The Abdus Salam
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Educational, Scientific and
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IAEA
International Atomic Energy Agency

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Ocean biological productivity and climate change - part 1

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U K

Ocean biological productivity and climate change

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Lecture 1: basin scale view

- Background state
- High latitude productivity

Lecture 2: subtropical gyres

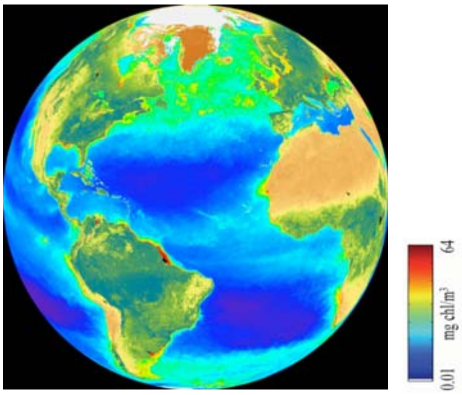
- Mid latitude productivity
- Eddy transfers

Lecture 3: boundary currents

- Barriers/blenders
- Eddy lifecycles

Lecture 4: Climate change

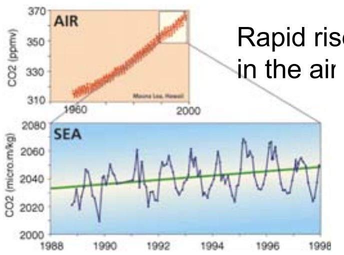
- Heat content changes in the N. Atlantic
- Ocean overturning



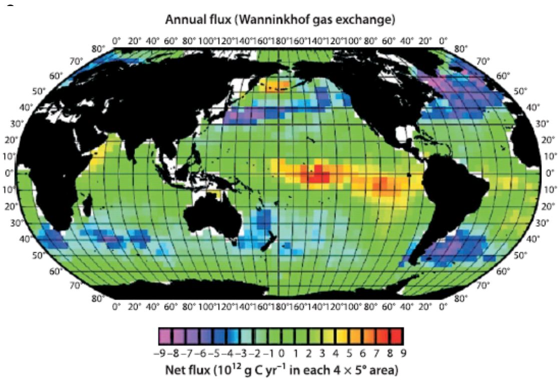
False colour picture of chlorophyll concentration

September 97 - August 98, SeaWIFS, NASA

Why study this topic?



Rapid rise in $[CO_2]$ in the air



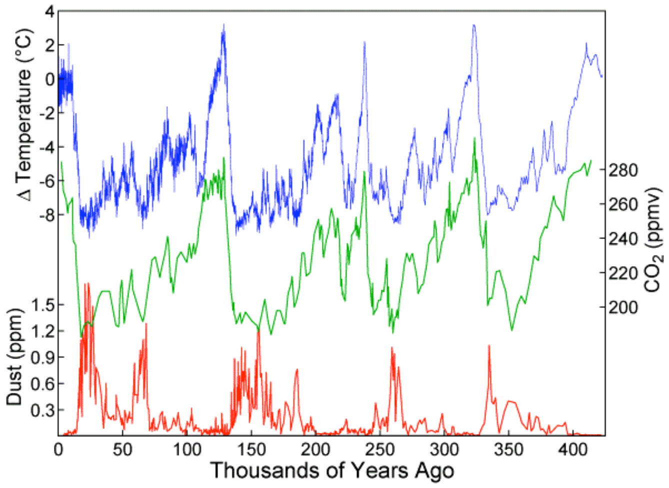
Air-sea flux of CO_2 (mol Cm^{-2}y^{-1}, outgassing, shaded) based on Takahashi et al. (2002) using Wanninkhof (1992) gas exchange coefficient. See Watson and Orr (2003)

- Anthropogenic increase in CO_2
- Air-sea exchange of CO_2

  — physical transfer to deep ocean

  — biological transfer

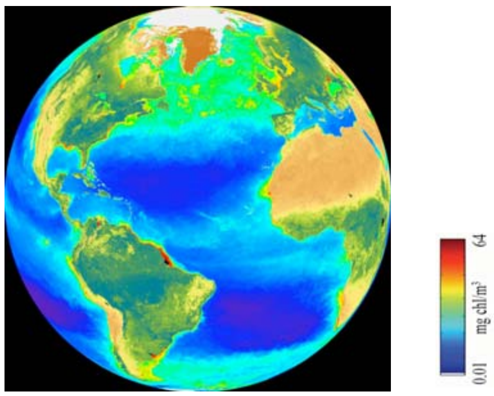
Atmospheric T, pCO_2 & dust over the last 400 000y at Vostok



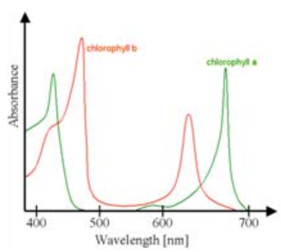
- Glacial-interglacial cycles in atmospheric CO_2
- No consensus as to controlling processes, but probably require changes in biological drawdown of CO_2

Chlorophyll concentration

September 97 - August 98, SeaWIFS, NASA



False colour picture of chlorophyll concentration (green pigment enabling photosynthesis, absorbs strongly in blue & red light)

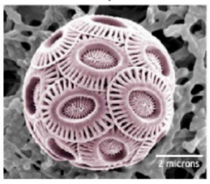


Micrographs of phytoplankton: coccolithophore (use Calcium)

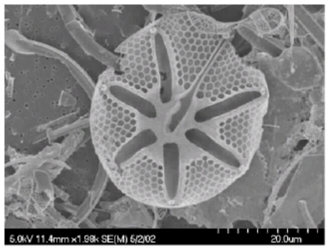
Diatoms (require silica)

