Sub-Mesoscale turbulence in the ocean: How does it affect oceanic pCO2 ?

Marina Levy
LOCEAN-IPSL, CNRS-INSU

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MOTIVATION

- The ocean plays in important role in mitigating climate change taking up nearly 30% of anthropogenic CO_2 emissions (Le Quéré et al., 2009)

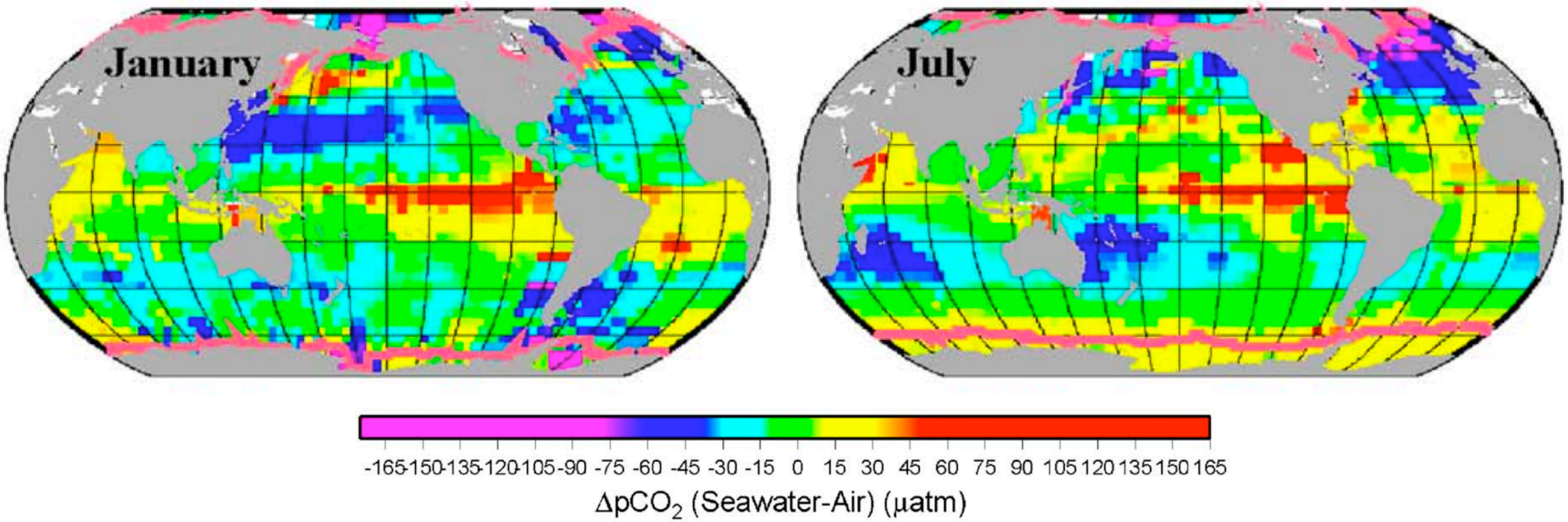
- The direct estimation of the air-sea flux of CO_2 requires a precise evaluation of the oceanic pCO_2 at the sea surface

- pCO_2 = f (DIC, T, ALK, S)

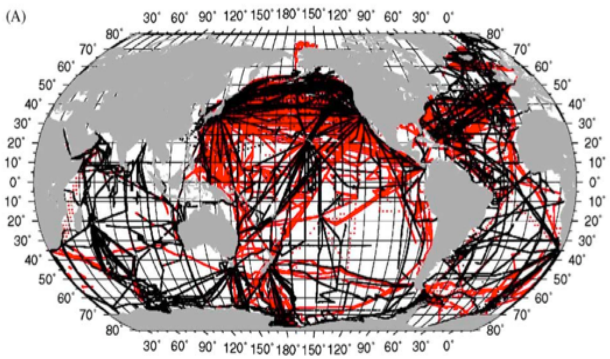
- pCO_2 responds to various processes :
  - Physical : mixing, upwellings, water mass formation
  - Biological: photosynthesis, respiration

→ Oceanic pCO_2 is highly variable in space and time over a wide range of scales

Large-scale, seasonal patterns of oceanic pCO2



Takahashi et al., 2009



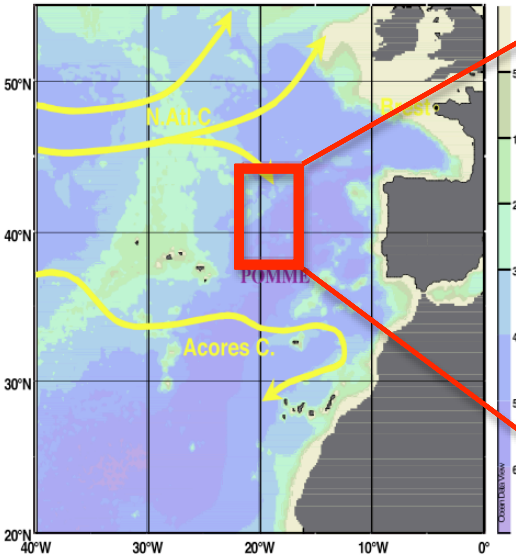
Ship tracks

Resolution : 4° (latitude) x 5° (longitude) x 1 month

500 km x 500 km grid cells

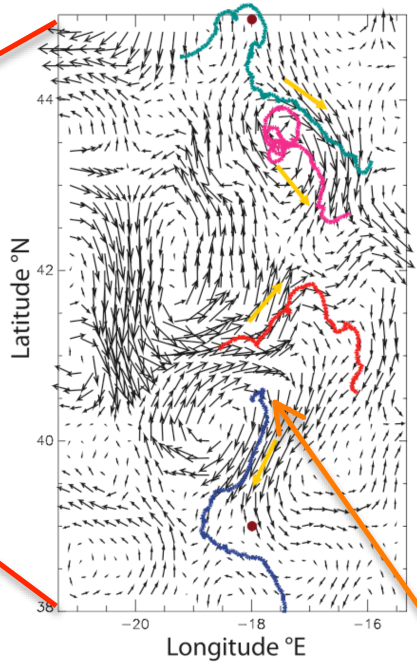
Sub-grid variation of oceanic pCO2 (< 1°, < 1 month)

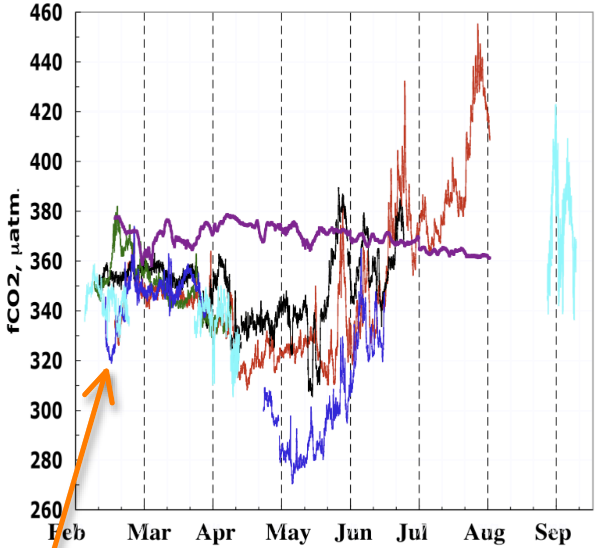
POMME experiment (2001)



