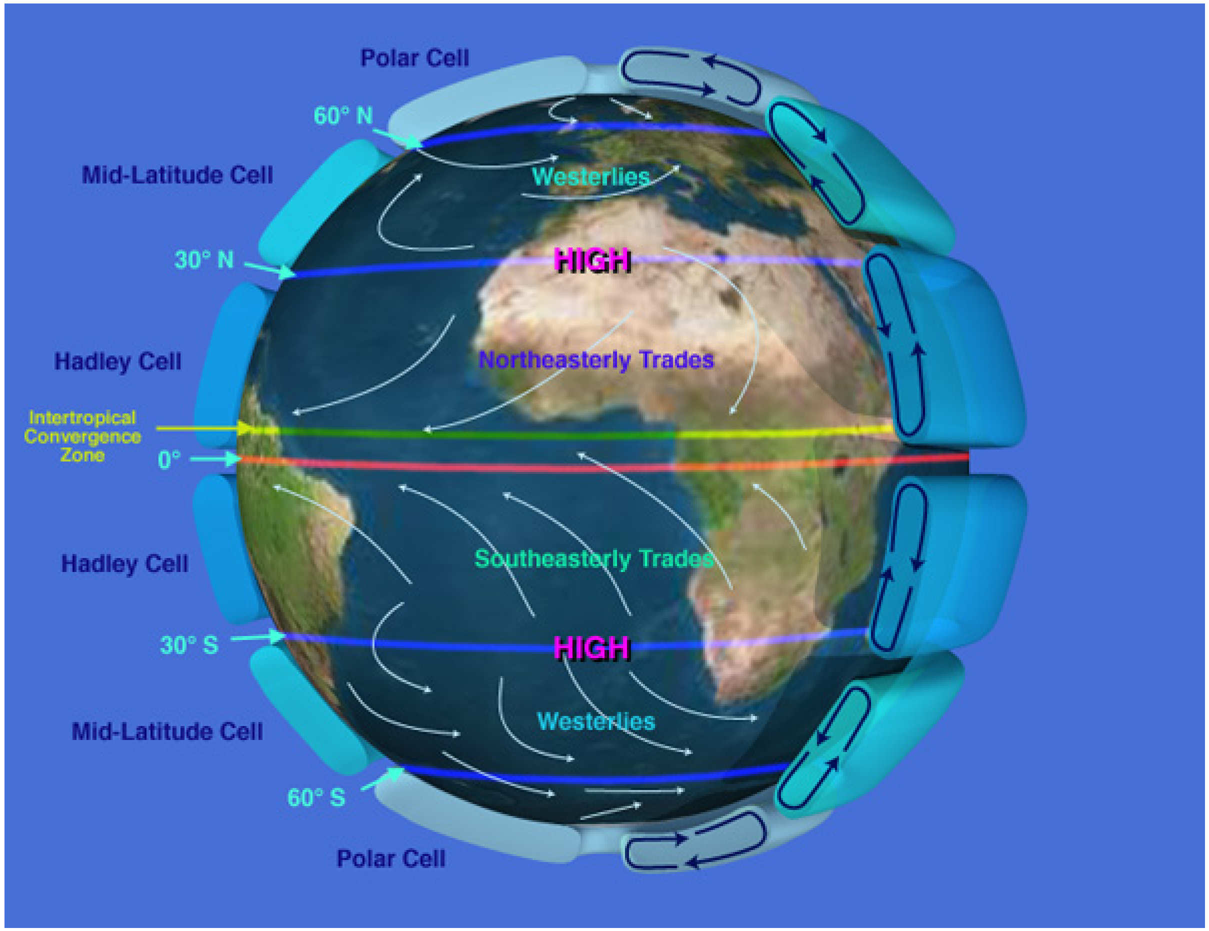
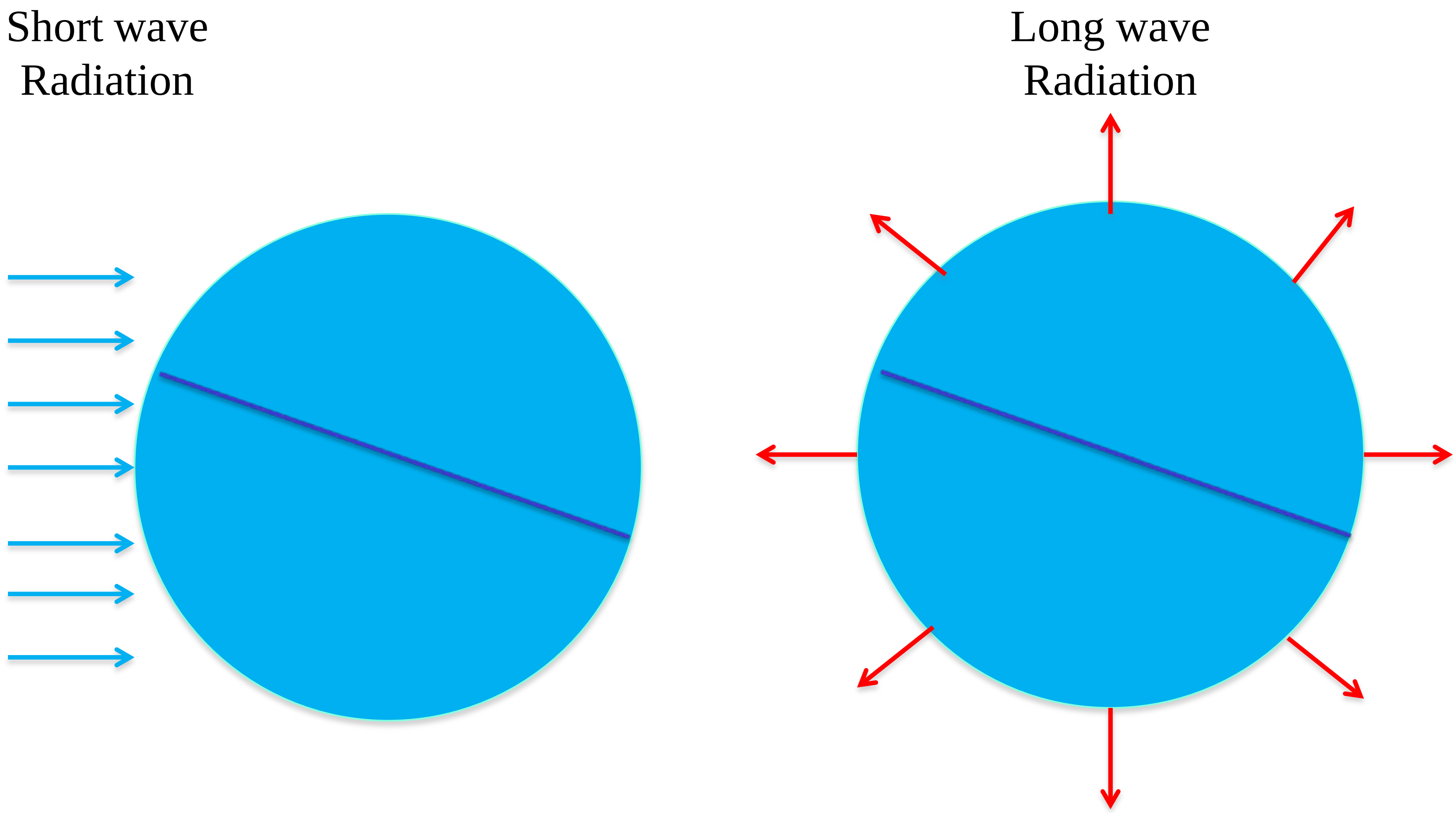
The Climate System is a GIANT engine moved by solar energy



Earth´s annual mean temperature is 15ºC. It is the result of the annual balance between incoming and outgoing radiation

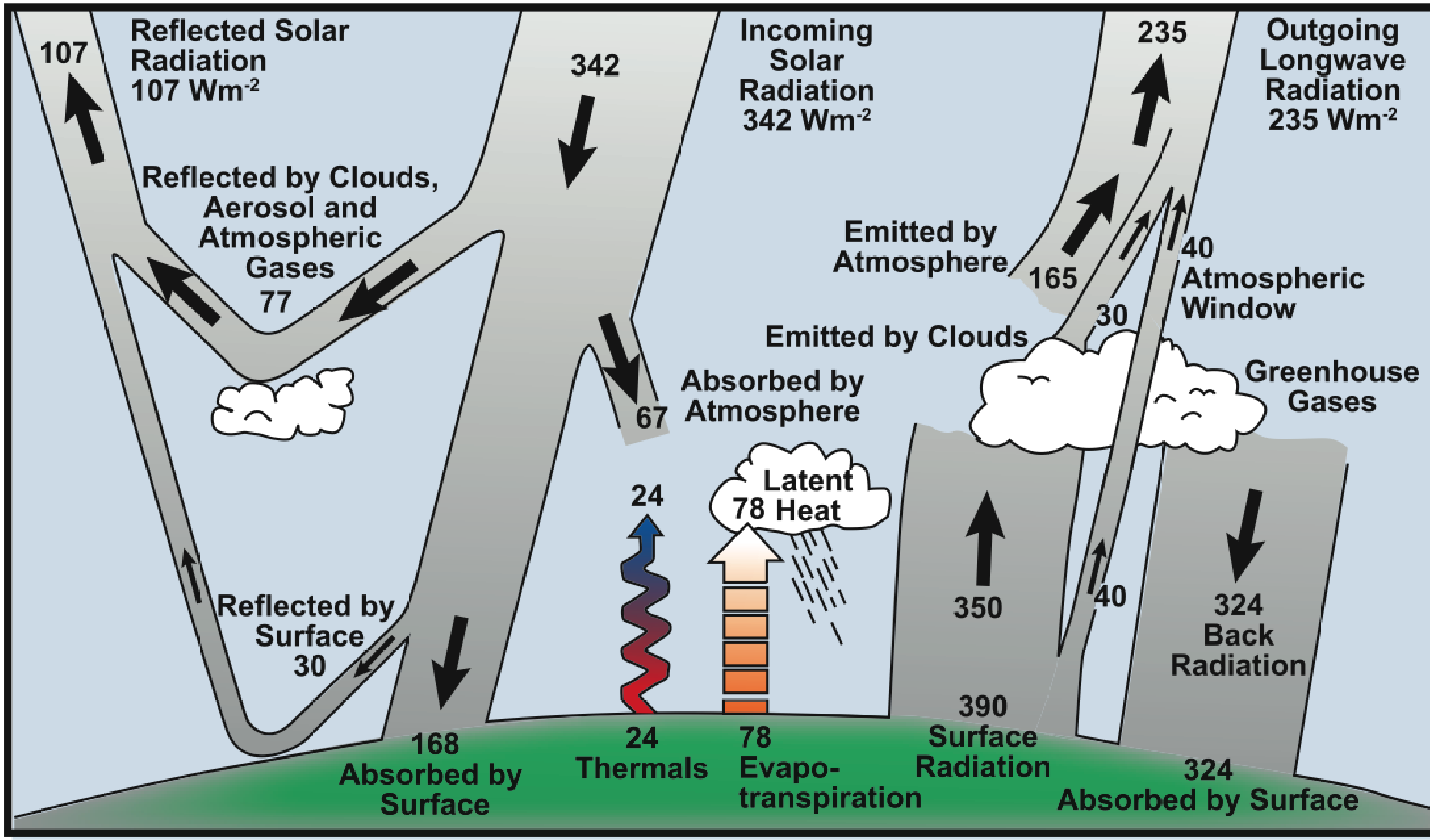


Incoming Radiation = Outgoing radiation

Main components of the Climate system

- Atmosphere
- Ocean
- Biosphere
- Lythosphere
- Cryosphere
- Antroposphere

Earth's annual mean energy balance



Energy balance. Incoming Radiation = Outgoing radiation

Kiehl and Trenberth (1997)

Heat transfer from Eart's surface to the Atmosphere

Radiation: Longwave radiation

Latent heat (Hidden heat).

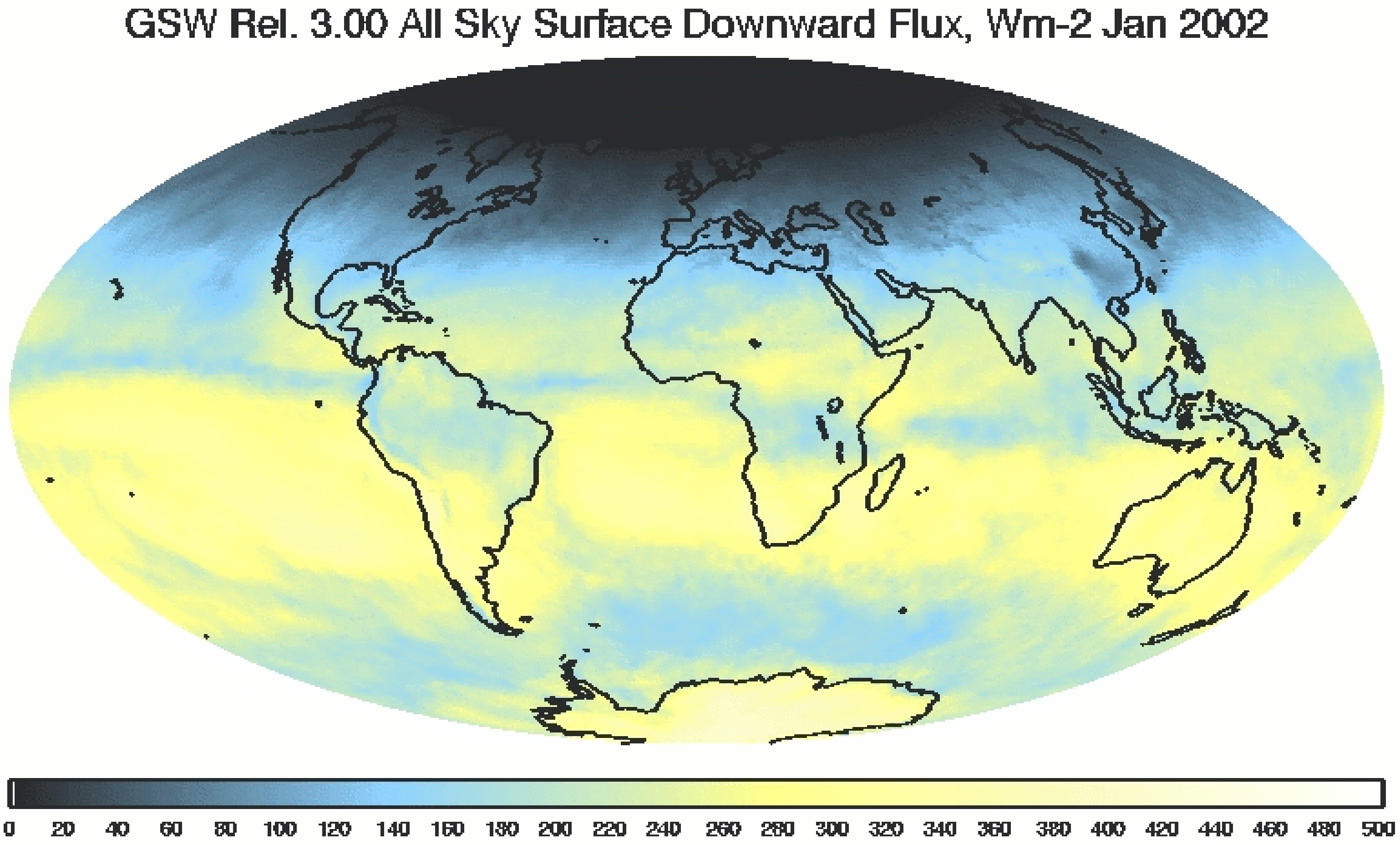
Flux of heat during evaporation

and released during condensation

Conduction and convection.

