Mesoscale and submesoscale variability and biogeochemical interactions

Annalisa Bracco

Georgia Institute of Technology

School of Earth and Atmospheric Sciences

Part 1

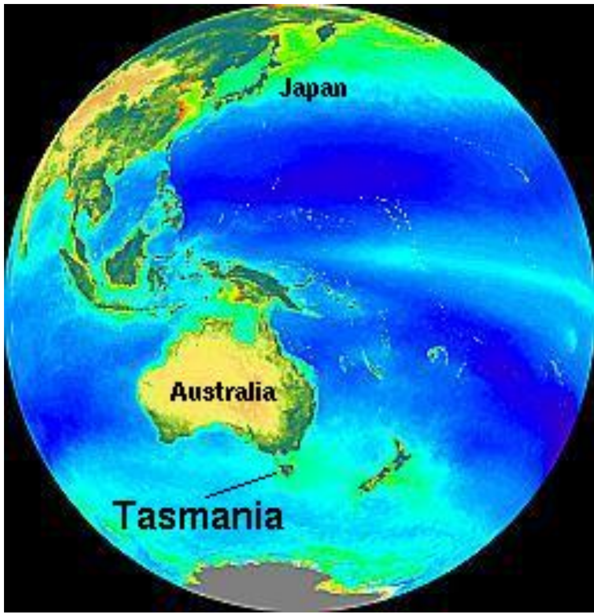
Mesoscale (eddy) dynamics and biogeochemical processes

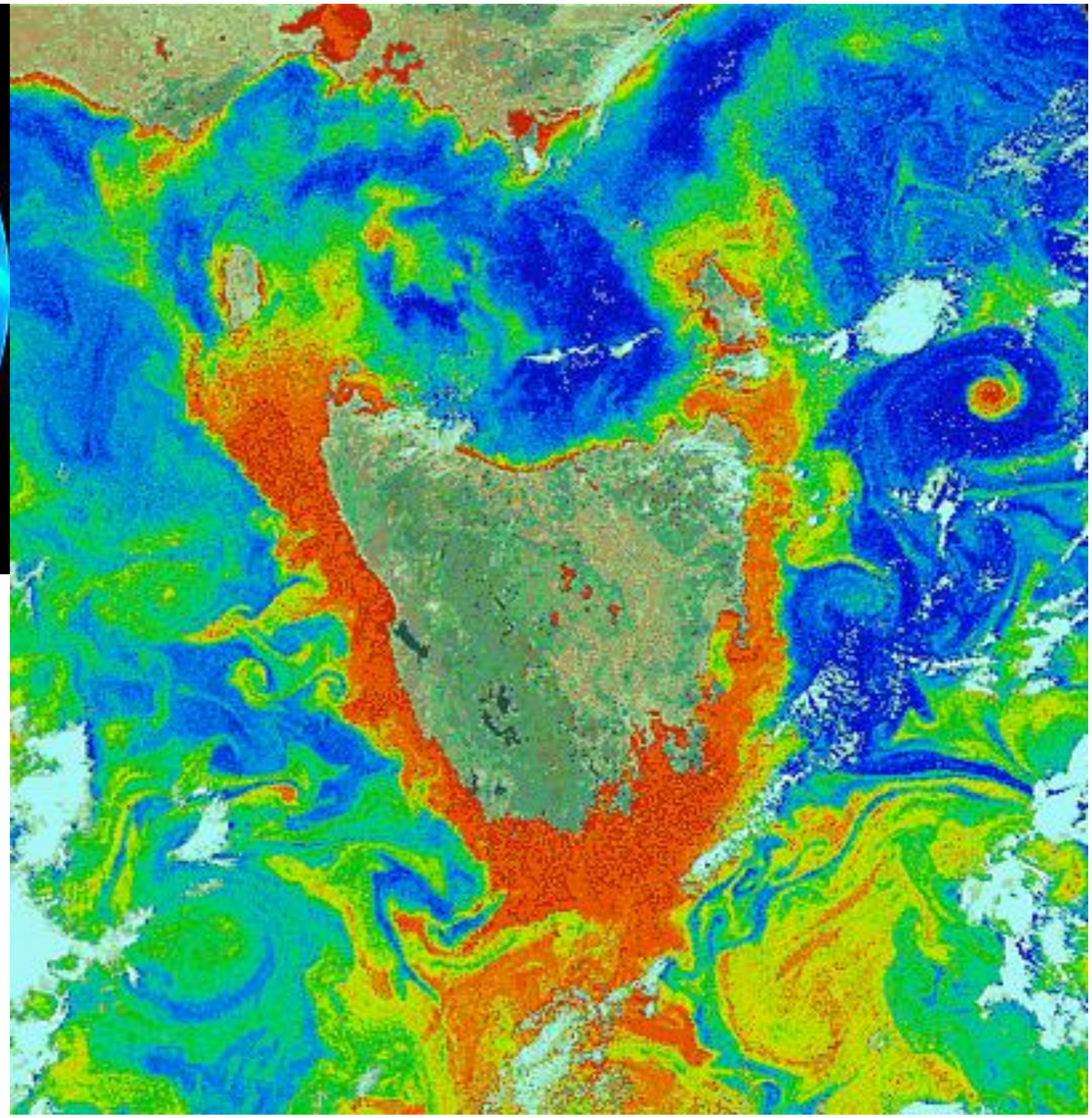
Outline

- Mesoscales and their role on the global scale (why we care)
- **Mechanisms** of eddy-induced variability in primary productivity
  - eddy stirring and eddy trapping (and possible role in community composition)
  - eddy pumping
  - eddy and wind effects

suggested reading: McGillicuddy, 2016 Annual Review of Marine Science

Mesoscale variability (10-250km)





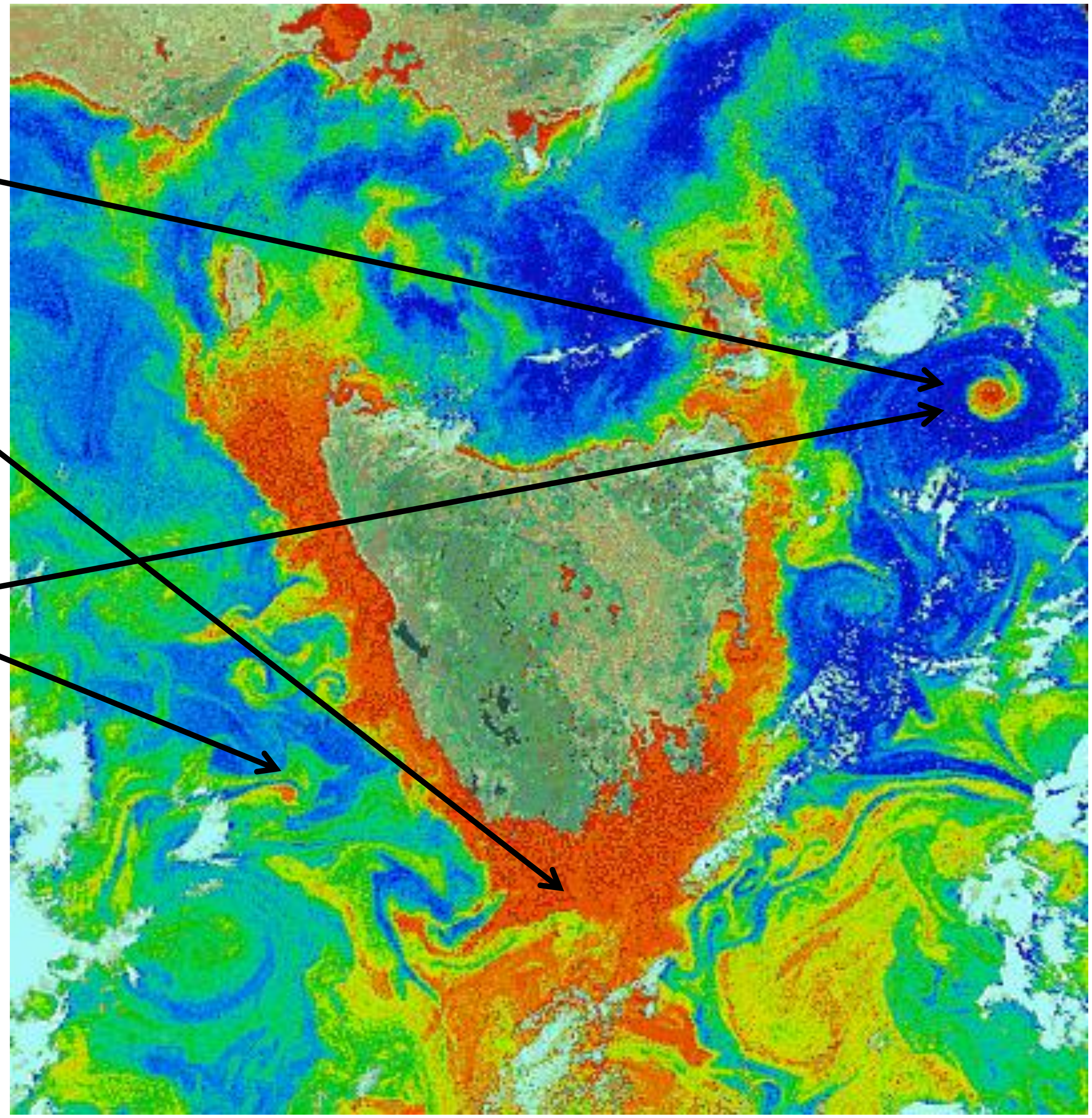
chlorophyll concentration around Tasmania in 1981 (Coastal Zone Color Scanner – CZCS)

Mesoscale variability (10-250km)

