Thermohaline and wind-driven circulation

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NCAR ASP Colloquium: Carbon climate connections in the Earth System

Tracer conservation and ocean transport

The tracer conservation equation describes

the time rate of change of a tracer at a given point and the processes that change its concentration

The processes include

1. **transport and mixing → physical** (decrease vertical contrast)
2. sources and sinks → biological and chemical transformations (increase nutrient concentrations in deep waters)

The tracer conservation eq. for a volume at a fixed location is

$$\frac{\partial C}{\partial t} = \left.\frac{\partial C}{\partial t}\right|_{advection} + \left.\frac{\partial C}{\partial t}\right|_{diffusion} + SMS(C)$$

where SMS(C) (mmol m^{-3} s^{-1}) represents internal sources minus sinks

Advection

The large-scale, depth integrated ocean circulation:

- The Meridional Overturning Circulation (MOC) or Thermohaline circulation
- The wind-drive gyre circulation

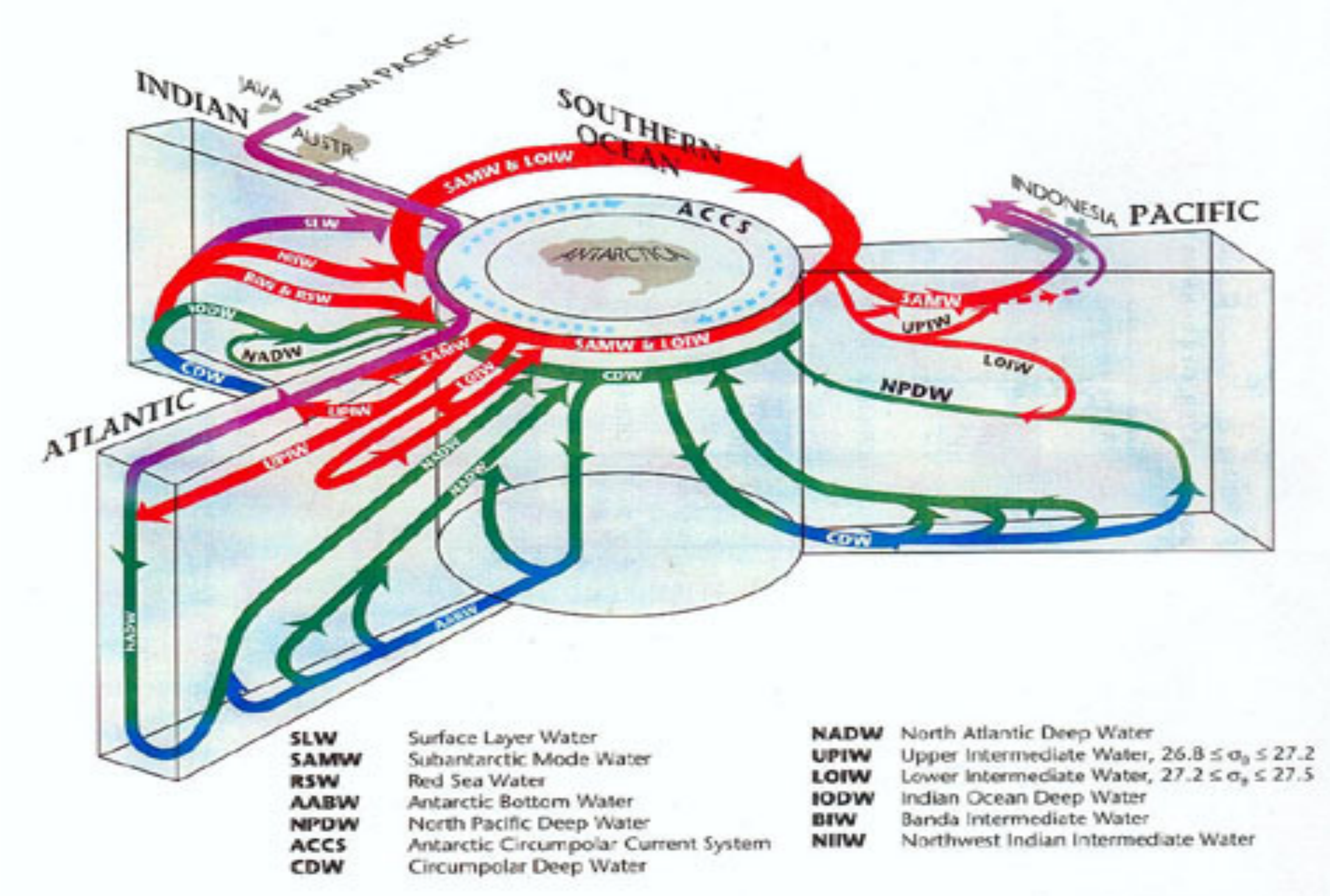
The MOC (or thermohaline circulation)

- The meridional overturning circulation is associated to the abyssal circulation in the ocean. In reality is not independent on the wind circulation, but a representation of it can be obtained considering buoyancy effects alone

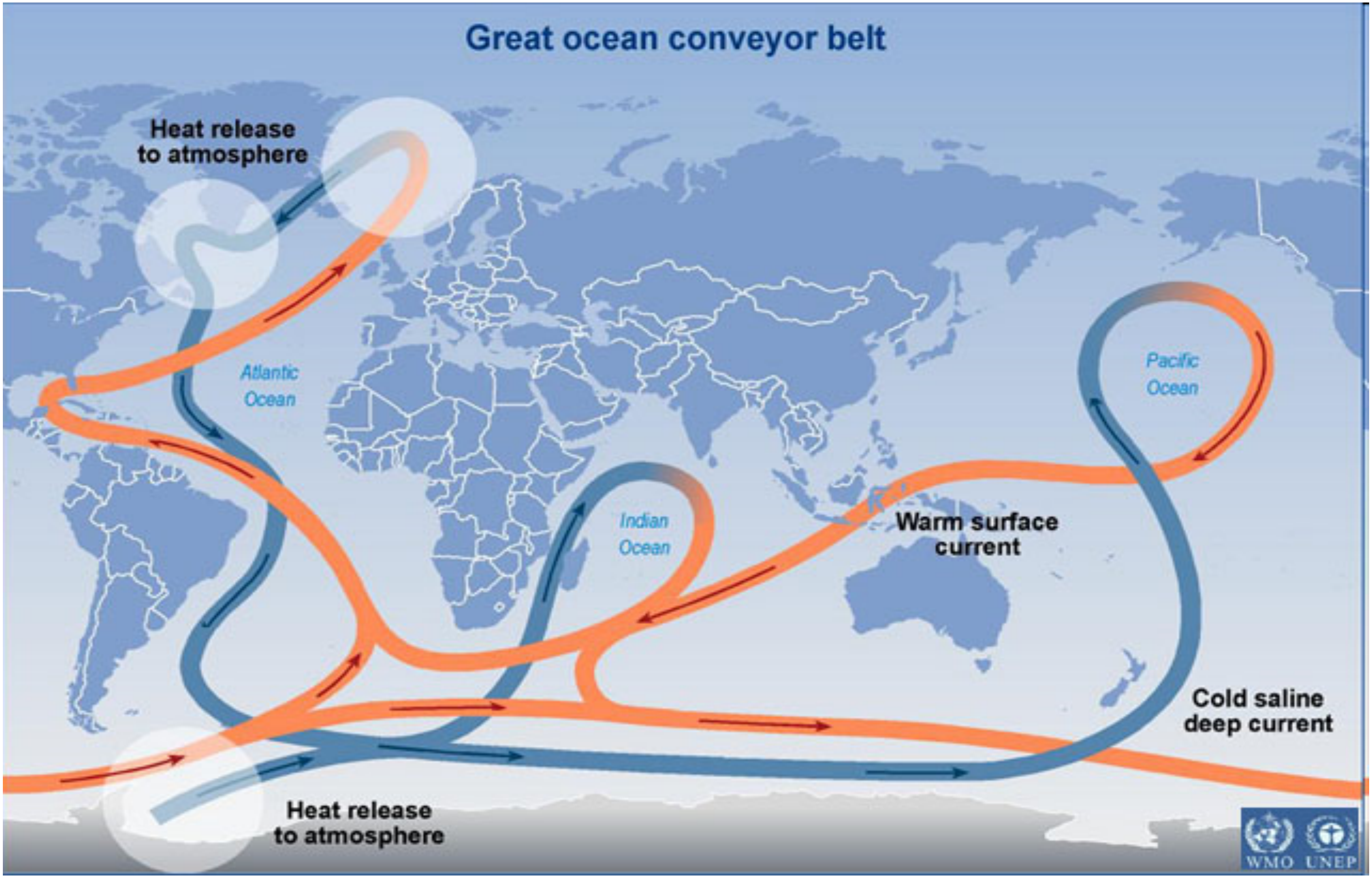
- It is also called thermohaline circulation because is driven principally –not exclusively- by temperature and salinity

- A satisfactory theory explaining the MOC is not available. Simple models lack important components and are not as complete and 'clear' as the one describing the wind-driven circulation

(From Siedler, 2001, figure 1.2.7, as taken from Schmitz, 1996).



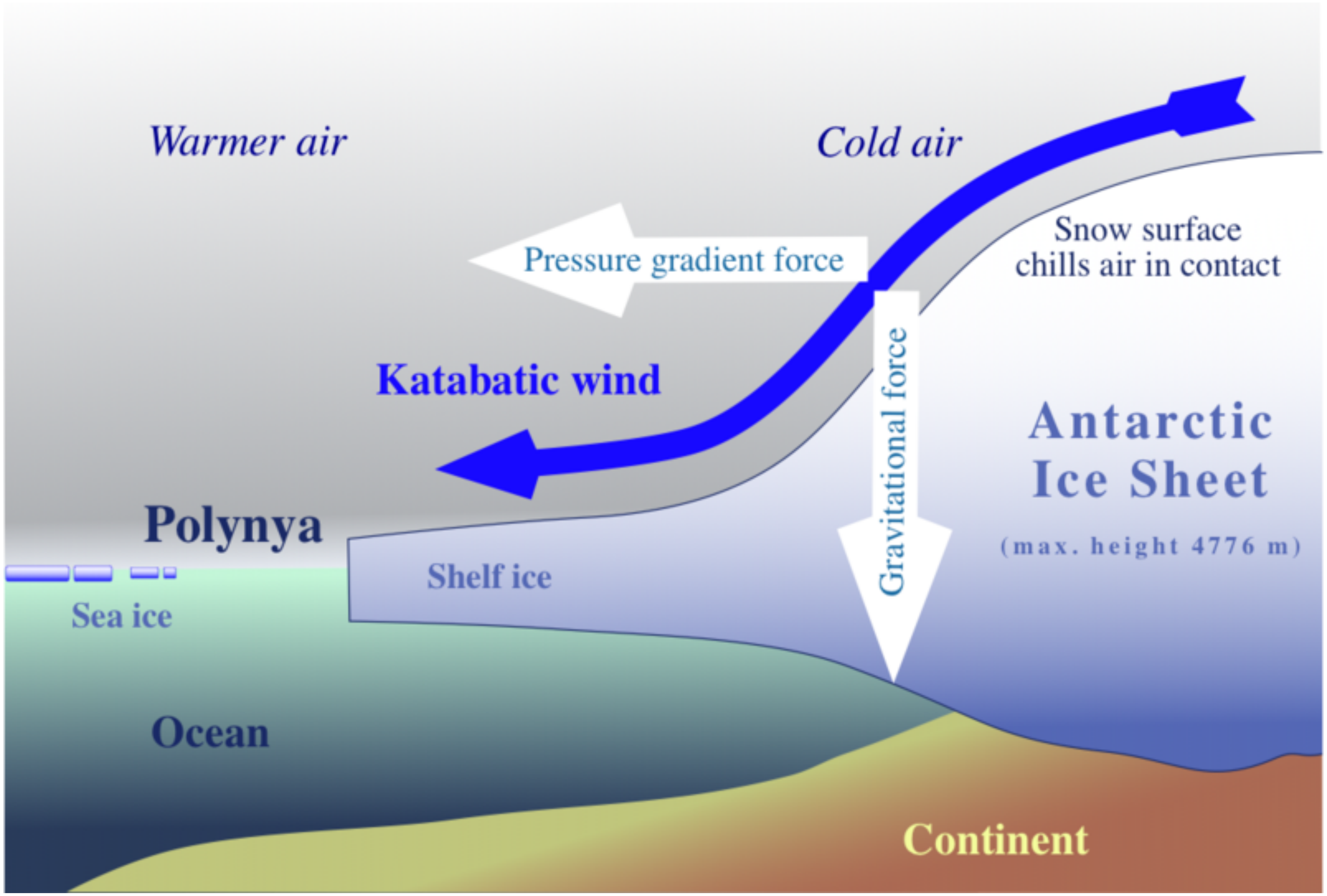
The MOC



Great ocean conveyor belt
Heat release to atmosphere
Atlantic Ocean
Indian Ocean
Pacific Ocean
Warm surface current
Cold saline deep current
Heat release to atmosphere
WMO UNEP