POMME domain: 7° x 5°

Carioca floats





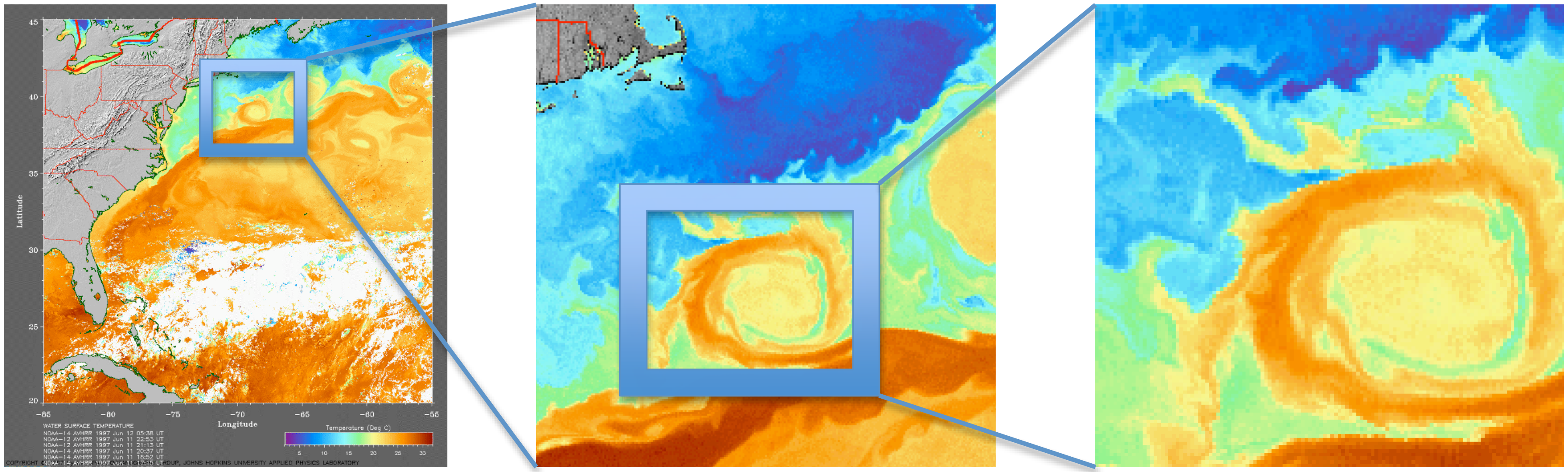
Merlivat et al., 2009

30 µatm

Challenging to observe: often undersampled, uncertainties in climatologies

Oceanic Mesoscale and sub-mesoscale turbulence

Can be observed with satellites (altimetrie, SST, Ocean Color)



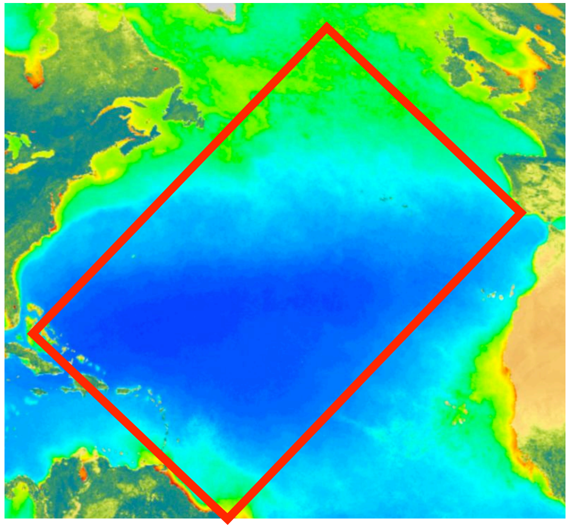
NOAA AVHRR SST

Baroclinic instability of large-scale fronts (like the Gulf Stream)

Oceanic eddies (100 km, months)

Sub-mesoscale filaments (10 km, days)

