

1. Model set up for the Marquesas archipelago
2. Investigating the island wake
3. Investigating the island mass effect
4. Conclusions et perspectives

# Processus physiques et biogéochimiques impliqués dans l'effet d'île dans l'archipel Marquises

Soutenance de Thèse – 13 septembre 2018

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Elodie MARTINEZ  
Keitapu MAAMAATUAIAHUTAPU

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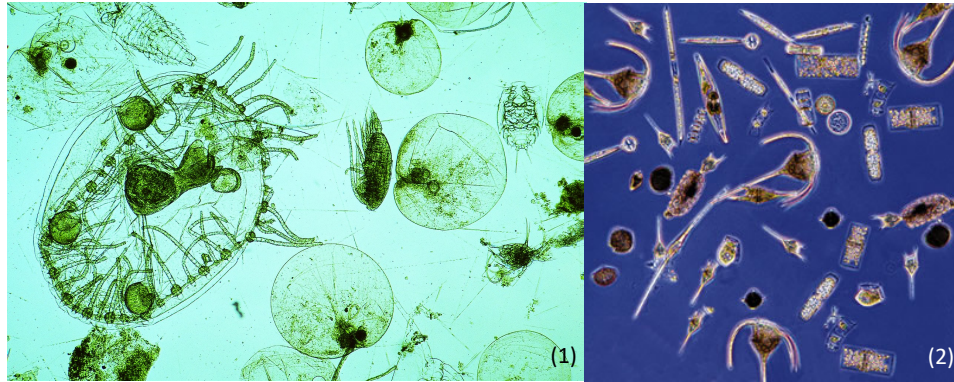
Why does it matter ?

The Marquesas : a hotspot in the Pacific Ocean

Why study this IME ?

How to study this IME ?

# Why does it matter ?



Phytoplankton :  
Microalgae similar to terrestrial plants

Photosynthesis = Light + Nutrients  
(Fe, NO<sub>3</sub>, PO<sub>4</sub>, Si, ...)  
=> O<sub>2</sub> production



Equivalent O<sub>2</sub> source (50%)

(1) [http://www.plancton-du-monde.org/module-formation/ou\\_vit\\_le\\_plancton2.html](http://www.plancton-du-monde.org/module-formation/ou_vit_le_plancton2.html)  
(2) Richard Davidson, courtesy of U.K. Fisheries Research Service  
(3) [https://www.huffingtonpost.com/paul-falkowski/taking-the-oxygen-out-of-the-room\\_b\\_8012378.html](https://www.huffingtonpost.com/paul-falkowski/taking-the-oxygen-out-of-the-room_b_8012378.html)



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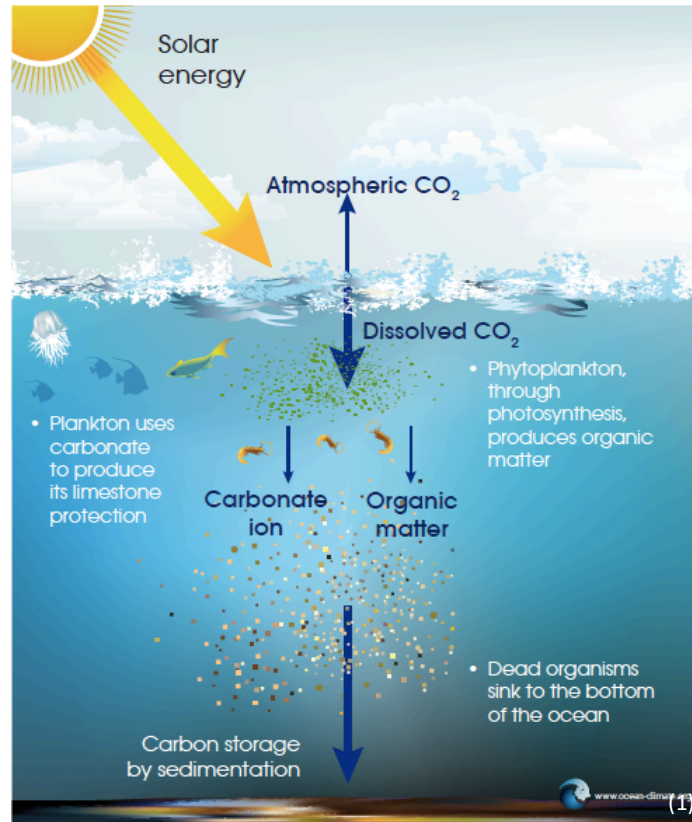
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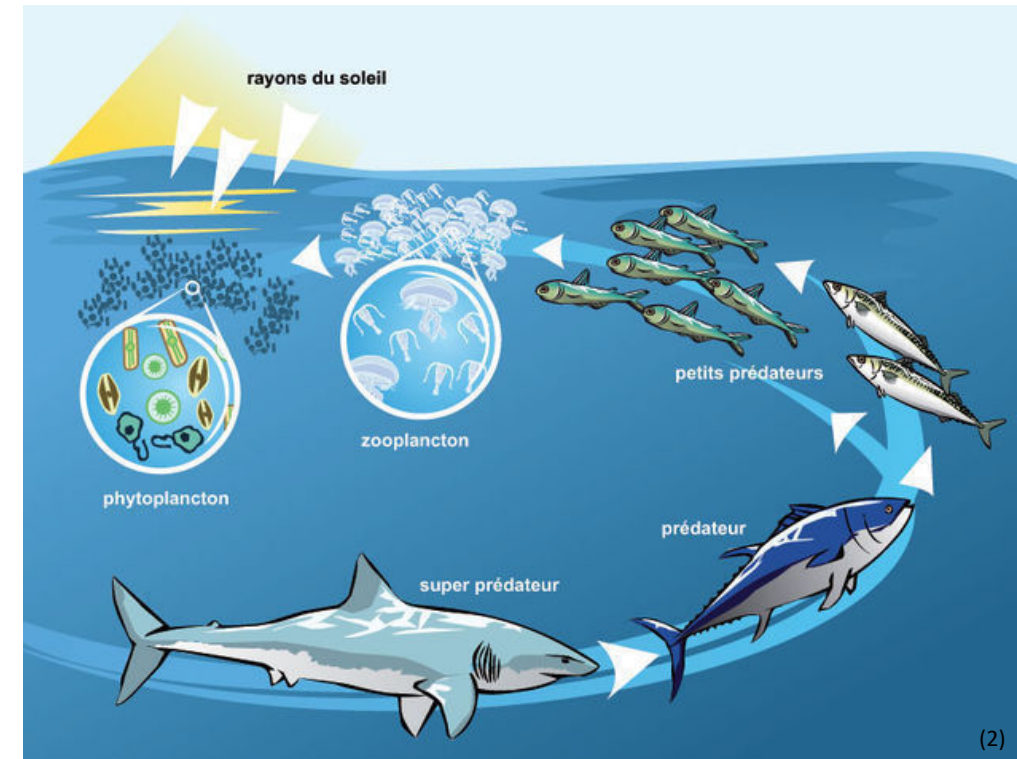
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# Why does it matter ?



CO<sub>2</sub> uptake from the atmosphere

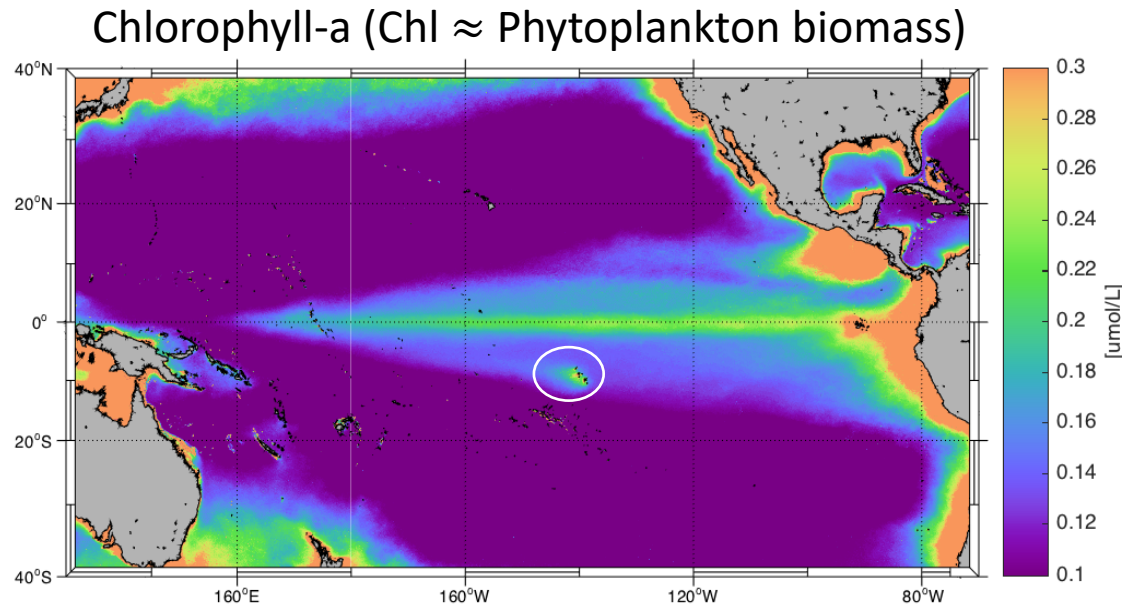


Key role for marine food chain  
=> Fundamental for insulated populations

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The phytoplankton : the base of marine food web  
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# The Marquesas : a hotspot in the Pacific Ocean



Between mesotrophic (equator)  
and oligotrophic area (subtropical gyre)

## Island Mass Effect:

A biological enrichment due to the presence of islands



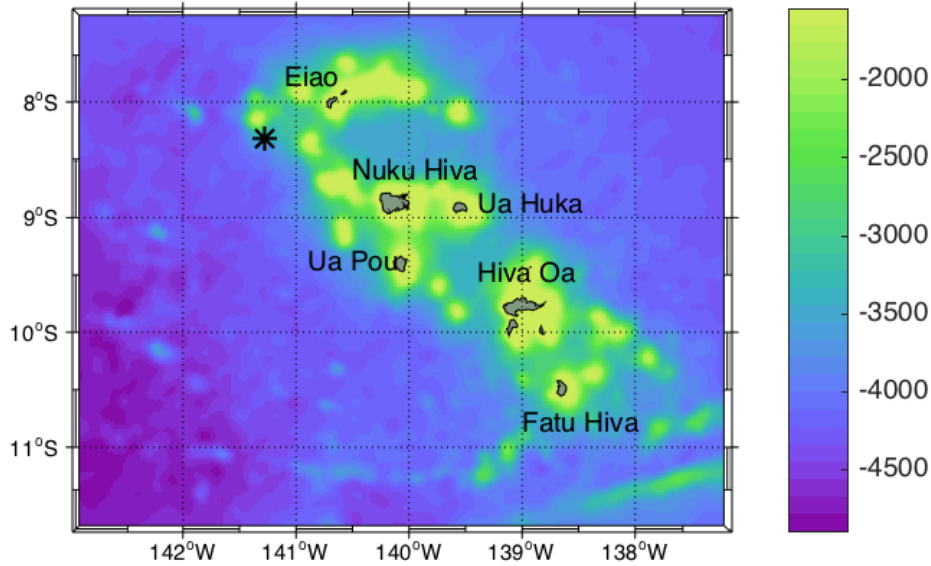
Archipelago rich in pelagic fishes  
(Tunas, Mahi-mahi, ...)



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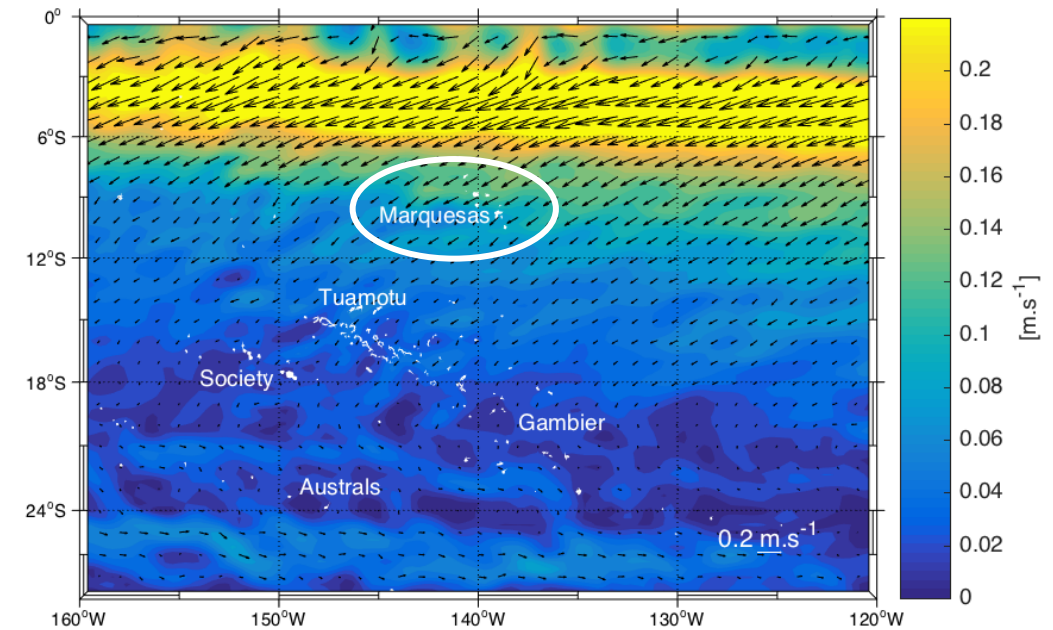
The phytoplankton : the base of marine food web  
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# The Marquesas : a hotspot in the Pacific Ocean



Archipelago :

- Dozen of volcanic islands
- Steep bathymetry
- Diameters < 30 km



SEC : South Equatorial Current

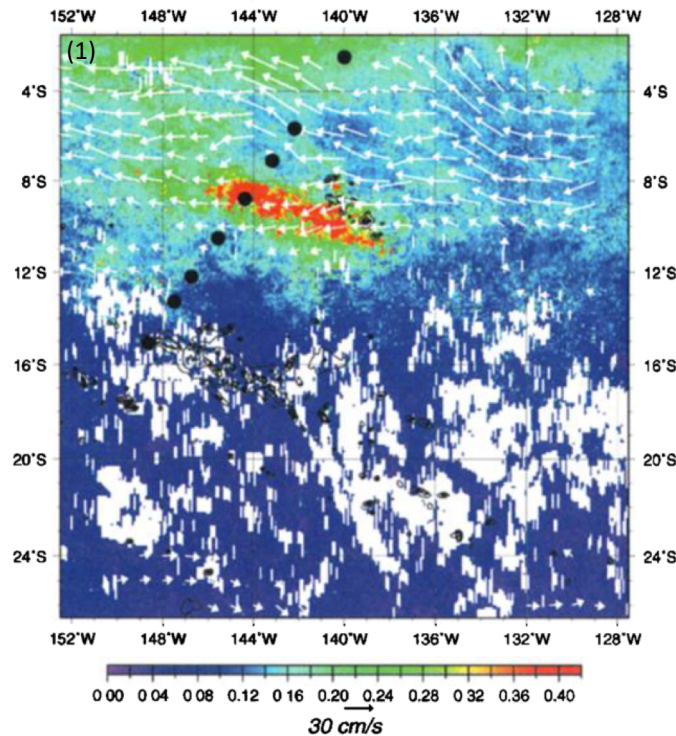


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# Why study this IME ?

## Poorly studied



Signorini et al. 1999

## *Remote sensing*

Signorini et al. 1999 :

Extended plume during La Niña  
Turbulent mixing + Advection

Martinez and Maamaatuaiahutapu 2004 :  
Seasonal, Episodic, La Niña blooms

**Hyp** : Turbulent mixing + Advection  
+ Land drainage + Hydrothermal ?

## *Oceanographic cruises*

BIOSOPE (2004)

=> **Mechanisms not understood**

TARA (2011)

Pakaihi i te Moana (2012)



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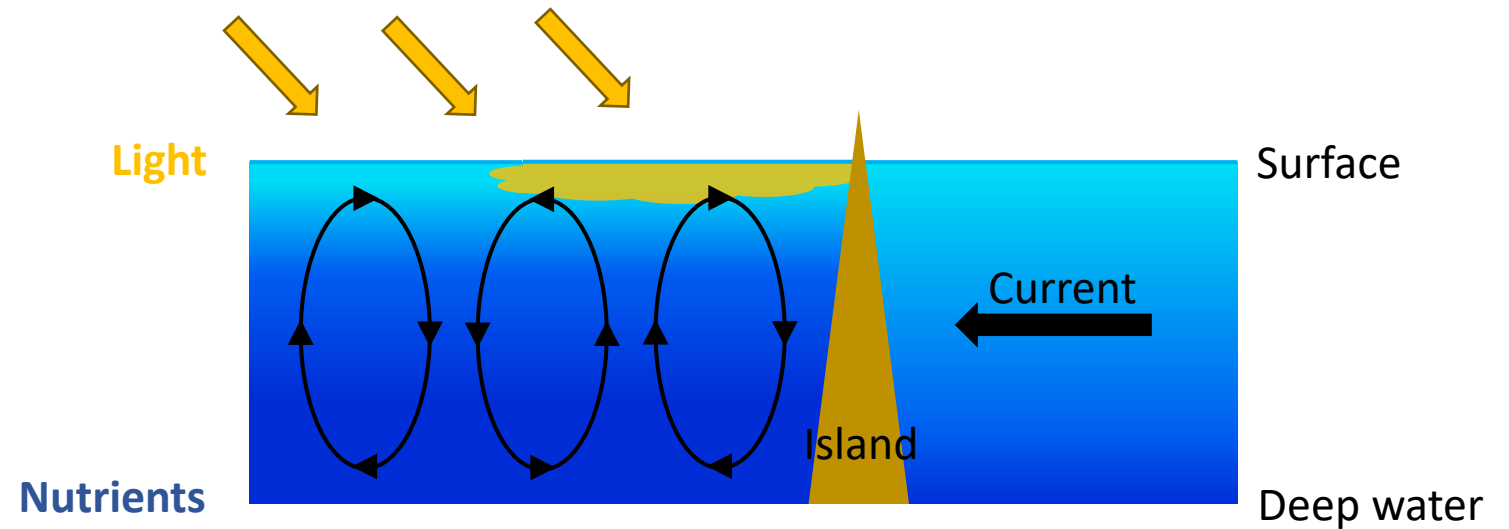
The phytoplankton : the base of marine food web  
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Why study this IME ?  
How to study this IME ?

