

# *Horizontal advection, diffusion and plankton power spectra at the ocean surface*

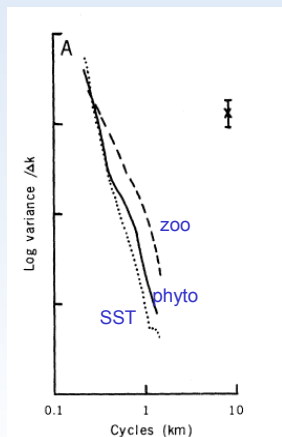
with Sophie Clayton and Claudia Pasquero



Bracco, Clayton, Pasquero, JGR – Oceans, 2009

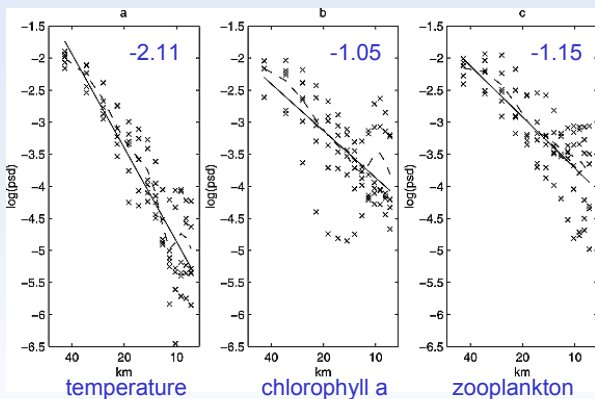


## Observations of spectral distributions at the ocean surface: in situ



Power spectra for phytoplankton, zooplankton and temperature along a ship transect in the North Sea.

(Mackas & Boyd, 1979; Horwood, 1981; Weber et al., '86; Levin et al. '89; Tsuda et al., '93)

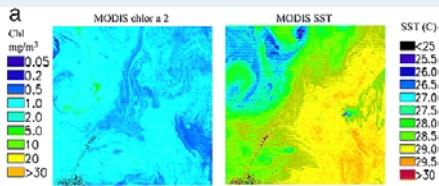


Spectral density data from ship transects in the North Atlantic, of potential temperature, chlorophyll a and zooplankton (250-500 $\mu$ m).

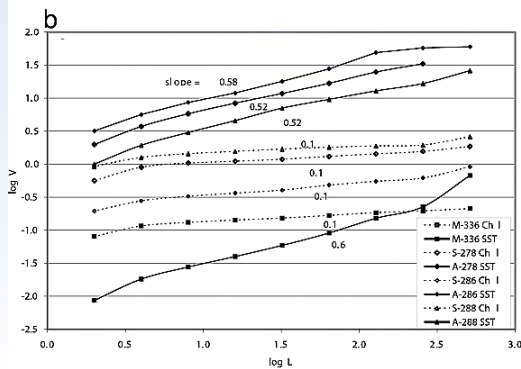
(Piontkovski et al., '97; Martin & Srokosz, 2002)

# From satellite

(Mahadevan & Campbell, 2002)



Simultaneous satellite images of sea surface temperature (SST) and chlorophyll (Chl) in the Arabian Sea acquired by the Moderate Resolution Imaging Spectroradiometer (MODIS) on December 1, 2000.



The variance–scale relationship of SST and chlorophyll. Chlorophyll has a patchier distribution than SST → flatter spectra

## Horizontal advection and large scale input

(Abraham, 1998)

carrying capacity

$$\frac{dC}{dt} = \frac{1}{R_t}(C_o - C)$$

$R_t$  = reaction time

phytoplankton

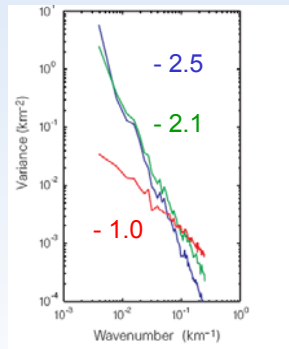
$$\frac{dP}{dt} = P\left(1 - \frac{P}{C}\right) - PZ$$

zooplankton

$$\frac{dZ}{dT} = P(t - \tau)Z(t - \tau) - \delta Z^2$$

$\tau$  = maturation time

$\delta$  = mortality rate



carrying capacity

phytoplankton

zooplankton

Large scale nutrient input: horizontal advection + direct turbulent (enstrophy) cascade + biology (DIFFERENT REACTION TIME):  
Explain relative flatter slope of zooplankton vs phyto