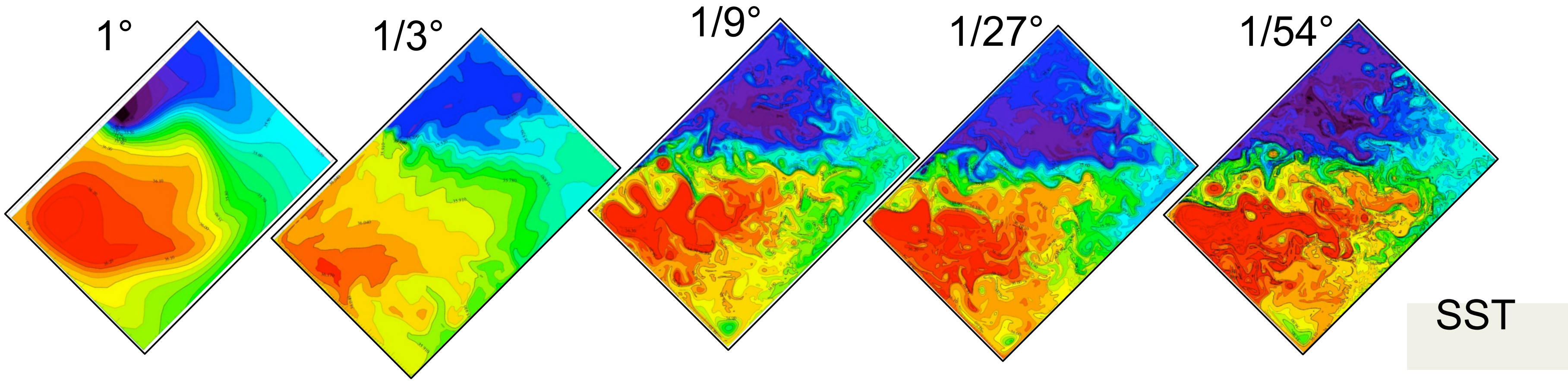
MOTIVATION



Oceanic turbulence in numerical models

Requires fine (2 km) horizontal grids

Challenging to model: often omitted



Climate models

Global Ocean models

Regional Ocean models

X 1.e5 computing time

Lévy et al., OM, in revision

Outline

1. Processes: how sub-mesoscale physics affect oceanic pCO_2

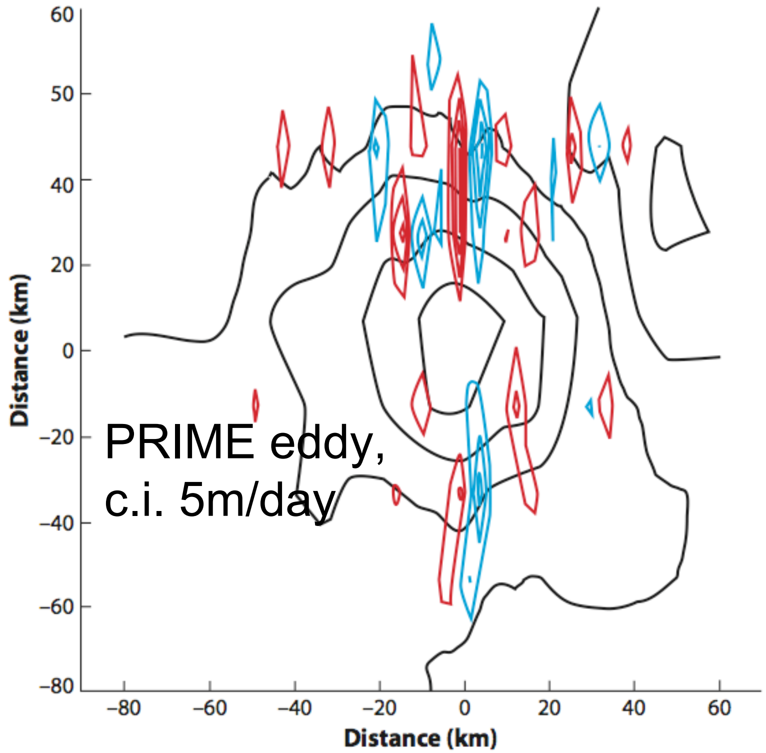
2. Quantification: errors due to undersampling in data, in models

→ Vertical processes
Horizontal processes

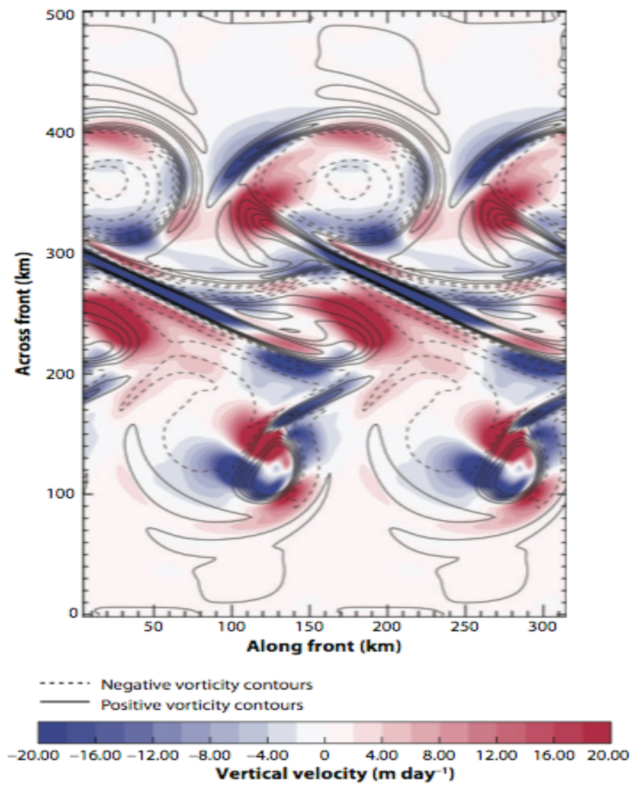
Vertical velocities

Sub-mesoscale filaments are associated with intense vertical velocities : 20-100 m/day !

Observation



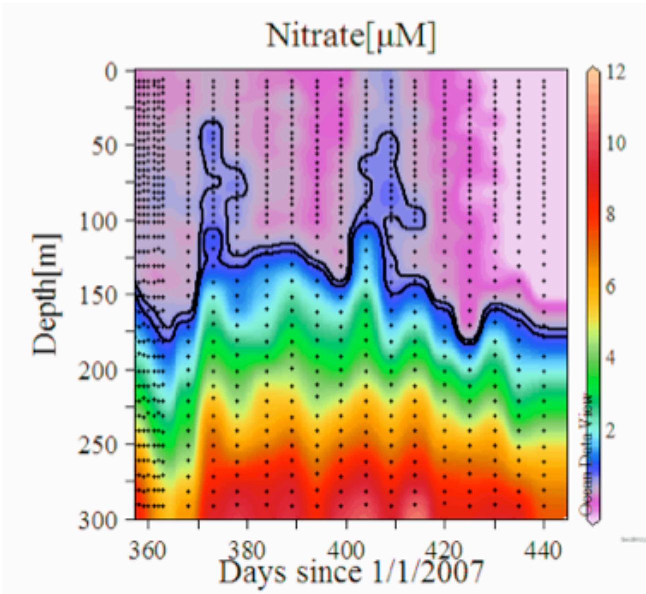
Model



Martin & Richards, DSR, 2001

Levy et al., JMR, 2001

Impact on primary production



Nitrate observations in the oligotrophic North Pacific Gyre (vicinity Hawaii)

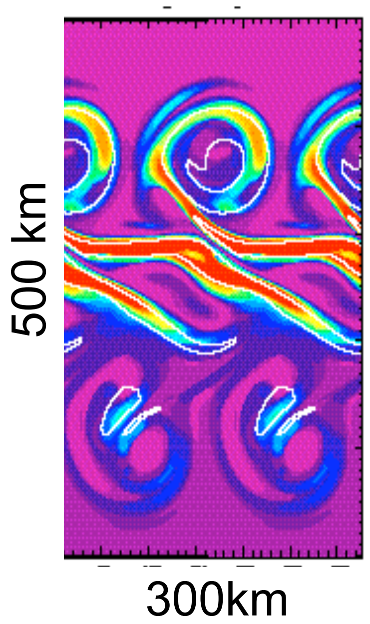
Courtesy Johnson, 2009

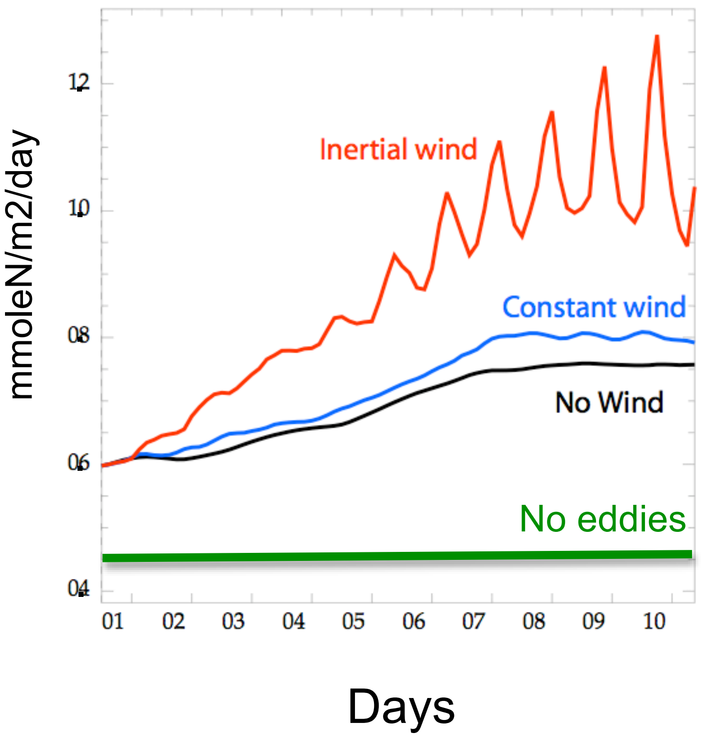
Enhancement of primary production through upwelling of limiting nutrients