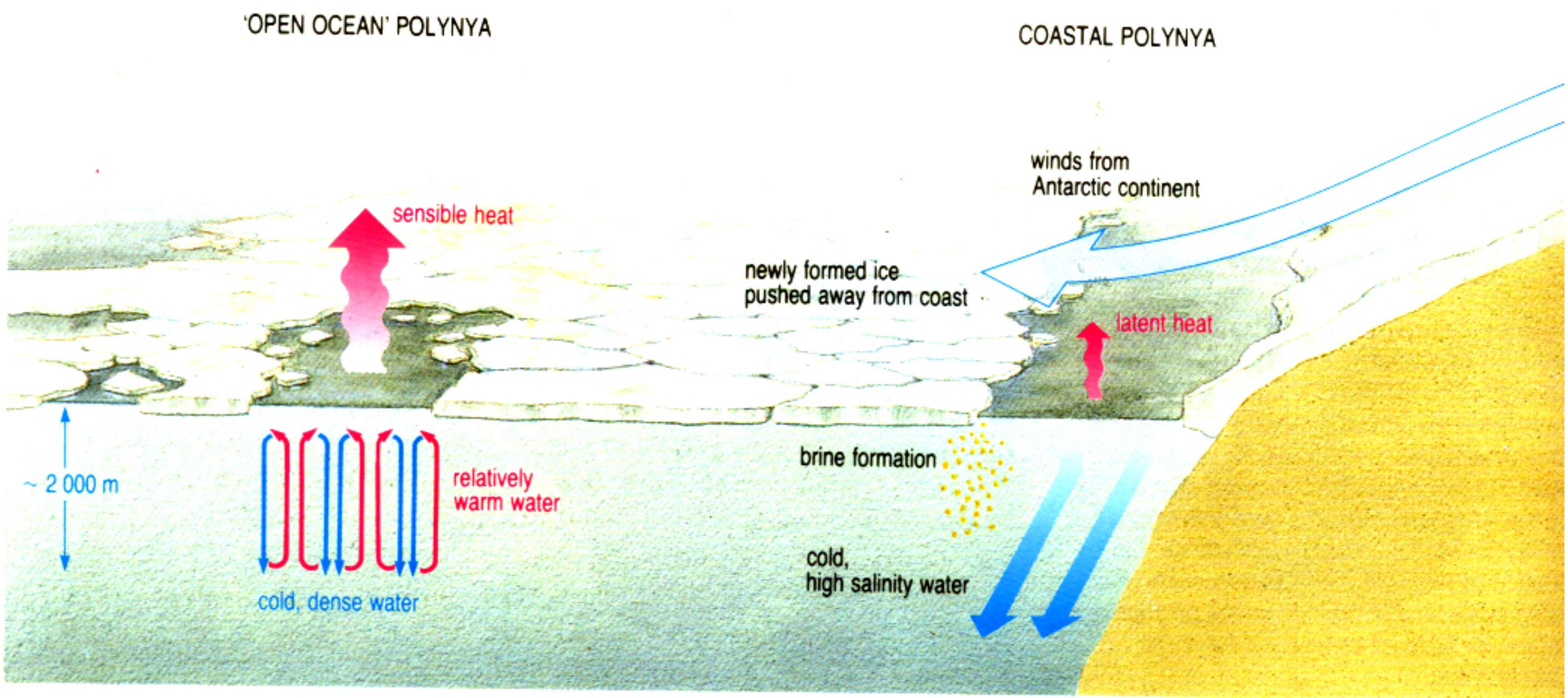
Antarctic Bottom Water (AABW)

- When sea ice freezes, it leaves salt behind
- Adds salt to coldest water on earth around Antarctica
- Becomes the densest water in the ocean and sinks

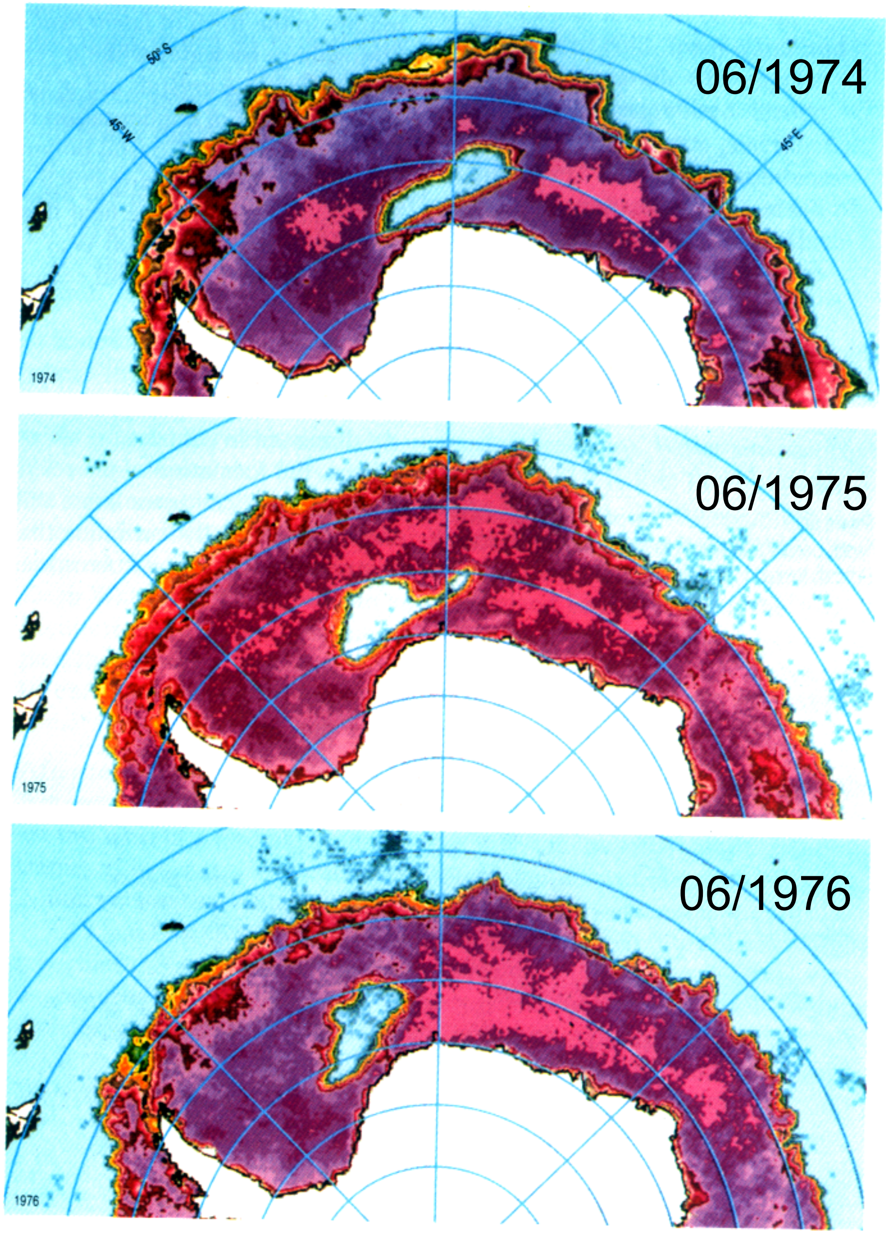


Warmer air
Cold air
Pressure gradient force
Snow surface
chills air in contact
Katabatic wind
Gravitational force
Antarctic
Ice Sheet
(max. height 4776 m)
Polynya
Shelf ice
Sea ice
Ocean
Continent