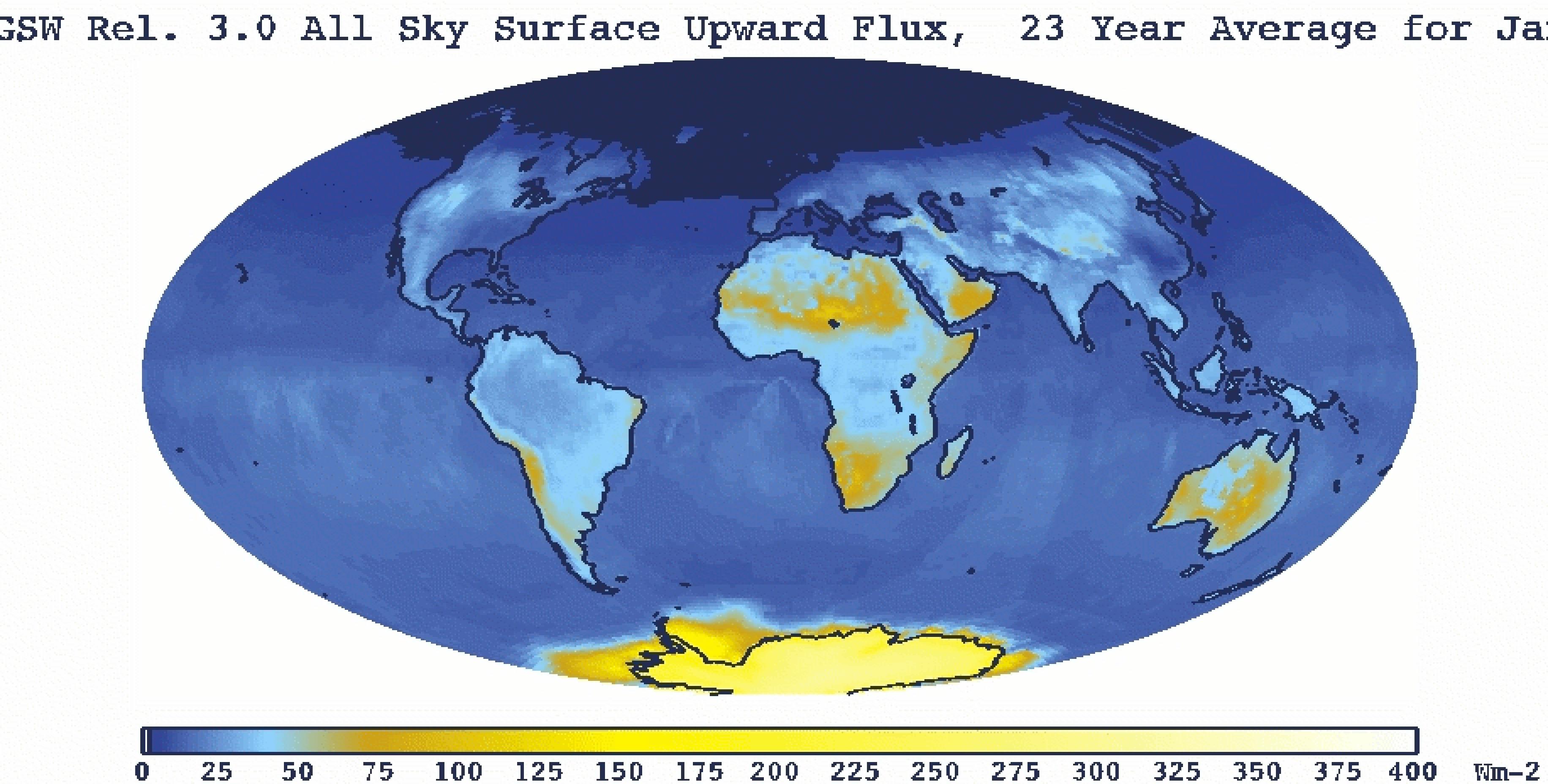
Heat is transferred by direct contact between the surface and the air layer inmediately above the ground or sea surface. The hot air particles rise due to thermal convection.

Seasonal changes in solar radiation that reaches the Earth's surface

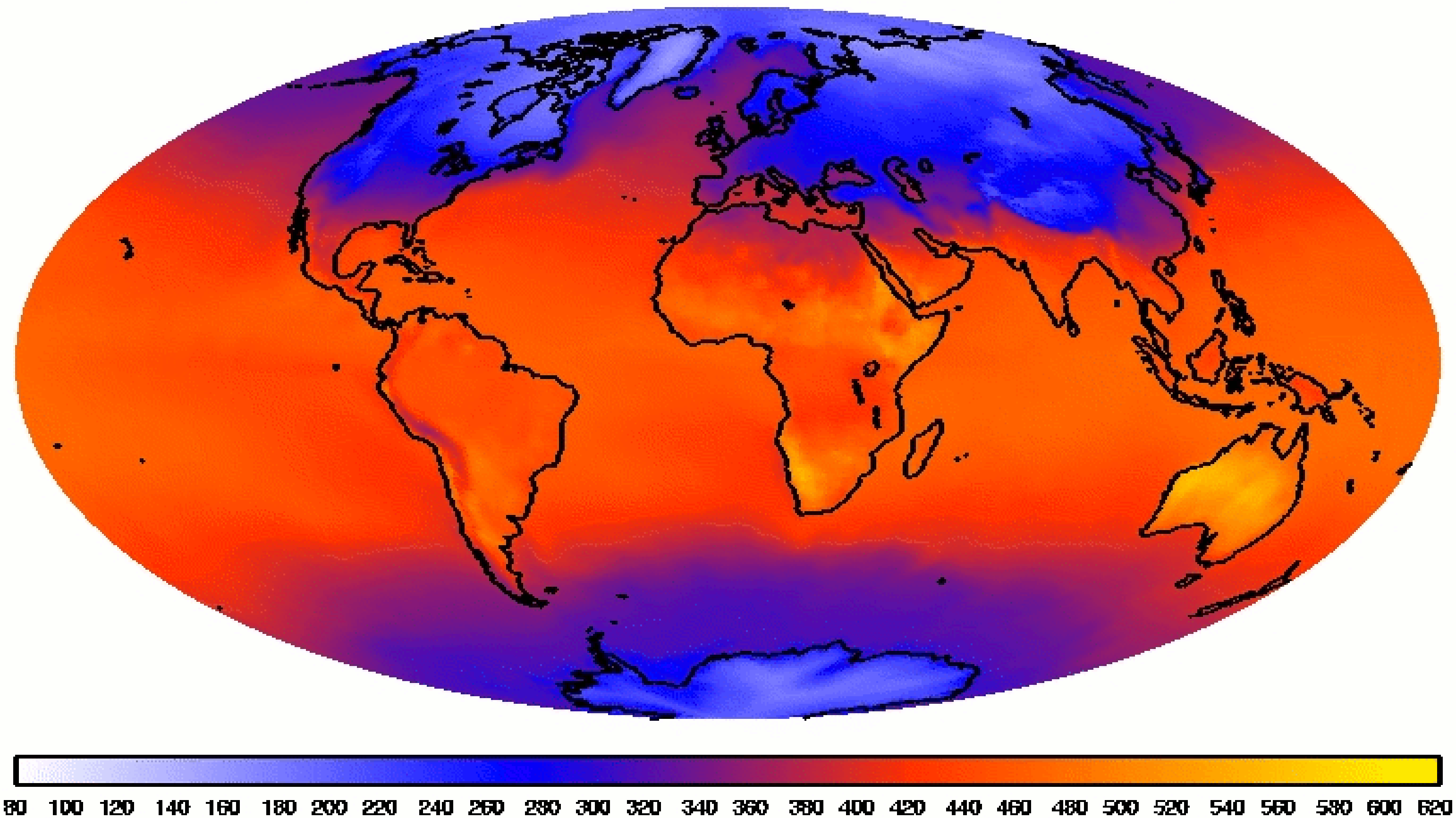


http://gewex-srb.larc.nasa.gov/

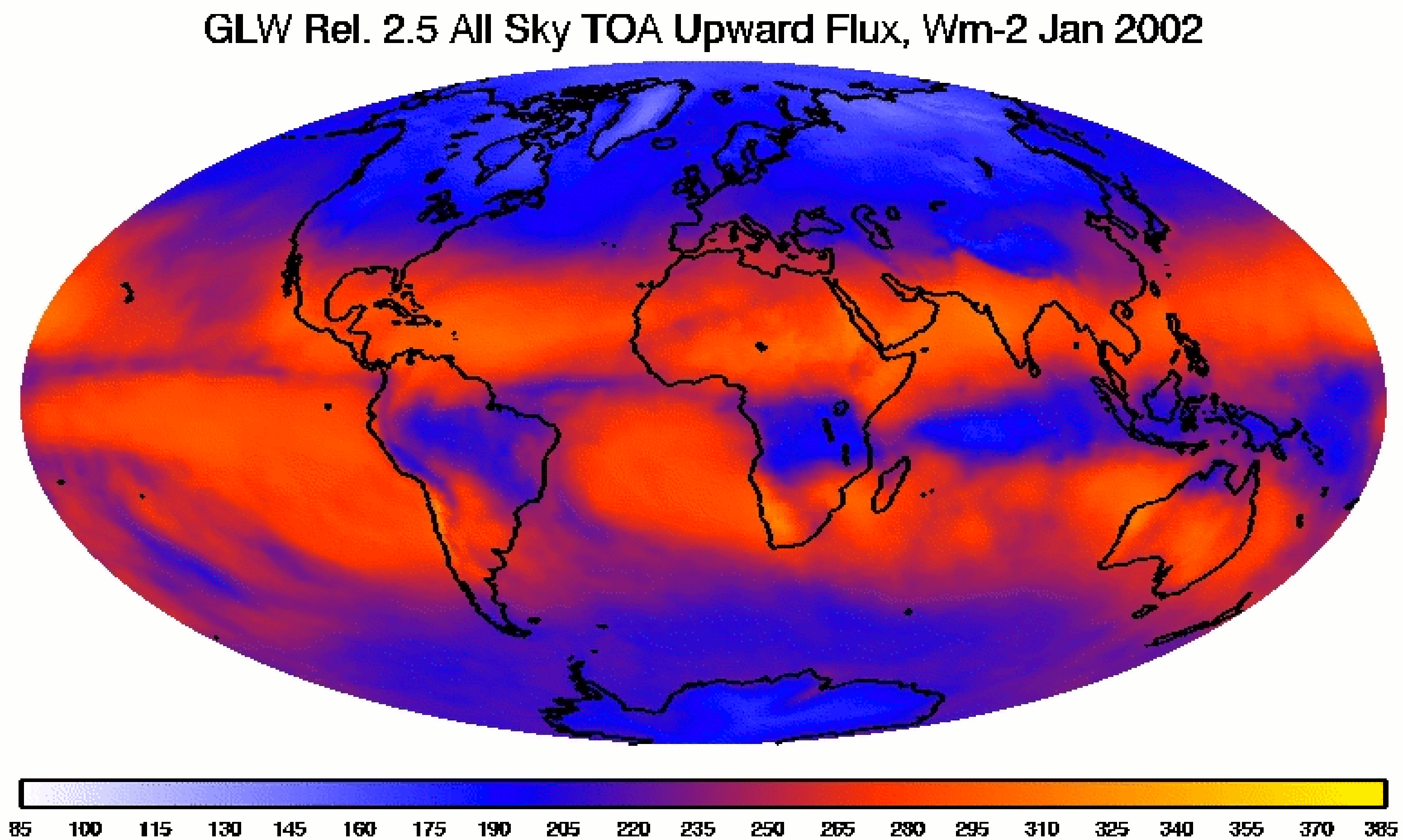
http://gewex-srb.larc.nasa.gov/



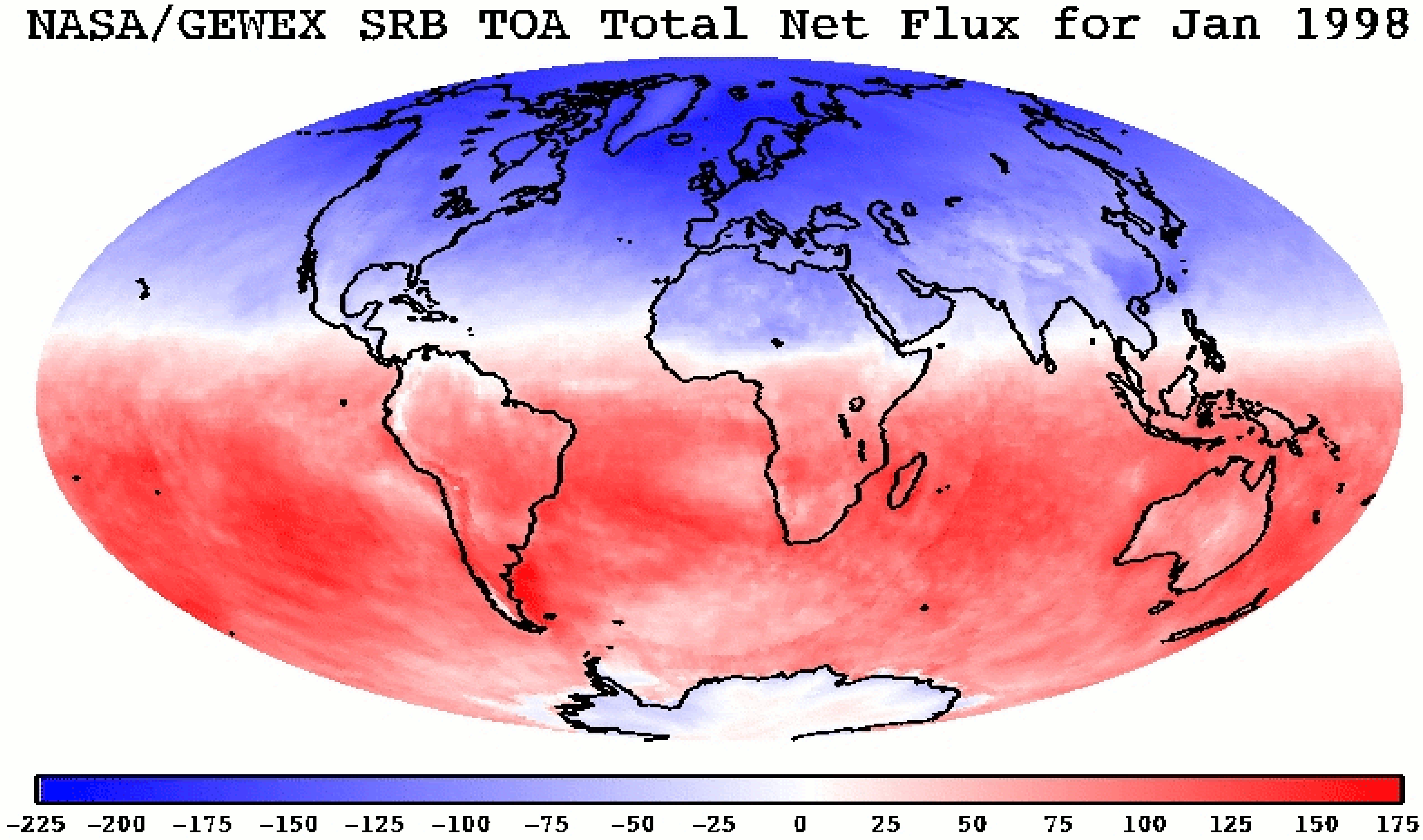
GLW Rel. 2.5 All Sky Surface Upward Flux, Wm-2 Jan 2002