Prochloroccus (small size)

coccolithophore



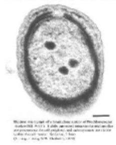
4 µm



20 µm

diatom

Prochlorococcus



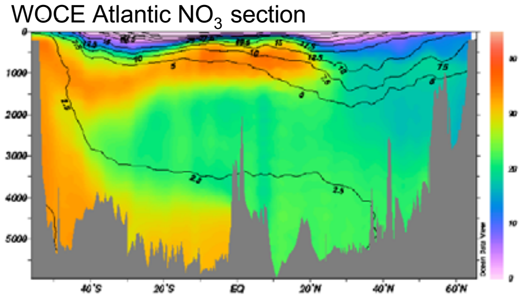
0.5 µm

$$106CO_2 + 16NO_3^- + H_2PO_4^- + 122H_2O + Xh\nu \rightleftharpoons C_{106}H_{263}O_{110}N_{16}P + 138O_2$$

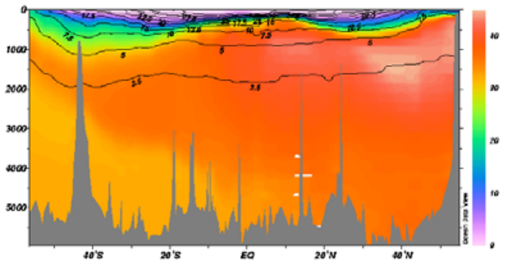
1. How is the background state determined?

- Why are nutrient concentrations greater at depth?
- Why are there basin contrasts?
- How does the thermocline/nutricline vary?
- Why are there extensive regions of low productivity?

WOCE Atlantic NO_3 section



WOCE Pacific NO_3 section



1.1 Why are nutrient concentrations greater at depth?

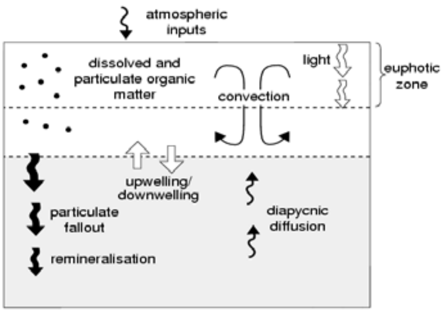
In surface sunlit zone, phytoplankton form with C: N: P ratios of 106:16:1 — need to supply N & P

• inorganic nutrients converted into organic matter

• gravitational fallout of organic matter

In ocean interior

• conversion of organic matter back to inorganic nutrients



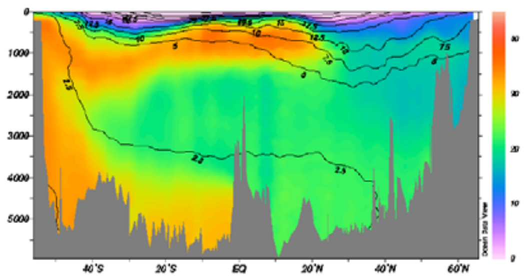
Traditional vertical view

$$\frac{\partial N}{\partial t} + w\frac{\partial N}{\partial z} = S + \frac{\partial}{\partial z}\kappa\frac{\partial N}{\partial z}$$

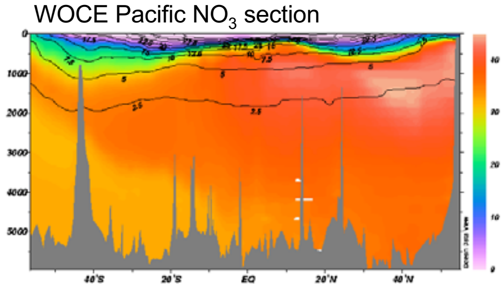
upwelling | diffusion
inorganic/organic conversions

1.2 Why are the nutrient concentrations in the ocean basins different?

WOCE Atlantic NO_3 section



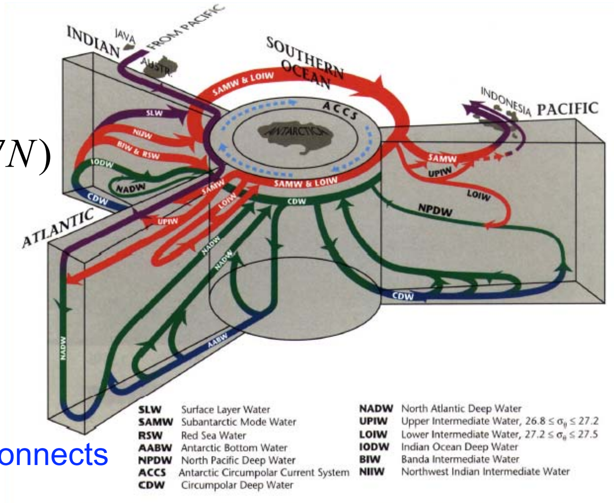
WOCE Pacific NO_3 section



Water-mass pathway view of the global circulation

$$u.\nabla N = S + \nabla.(\kappa \nabla N)$$

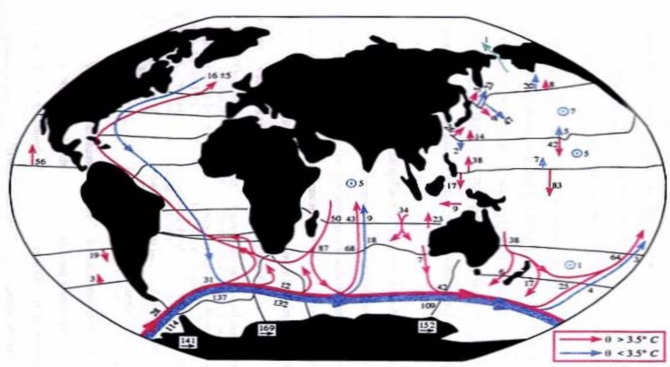
Overturning circulation



- Southern Ocean connects all the basins
- Overturning cells in each basin

Schmitz (1996)

