Physical biological interactions in the upper ocean

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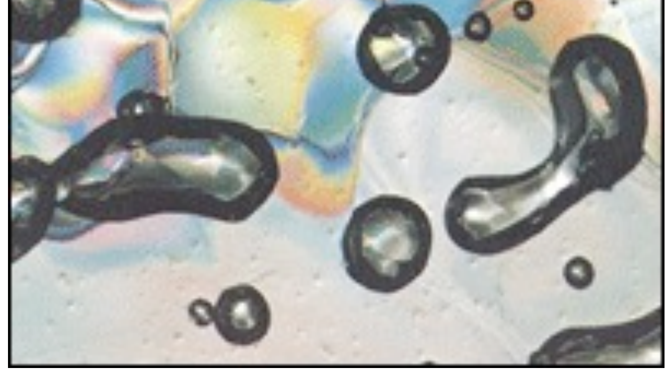
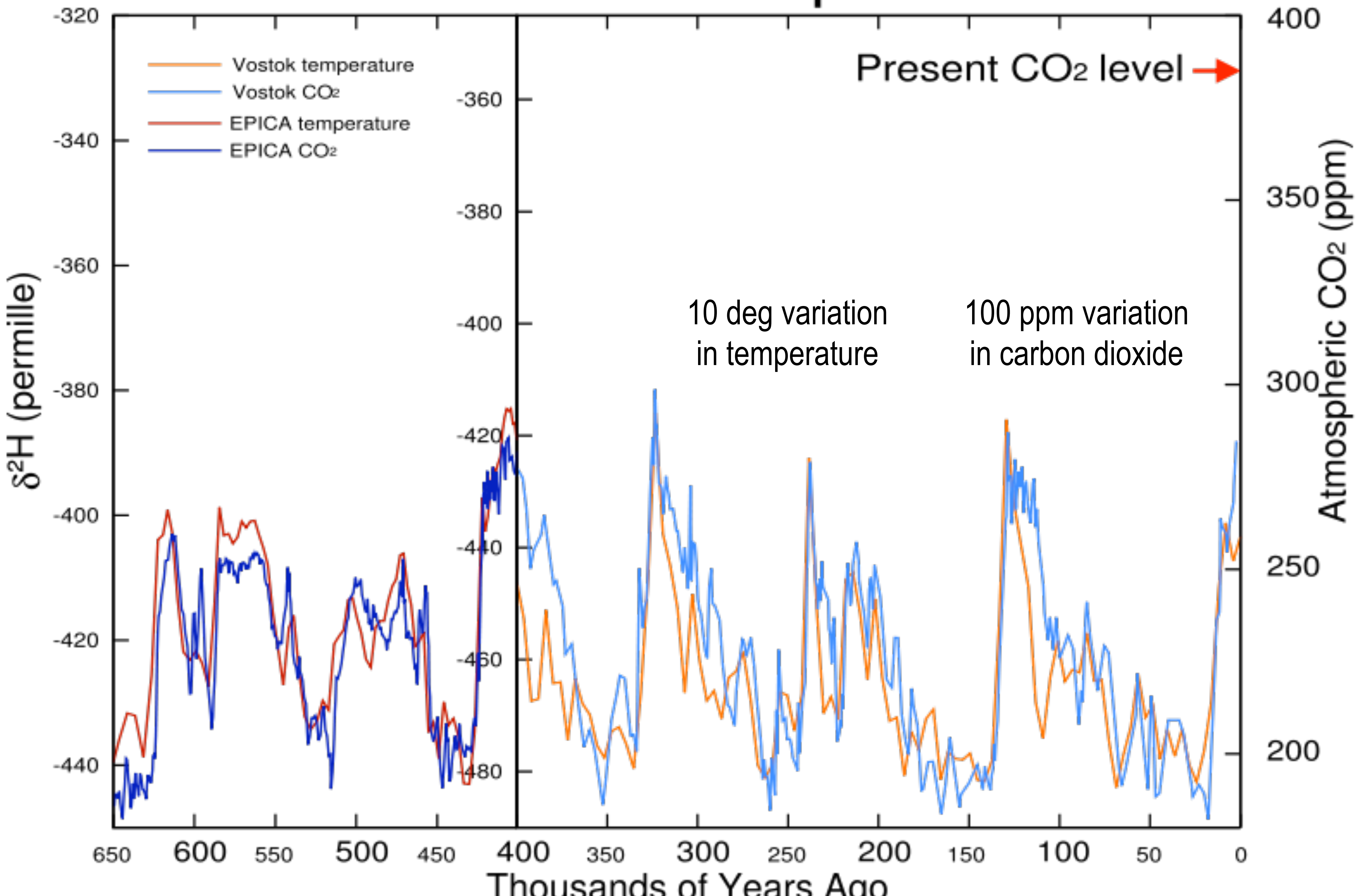


< Gas bubbles in ice

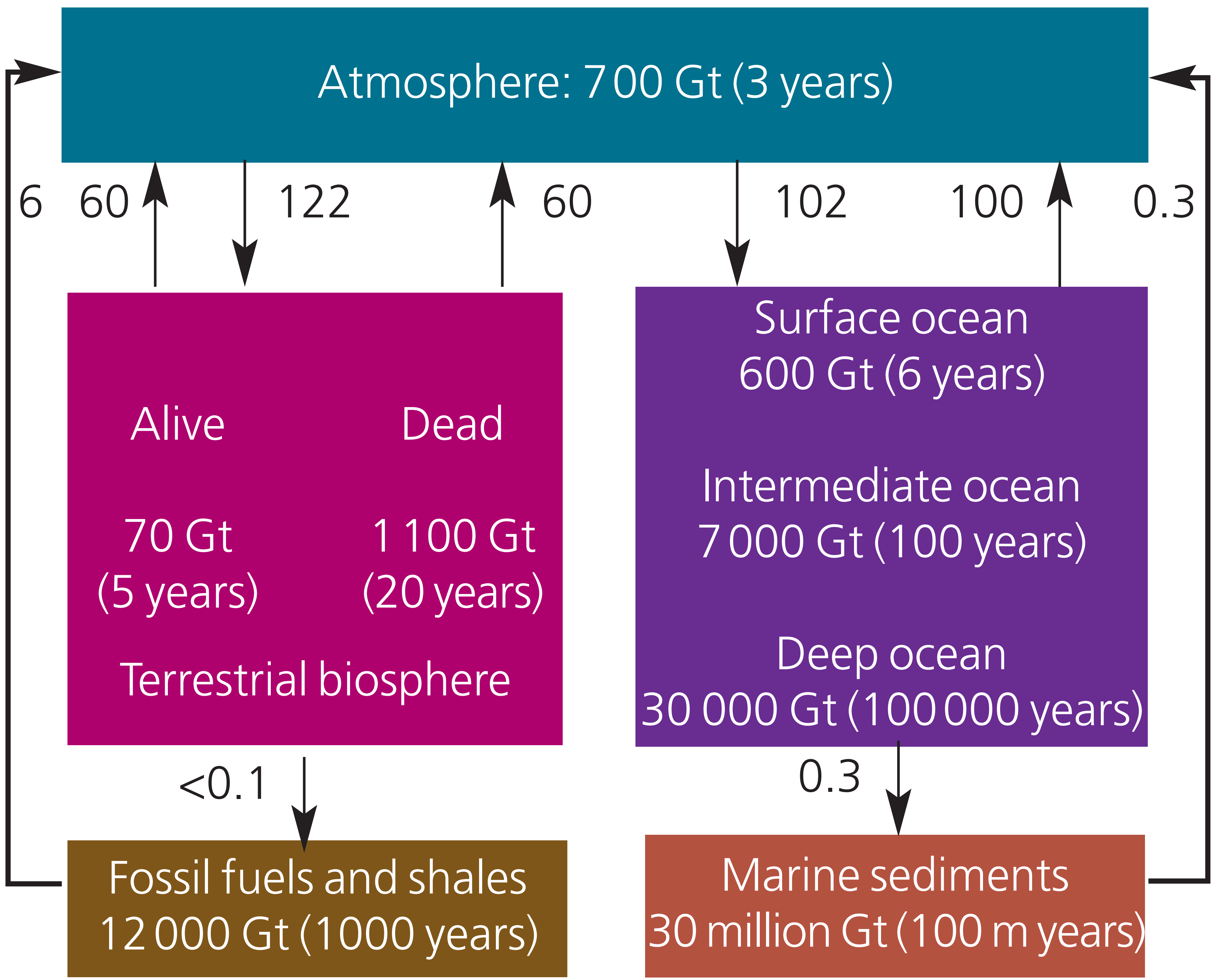
<< EPICA Dome C
Ice Core, Antarctica

The last 600K yrs

Carbon Dioxide and Temperature Records



Carbon reservoirs and fluxes



From the Royal Society report on Ocean Acidification, 2005

Mean annual air-sea flux of CO2

Red: out of the ocean

Blue: into the ocean

Amounts to an influx of about 2.4 gt C per year

$$F_{a-s} = k\ \Delta pCO_2$$

Piston velocity k

k = f (wind speed, solubility)

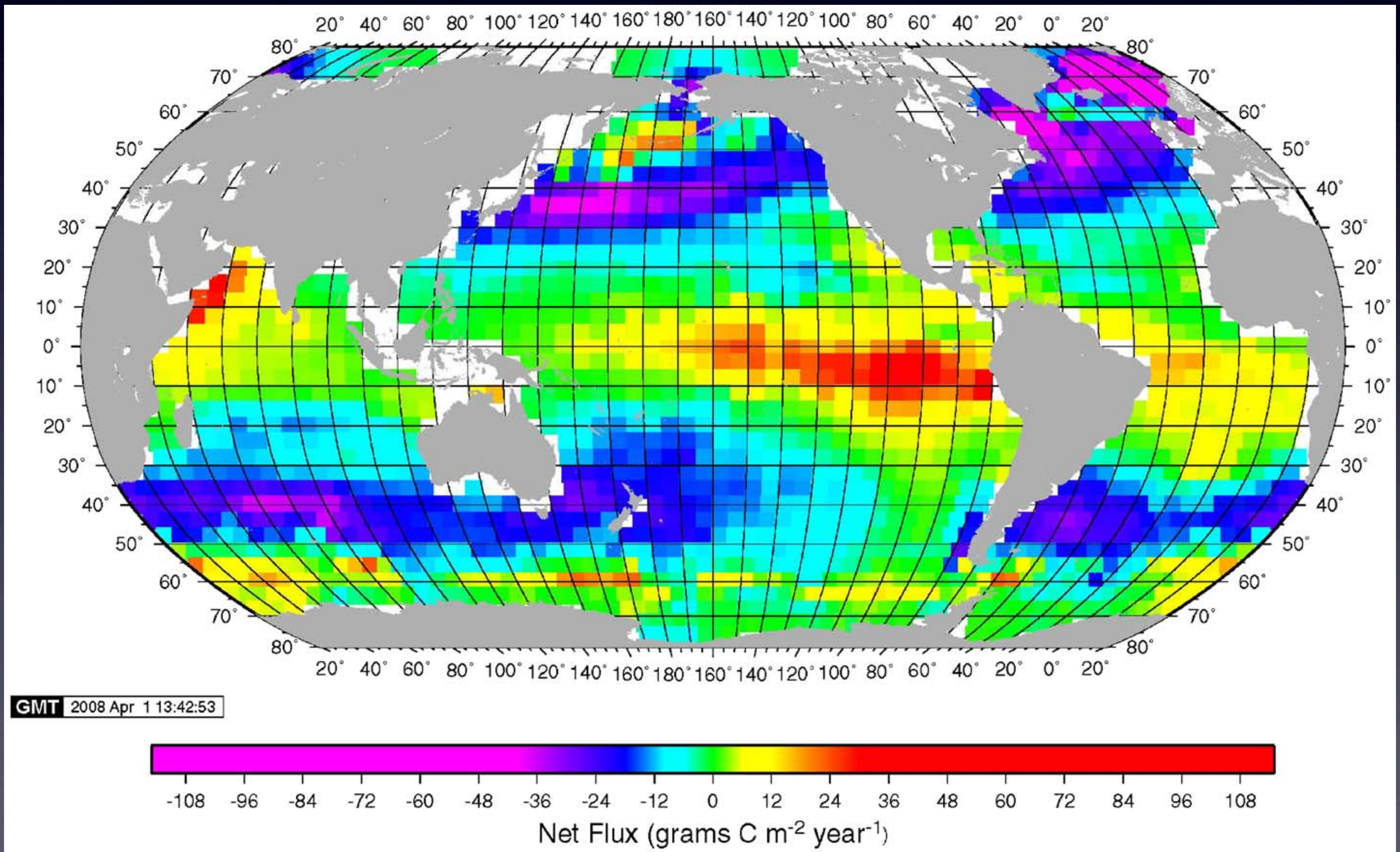
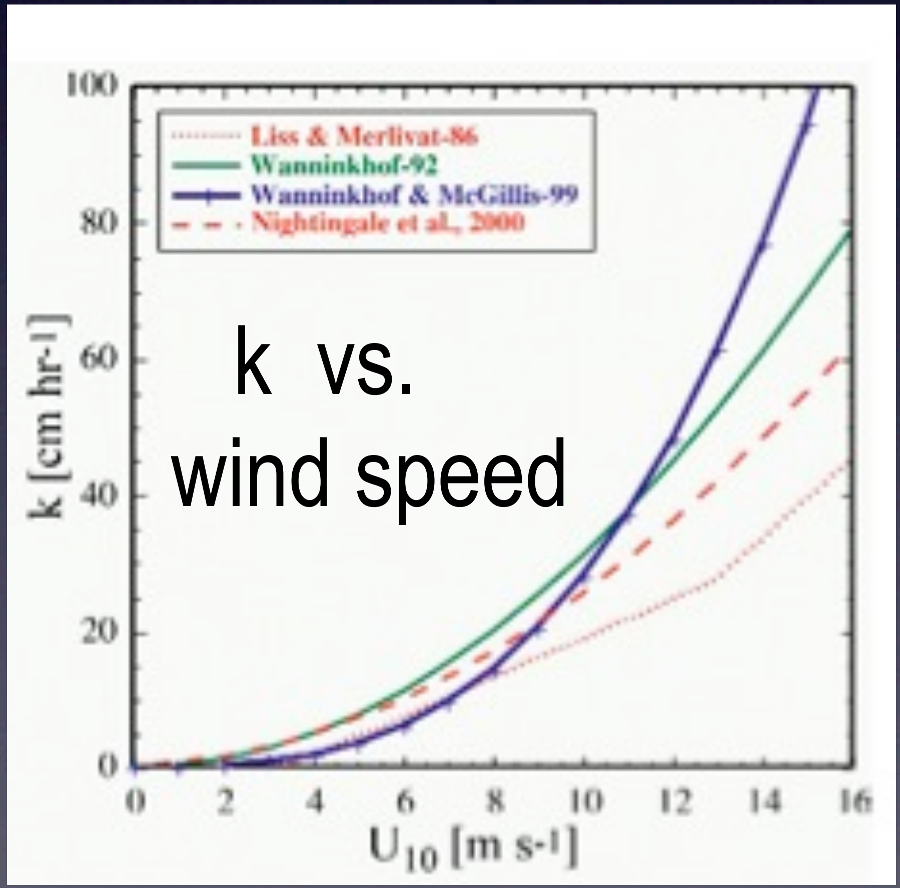


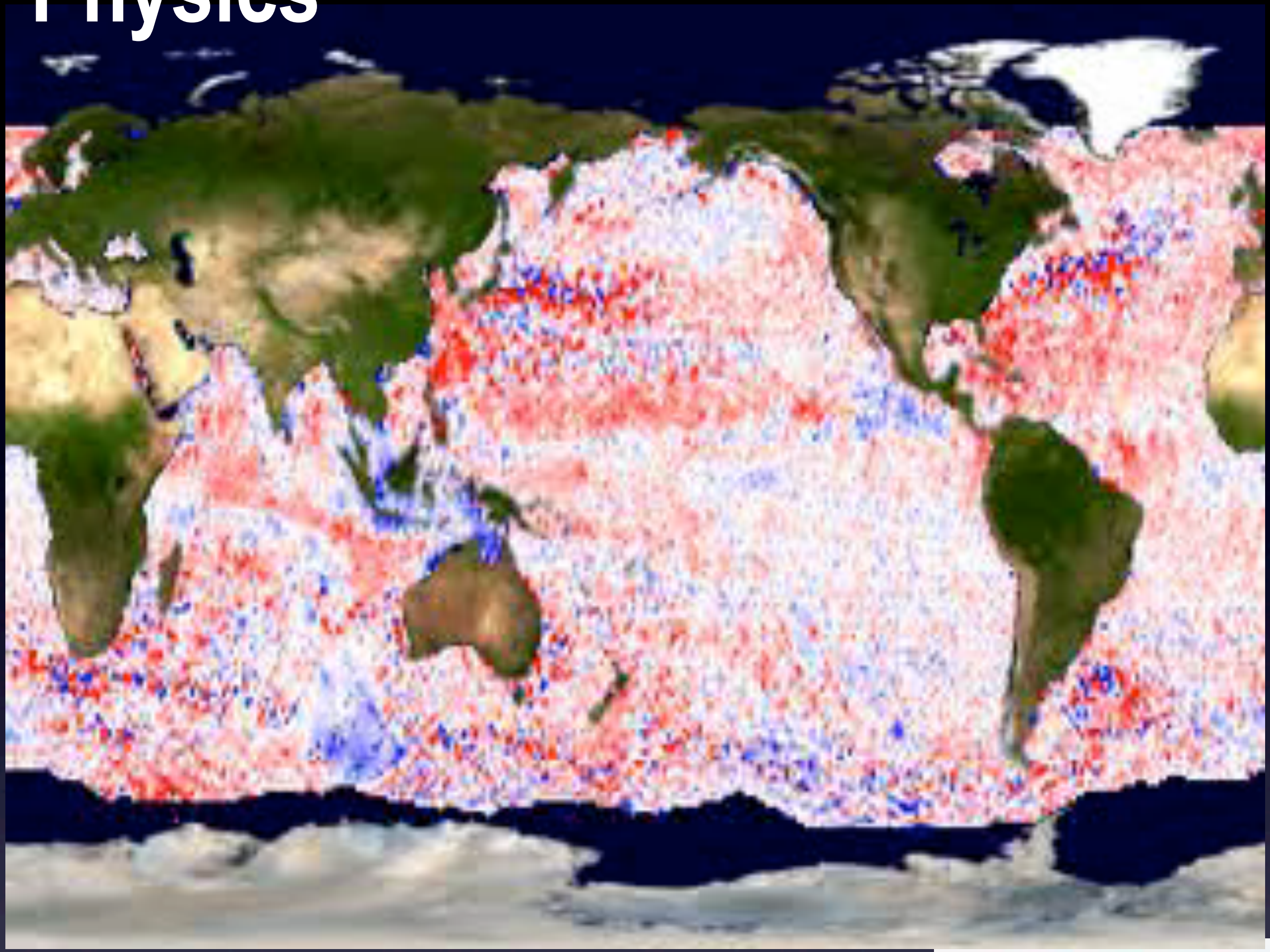
Fig. 13. Climatological mean annual sea–air CO_2 flux (g-C m^{-2} yr^{-1}) for the reference year 2000 (non-El Niño conditions). The map is based on 3.0 million surface water pCO_2 measurements obtained since 1970. Wind speed data from the 1979–2005 NCEP-DOE AMIP-II Reanalysis (R-2) and the gas transfer coefficient with a scaling factor of 0.26 (Eq. (8)) are used. This yields a net global air-to-sea flux of 1.42 Pg-C y^{-1}.