Eddy trapping/stirring

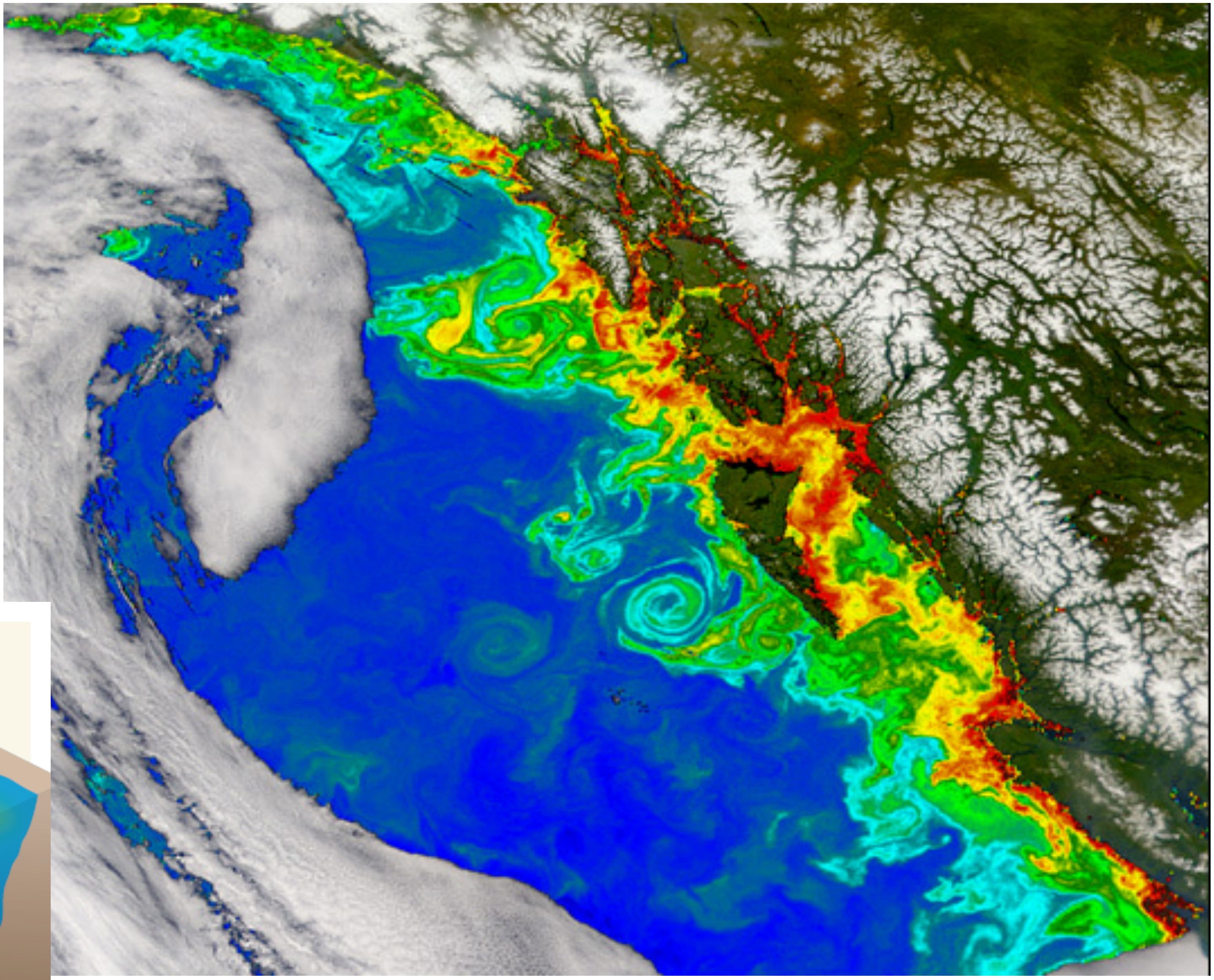
Mesoscale turbulent stirring

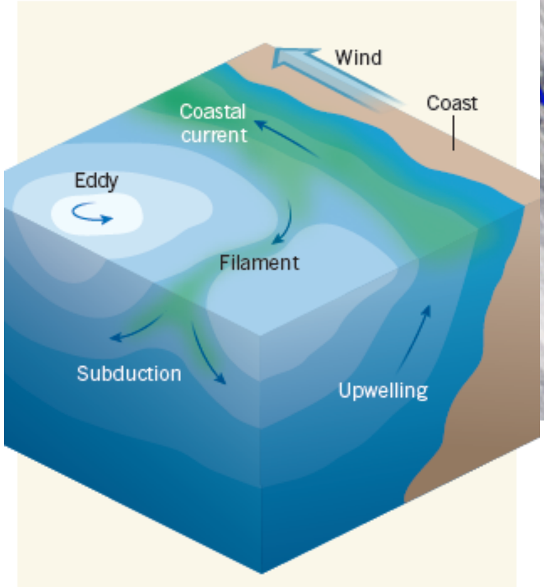
Impact on coastal upwelling



NASA, Earth Observatory, SeaWiFS data, June 13, 2002.

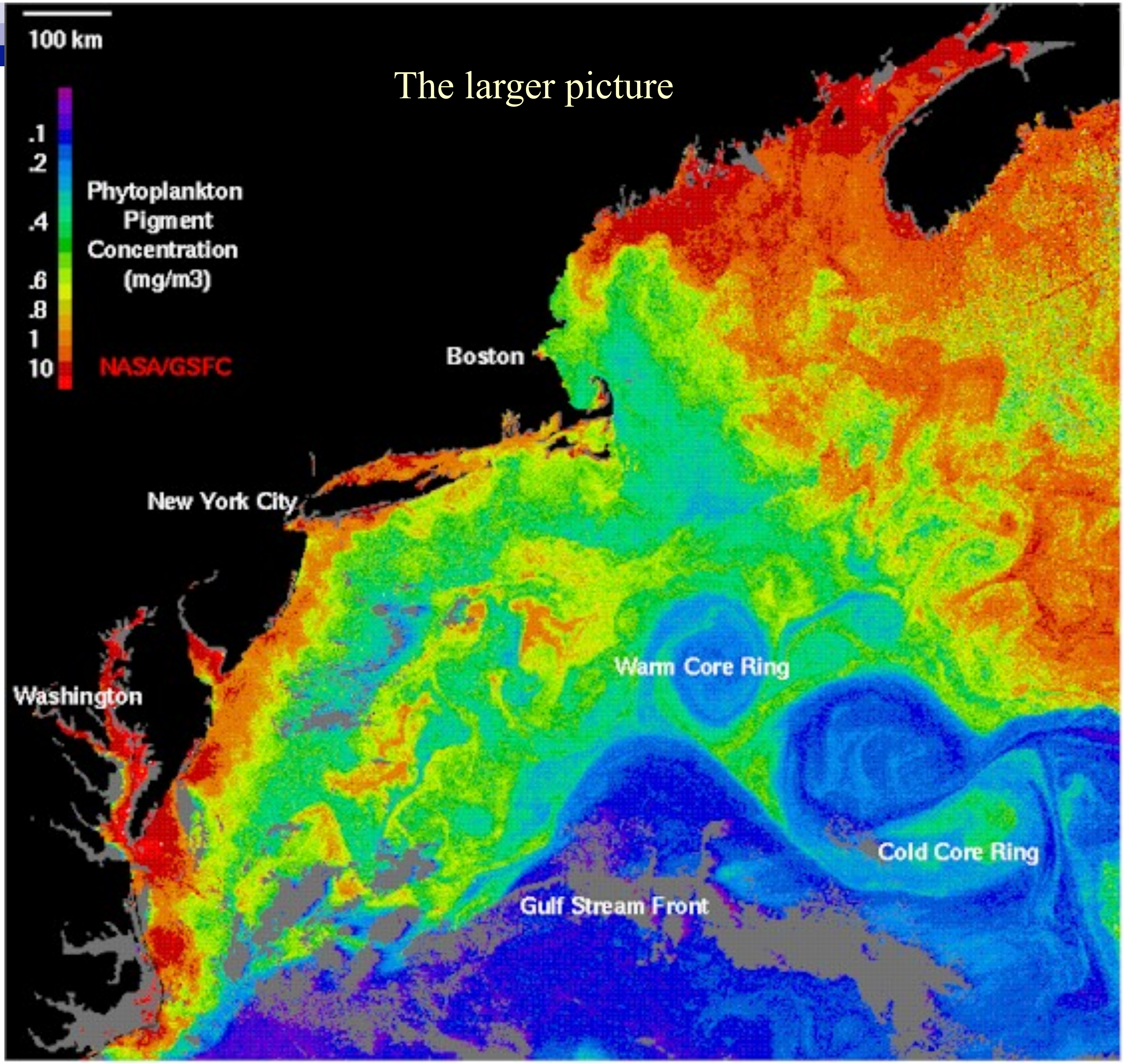
Location: coastline of British Columbia/ Alaska



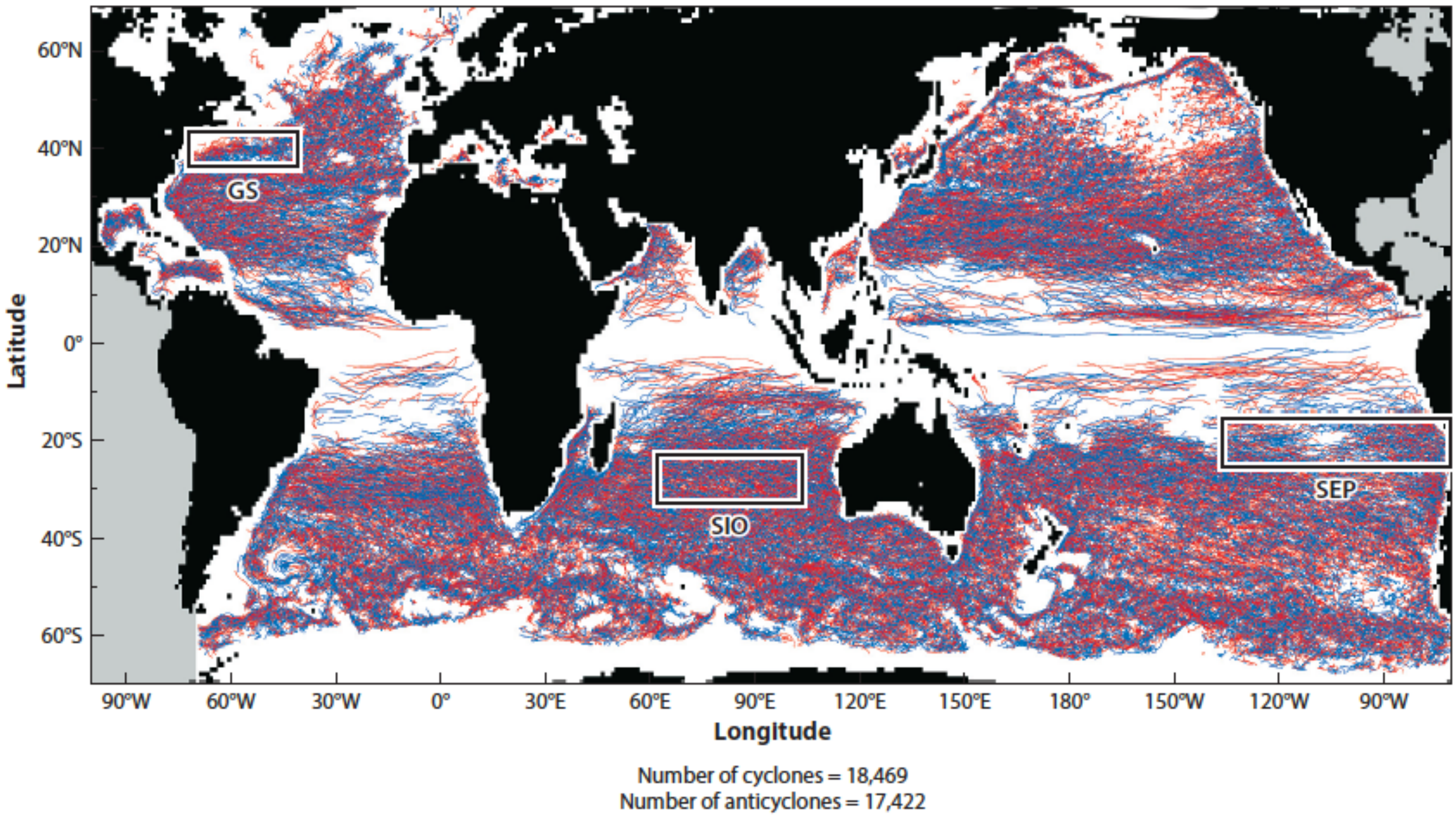


Schematic for a South Equatorial boundary current
Mahadevan, 2014

The larger picture



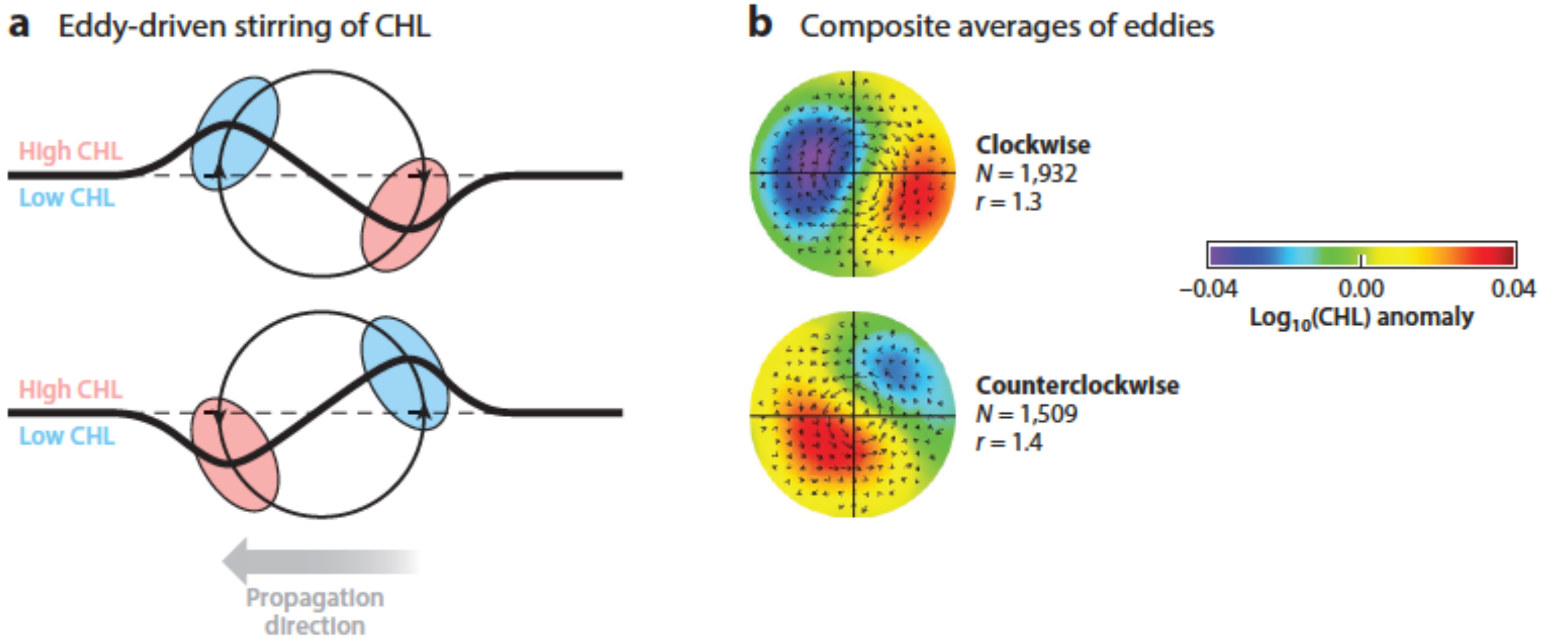
Mesoscale eddies are (almost) everywhere