## How to study this IME ?

Phytoplankton growth : **Nutrients + Light**

Surface : Light availability

Deep water : Nutrient rich



Turbulent mixing, input from the islands, upwelling, ...

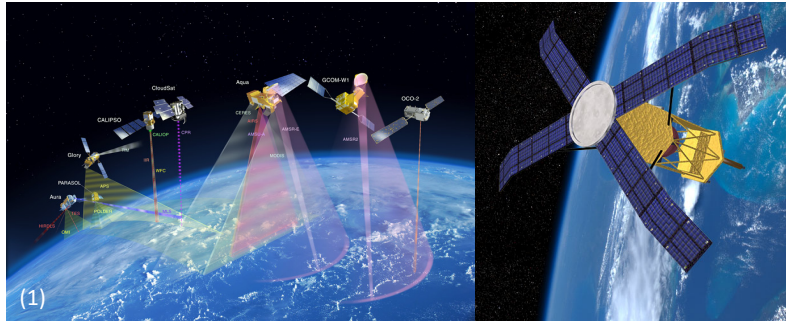
**Nutrient enrichment of surface waters**

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## How to study this IME ?

### Remote sensing

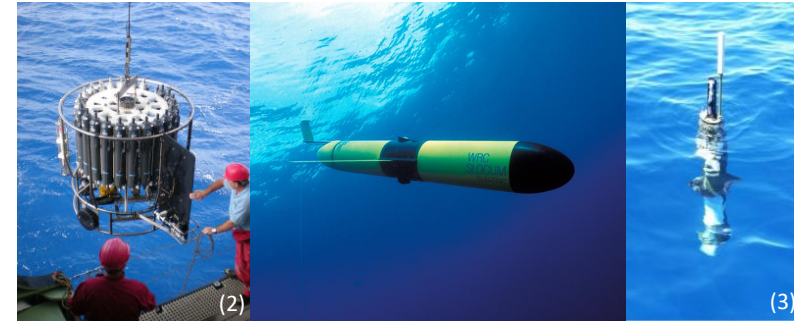


- No information on the vertical
- Limited spatial resolution (few-100 km)

### Numerical modeling

- No spatial or temporal limitation

### In-situ measurements



- No temporal and/or spatial tracking
- Very few measurements

**=> Allow resolving processes**

(1) <http://innovim.com/remote-sensing-earth-or-asteroid-its-all-about-instruments/>

(2) <http://www.thesearethevoyages.net/jc44/ctd.html>

(3) <https://lejournal.cnrs.fr/diaporamas/ces-robots-que-vous-croiserez-peut-etre-dans-un-laboratoire>

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## Objective

Characterizing the processes and their seasonal variability  
implied in the Marquesas island mass effect

## **1. Model set up for the Marquesas archipelago**

- Comparison of several implementations

## **2. Investigating the island wake**

- Dynamical properties of the island wake

## **3. Investigating the island mass effect**

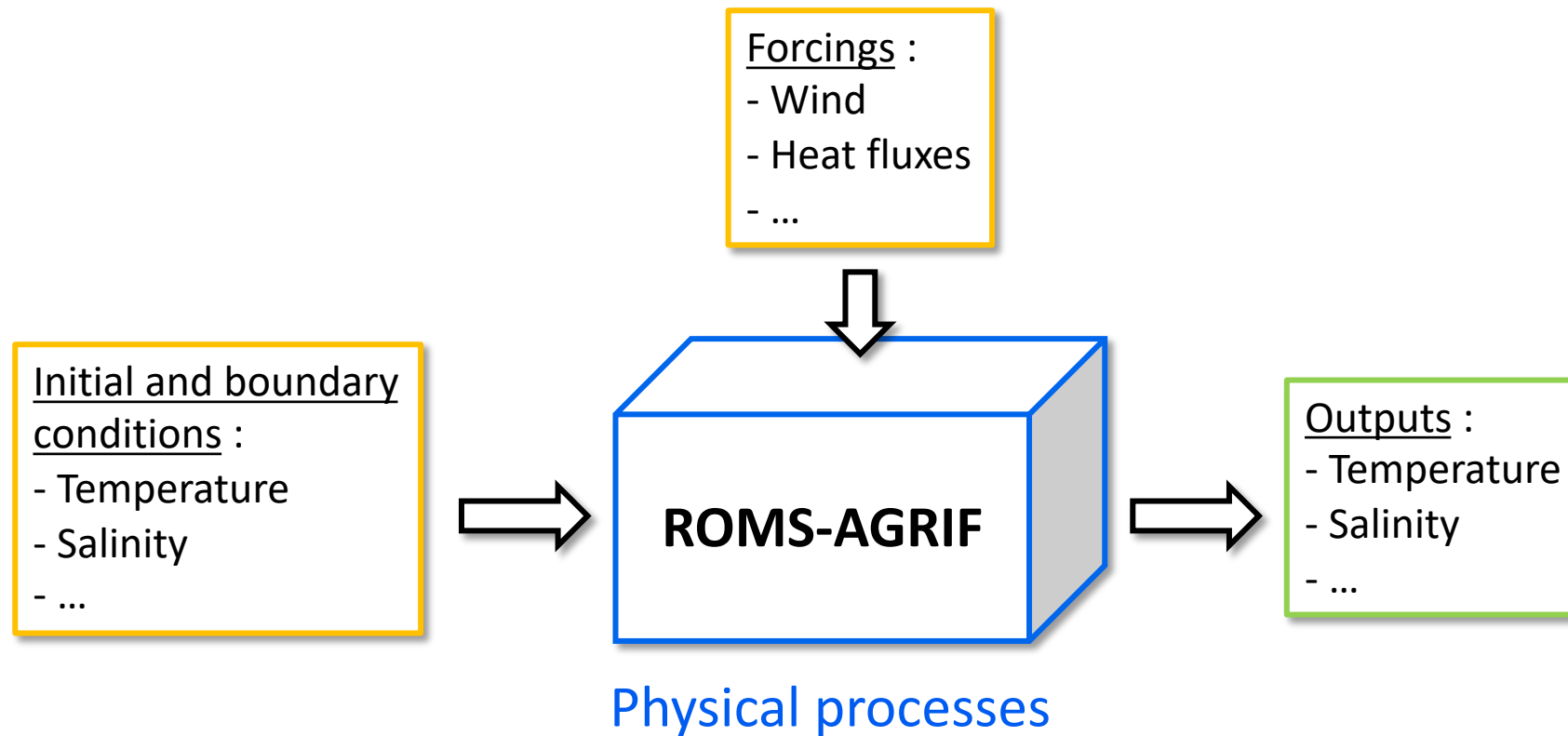
- Biogeochemical properties of the island wake

## **4. Conclusions & perspectives**

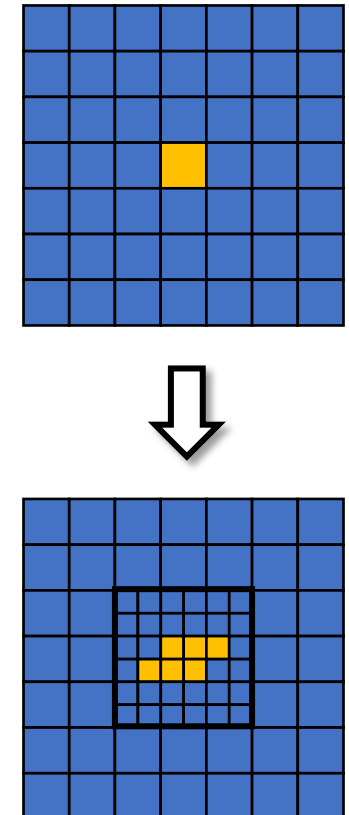


# ROMS-Agrif configurations

## Regional Ocean Modeling System – Adaptive Grid Refinement in Fortran



### Embedding grids

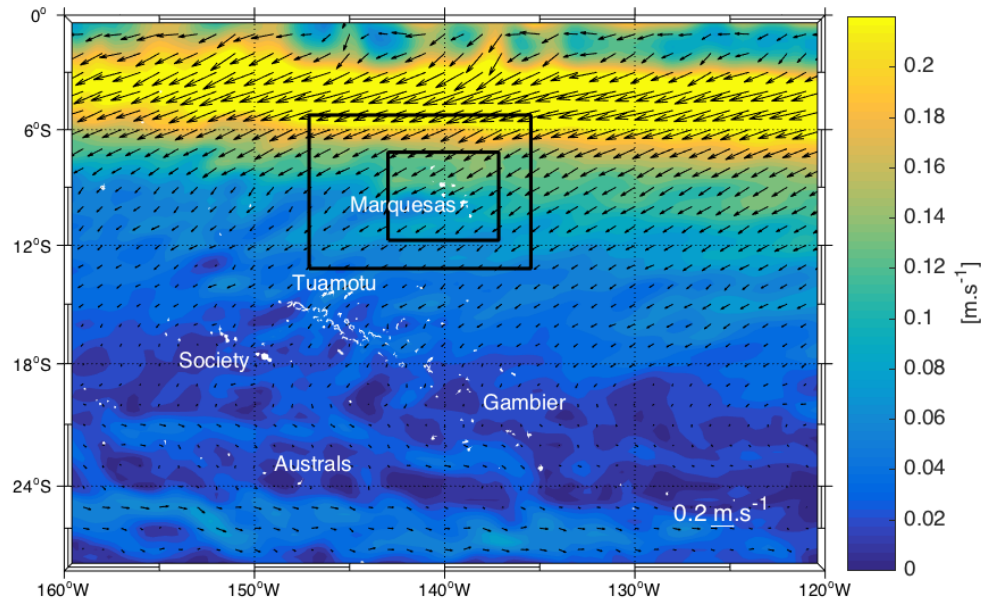


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ROMS-Agrif configuration  
 Model-observation comparison metrics  
 Thermohaline properties

Dynamical properties  
 W13-Q simulation  
 Conclusion

# ROMS-Agrif configurations



<b>Embedding</b>	2 Grids ; 2-way
<b>Resolutions</b>	1/15° ; 1/45°
<b>Temporal</b>	2 days
<b>Vertical grid</b>	32 Sigma levels
<b>Bathymetry</b>	ETOPO2
<b>Closure scheme</b>	Large et al. [1994]

10 year simulations  
 => Year 4 to 10

	W09-Q	CARS-Q	W13-Q
<b>Atmospheric forcings</b>	COADS/QuikSCAT		
<b>Boundaries and Initialization</b>	WOA 2009 (1°)	CARS 2009 (1/2°)	WOA 2013 (1/4°)

## Model-observation comparison metrics

Normalized Root Mean Square Error

$$NRMSE = \frac{\sqrt{\frac{1}{n} \sum_{i=1}^n (\langle V_{ROMS,i} \rangle - \langle V_{SAT,i} \rangle)^2}}{\frac{1}{n} \sum_{i=1}^n \langle V_{SAT,i} \rangle} * 100 \%$$

**The smaller = The better**

WOA 2009, CARS 2009 and WOA 2013 based on in situ observations

=> Comparisons with **independent** data : Remote sensing

Surface model outputs vs. remote sensing

Data interpolated on the same grid

SST : Sea Surface Temperature

KE : Kinetic Energy

SSS : Sea Surface Salinity

EKE : Eddy Kinetic Energy

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# Thermohaline properties

## Sea Surface Temperature (SST) : Annual mean

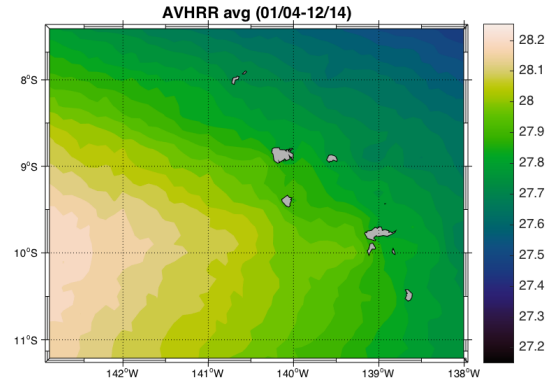
**AVHRR** (Remote sensing)

Years :

2004 – 2014

Resolution :

9 km



- North-East / South-West gradient



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# Thermohaline properties

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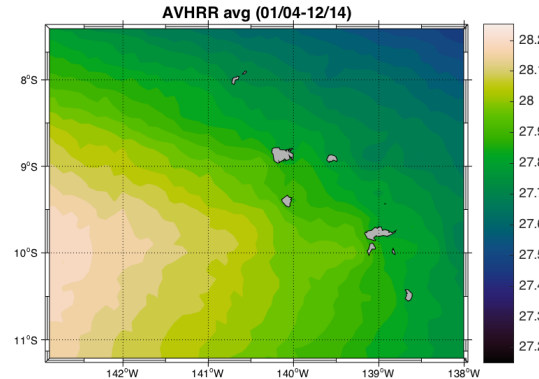
**AVHRR** (Remote sensing)

Years :

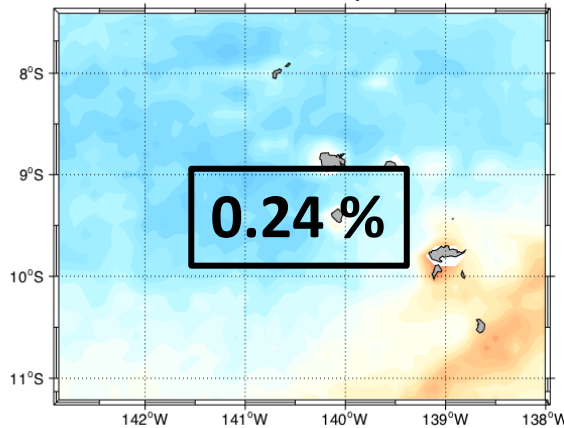
2004 – 2014

Resolution :

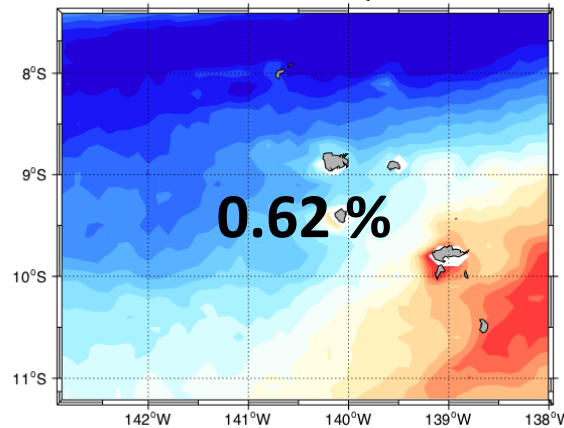
9 km



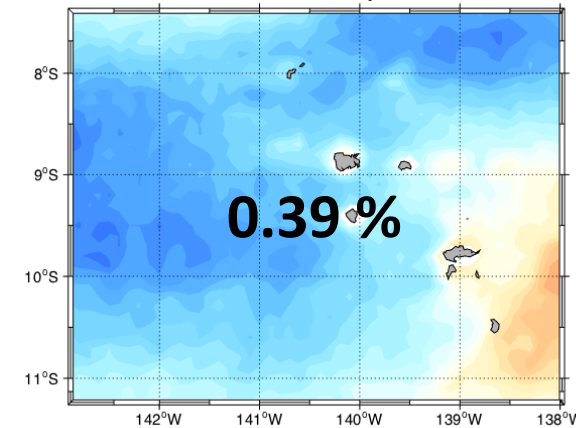
**W09-Q**



**CARS-Q**



**W13-Q**



**MODEL**

Years :

4 to 10

Resolution :

2,5 km

Similar results for salinity

# Dynamical properties

## Kinetic Energy (KE) : Annual mean

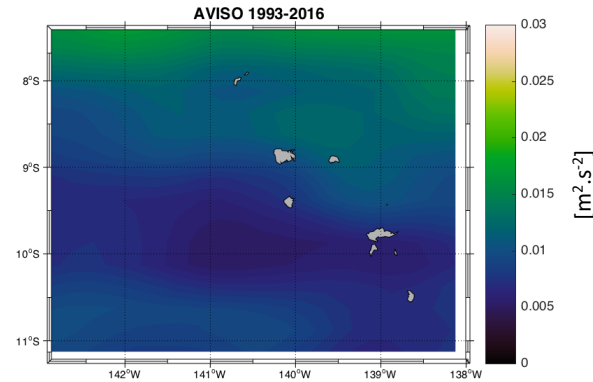
**AVISO** (Remote sensing)