Takahashi et al., 2009

The Ocean's Role in Climate

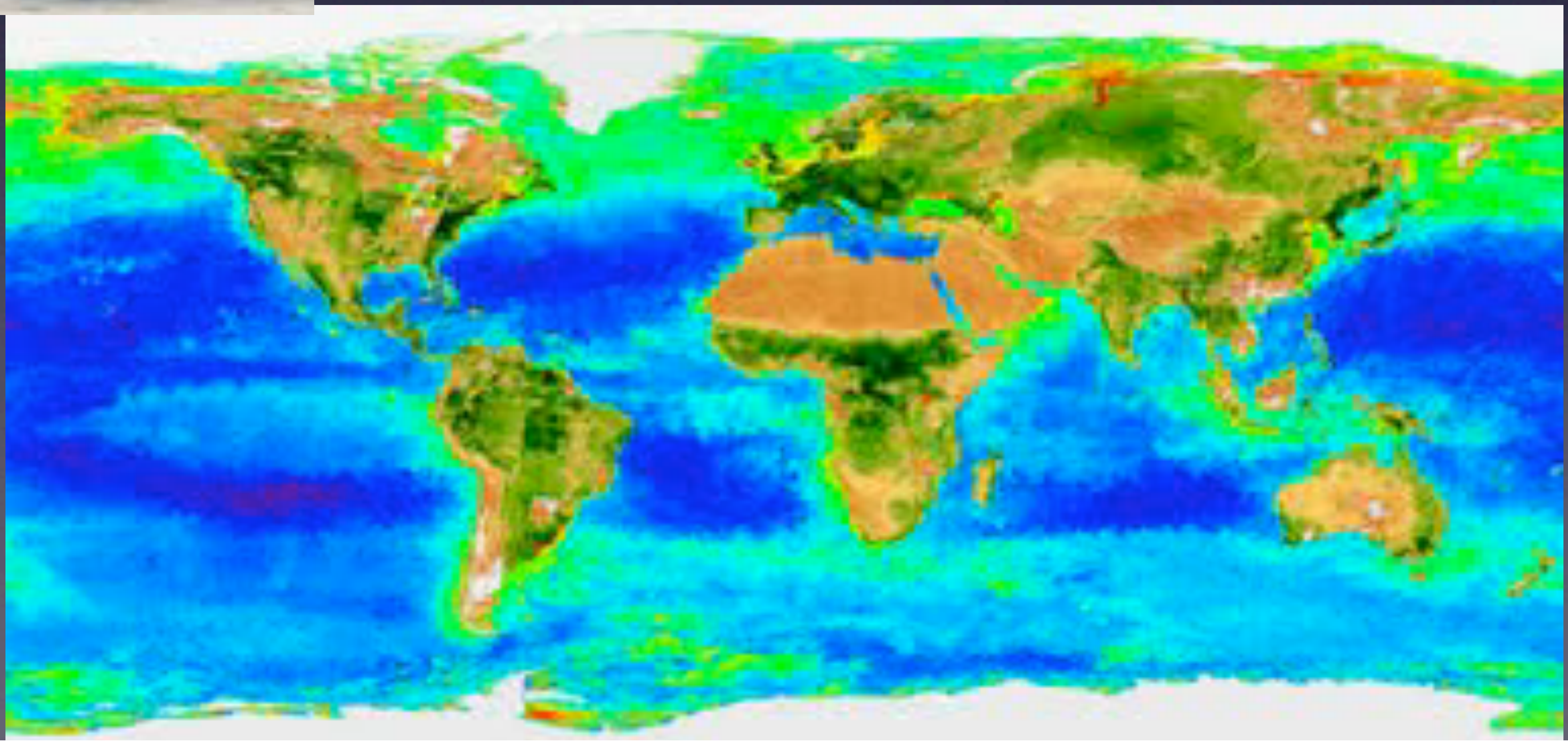
Physics



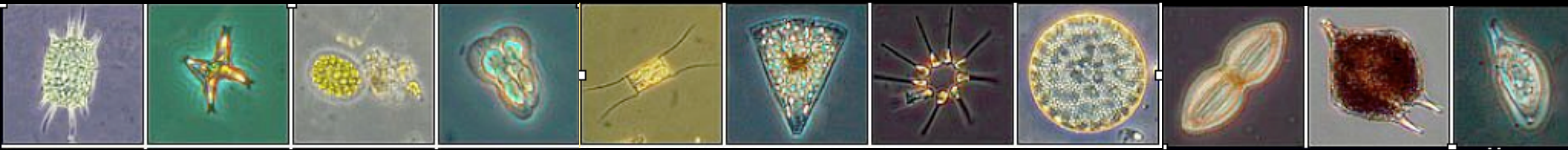
SSH anomaly 2003-05

Biology

SeaWiFS Biosphere 6 yrs



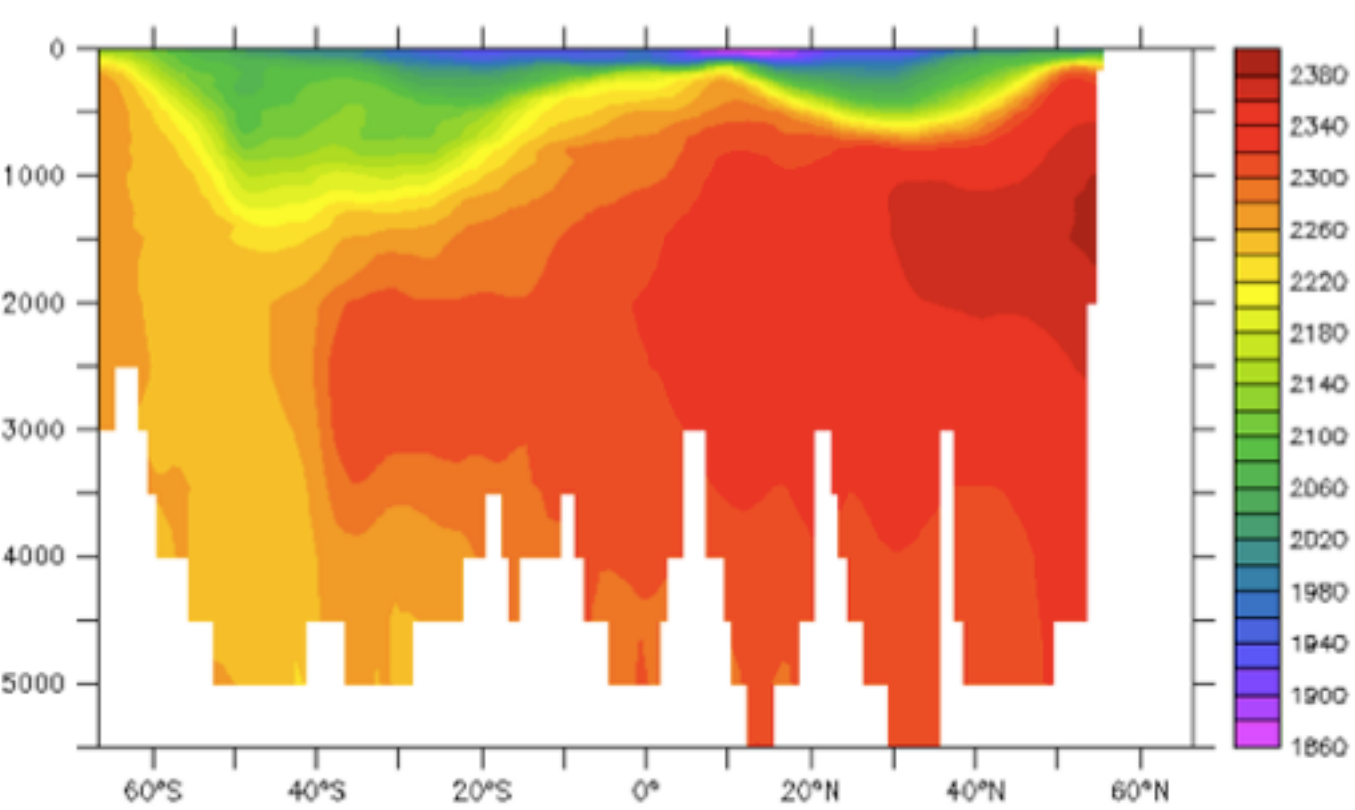
Some species of marine phytoplankton



Marine Biological Pump

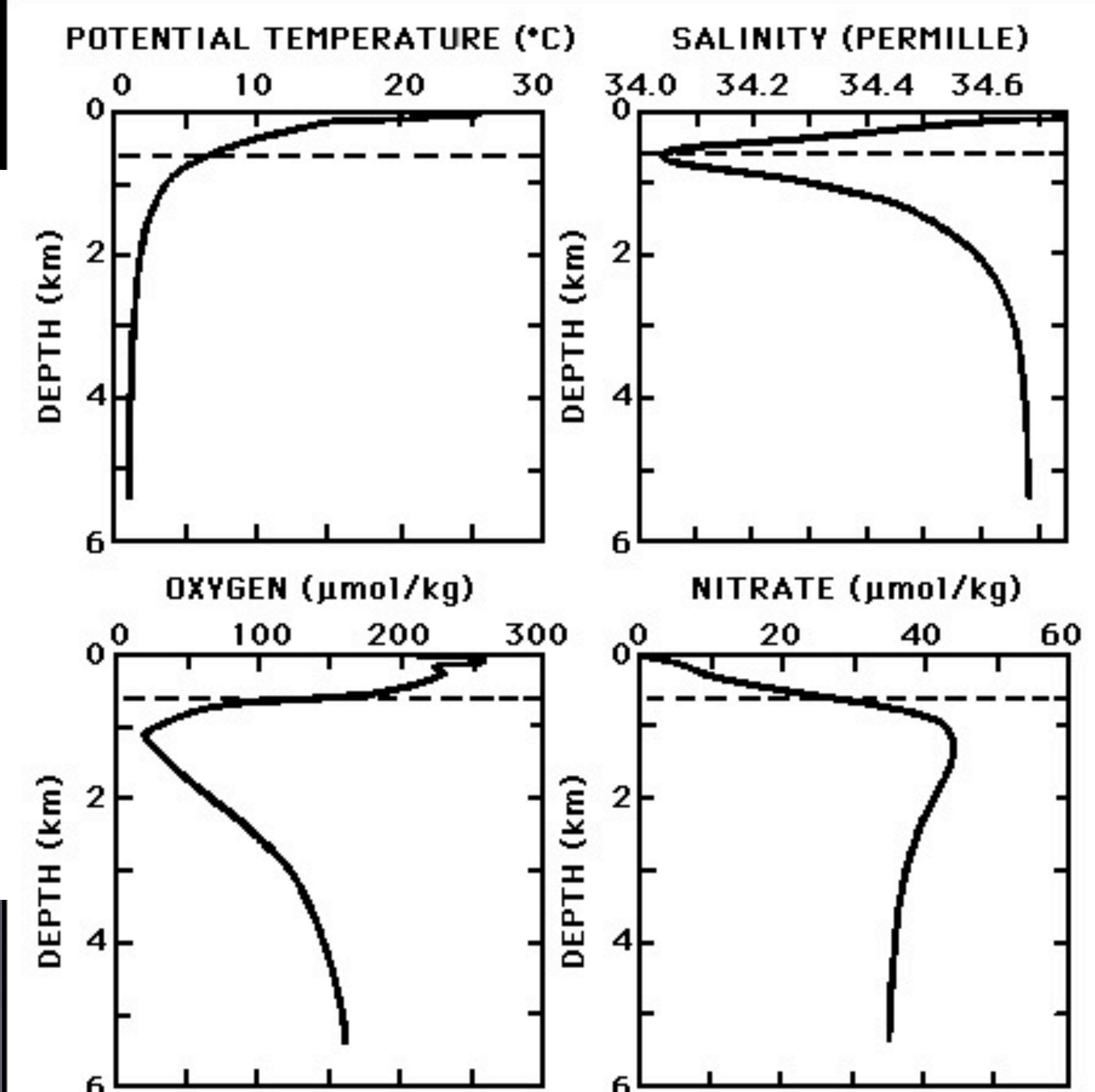
upwelling of nutrients - production of particulate carbon - ingestion - sinking of organic matter - mixing and advection

Nutrients (nitrate, phosphate) are depleted from the surface sunlit layer



Dissolved Inorganic Carbon (Total CO2)

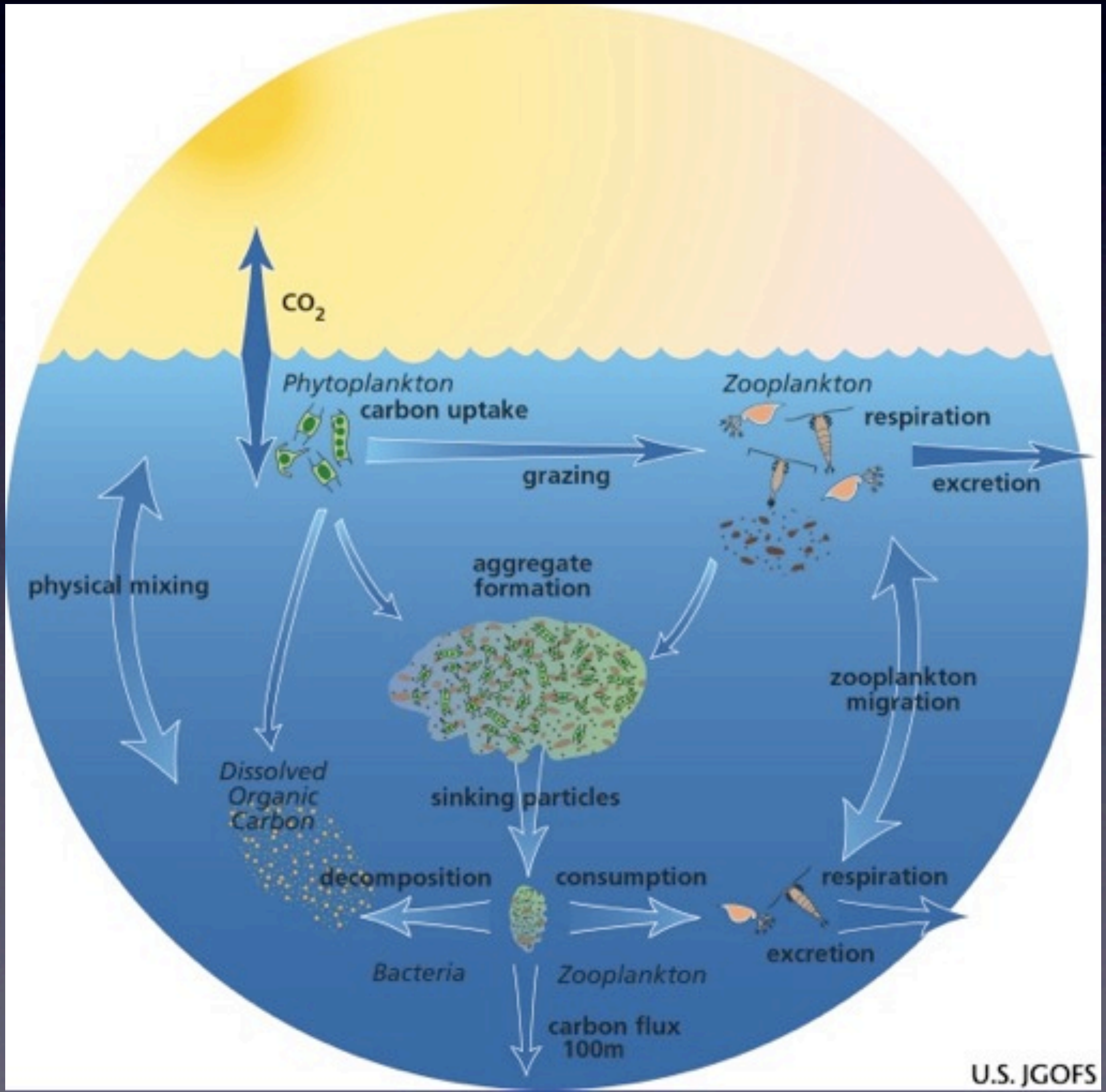
South to North Vertical Section Atlantic Ocean



Mean vertical profiles of oceanic properties

Marine Biological Pump

upwelling of nutrients
production of particulate carbon
food chain
sinking of organic matter
mixing and advection



Rates of (new) production and export of organic matter

Production depends on...

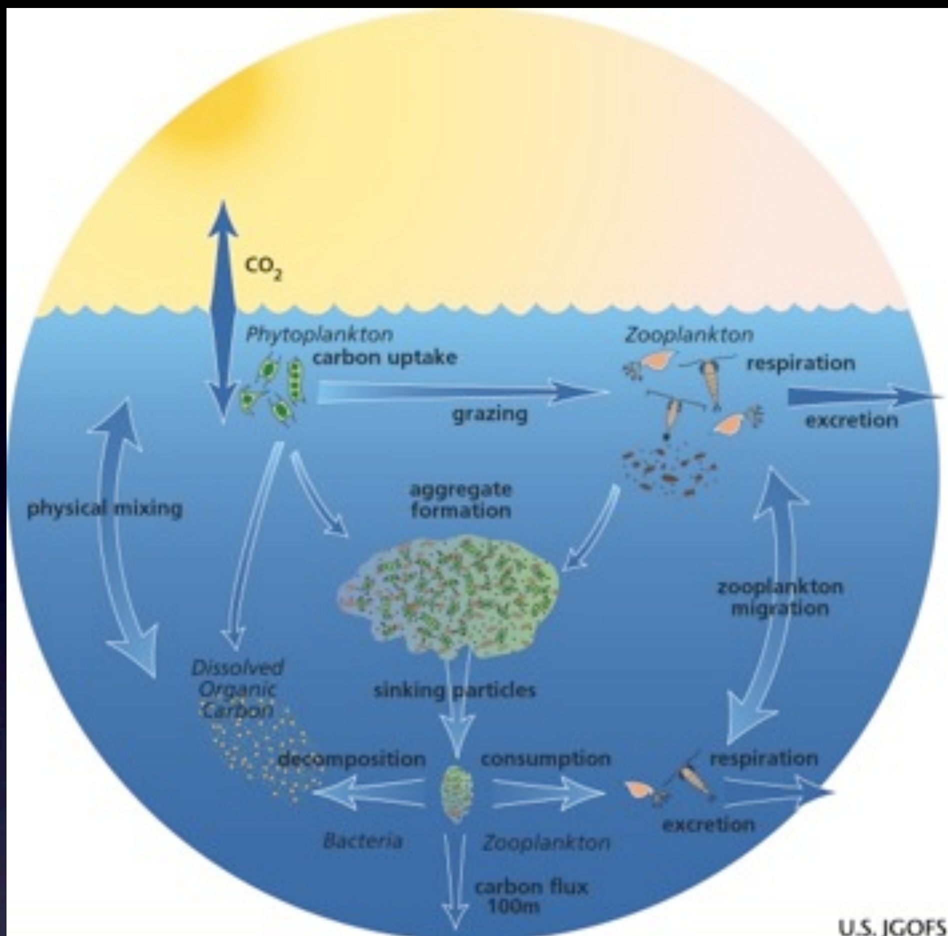
Nutrient supply
Light exposure
Growth rates

Recycling
Remineralization

Export (sinking flux) depends on...

Species, cell size,
Composition (ballasting)
Detritus formation
Coagulation
Remineralization rate

NPZD Modeling



Nutrient $DN/Dt = -P_{growth}(light, N, P) + R_{\text{remineralization}}$

Phyto-plankton $DP/Dt = +P_{growth}(light, N, P)$

$-Z_{growt}(P, Z) - sinking - mortality$

Zoo-plankton $DZ/Dt = Z_{growth}(P, Z)$

$-detritus formation - mortality$

Detritus $DD/Dt = detritus formation - R_{\text{remineralization}}$

$$P_{growth} = \mu(I)\left(\frac{N_0}{k+N}\right)P$$

$$\mu(I) = 1 - \exp(-I(z)/I_0)$$

$$Sinking = w_s P$$

$$Mortality = mP$$

$$Z_{growth} = \lambda ZP$$

$$Detritus formation = \alpha Z_{growth}$$

$$R_{\text{remineralization}} = (species, size, composition)$$

$$Mortality = \gamma Z$$

The oceans are very poorly mixed, vert. vel << hor. vel
Forced at surface, constrained by rotation and stratification

Non-dissipative 2-D → How do energy and properties get fluxed downscale? → Dissipative 3-D

Mesoscales

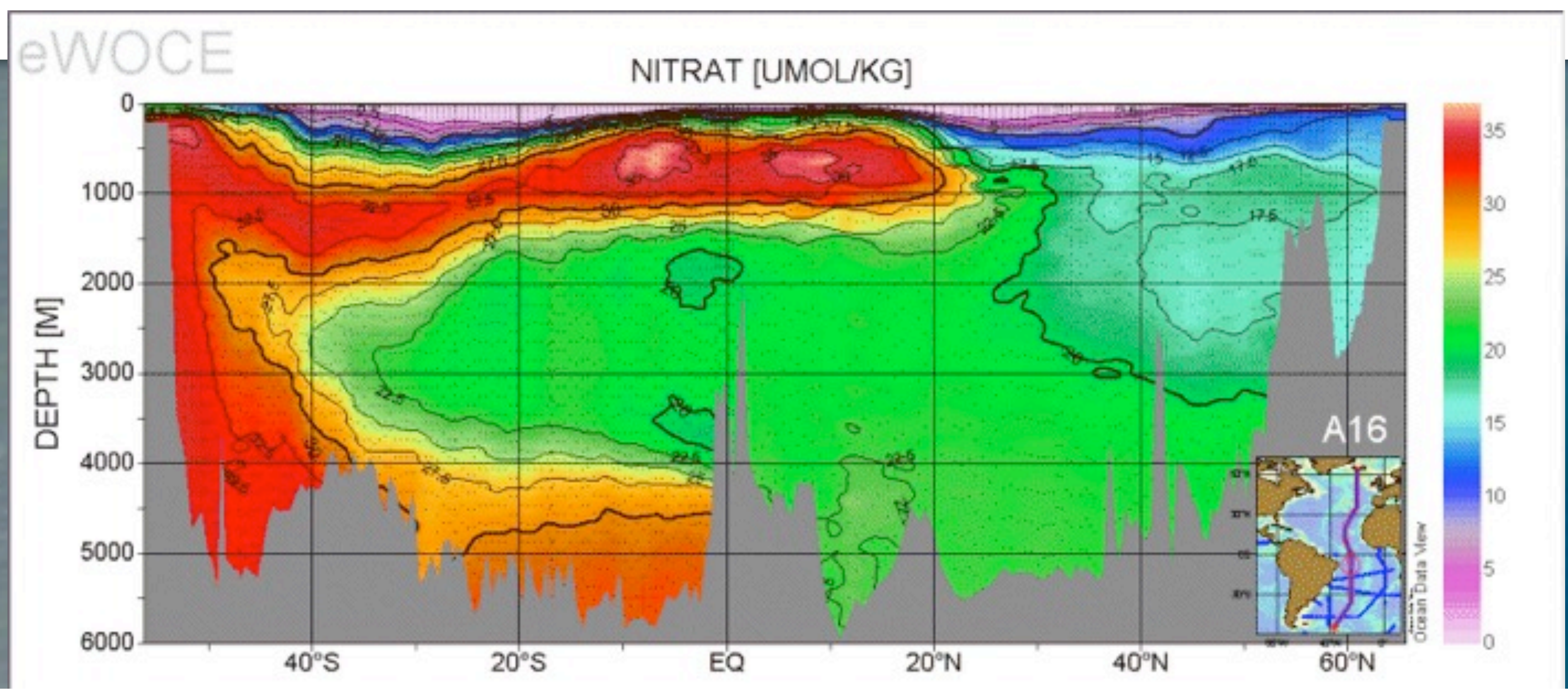
Ro << 1, Ri >> 1
L ~ 10 - 100 km
D/L << 1, hydrostatic

Submesoscales?