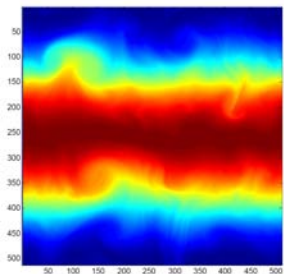
# Large scale upwelling

No diffusion

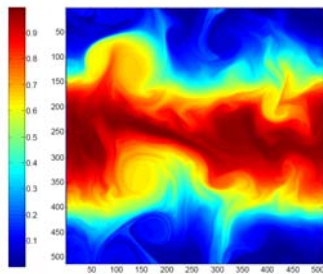
$$R_{t-SST} \propto \frac{\Delta T \rho h C_p}{Q} \approx 6 \text{ weeks}$$

for  $\Delta T = 1$  and  $h = 50m$

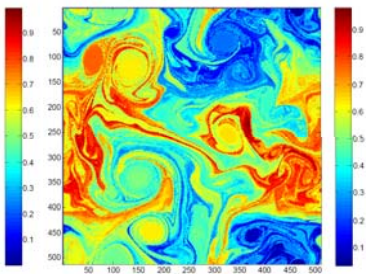
??



$R_t \sim 4$  days  
(phytoplankton)



$R_t \sim 12$  days  
(zooplankton)



$R_t \sim 40$  days  
Temperature

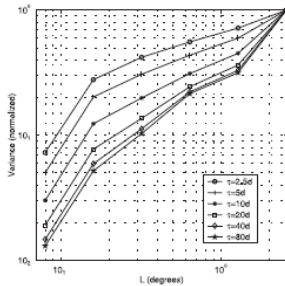
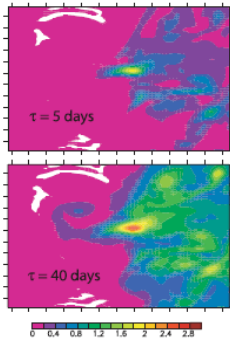
Advective time scale = 15 days

Upwelling at small scales. Interpretation: inverse turbulent cascade coupled to different reaction time

(Mahadevan & Campbell, 2002)

Ocean model coupled to a simple reactive tracer:

$$\frac{\partial C}{\partial t} + \vec{u} \cdot \nabla C = \text{Source} / \text{Sink} = -\tau^{-1} C$$



$\tau$   
slope increases  
for  $\tau$  increasing

## physical processes influencing the relative distributions of tracers at the ocean surface :

- 1) the spatial scale of tracer supply
- 2) horizontal advection and the presence of coherent structures (eddies, filaments, fronts)
- 3) diffusion (so far neglected)

Simplest possible reactive tracer:

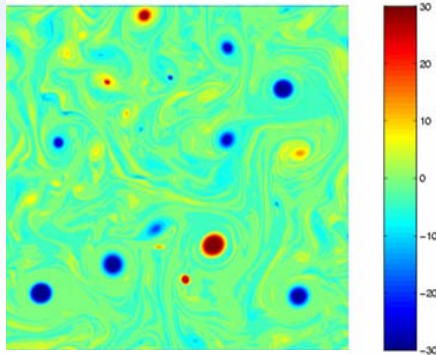
$$\frac{dC}{dt} = \frac{\partial C}{\partial t} + [\psi, C] = \frac{1}{R_t} [C_0(x, y) - C(x, y)] + \lambda \nabla^2 C \quad .$$