Years :

1993 – 2016

Resolution :

25 km



$$KE = \frac{1}{2} (u^2 + v^2)$$

- Stronger Kinetic Energy in the North

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# Dynamical properties

## Kinetic Energy (KE) : Annual mean

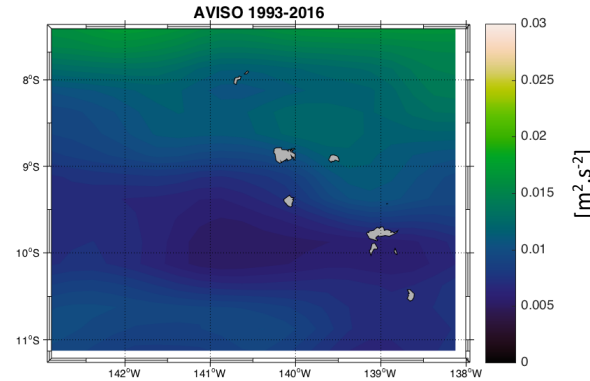
**AVISO (Remote sensing)**

Years :

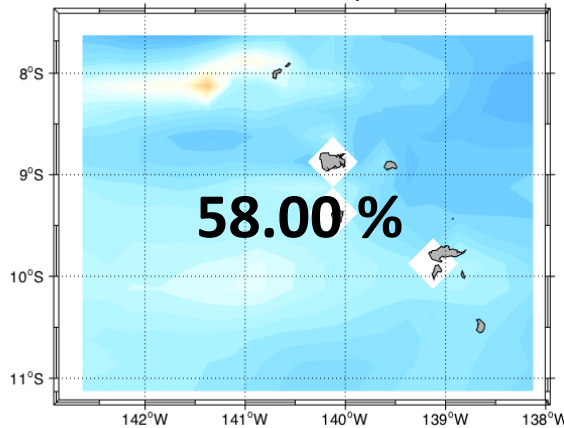
1993 – 2016

Resolution :

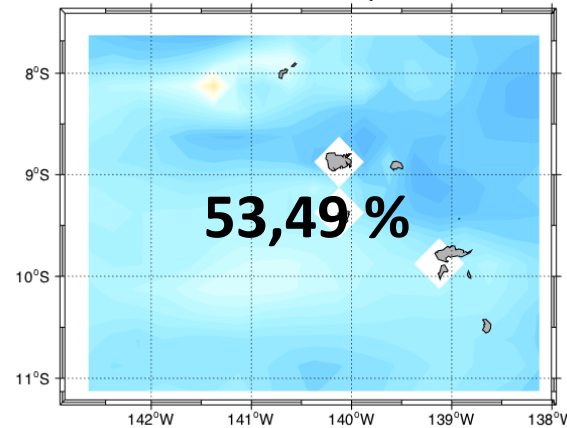
25 km



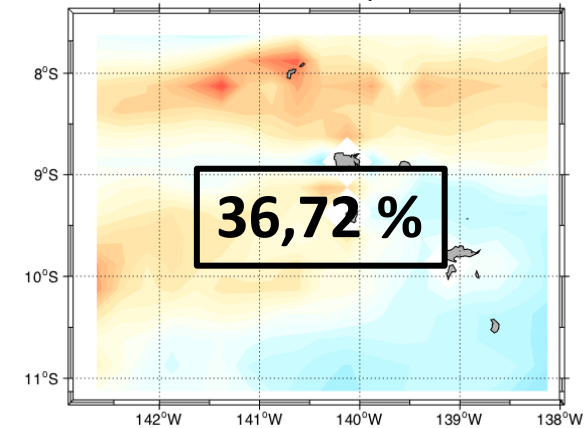
**W09-Q**



**CARS-Q**



**W13-Q**



**MODEL**

Years :

4 to 10

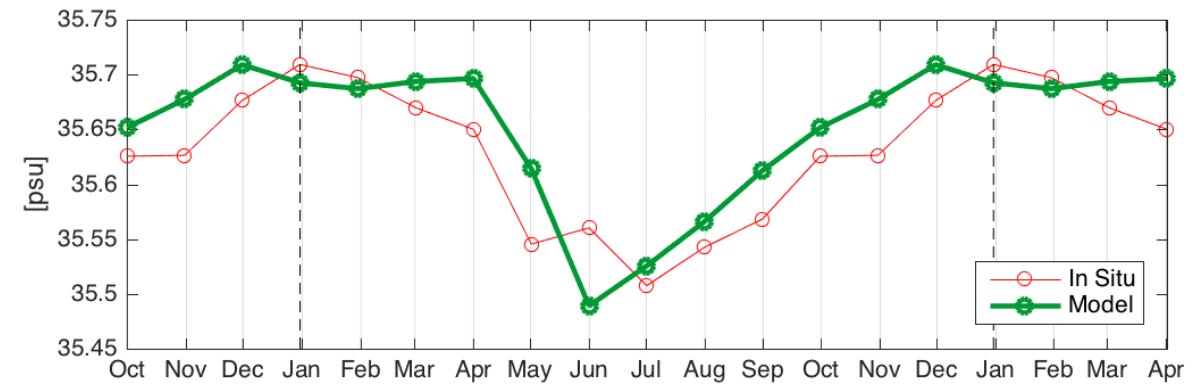
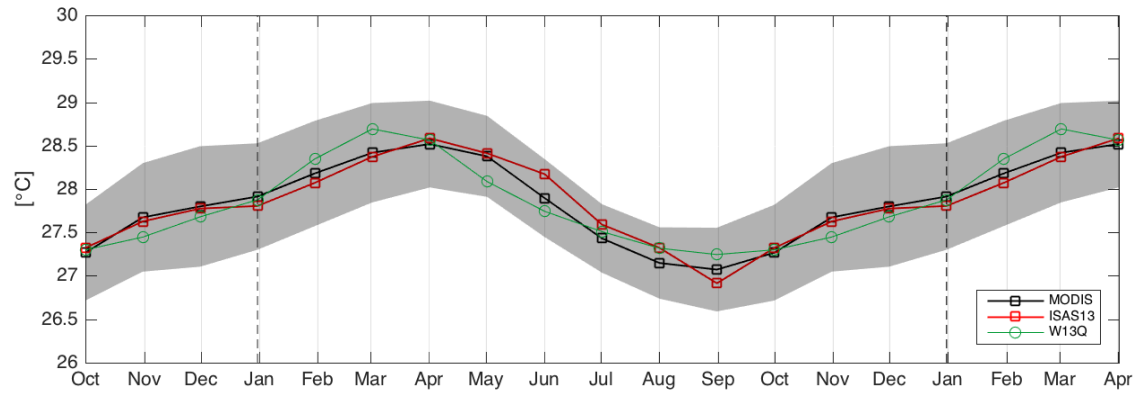
Resolution :

2,5 km

Similar results for EKE

# W13-Q simulation

## Sea Surface Temperature and Salinity (SST & SSS) : Seasonal variability



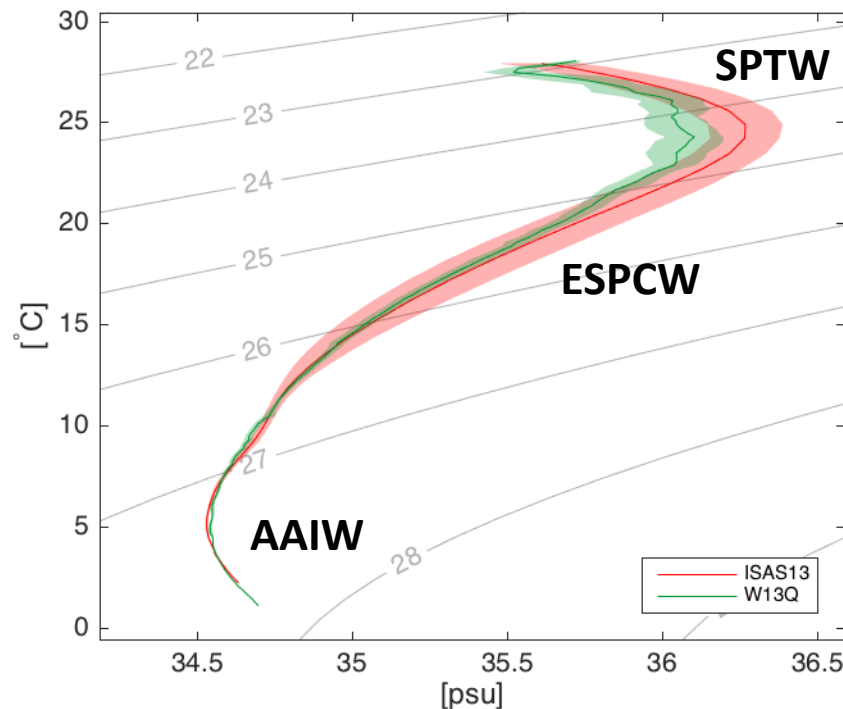
- Maximum temperature during summer and minimum during winter
- Model and observations very close seasonality



# W13-Q simulation

## T - S diagram : Annual mean

### Information on water masses



SPTW : South Pacific Tropical Water  
ESPCW : Eastern South Pacific Central Water  
AAIW : Antarctic Intermediate Water

- Model and observations are close

=> Good performance

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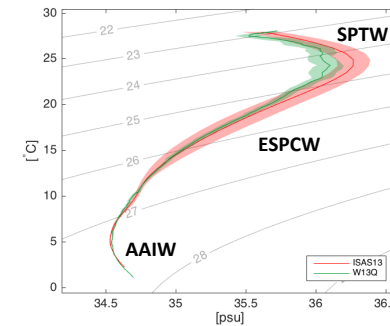
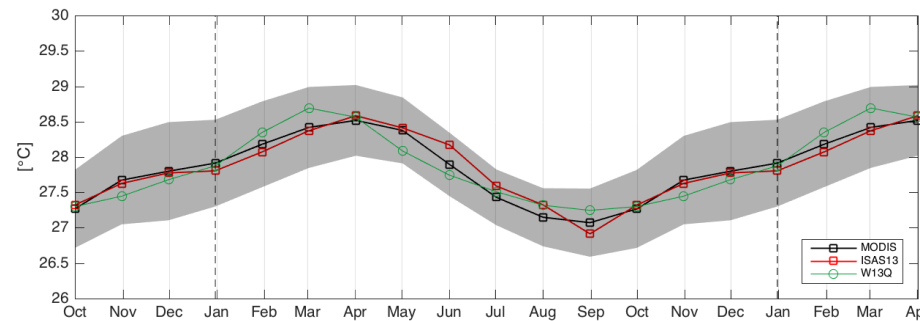
ROMS-Agrif configuration  
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# Conclusion

Parameter	SST	SSS	KE	EKE
Minimum NRMSE	W09-Q	W13-Q	W13-Q	W13-Q

WOA 2013 = most realistic forcing



Thermohaline parameters well represented

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- Comparison of several implementations

## 2. Investigating the island wake

- Dynamical properties of the island wake

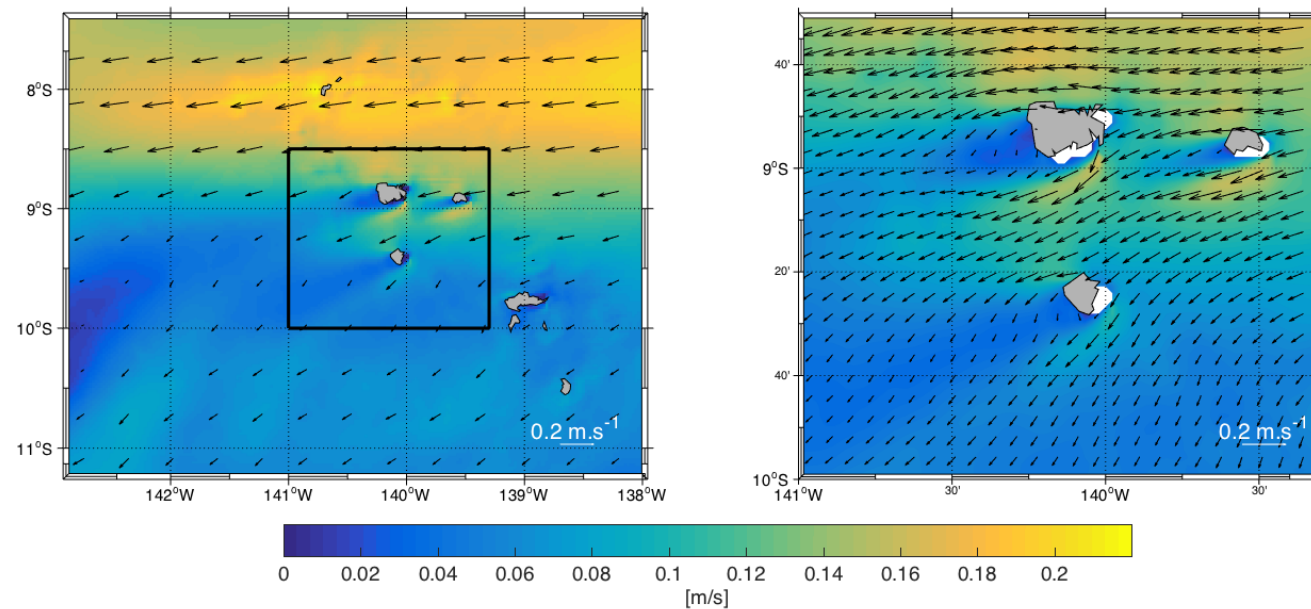
## 3. Investigating the island mass effect

- Biogeochemical properties of the island wake

## 4. Conclusions & perspectives

# Calm wakes

## Surface Current : Annual mean

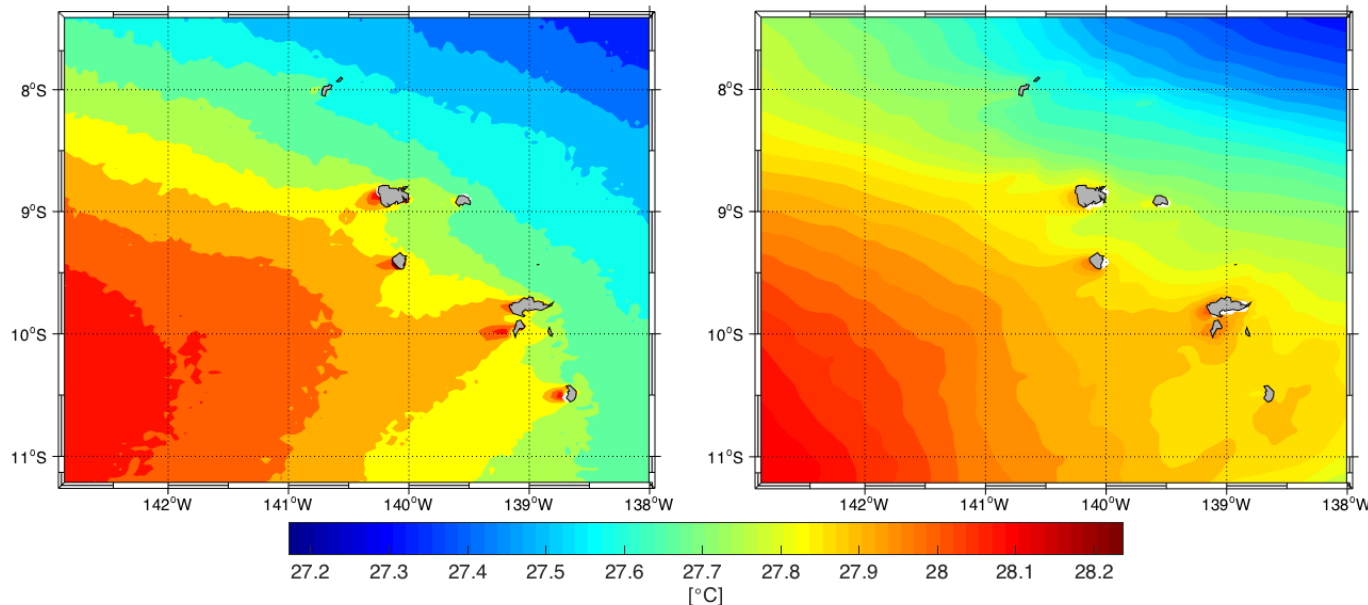


- SEC well represented
- Weak current leeward the islands

# Calm wakes

## Sea Surface Temperature (SST) : Annual mean

**MODIS**  
Years :  
2004 – 2014  
Resolution :  
4 km



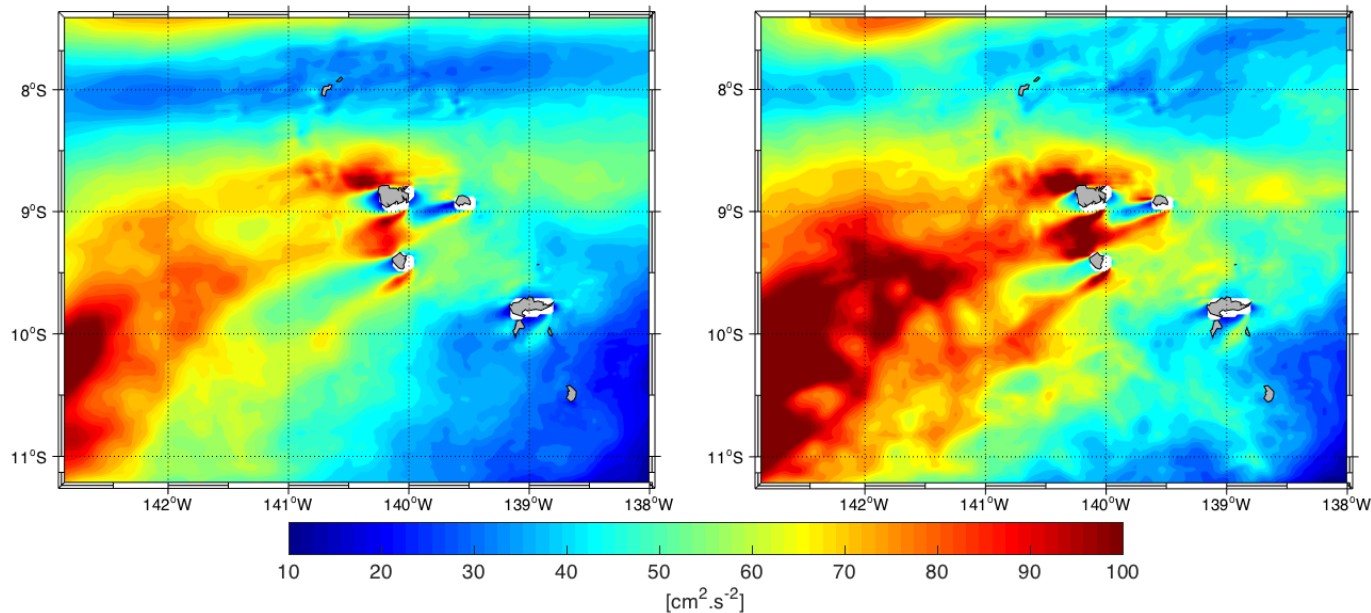
**W13-Q**  
Years :  
4 to 10  
Resolution :  
2,5 km