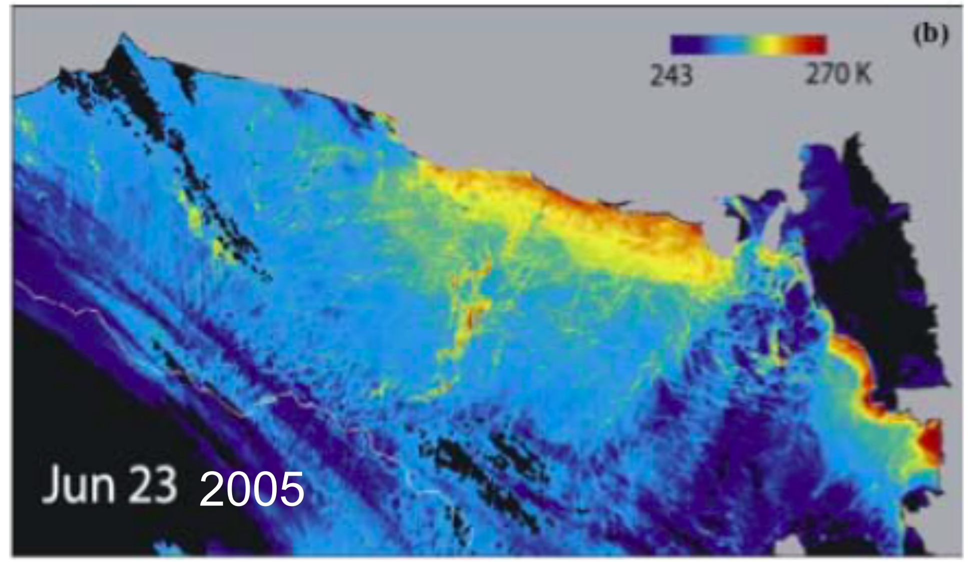
Formation of Antarctic Bottom Waters



Weddell Polynya

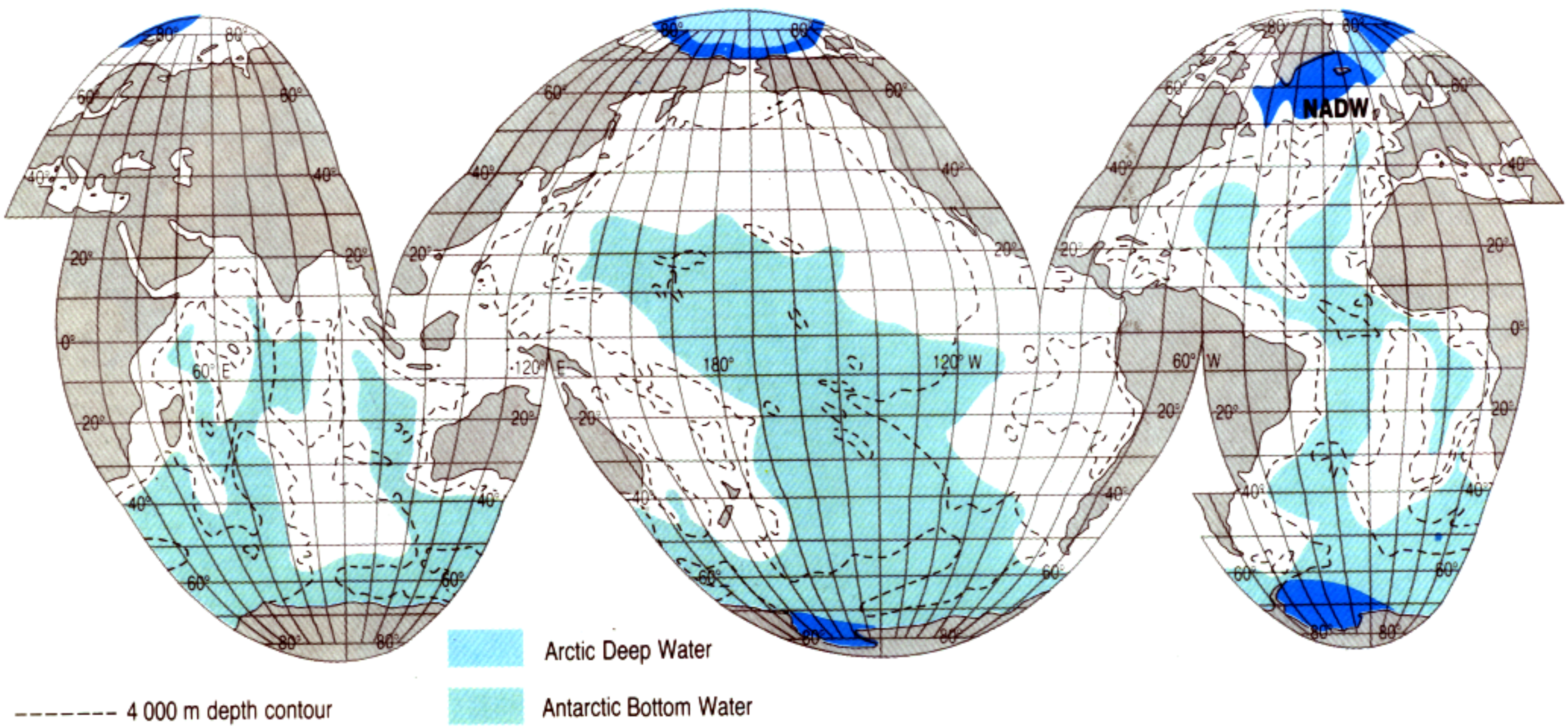


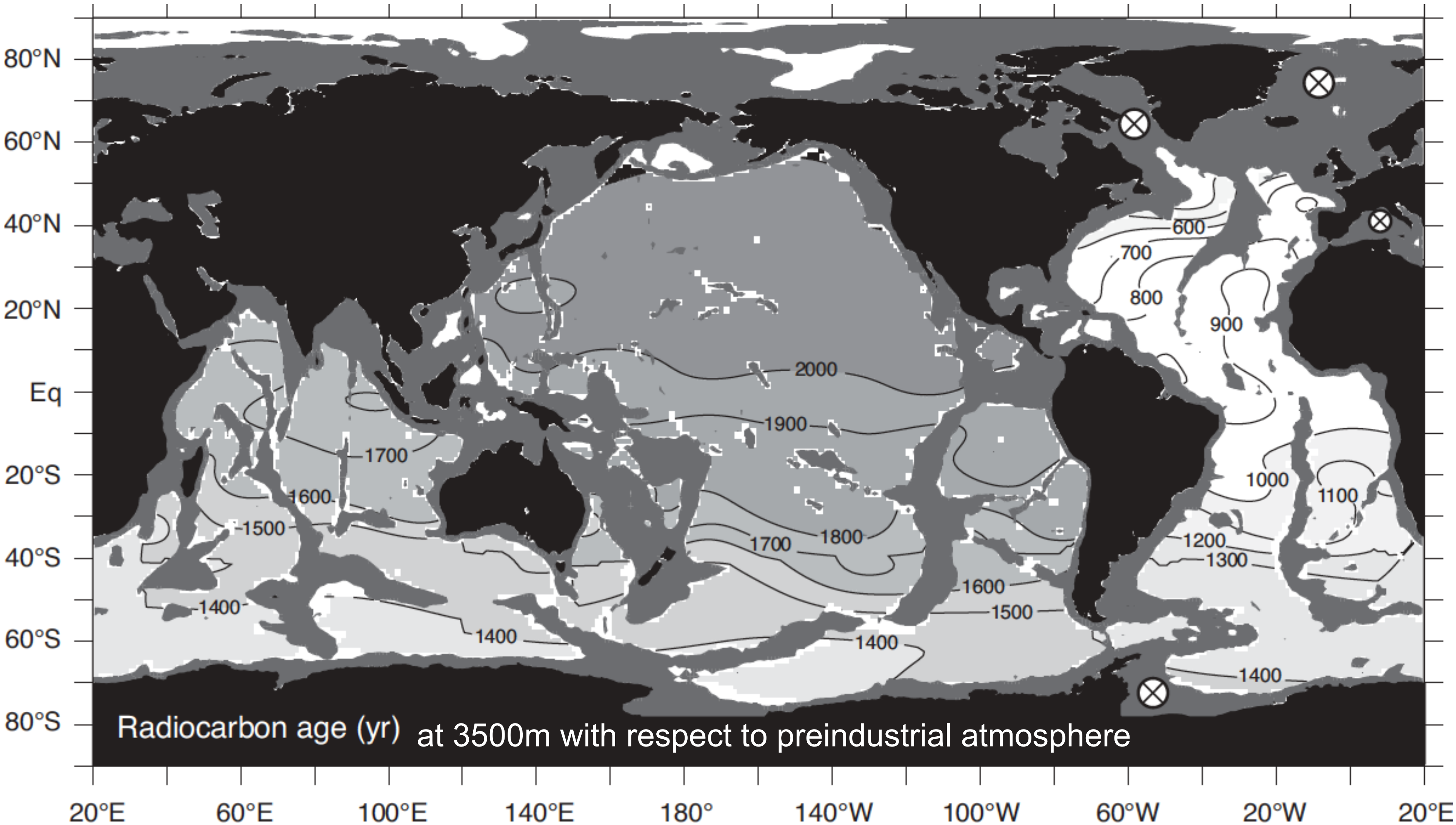
Ross Sea Polynya



Ross Sea image from
MODIS (from Kwot et al., 2007)

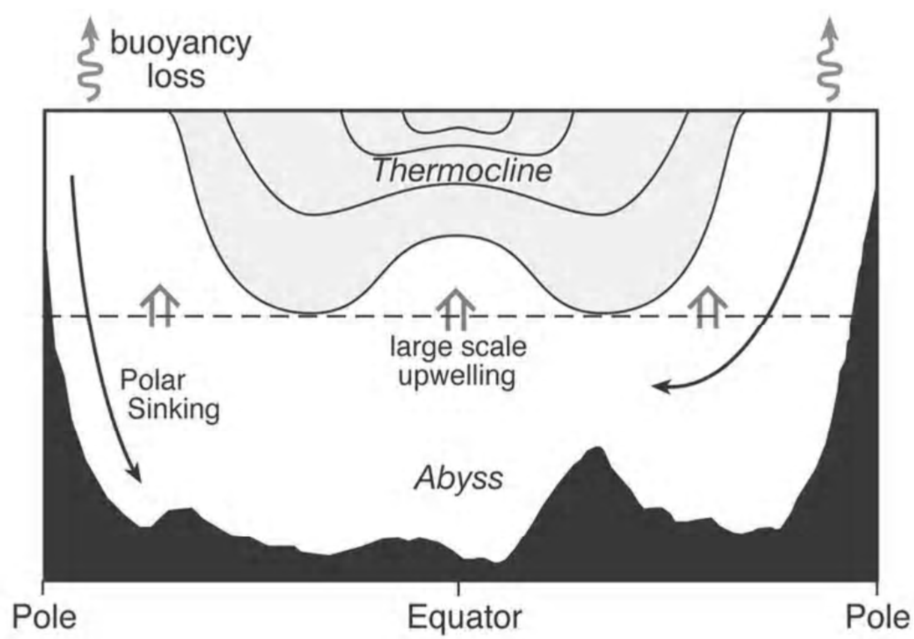
Spread of the AABW





from Sarmiento & Gruber, 2006

- Most of the stratification is concentrated in the first upper kilometer
- The relatively unstratified abyss water originates at high latitudes (the outcropping happens only in the North Atlantic subpolar gyre and in the Antarctic Circumpolar Current (ACC))



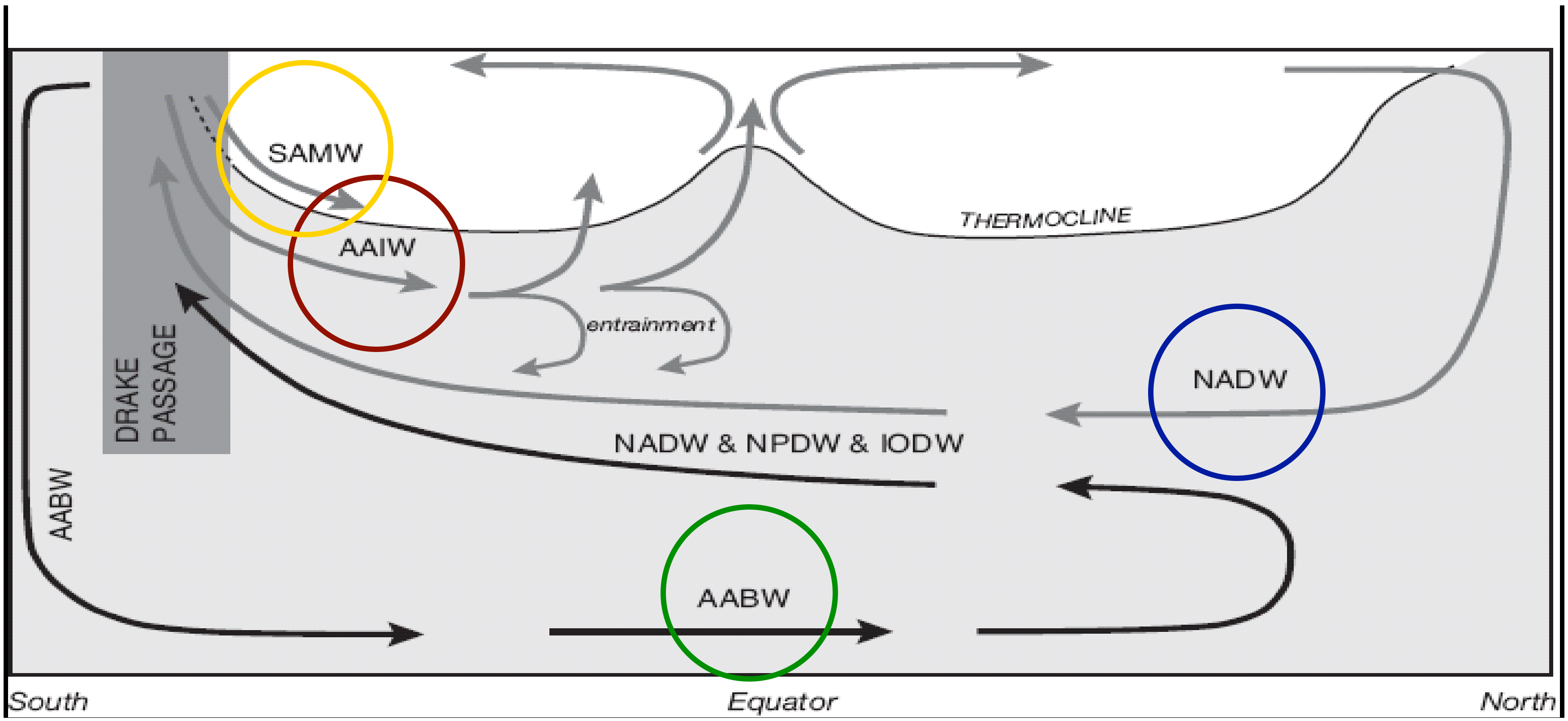
MOC plays a key role in

- transporting nutrients
- modulating biological productivity

- Broad nutrient distributions reflects temperature but with greater basin-to-basin and vertical contrasts (iron is an exception)

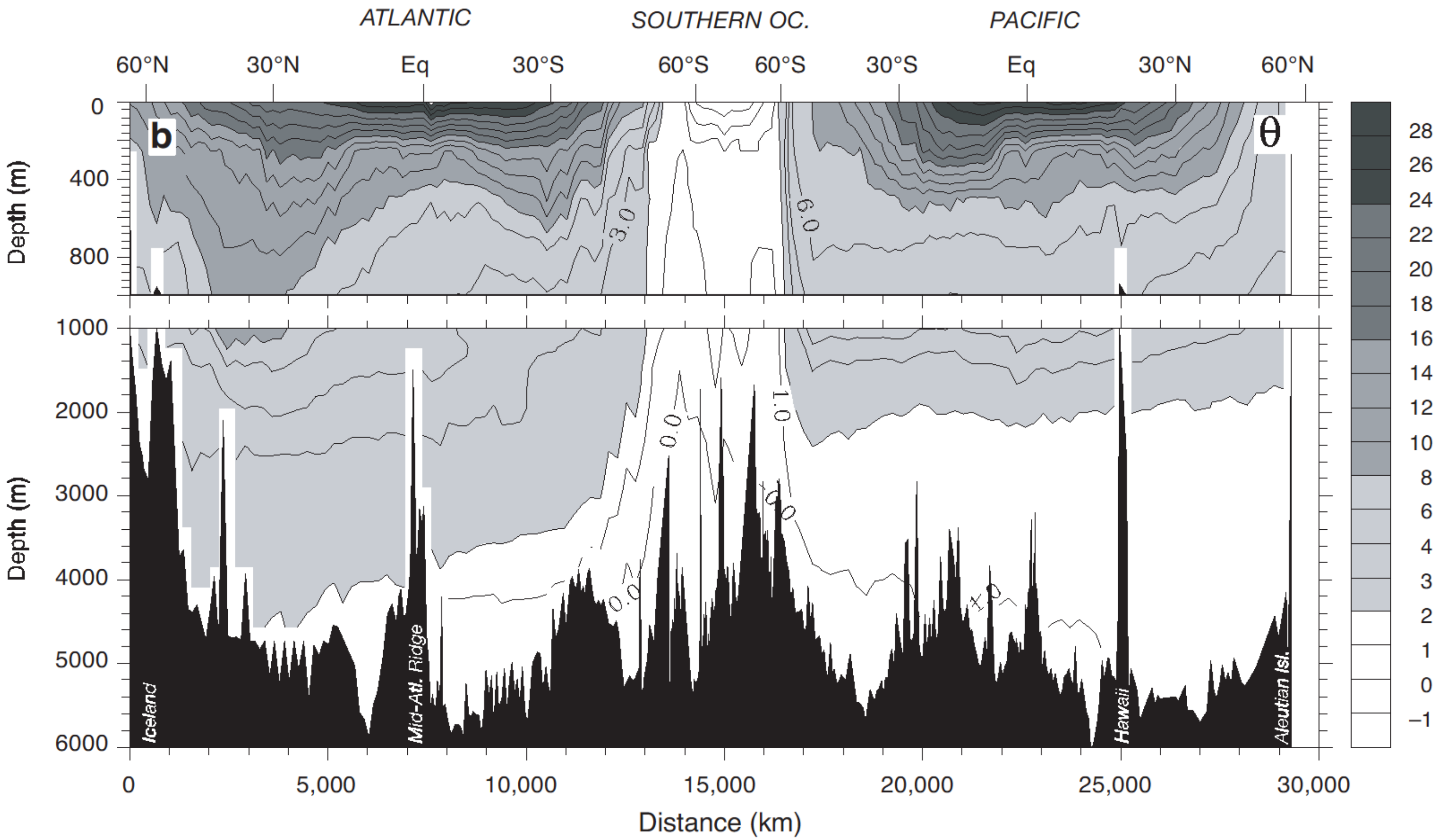
Associated with the MOC there is a distinctive stratification.