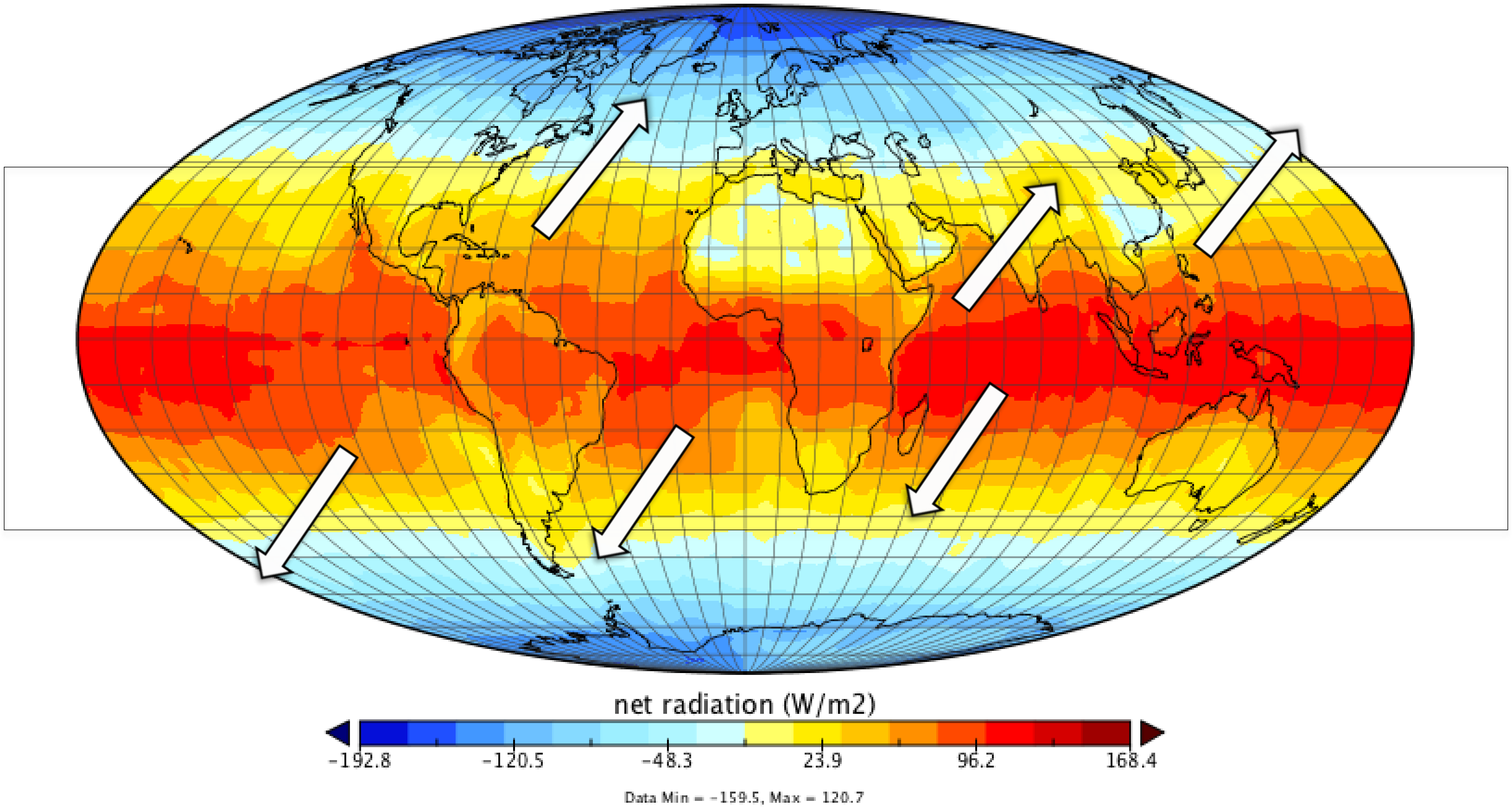
http://gewex-srb.larc.nasa.gov/



http://gewex-srb.larc.nasa.gov/

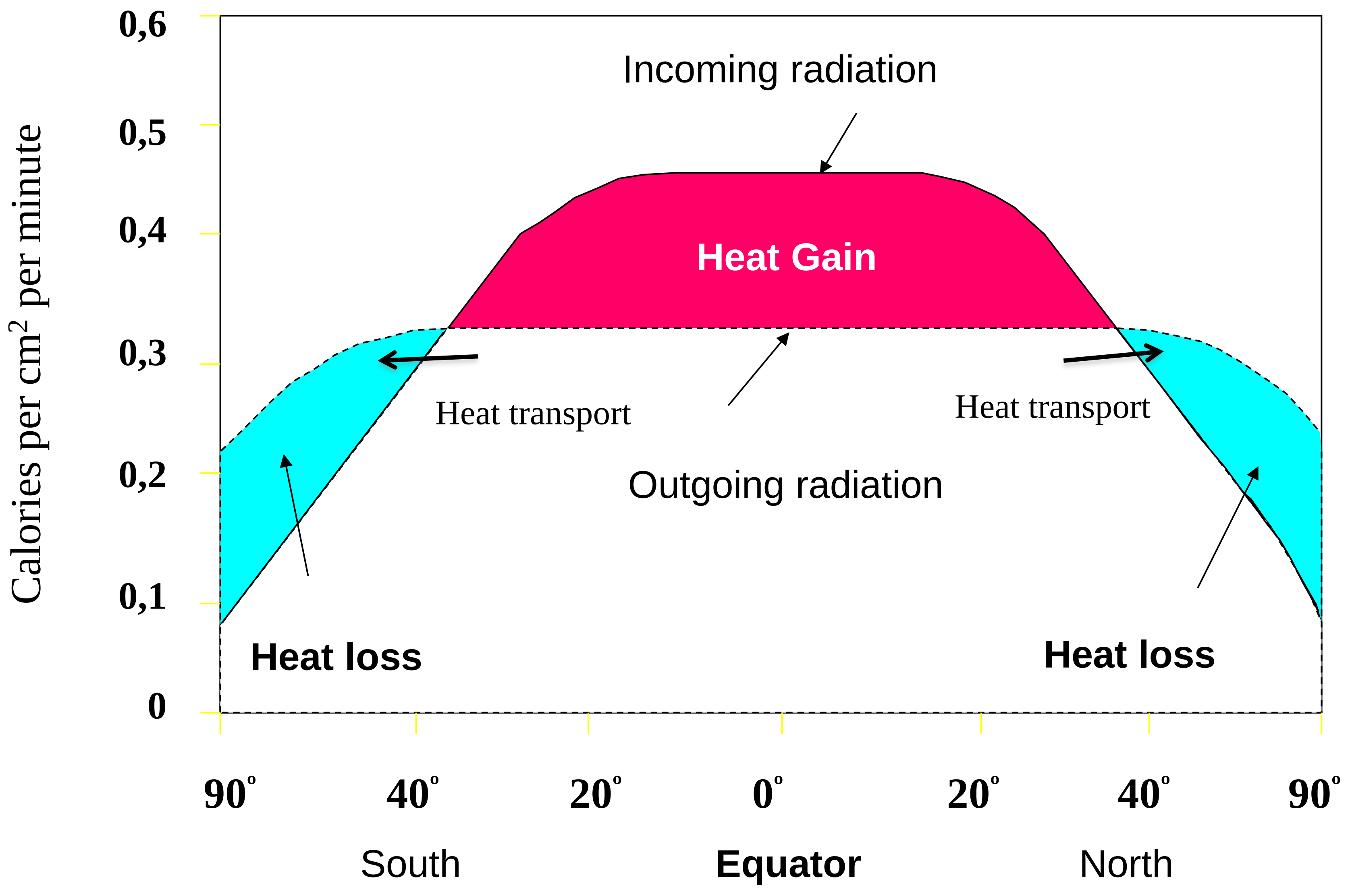


ANNUAL MEAN NET RADIATION

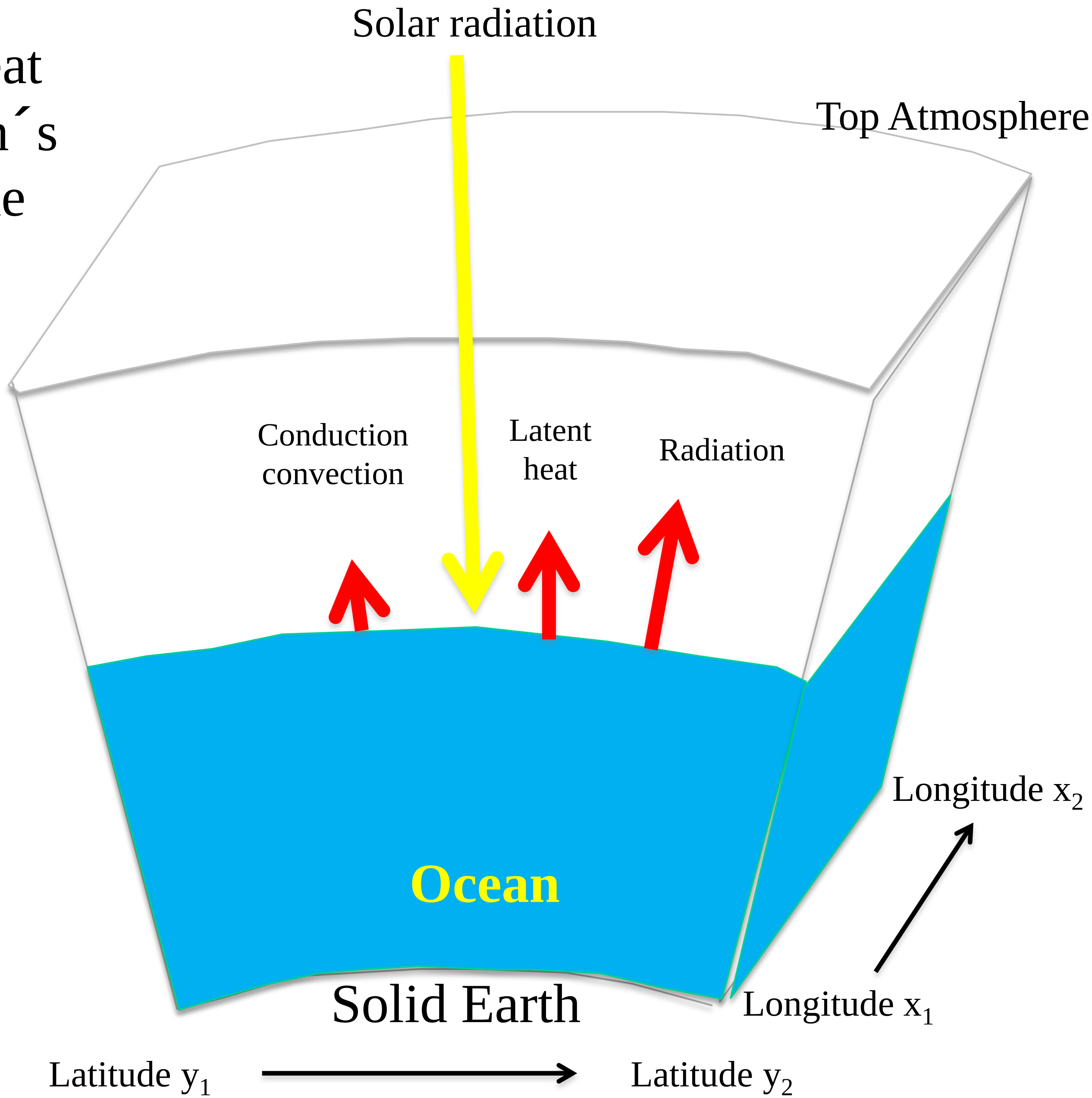


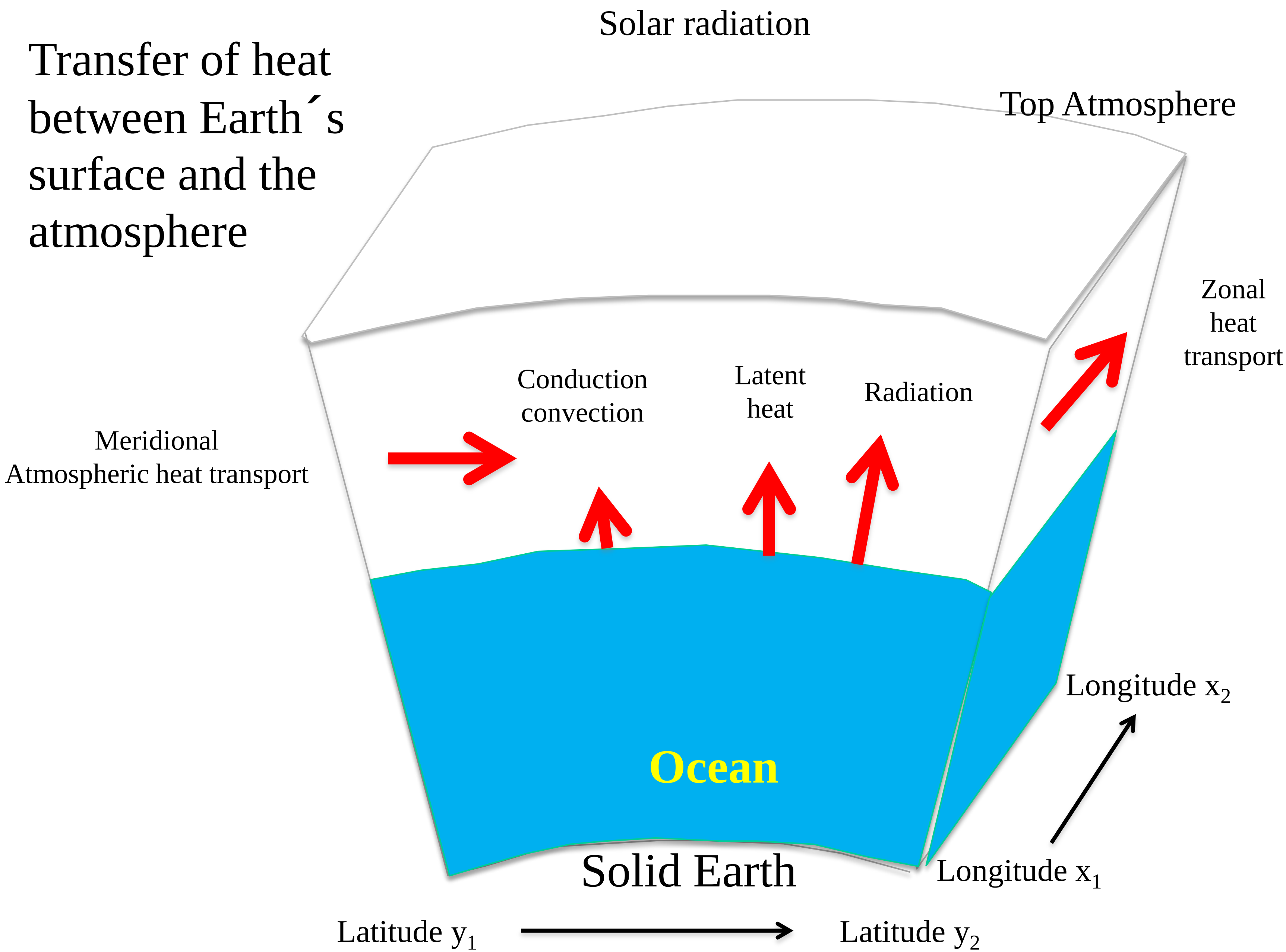
The atmosphere and Ocean transfer heat from the regions of heat excess to the regions of deficit