Inverse-model view of the global circulation



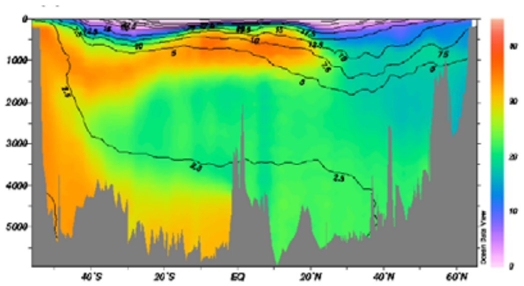
- Atlantic northwards heat flux
- S. Ocean connects basins
- Recirculations

Macdonald and Wunsch (1996) inversion

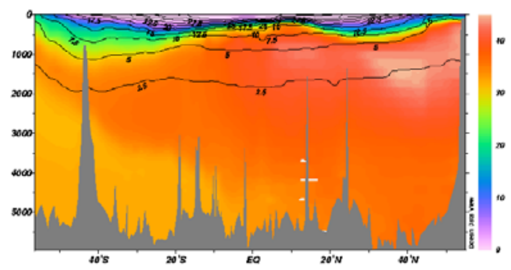
Volume flux of warm & cold water

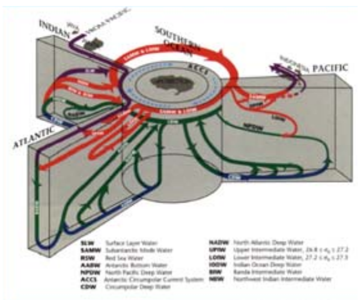
- Continual fallout of organic nutrients
- Remineralisation at depth
- Greater inorganic nutrient concentrations in `older' waters

WOCE Atlantic NO_3 section

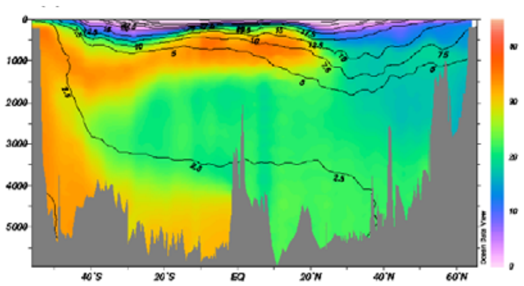


WOCE Pacific NO_3 section

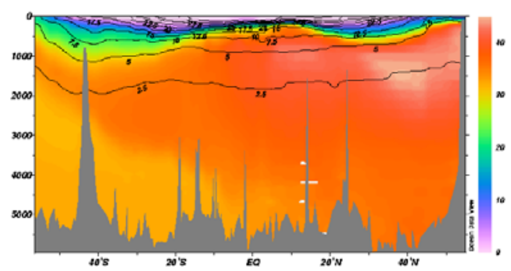




WOCE Atlantic NO_3 section



WOCE Pacific NO_3 section



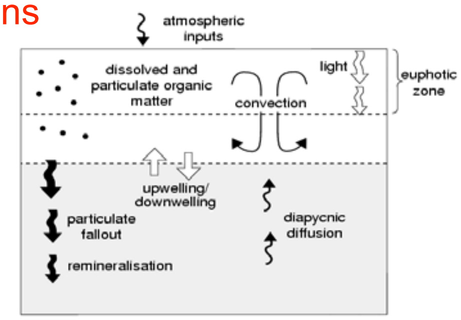
- **Surface nutrient concentrations higher in S. Ocean**
- **Higher nutrient concentrations in basins ventilated from S. Ocean**

1.3 Regional-scale variations

Traditional vertical view

$$\frac{\partial N}{\partial t} + w\frac{\partial N}{\partial z} = S + \frac{\partial}{\partial z}\kappa\frac{\partial N}{\partial z}$$

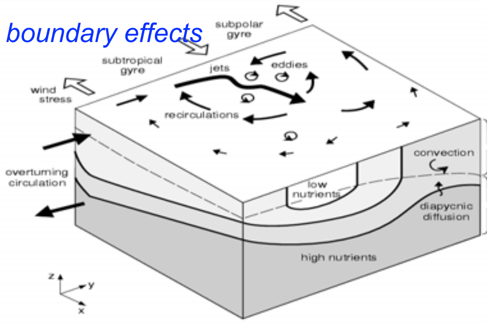
upwelling | inorganic/organic conversions | diffusion