- Most of stratification is concentrated in the first upper kilometer
- The relatively unstratified abyss water originates at high latitudes (with outcropping only in the North Atlantic subpolar gyre and in the Antarctic Circumpolar Current - ACC)

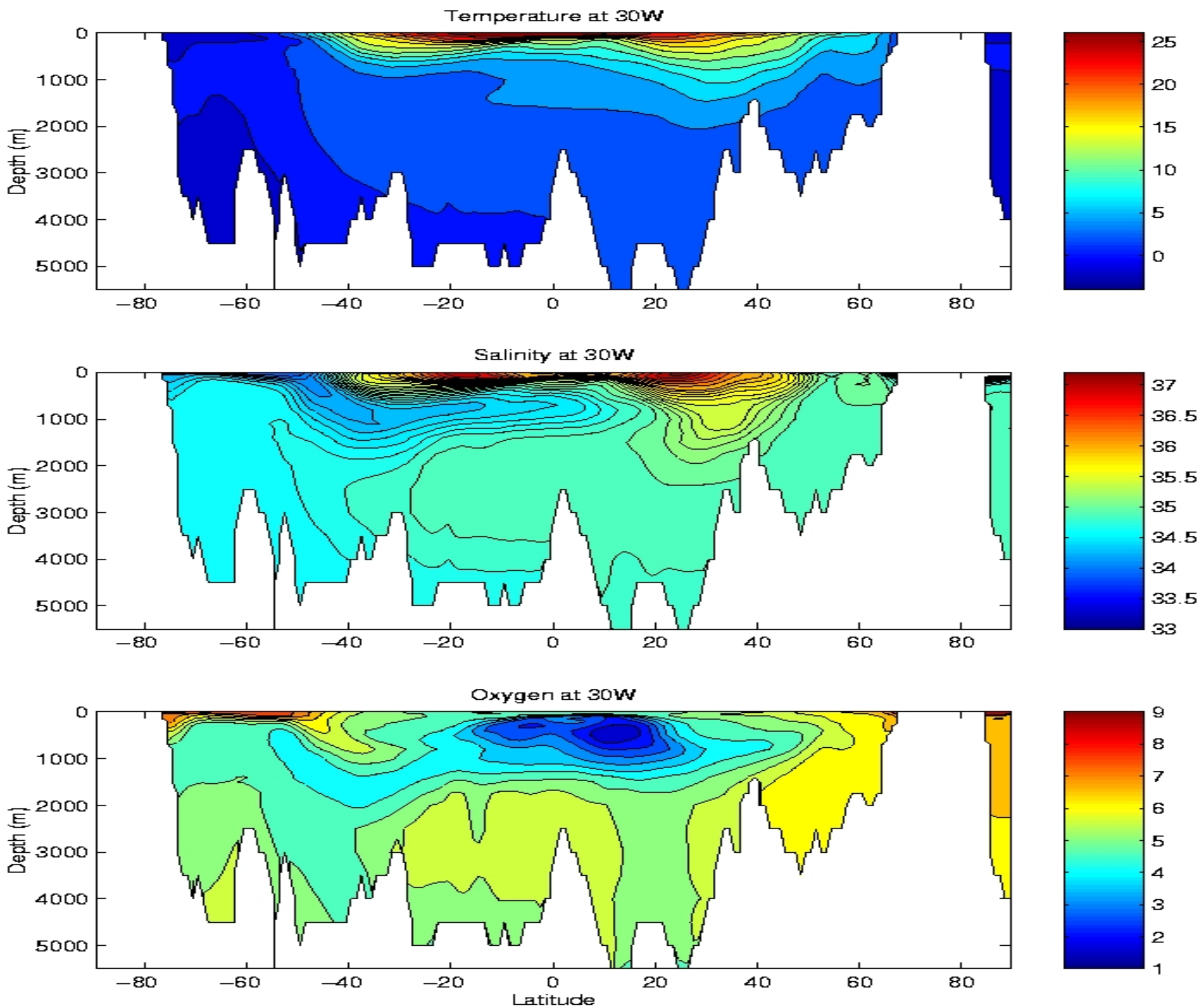


from Sarmiento & Gruber, 2006

Potential temperature

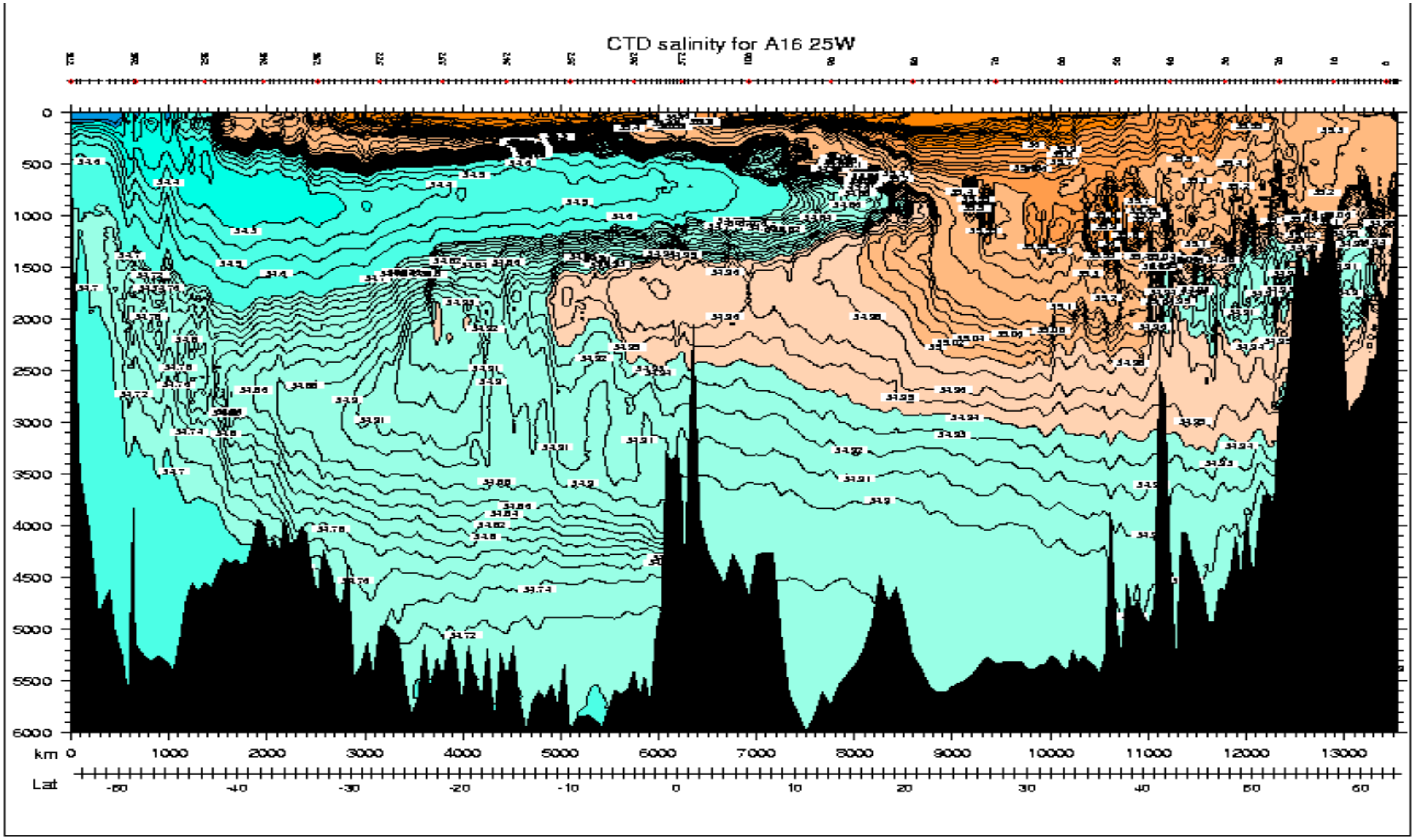


from Sarmiento & Gruber, 2006

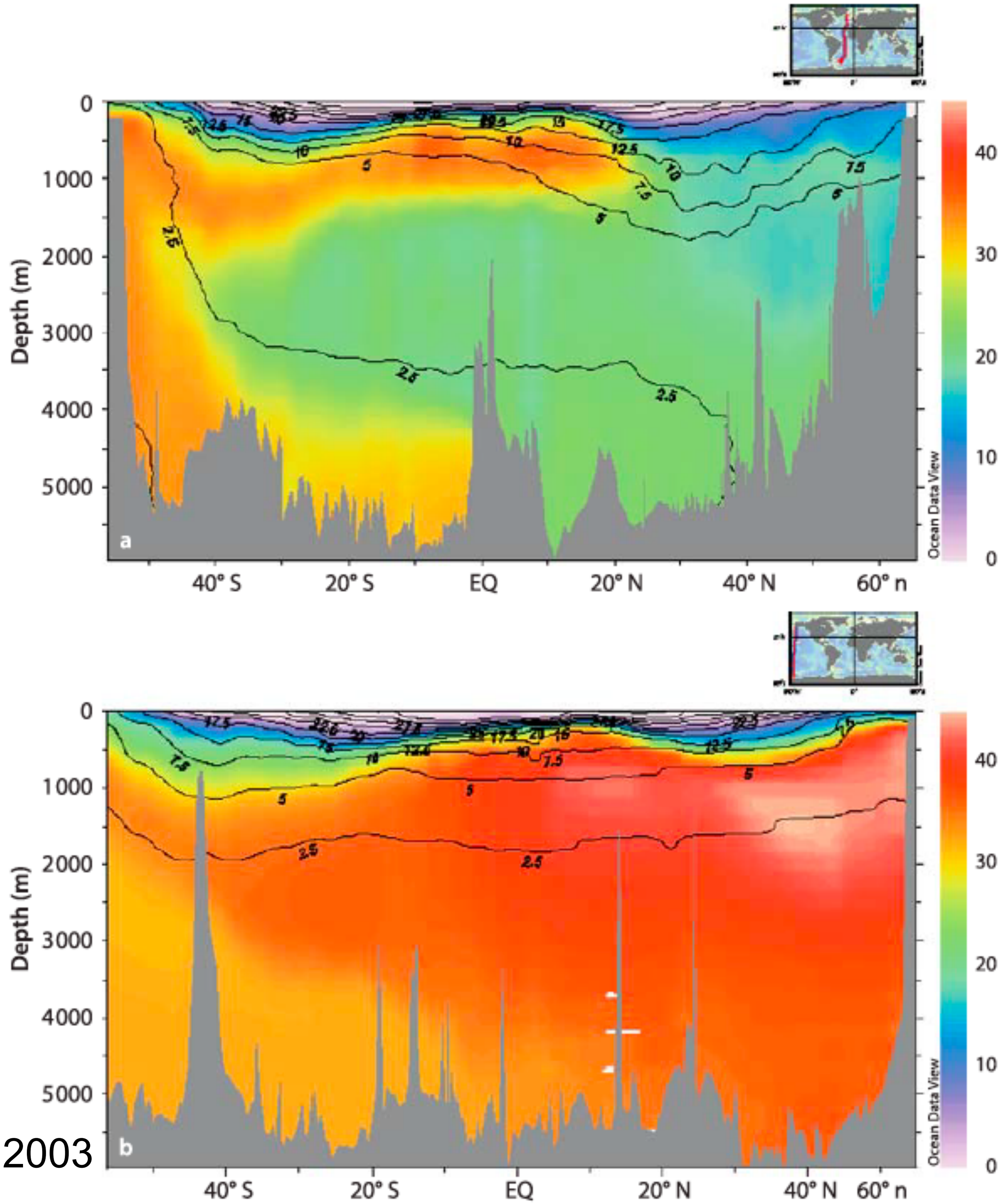


North-south sections of (a) temperature, (b) salinity, and (c) oxygen along the 30^{o}W transect in the Atlantic ocean. Note the salinity tongues indicating the interleaving of water masses from sources in the Antarctic and the North Atlantic.