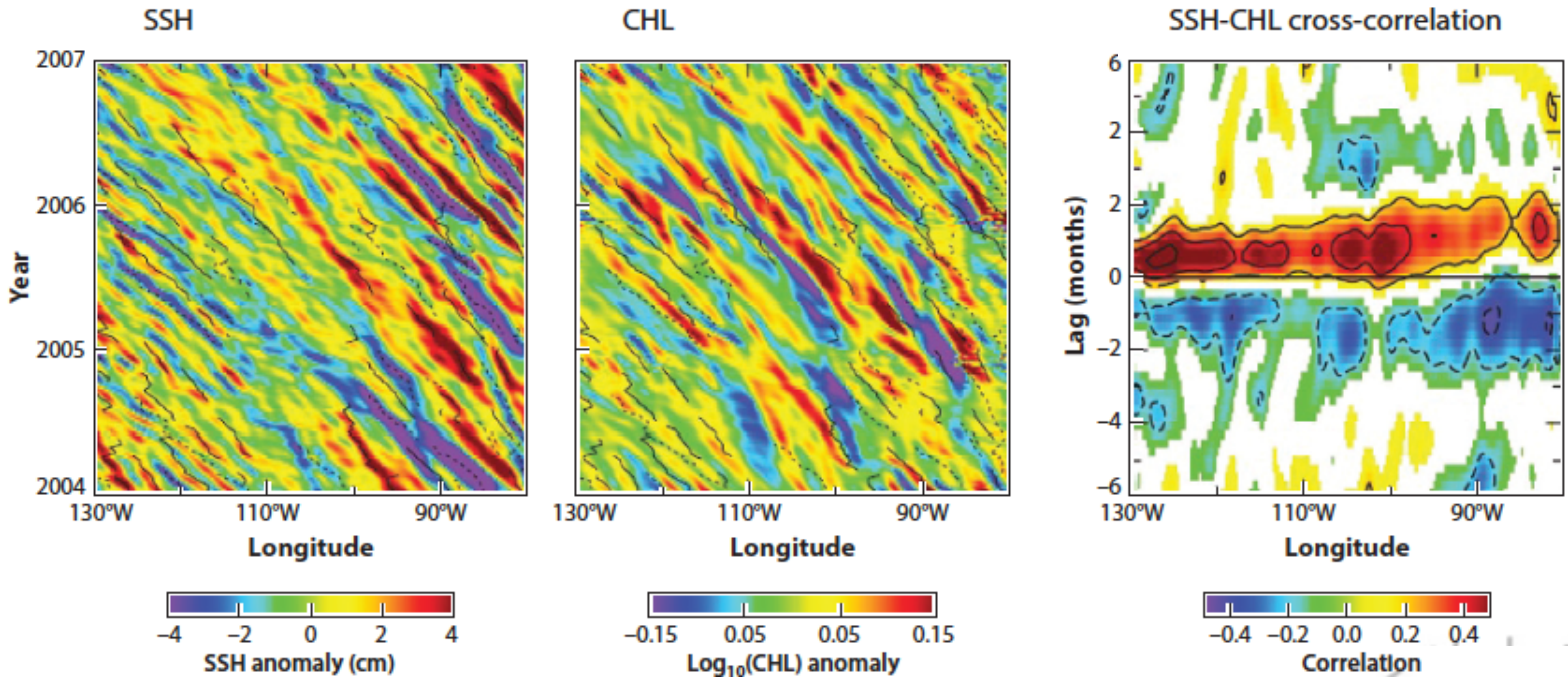
Eddy with lifespan > 16 weeks identified in altimetric data between 1992 and 2008. Blue = cyclones; red = anticyclones

Chelton et al., 2011

- Eddies are nonlinear
- They trap fluid and tracers at their interior
- They are responsible for a coherent signal in propagation of SSH and Chl anomalies



(a) Schematic for eddy-driven stirring of chlorophyll (CHL) for westward eddies and northward CHL gradient. A smooth contour of CHL (dashed lines) is distorted by the eddy velocity field (solid lines). Advection of CHL within the large-scale background CHL gradient results in the positive and negative CHL anomalies (red and blue regions). (b) Composite averages for clockwise (top) and counterclockwise (bottom) eddies in the Southeast Pacific (SEP) region (from McGillicuddy, 2016)

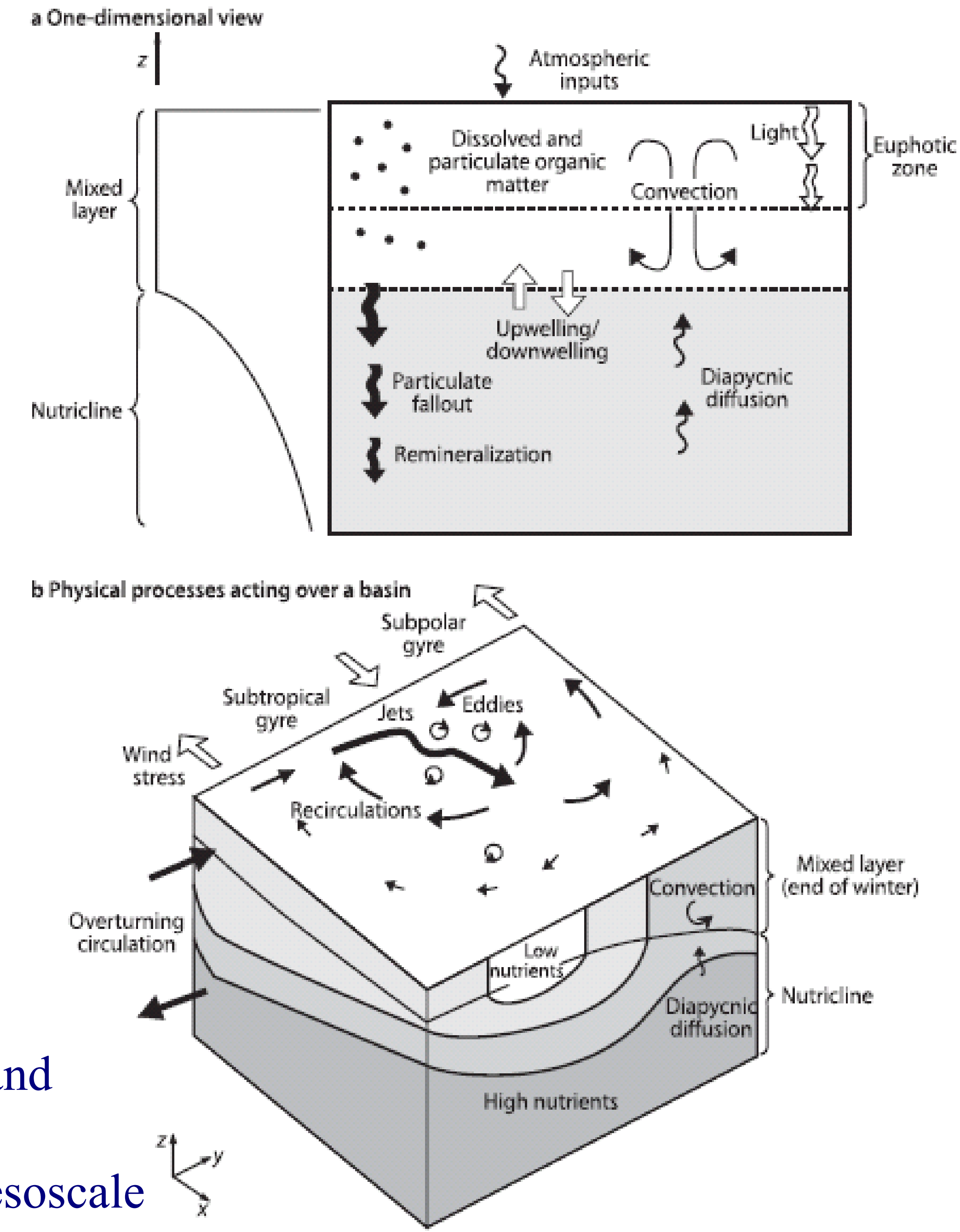


Left: SSH with eddy tracks within ±2◦ of 20◦S overlaid (dashed and solid lines for clockwise- and counterclockwise-rotating eddies). Center: Log10(CHL) with the same eddy tracks overlaid. (f) Lagged cross-correlation between log10(CHL) at time t and SSH at time t +lag, calculated over ten year. Positive lags correspond to log10(CHL) leading SSH.

From McGillicuddy, 2016 adapted from Chelton et al. (2011a)

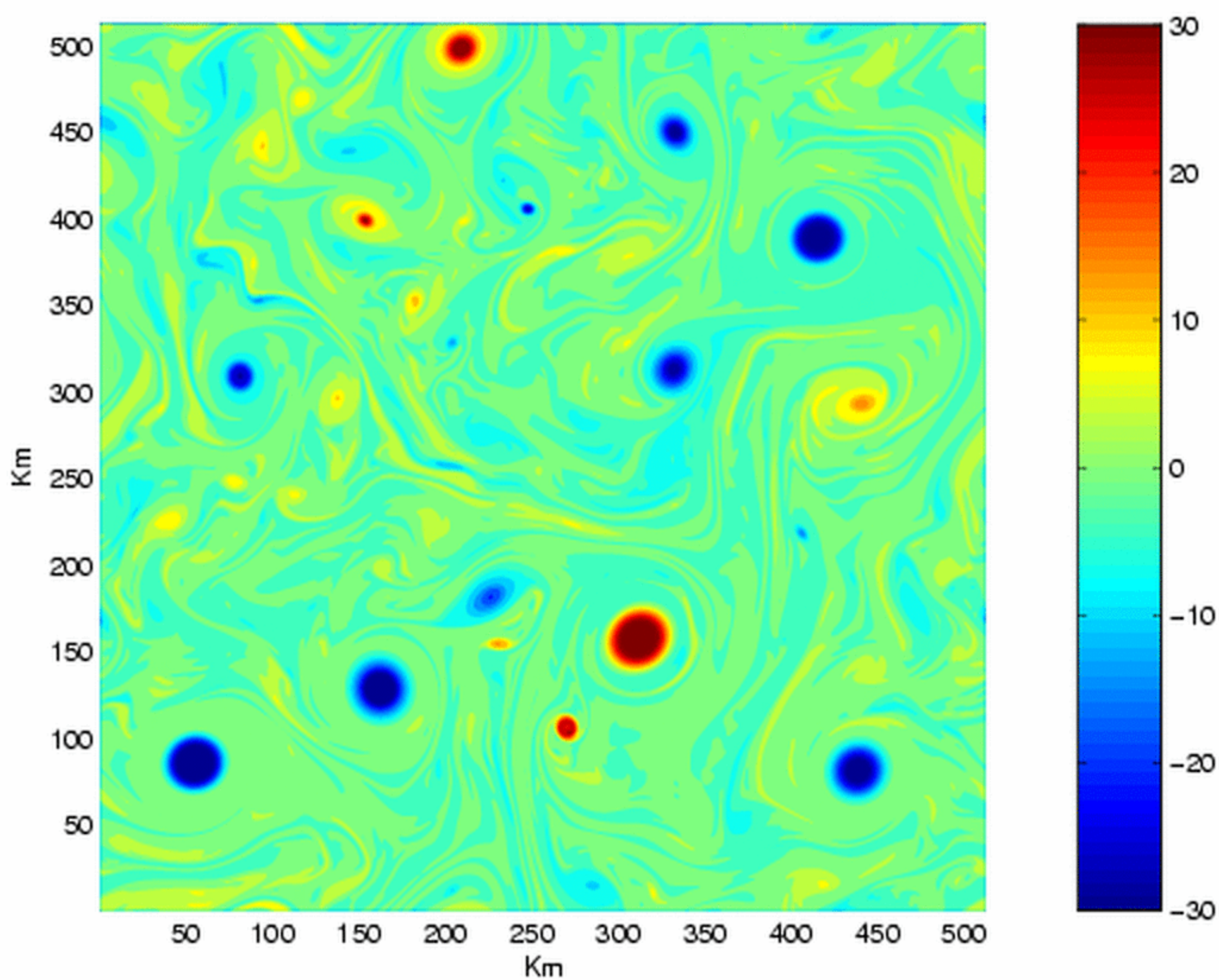
Mechanisms

Fig. 2.1.
Schematic figure displaying one- and three-dimensional views of the physical processes affecting biological production: a In the vertical, there is a phytoplankton growth within the ecosystem, export of organic matter and remineralisation at depth, which is partly maintained through the physical transfer of nutrients within the ocean involving vertical advection, diapycnic diffusion and convection; b a more complete view includes the physical transfer of nutrients by the three-dimensional circulation involving contributions from the overturning, gyre, eddy and frontal circulations, as well as involving interactions with spatial variations in convection