Quantification of Primary Production increase with a model

Idealized model with horizontal resolution of 2 km
Extreme situation: highly oligotrophic, strong W
Spin-down of a front generating transient sub-mesoscale vertical transport

Primary Production



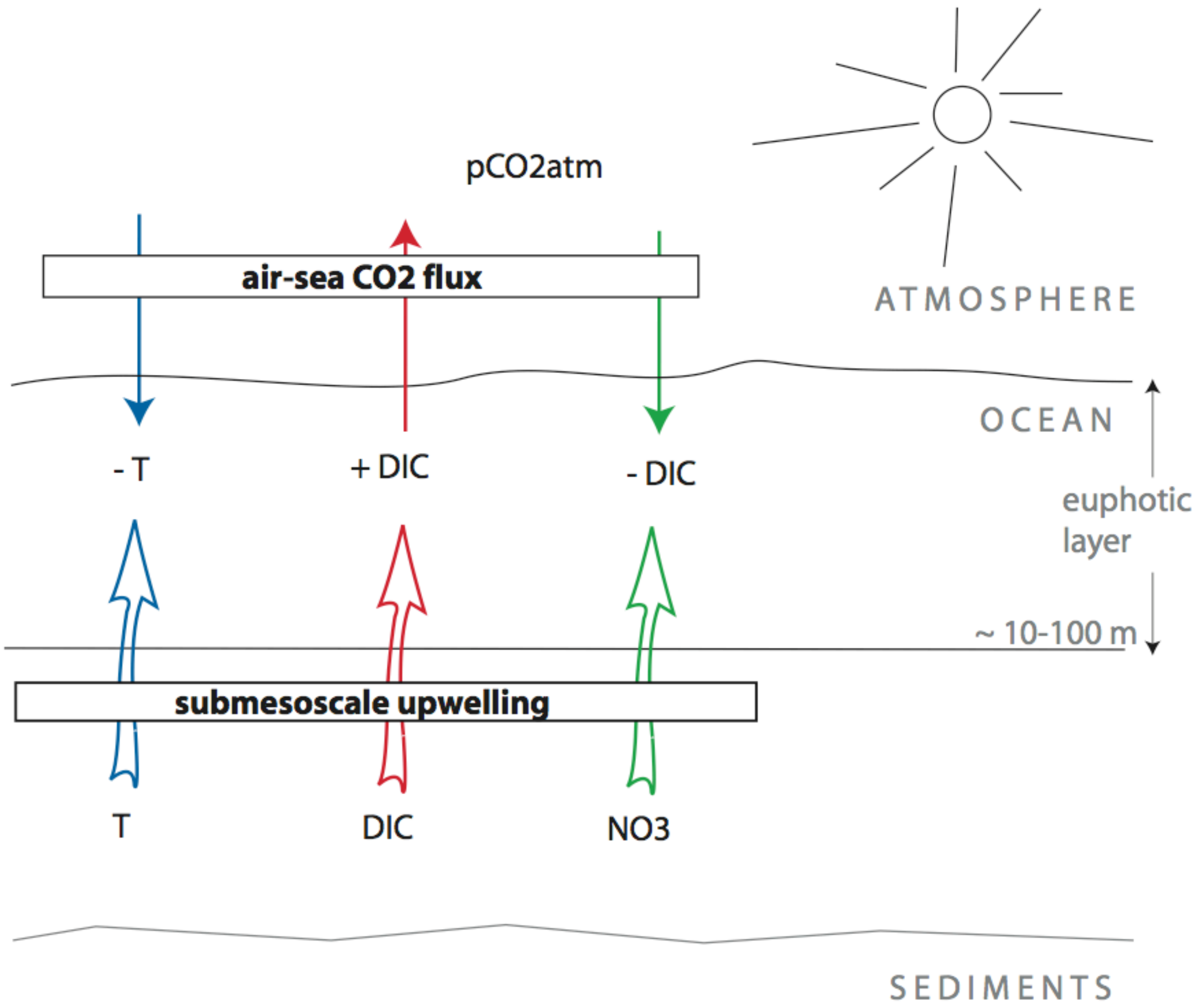


With eddies + HF wind : X 3

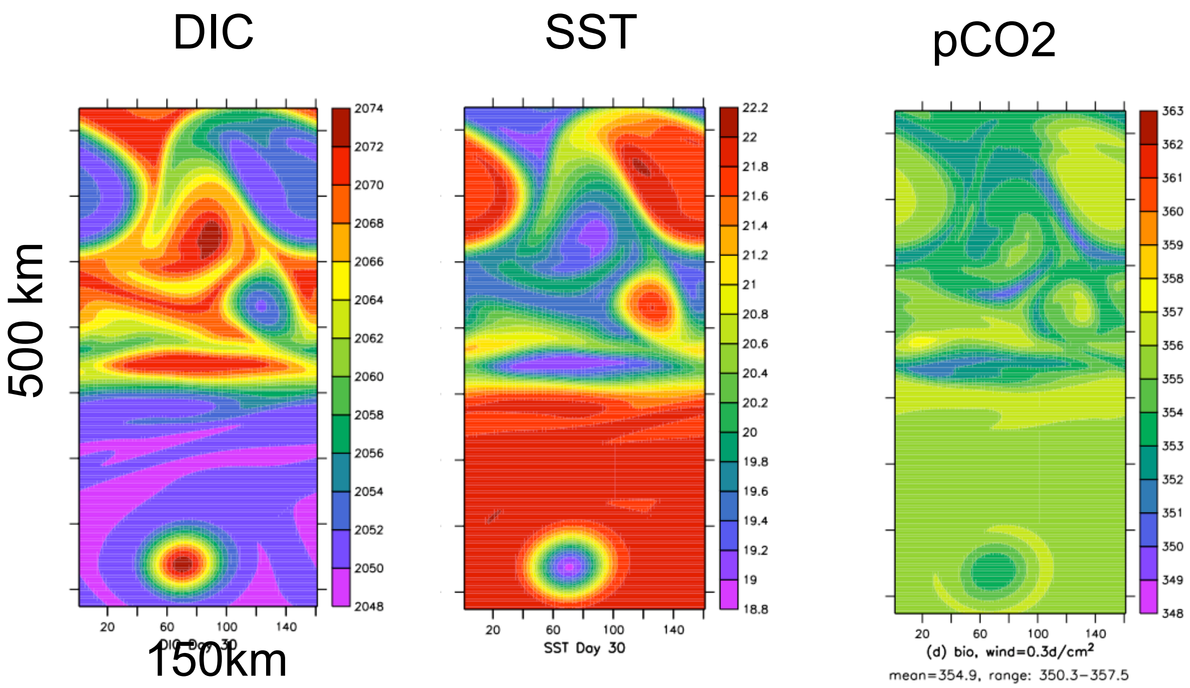
With eddies : X 2

Levy et al., GRL, 2009

Impact on pCO2 ?