Map of salinity at 25W in the NA showing salinity maximum of MOW (30-40N at 1000m), salinity minimum of LSW (40-60N at 1500-2000m). Also - salinity minimum of AAIW (south of 20N at 500-1000m) and overall salinity maximum of NADW (south of 20N and 1500-3000m)



Meridional WOCE sections of nitrate (*colour shading* in μmol kg^{-1}) and potential temperature (*contours* in °C) for **a** Atlantic (A16) and **b** Pacific (P15). In the Atlantic, there are signals of a southwards spreading of North Atlantic Deep Water (*green*), as well as northwards spreading of Antarctic Intermediate Water and Antarctic Bottom Water (*upper and lower orange plumes*). In the Pacific, there is a northwards influx of bottom and deep water from the Southern Ocean, which is probably returned southwards at mid-depth

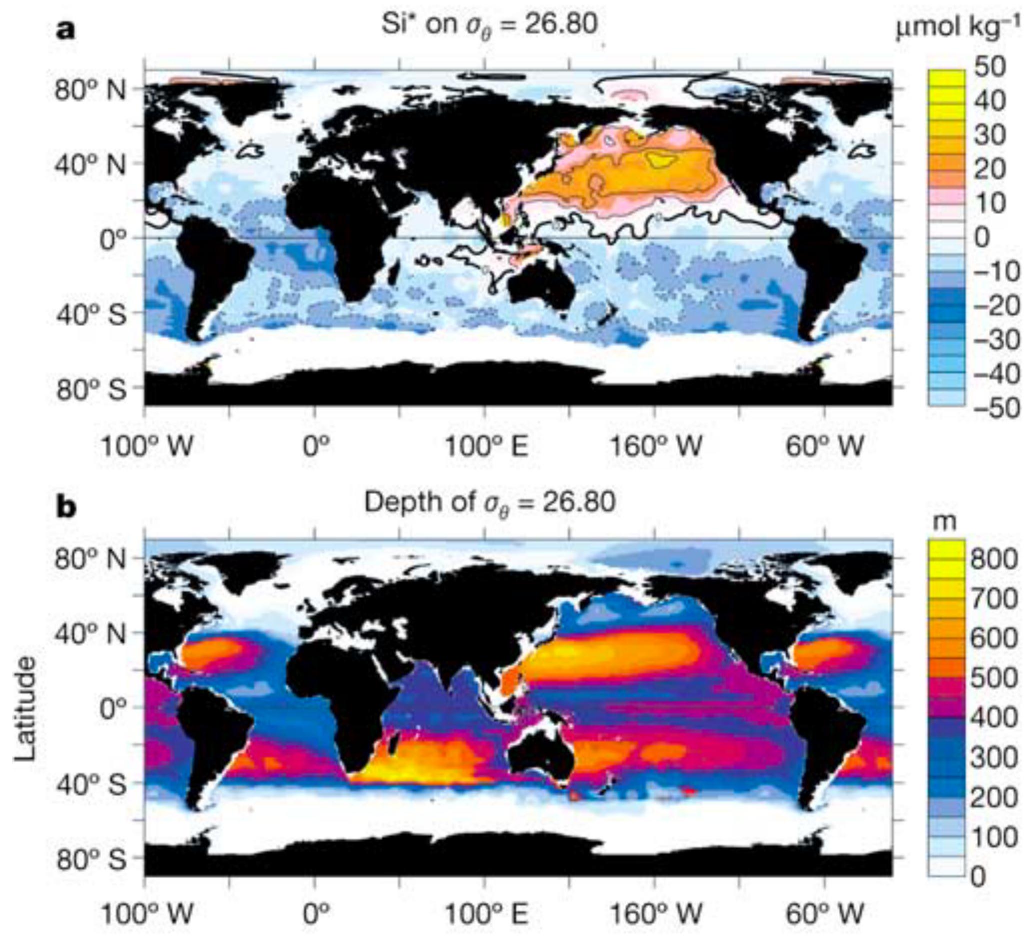


from Williams and Follows, 2003

The Southern Ocean (SO) plays a key role in the nutrient supply to the thermocline

The Subantarctic Mode Water (SAWM) represents the main conduit of nutrients from the SO

Global maps of nutrient properties mapped on the potential density surface σ_θ = 26.80.
Si* = $[Si(OH)_4] - [NO_3^-]$ ~ -10 : -15 µmolkg^{-1} at SAWM formation sites



from Sarmiento et al., 2004

Schematic showing SO control on thermocline nutrient concentrations from Sarmiento et al., 2004
Top: water pathways.
Bottom: surface processes at play

CDW=circumpolar Deep Water
APF=Antarctic Polar Front
PFZ=Polar Front Zone
AAIW= Antarctic Intermediate Water
SAMW=Subantarctic Mode Water
SAF=Subantarctic Front
SAZ=Subantarctic Zone
STF=Subtropical Front

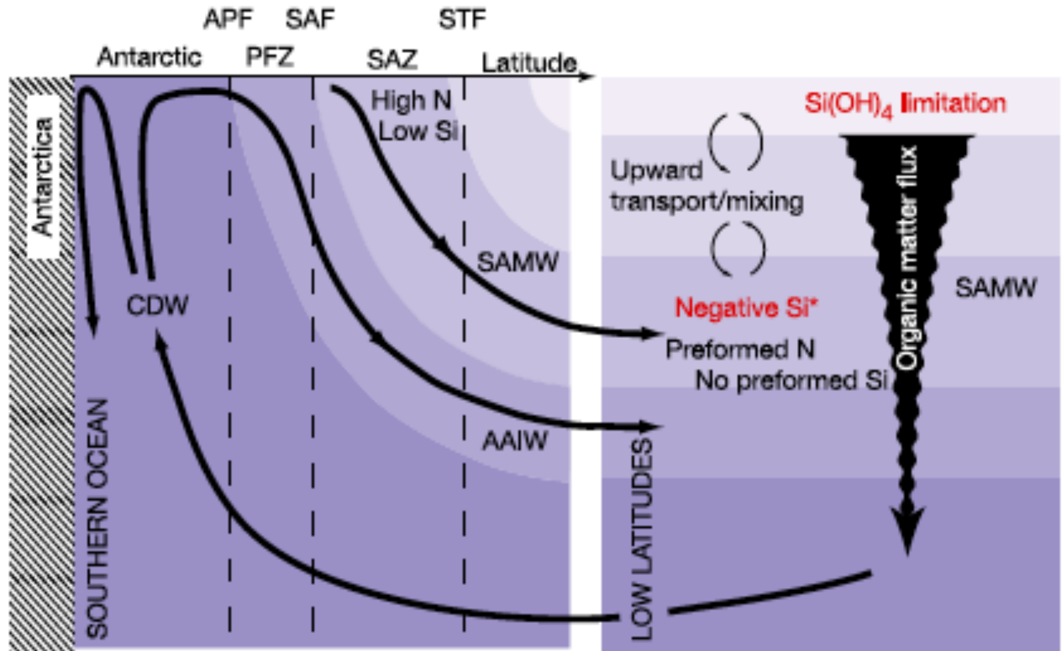


Figure 4 Southern Ocean control on thermocline nutrient concentrations. Conceptual diagram depicting the Southern Ocean physical and biological processes that form low-Si* waters and feed them into the global thermocline. Top, water pathways; bottom, details of surface processes. Upper Circumpolar Deep Water (CDW) upwells to the surface in the Southern Ocean, and is transported to the north across the Antarctic Polar Front (APF) into the Polar Front Zone (PFZ), where Antarctic Intermediate Water (AAIW) forms, and then across the Subantarctic Front (SAF) into the Subantarctic Zone (SAZ), which is bounded to the north by the Subtropical Front (STF). Silicic acid is stripped out preferentially over nitrate as the water moves to the north, thus generating negative Si* values. This negative-Si* water is Subantarctic Mode Water (SAMW), which sinks into the base of the main thermocline and feeds biological production in the low latitudes.

- The **overturning circulation** determines the broad patterns in the global distribution of nutrients (N, P, Si) (but not of iron! for which Atlantic > Indian > Pacific > Southern Ocean)

- However, on seasonal to interannual time scales biological productivity is more sensitive to the **basin-scale gyre circulation**

The wind-driven circulation

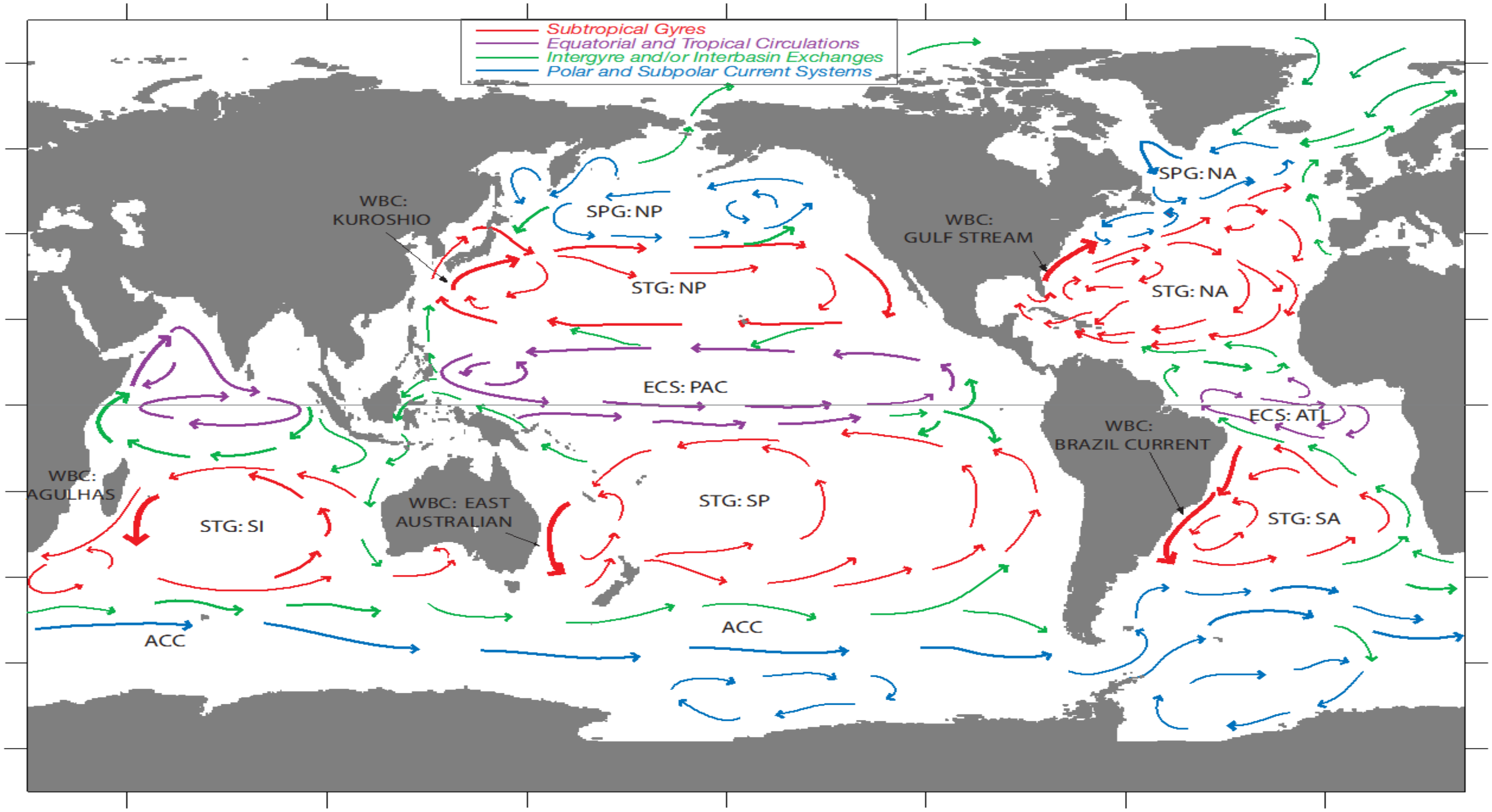
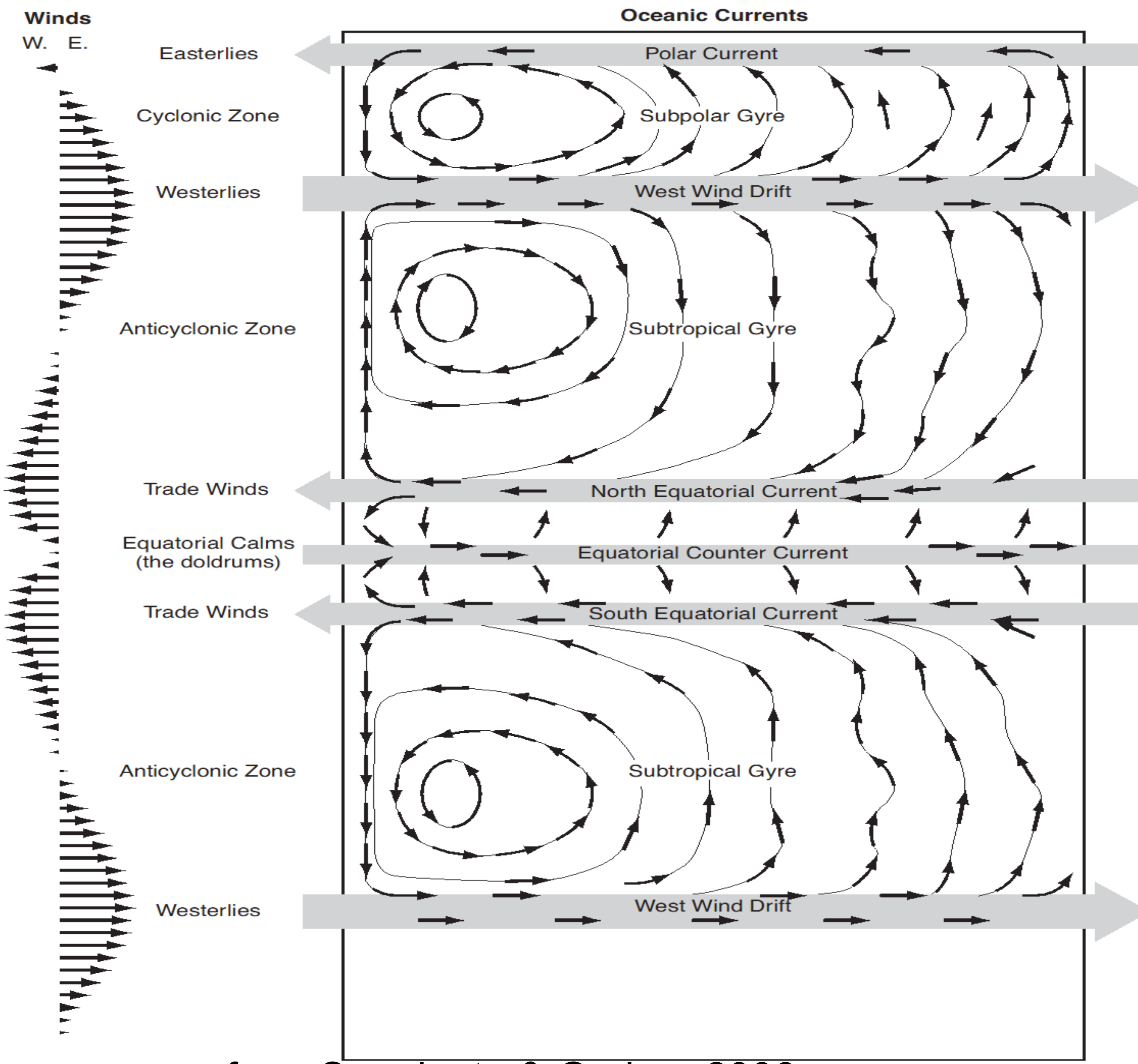