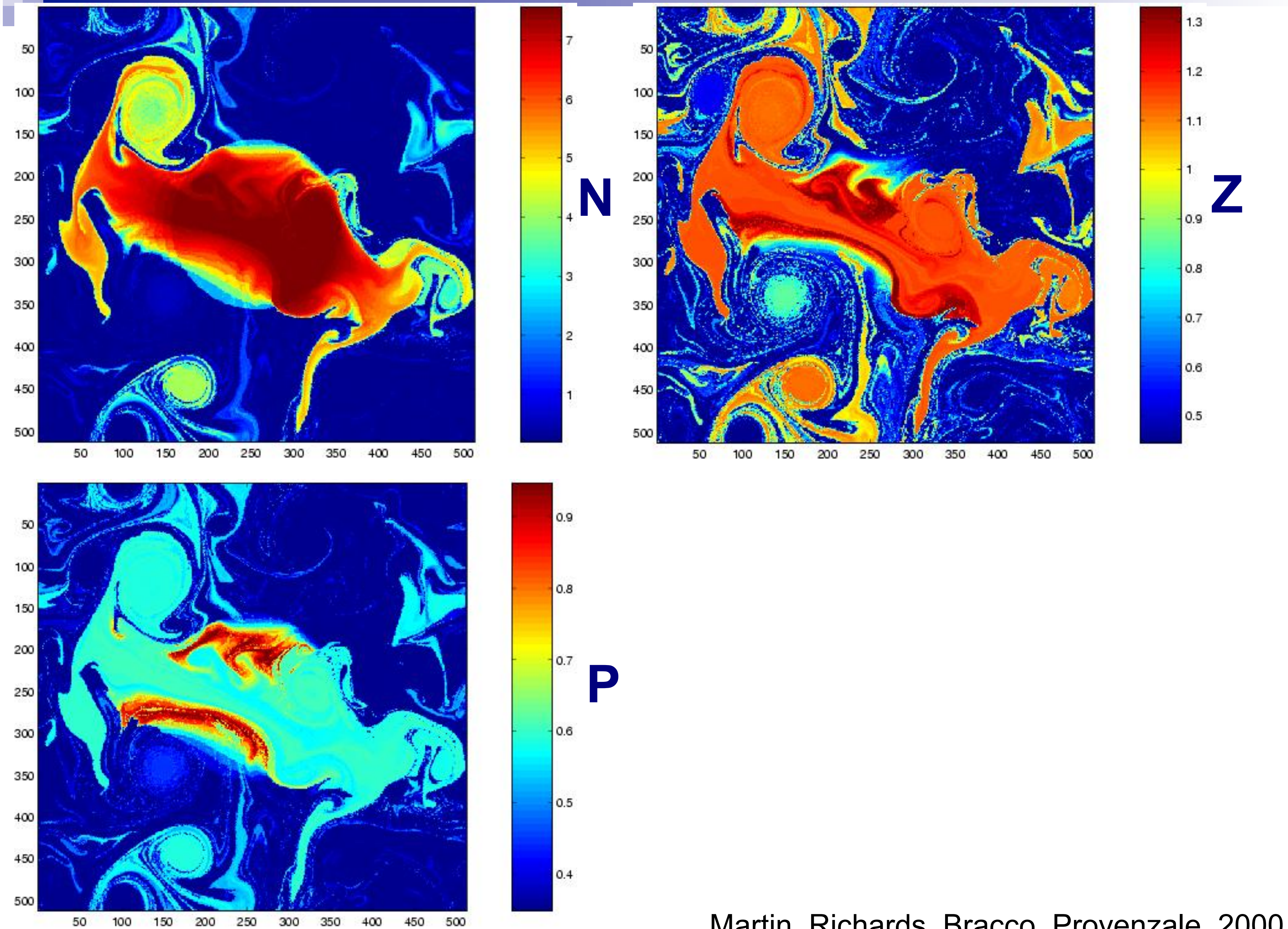


From Williams and Follows, 2003: Schematic of mesoscale processes involved in plankton dynamics

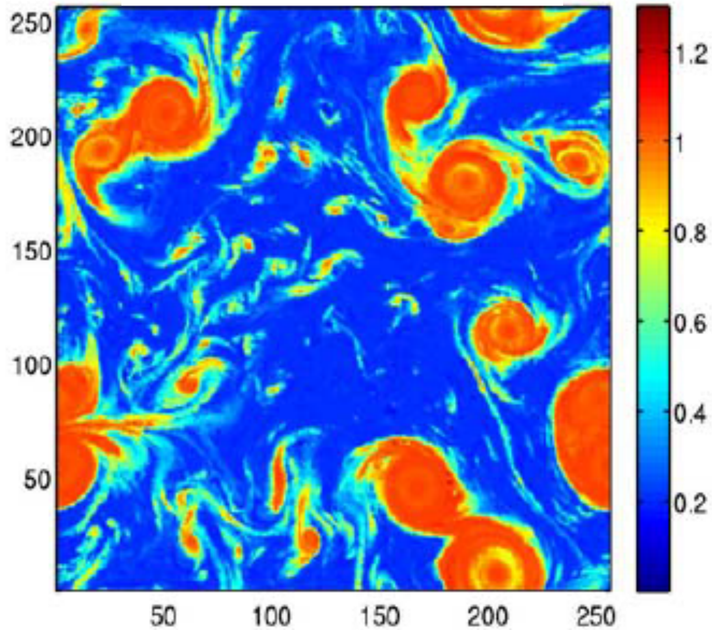
Eddy stirring and trapping



Martin, Richards, Bracco, Provenzale, 2000



Martin, Richards, Bracco, Provenzale, 2000

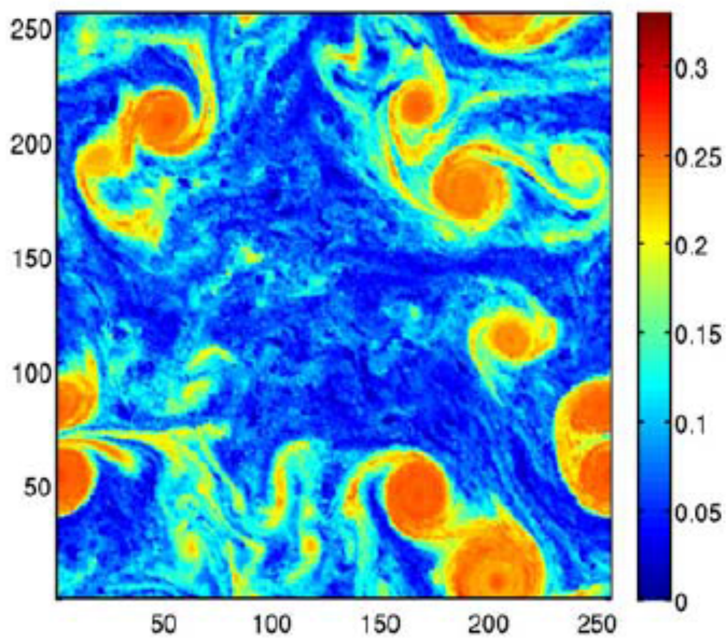


P

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

$$\frac{dP}{dt} = g(N,P,Z) + \lambda'\nabla^2 P = \beta\frac{N}{k_N + N}P - \frac{\alpha\varepsilon P^2}{\alpha + \varepsilon P^2}Z - \mu_P P + \lambda'\nabla^2 P,$$

$$\frac{dZ}{dt} = h(N,P,Z) + \lambda''\nabla^2 Z = \gamma\frac{\alpha\varepsilon P^2}{\alpha + \varepsilon P^2}Z - \mu_Z Z^2 + \lambda''\nabla^2 Z,$$



Z

Bracco et al, 2009

Same advection and a simple competition model

2 phytoplankton populations, A and B
For every fluid element j, $a_j(t)$, $b_j(t)$ = concentrations of A and B

$$d\vec{x} = \vec{u}(\vec{x},t)dt$$

$$a'_\varepsilon(x,y,t) = \frac{\alpha a_\varepsilon}{\alpha a_\varepsilon + \beta b_\varepsilon} \quad ; \quad b'_\varepsilon(x,y,t) = \frac{\beta b_\varepsilon}{\alpha a_\varepsilon + \beta b_\varepsilon}$$

$a(t) + b(t) = 1$ or slowing decaying function

ε = length of small-scale homogenization

no annual cycle, sinking, vertical mixing, relative grazing…

The 2D advection is determined according the quasigeostrophic flow, a random walk or a Ornstein-Uhlenbeck process

Random walk: $d\vec{x} = \sqrt{\sigma^2 T_L}\, d\vec{W}$

Ornstein-Uhlenbeck stochastic model:

$$d\vec{x} = \vec{u}dt$$

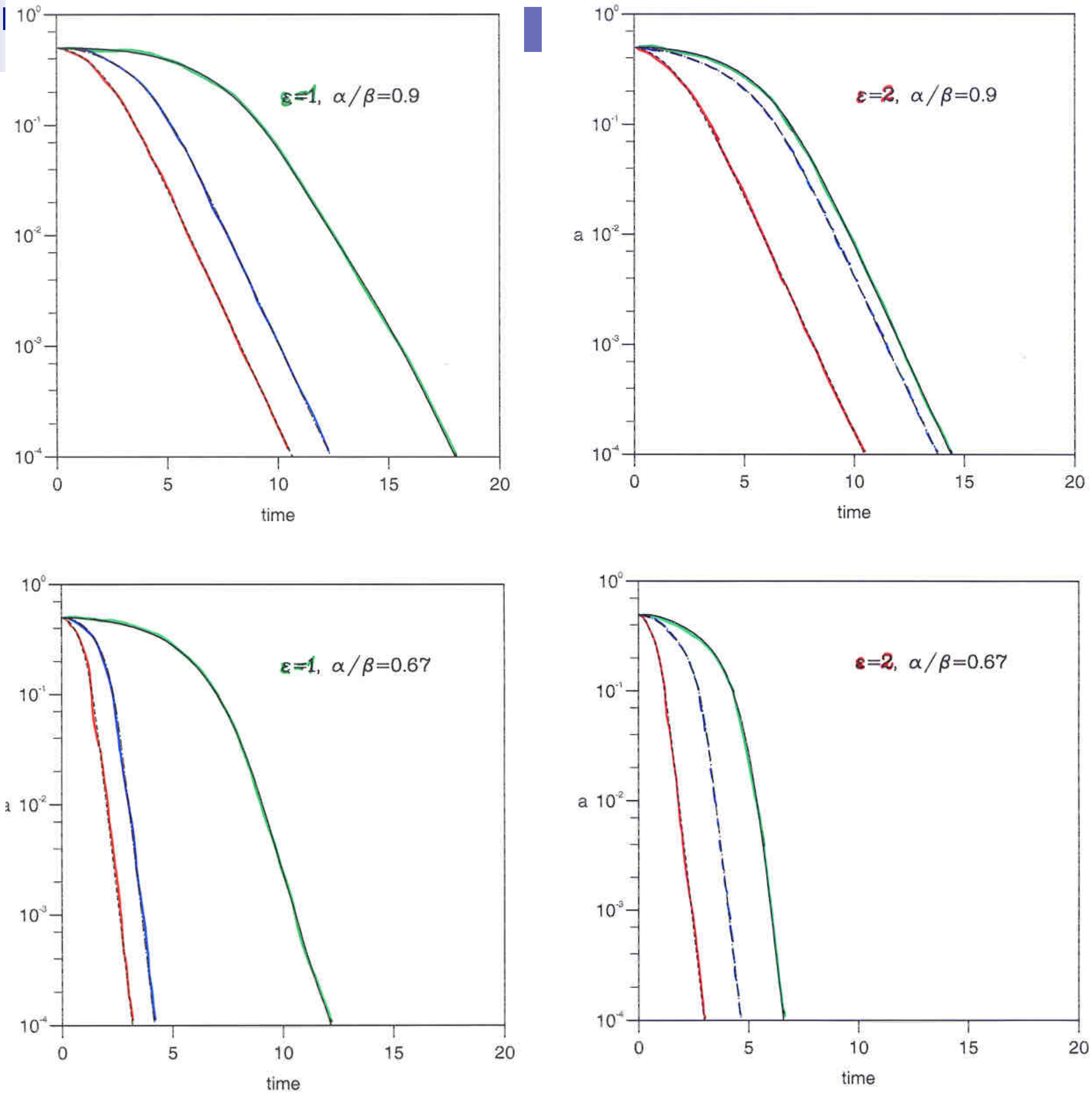
$$d\vec{u} = -\frac{1}{T_L}\vec{u}dt + \sqrt{\sigma^2 T_L}\, d\vec{W}$$