Idealized model study: conditions of the NE Atlantic



pCO2 variance :
< 5 μatm

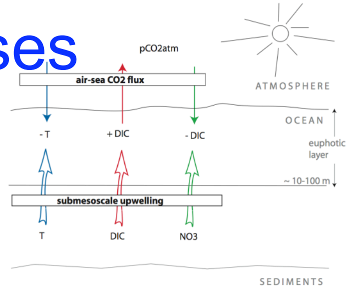
Mahadevan et al. 2004

Strong impact of sub-mesoscale upwelling on PP but weak impact on pCO2 :

Compensating effects between : lowered T, increased DIC

General feature or specific to the NE Atlantic ?

Global evaluation of the impact of vertical processes



pCO_2 = f (DIC, T, ALK, S)

$$\frac{\partial \mathrm{pCO_2}}{\partial t} = \frac{\partial \mathrm{pCO_2}}{\partial \mathrm{T}}\frac{\partial \mathrm{T}}{\partial t} + \frac{\partial \mathrm{pCO_2}}{\partial \mathrm{DIC}}\frac{\partial \mathrm{DIC}}{\partial t} + \frac{\partial \mathrm{pCO_2}}{\partial \mathrm{ALK}}\frac{\partial \mathrm{ALK}}{\partial t} + \frac{\partial \mathrm{pCO_2}}{\partial S}\frac{\partial s}{\partial t}$$

$$\frac{\partial \chi}{\partial t} = -\frac{1}{H}\,\kappa\frac{\partial \chi}{\partial z}\Big|_{z=-H} + S_{\chi}.$$

Variations of T, DIC, ALK and S are assumed to result from vertical mixing (K) at the base of the mixed-layer (H) + Sources/sink terms S

Framework also applies to other episodic events : storms, hurricanes

Potential change of pCO2 due to small scale upwelling

$$\frac{\Delta pCO_2}{pCO_{2s}} =$$ TEMP effect + DIC effect + ALK effect + BIO effect

$$\text{TEMP effect} = -\frac{\kappa \Delta t}{H}\left(\beta \frac{\partial T}{\partial z}\right)$$

$$\text{DIC effect} = -\frac{\kappa \Delta t}{H}\left(\frac{\xi}{DIC}\frac{\partial DIC}{\partial z}\right)$$

$$\text{ALK effect} = -\frac{\kappa \Delta t}{H}\left(\frac{\xi_A}{ALK}\frac{\partial ALK}{\partial z}\right)$$

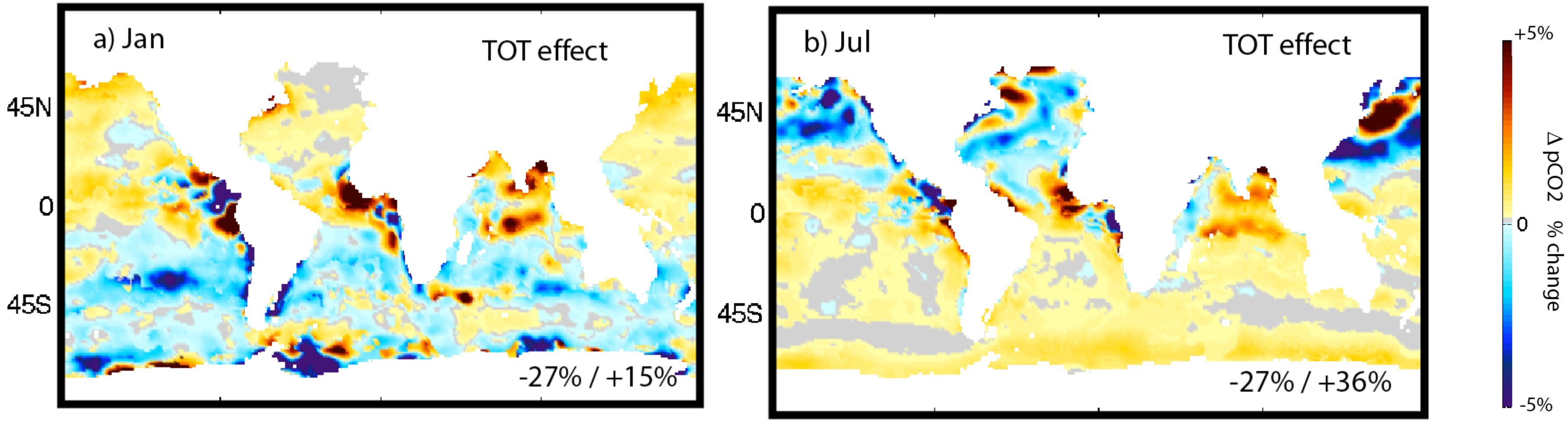
$$\text{NO}_3\text{effect} = \frac{\kappa \Delta t}{H} R_{C:N} L \frac{\partial NO_3}{\partial z}.$$

κ strength of mixing

Estimate the different effects using available climatologies:
-De Boyer Montegut Mixed-layer depth climatology
-Levitus climatology for T, S, NO3
-GLODAP climatology for DIC, ALK