Fig. 14.1 A schema of the main currents of the global ocean. Key: STG – Sub-Tropical Gyre; SPG – Sub-Polar Gyre; WBC – Western Boundary Current; ECS – Equatorial Current System; NA – North Atlantic; SA – South Atlantic; NP – North Pacific; SP – South Pacific; SI – South Indian; ACC – Antarctic Circumpolar Current; ATL – Atlantic; PAC – Pacific.

from Vallis, 2006



from Sarmiento & Gruber, 2006

- The large-scale surface circulation consists of subpolar (cyclonic) and subtropical (anticyclonic)gyres
- Exception at the equator → surface currents are predominantly westwards and the vertical integrated flow is eastward
- The gyres are strongest in the west → intensification of western boundary currents
- Western boundary currents from subpolar and subtropical gyres lead to the Gulf Stream, Kuroshio and Brazilian currents

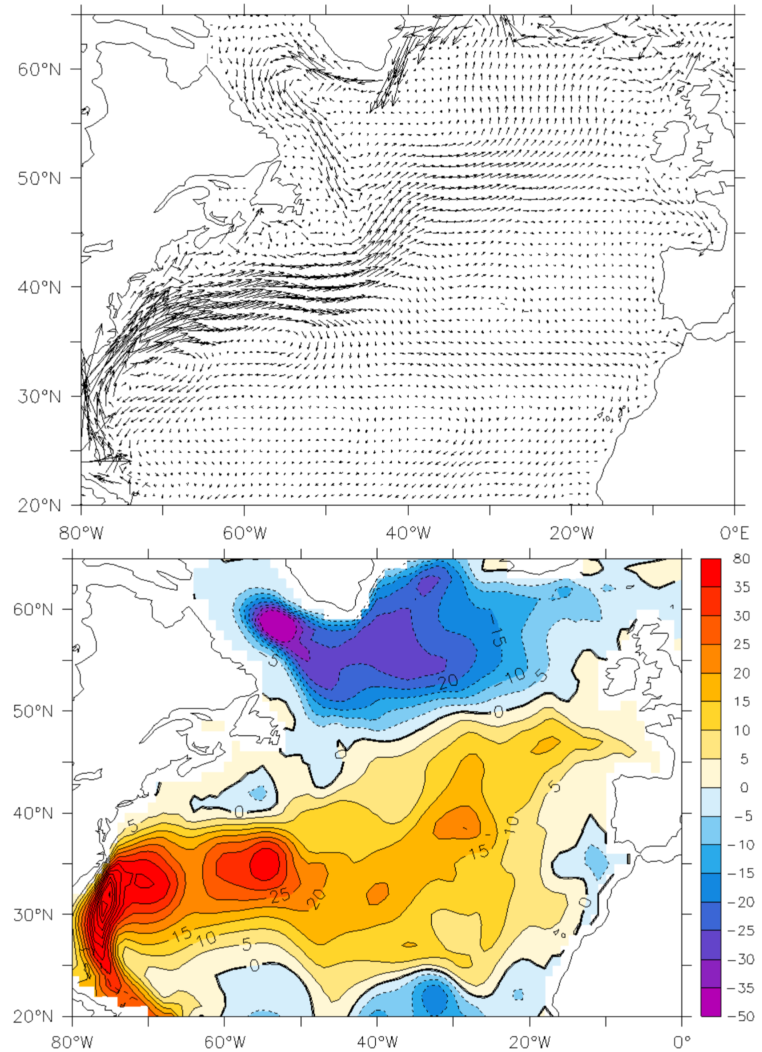


Fig. 14.2 Top: The time-averaged velocity field at a depth of 75 m in the North Atlantic, obtained by constraining a numerical model to hydrographic observations. Bottom: The streamfunction of the vertically integrated flow, in Sverdrups. Note the presence of an anticyclonic subtropical gyre, a cyclonic subpolar gyre, and intense western boundary currents.[3]

The zero-order features of the ocean gyre circulation has been described by a **steady, forced-dissipative, homogeneous** model proposed by Stommel (1948)

from Vallis, 2006

The Stommel model

The planetary geostrophic eq. for a Boussinesq fluid in the limit of small Rossby number are:

$$\frac{Db}{Dt} = \dot{b}$$

thermodynamic eq

$$\nabla \cdot \vec{v} = 0$$

continuity

$$\vec{f} \times \vec{u} = -\nabla \phi + \frac{1}{\rho_o} \frac{\partial \vec{\tau}}{\partial z}$$

horizontal momentum
(geostrophic balance + wind stress)

$$\frac{\partial \phi}{\partial z} = b$$

vertical momentum
(geostrophic balance)

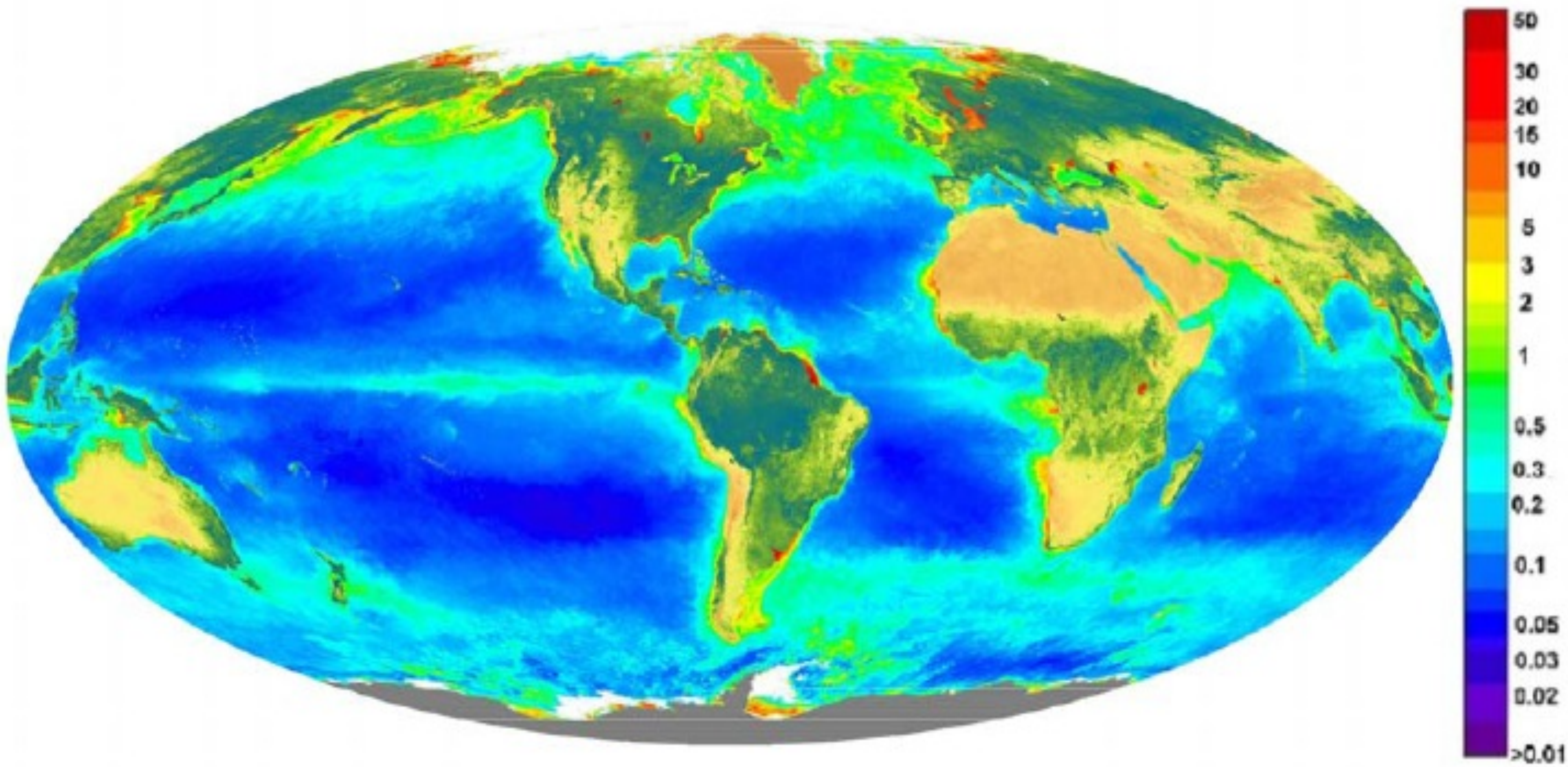
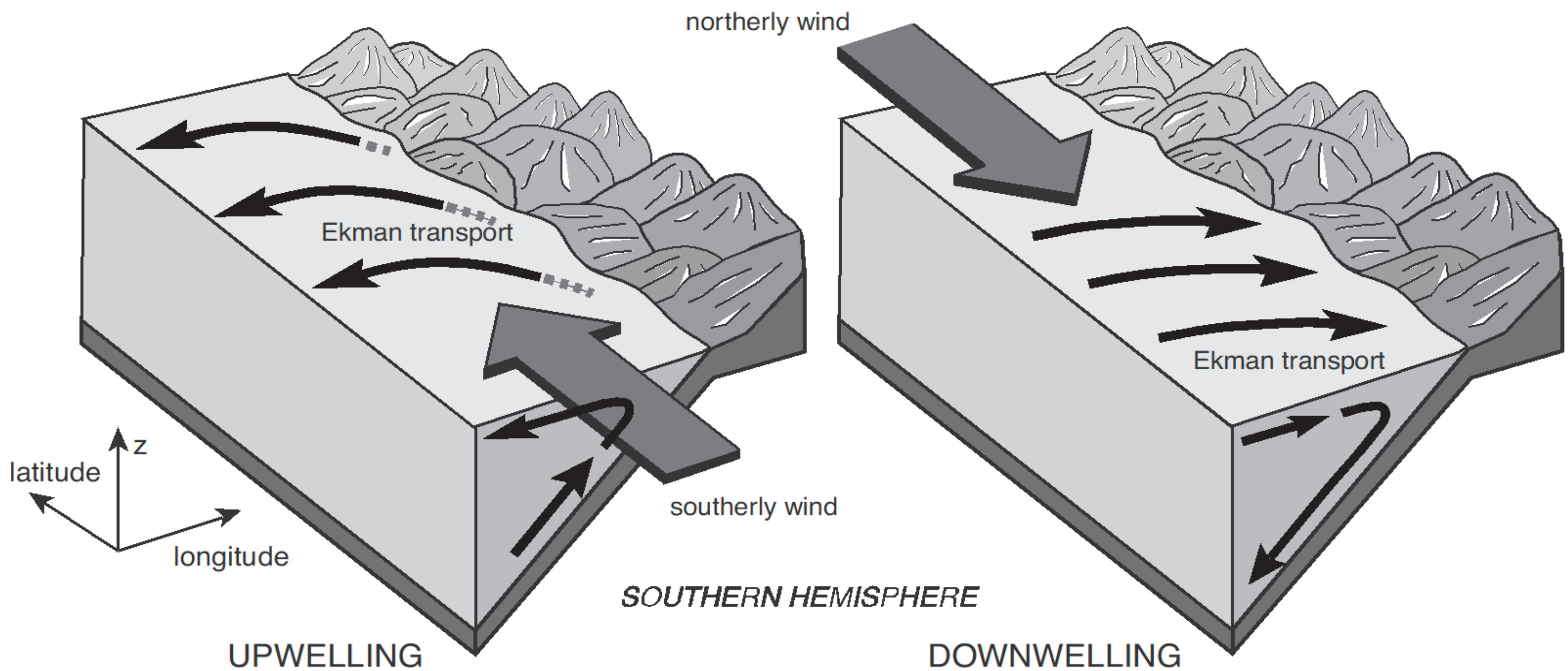


Figure 2: Estimate of phytoplankton distribution in the surface ocean: global composite image of surface chlorophyll a concentration (mg m^{-3}) estimated from SeaWiFS data (Source: NASA Goddard Space Flight Center, Maryland, USA and ORBIMAGE, Virginia, USA).