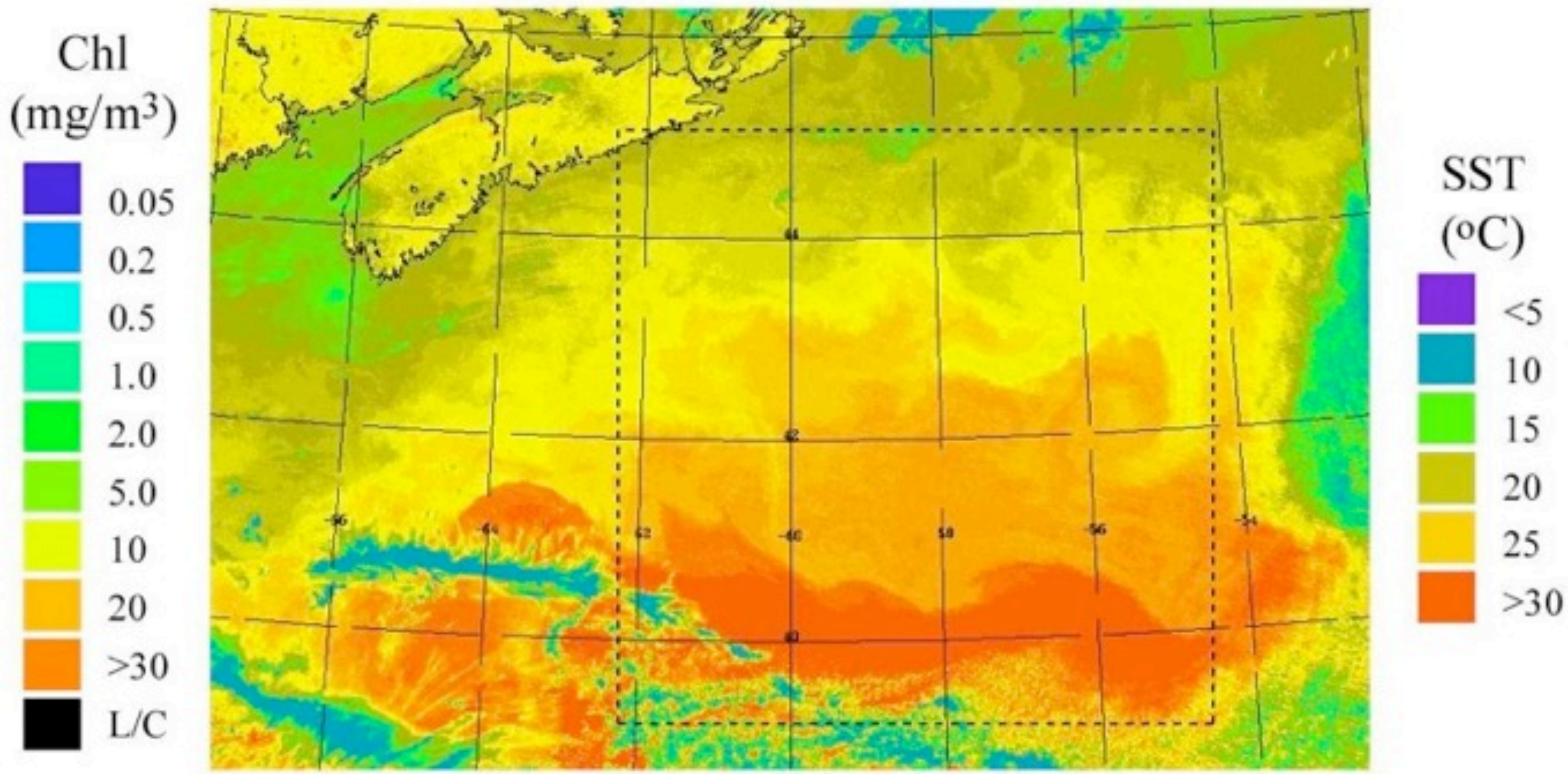
Ro and Ri are O(1)
L ~ 1 km
D/L << 1, hydrostatic

Small scales

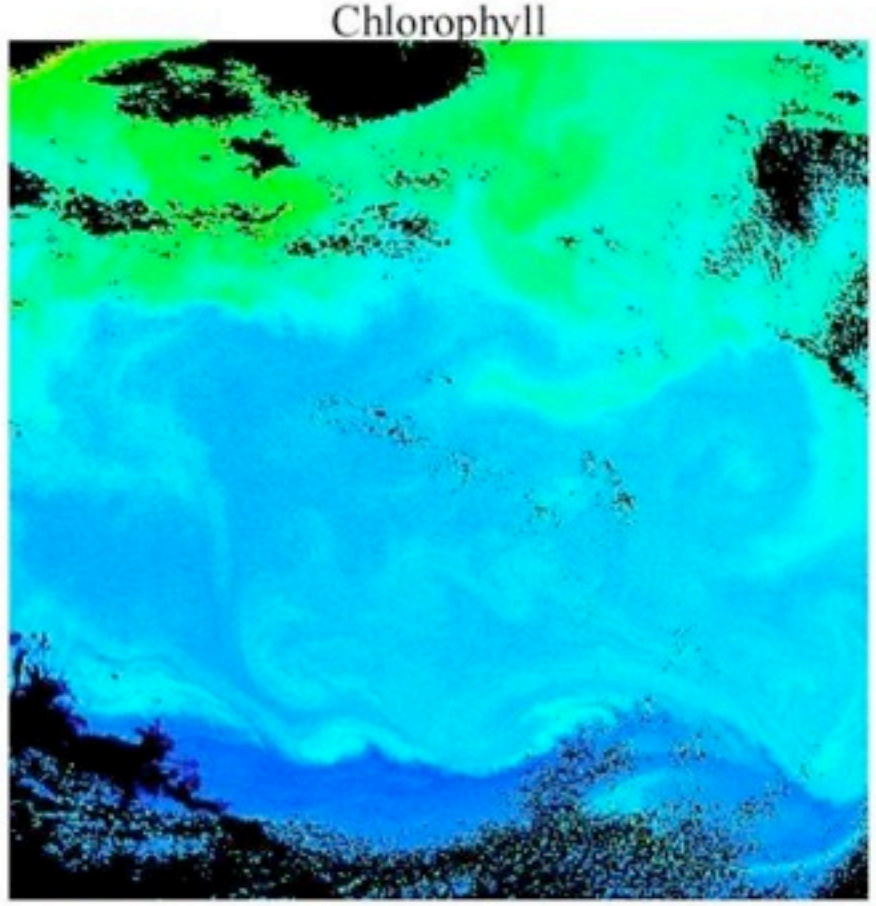
Ro >> 1, Ri << 1
L < 100 m
D/L ~ 1, nonhydrostatic



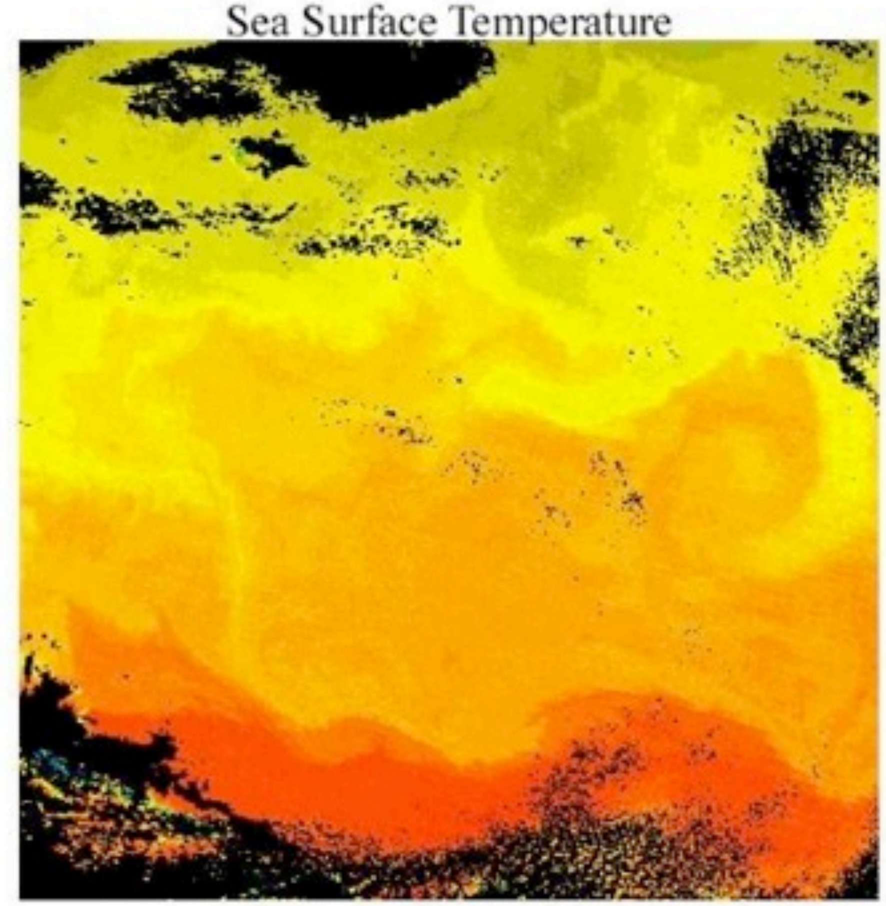
MODIS SST image - Oct. 1, 2000



Chlorophyll

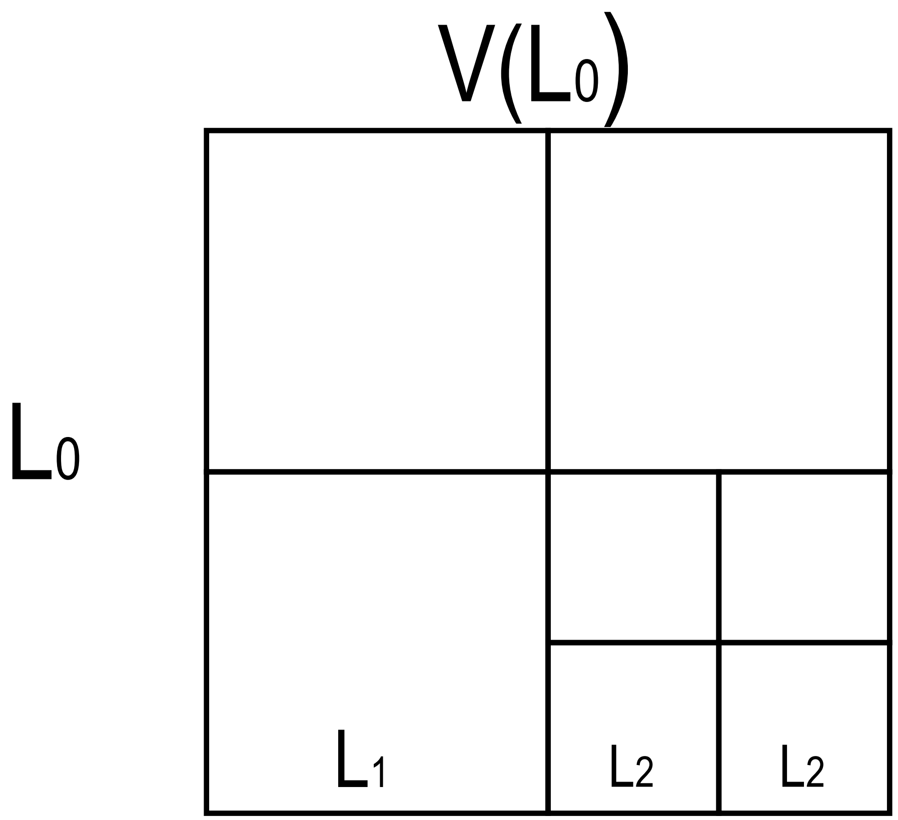


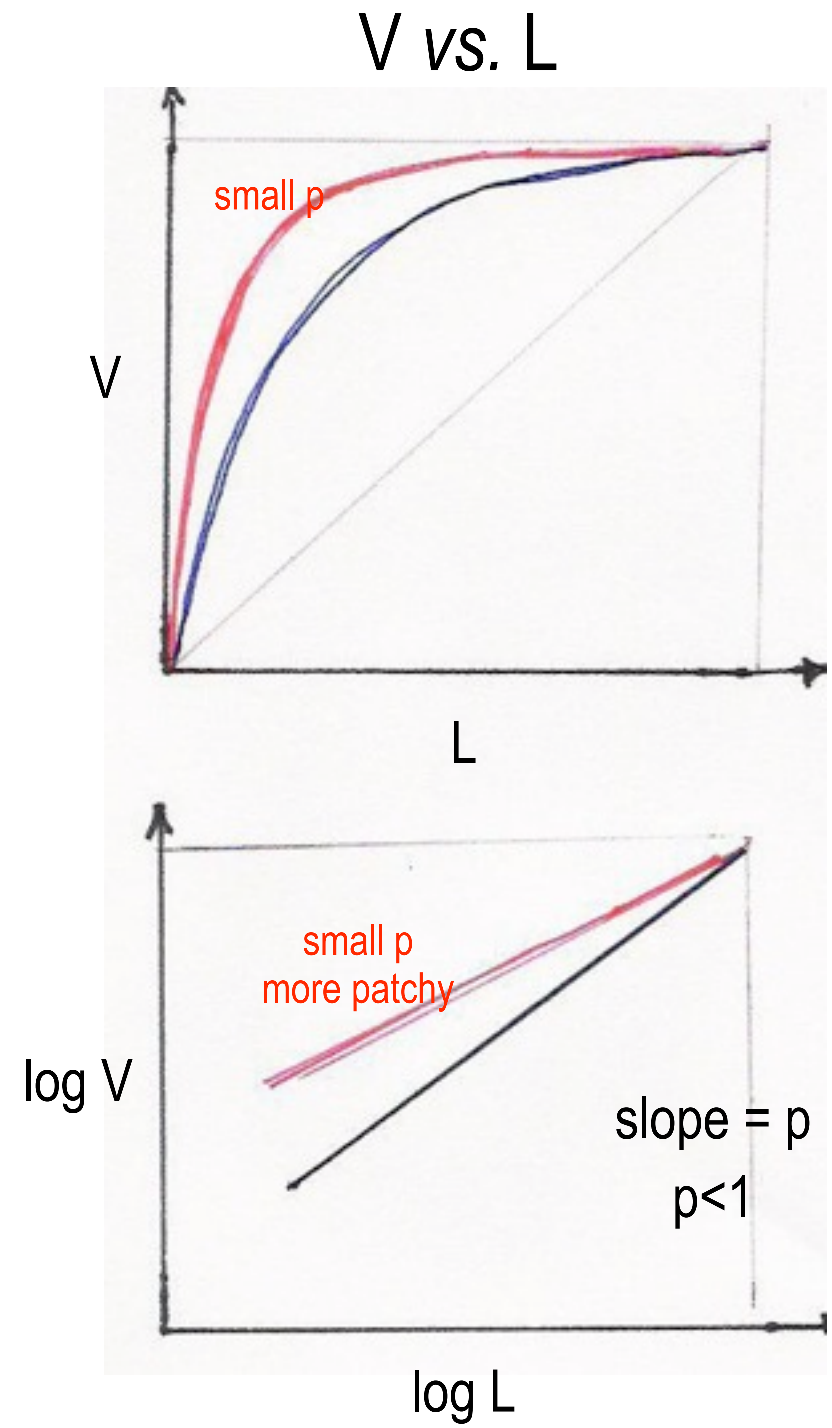
Sea Surface Temperature



How can we quantify spatial heterogeneity or patchiness?

Analyze Property Variance at the Sea Surface





$V(L_0)$, $V(L_1)$, $V(L_2)$, ... etc.

$$V = \frac{1}{N}\sum_N C'^2, \text{ where } C' = C - \overline{C}$$

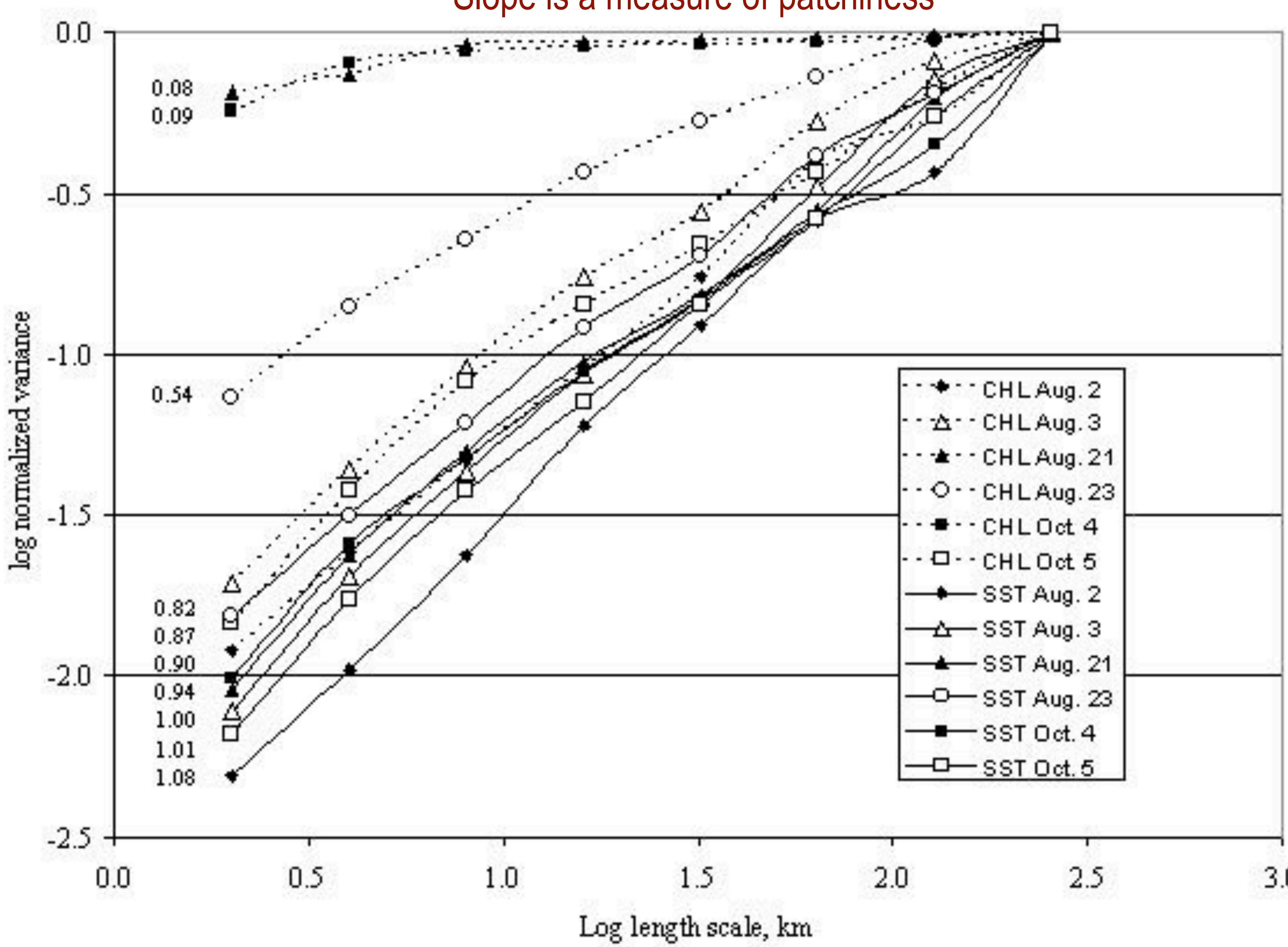
$$V \sim L^p, \text{ where } p \text{ is an index of Patchiness}$$

Variance Analysis

Mahadevan & Campbell, 2002

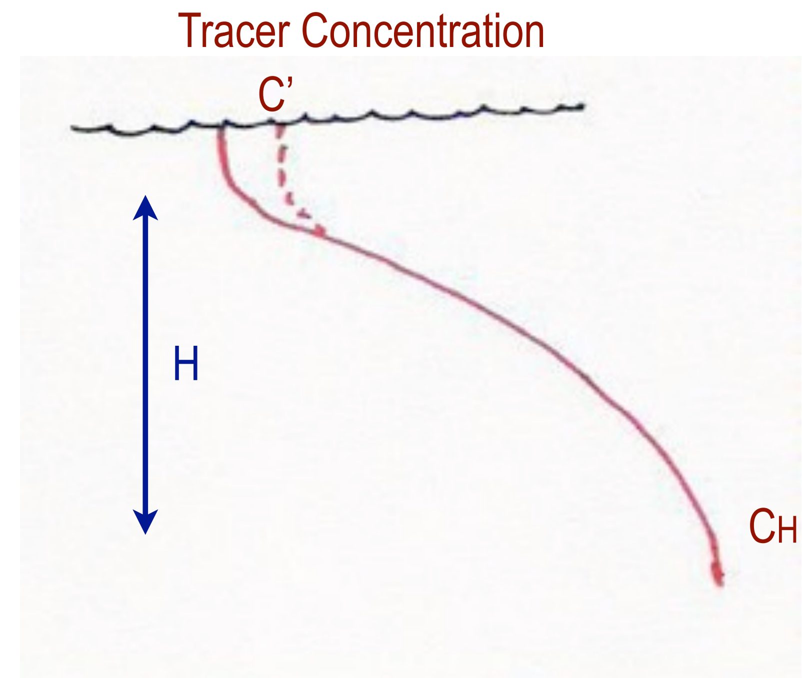
log V *vs.* log L

Slope is a measure of patchiness



Surface Chl is always more patchy than temperature. Why?