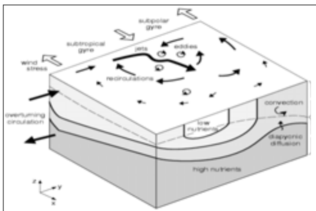


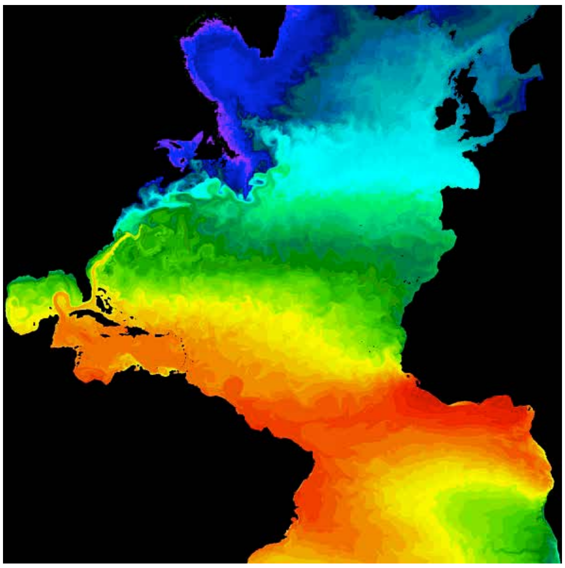
Need to include full 3-D gyre and boundary effects

$$\frac{\partial N}{\partial t} + u\ .\nabla N = S + \nabla.(\kappa\nabla N)$$

Together with rectification of time-varying fine scales

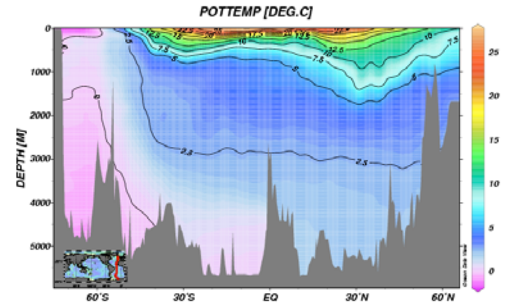


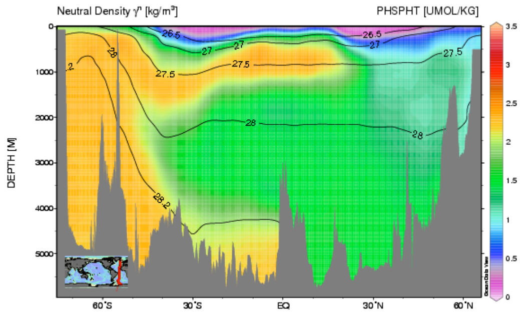


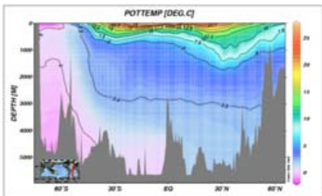


Miami Isopycnic Circulation Model: surface temperature

1.4 How does the thermocline & nutricline vary?







Why is there a thermocline?

Traditional vertical view

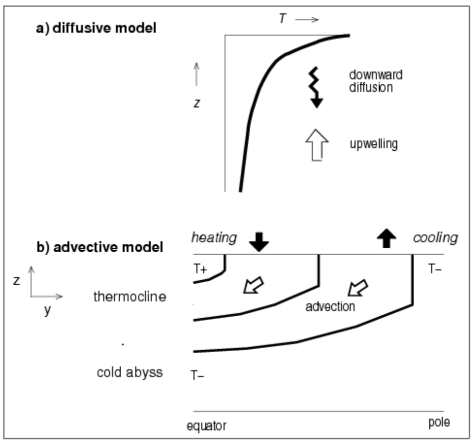
a) diffusion

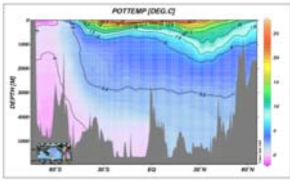
$$w\frac{\partial T}{\partial z} = \frac{\partial}{\partial z}\kappa\frac{\partial T}{\partial z}$$

b) ventilation

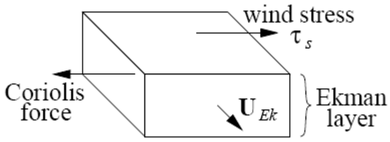
$$u\,.\nabla T = 0$$ in interior

tilting of surface *T* contrasts into the vertical





Why does the thermocline vary?



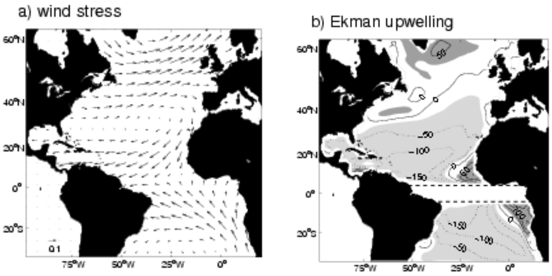
Wind stress drives a horizontal Ekman volume flux (to the right when f>0)

$$U_{ek} = \frac{\tau_y^s}{\rho f} \qquad V_{ek} = -\frac{\tau_x^s}{\rho f} \qquad w_{ek} = \frac{\partial U_{ek}}{\partial x} + \frac{\partial V_{ek}}{\partial y}$$

Upwelling from horizontal divergence of Ekman volume flux

a) wind stress

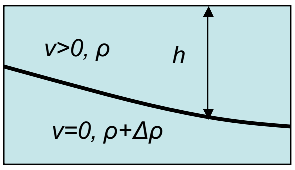
b) Ekman upwelling



f is Coriolis paramater, w_{ek} is Ekman upwelling

One and half layer model

Consider a single moving layer of fluid over a motionless deep ocean



geostrophy $$v = \frac{g'}{f}\frac{\partial h}{\partial x} \qquad u = -\frac{g'}{f}\frac{\partial h}{\partial y} \qquad (1)$$