$$\text{where } \left\langle d\vec{W} \right\rangle = 0$$

$$\left\langle d\vec{W}_i(t) d\vec{W}_j(t) \right\rangle = 2\delta_{i,j}\delta(t-t')dt$$

$$T_L = \int_0^\infty R(\tau)d\tau$$

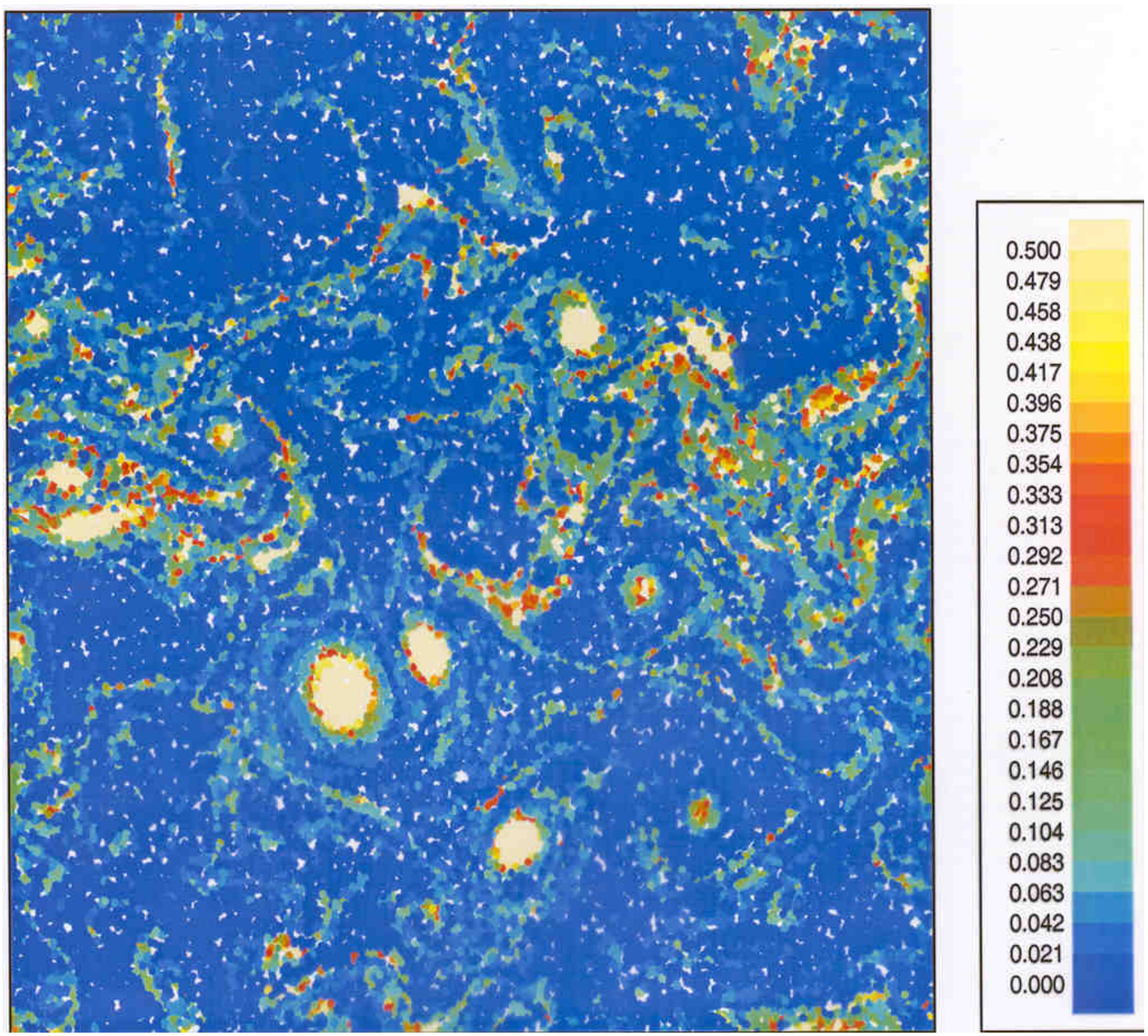
$$R(\tau) = \lim_{T\to\infty} \frac{1}{\sigma^2} \int_0^T \left\langle \vec{u}(t)\cdot\vec{u}(t+\tau)dt \right\rangle$$



- random walk
- Ornstein-Uhlenbeck
- barotropic turbulence

ε=diffusive scale for plankton homogenization. ε=1~2km

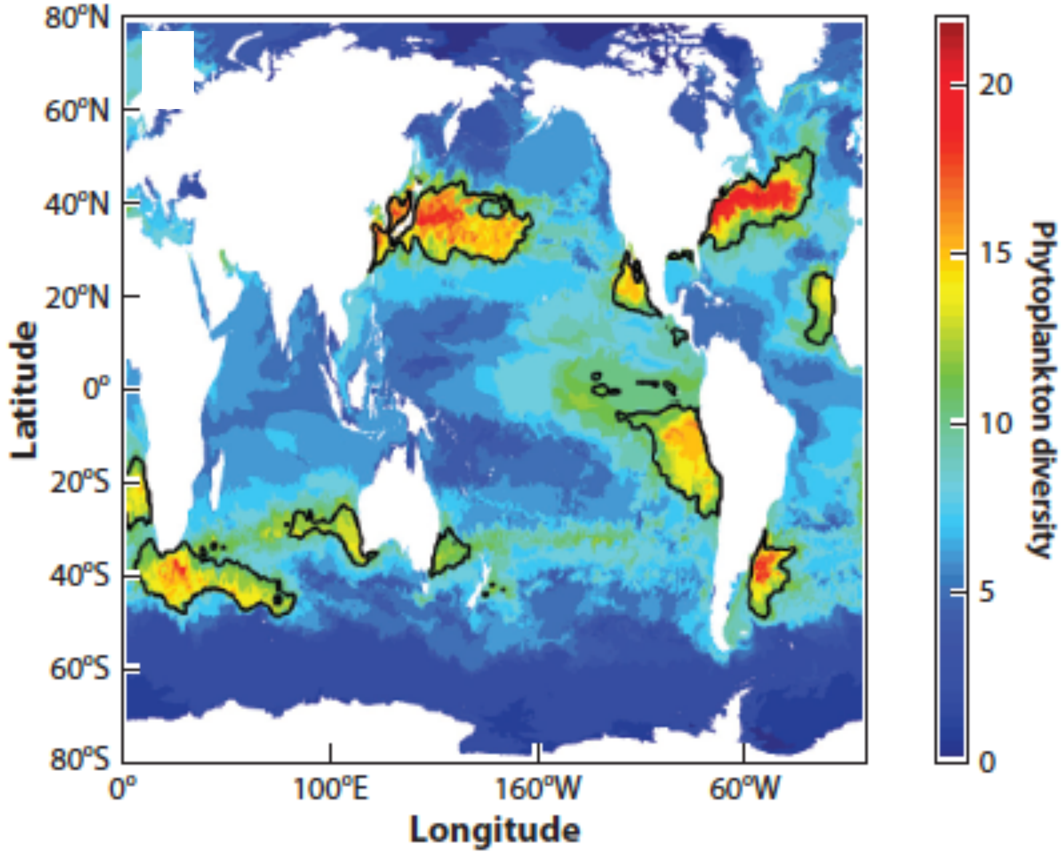
after 10 months



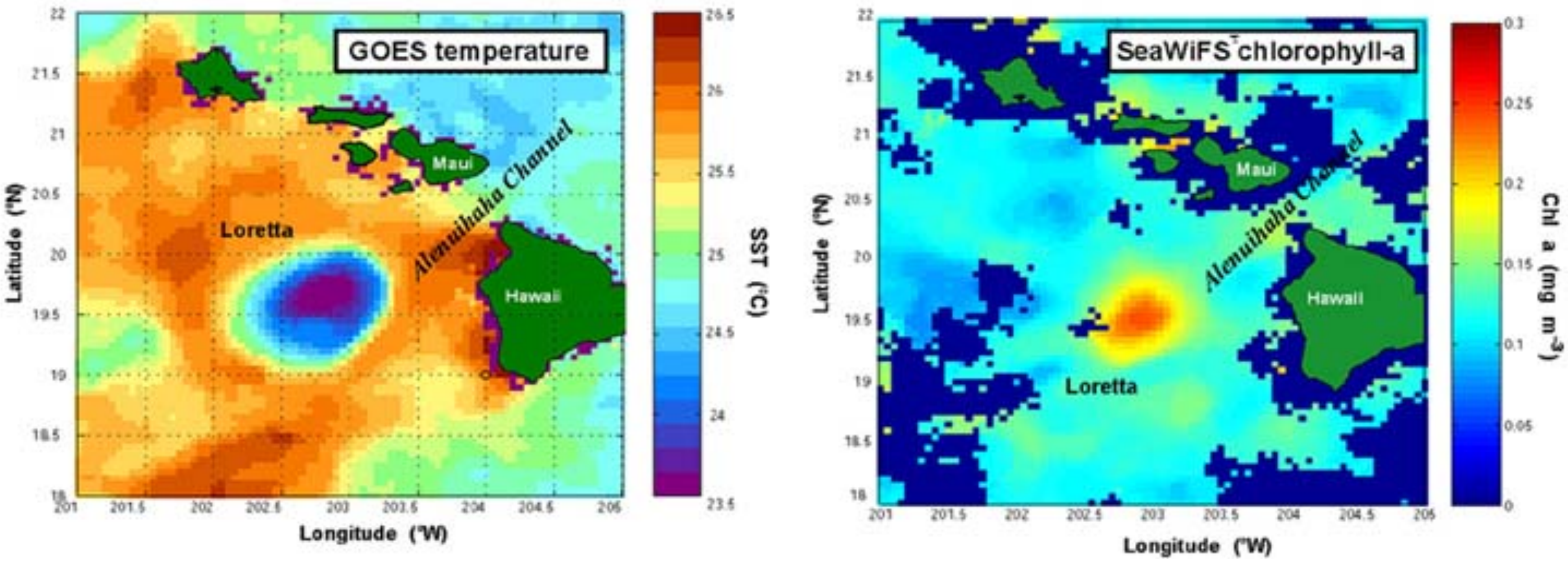
Eddies may preserve diversity by isolating populations

Bracco et al., 2000

(Perruche et al., 2011 repeated the exercice considering SQG turbulence: upwelling in filaments stimulates competition)



Diversity in the surface layer in an eddy-permitting global ocean model (Clayton et al., 2013). Diversity here is defined as the total number of phytoplankton types with biomass greater than 0.001% of the total phytoplankton biomass. Black contour lines indicate phytoplankton diversity hotspots and coincide with regions of elevated eddy activity.