Model



Nutrient-like Tracer

$$\frac{DC}{Dt} = -\frac{1}{\tau}C \quad \text{above the euphotic depth}$$

$$= 0 \quad \text{below the euphotic depth}$$

Tracer response time scale

$$\tau = 2.5, 5, 10, 20, 40, 80 \text{ days}$$

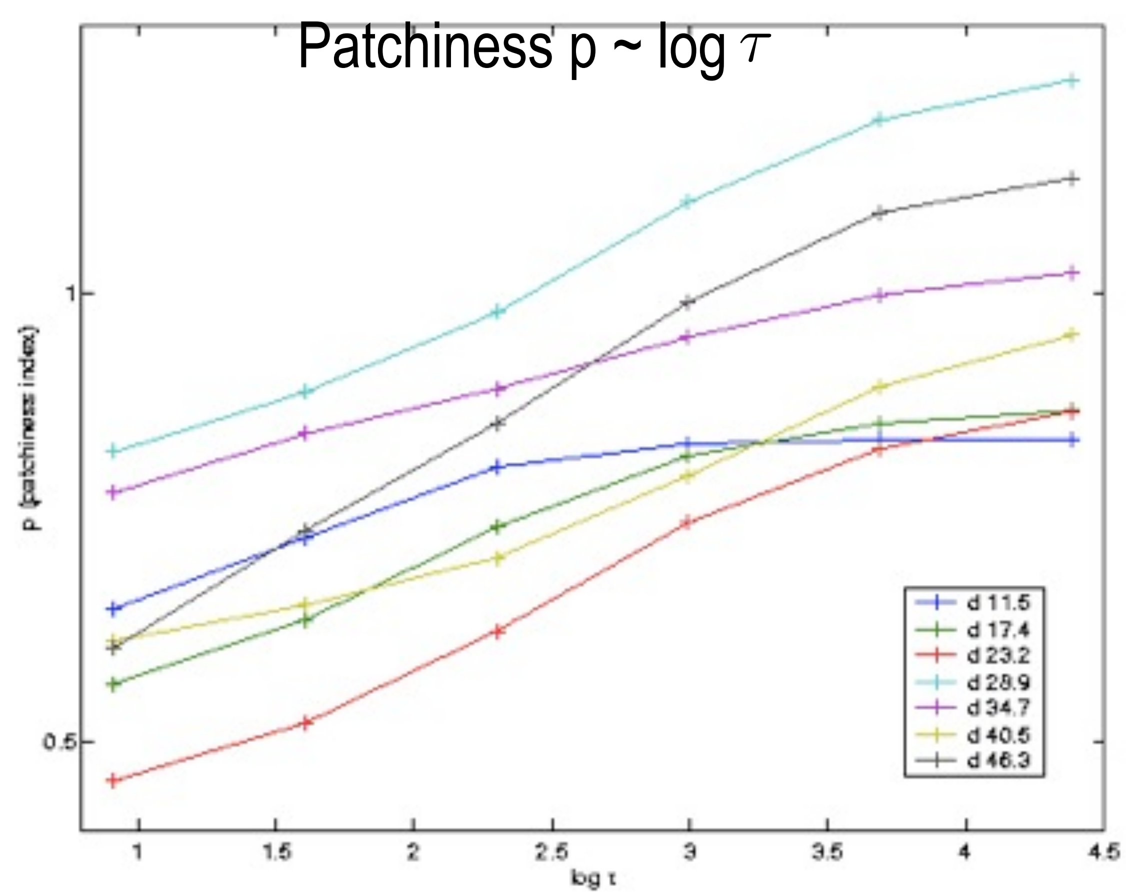
$$w\frac{\partial C}{\partial z} = -\frac{1}{\tau}C$$

$$\frac{W}{H}C_H \sim -\frac{1}{\tau}C'$$

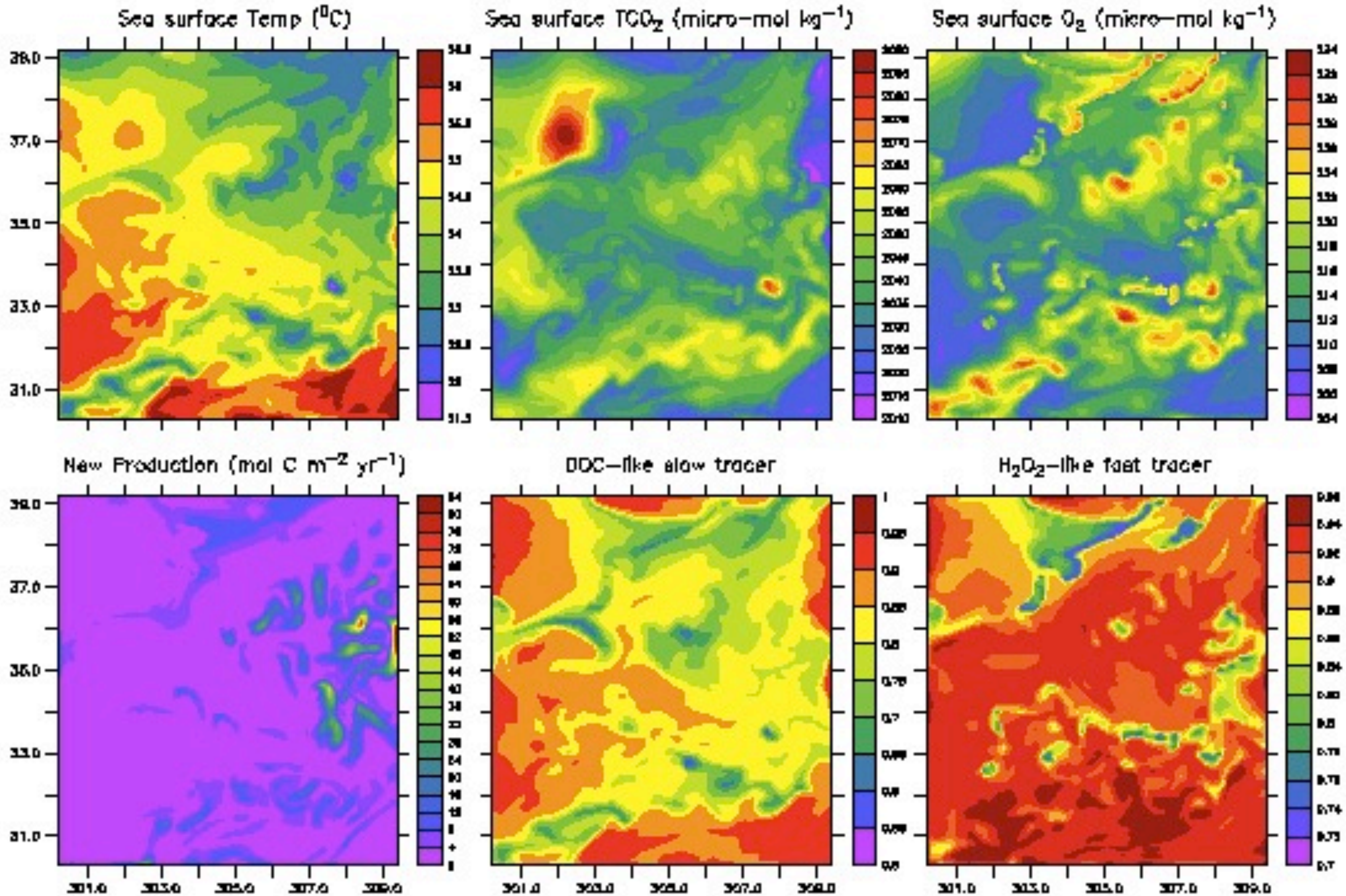
$$\log\frac{C'}{C_H} \sim -\log\frac{\tau}{W/H}$$

Patchiness $p \sim \log\frac{\tau}{W/H}$

since $V = C'^2$ and $p = \frac{\log V}{\log L}$



Modeled Tracer Fields at Sea Surface



Mahadevan & Archer 1998, 2000

Dynamics (large scale)

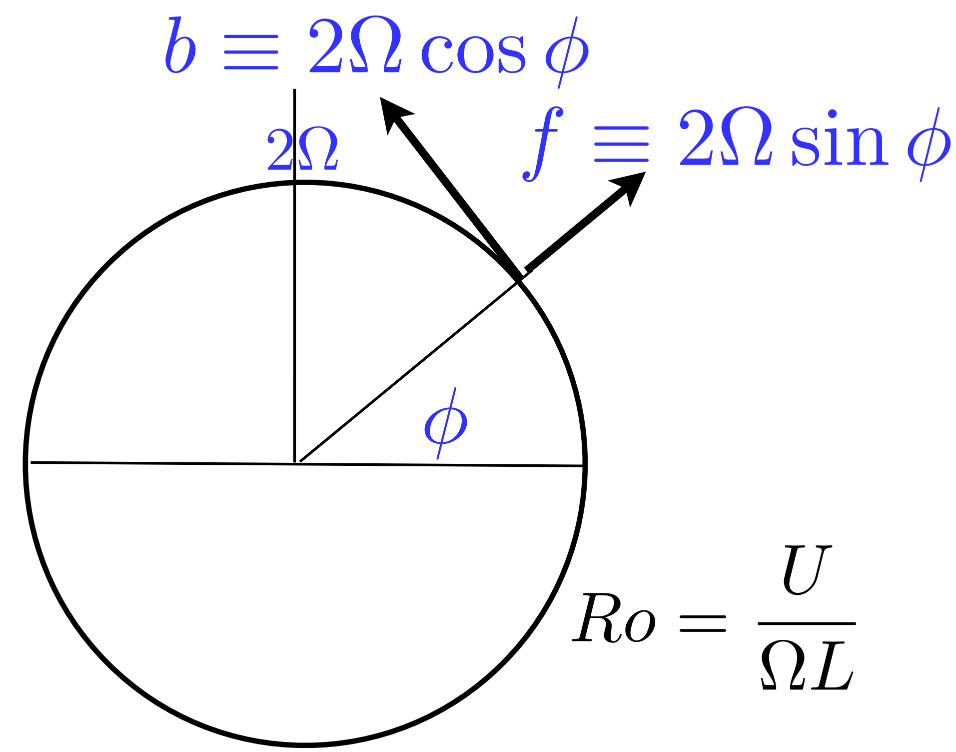
$$\frac{D\mathbf{u}}{Dt} + \rho^{-1}\nabla p + 2\Omega \times \mathbf{u} + \Delta\phi = F$$

$$\frac{U^2}{L} \qquad \frac{P}{\rho L} \qquad \Omega U \qquad g \qquad small$$

$$For\ \ U = 0.1m/s, L = 100km, \Omega = 10^{-4}/s$$

$$U^2/L << \Omega U$$

Rossby number $R_o = \dfrac{U}{\Omega L} << 1$ $\qquad Also,\ \delta = D/L << 1$



$$Du/Dt + Ro^{-1}(p_x - fv) = F^x$$

$$Dv/Dt + Ro^{-1}(p_y - fu) = F^y$$

$$\frac{\partial p}{\partial z} = -\rho g$$

Hydrostatic balance

$$w_z = -Ro^{-1}(u_x + v_y) \qquad W \sim Ro\,\delta\,U$$

Hydrostatic Pressure gradient

$$p_x = gh_x + r_x$$

$$r_x = \frac{\partial}{\partial x}\int_z^h \rho dz$$

Model

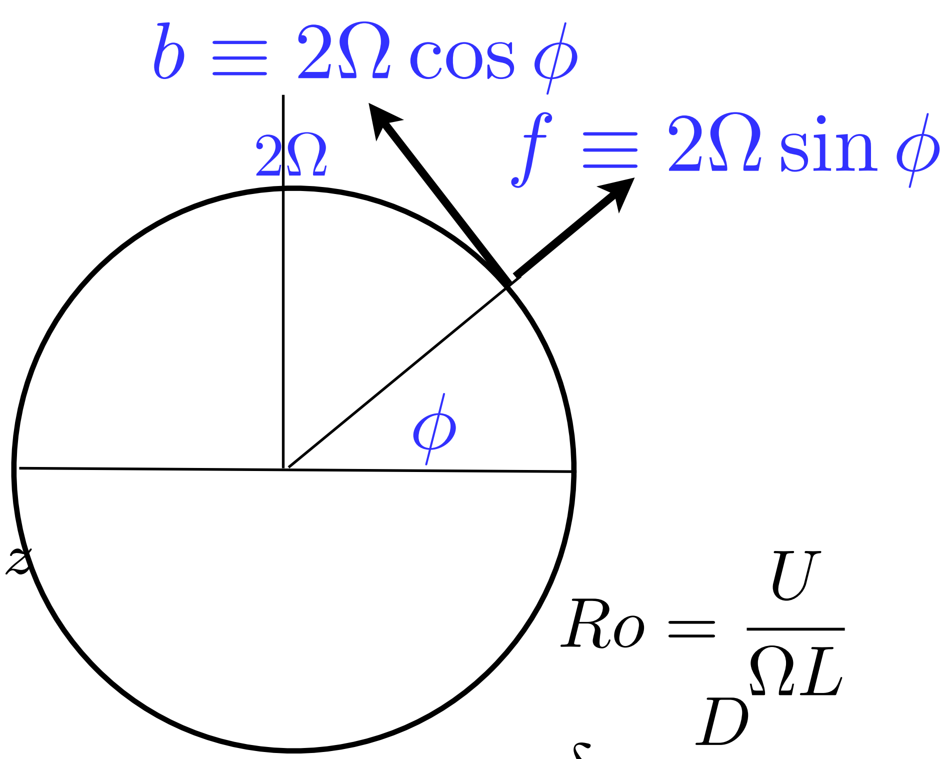
p = Hydrostatic pressure
q = Nonhydrostatic pressure
$P = p + \delta q$

$$D_t u + Ro^{-1}(p_x + \delta q_x - fv + Ro\,\delta\, bw) = F^x$$

$$D_t v + Ro^{-1}(p_y + \delta q_y + fu) = F^y$$

$$D_t w + Ro^{-2}\delta^{-2}(\rho^{-1} p_z + g + \delta q_z - \delta\, bu) = F^z$$

$$u_x + v_y + Ro\, w_z = 0$$



$Ro = \dfrac{U}{\Omega L}$

$\delta = \dfrac{D}{L}$

$W \sim Ro\,\delta\, U$

Hydrostatic $\delta \to 0$ $\boxed{p_z + \rho g = 0}$ $w_z = -Ro^{-1}(u_x + v_y)$

Free-surface height
...and density => p

$$h_t + \partial_x \int_{z_b}^{h} u dz + \partial_y \int_{z_b}^{h} v dz = 0$$

Nonhydrostatic (δ does not $\to 0$) $\boxed{D_t w + Ro^{-2}\delta^{-1}(q_z - bu) = F^z}$

Well-posed with open boundaries

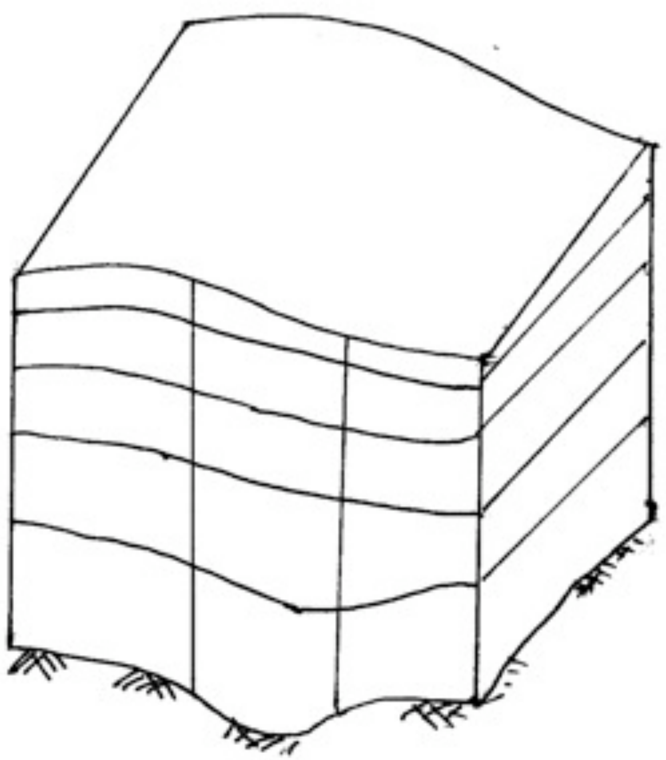
Mahadevan et al., 1996a,b, Mahadevan & Archer 1998

Nonhydrostatic Model

3-D pressure field to be determined

Using incompressibility $$q_{xx} + q_{yy} + \delta^{-2} q_{zz} = F$$

Discretized ... $$(q_{i+1} - 2q_i + q_{i-1}) + (q_{j+1} - 2q_j + q_{j-1}) + \delta^{-2}(q_{k+1} - 2q_k + q_{k-1}) = F$$



$$\begin{bmatrix} 2/\delta^2 & \delta^{-2} & .. & 1 & 1 & .. \\ 1/\delta^2 & 2/\delta^2 & 1/\delta^2 & .. & 1 & 1 \\ .. & 1/\delta^2 & 2/\delta^2 & 1/\delta^2 & .. & 1 \\ .. & .. & .. & .. & .. & .. \\ 1 & 1 & .. & 1/\delta^2 & 2/\delta^2 & 1/\delta^2 \\ .. & 1 & 1 & .. & 1/\delta^2 & 2/\delta^2 \end{bmatrix} \begin{bmatrix} .. \\ ... \\ q_{ijk} \\ .. \\ .. \\ .. \end{bmatrix} = \begin{bmatrix} .. \\ ... \\ F_{ijk} \\ .. \\ .. \\ .. \end{bmatrix}$$

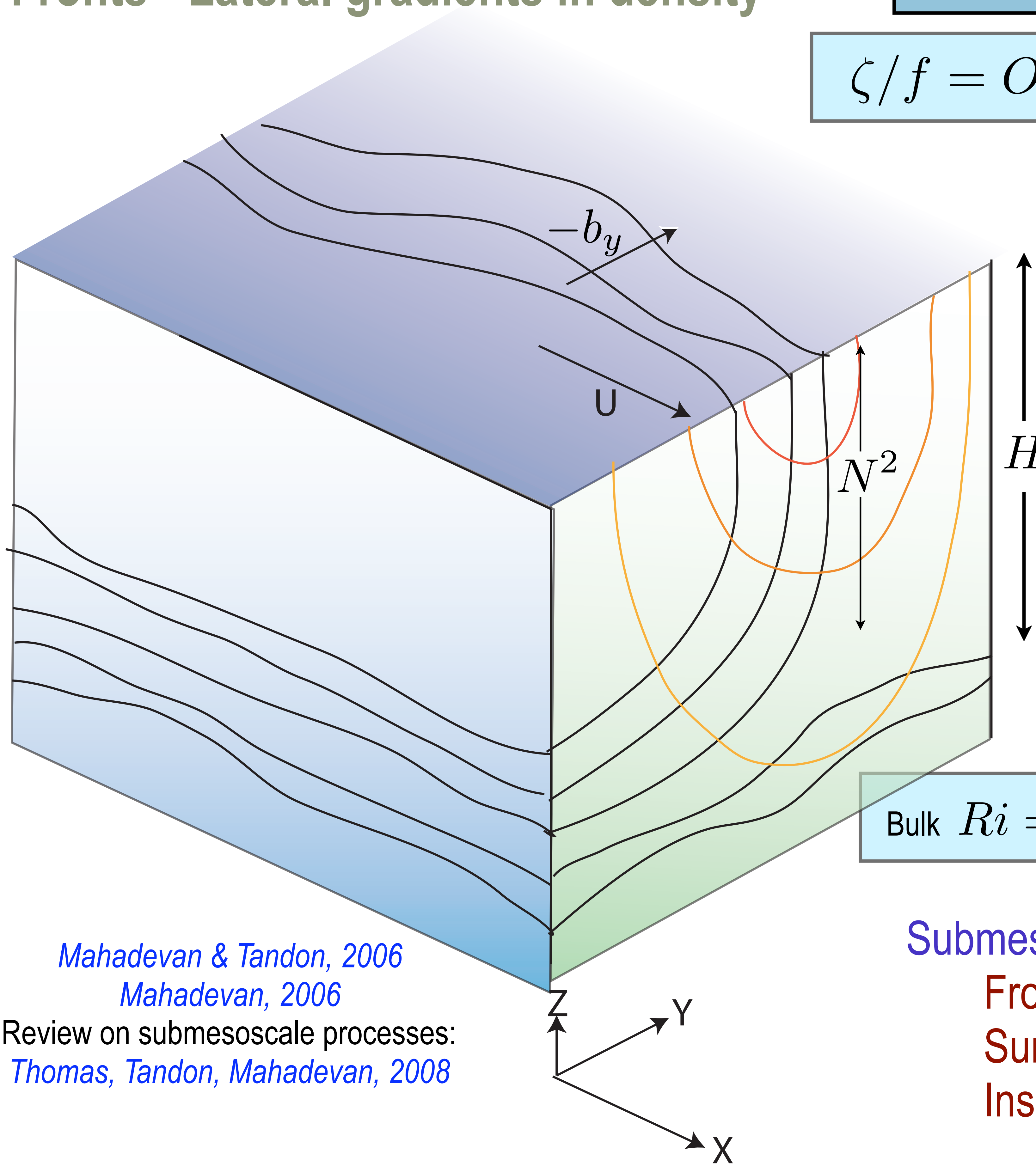
Solved efficiently using the multigrid method and line by line (block) relaxation.