g' is reduced gravity, β=df/dy,

Sverdrup balance $$\beta v h = f w_{ek} \qquad (2)$$

Polewards transport

Vertical upwelling from curl of wind

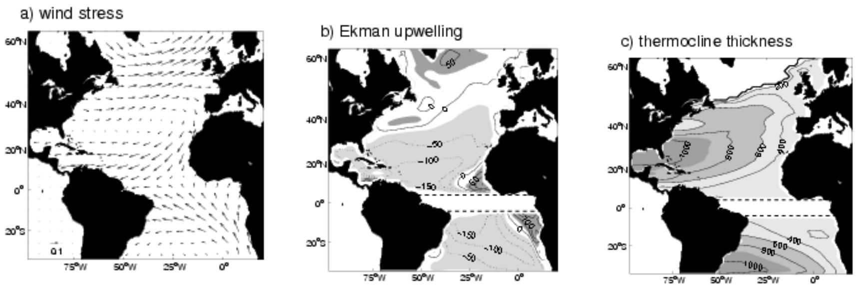
Combining (1) & (2)

$$\frac{\partial h^2}{\partial x} = \frac{2f^2}{\beta g'} w_{ek}$$

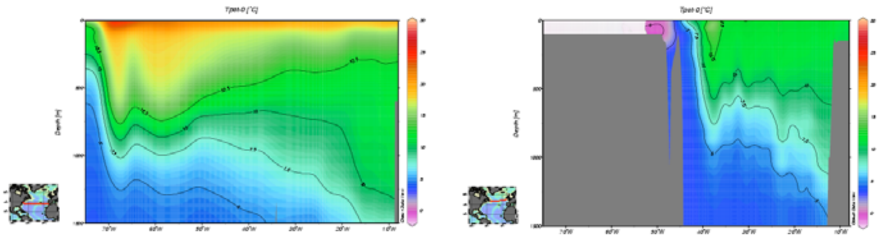
Integrating from eastern boundary

$$h^2(x,y) = h_e^2 - \frac{2f^2}{\beta g'}\int_x^{x_e} w_{ek}\,dx$$

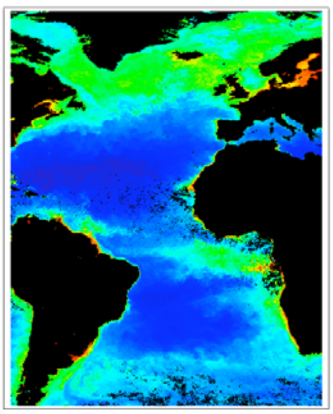
One and half layer model of the thermocline

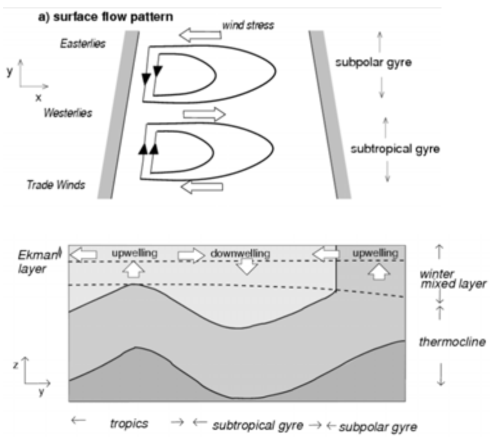


Observations of the thermocline



1.5 How does the surface chlorophyll vary?



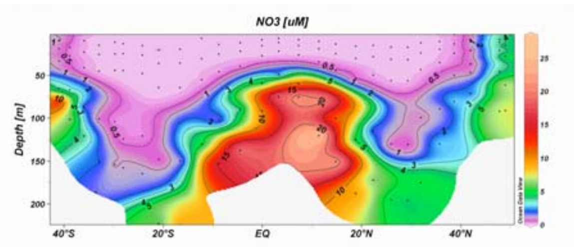


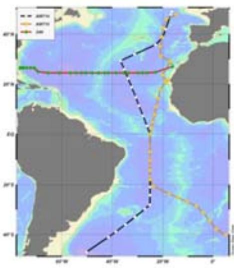
High concentrations of chlorophyll in tropics and subpolar gyre

Low concentrations of chlorophyll in subtropical gyre

Why are there extensive regions of low producitivity?

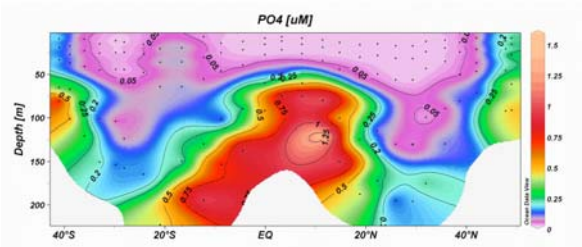
NO_3





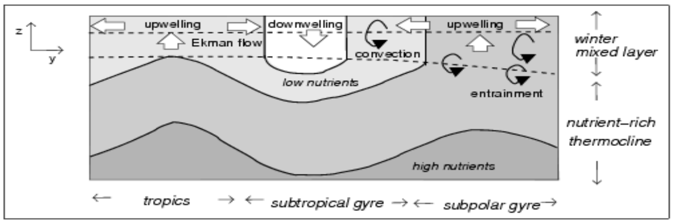
AMT14 April-June 2004

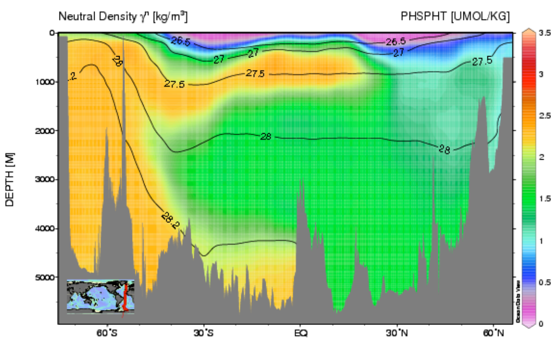
PO_4



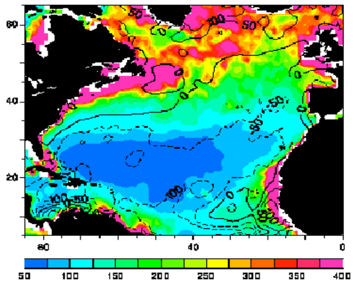
Surface inorganic nutrients are depleted over surface waters in mid latitudes