Global estimate of % pCO_2 change due to localized upwelling

% calculated for a given strength of mixing κ=1.e^{-3} m^2/s^2 and for Δt= 1 day

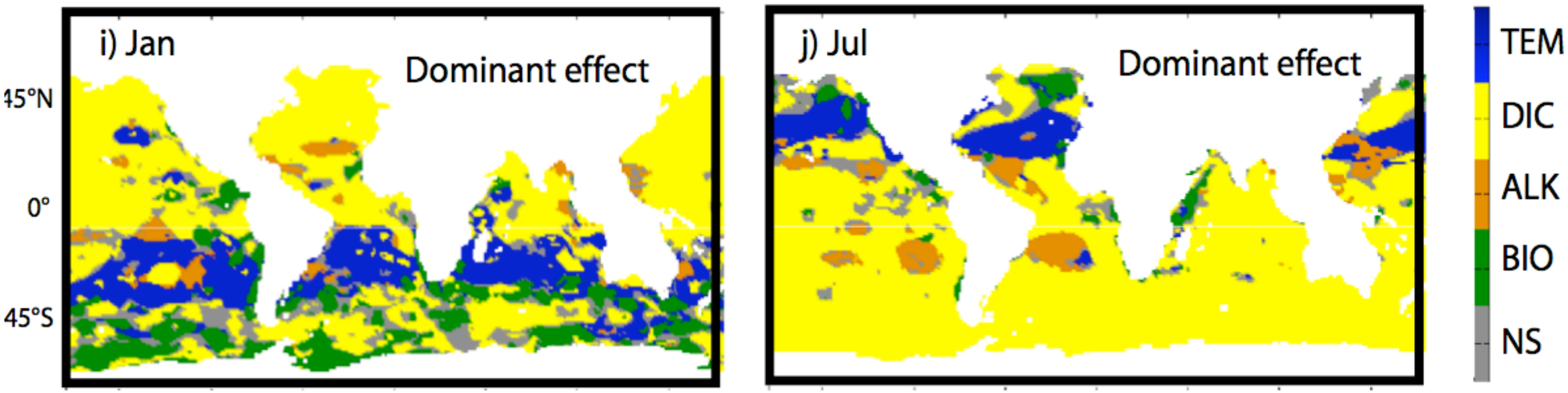


Mahadevan et al., submitted

- -Net response of pCO_2 to localized mixing is highly variable in space and time
- -Large areas show little sensitivity due to compensating effects
- -Some regions indicate an increase in pCO_2, others a decrease
- -Large seasonality
- -Contrasting responses can occur in proximity (+/- 40 μatm)
- -Large sensitivity along eastern equatorial margins (up to +/- 60 μatm)

Today and tomorrow

Today's Ocean: DIC (yellow) effect is dominant :
Submesoscale upwelling increases pCO2 in yellow regions, decreases pCO2 in blue regions



This effect is very likely to change in a warmer, higher CO_2 world :

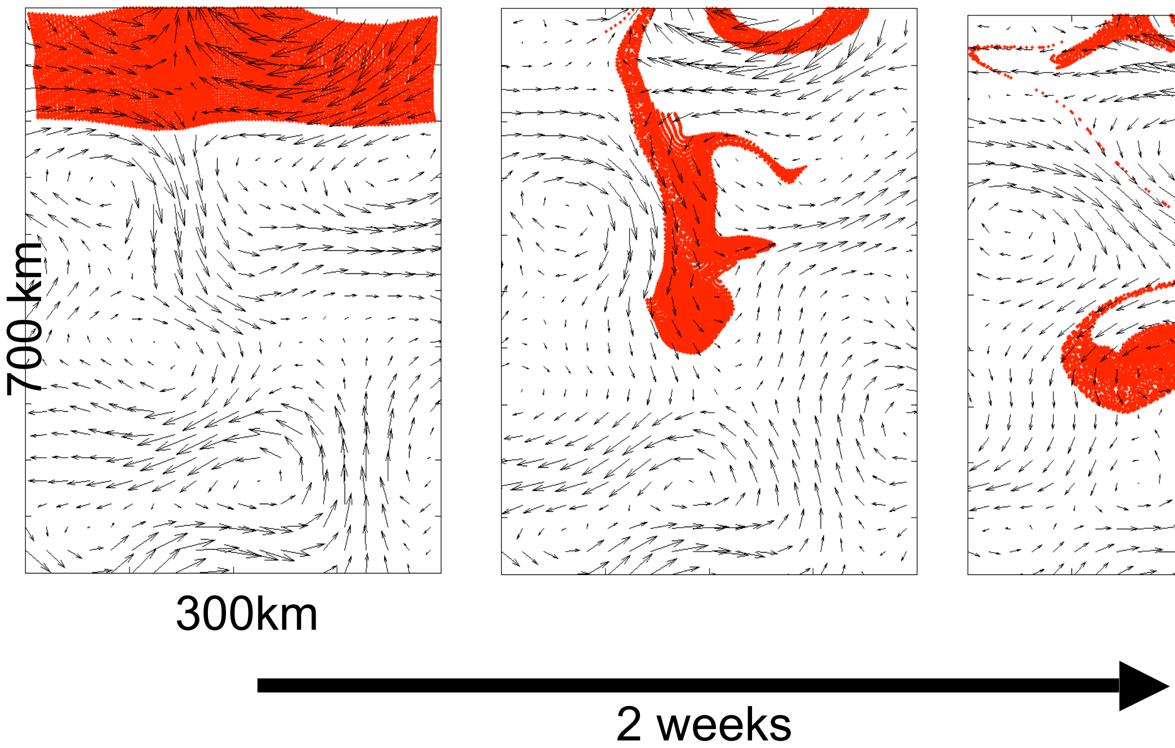
-Decrease of vertical DIC gradient due to uptake of anthropogenic CO2
-Increase of T gradient due to warming at the surface
-Increase of stratification

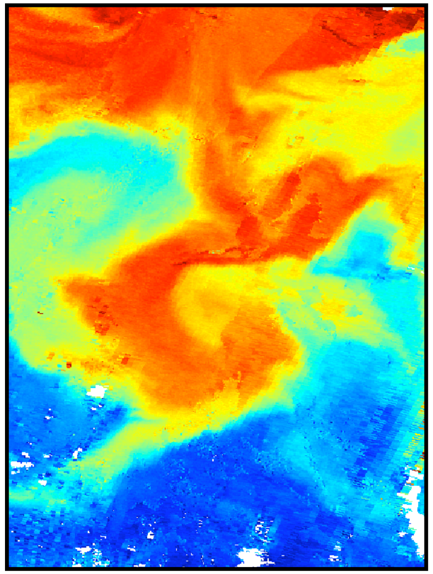
Possible change of sign and lowering of the effects of localized upwelling in the future