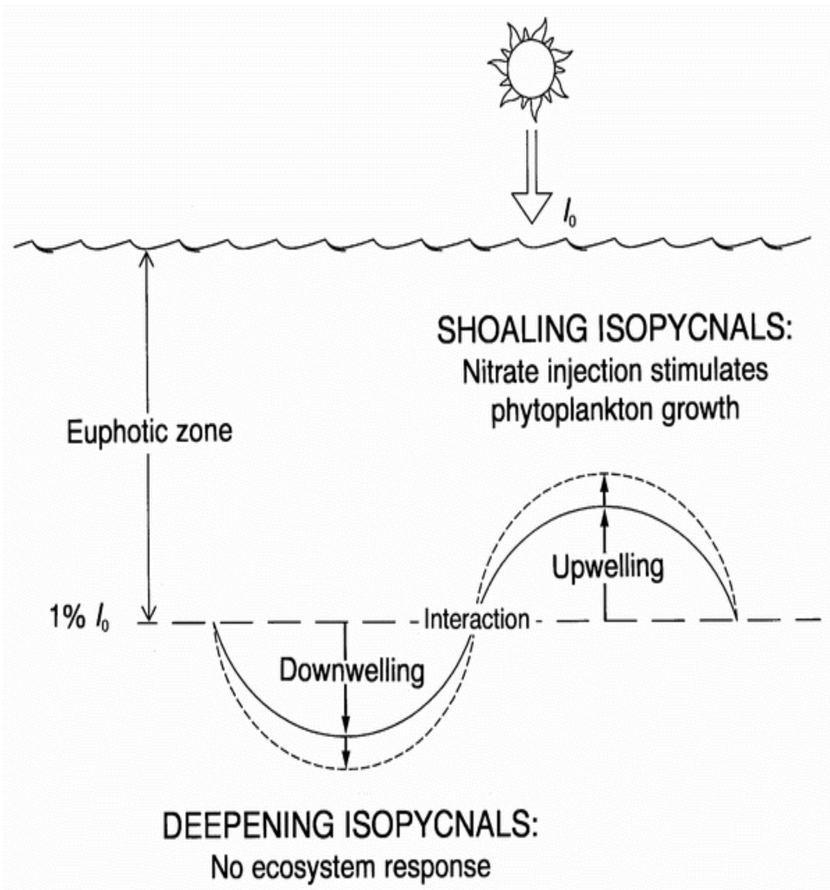
The ‘Loretta’ cyclonic eddy in the Alenuihaha Channel between the islands of Hawaii and Maui .

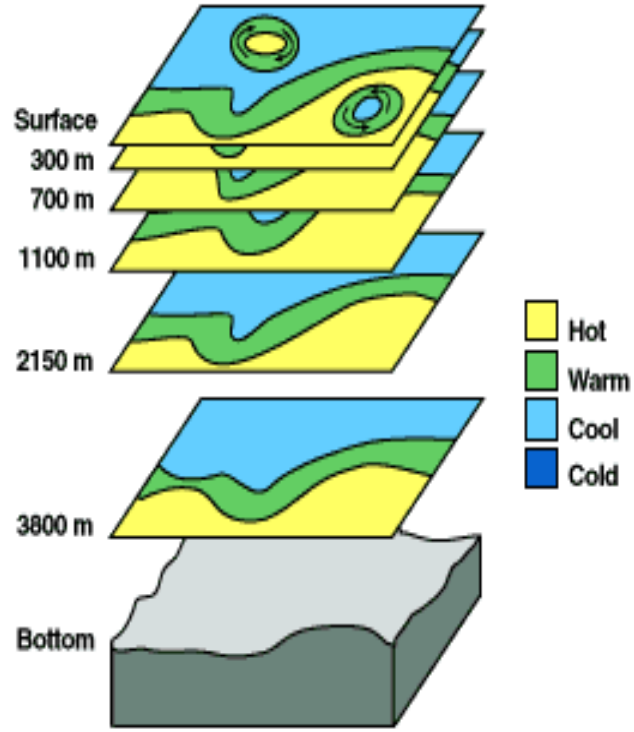
LEFT: Two-day composite of GOES sea-surface temperature during 3-4 September 1999.

RIGHT: eight-day composite of SeaWiFS chlorophyll during 29 August - 5 September 1999.

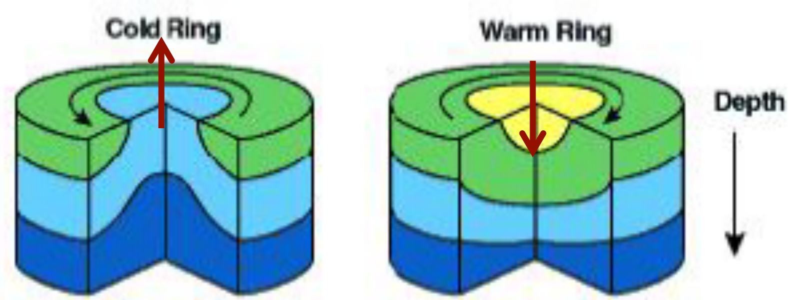
from Seki et al., GRL , 2001

Eddy pump: geostrophic (balanced) flow



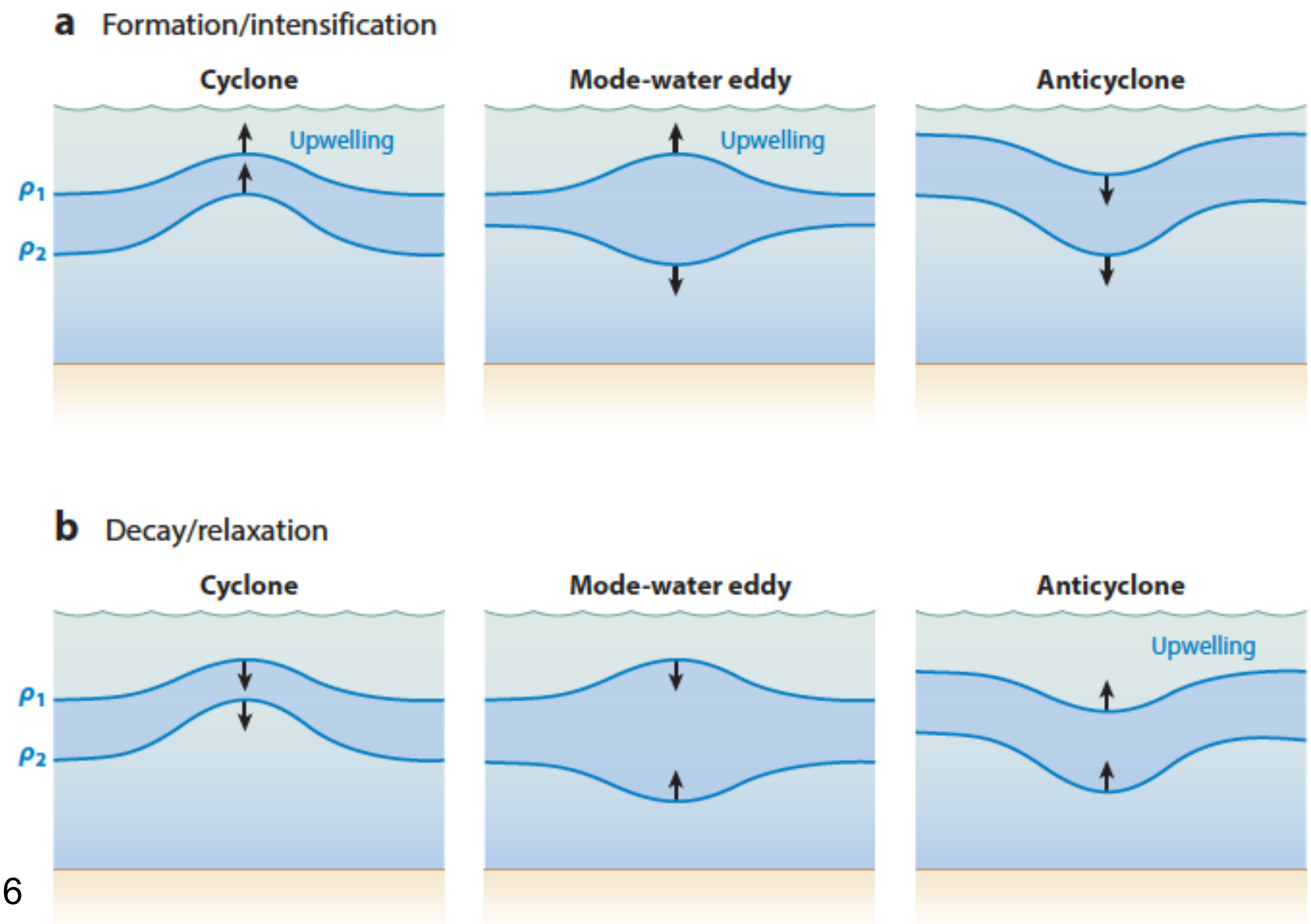


Upwelling Downwelling



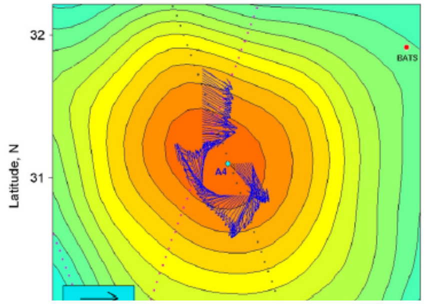
McGillicuddy et al., 1998

Baroclinic instability leads to the formation of cyclonic eddies with a raised thermocline and anticyclonic eddies with a depressed thermocline. **IF** the nutricline and the thermocline coincide, around time of eddy formation production is enhanced inside cyclonic eddies