2 How is productivity at high latitudes sustained?

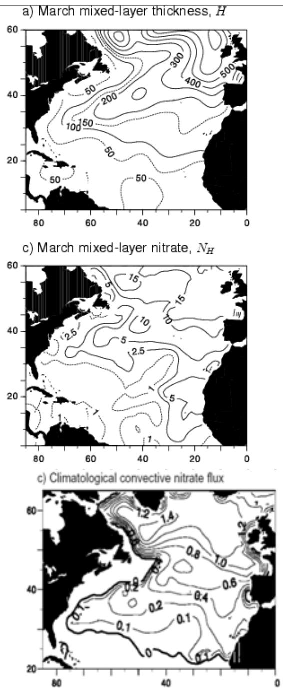




2.1 Role of Convection



Satellite estimate of primary production (gC m^{-2} y^{-1})
Sathyendranathan et al. (1995)



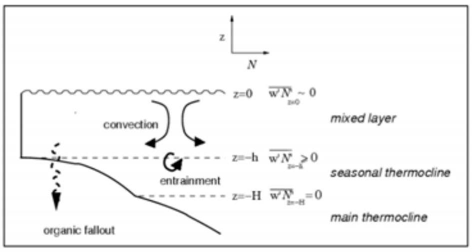
Williams et al. (2000)

Is convection alone sufficient?

Limitation of convection

$$\frac{\partial N}{\partial t} \approx S + \frac{\partial}{\partial z}\overline{w'N'}$$

Convective fluxes

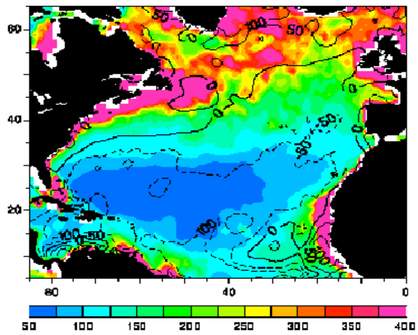


Prime is turbulent event,

Overbar is time-average

Need some advective influx of nutrients to seasonal boundary layer

2.2 Role of upwelling



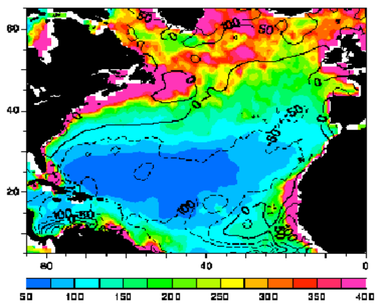
Satellite estimate of primary production (gC m^{-2} y^{-1})
Sathyendranathan et al. (1995)

Upwelling where solid contours

$$\frac{\partial N}{\partial t} + w\frac{\partial N}{\partial z} = S$$

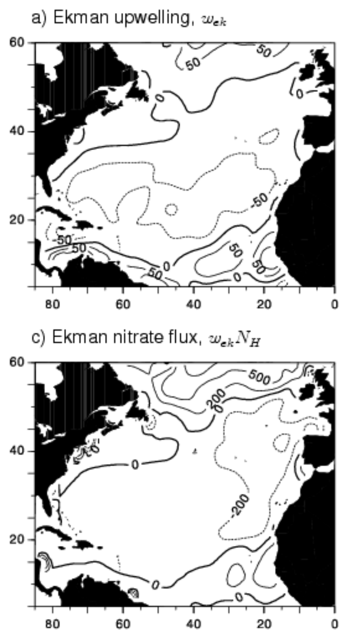
upwelling

Conversion of organic to inorganic N



Satellite estimate of primary production (gC m^{-2} y^{-1})
Sathyendranathan et al. (1995)

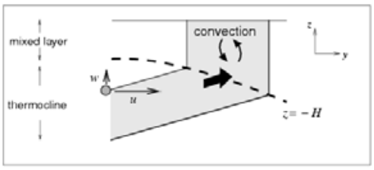
$w_{ek}N$

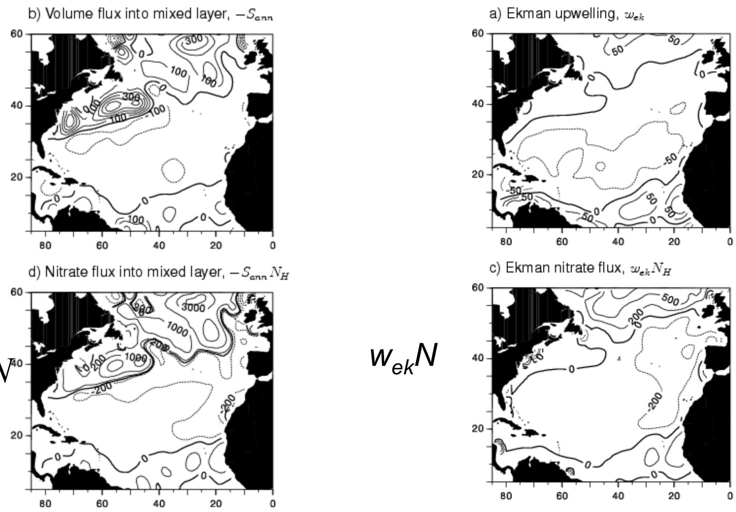


2.3 Isopycnal transfer

$$\frac{\partial N}{\partial t} + u\ .\nabla N = S$$

isopycnic advection



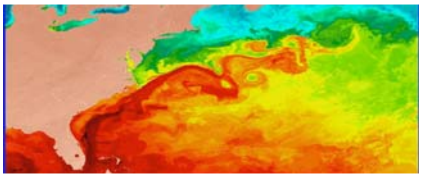


$(w + u.\nabla H)N$

$w_{ek}N$

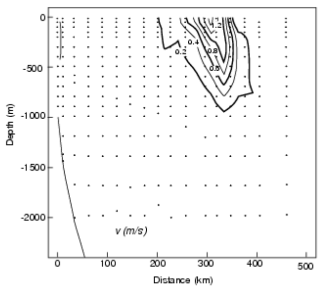
Williams et al. (2006)