## The Lagrangian approach

- 2D turbulence model equation for horizontal advection:

$$\frac{\partial \omega}{\partial t} + [\psi, \omega] = D + F$$

forcing scale  $\sim 25$  km  
resolution 0.5 km (effective  
1km)  
kinetic energy  $8 \cdot 10^{-4} \text{ m}^2/\text{s}^2$   
eddy diffusivity  $1200 \text{ m}^2/\text{s}$



vorticity field

1. 256 km<sup>2</sup> periodic domain with 262144 passively advected Lagrangian particles. Each of them carries a concentration  $C$  of tracer
2. Advection, diffusion and reaction processes can be looked at separately more easily.
3. Lagrangian representation of Fick's law  $\frac{\partial C}{\partial t} = \lambda \nabla^2 C$

given two water parcels,  $i$  and  $j$ , at distance  $r_{ij}$  with concentration  $C_i$  and  $C_j$   $\longrightarrow$  there is a flux towards the parcel with the lower concentration with mixing law

$$C_{i \text{ mixed}} = C_i + h(r_{ij})(C_j - C_i)$$

for any  $i$  and  $j$  closer to each other than a given threshold. The weight function is  $h(r) = \alpha \exp(-r^2/r_0^2)$ ,  $r_0$  measuring the scale of mixing.

## Turbulent diffusion in the ocean

The turbulent diffusivity coef.  $\lambda$  for a reactive tracer is a function of its reaction time (Plumb, 1979; Pasquero, 2005; Richards and Brentnall, 2006)

If a biochemical tracer reacts with  $R_t \leq$  Lagrangian decorrelation time  $\longrightarrow$  no constant spreading rate of the Brownian regime  $\longrightarrow$  tracers with small  $R_t$  will spread less than tracers with large  $R_t$ .

In the ocean (from NATRE) at scales  $< 1\text{km}$ :

$$R_t(\text{temp}) \sim 40 \text{ days} \rightarrow \lambda \sim 1\text{m}^2\text{s}^{-1}$$

$$R_t(\text{zoo}) \sim 12 \text{ days} \rightarrow \lambda \sim 0.5\text{m}^2\text{s}^{-1}$$

$$R_t(\text{phyto}) \sim 4 \text{ days} \rightarrow \lambda \sim 0.05\text{m}^2\text{s}^{-1}$$

## The simplest reactive tracer equation + a 2D turbulent flow + diffusion

C relaxes towards  $C_0$  with the assumption of abundant reservoir

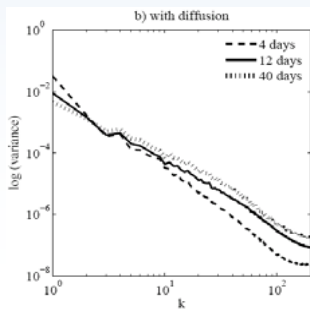
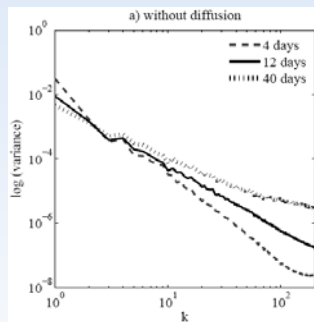
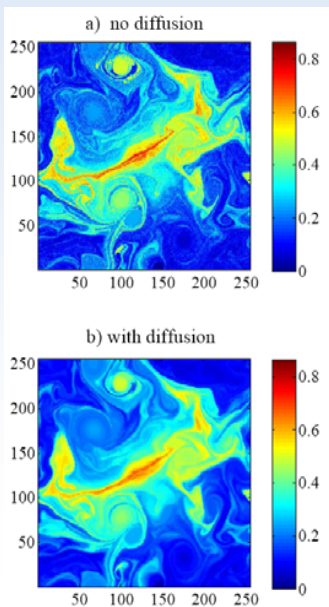
3 configurations:

1)  $C_0 = [1 - \cos(2\pi y/L)] [1 - \cos(2\pi x/L)] / 2$

2)  $C_0 = [1 - \cos(64 * 2\pi y/L)] [1 - \cos(64 * 2\pi x/L)] / 2$

3)  $C_0 = C_A = 1$  inside vortices and filaments and  
 $C_0 = C_N = 0$  in the background turbulence

## Large scale supply

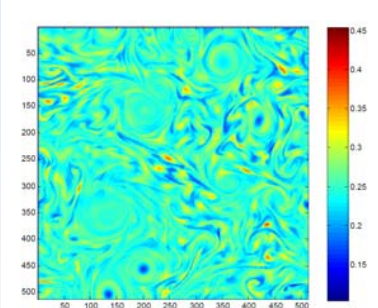
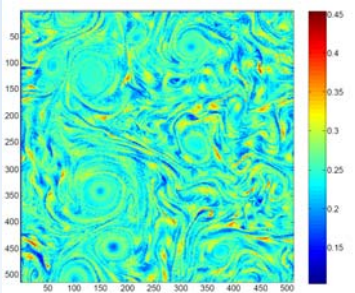