- **Warm waters** leeward the islands : absence of upwelling
- North-east / South-West gradient
- Close SST and spatial distribution

## Dynamical properties

Surface Eddy Kinetic Energy :  $EKE = \frac{1}{2} (u'^2 + v'^2)$

Annual mean & standard deviation



- Eddy activity near the northern islands
- Low energy in the calm lee

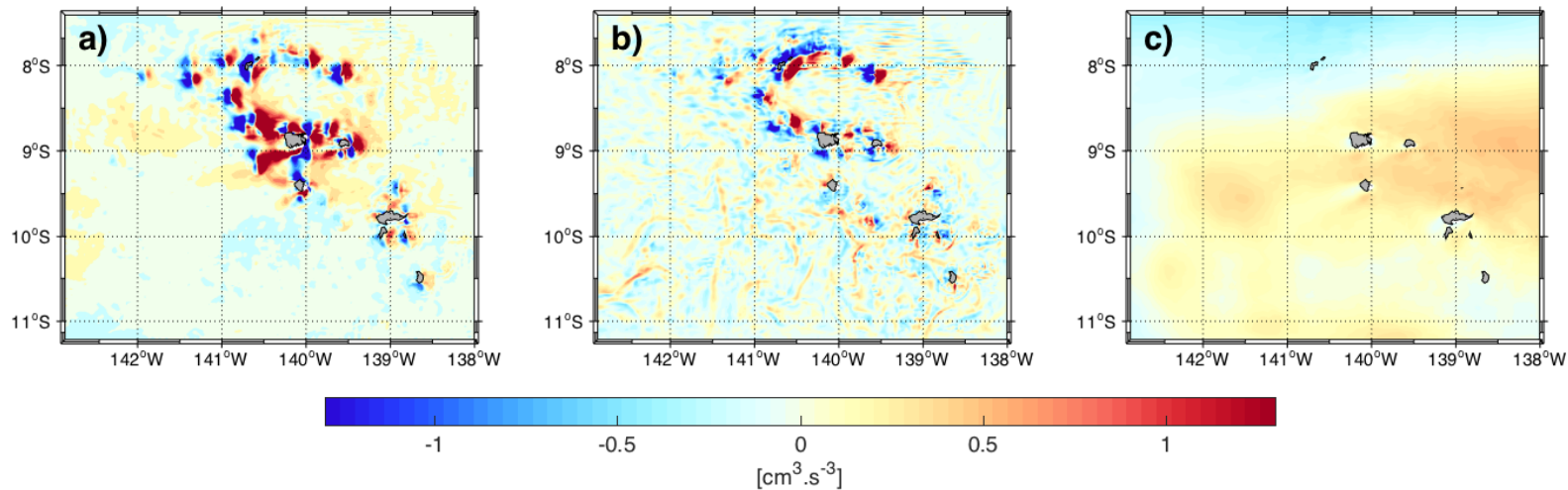


# Dynamical properties

## Energy budget : Annual mean

EKE = composite of **KMKE**, **PEKE** and **FEKE**

- a) **KMKE** => **Barotropic energy conversion**
- b) **PEKE** => **Baroclinic energy conversion**
- c) **FEKE** => **Wind work**



**KMKE dominance**

# Dynamical properties

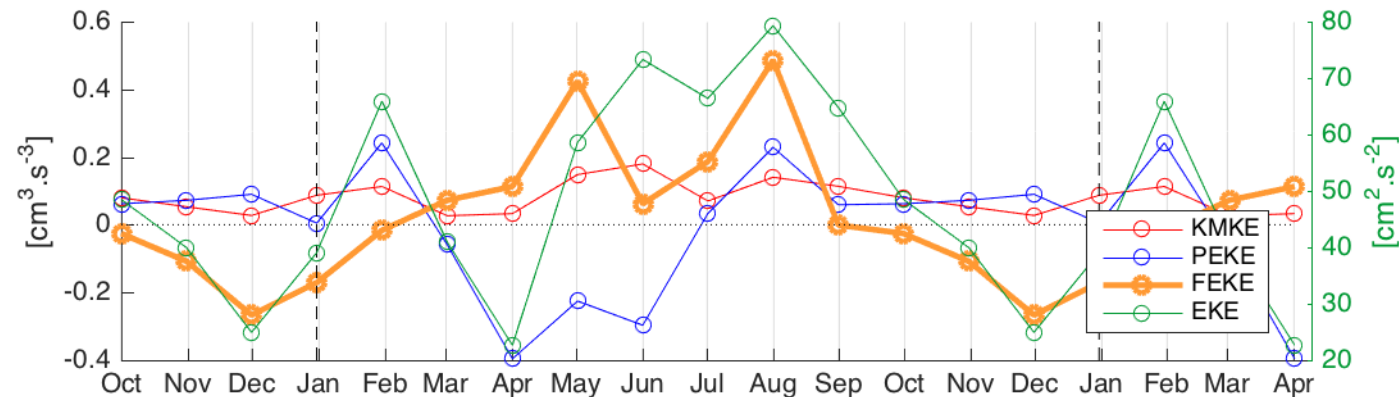
## Energy budget : Seasonal variability

**EKE** = composite of **KMKE**, **PEKE** and **FEKE**

**KMKE** => **Barotropic energy conversion**

**PEKE** => **Baroclinic energy conversion**

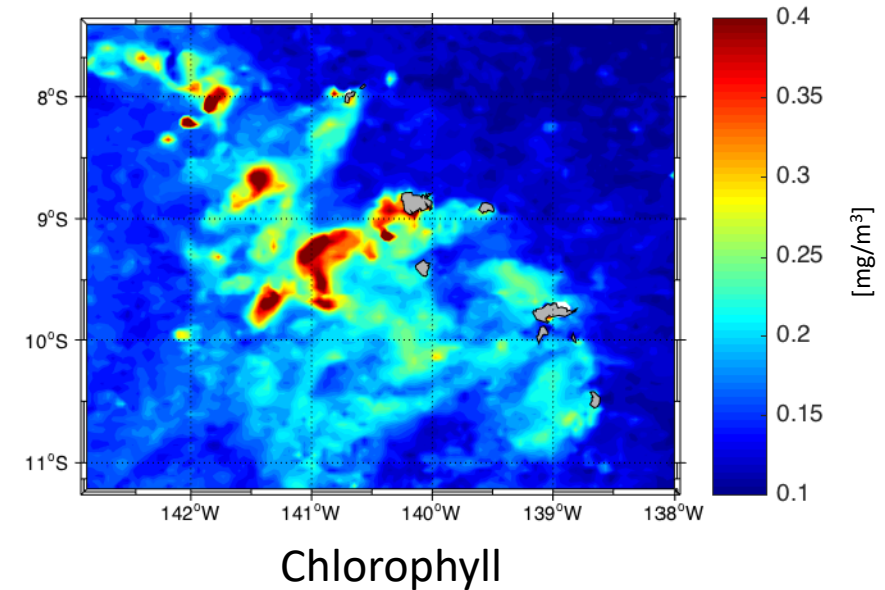
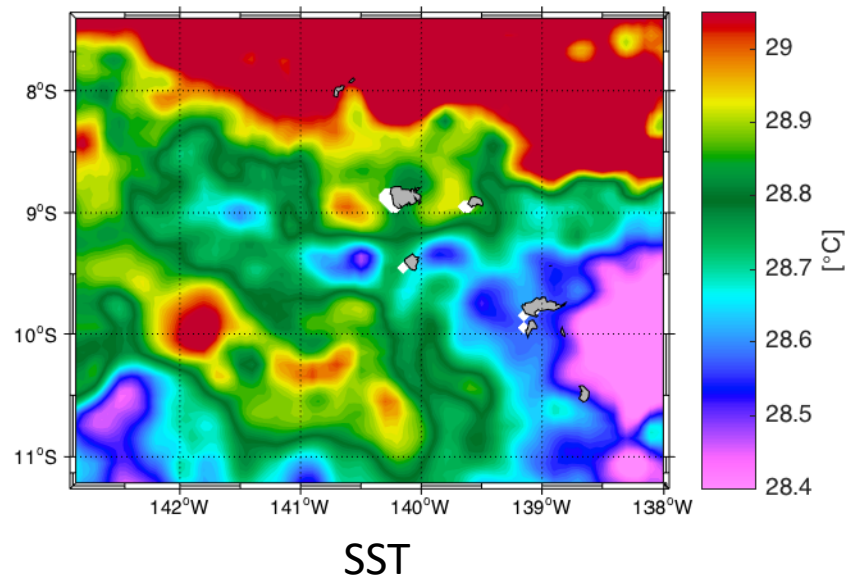
**FEKE** => **Wind work**



## PEKE and FEKE modulation

# Eddy activity

## Remote sensing observations

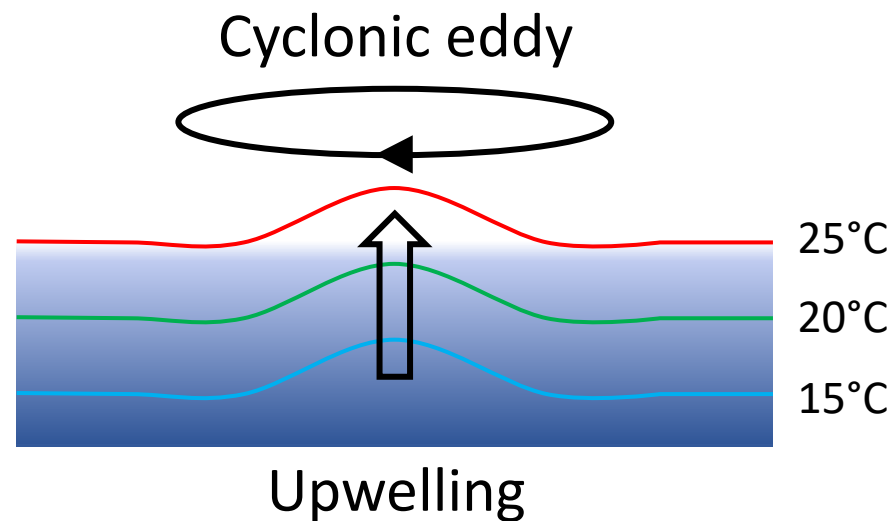


**Eddy structures ?**

# Eddy activity

Eddy detection :

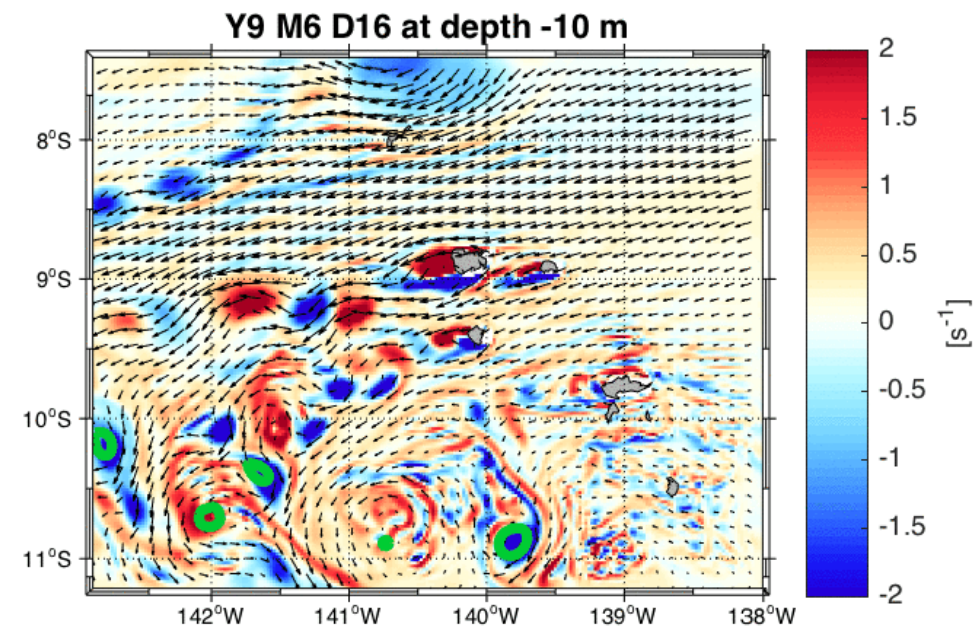
**Southern hemisphere**



Anticyclonic eddy => Downwelling

Nencioli et al. 2010 :

Based on the geometry of the flow



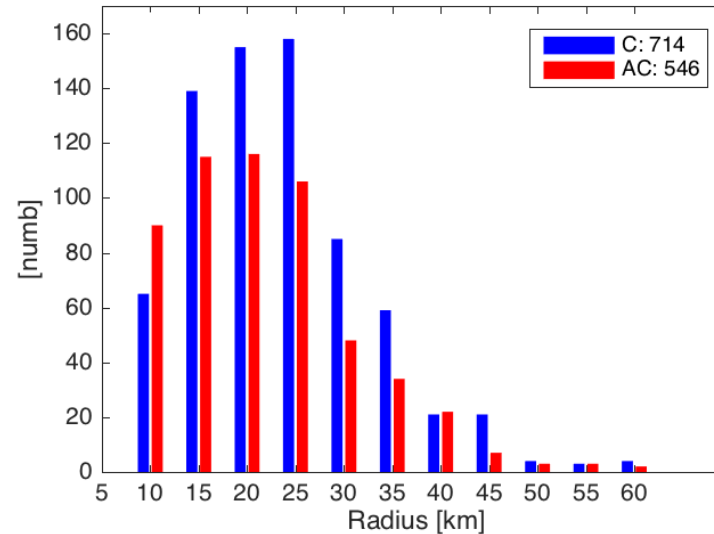
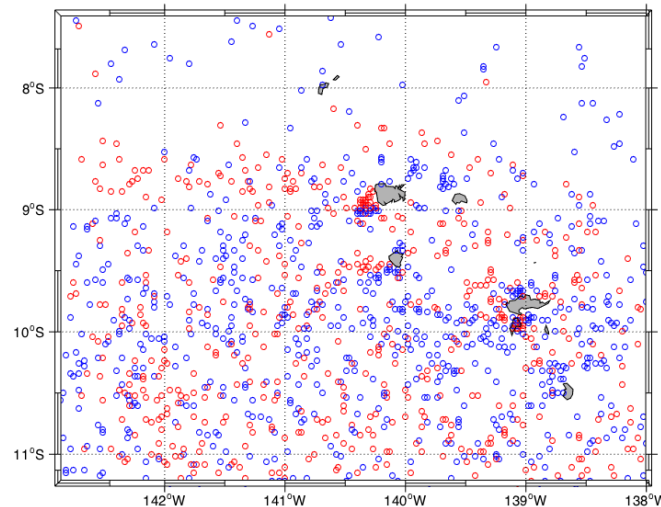
$$\zeta = \text{rot } \mathbf{V} = \frac{\partial v}{\partial x} - \frac{\partial u}{\partial y}$$