McGillicuddy, 2016

from Ledwell et al., 2008



Example of mode water eddy

Fig
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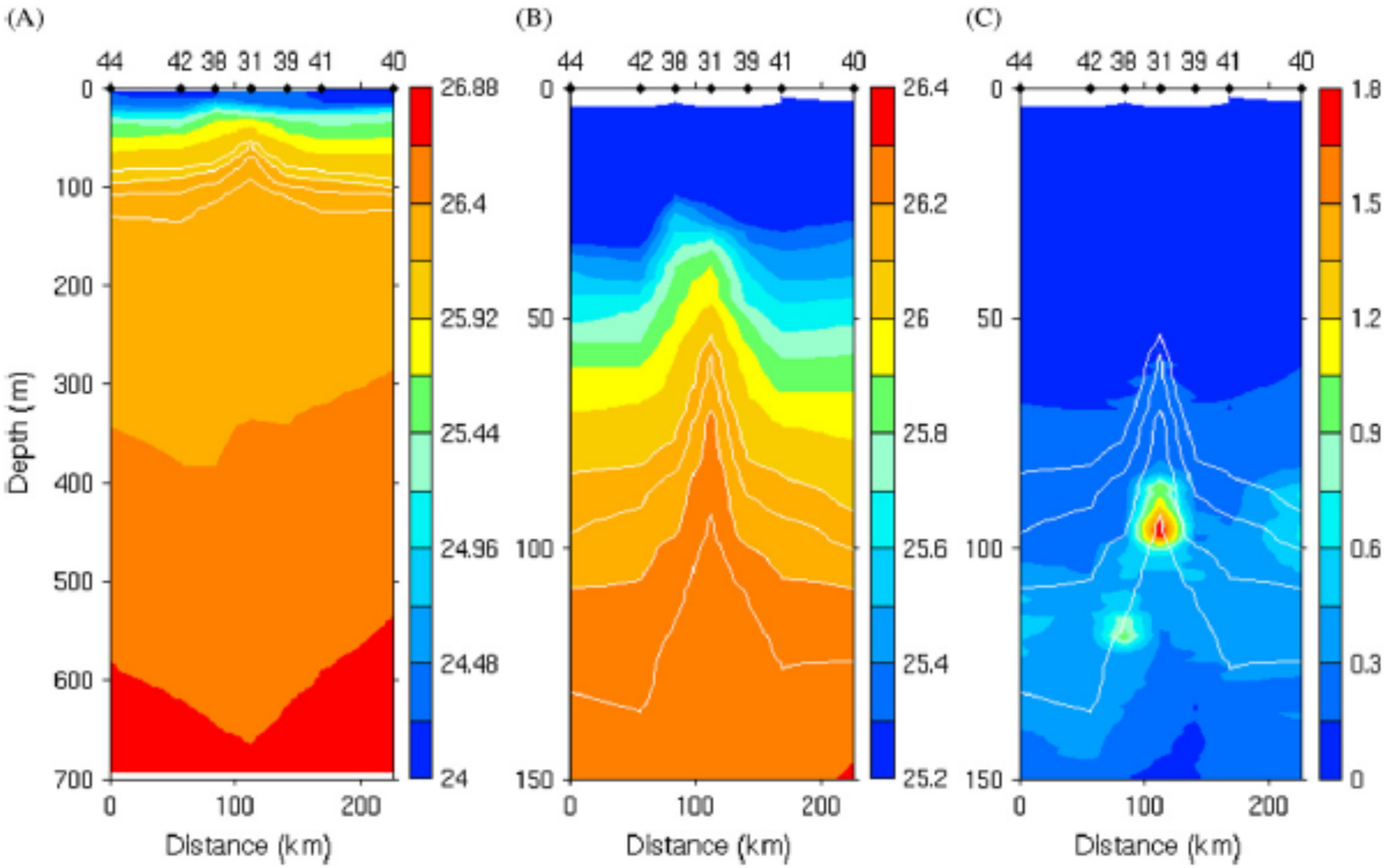
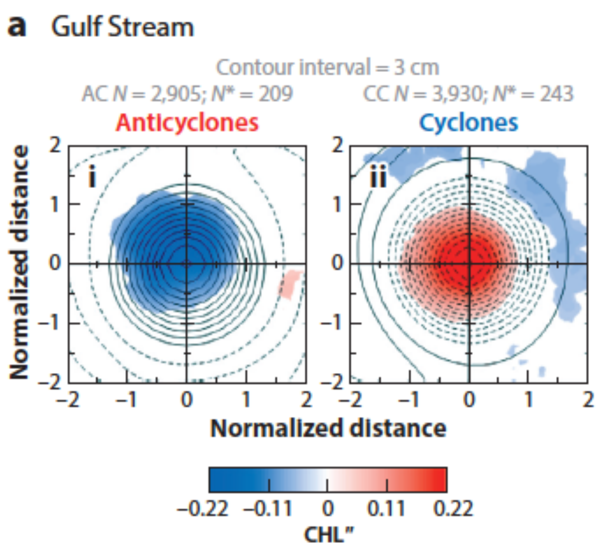
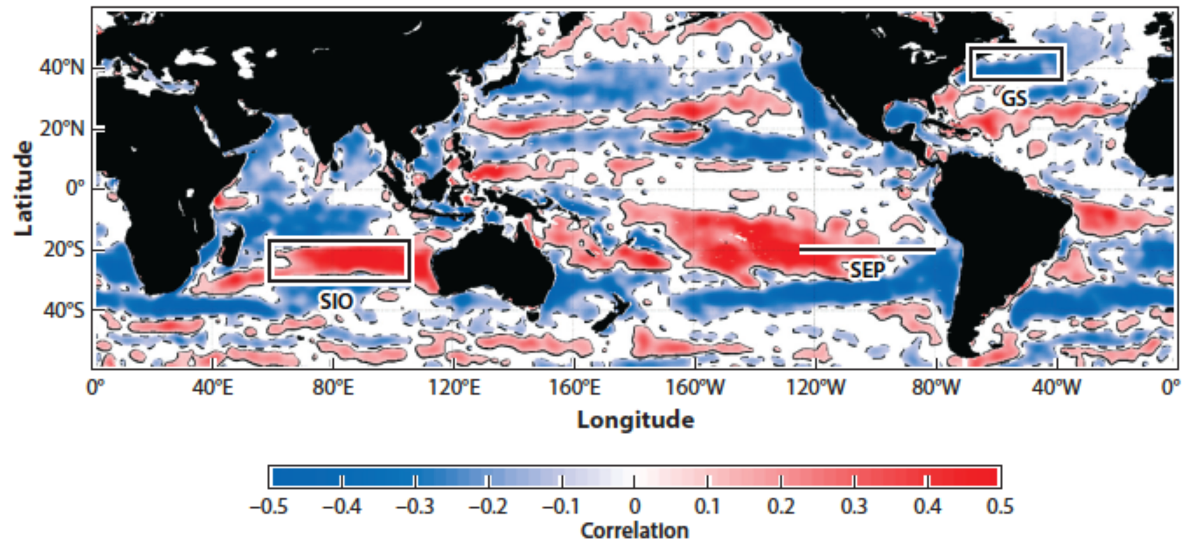
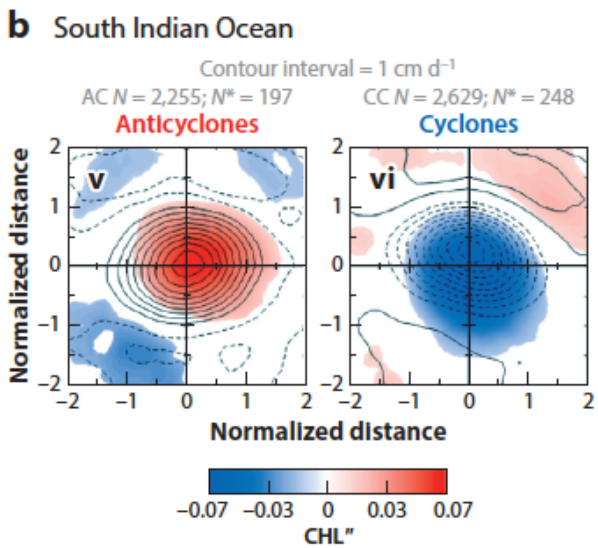


Fig. 2. Cross sections of potential density anomaly, σ_θ, and fluorescence, from stations occupied 4–6 July 2005 during cruise OC415-1. CTD statio locations are indicated along the top axis. (A) σ_θ (kg/m^3); (B) σ_θ (kg/m^3) and (C) fluorescence (RFU).





Map of correlations between SSH and Chl anomalies
Negative correlations: Chl is anomalously high in cyclones and viceversa. Gaube et al., 2014

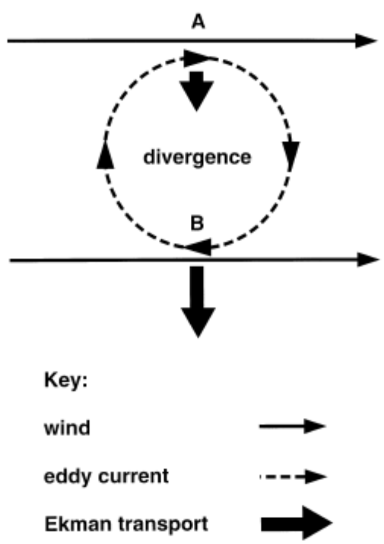


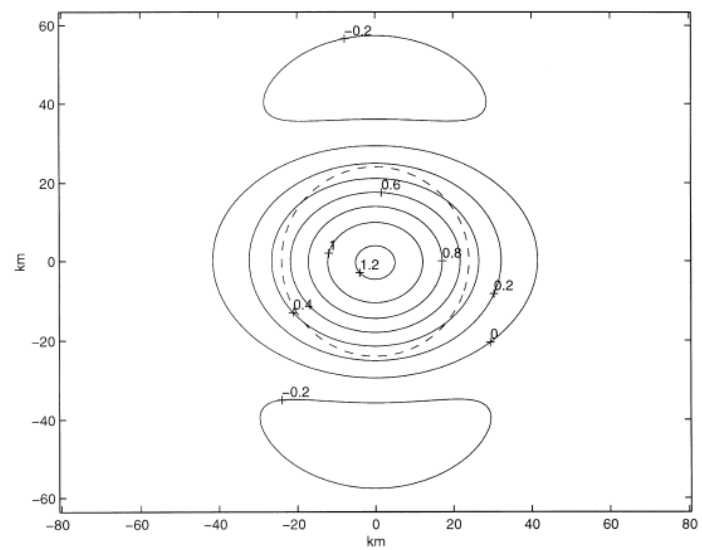
Composite averages of eddy-associated Chl anomalies in the Gulf Stream and Indian Ocean. Gaube et al., 2014

Eddies and wind

How do eddies and wind interact? Three ways:

- SST feedback: Cold anomalies stabilize the atmospheric boundary layer and viceversa → increase surface wind speeds over warmer than surrounding water and decrease over colder water (Chelton et al., 2004)
- Interaction between wind stress and surface currents (Martin & Richards, 2001)

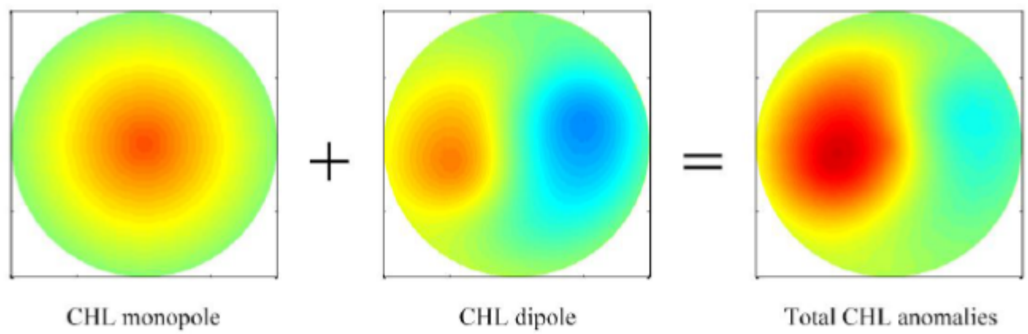




Ekman upweling inside anticyclones and downwelling in cyclones

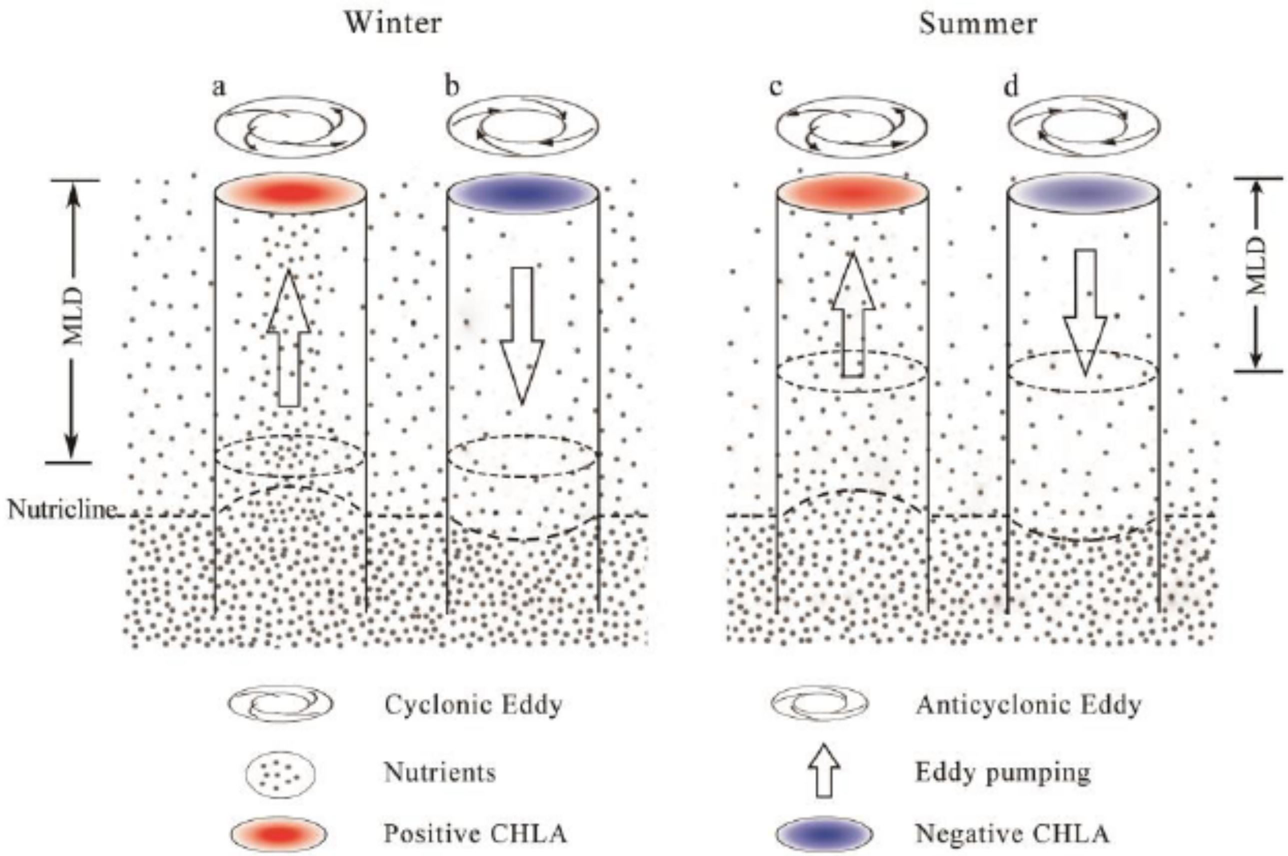
- Submesoscale ageostrophic circulations that can create patches of vertical velocity. If wind is uniform and the eddy is symmetric, this creates a dipole of upwelling and downwelling (Flierl and McGillicuddy, 2002) but may get more complicated (see next lecture)