Annual radiation budget

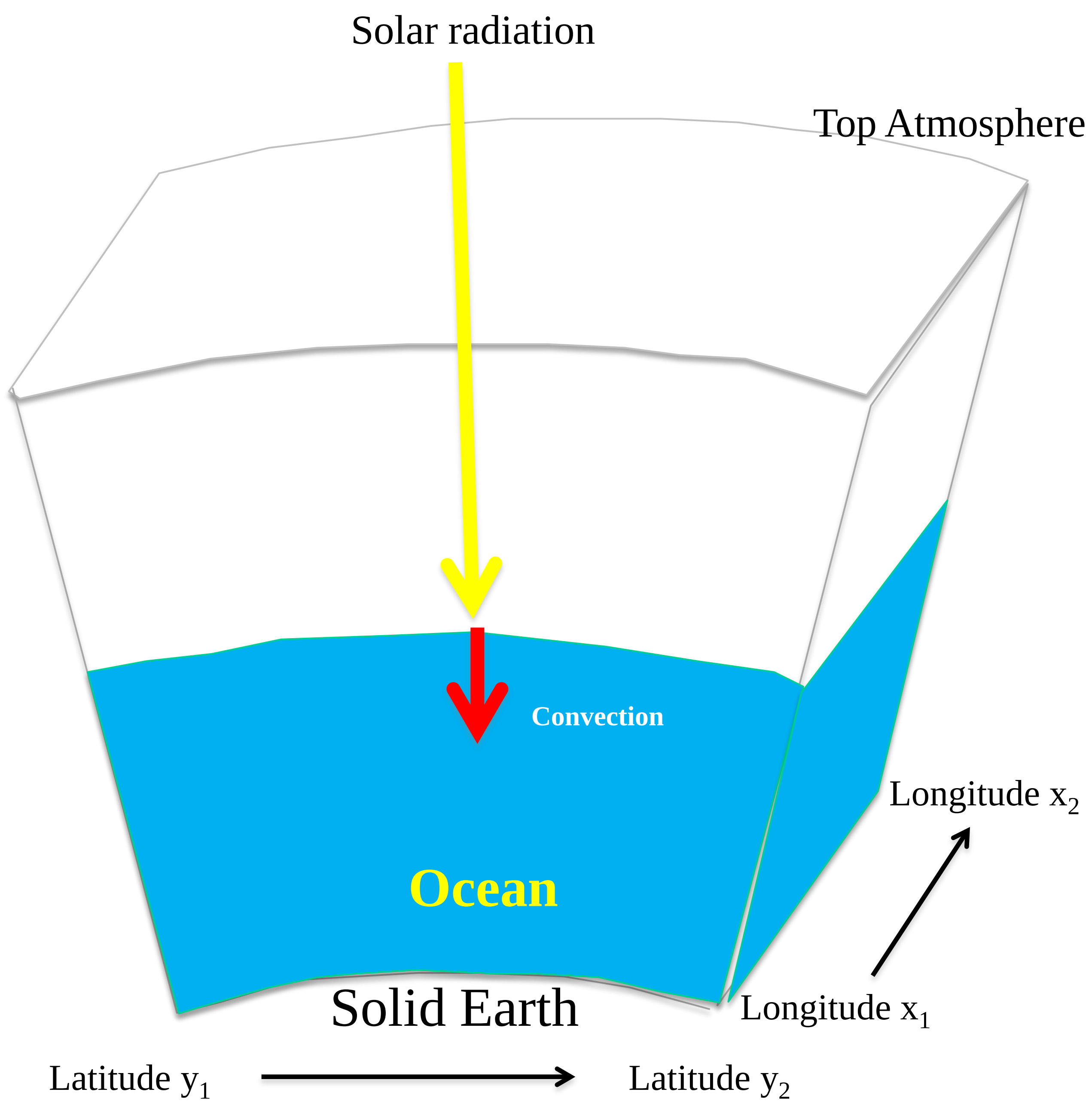


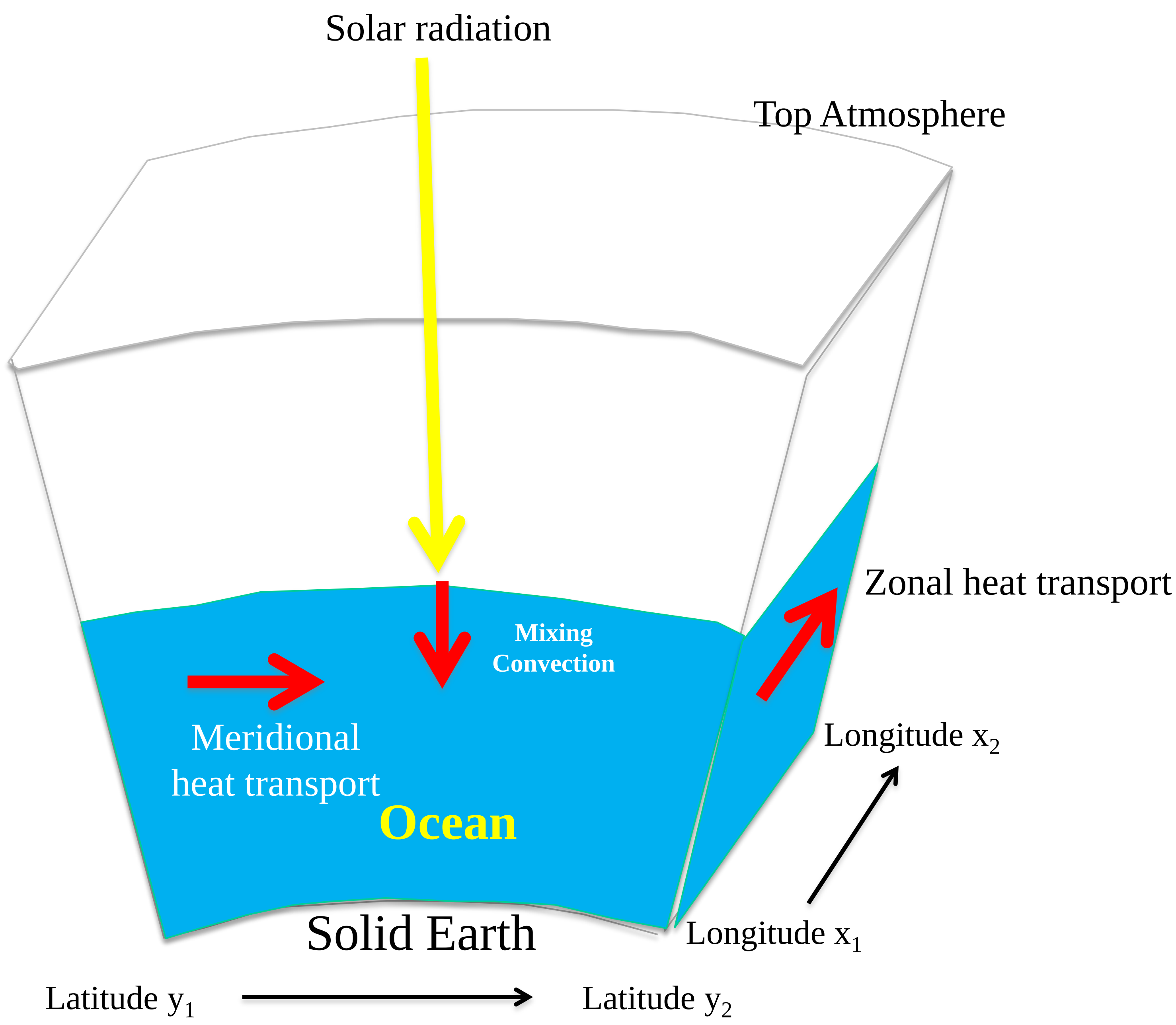
Transfer of heat between Earth´s surface and the atmosphere



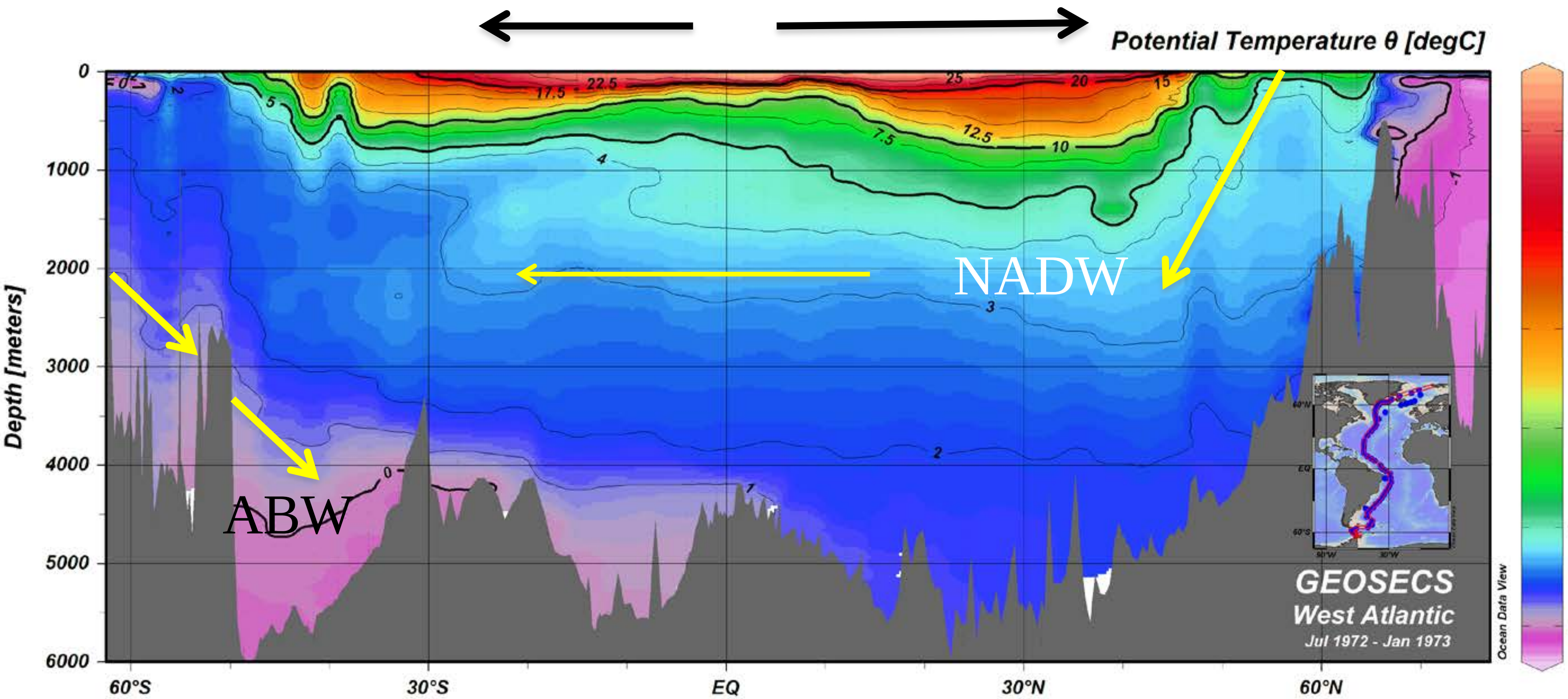


Transfer of heat between Earth´s surface and the atmosphere
Solar radiation
Top Atmosphere
Zonal heat transport
Conduction convection
Latent heat
Radiation
Meridional Atmospheric heat transport
Ocean
Solid Earth
Longitude x_2
Longitude x_1
Latitude y_1
Latitude y_2


Solar radiation
Top Atmosphere
Convection
Ocean
Longitude x_2
Longitude x_1
Solid Earth
Latitude y_1
Latitude y_2

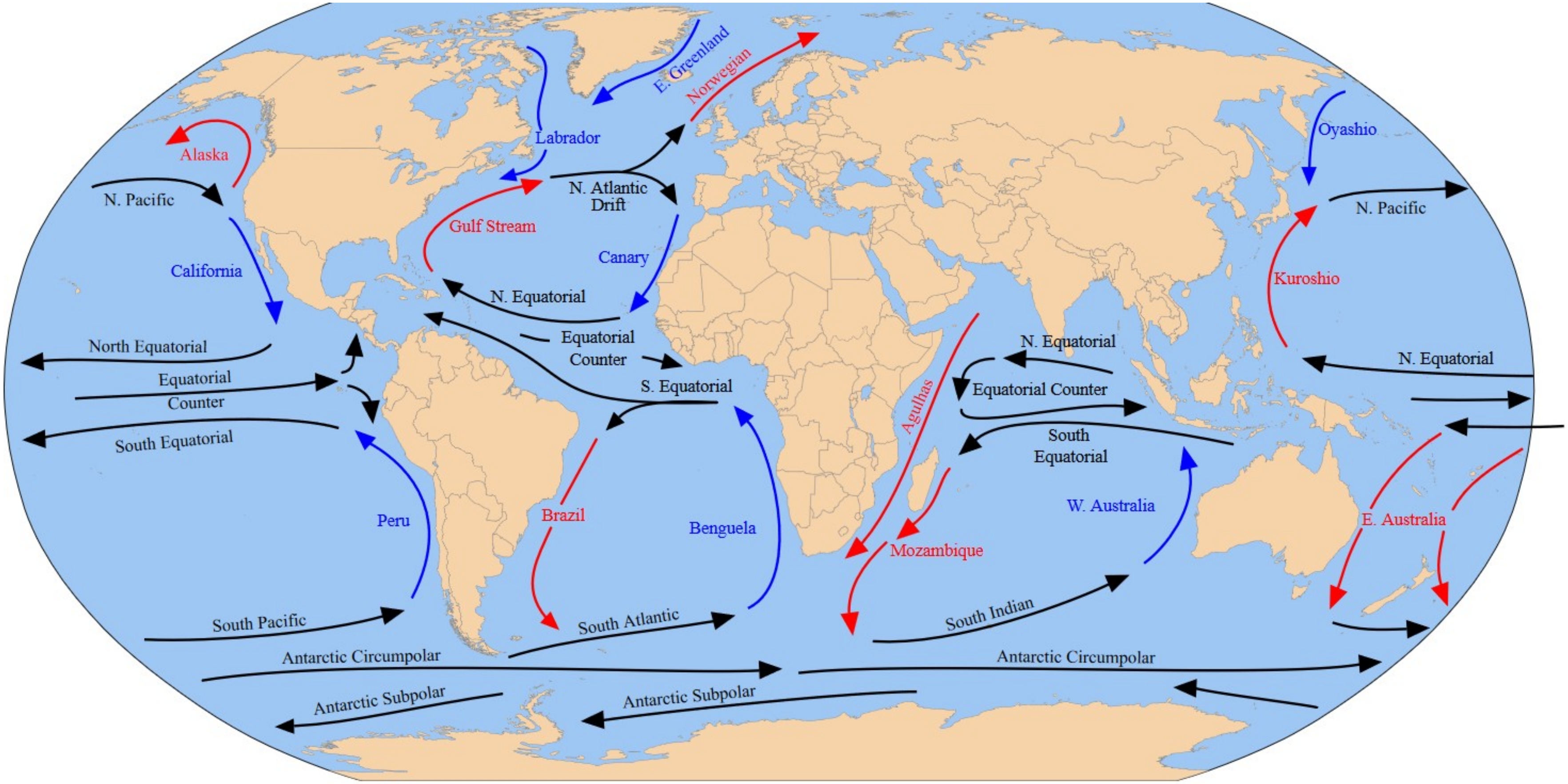

Solar radiation
Top Atmosphere
Zonal heat transport
Mixing
Convection
Meridional
heat transport
Ocean
Longitude x2
Longitude x1
Solid Earth
Latitude y1
Latitude y2

Zonal and Meridional heat transport in the Ocean are mainly driven by sea surface circulation and thermohaline circulation