=> Eddy activity

# Eddy activity

## Characterization of the eddy activity

### Cyclonic and anticyclonic eddies



### Eddy generation leeward the island

Small eddies

=> Not detected on remote sensing

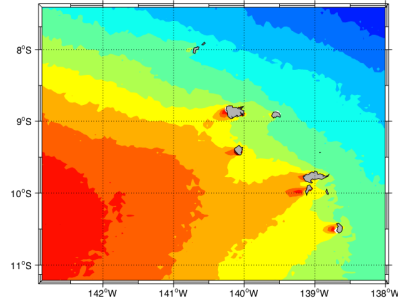
Cyclonic eddy dominance

=> Favorable for upwelling

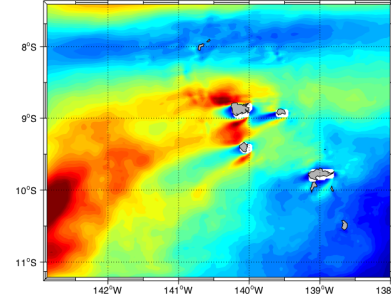
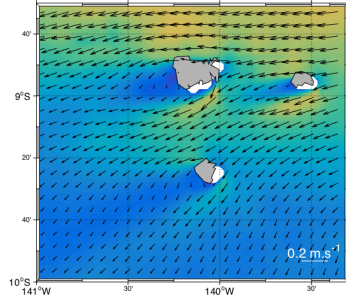
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Calm wakes  
 Dynamical properties  
 Eddy activity  
 Conclusion

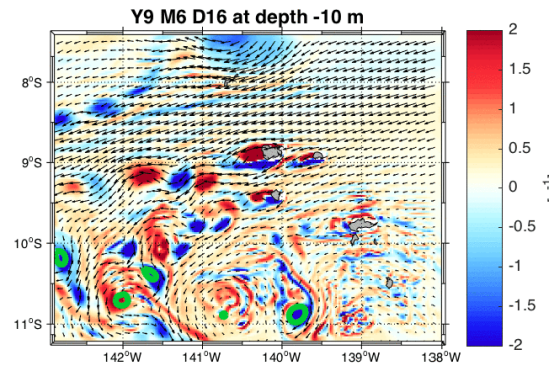
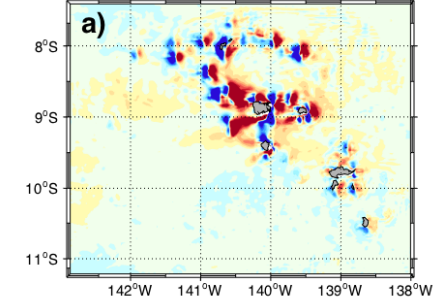
# Conclusion



Calm zone leeward the islands



Investigation of the dynamical processes



Eddy activity in the archipelago



## 1. Model set up for the Marquesas archipelago

- Comparison of several implementations

## 2. Investigating the island wake

- Dynamical properties of the island wake

## 3. Investigating the island mass effect

- Biogeochemical properties of the island wake

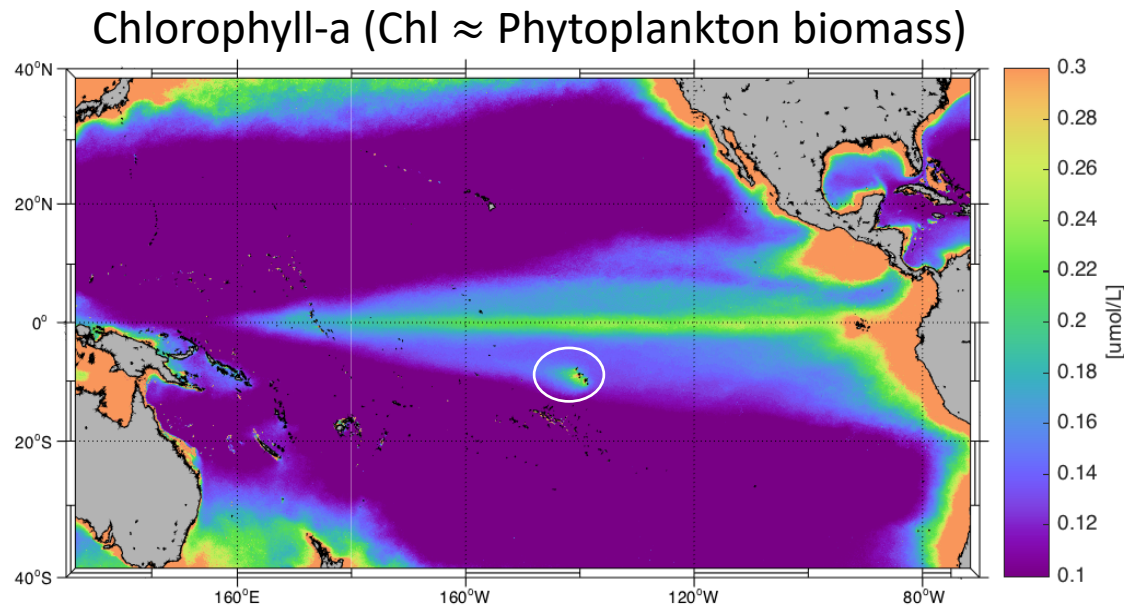
## 4. Conclusions & perspectives

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Biogeochemical context  
ROMS-PISCES  
Surface chlorophyll  
Chlorophyll vertical distribution

Chlorophyll seasonal variability  
Sediment enrichment  
Eddy induced enrichment ?  
Conclusion

## Biogeochemical context



Between mesotrophic (equator)  
and oligotrophic area (subtropical gyre)

Oceanographic campaign :

- BIOSOPE (2004)

Blain et al. 2008

- Pakaihi i te Moana (2012)

Martinez et al. 2016

High macronutrient concentrations  
(NO<sub>3</sub>, PO<sub>4</sub>, Si)

**=> Iron depleted waters**

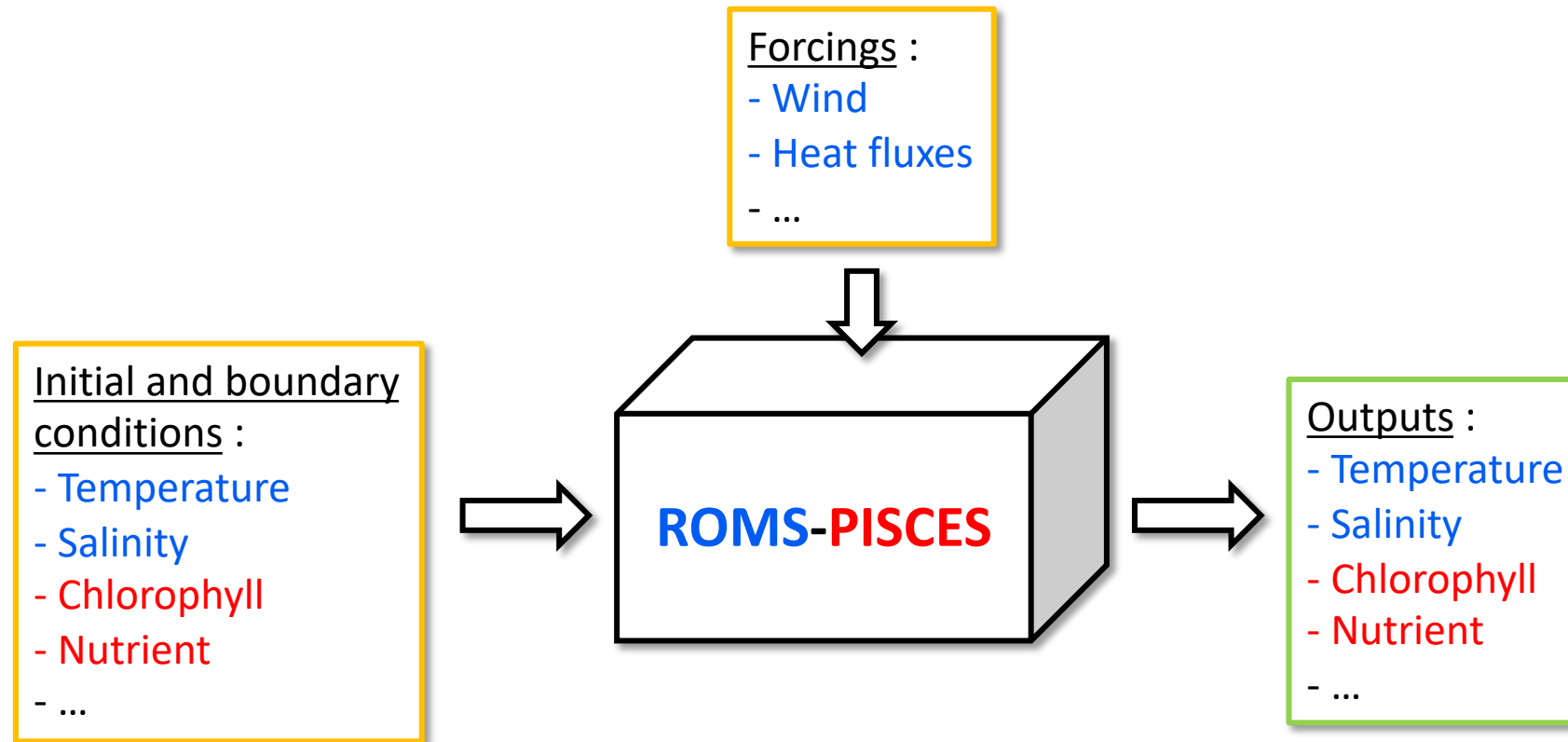
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Eddy induced enrichment ?  
Conclusion

# ROMS-PISCES

## PISCES model : Pelagic Interaction Scheme for Carbon and Ecosystem Studies



Physical and Biogeochemical processes

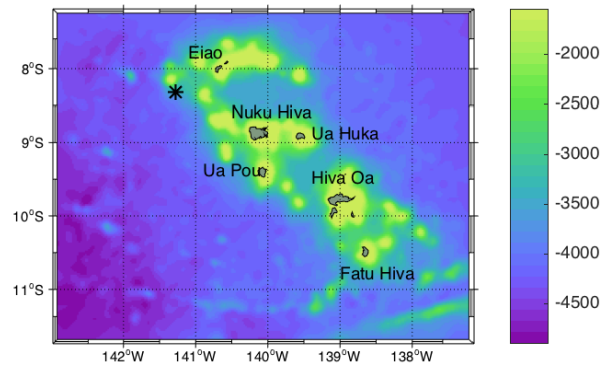
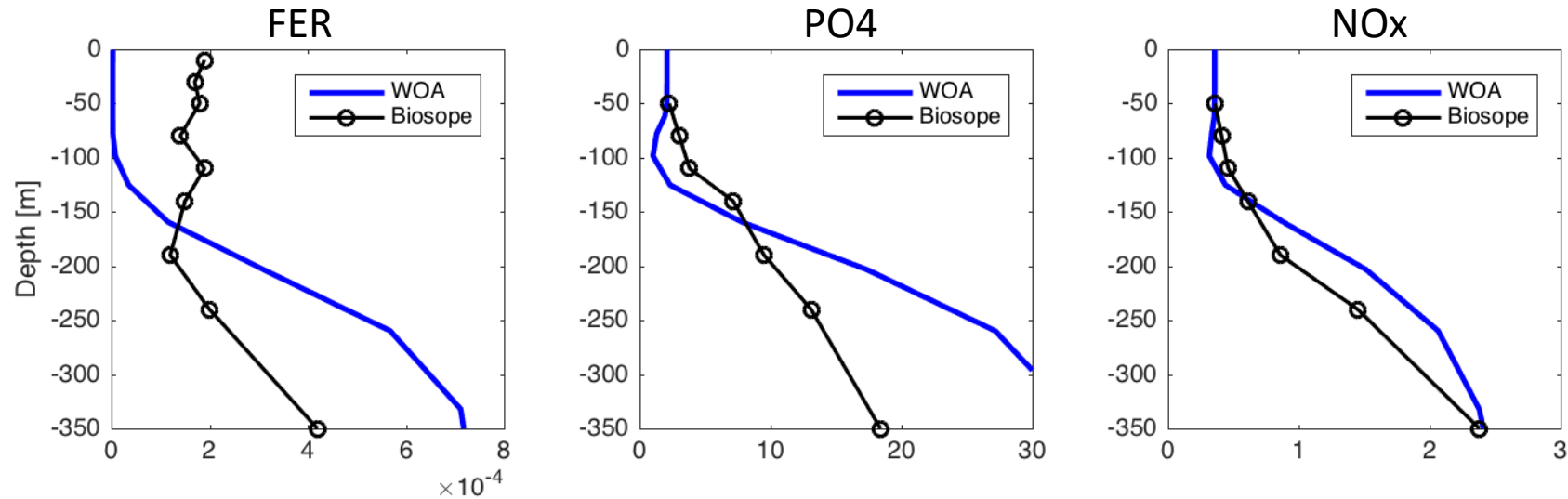
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# ROMS-PISCES

## Forcings and available vertical profiles comparison (BIOSOPE - 2004)



FER : **WOA-PISCES** < BIOSOPE

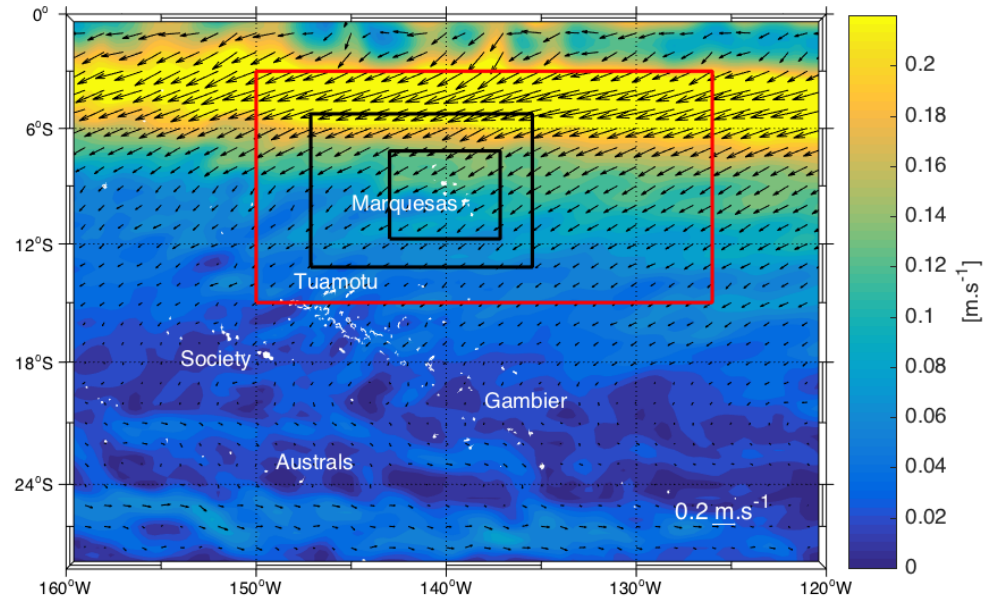
=> 4 implementations with different iron input

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# ROMS-PISCES



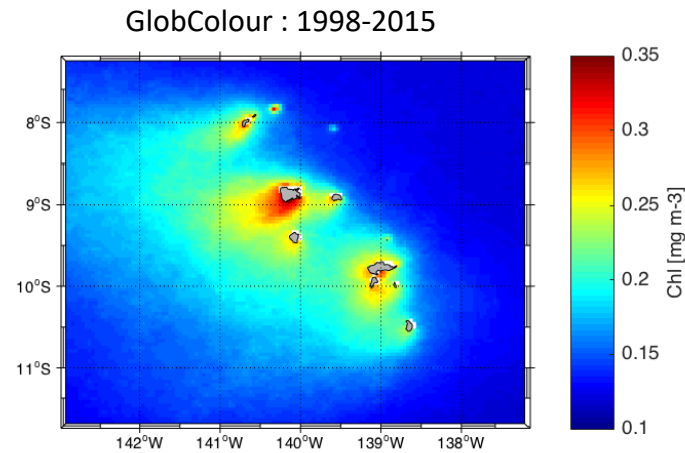
## Run W13-Q

Embedding	3 Grids ; 2-way
Resolution	1/5° ; 1/15° ; 1/45°

5 year simulations  
 => Year 4 & 5

	Ref	Biosope	Sed2.5	Sed5
<b>Biological</b>	WOA-PISCES			
<b>Iron</b>	WOA-PISCES	Fit to <b>BIO SOPE</b> observations for the upper layer	WOA-PISCES + <b>2.5 nmol m<sup>-2</sup> d<sup>-1</sup></b> Fe flux from sediment	WOA-PISCES + <b>5 nmol m<sup>-2</sup> d<sup>-1</sup></b> Fe flux from sediment