Mahadevan et al., 1996a,b, Mahadevan & Archer 1998

Fronts - Lateral gradients in density

Submesoscale Processes

$$\zeta/f = O(1), \quad Ro = U/fL = O(1)$$



$$L = b_y H/f^2 = NH/f$$

since (Tandon & Garrett, 1994) $b_y \sim Nf$

Vertical velocity $W \sim Ro\,\delta\,U = \delta\,U$

where $\delta = H/L = f/N$

Bulk $Ri = N^2H^2/U^2 = Ro^{-1/2} = O(1)$

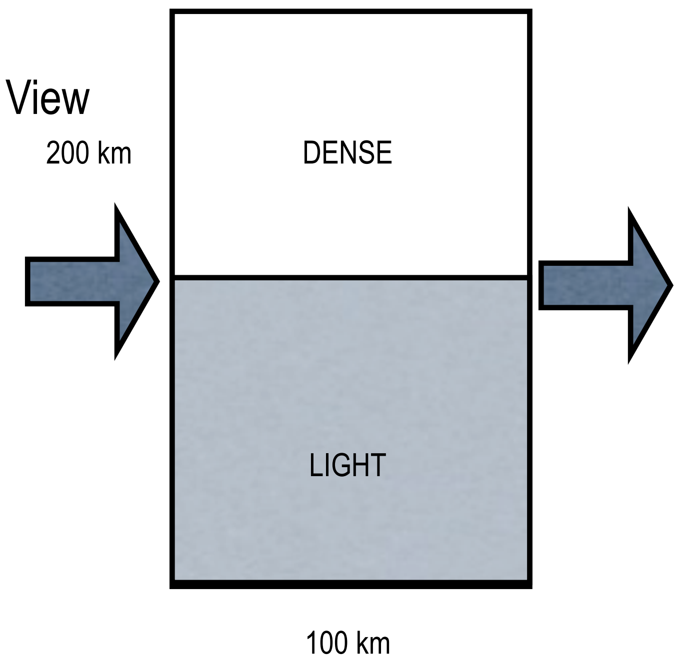
Mahadevan & Tandon, 2006
Mahadevan, 2006
Review on submesoscale processes:
Thomas, Tandon, Mahadevan, 2008

Submesoscale motion can arise from:
- Frontogenesis
- Surface forcing
- Instabilities, ...

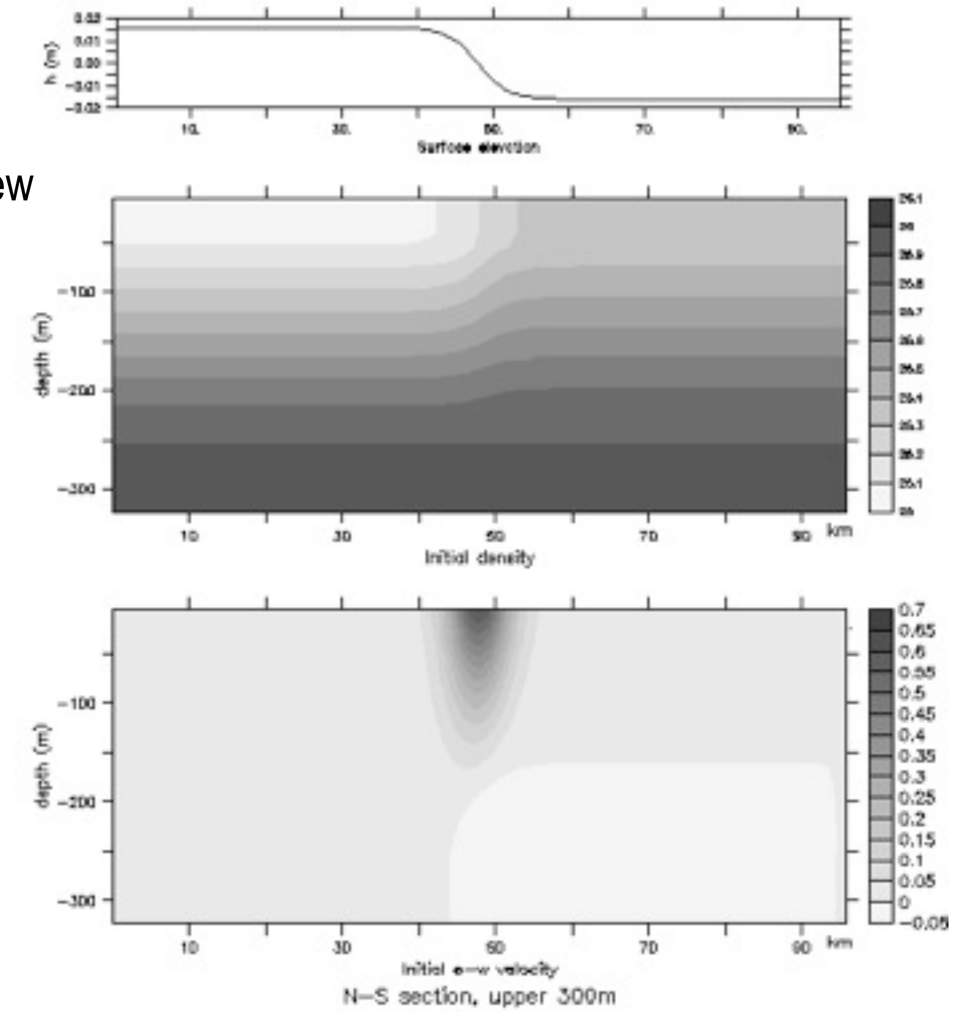
Numerical Modeling
Periodic Channel

Initial Conditions

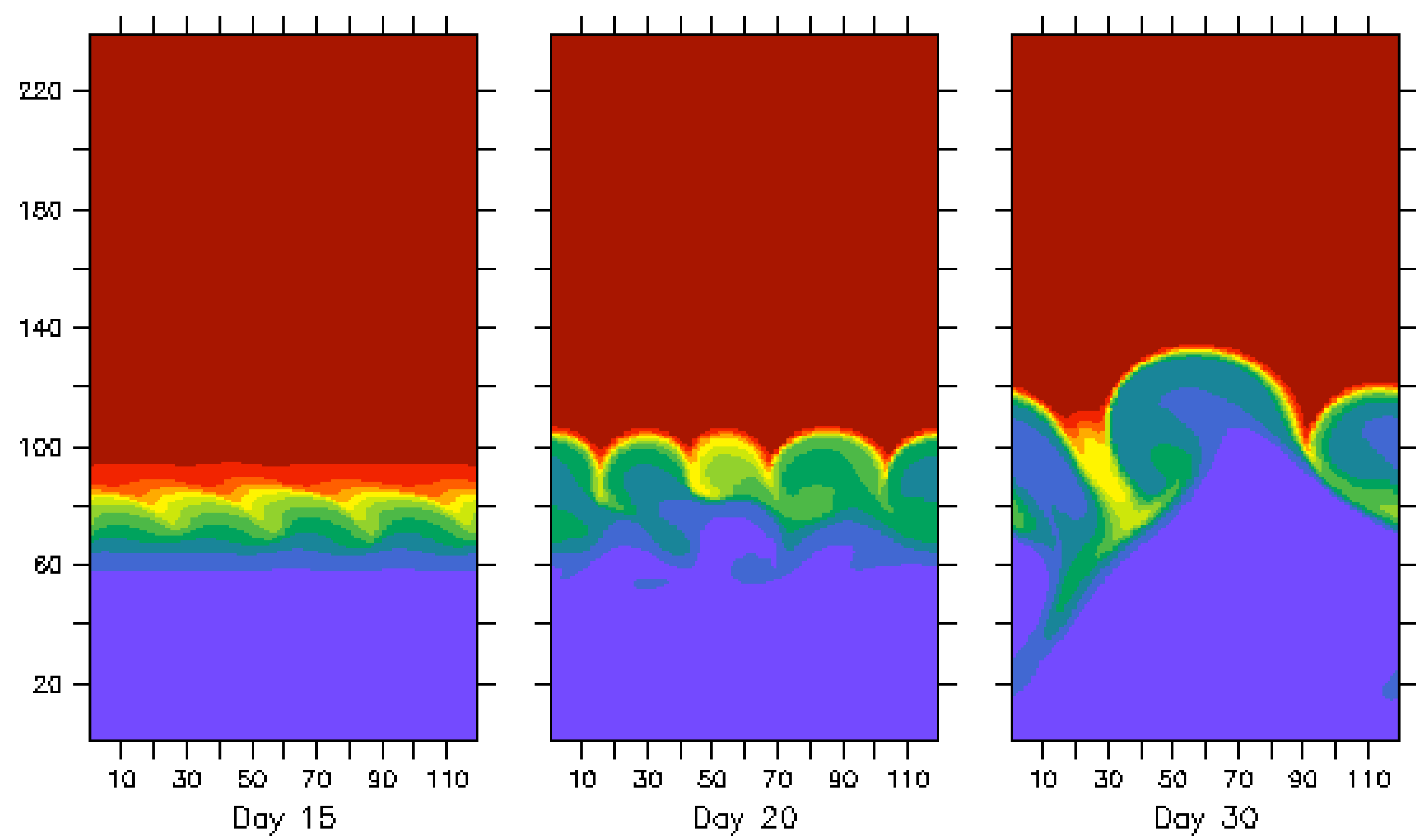
Surface View

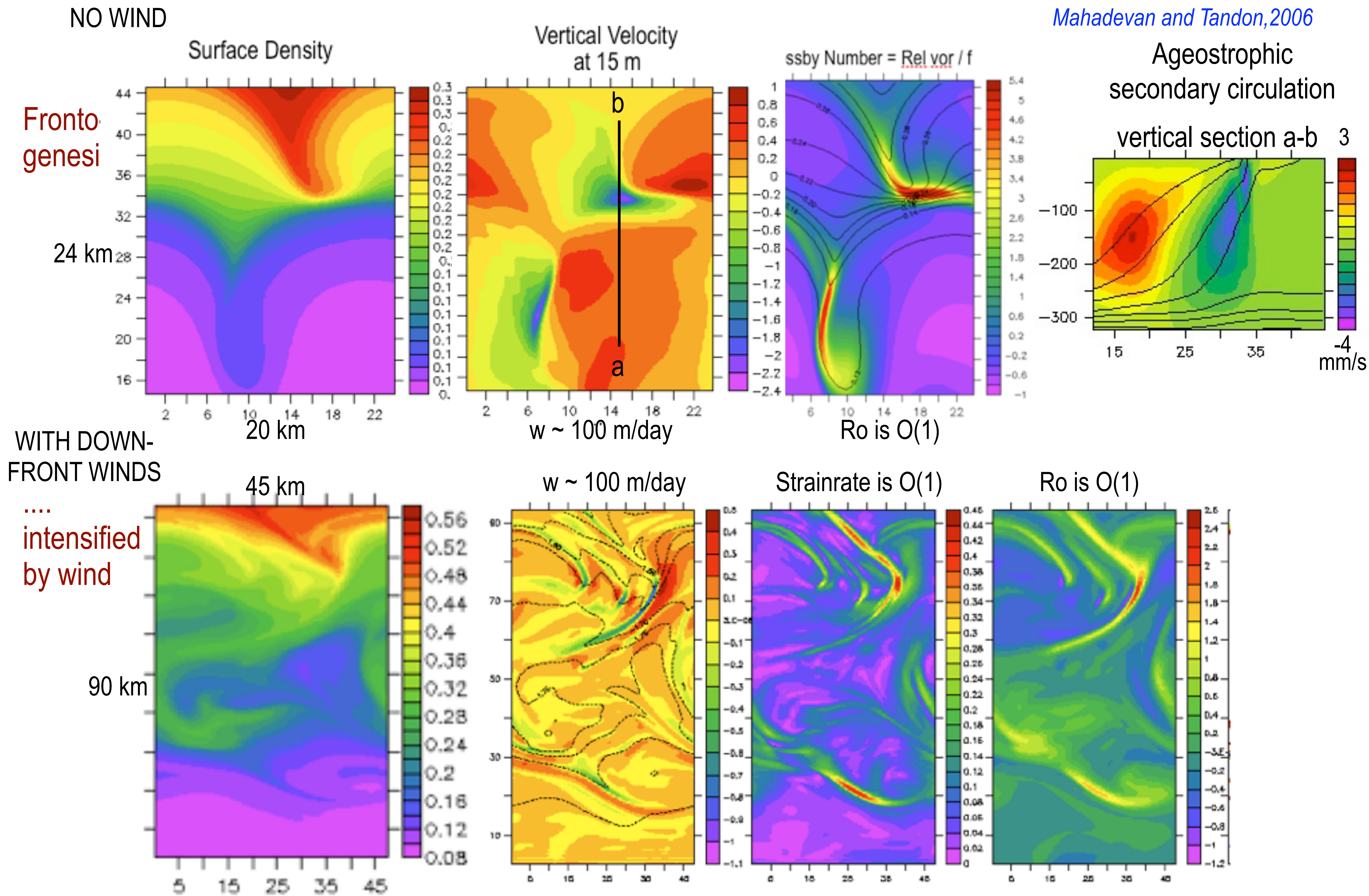


Sectional View



DAYS 15-30





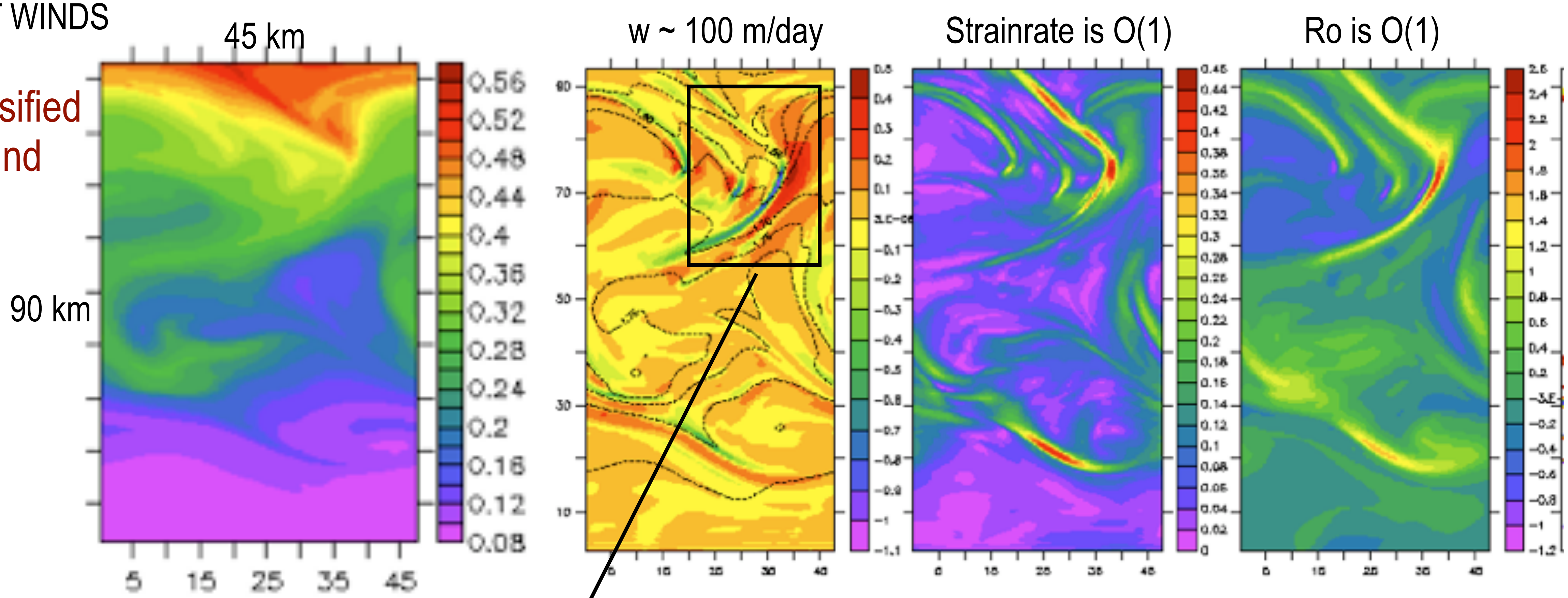
Submesoscale processes: **Large, O(1) Ro, ζ+> ζ-, small O(1) Ri, large lateral strainrate, large w (~100 m/d) in narrow regions**

Wind forced

(Mahadevan and Tandon, 2006)