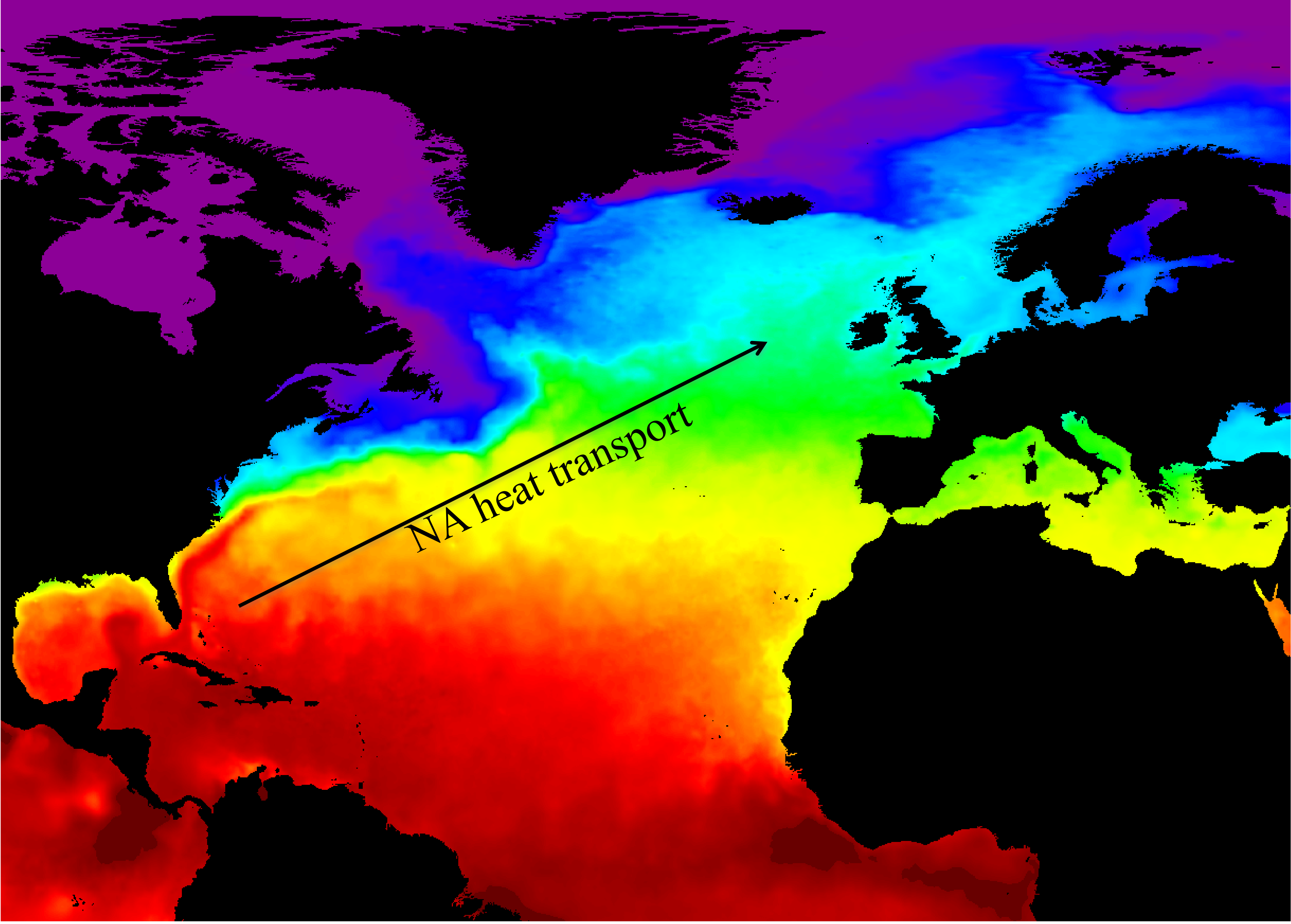


Ocean currents continuously move heat from low to high latitudes and from surface to deeper waters. The Ocean can absorb sunlight in one place, increasing the heat content and release it thousands of km away and decades later.

Sea surface circulation is driven by winds and consequently by atmospheric circulation



In the tropics, heat mainly moves westward, while in midlatitudes it moves eastward

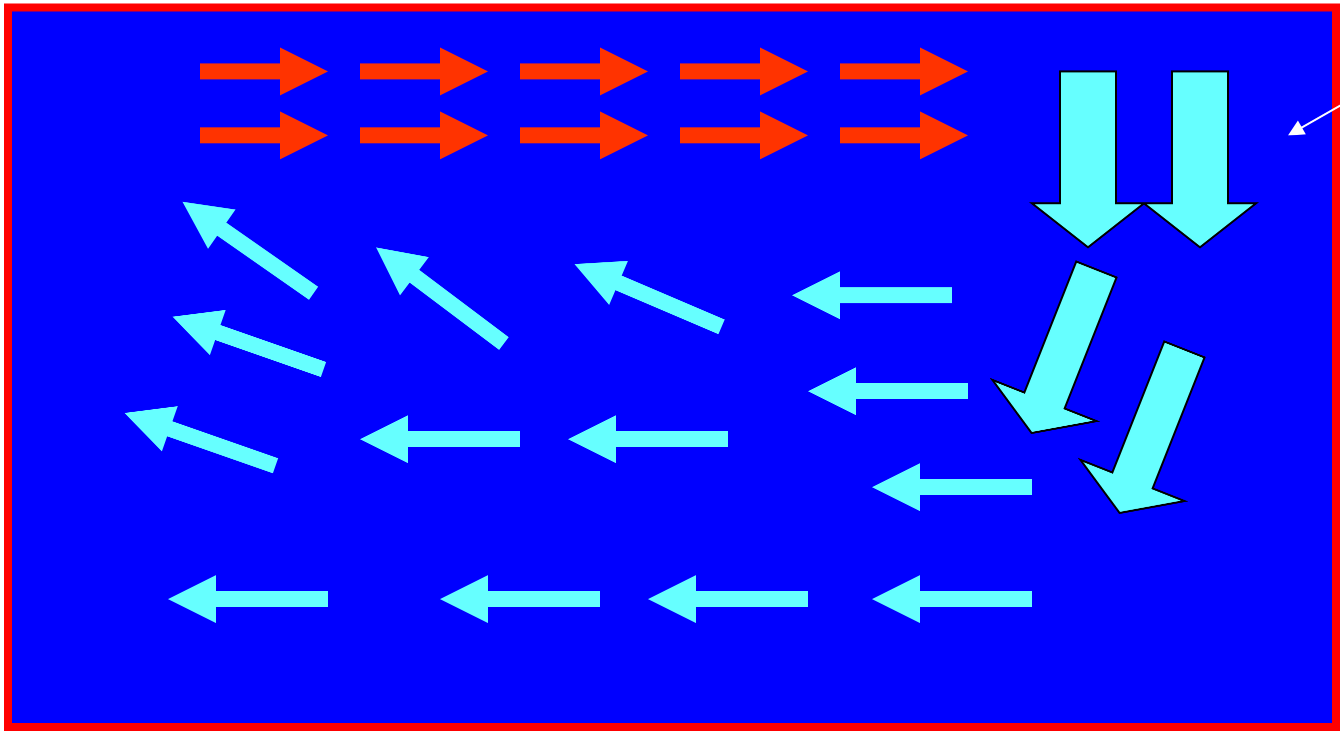

NA heat transport

Heat transport in the Atlantic is mainly associated to Meridional ocean overturing

Greenland-Norway Labrador seas

High heat flux towards the North Atlantic

High heat loss to the atmosphere



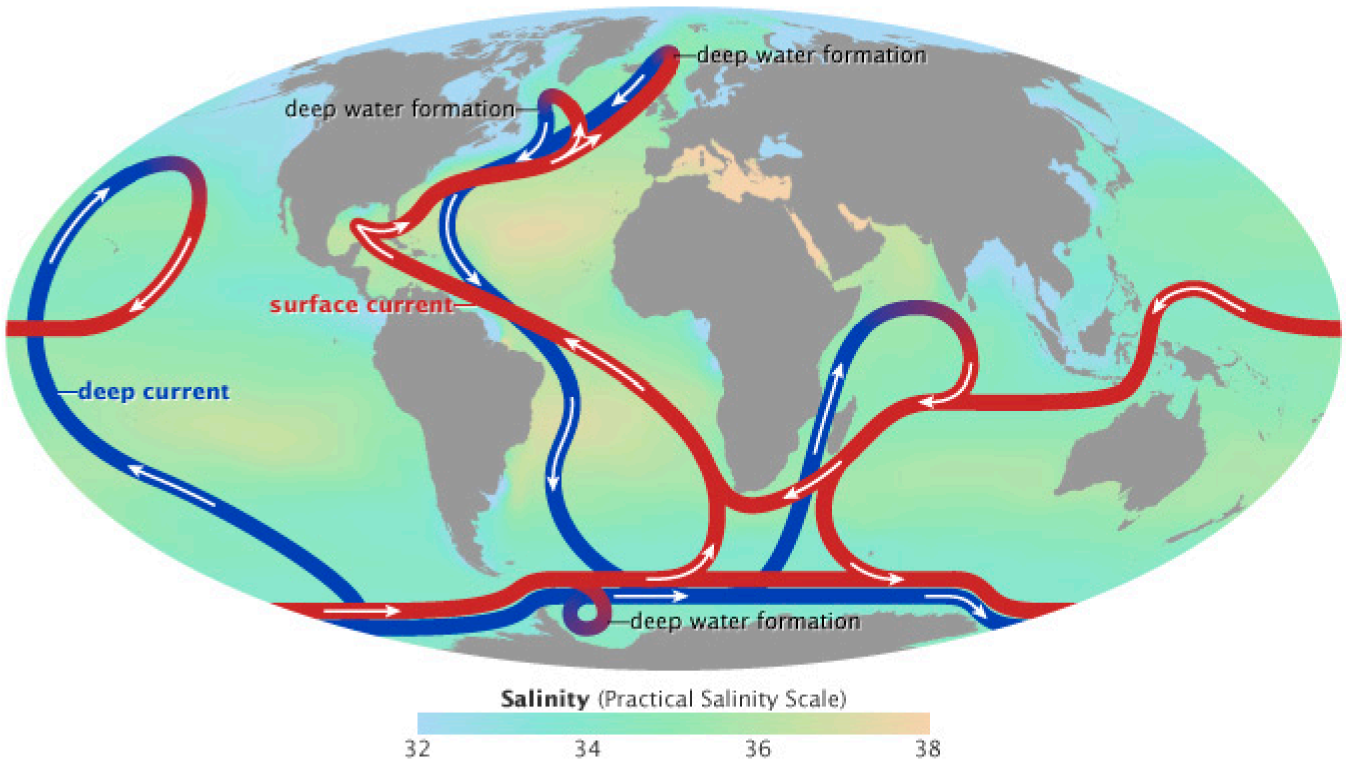
Downwelling

$17\ 10^6\ m^3/s$

Equator

70º N

The global oceanic conveyor belt



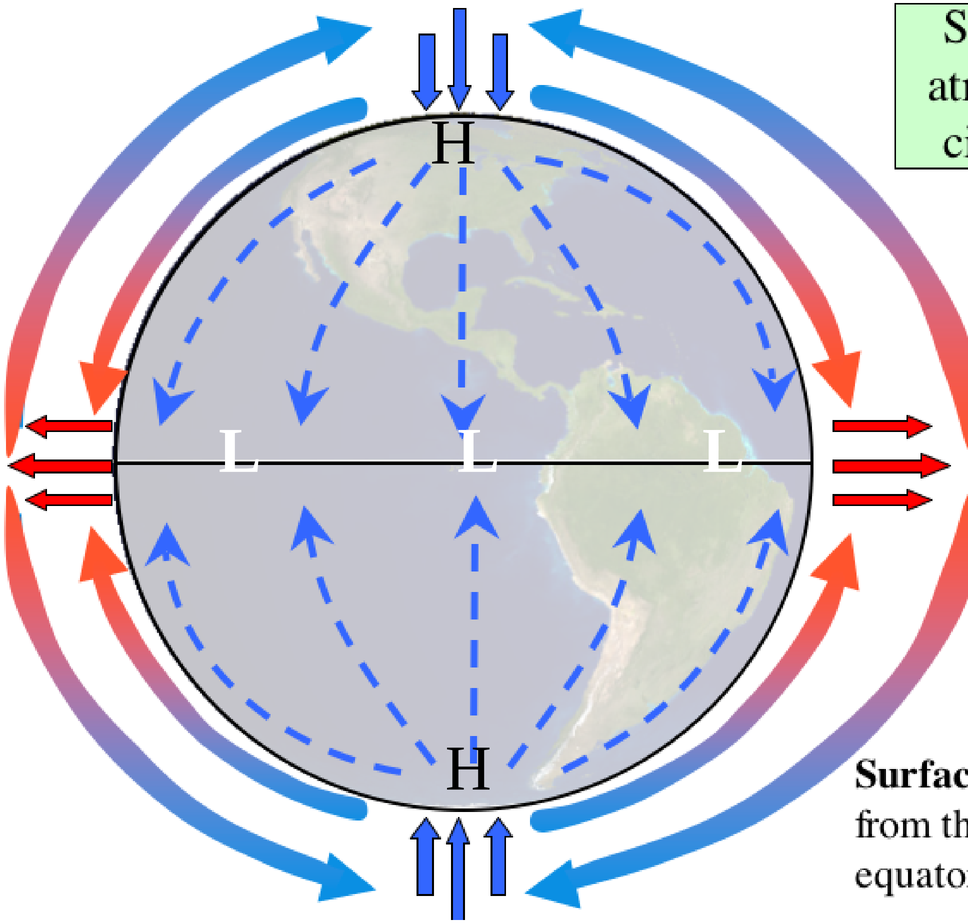
The surface warm and salty water from the North Atlantic move northward, loose heat to the atmosphere and cools, getting denser and sinking in the Labrador, Greenland-Norway seas, setting the global conveyor belt

https://earthobservatory.nasa.gov/features/IceBridge/page4.php

Routes of amospheric heat and moisture transport in the Climate system

determined by atmospheric circulation

Theorethical atmospheric circulaton in a non rotating-planet



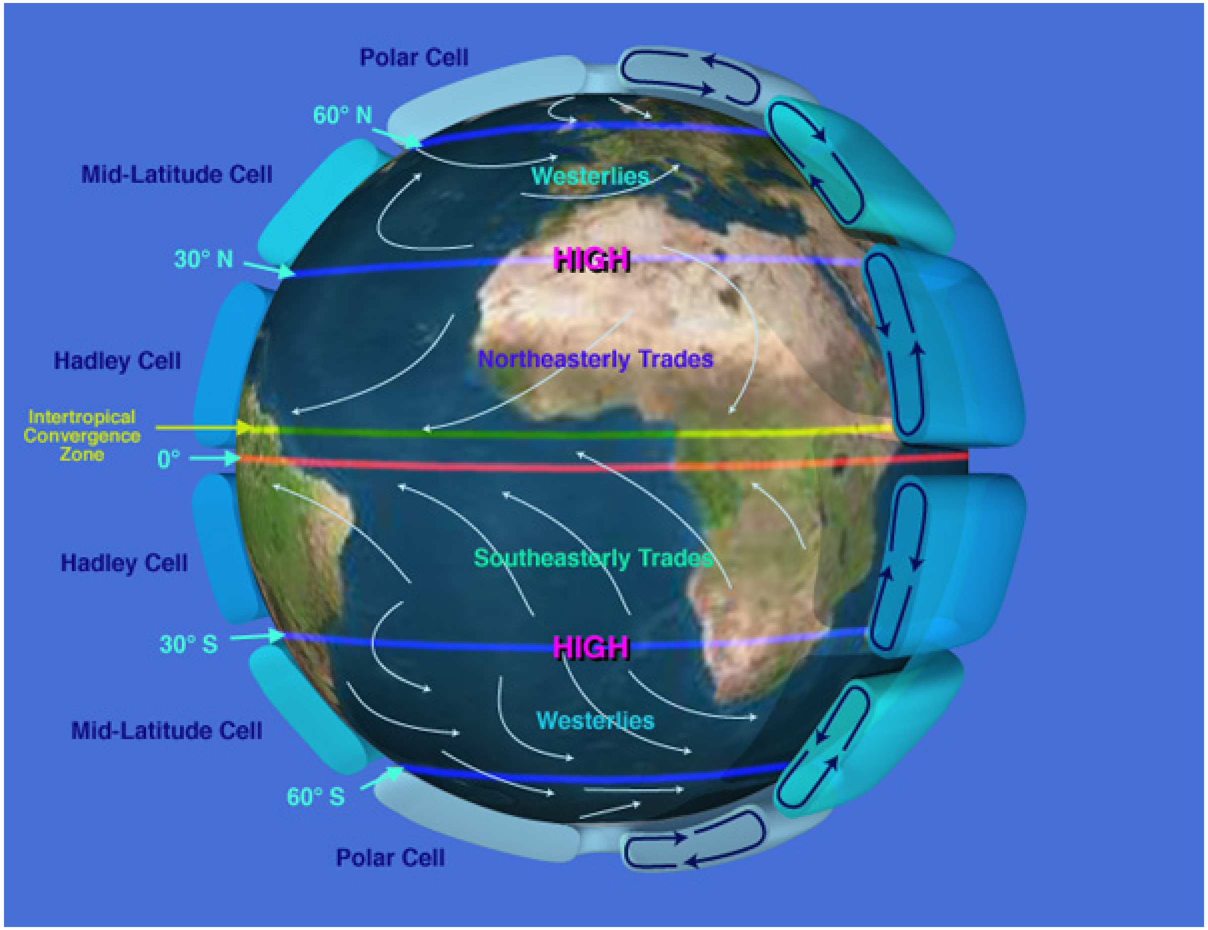
Single cell atmospheric circulation

Tropics:

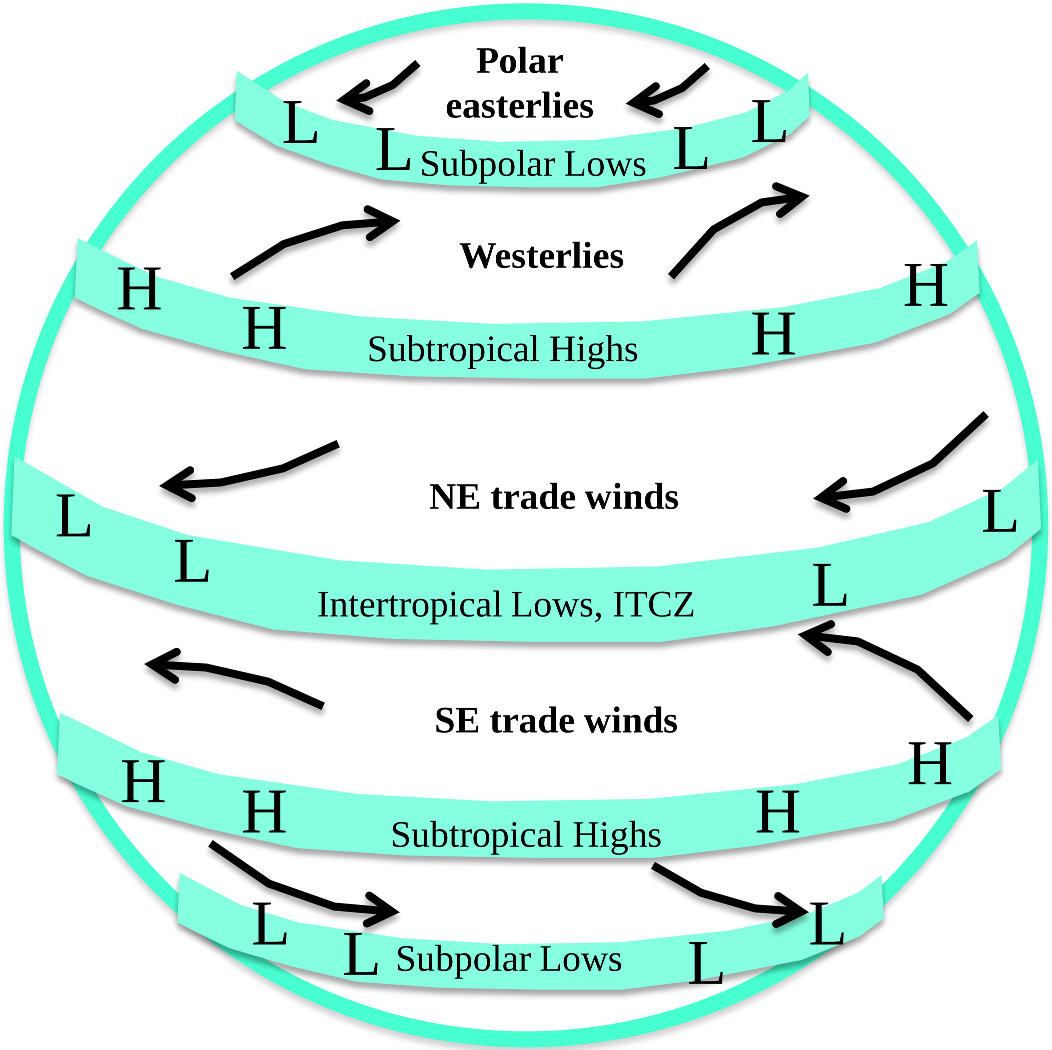
Convergence
In the lower atmosphere

Divergence
In the upper atmosphere

Surface winds blow from the poles to the equator.


Polar Cell
60° N
Mid-Latitude Cell
Westerlies
30° N
HIGH
Hadley Cell
Northeasterly Trades
Intertropical
Convergence
Zone
0°
Hadley Cell
Southeasterly Trades
30° S
HIGH
Mid-Latitude Cell
Westerlies
60° S
Polar Cell

Zonal atmospheric circulation



Different heat storage capacity of oceans and continents

Completely different behaviour between Continents and Oceans due to the different specific heat capacity of land and water

Specific Heat = the amount of heat needed to increase 1^{o} C the temperature of a unit of mass of a material.

The Ocean can absorb and store more energy than the continents
The land cools and warms faster than the sea.

Specific heat capacity of different substances

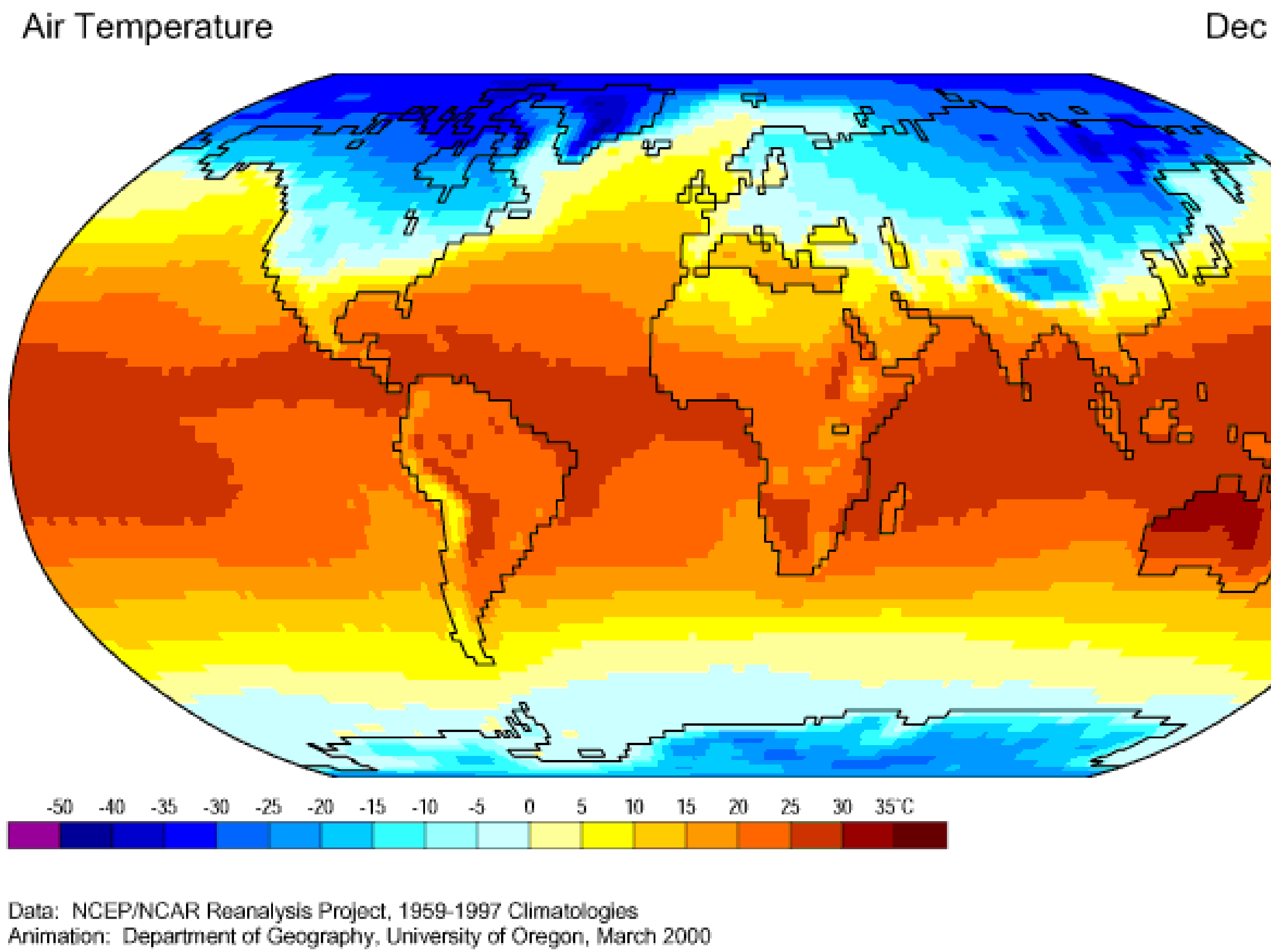
Pure water (20ºC)	4.182 J/g ºC= 1 cal/gºC
Dry soil	0.8
Granite	0.79
Limestone	0.909
Sand, quartz	0.83
Ice, snow	0.209
Dry air	1.01
Water vapor	2.0

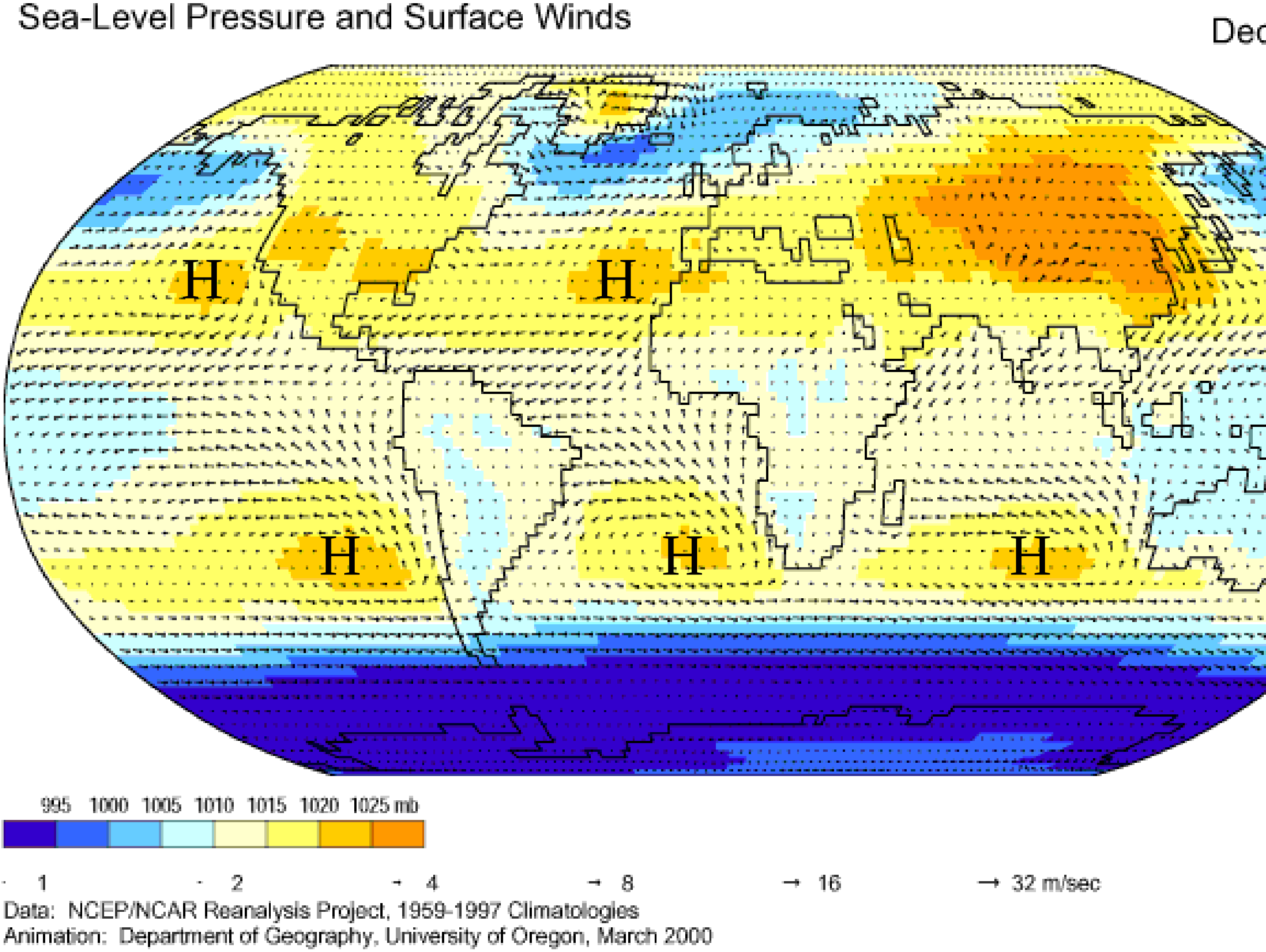
Water can absorb great amounts of energy before getting hot

1 calorie of solar radiation will increase 1ºC the temperature of 1 g of water,

The same calorie will increase 5ºC 1 g of granite

The Ocean: Large heat storage capacity, tends to stabilize the system
Land (low storage capacity) warms up in summer and cools in winter