Horizontal stirring

Advection of a passive tracer

SeaWifs Chlrophyll



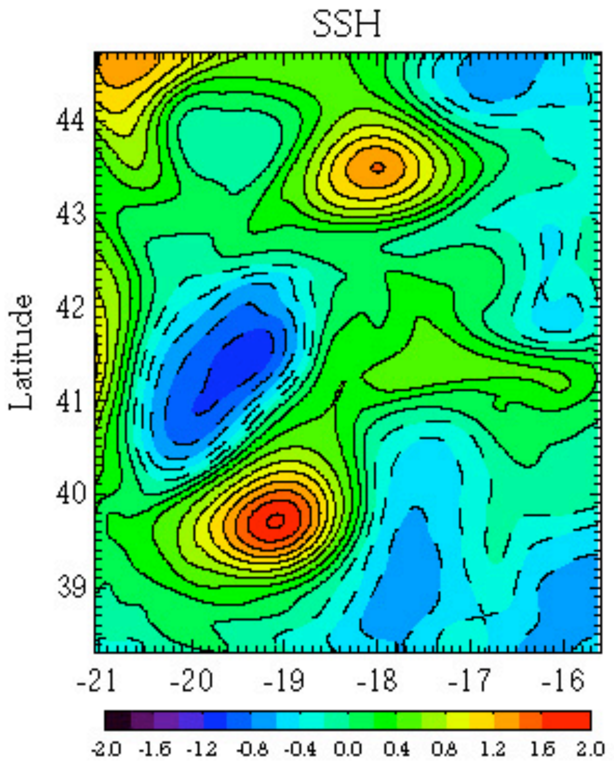


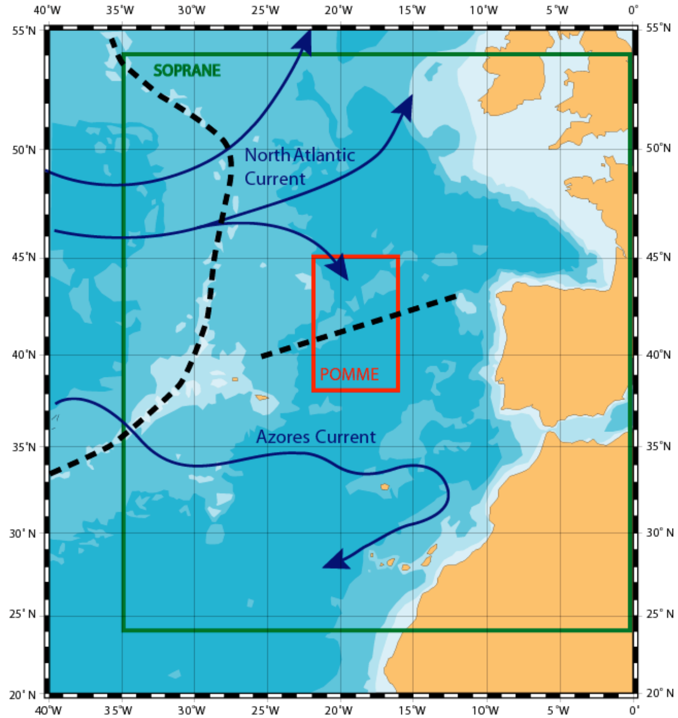
Currents derived from Altimetry

Lehahn et al., JGR, 2007

Regional model study of the POMME experiment

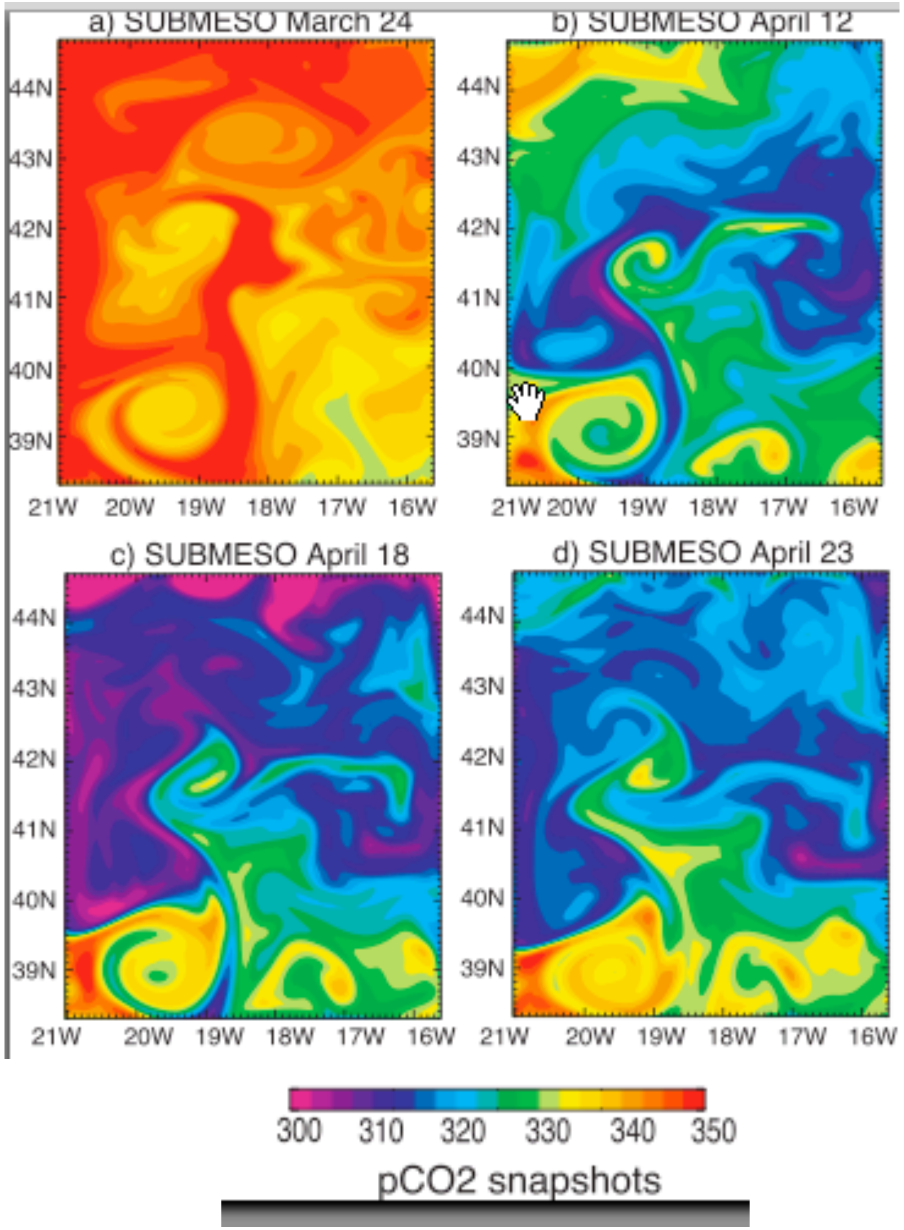
Spring bloom
Numerous mesoscale eddies





POMME program
(field work: 2001)