# Surface chlorophyll



## GlobColour

- Obtained using an FFT
- South-western plume

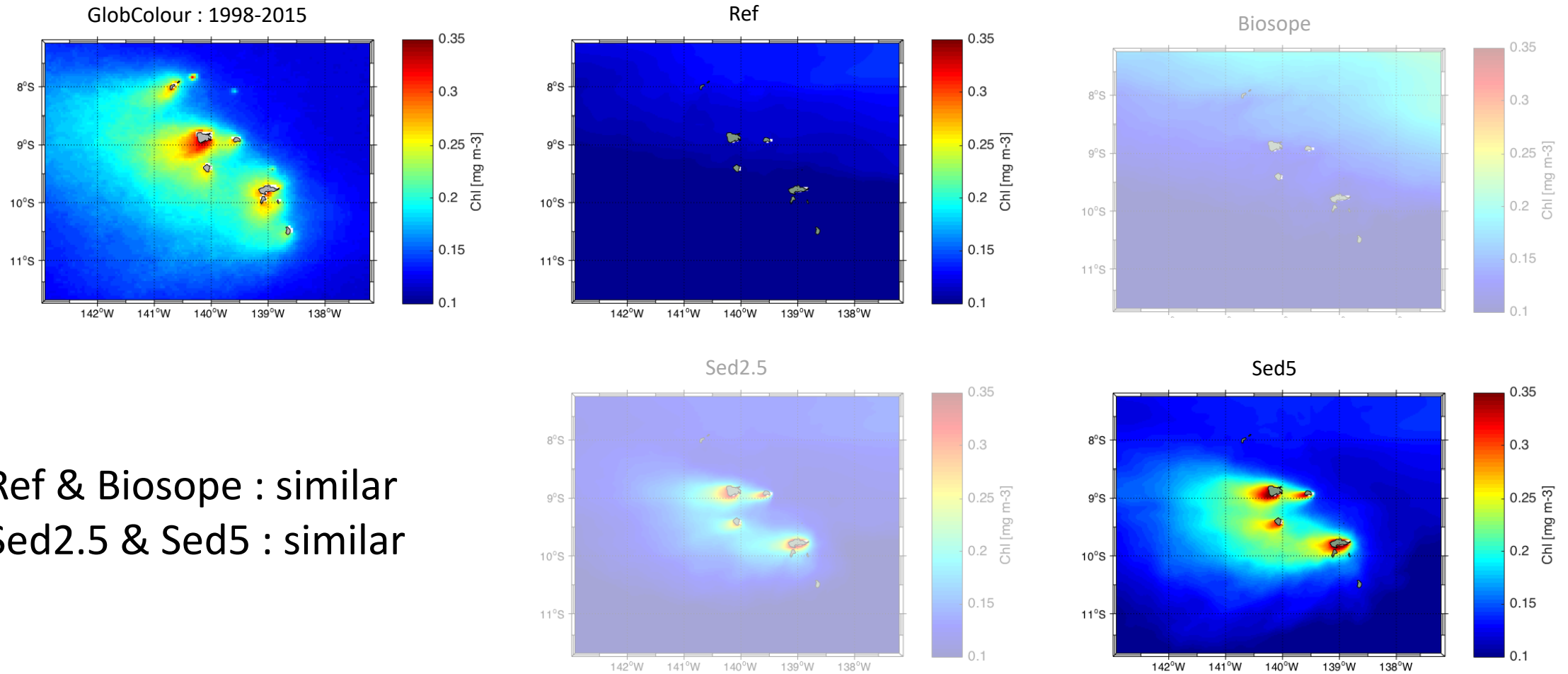


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# Surface chlorophyll



Ref & Biosope : similar  
Sed2.5 & Sed5 : similar

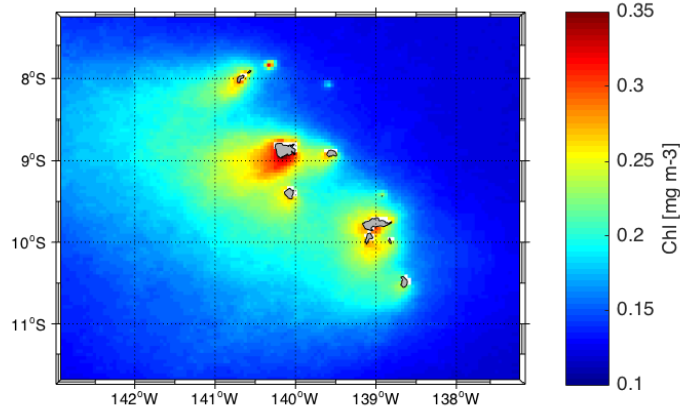
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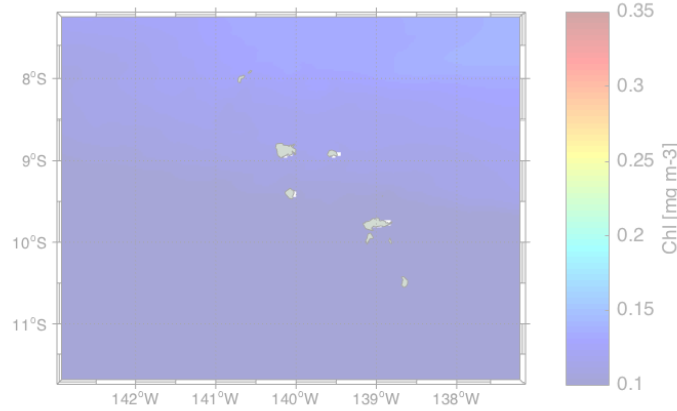
Chlorophyll seasonal variability  
 Sediment enrichment  
 Eddy induced enrichment ?  
 Conclusion

# Surface chlorophyll

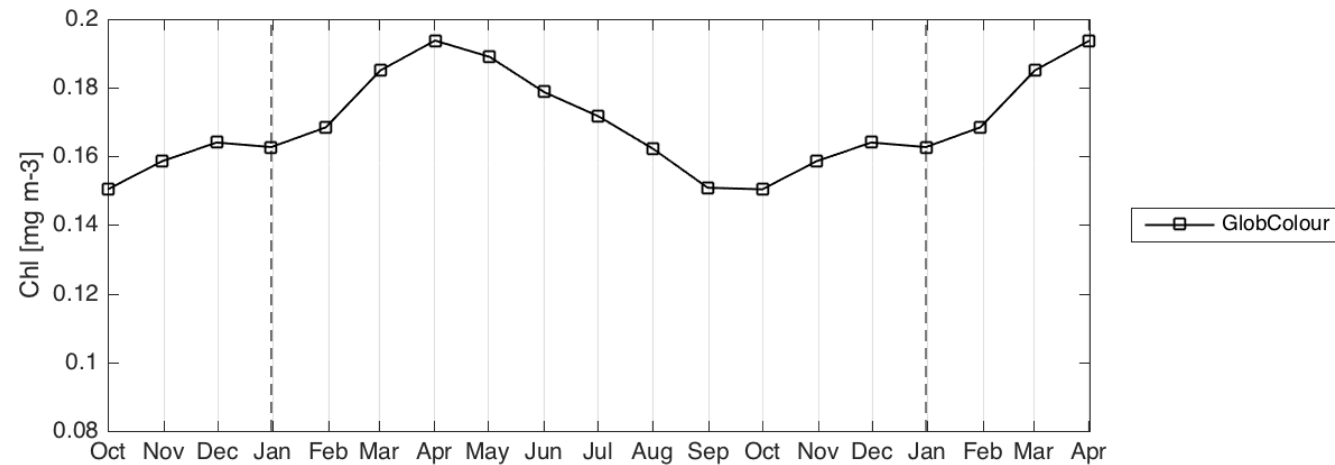
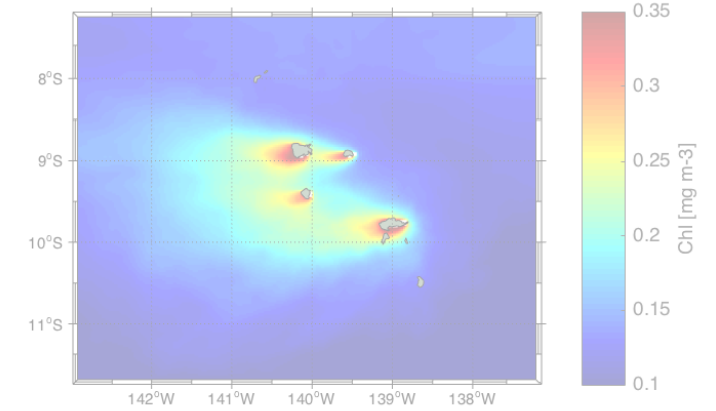
GlobColour : 1998-2015



Ref



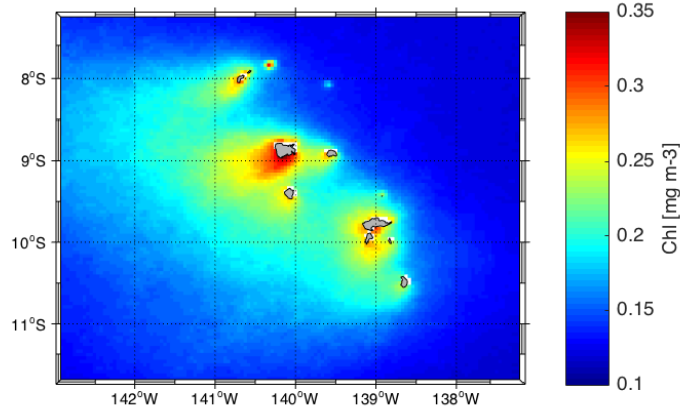
Sed5



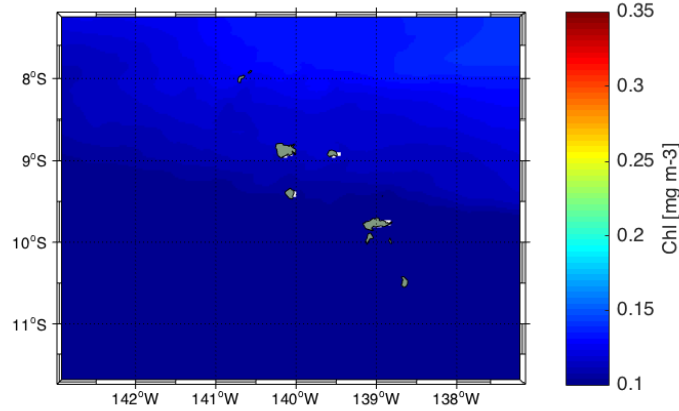
GlobColour  
 - Maximum in Apr and Dec

# Surface chlorophyll

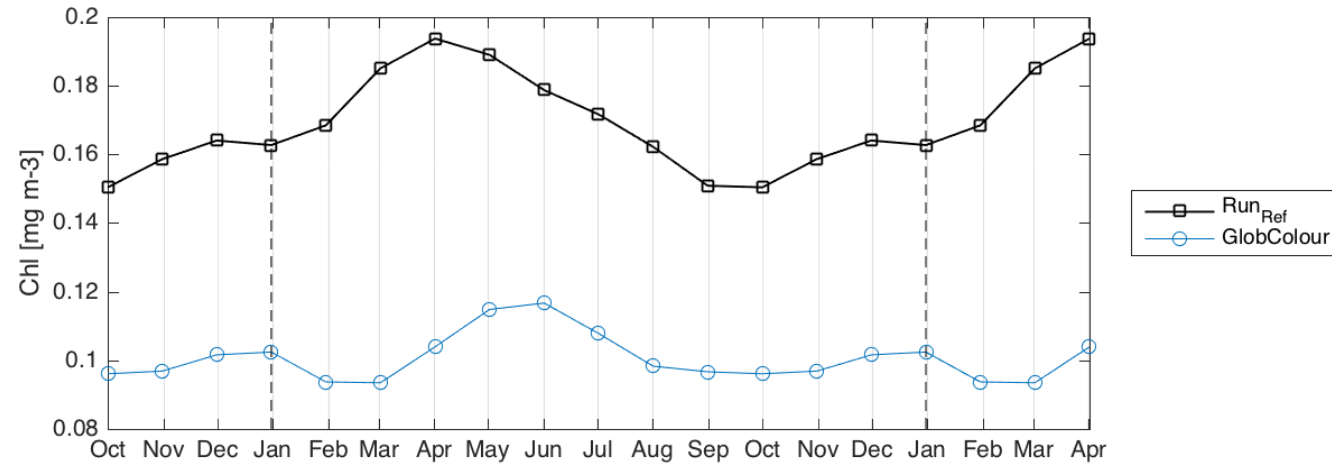
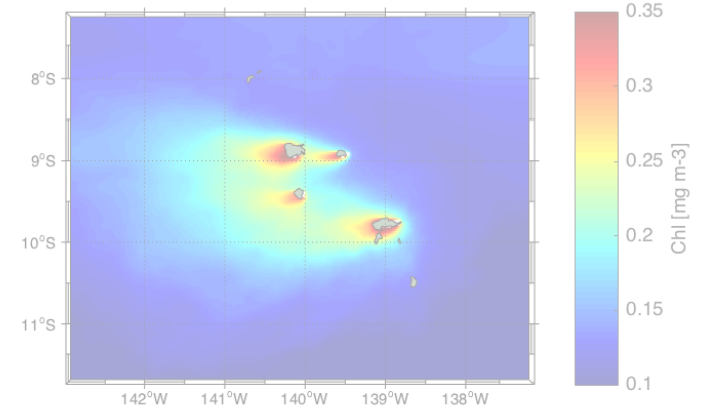
GlobColour : 1998-2015



Ref



Sed5

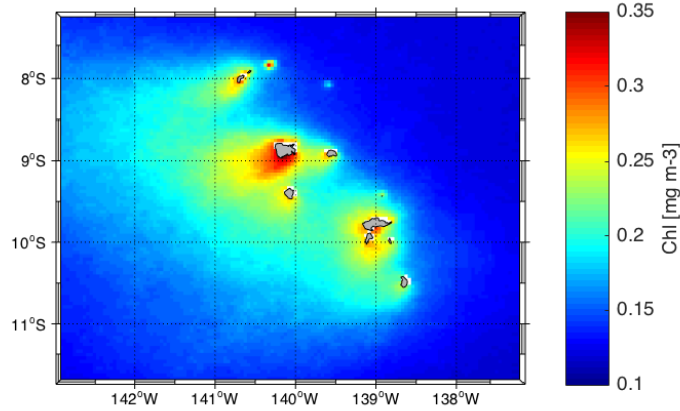


## Ref

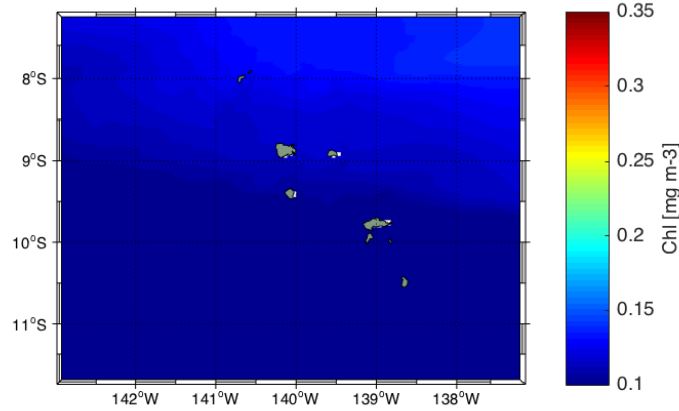
- No biological enhancement
- Close variability with weak values

# Surface chlorophyll

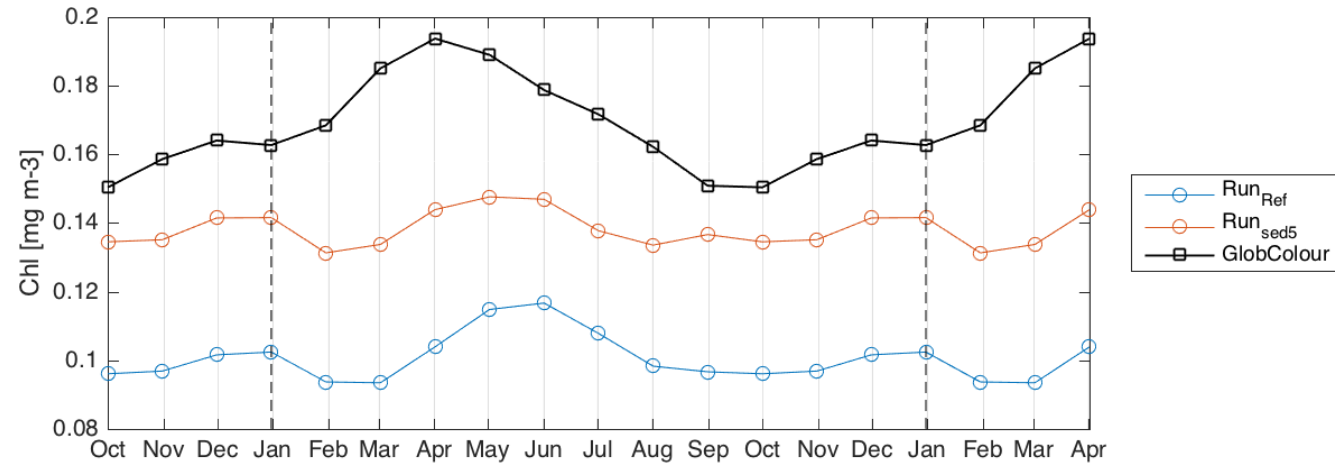
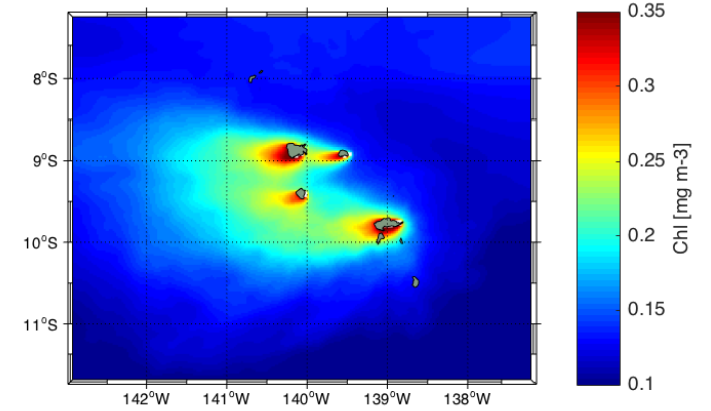
GlobColour : 1998-2015