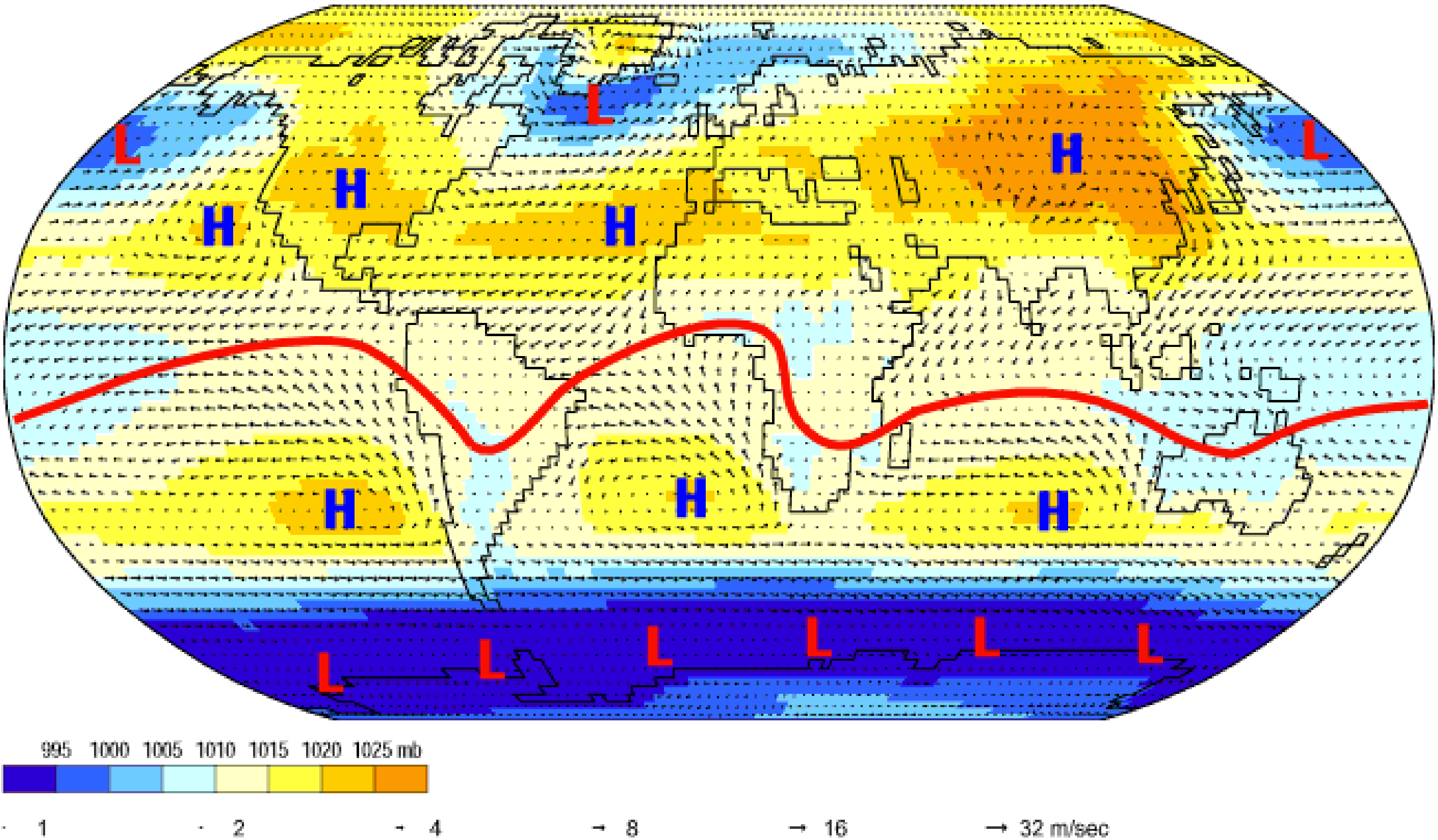




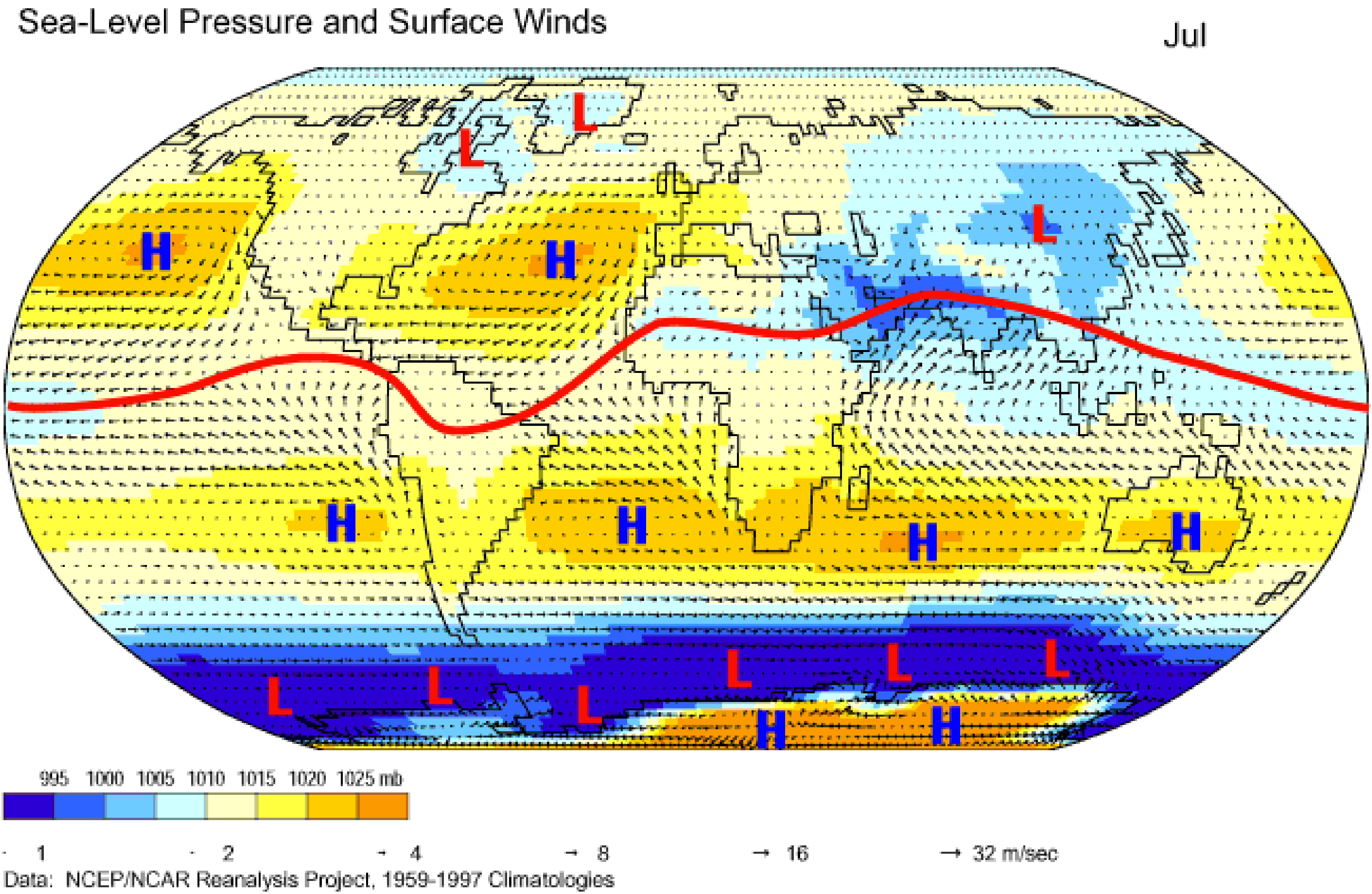
Sea-Level Pressure and Surface Winds
Dec
H
H
H
H
H
995 1000 1005 1010 1015 1020 1025 mb
1
2
4
8
16
32 m/sec
Data: NCEP/NCAR Reanalysis Project, 1959-1997 Climatologies
Animation: Department of Geography, University of Oregon, March 2000