Large scale input	$\lambda$ (diffusivity coefficient)			
	0.0 m <sup>2</sup> /s	0.05 m <sup>2</sup> /s	0.5 m <sup>2</sup> /s	1 m <sup>2</sup> /s
$R_t$ (days)				
4	-2.5	<b>-2.5 ± 0.05</b>	-2.5	-2.6
12	-2.1	-2.13	<b>-2.35 ± 0.05</b>	-2.47
40	-1.3	-1.44	-1.95	<b>-2.1 ± 0.05</b>

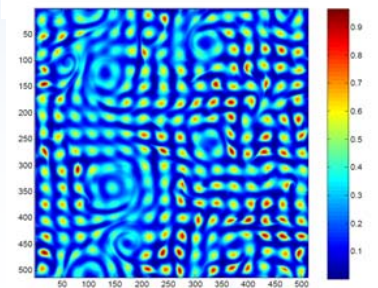
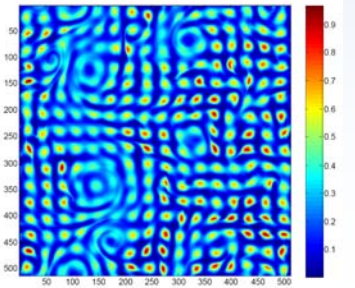
Abraham' idea is confirmed, but differences are reduced by diffusion

# Small scale supply (unrealistic)

$R_t = 40$  days



$R_t = 4$  days

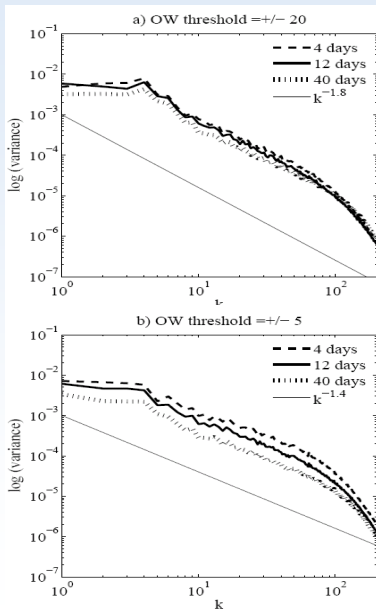


no diffusion

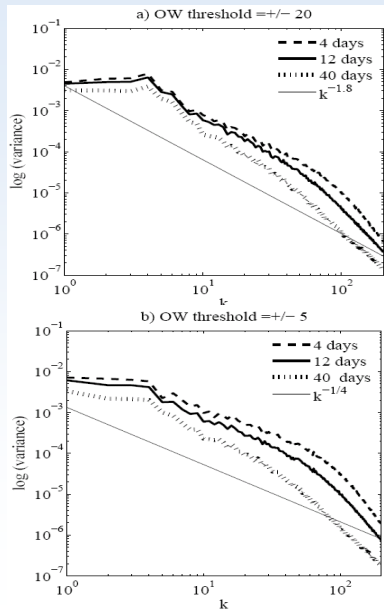
with diffusion

Small (4km) scale input	$\lambda$ (diffusivity coefficient)			
	$R_t$ (days)	0.0 m <sup>2</sup> /s	0.05 m <sup>2</sup> /s	0.5 m <sup>2</sup> /s
4	-4.75	<b>-4.8 ± 0.05</b>	-4.8	-4.8
12	-3.0	-3.0	<b>-3.1 ± 0.05</b>	-3.2
40	-1.25	-1.4	-1.75	<b>-1.9 ± 0.05</b>

## Supply in Vortices and filaments



no diffusion



with diffusion

OW threshold +/- 20	$\lambda$ (diffusivity coefficient)			
$R_t$ (days)	0.0 m <sup>2</sup> /s	0.05 m <sup>2</sup> /s	0.5 m <sup>2</sup> /s	1 m <sup>2</sup> /s
4	-1.75	<b>-1.75 ± 0.05</b>	-1.78	-1.80
12	-1.75	-1.75	<b>-1.80 ± 0.05</b>	-1.92
40	-1.90	-1.95	-2.0	<b>-2.0 ± 0.05</b>
OW threshold +/- 5				
4	-1.35	<b>-1.35 ± 0.05</b>	-1.35	-1.38
12	-1.4	-1.45	<b>-1.6 ± 0.05</b>	-1.7
40	-1.45	-1.55	-1.8	<b>-1.95 ± 0.05</b>