Regional model constrained with POMME observations



POMME model results

Seasonal drawdown associated with the bloom

Weakly energetic area : W < 5 m/day

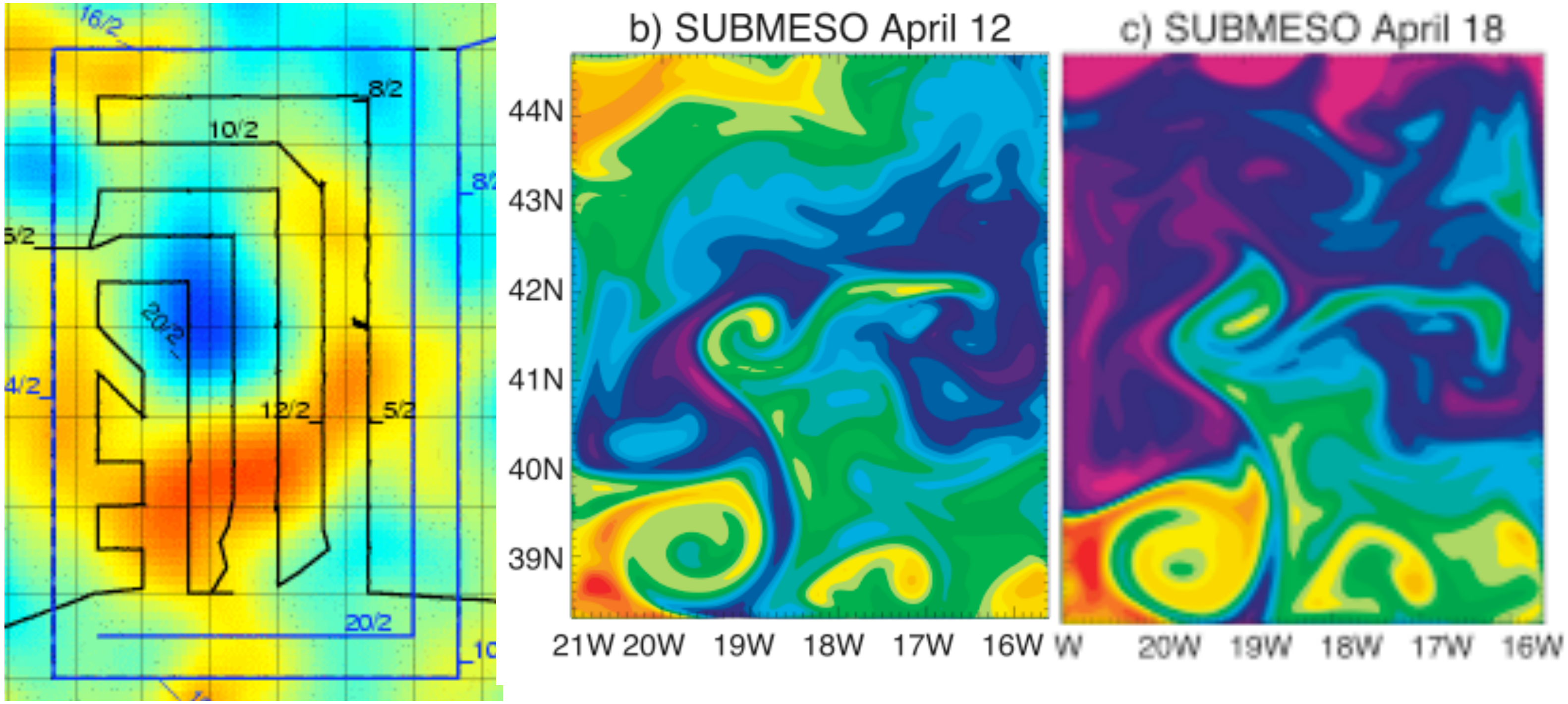
Large pCO_2 gradients (30 μatm over 10 km) generated by horizontal stirring

pCO2 variance :
> 20 μatm

Resplandy et al., GBC, 2009

Evaluation of undersampling errors due to horizontal stirring

Strong space and time variations: difficult to sample

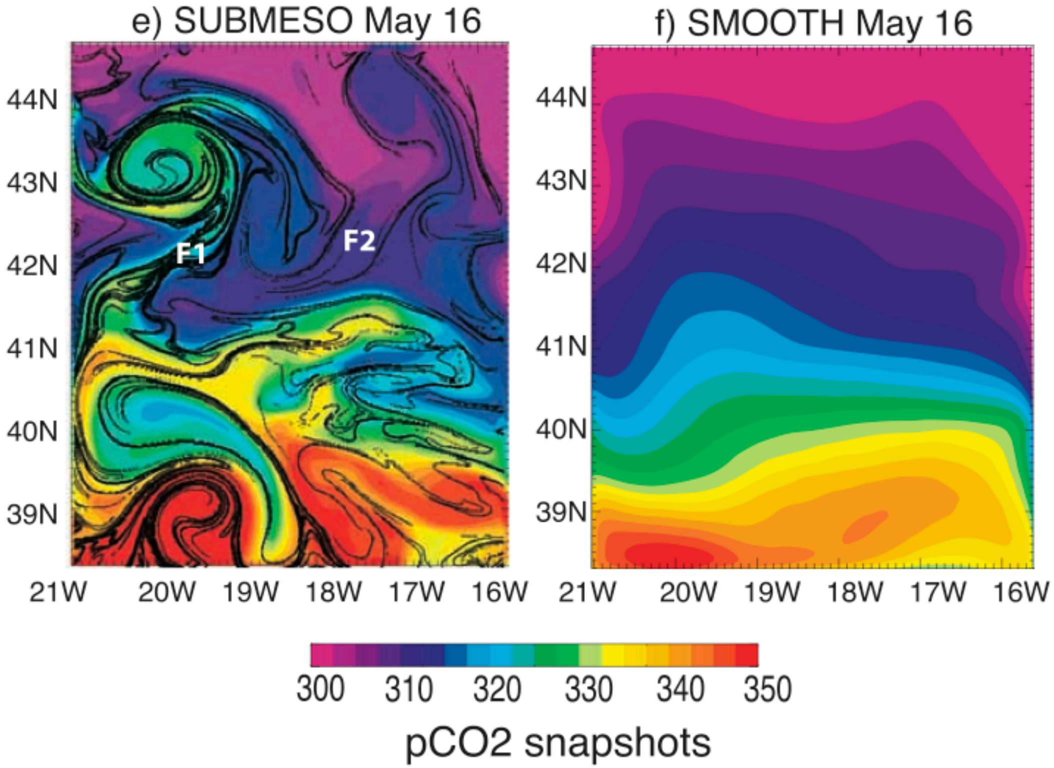


Network sampling: 3 weeks, 50 km between stations

- > 10 to 30 % error on air-sea CO_2 flux due to undersampling

Resplandy et al., GBC, 2009

Evaluation of model errors due to horizontal stirring



Weak modifications of mean model-predicted pCO2 (< 5 %) :

Because the changes are due mostly to redistribution on the horizontal by stirring (small contribution of vertical advection)

Resplandy et al., GBC, 2009

Summary

Sub-mesoscale physics affect oceanic pCO_2 through :
-Vertical advection of T, S, DIC, ALK, NO_3
-Horizontal stirring of adjacent water masses with different properties

Impact of Vertical advection on pCO_2
•Weak because of combined effects that cancel each other (T and DIC)
•**Large in some specific regions** and with opposite signs
•Likely to change in the future

Impact of Horizontal stirring on pCO_2
•Large: generates very strong inhomegeneity of pCO_2
•**Source of errors in the estimation of air-sea CO_2 fluxes from observations**
•Small source of errors in models

Concluding remarks

Sub-mesoscale variability is responsible for large uncertainties in oceanic pCO2 estimates, both from observations and from models

Quantification of these uncertainties in under way: highly variable regionally

Potential for reducing these uncertainties in the next 20 years by :
Expanded surveys
Higher - resolution models

Contributions from : L. Bopp, P. Karleskind, P. Klein, Y. Lehahn, A. Lenton, A. Mahadevan, L. Memery, L. Merlivat, F. d'Ovidio, L. Resplandy, A. Tabliaglue