Ref



Sed5

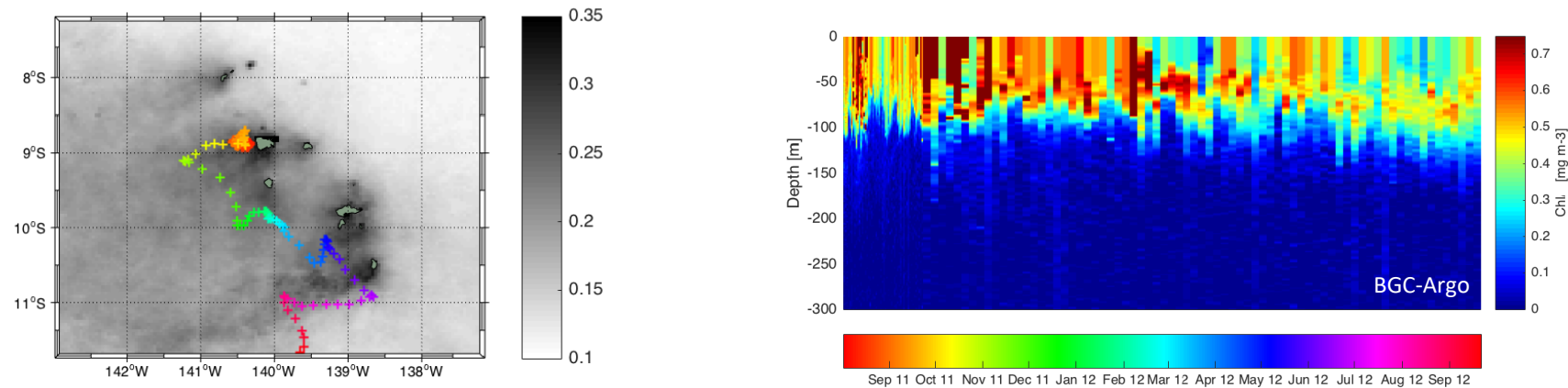


## Sed5

- IME well reproduced
- Closer variability

# Chlorophyll vertical distribution

## BGC-Argo float : August 2011 – September 2012



Noticeable N/S difference<sup>(1)</sup> :

- North : Homogeneous in the ML
- South : Presence of DCM\*

Martinez et al. 2016

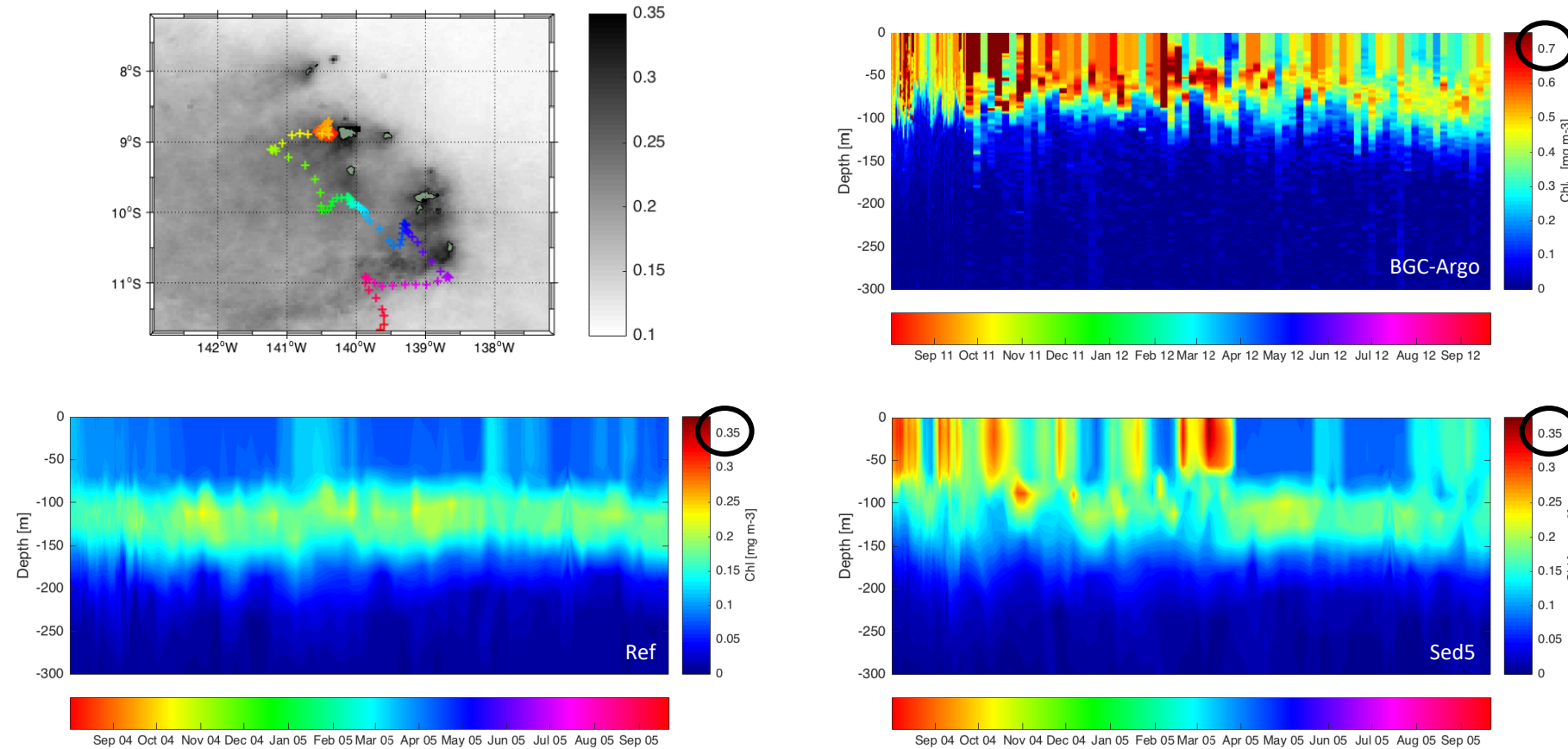
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# Chlorophyll vertical distribution

## BGC-Argo float : August 2011 – September 2012



Presence of a DCM

Similar patterns than BGC-Argo

\* Deep Chlorophyll Maximum



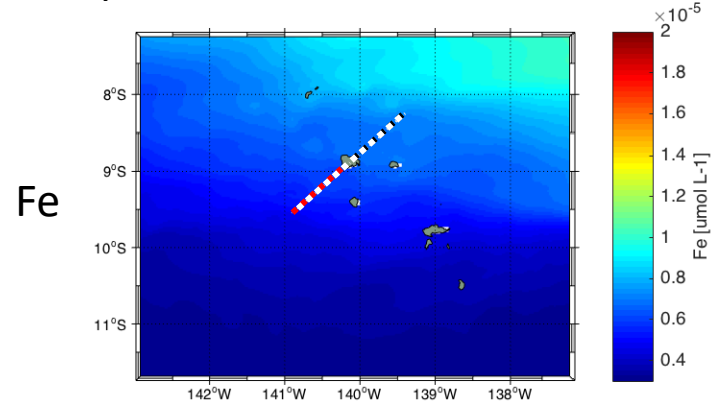
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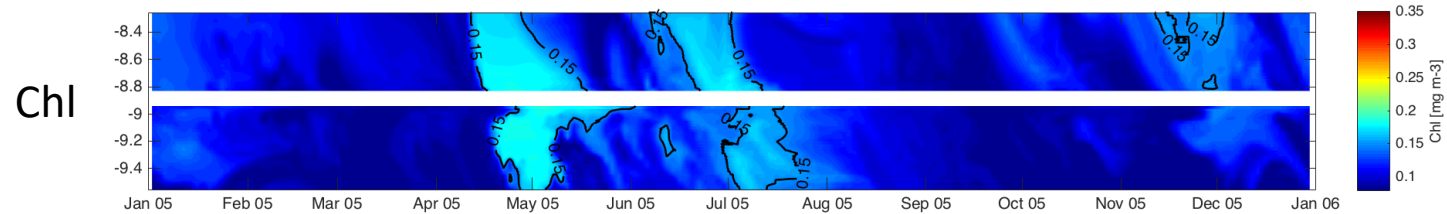
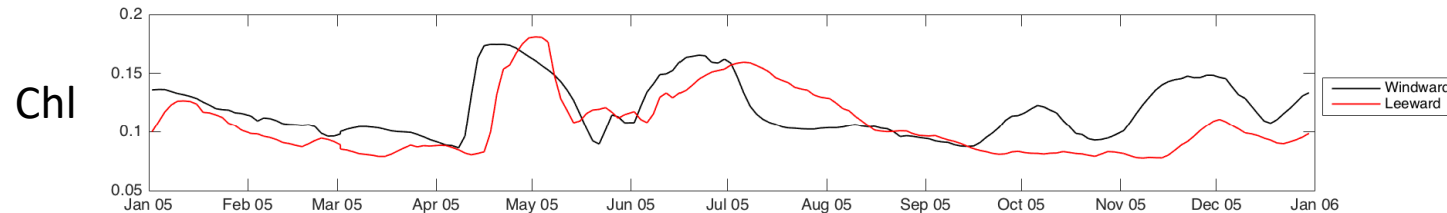
# Chlorophyll seasonal variability

Upstream/ downstream at - 10 m



Run Ref

+ Fe at the equator (Equatorial upwelling)



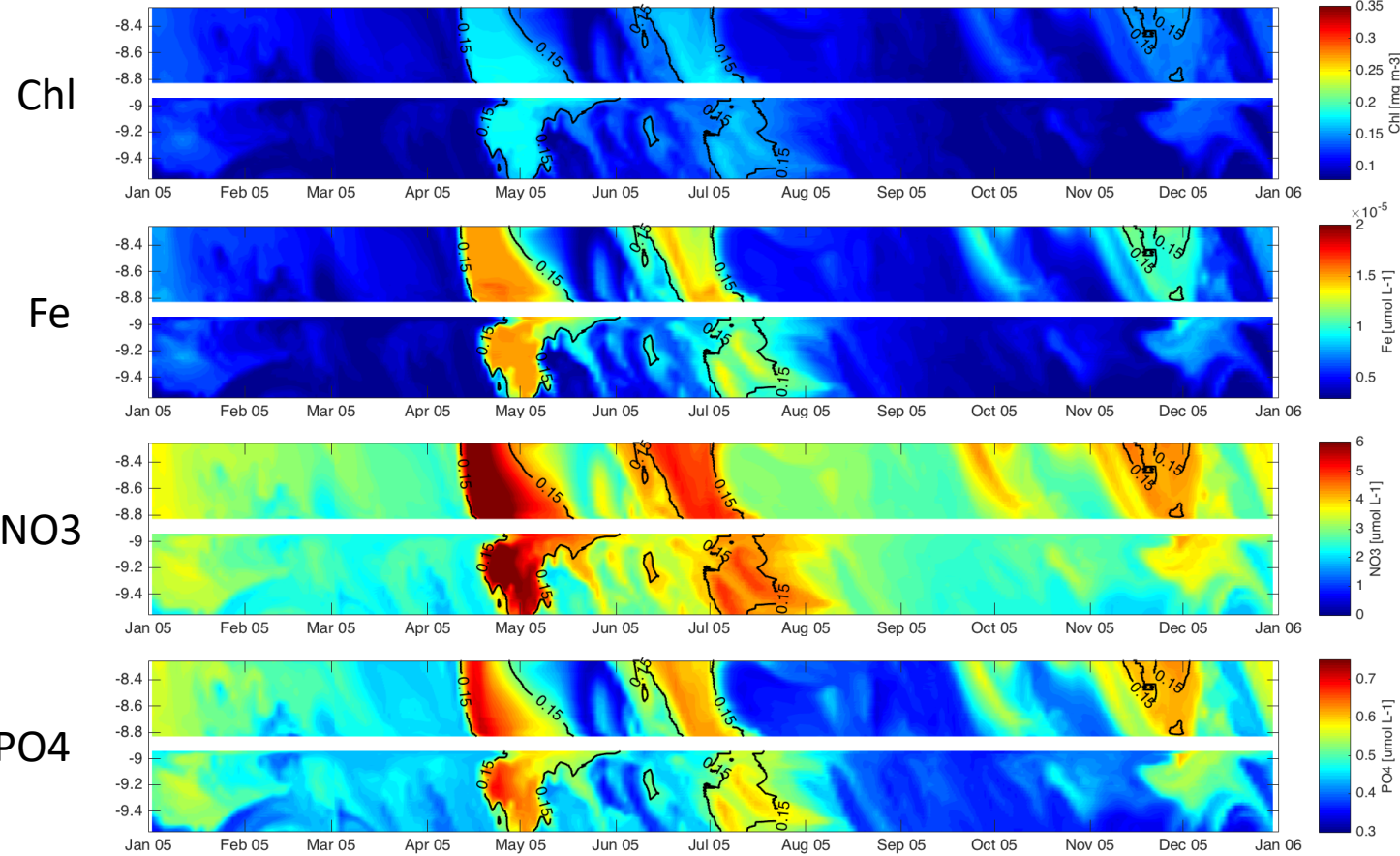
Upstream/Downstream similar  
 => No IME

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# Chlorophyll seasonal variability



## Run Ref

Phytoplankton vs. Nutrients  
- Similar patterns

=> Simultaneous inputs

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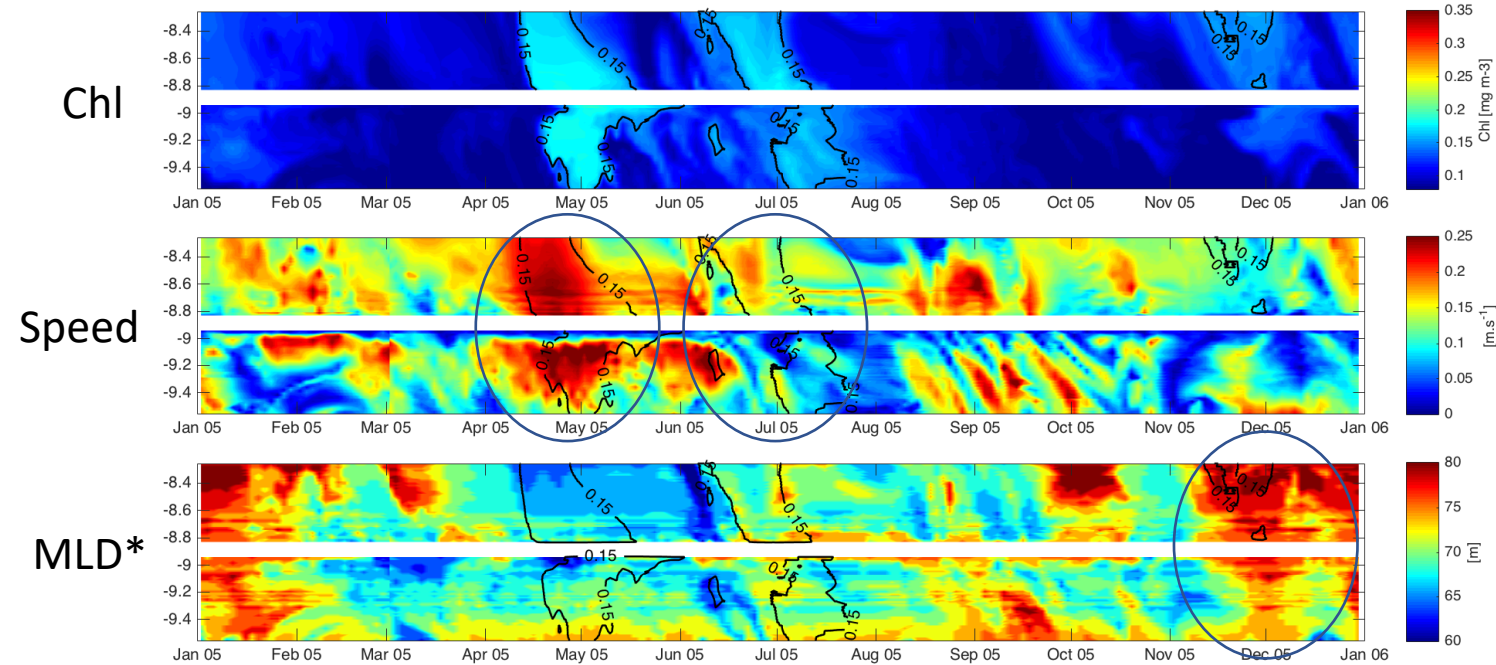
Chlorophyll seasonal variability  
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# Chlorophyll seasonal variability