# The role of biology

## Abraham model

$$\frac{dC}{dt} = \frac{1}{R_t} [C_0(x, y) - C(x, y)] + \lambda \nabla^2 C$$

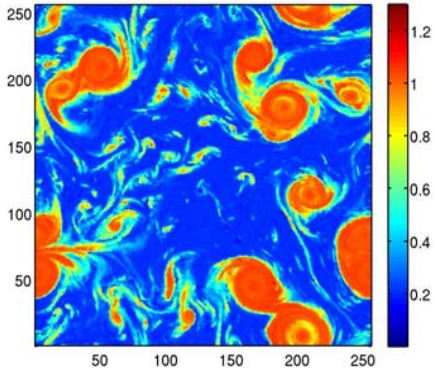
$$\frac{dP}{dt} = g(C, P, Z) + \lambda' \nabla^2 P = P(1 - P/C) - PZ + \lambda' \nabla^2 P$$

$$\frac{dZ}{dt} = h(C, P, Z) + \lambda'' \nabla^2 Z = \gamma P(t - \tau) Z(t - \tau) - \mu_z Z^2 + \lambda'' \nabla^2 Z$$

everything applies here if an effective reaction time is considered:

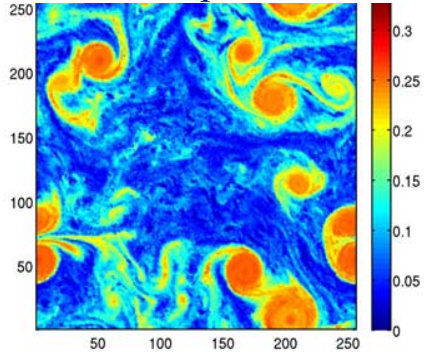
$$\langle R_t \rangle = \langle 1/P(Z) dP(Z)/dt \rangle$$

## Phytoplankton (NP model)



Supply in vortices and  
filaments. PZ model

## Zooplankton



## Fasham model

$$\begin{aligned}\frac{dN}{dt} &= \Theta - \beta \frac{N}{k_N + N} + \mu_N \left[ (1-\gamma) \frac{\alpha \varepsilon P^2}{\alpha + \varepsilon P^2} Z + \mu_P P + \mu_Z Z^2 \right] + \lambda \nabla^2 N, \\ \frac{dP}{dt} &= \beta \frac{N}{k_N + N} P - \frac{\alpha \varepsilon P^2}{\alpha + \varepsilon P^2} Z - \mu_P P + \lambda' \nabla^2 P, \\ \frac{dZ}{dt} &= \gamma \frac{\alpha \varepsilon P^2}{\alpha + \varepsilon P^2} Z - \mu_Z Z^2 + \lambda'' \nabla^2 Z\end{aligned}$$

$\langle R_t(\text{zooplankton}) \rangle \sim \langle R_t(\text{phytoplankton}) \rangle \sim 2\text{-}3$  days  
for any realistic set of parameters and the  
spectra slopes of P and Z are  $\sim$  indistinguishable

## in summary

- **Turbulent diffusion determines the spectral distribution of tracers with  $R_t$  longer than the Lagrangian decorrelation time scale (i.e.  $> \sim 2$  weeks), as for SST**
- **If the supply is uncorrelated with the flow, whether at small or large scales, the faster the reaction time, the steeper the spectral slope (Abraham's idea). Diffusion only reduces differences**

- **If the supply is coupled with the coherent structures (vortices and filaments):**
  - ✓ **a) with NO DIFFUSION - and constant relaxation !limitation! - the eddy lifetime + the eddy distribution and impermeability to in/out fluxes set the spectral slope ~ independently of  $R_T$ .**
  - ✓ **b) WITH DIFFUSION tracers with slow  $R_T$  have spectra steeper than tracers with shorter  $R_T$ , because they are given more time to reach a higher degree of homogenization.**