2.4 Role of boundary currents

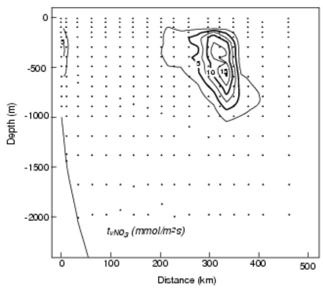


Pelegri & Csanady (1991)

v

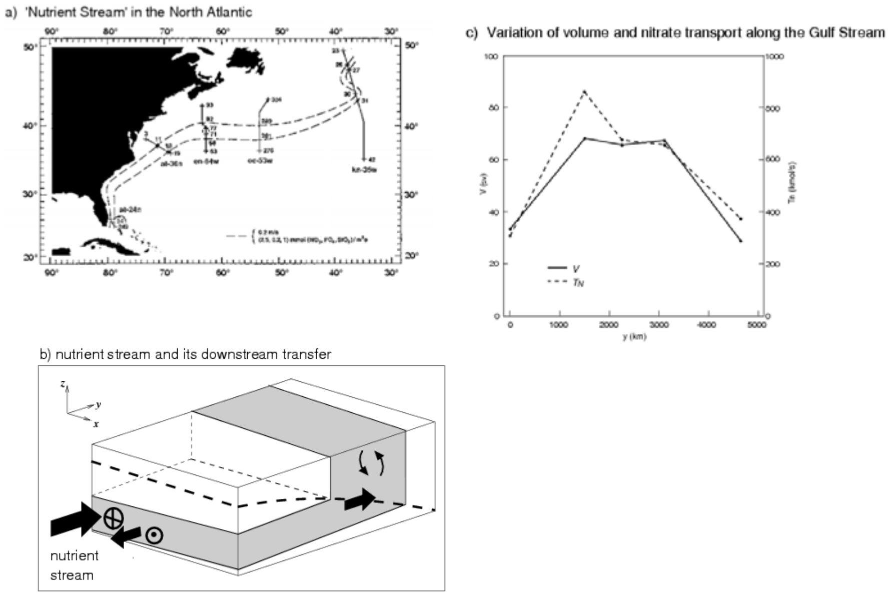


v N at 36N



$$\frac{\partial N}{\partial t} + u\ .\nabla N = S$$

Downstream variation of boundary flux

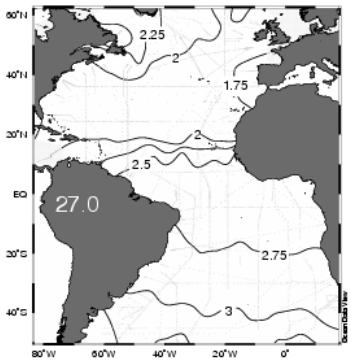


2.5 How are the nutrients supplied to the Gulf Stream?

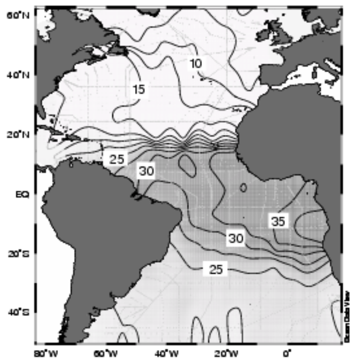
Isopycnal distributions

Nutrient conserved with biotic interactions

$PO_4^* = PO_4 + O_2/175$

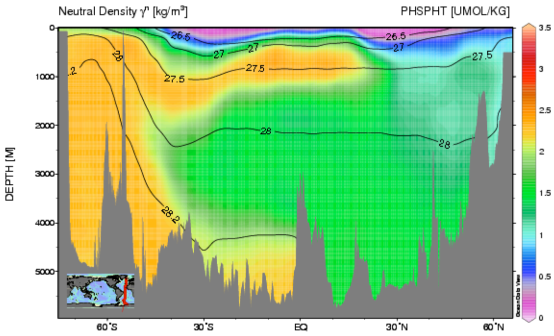


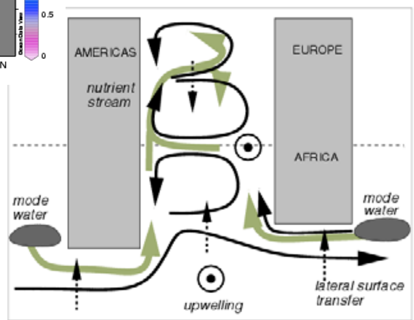
nitrate (μM)