WITH DOWN-FRONT WINDS

.... intensified by wind

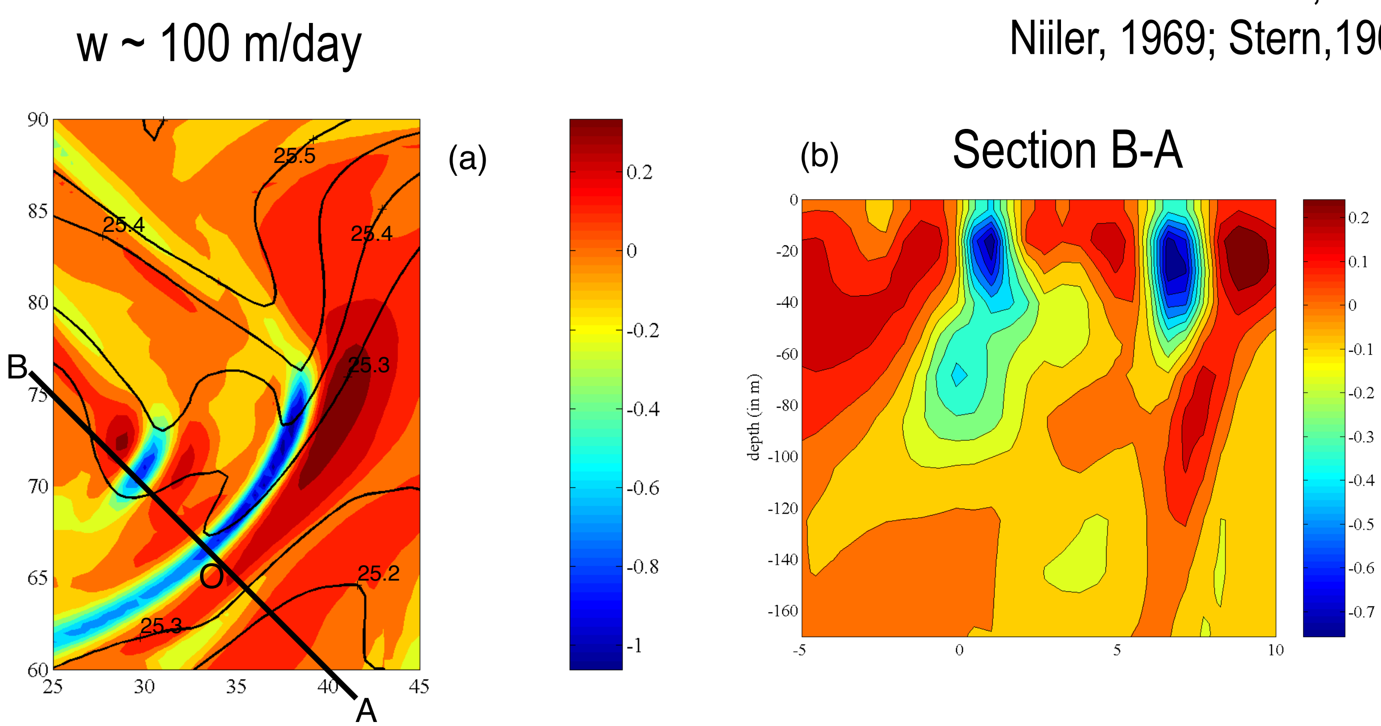


Nonlinear Ekman Effects

Thomas & Rhines, 2002; Niiler, 1969; Stern,1965

$$M_E = \frac{-\tau}{\rho(f+\zeta)}$$

$$\zeta = v_x - u_y$$



$$w_E = \frac{-1}{\rho A}\frac{\partial \tau}{\partial n} + \frac{\tau}{\rho A^2}\frac{\partial \zeta}{\partial n},$$

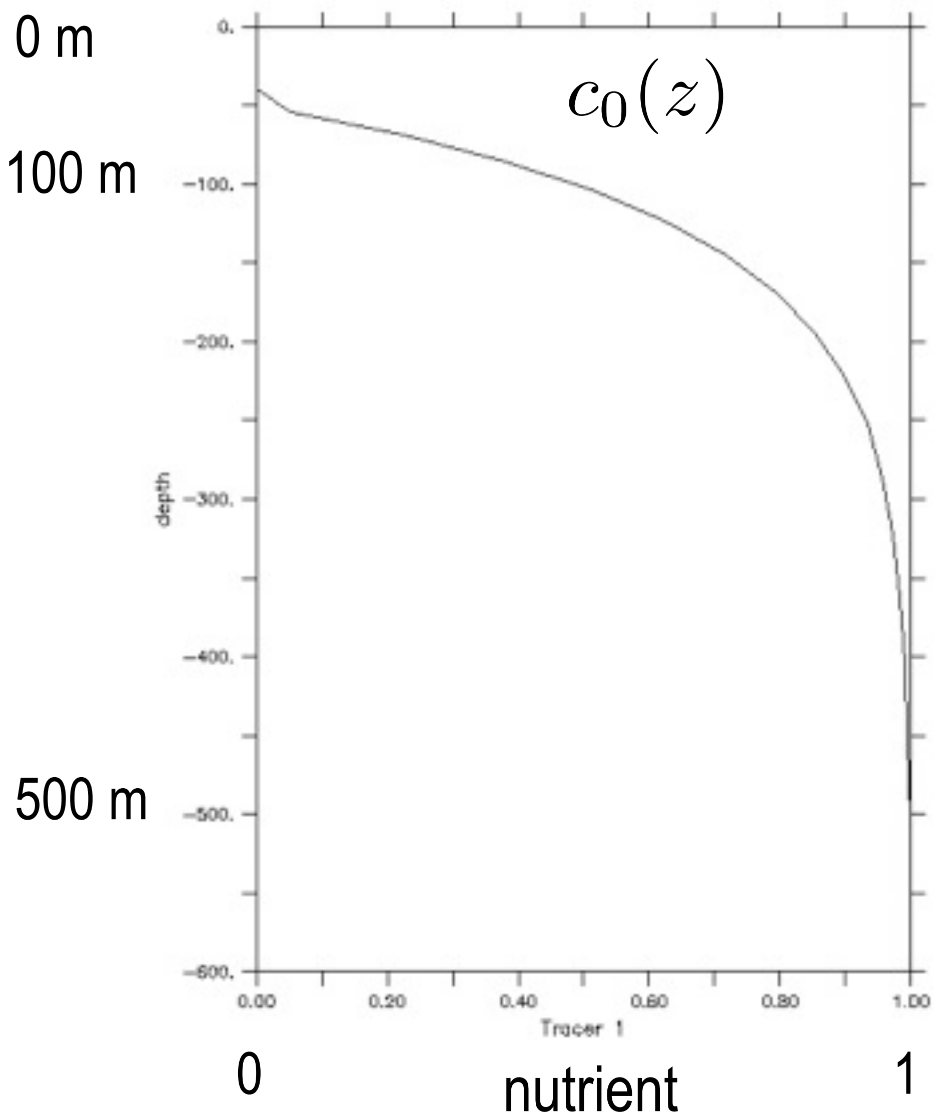
$$A = \zeta + f$$

An (over-simplified) model for nutrient and phytoplankton

The vertical flux of nutrient depends on its rate of uptake

$$\frac{\partial c}{\partial t} + \mathbf{u}_H \cdot \nabla c + w c_z = -\frac{1}{\tau}\left(c - c_0(z)\right)$$

rhs = Consumption of nutrient
= production of phytoplankton



$$\tau = 1, 2, 4, 8, 16, 32 \quad \text{days}$$

$$c' = c - c_0(z)$$

Average horizontally .... and over time

Produc. Rate $$\frac{1}{z_e}\left[\overline{w'c'}\right]_{z_e} = \frac{1}{z_e \tau}\int_{z_e}^{0} \overline{c'} dz$$

$$\text{As } \tau \downarrow, \int \overline{c'} dz \downarrow, \ \overline{w'c'} \uparrow$$

Sensitivity to growth / uptake time scales

$$\frac{\partial c}{\partial t} + \mathbf{u}_H \cdot \nabla c + w c_z = -\frac{1}{\tau}\left(c - c_0(z)\right)$$

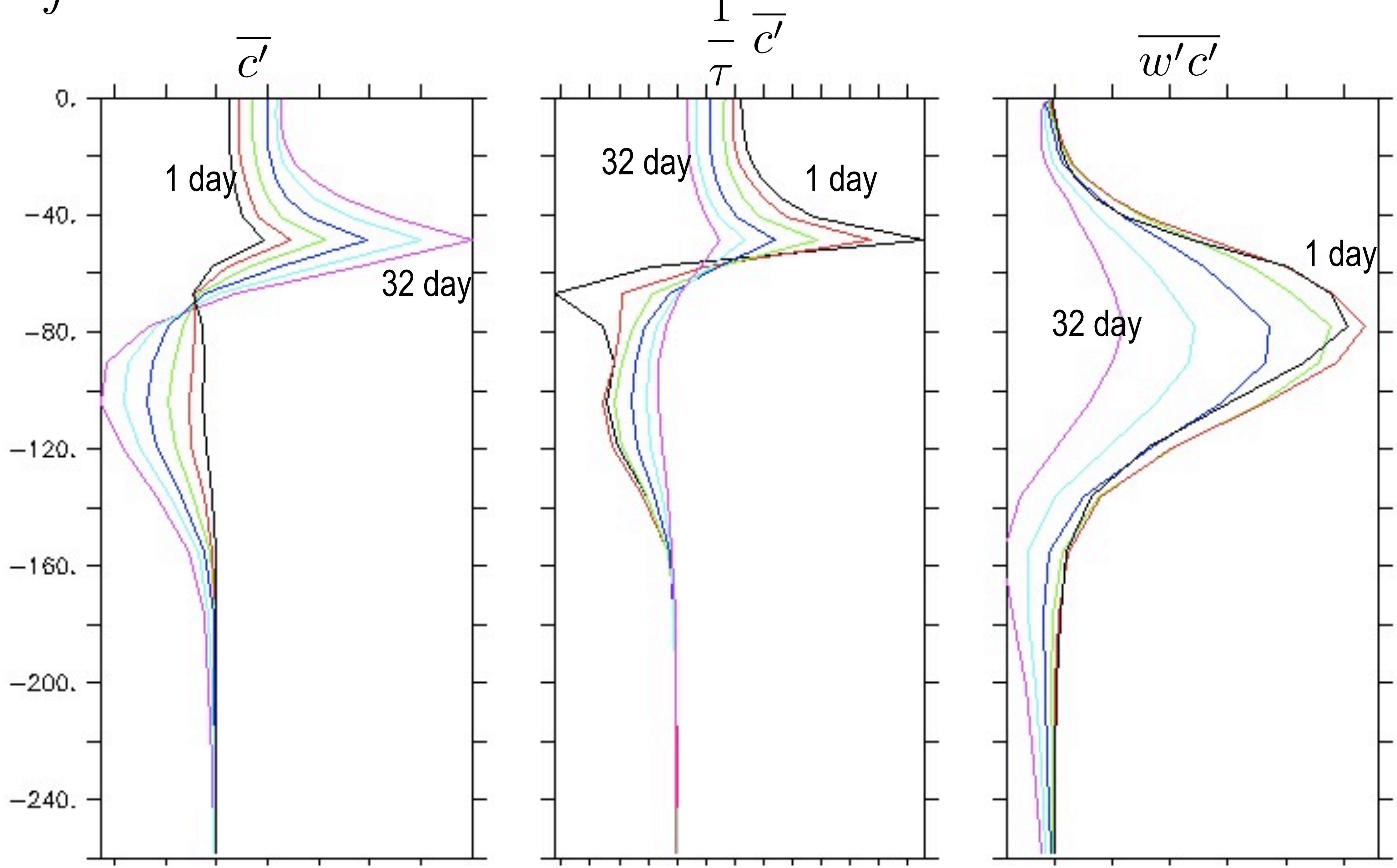
$$c' = c - c_0(z)$$

As $\tau \downarrow, \int \overline{c'} dz \downarrow, \ \overline{w'c'} \uparrow$ **but only up to a point!**

Average horizontally ....

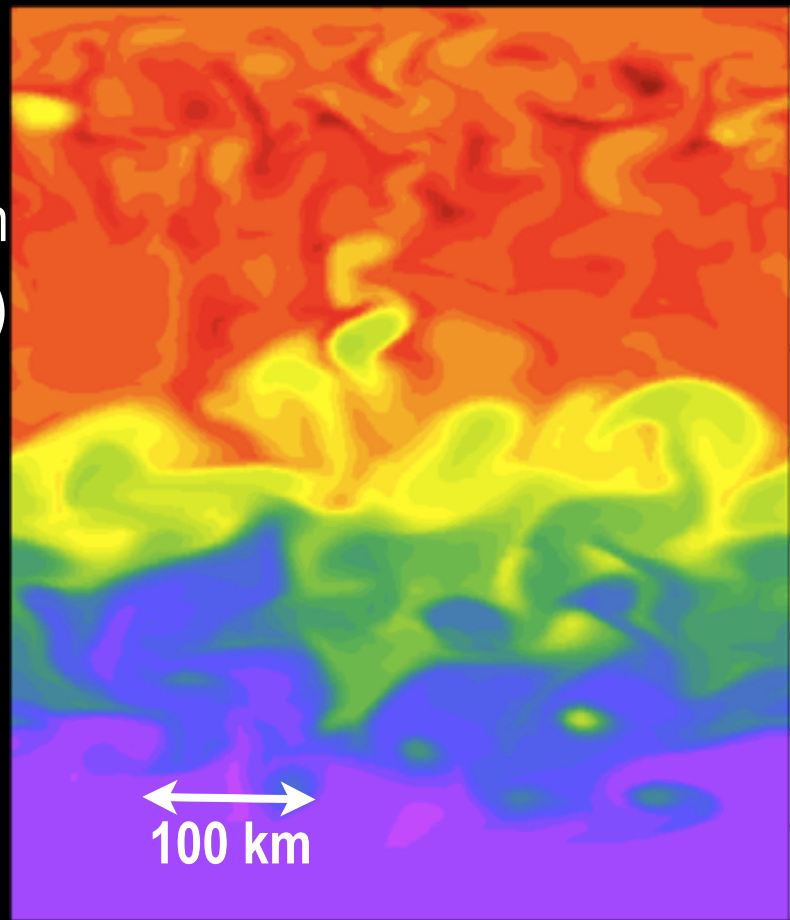
$$\frac{1}{z_e}\left[\overline{w'c'}\right]_{z_e} = \frac{1}{\tau}\int_{z_e}^{h} \overline{c'} dz$$

$$\tau = 1, 2, 4, 8, 16, 32 \quad \text{days}$$

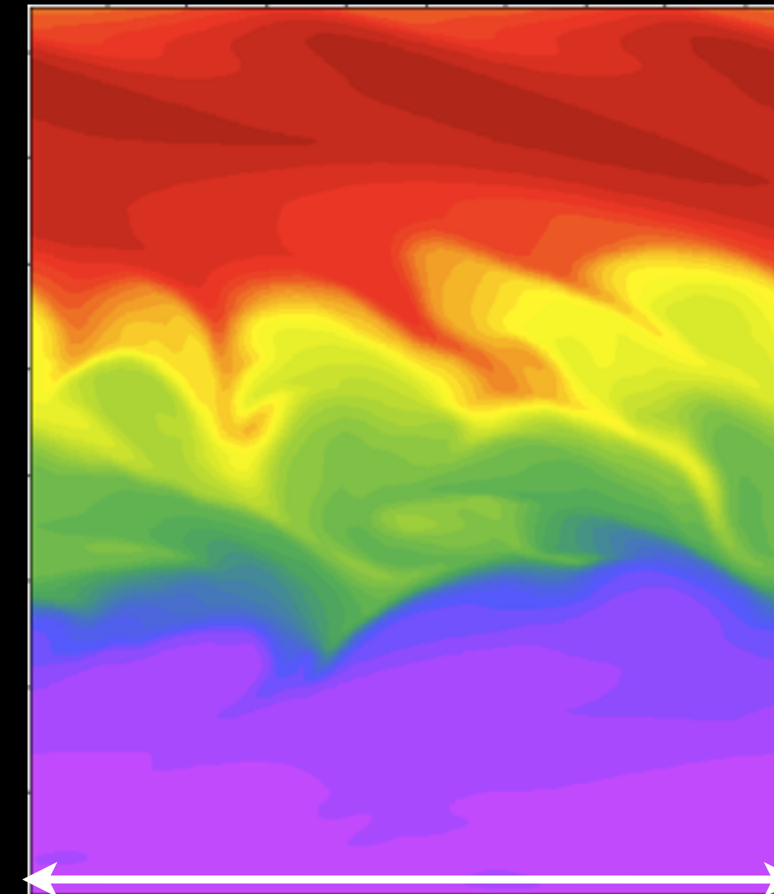


Mesoscale Experiment
480 km x 960 km
(5 km grid resol)

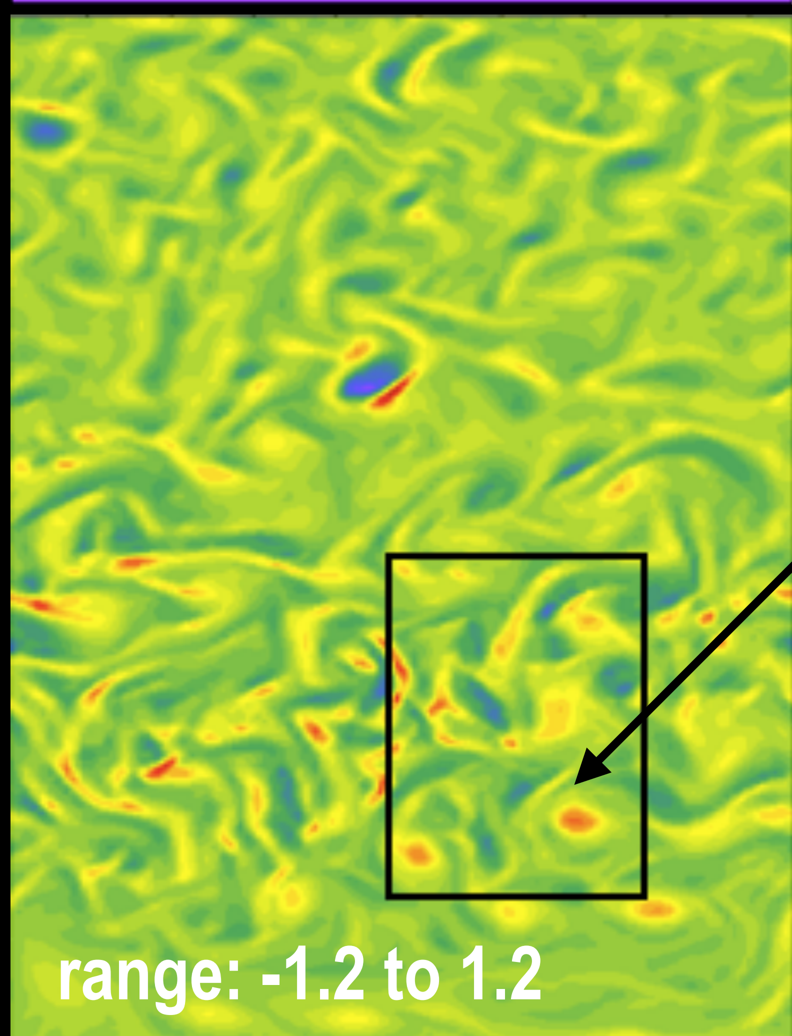
Surface Density

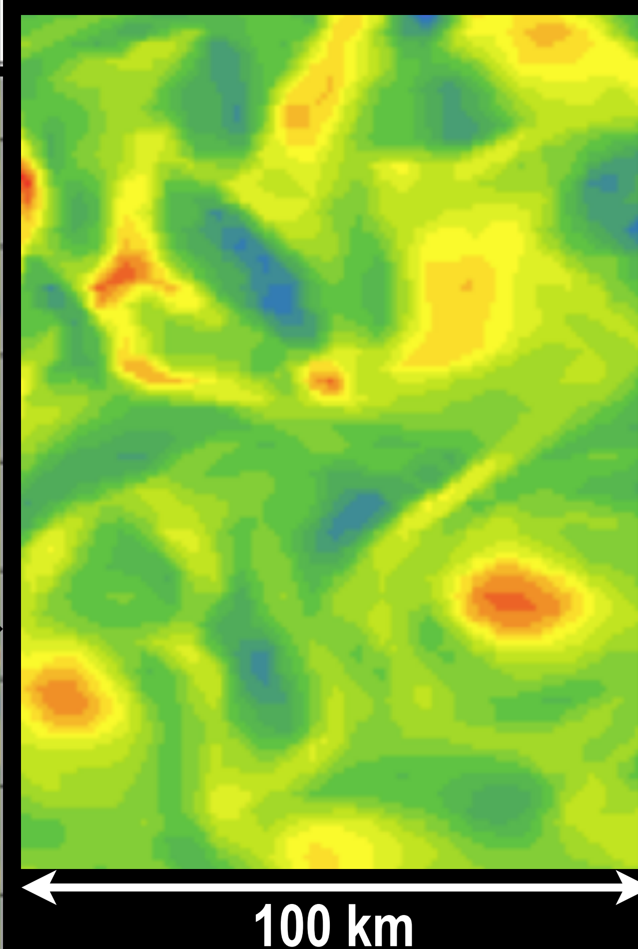


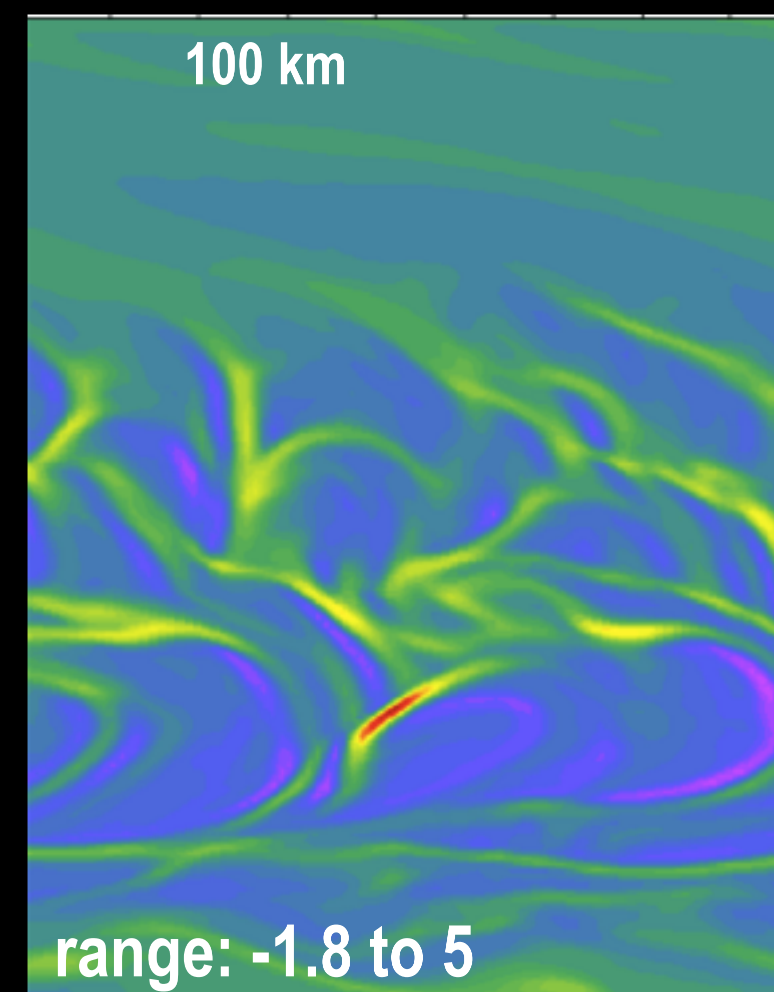
Submesoscale Experiment
96 km x 192 km
(1 km grid resol)