## Run Ref

Current intensification  
=> Nutrient advection  
from the equator

Deepening of the MLD\*  
=> Input from the nutricline



\*Mixed Layer Depth

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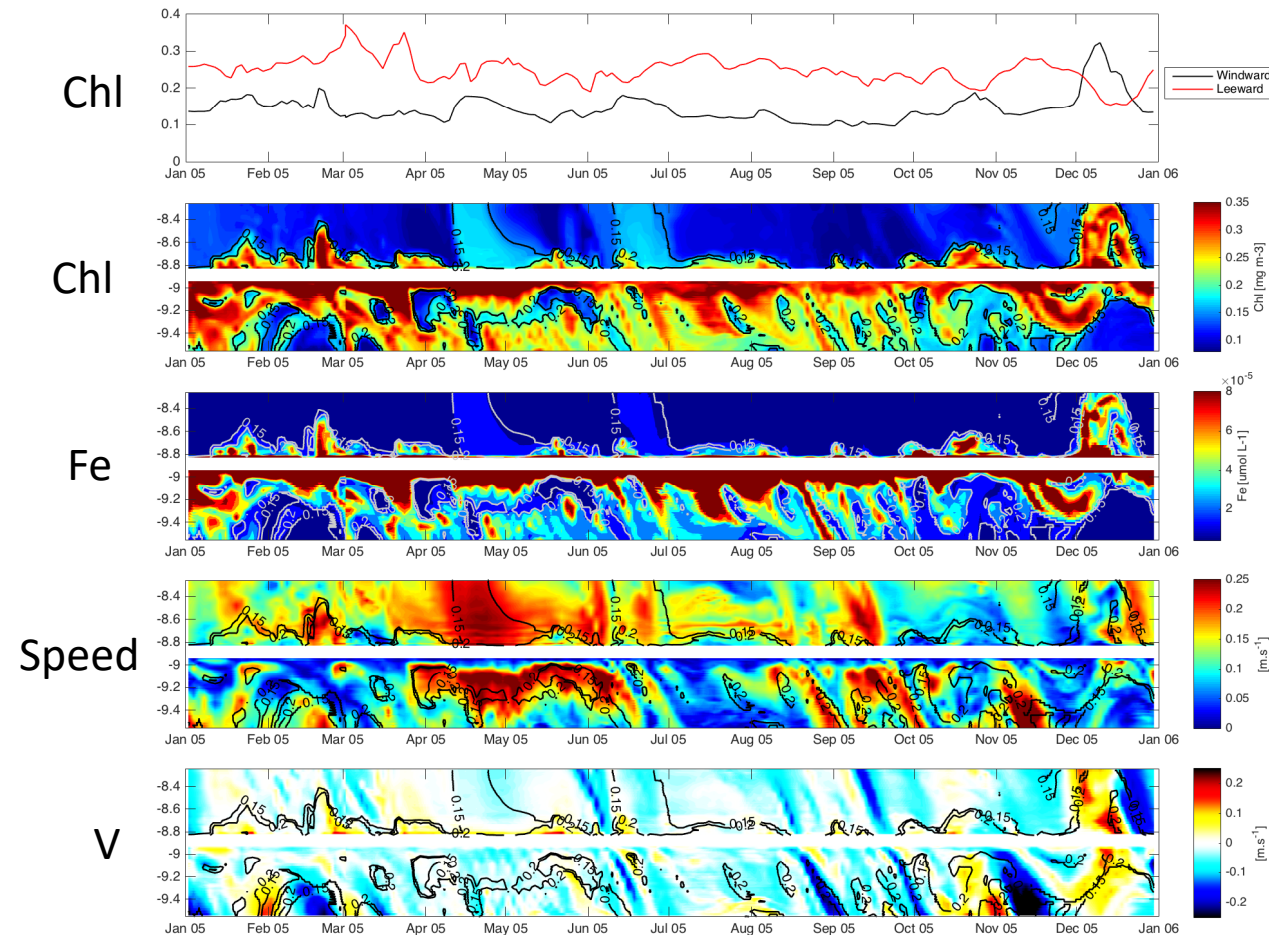
# Sediment enrichment

## Run Sed5

Stronger Chl downstream  
=> Pronounced IME

Upstream enrichment :  
Apr – Jun : Advection  
Dec : Meridional current >0

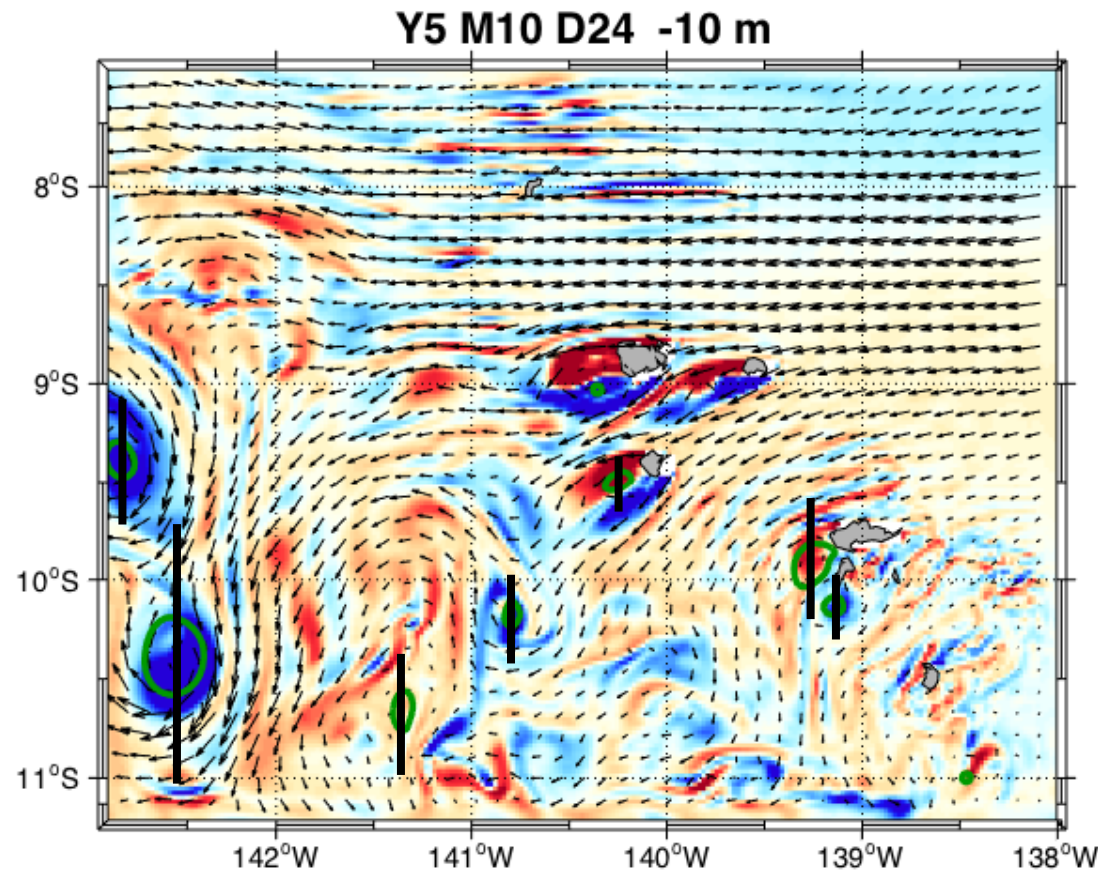
Downstream enrichment :  
Always rich near the coast  
Strong current = Chl advection





# Eddy induced enrichment ?

## Eddy composite anomaly (Y4-Y5)



## Run Ref

Mean impact of the eddies :

- Temperature
- Chlorophyll

AVG : Average of transects

Var<sub>n</sub> : Var at eddy mid-life

$$AVG = \frac{1}{n} \sum_1^n Var_n$$

$$X = \frac{1}{n} \sum_1^n AVG - Var_n$$

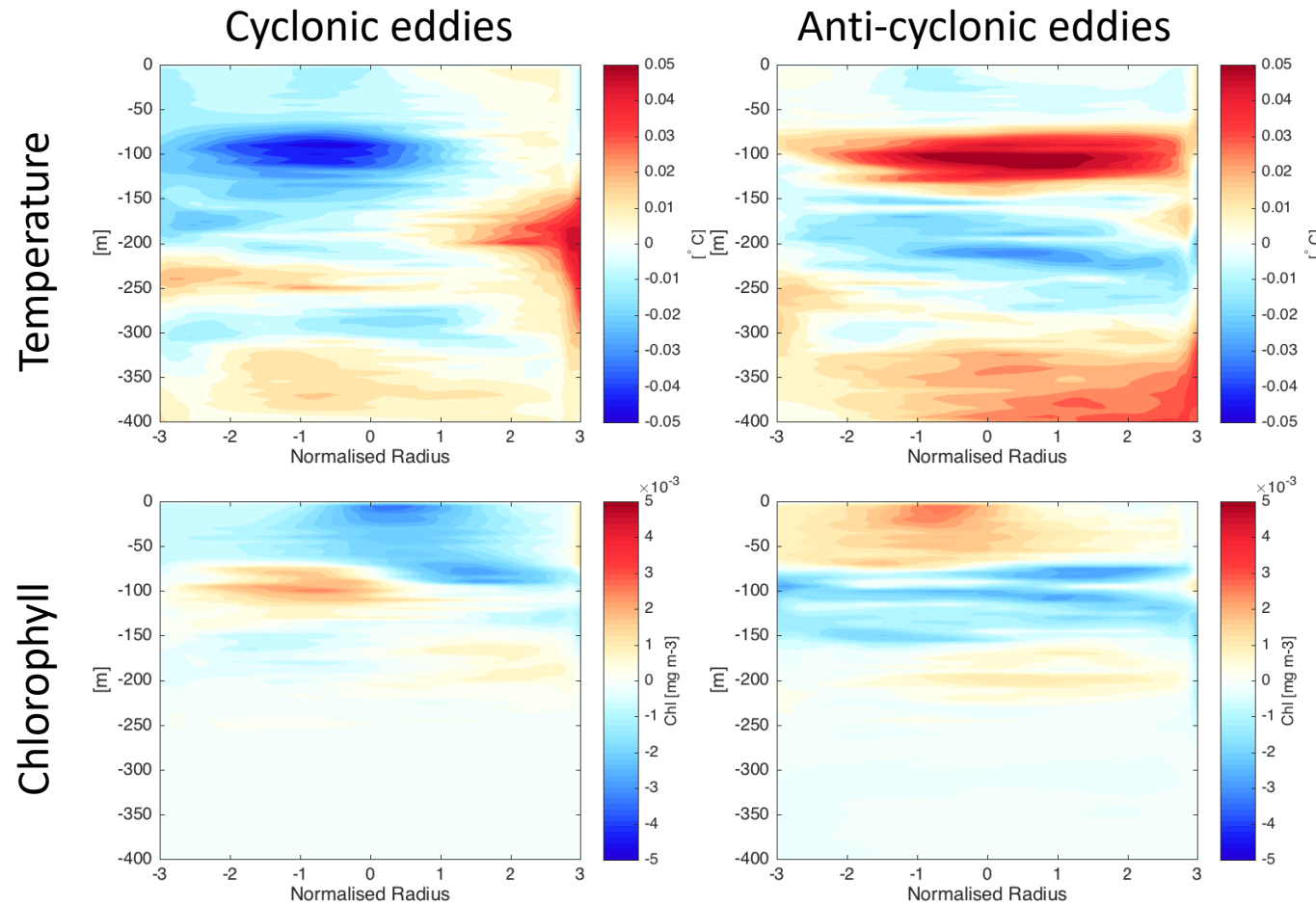
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# Eddy induced enrichment ?

## Eddy composite anomaly



## Run Ref

Cyclonic : Cooling  
Anti-cyclonic : Warming  
=> Weak impact

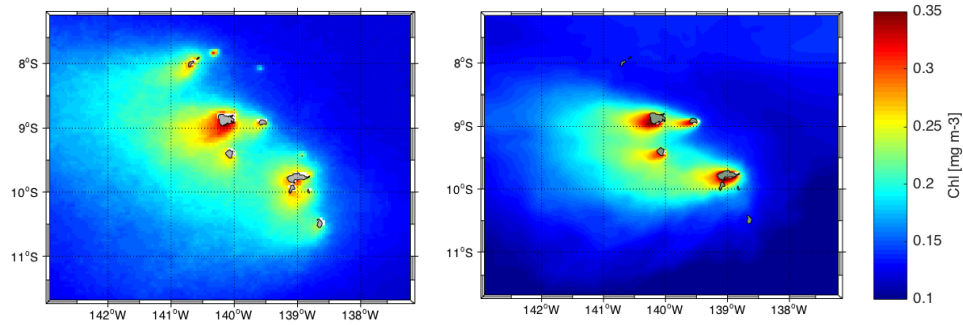
Cyclonic : surface decrease  
Anti-cyclonic : surface increase  
=> Weak impact

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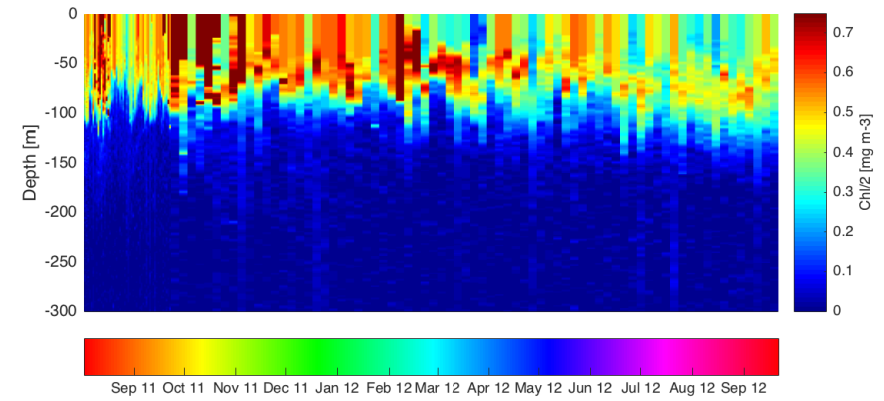
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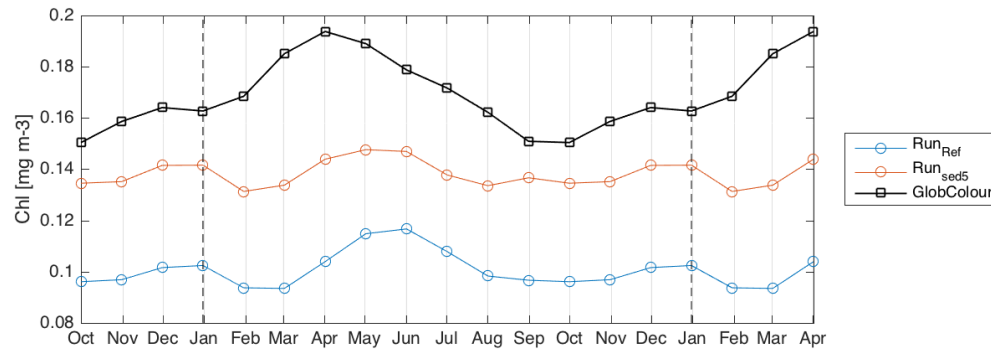
# Conclusion



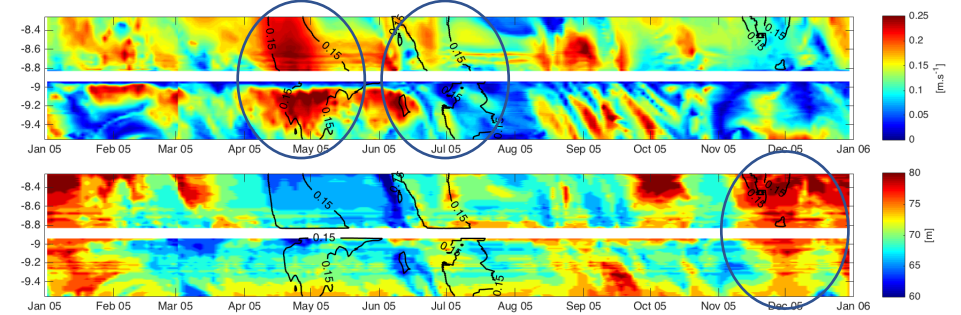
Run<sub>Sed5</sub> : IME when using sediment



BGC-Argo : N-S phytoplankton distribution



GlobColour vs model : close seasonality



Run<sub>Ref</sub> : Advection and MLD



# Plan

## 1. Model set up for the Marquesas archipelago

- Comparison of several implementations

## 2. Investigating the island wake

- Dynamical properties of the island wake

## 3. Investigating the island mass effect

- Biogeochemical properties of the island wake

## 4. Conclusions & perspectives

# Conclusions

## Implementation of a physical model for the archipelago :

- Higher resolution = best results

## Investigation of the island wake :

- Good performance of the model
- Warm and calm area the leeward
- Small scale eddy activity in the archipelago

## Investigation of the island mass effect :

- Iron from the sediment required
- Seasonal variability
- With sediments : rich waters in the calm lee

# Perspectives

## Seasonal scale

### **Forcings :**

- Physical (High resolution)
- Bathymetry with higher spatial resolution

### **Input of iron :**

- Time variation of sediment
- Seasonal variability : river input, internal waves ...
- Particulate fraction of iron

### **Other processes :**

- Internal waves breaking
- Upwelling
- ...

# Perspectives

## Interannual scale

### **Interannual run :**

- Boundary condition : GLORYS (1998-2016)
- Surface forcings : ERA-Interim

**=> ENSO influence ?**

## Interdecadal scale

### **Interdecadal Pacific Oscillation :**

- Forcings using climatology for positive and negative phases

**=> IPO influence ?**

# Perspectives

## In-situ measurements

- Drifting buoys for eddy characterization ?
- Transect of eddies using drifters ?
- Iron sources ? (land drainage, hydrothermal, ...)
- Internal waves
- Land drainage
- ...

**=> Better characterization of the IME**

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# Processus physiques et biogéochimiques impliqués dans l'effet d'île dans l'archipel Marquises

**MERCI POUR VOTRE ATTENTION**

# Sediment enrichment

2003 : ENSO neutral