See highest maxima in PO^*_4 in S. Ocean and Labrador Sea

2.6 Link to the Southern Ocean

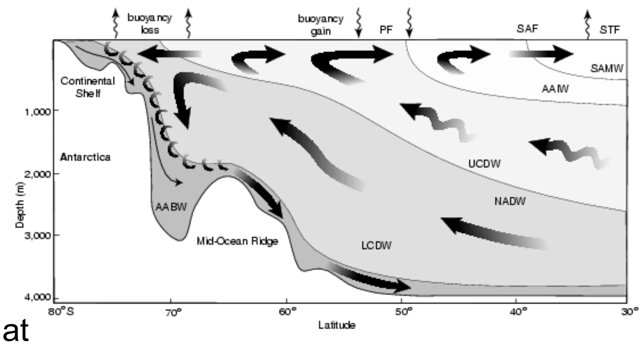




Sarmiento et al. (2004),
Williams et al. (2006)

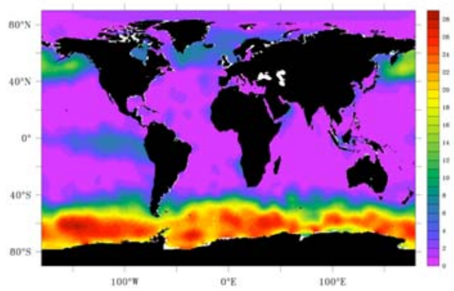
Southern Ocean

- northwards Ekman flux
- northwards bottom flux
- eddy-driven southwards flux at mid-depths



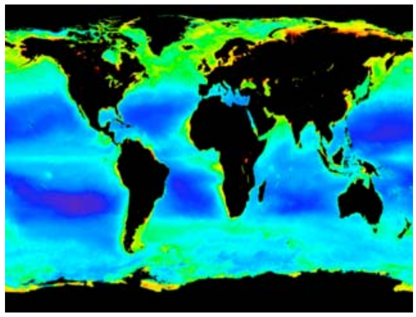
Speer et al. (2000)

2.7 Why are there high surface nutrient concentrations in the Southern Ocean?



Surface NO_3 (uM) World Ocean Atlas (2001)

Chl a (SeaWiFS)

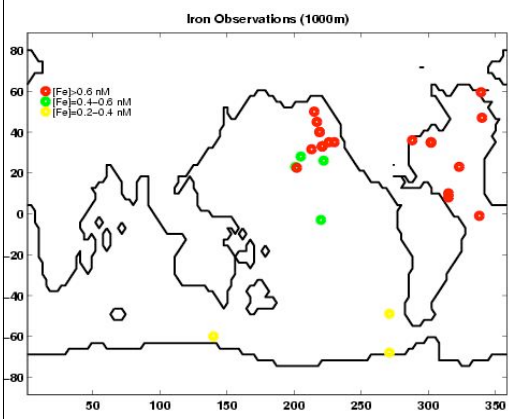


High Nitrate Low Chlorophyll (HNLC) regions.

Phytoplankton also require inputs of iron

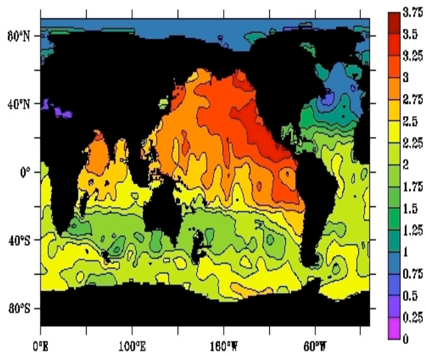
- deep waters depleted in iron relative to macro-nutrients

Dissolved iron, 1000m (nM)



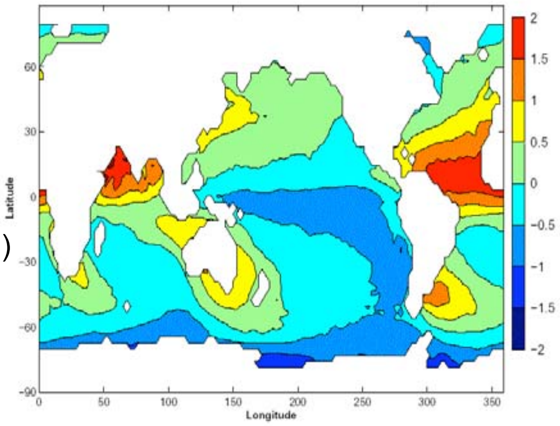
Parekh et al., (2004)

Dissolved PO_4, 1000m (uM)



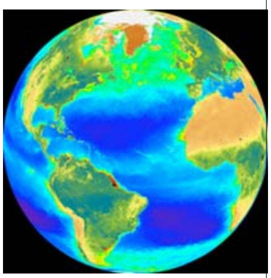
atmospheric supply is significant close to land

atmospheric iron flux:
Mahowald *et al.* (2003)



=> iron limitation of HNLC regions   ...

Conclusions



Background state

- Conversion of inorganic to organic nutrients in sunlit, surface ocean, gravitational fallout of organic matter
- Contrasts between basins reflect meridional overturning, surface nutrients and remineralisation of fallout
- Wind-forced undulations of thermocline/nutricline

High latitudes

- Lateral transfers of nutrients via boundary currents/gyres
- Link to Southern Ocean and iron supply

Next lecture: discuss how productivity is sustained at mid latitudes and the role of eddies

Further reading, reviews:

Williams, R. G. and M. J. Follows, 2003: Physical transport of nutrients and the maintenance of biological production, 19-51, In `Ocean Biogeochemistry: The role of the ocean carbon cycle in global change', Ed. M. Fasham, Springer, ISBN: 3-540-42398-2.

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Williams, R.G., A. McLaren and M.J. Follows, 2000: Estimating the convective supply of nitrate and implied variability in export production. Global Biogeochem. Cycles, 14, 1299-1313.

Williams, R.G., V. Roussenov and M.J. Follows, 2006: Nutrient Streams and their induction into the mixed layer.' *Global Biogeochemical Cycles,* 20, GB1016