Surface Vorticity/f



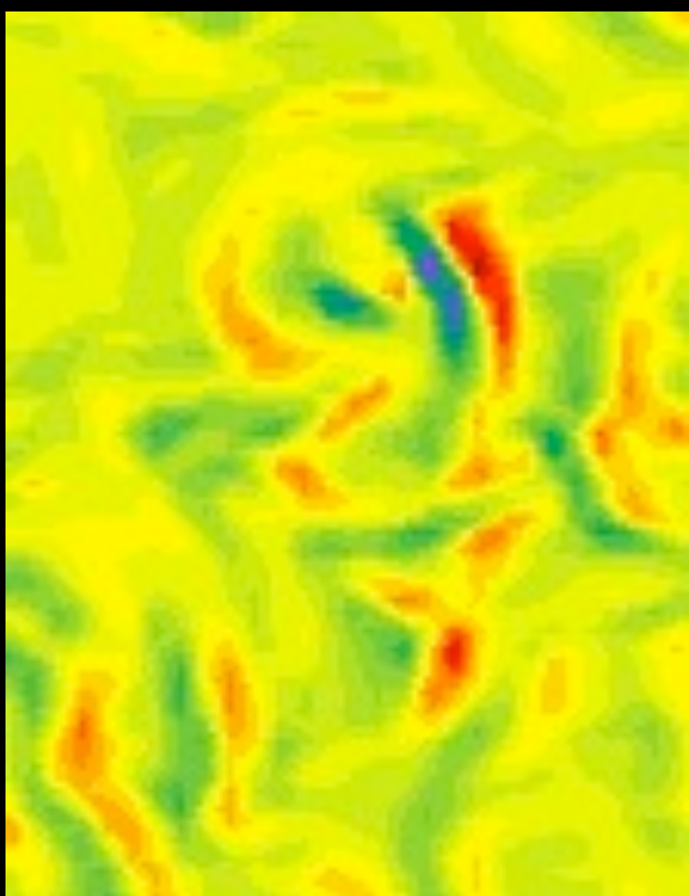




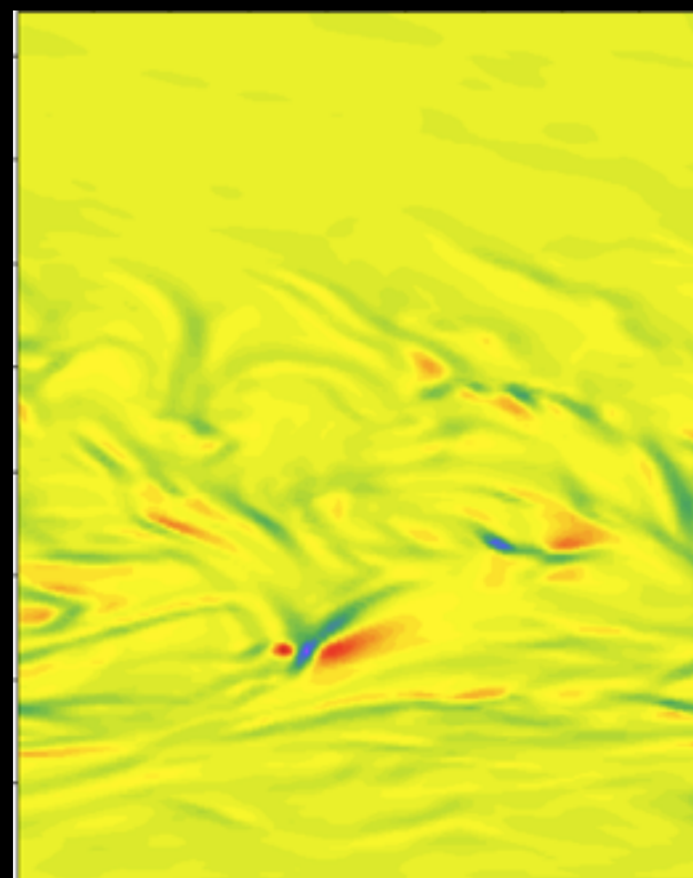
Mesoscale 5 km res   Submesoscale 1 km res.

100x180 km

100 km



100 km

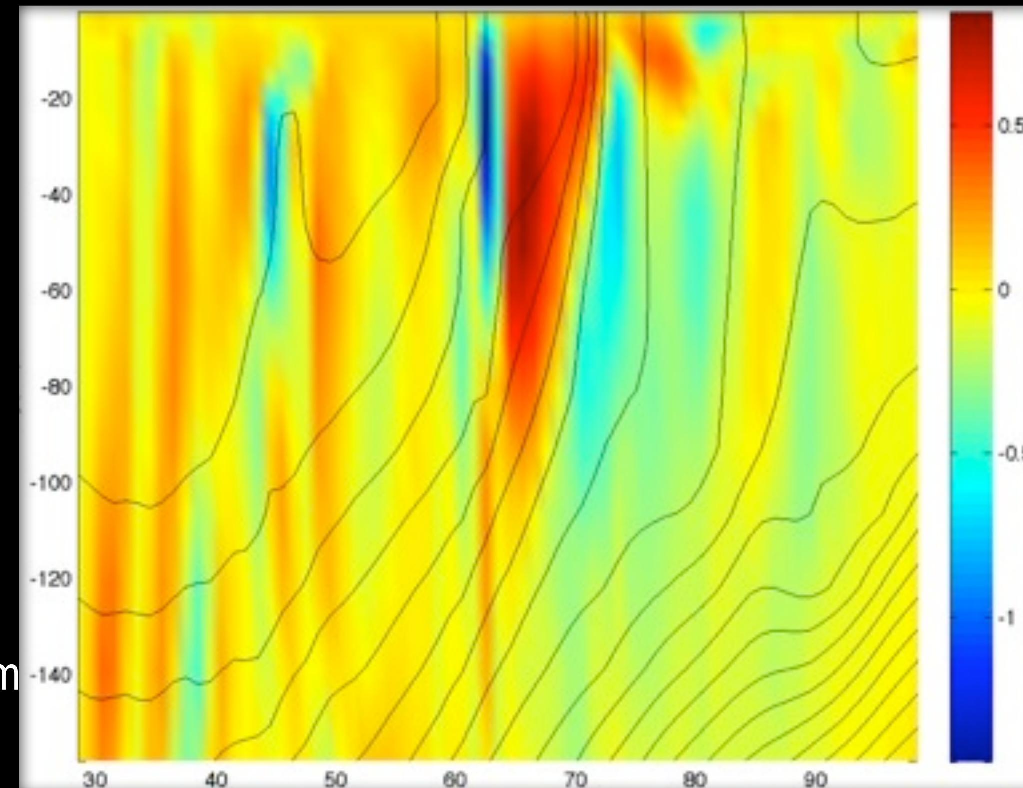


range: -0.75 -- 0.5   range: -2.6 -- 1.7

Vertical velocity at 100 m
in mm/s

vertical section
Vertical velocity

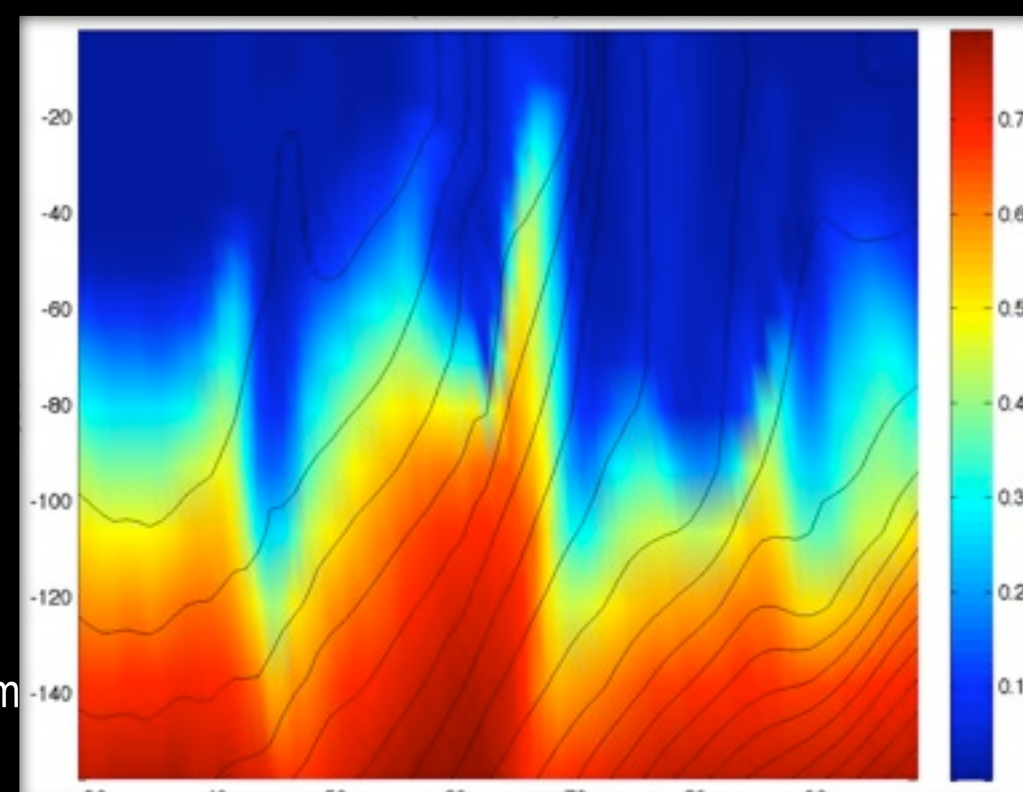
140m



70km

Nutrient

140m

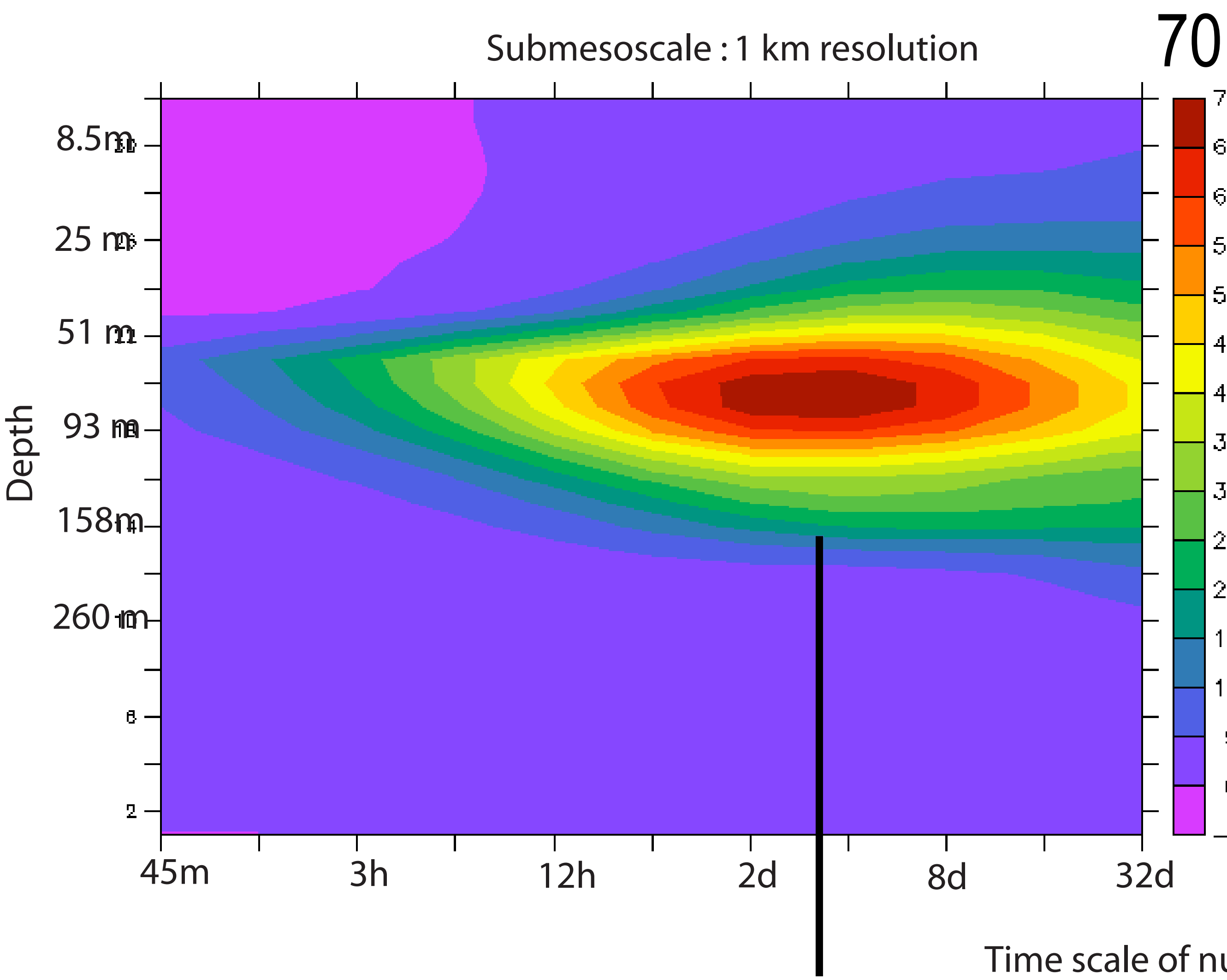


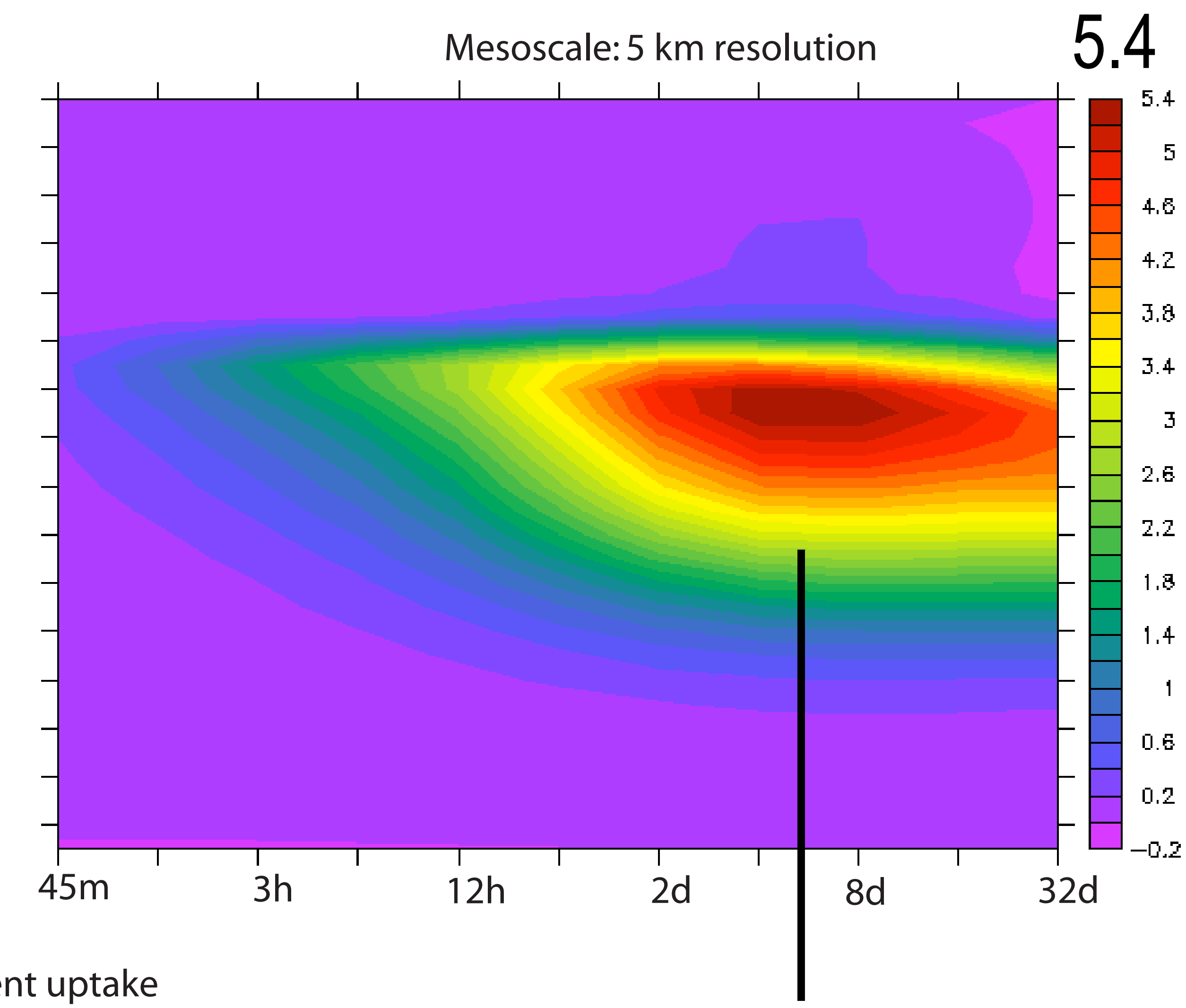
70km

There must be an optimum τ, but it would depend on the characteristics of the flow

$\overline{w'c'}$ Averaged horizontally over the entire domain, but at one instant of time

Submesoscale 1 km res. | Mesoscale 5 km res





Time scale of nutrient uptake

Vertical motion with similar time scales to that of phytoplankton have the most impact on biology.

Time scale of phytoplankton growth ≈ optimum for submesoscale vertical nutrient fluxes!!

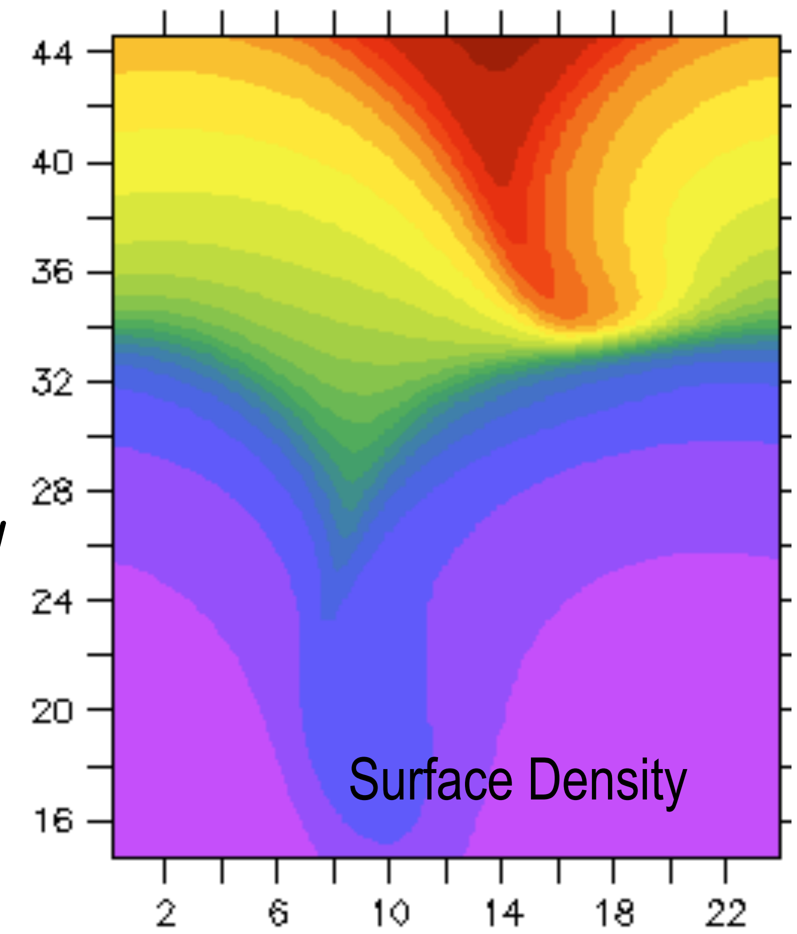
Phytoplankton have adapted to maximize productivity?!