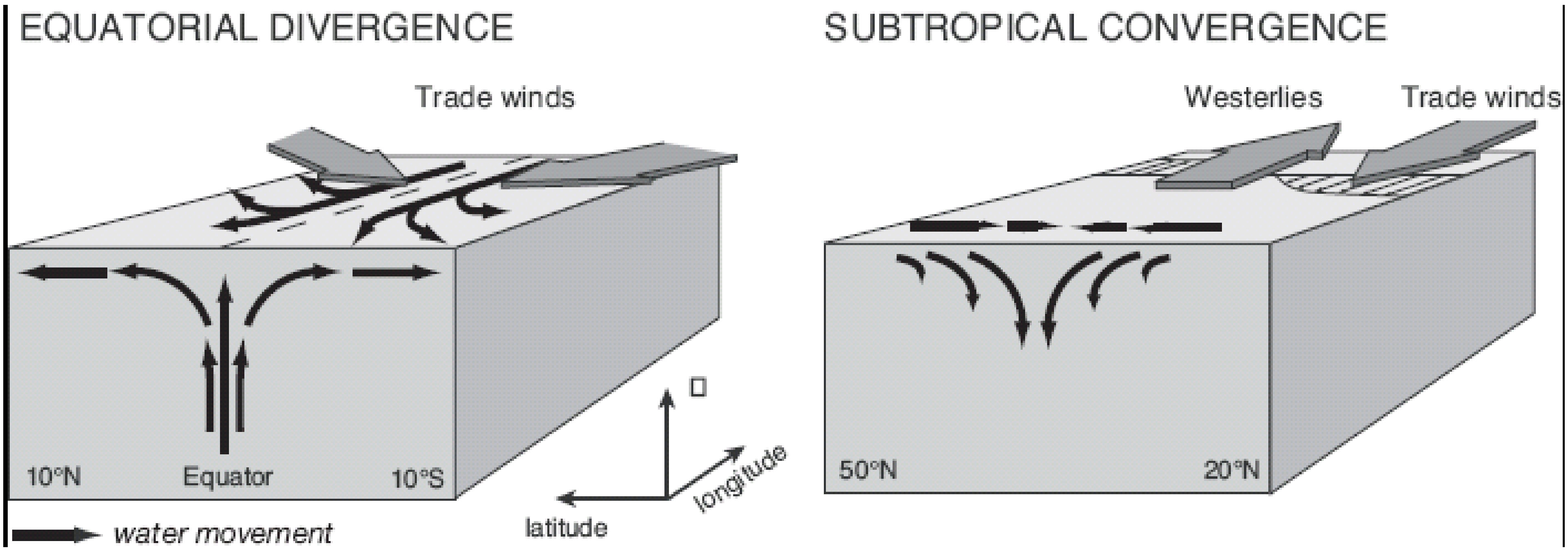
Upwelling and downwelling associated to the Ekman transport

cyclonic circulation **anticyclonic circulation**



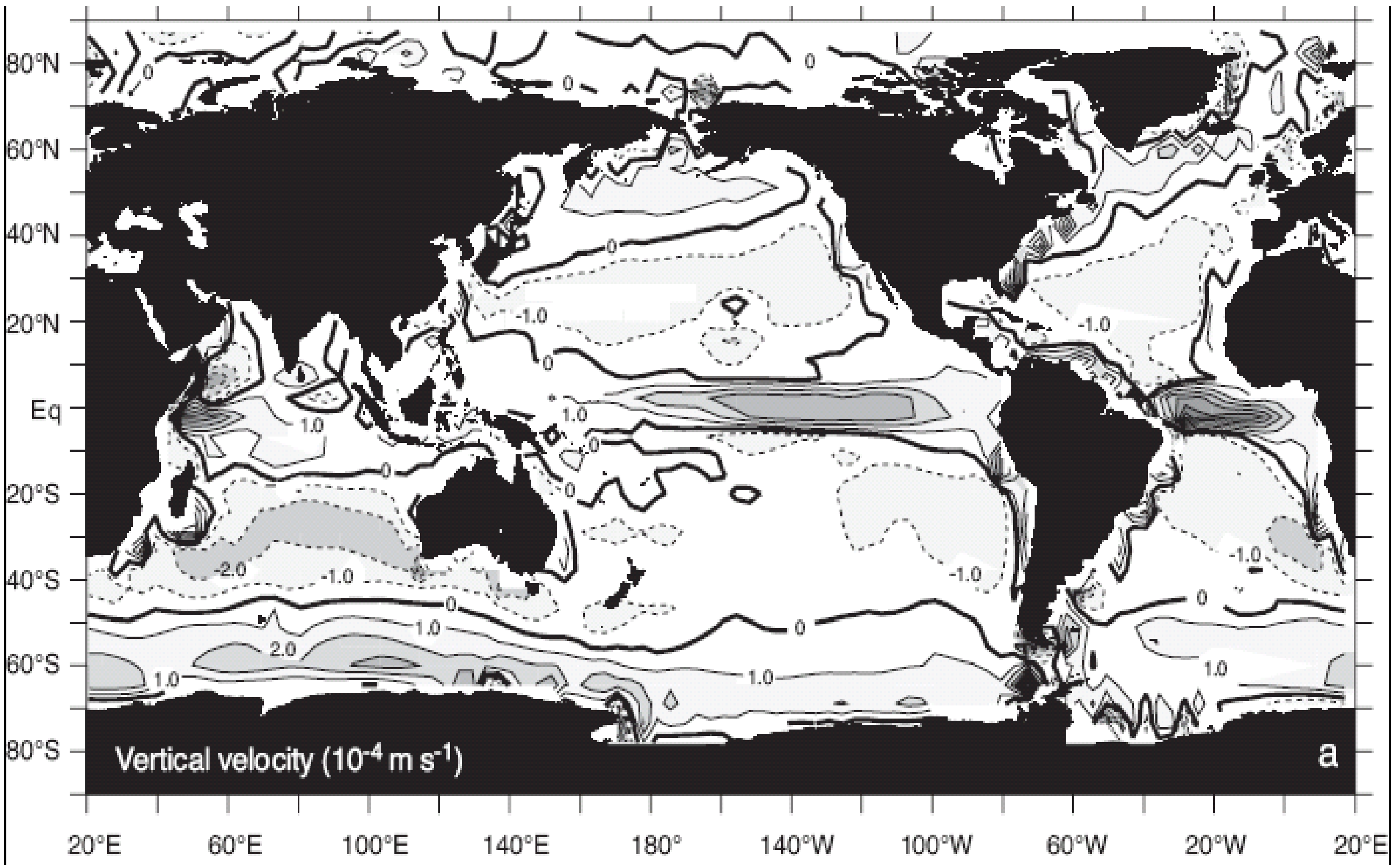
from Sarmiento & Gruber, 2006

and to equatorial divergence and subtropical convergence



from Sarmiento & Gruber, 2006

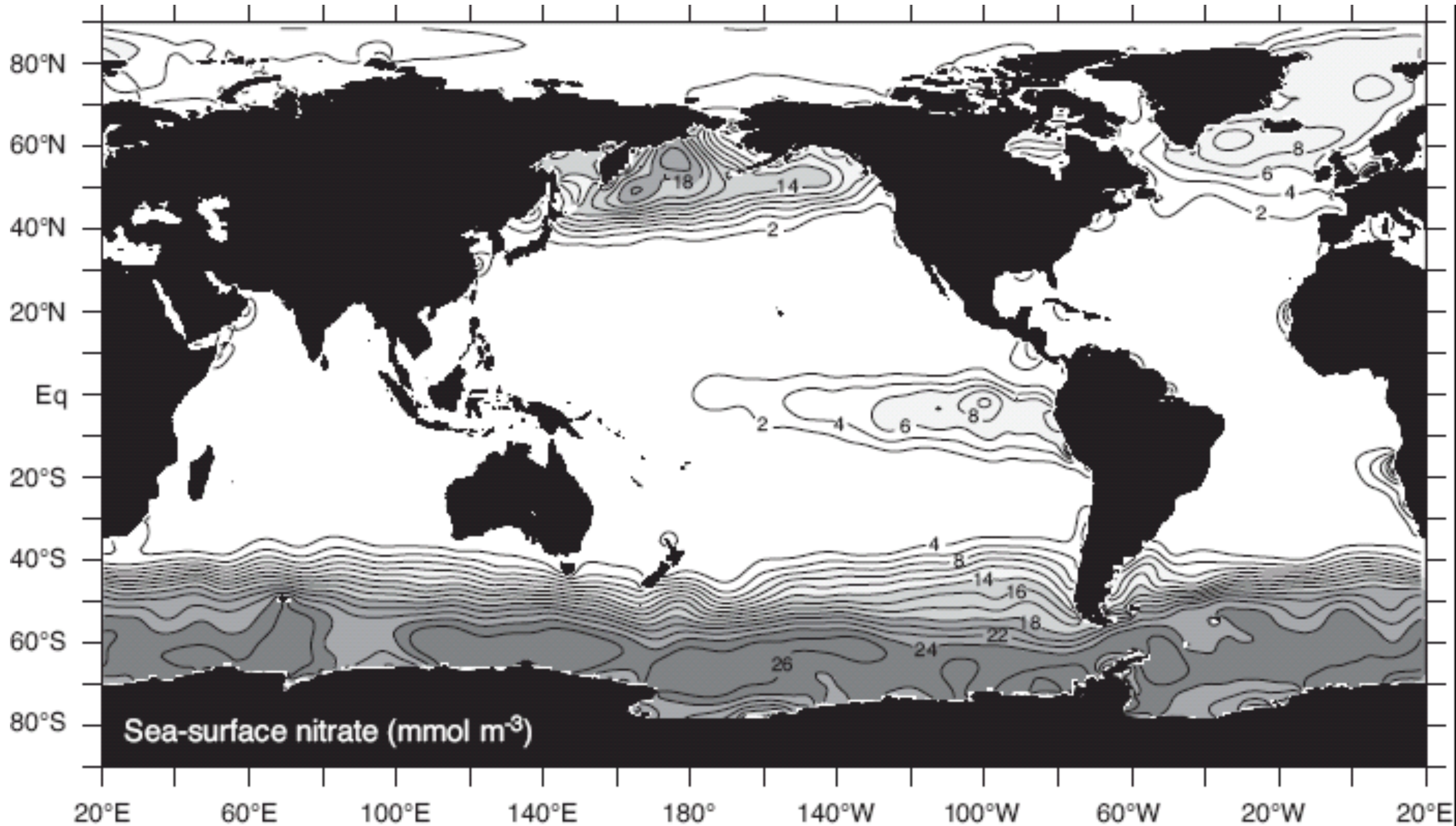
averaged vertical velocities



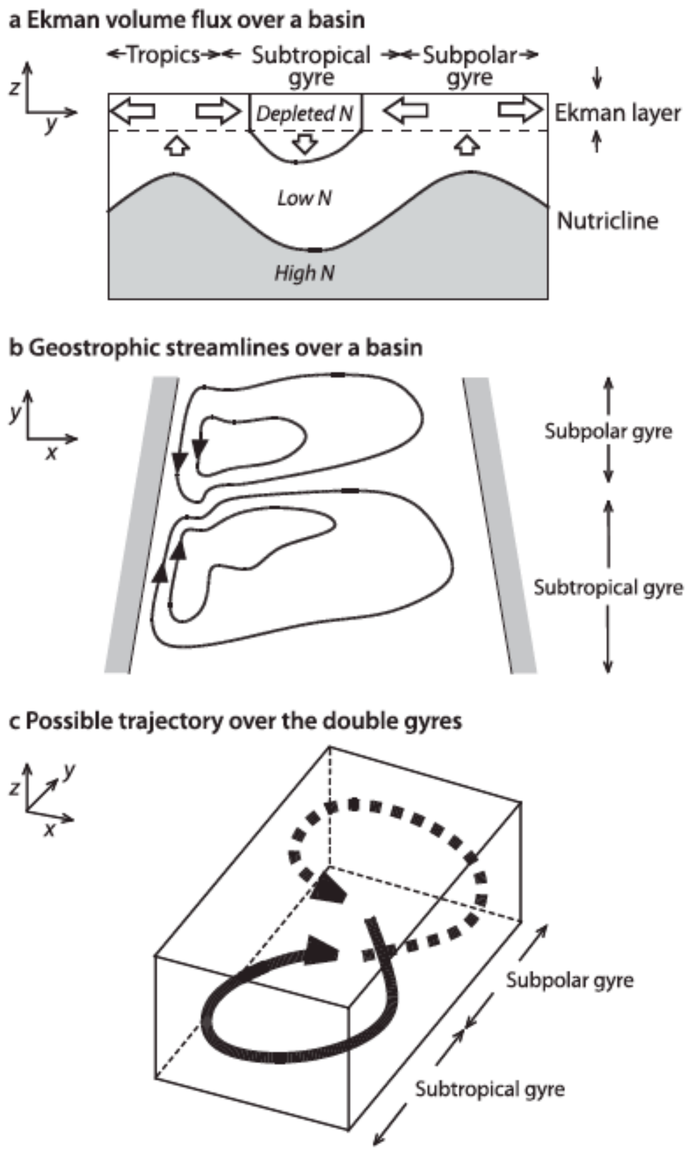
from Sarmiento & Gruber, 2006

Focusing on the averaged concentration of nitrate

observed



impact on biogeochemistry: production associated with the vertical velocities in the gyres



