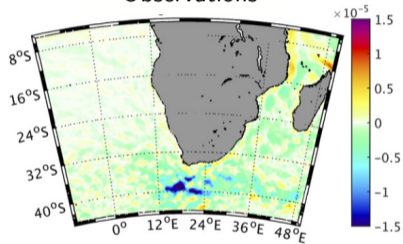
Current Feedback

Implications for Atmospheric Dynamics

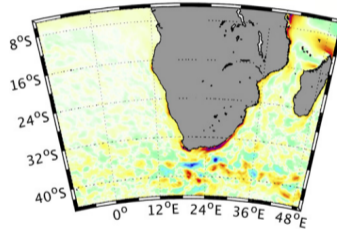
Transfer of Energy from Mesoscale Eddies to the Atmosphere

Mean Eddy Windwork

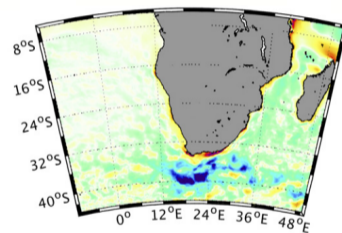
$F_e K_{eg}$ Observations



NO CFB



CFB



$$F_e K_{eg} = \frac{1}{\rho_0} (\tau'_x u'_{og} + \tau'_y v'_{og})$$

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

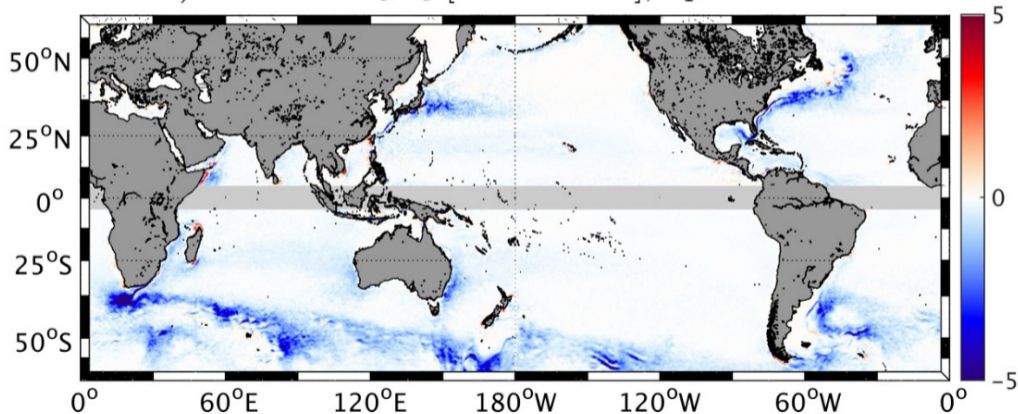
[Renault et al., 2017a]

Current Feedback

Surface atmospheric response in term of energy

Globalisation of that Result:

c) Observed $\overline{F_e K_e}$ [$10^{-6} \text{ m}^3 \text{ s}^{-3}$], Spatial Filter



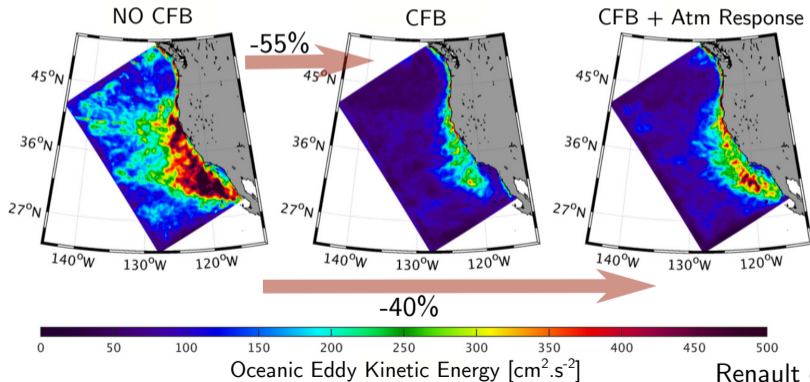
Renault et al. [2017b]

Current Feedback

Implications for Ocean Dynamics

Large Effect on Mesoscale Activity: Eddy Killig

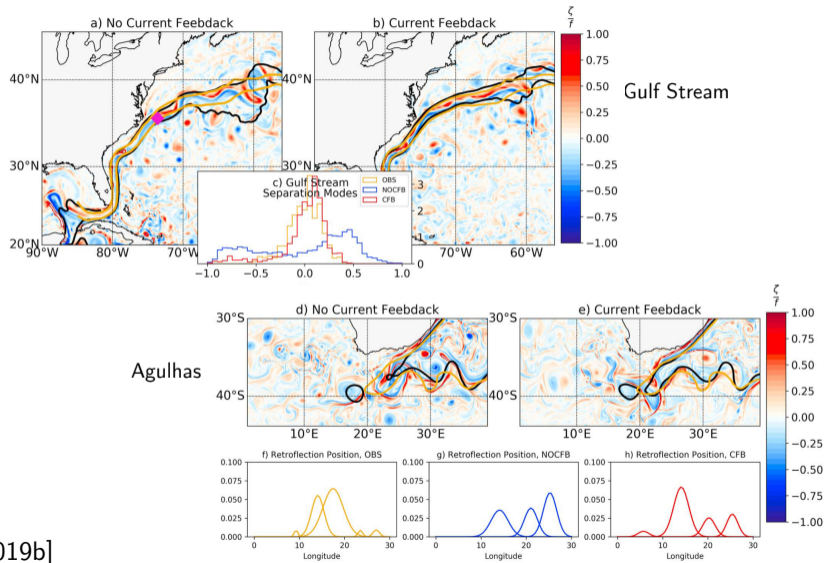
- Slow Down the mean circulation
- Sinks of Energy from Mesoscale Current to the Atmosphere
- Dampening of the EKE.. but with a partial **re-energization** by taking account the wind response



Renault et al. [2016c]

Current Feedback Effect on Ocean Dynamics

Control of the Western Boundary



Renault et al. [2019b]

Current Feedback

Take home message

- 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

Non exhaustive list:

- Jullien et al. [2020]
Renault et al. [2016ab;2017ab;2018;2019abc;2020ab]
Desbiolles et al. [2018;2020;2021; in prep]
Seo et al. [2016; 2017]
Pasquero et al. [2021]
Meroni et al [2020;in press]
Chelton et al. [2007]
Small et al. [2008]
Voldoire et al. [2017]:
Coupling with OASIS within SURFEX (in discussion
online [HERE](#)

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