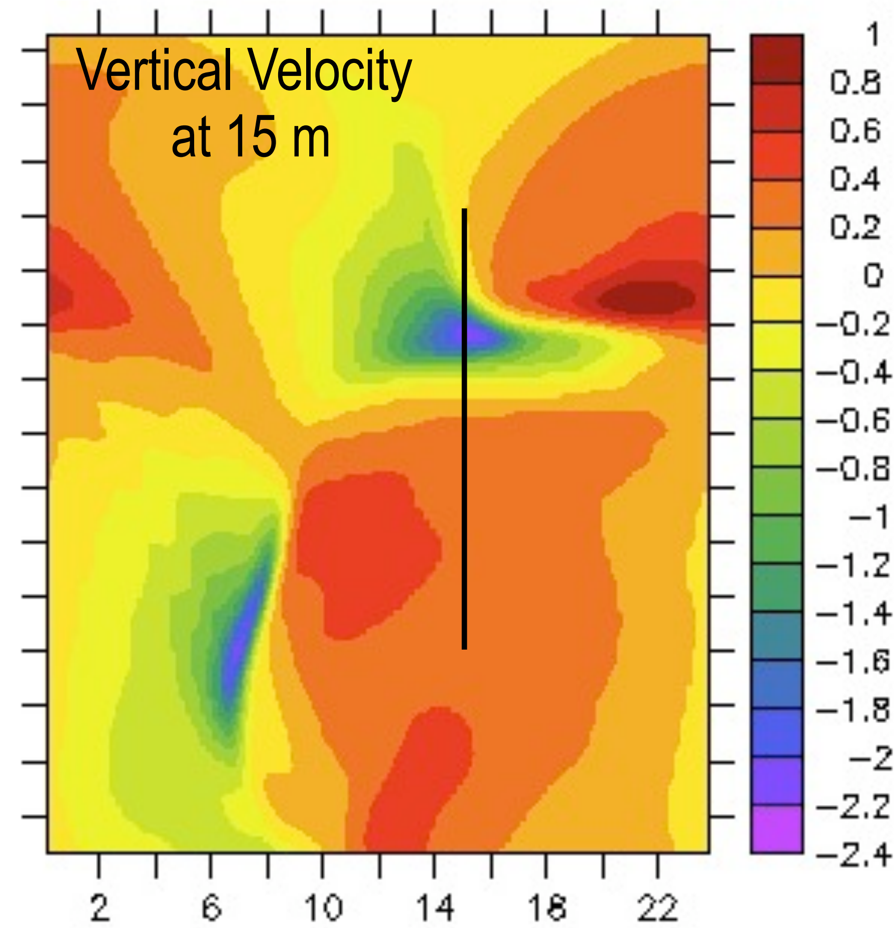
Frontogenesis

$$b = \frac{-g\rho;}{\rho_0}$$

$$u = u_g \qquad f u_{gz} = -b_y$$

$$(v_a, w) = (\psi_z, -\psi_y)$$

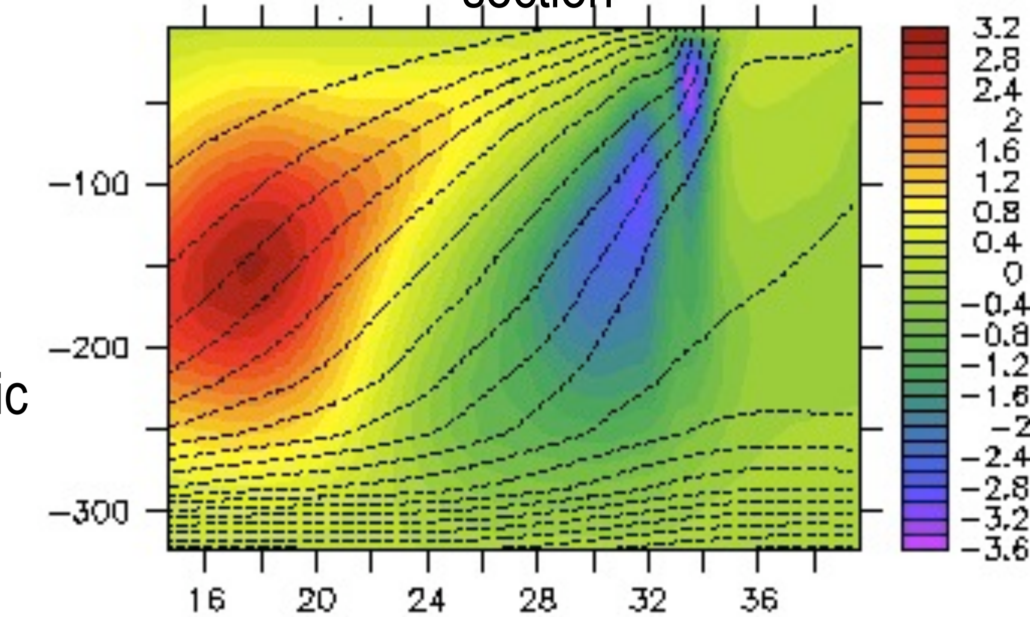




$$\frac{Db}{Dt} = 0; \frac{D}{Dt} b_y = -u_y b_x - v_y b_y = Q_2$$

$$D_g u_g - f v_a = 0; \qquad D_g b + N^2 w = 0$$

section

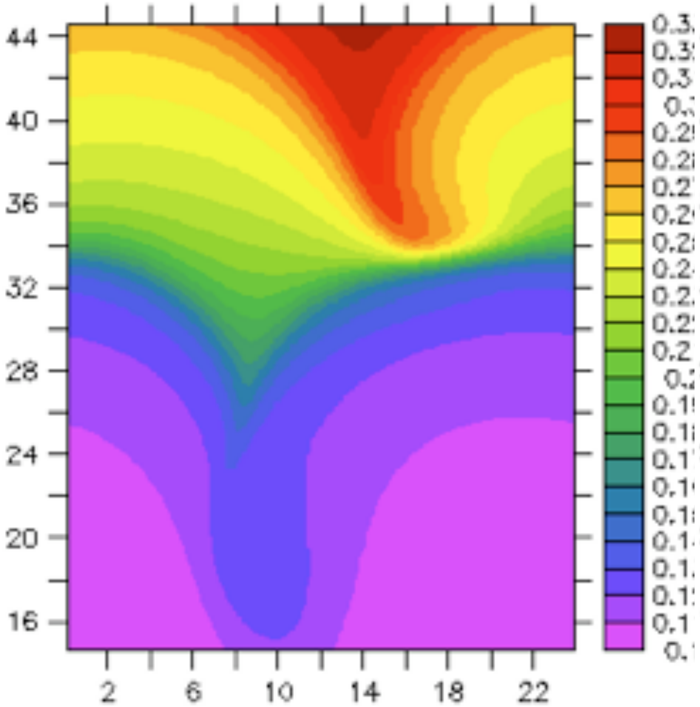


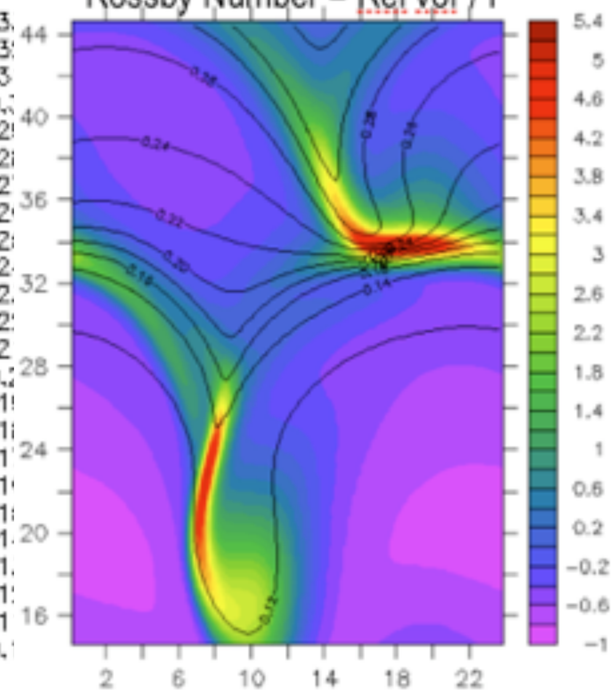
Ageostrophic secondary circulation

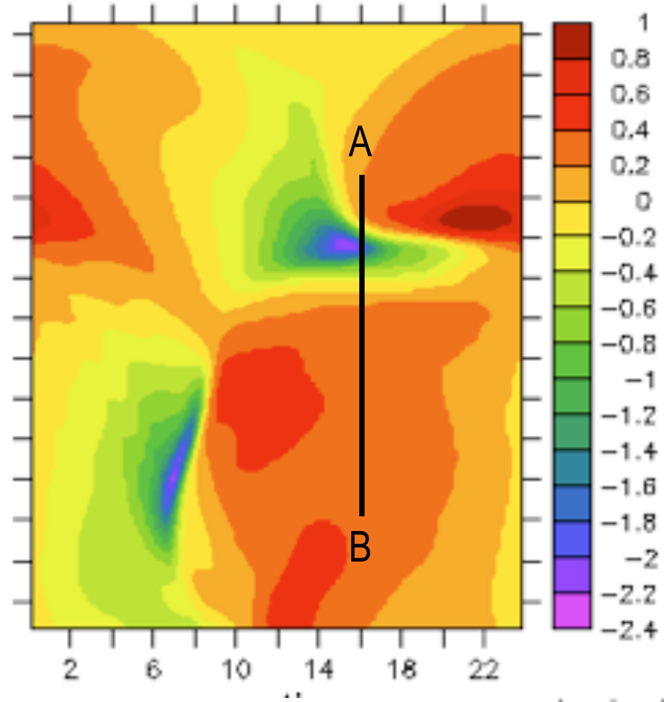
$$N^2 w_y - f^2 v_{az} = Q_2$$

QG: $$N^2 \psi_{yy} + f^2 \psi_{zz} = -Q_2$$

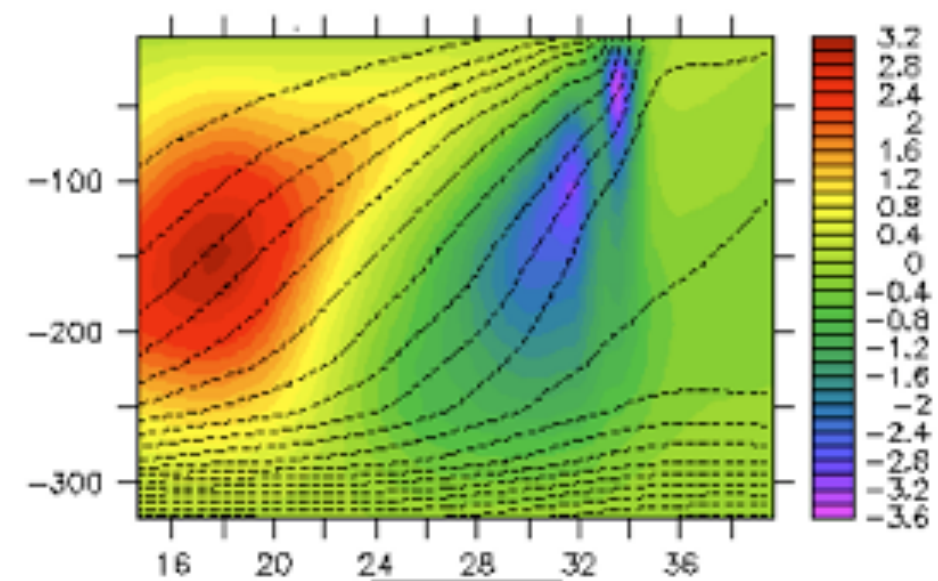
A closer look at a single feature







Frontogenesis



A simpler model for circulation in the vertical plane

Semi-geostrophic: higher order in Ro

$$b = \frac{-g\rho;}{\rho_0}$$

$$F_2^2 \frac{\partial^2 \psi}{\partial z^2} + 2S_2^2 \frac{\partial^2 \psi}{\partial z \partial y} + N^2 \frac{\partial^2 \psi}{\partial y^2} = -2Q_2^g,$$

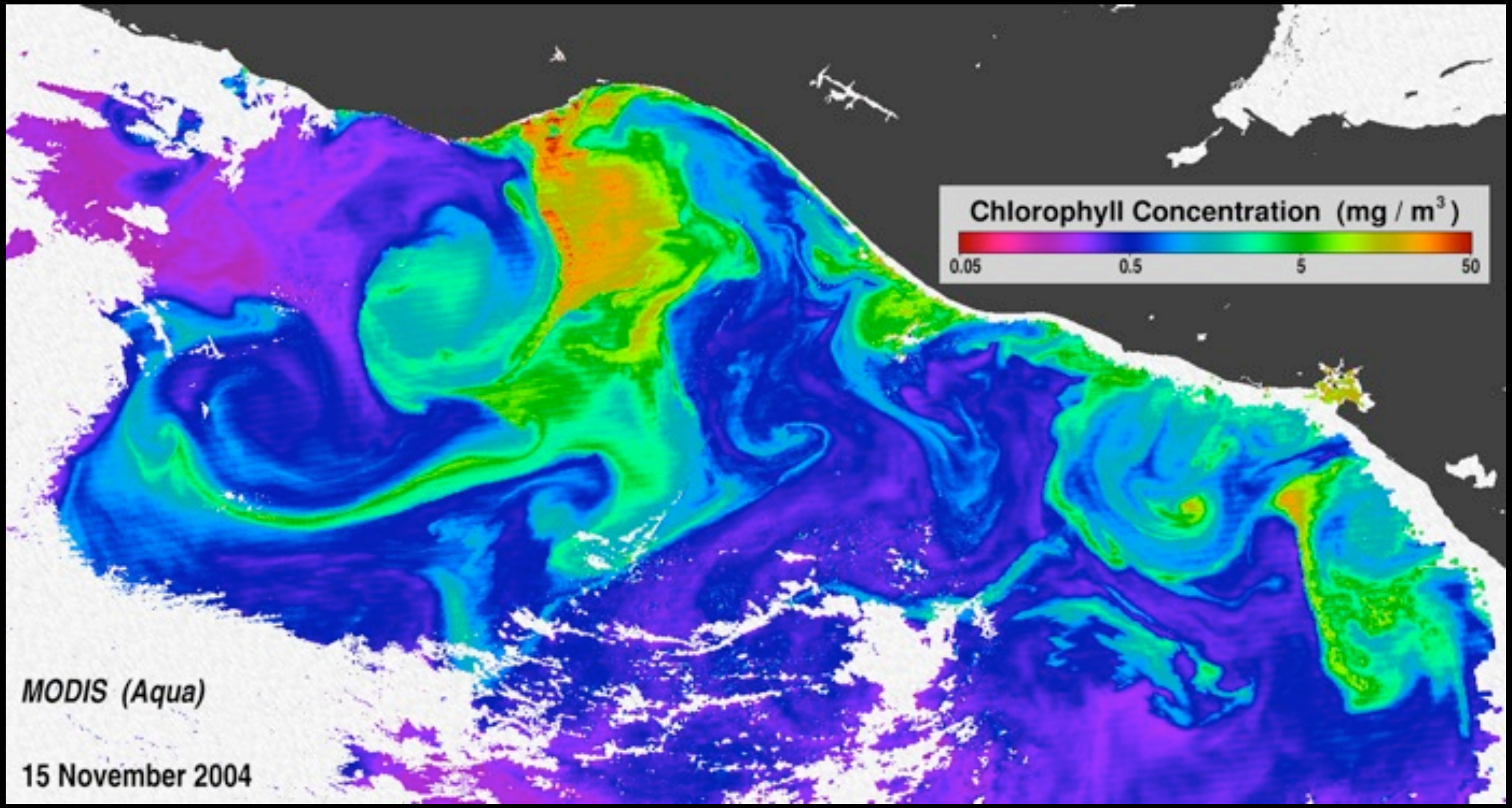
$$\text{where } N^2 = b_z,\ S_2^2 = -b_y = f u_{gz},\ F_2^2 = f(f - u_{gy})$$

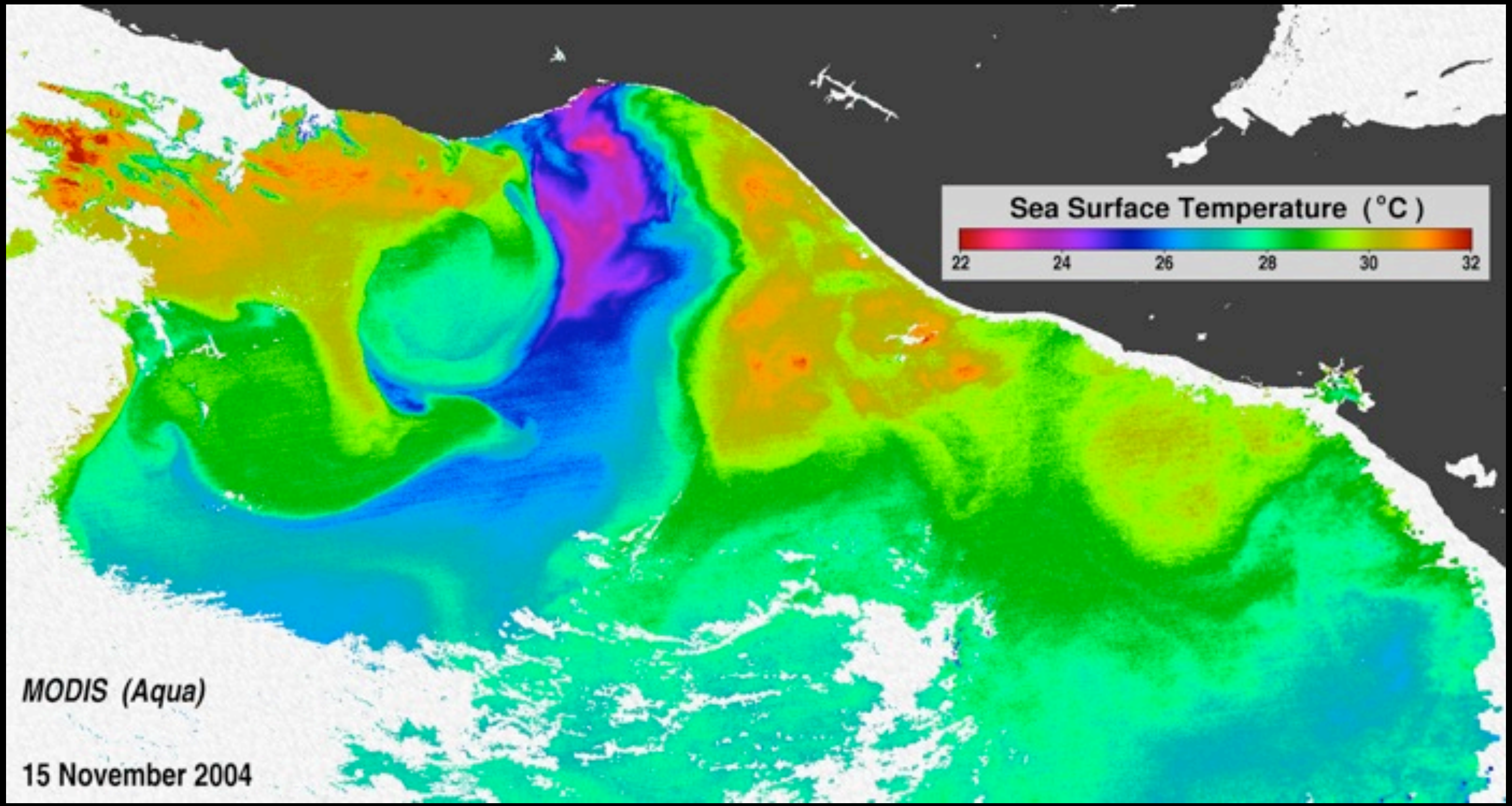
$$\text{Potential vorticity} \quad = \quad q_{2D} = \frac{1}{f}(F_2^2 N^2 - S_2^4)$$

< generally positive, but when it changes sign, this is not solvable

Loss of balance -- leads to vertical motion and mixing.

$$\mathbf{Q}^g = (Q_1^g, Q_2^g) = \left(-\frac{\partial \mathbf{u}_g}{\partial x} \cdot \nabla b, -\frac{\partial \mathbf{u}_g}{\partial y} \cdot \nabla b\right)$$





Distribution of phytoplankton responds to vertical or lateral advection?