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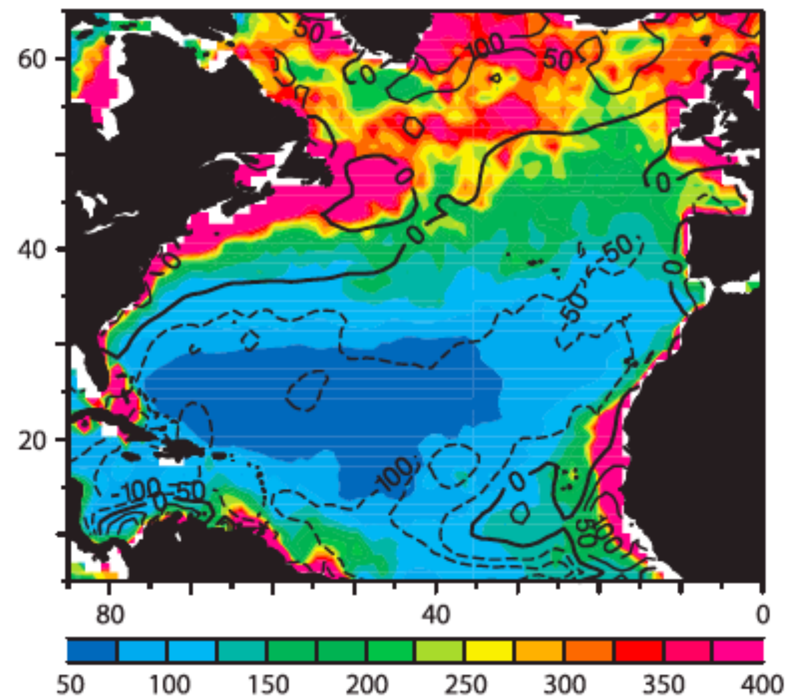
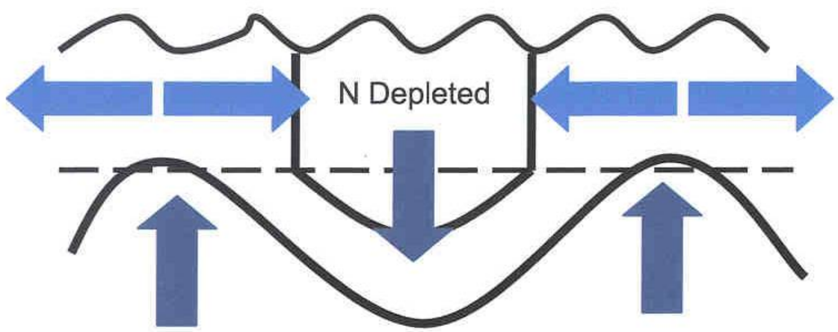
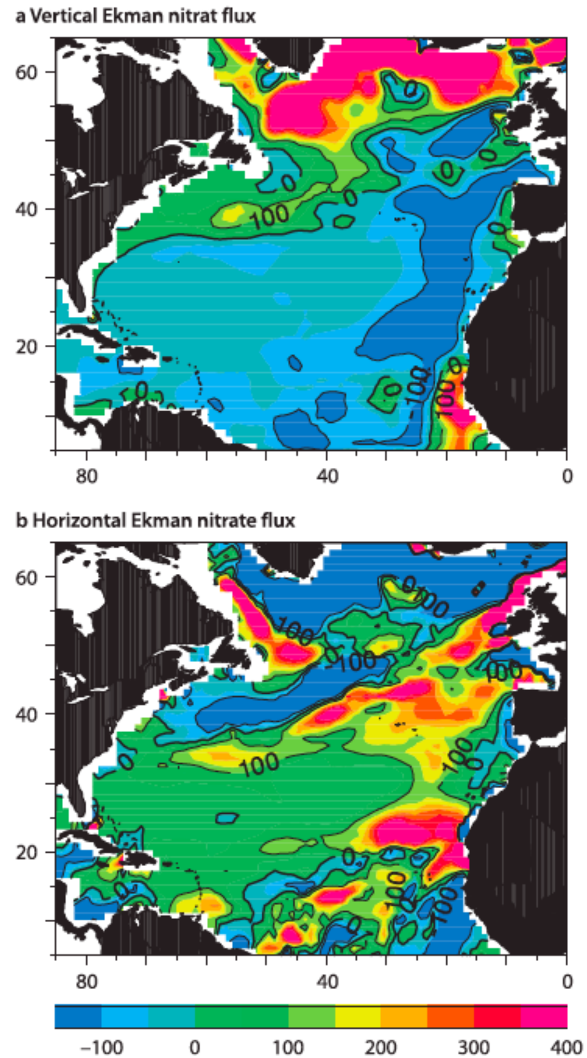


Fig. 2.10. Annual primary productivity (*colour shaded* in mol C m^{-2} yr^{-1}) and wind-induced (Ekman) upwelling (*solid contours* in m yr^{-1}). The annual primary productivity is inferred from satellite observations of surface chlorophyll by Sathyendranath et al. (1995) and the upwelling inferred from a wind-stress climatology. The primary productivity shows maximum values in the subpolar gyre and reduced values over the subtropical gyre, broadly following the patterns of gyre-scale upwelling (reproduced from Williams and Follows (1998b))

impact on biogeochemistry: production associated with the horizontal velocities

Lateral transfer of nitrate





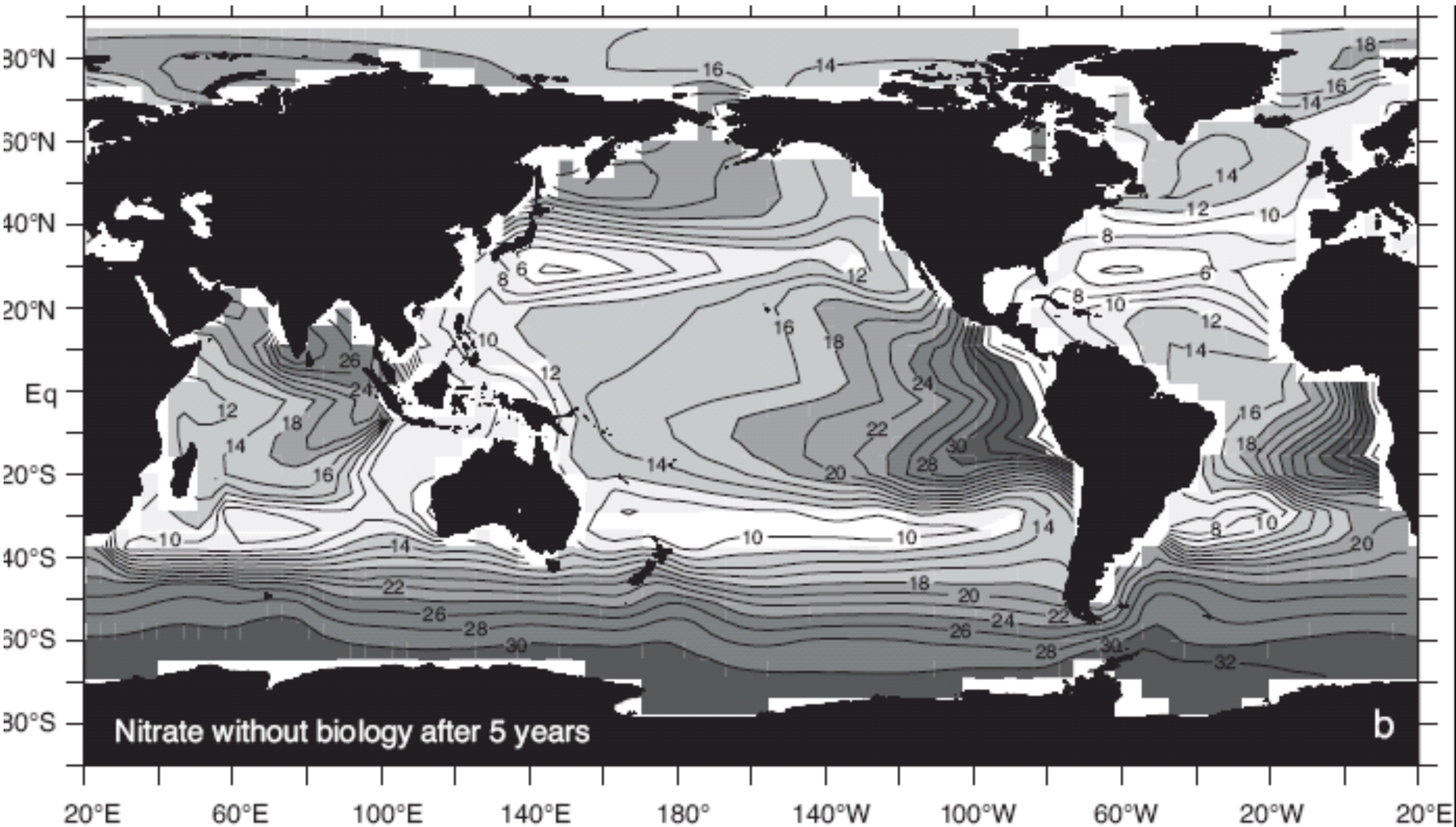
Williams & Follows(1998)

Tracer conservation equation

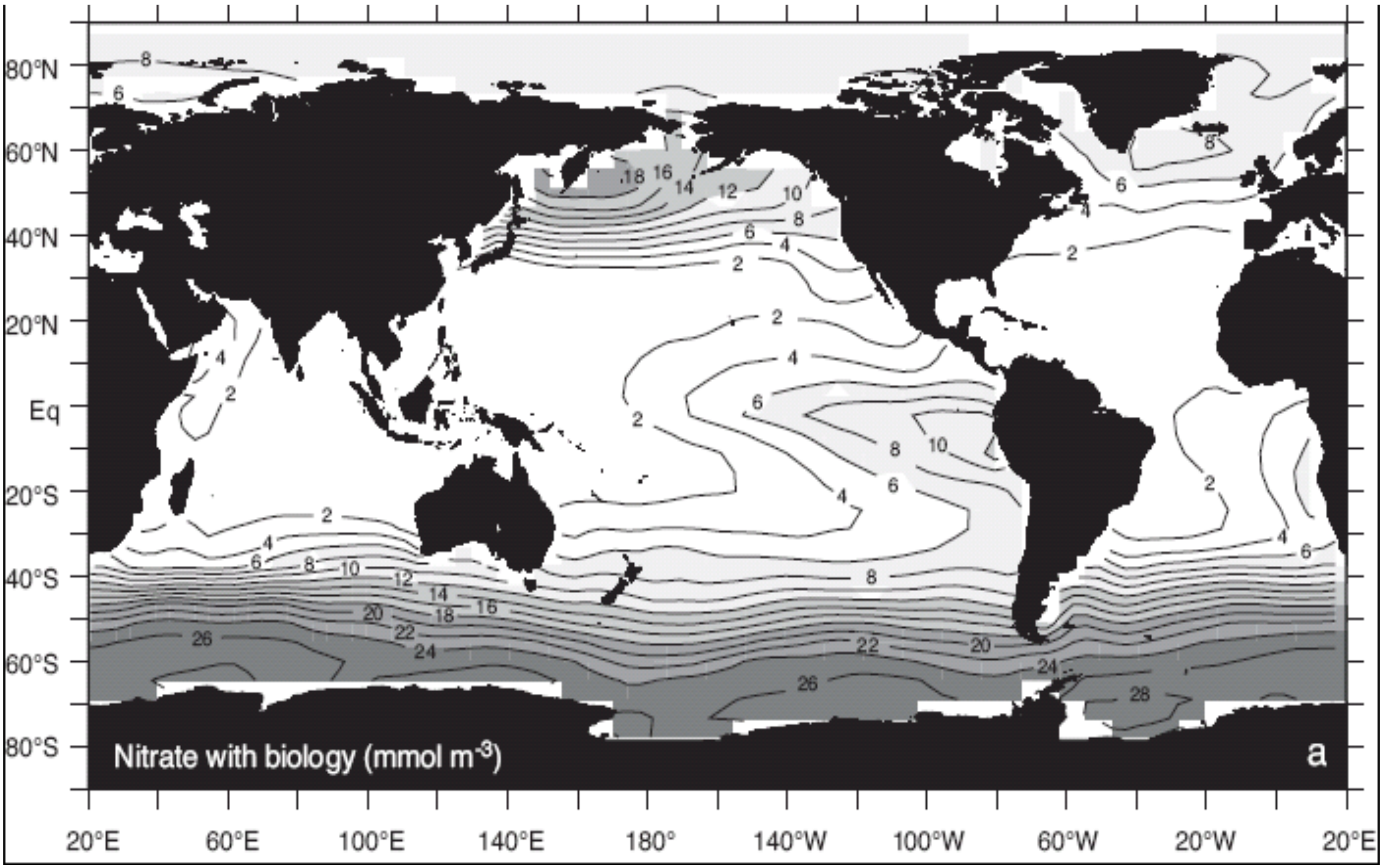
$$\frac{\partial C}{\partial t} = \text{Advection + diffusion + reaction}$$

The advection due to the large scale circulation (wind-driven + MOC) explains the average distribution of chemicals in the absence of biological reactions

modeled distribution of nitrate in the absence of biology



modeled distribution including biology



What else?

- Time-dependence: so far steady state circulation. By including time dependence we add a rich set of processes (waves, eddies, convection) and various modes of climate variability from intraseasonal to inderdecadal (ENSO, NAO, PDO, NPGO etc….)
- (Diffusion – molecular, turbulent diffusion...)