He et al., 2014



According to recent work by Gaube et al. (2015) the SST effect is the smallest of the three. Effect #2 is generally dominant and can explain positive Chl in anticyclones and negative in cyclones (true for Indian Ocean eddies, but from satellite images emerges than anomalies are present at detection – trapping of coastal waters at formation (Moore et al., 2007)

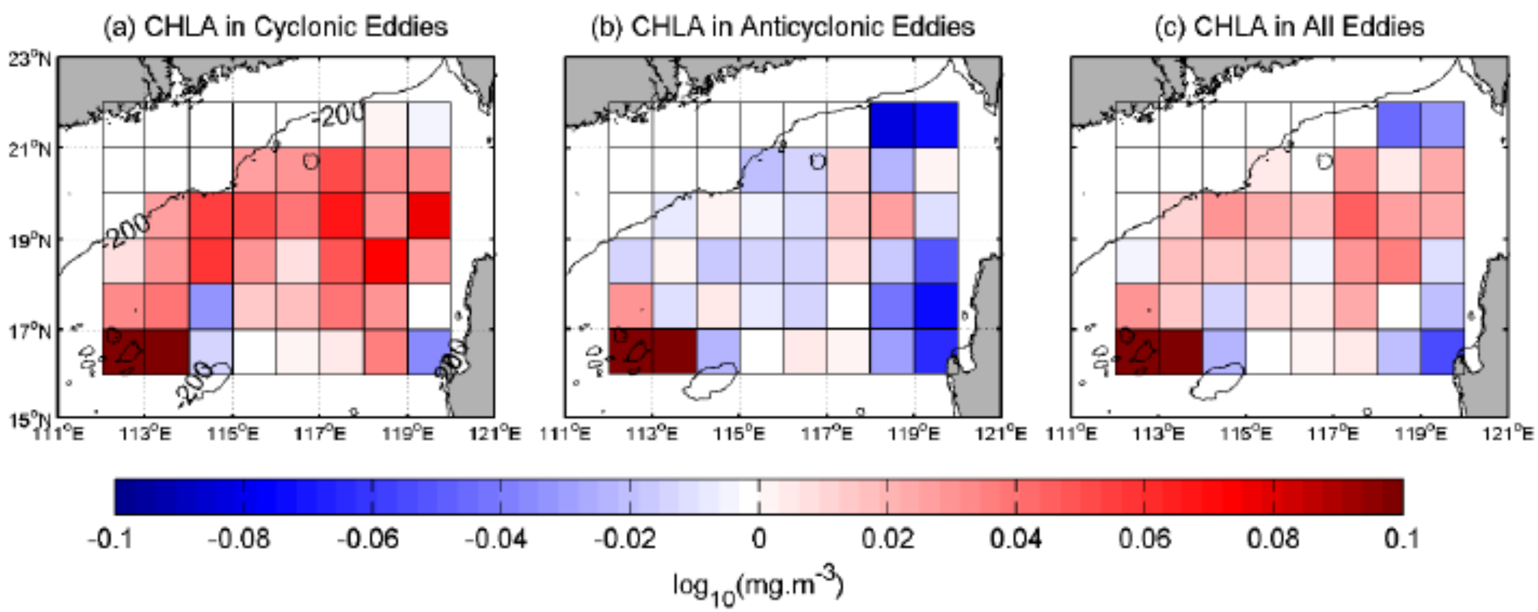
MLD, eddy pumping and wind



Schematic diagram from He et al. summarizing impacts in winter (deep MLD and strong winds) and summer (shallow MLD and weaker, less variable winds)

Contribution of eddy induced flux to primary productivity budgets

- Difficult to measure / large geographical variability

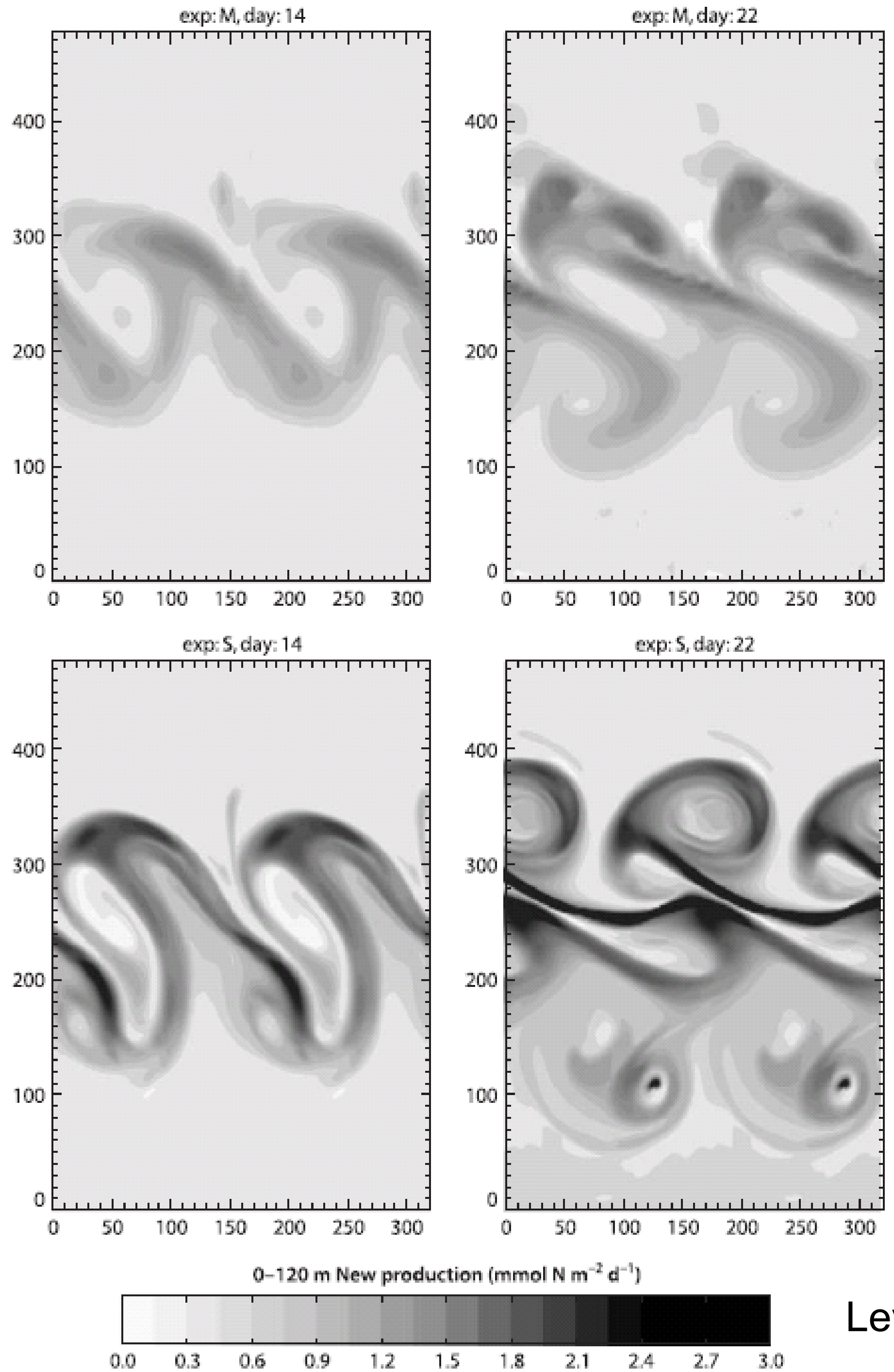


He et al., 2013

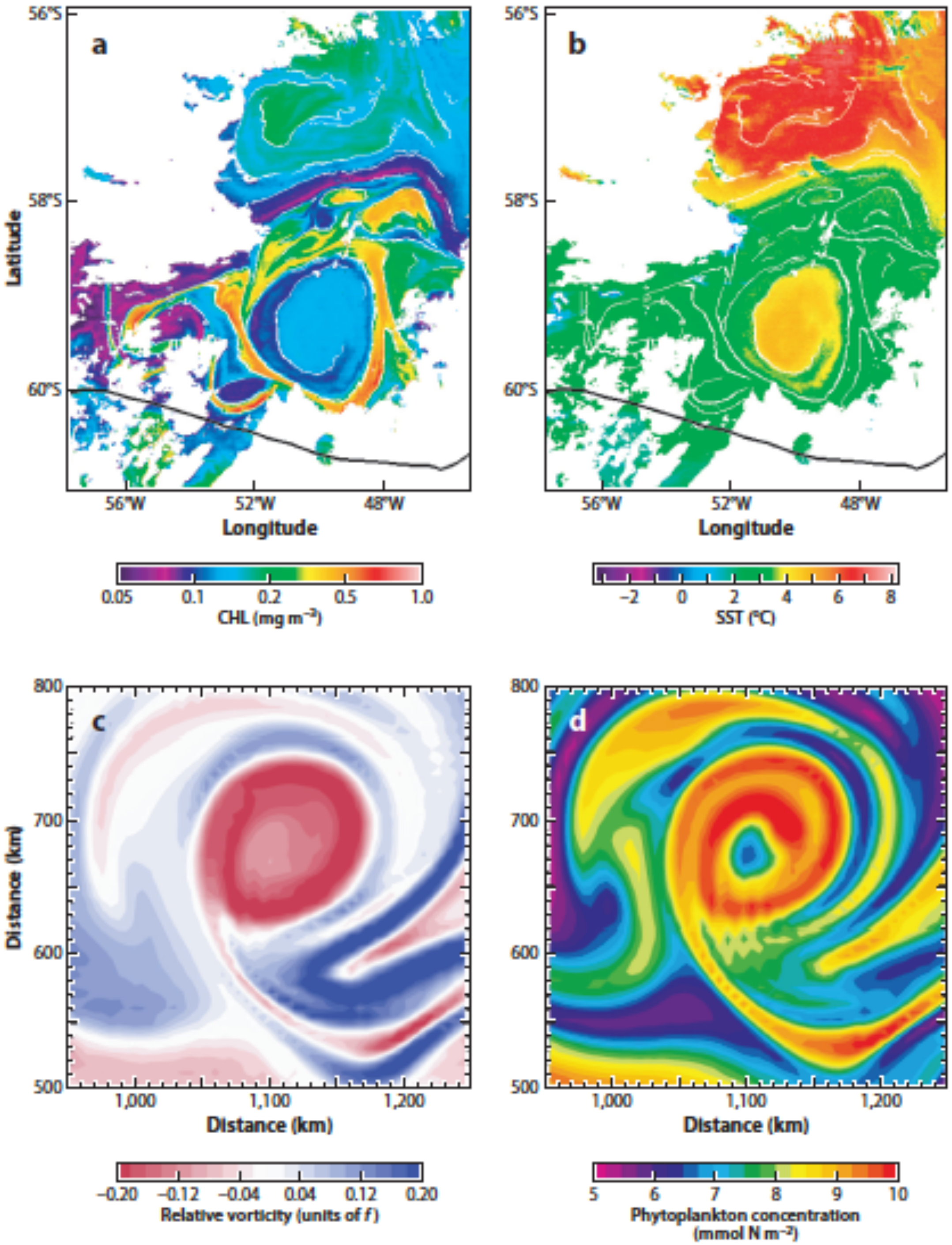
- Hard to quantify relative contribution of processes at play (but we have/will soon have better towed instruments and finer resolution in altimeter missions)
- It is a coupled problem
- Different models give different results
- Results are resolution dependent (but modeling capabilities are improving and coupled high res runs are possible)

Eddies and fronts

Modelled new production (10^{-3} mol N m^{-2}) within the euphotic layer for a zonal jet undergoing baroclinic instability (Lévy et al. 2001). Snapshots of the new production are shown at days 14 and 22 for integrations at mesoscale (*upper panel*) and sub-mesoscale (*lower panel*) resolutions of 6 km and 2 km respectively. Over the integration, meanders develop leading to anticyclones to the north and cyclones to the south of the jet. The new production increases in intensity as the resolution increases and becomes concentrated along anticyclonic filaments. The area-averaged new production increases from 6.5 to 10.7×10^{-3} mol N m^{-2} as the resolution is increased from 6 km to 2 km; in comparison, the area-averaged new production only reaches 3.7×10^{-3} mol N m^{-2} if the resolution is reduced to 10 km



Levy et al., 2001



Anticyclone north of the ACC
in January 2004
Observations (top) from
Kahru et al., (2007)
and model (bottom) from
Levy & Klein (2004)