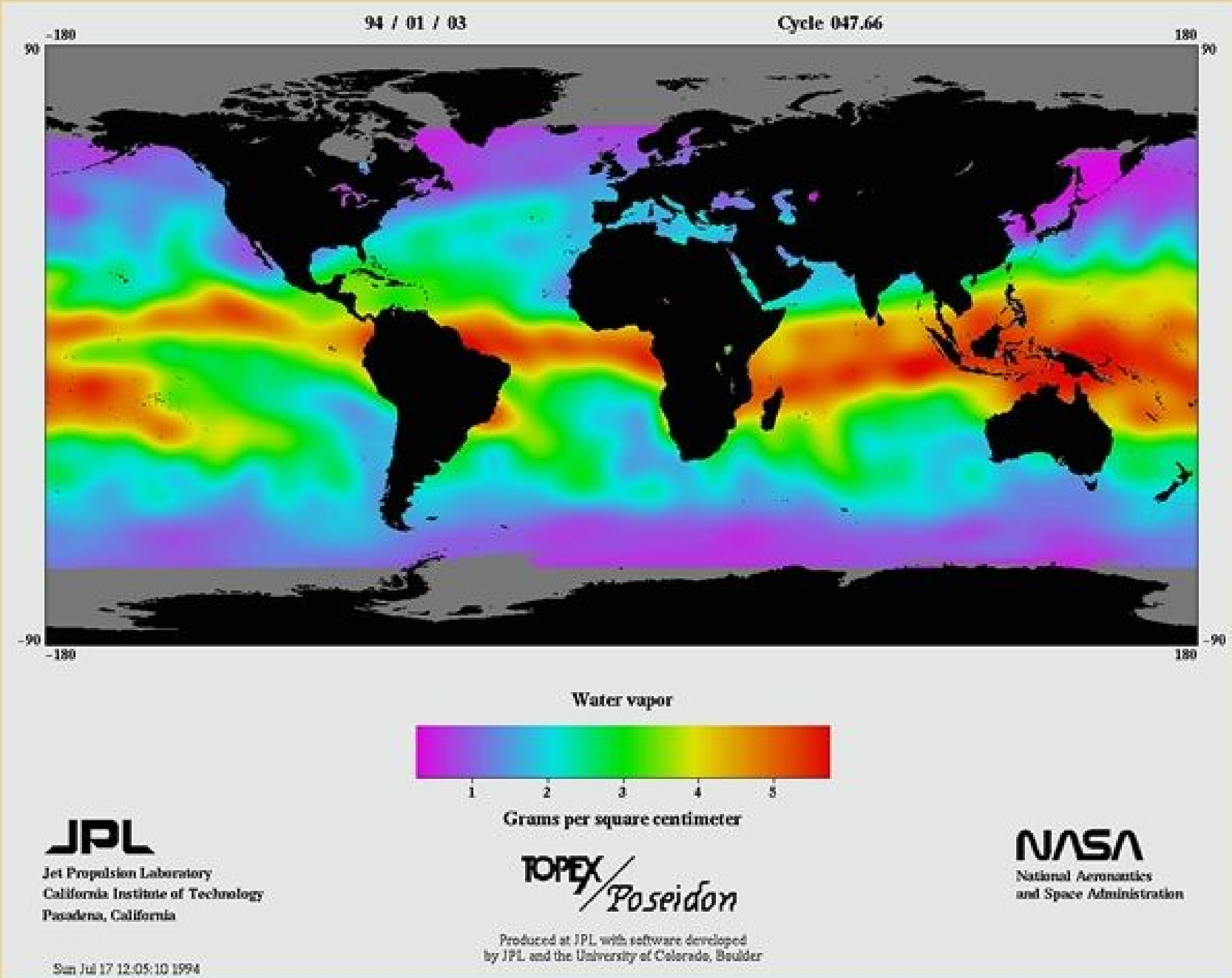
Sea-Level Pressure and Surface Winds

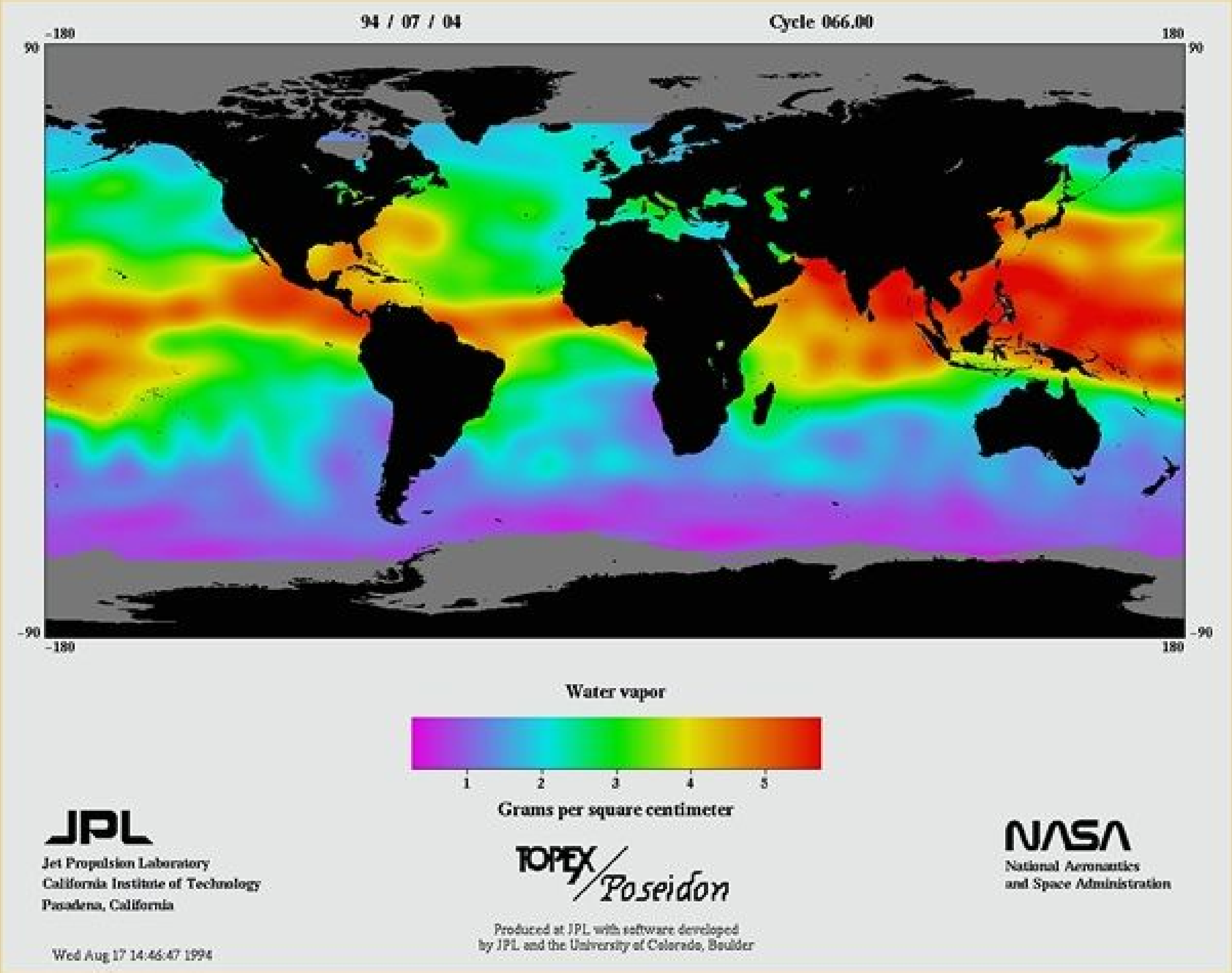
Jan



Data: NCEP/NCAR Reanalysis Project, 1959-1997 Climatologies

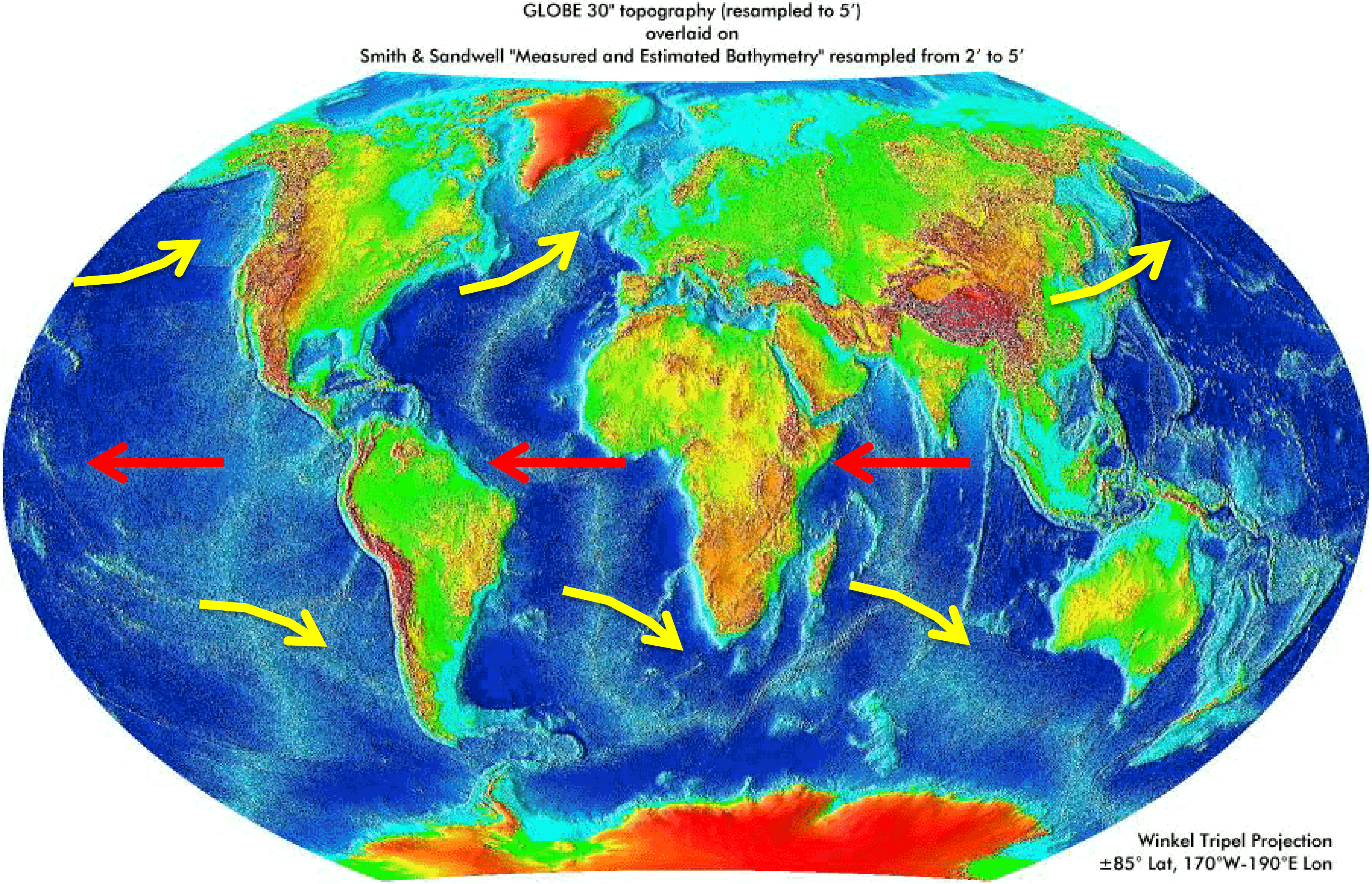

Sea-Level Pressure and Surface Winds
Jul
995 1000 1005 1010 1015 1020 1025 mb
1 2 4 8 16 32 m/sec
Data: NCEP/NCAR Reanalysis Project, 1959-1997 Climatologies


94 / 01 / 03
Cycle 047.66
-180
180
90
-90
Water vapor
1
2
3
4
5
Grams per square centimeter
JPL
Jet Propulsion Laboratory
California Institute of Technology
Pasadena, California
TOPEX/Poseidon
Produced at JPL with software developed
by JPL and the University of Colorado, Boulder
NASA
National Aeronautics
and Space Administration
Sun Jul 17 12:05:10 1994

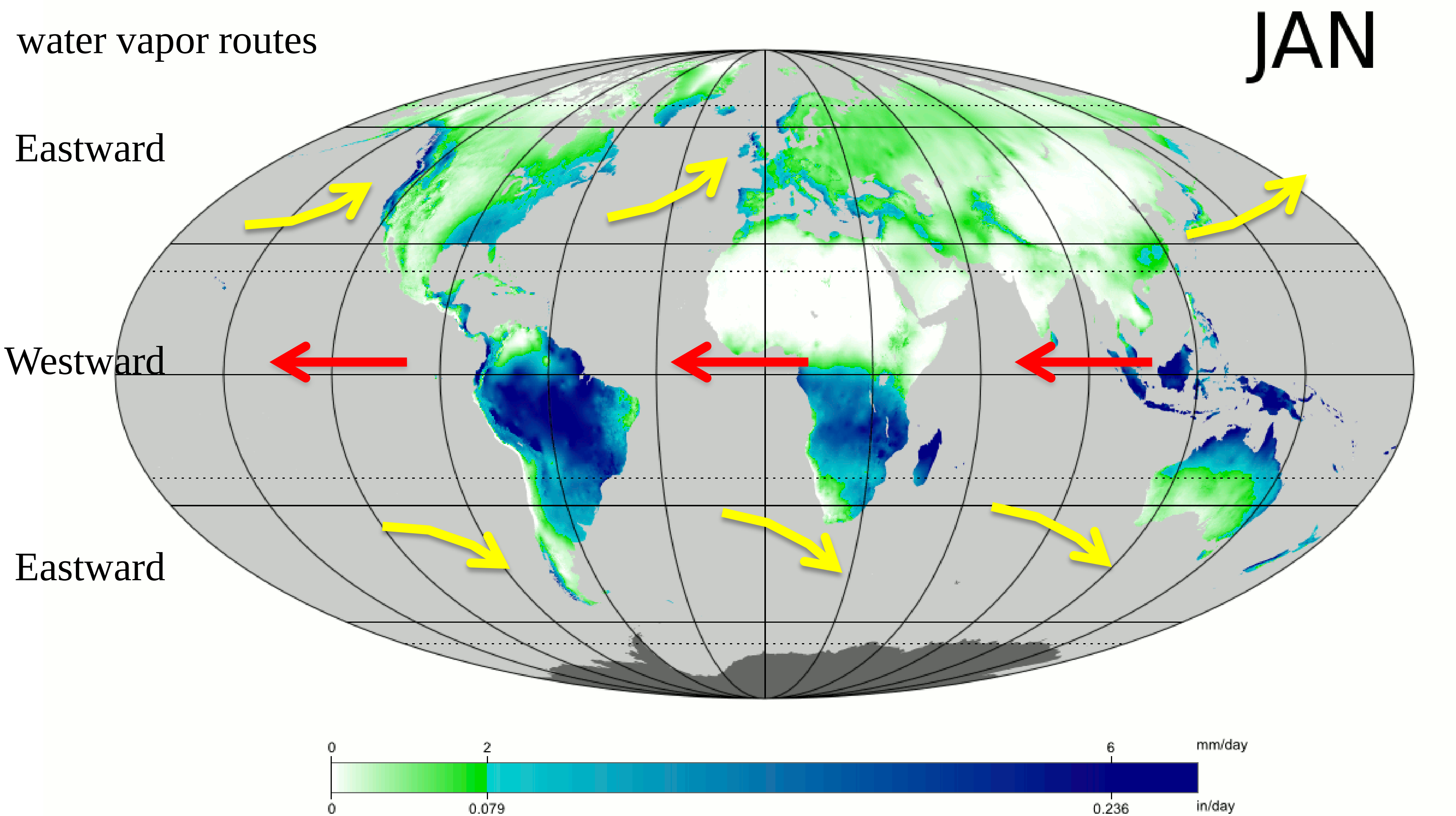

94 / 07 / 04
Cycle 066.00
-180
180
90
-90
Water vapor
1
2
3
4
5
Grams per square centimeter
JPL
Jet Propulsion Laboratory
California Institute of Technology
Pasadena, California
Wed Aug 17 14:46:47 1994
TOPEX/Poseidon
Produced at JPL with software developed
by JPL and the University of Colorado, Boulder
NASA
National Aeronautics
and Space Administration

Role of lithosphere on moisture and heat atmospheric transport

Mountain chains interfere in the atmospheric heat and moisture transport between the major ocean basins

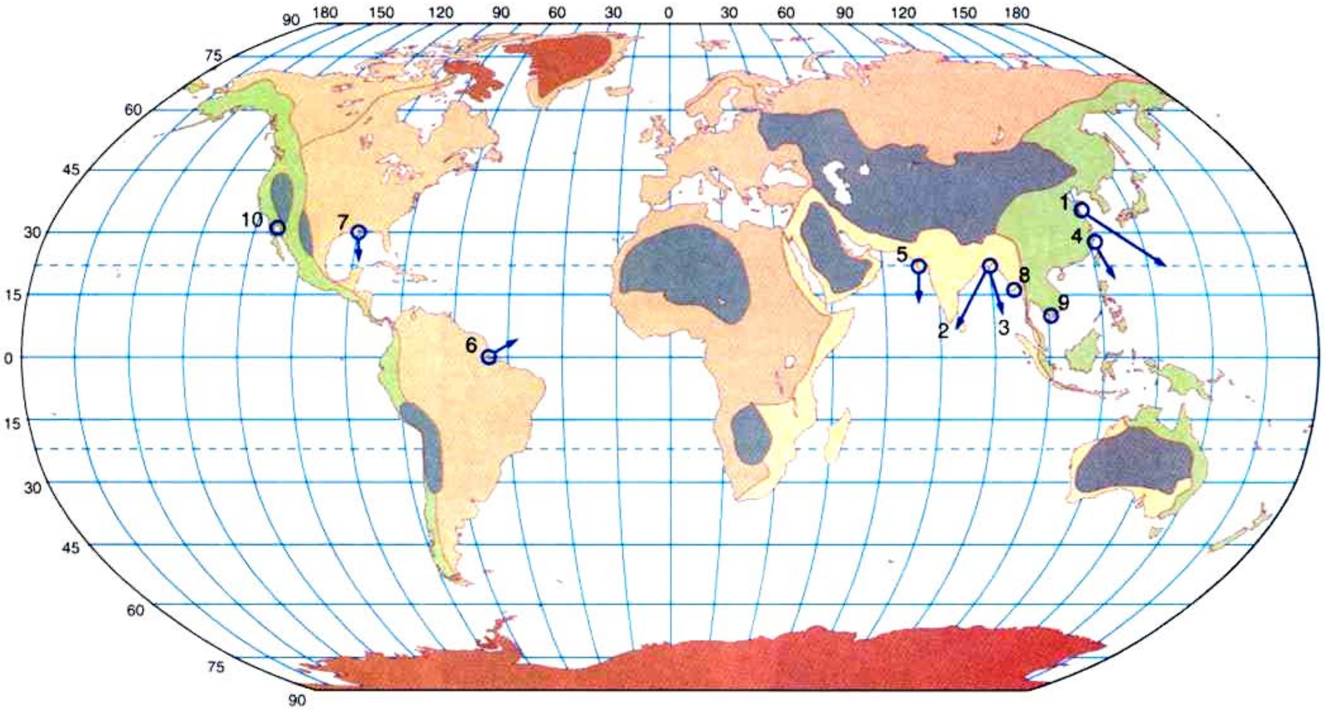


Seasonal precipitation



Ocean drainage basins

A vast extension of America, Eurasia and Africa contribute its water to the Atlantic, but its hydrologic budget is negative



Sediment discharge in millions of tons/year

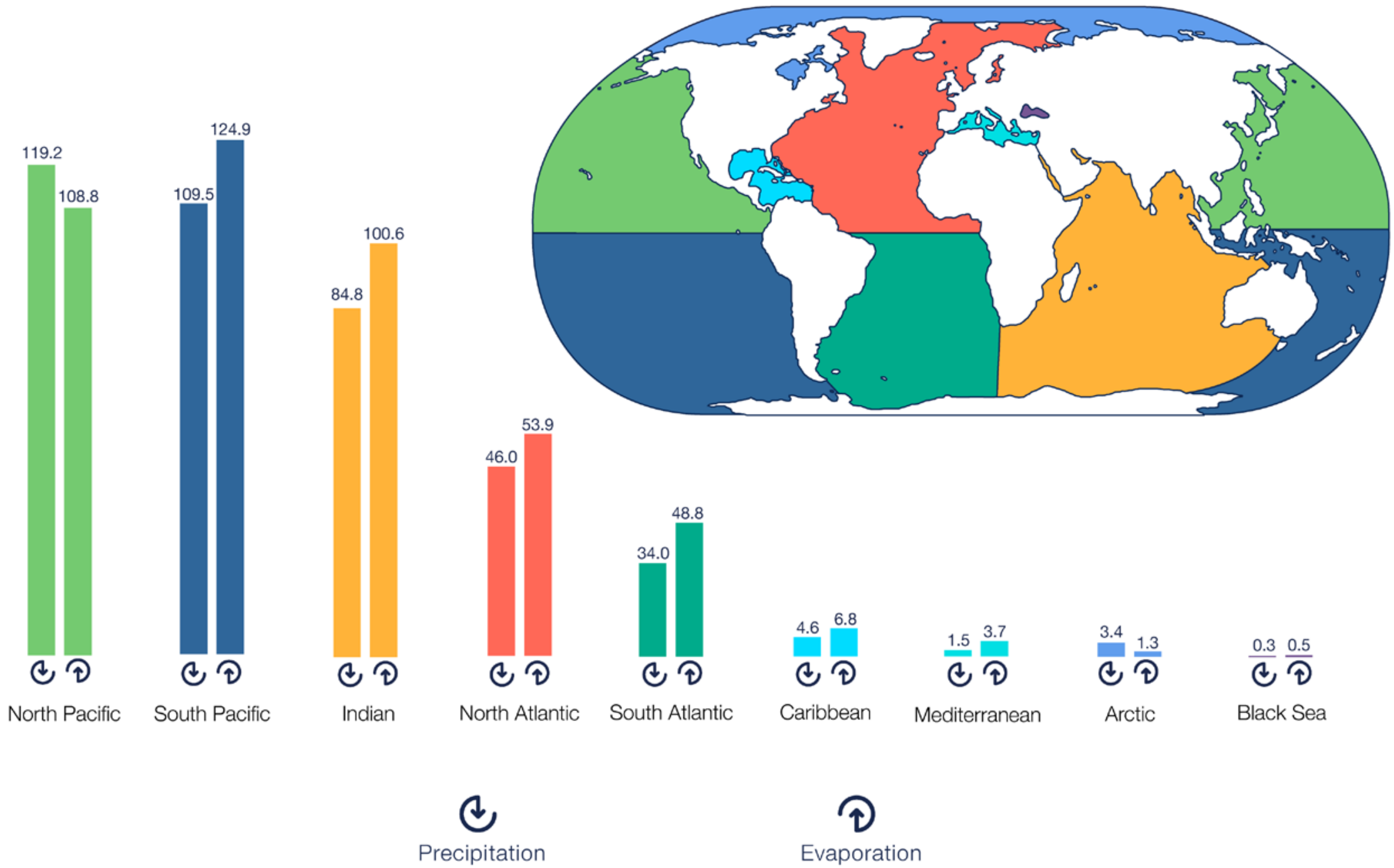
1. Hwang Ho – 2100	6. Amazon – 400
2. Ganges – 1600	7. Mississippi – 340
3. Brahmaputra – 800	8. Irrawaddy – 330
4. Yangtze – 550	9. Mekong – 190
5. Indus – 480	10. Colorado – 150

- River runoff to Atlantic Ocean and Arctic Sea
- Runoff to Pacific Ocean
- Runoff to Indian Ocean
- No runoff to oceans–source of windblown sediment
- Source of glacial sediment

Figure 5-1 Sources of Windblown, Glacial, and River-borne Sediments to the Major Ocean Basins

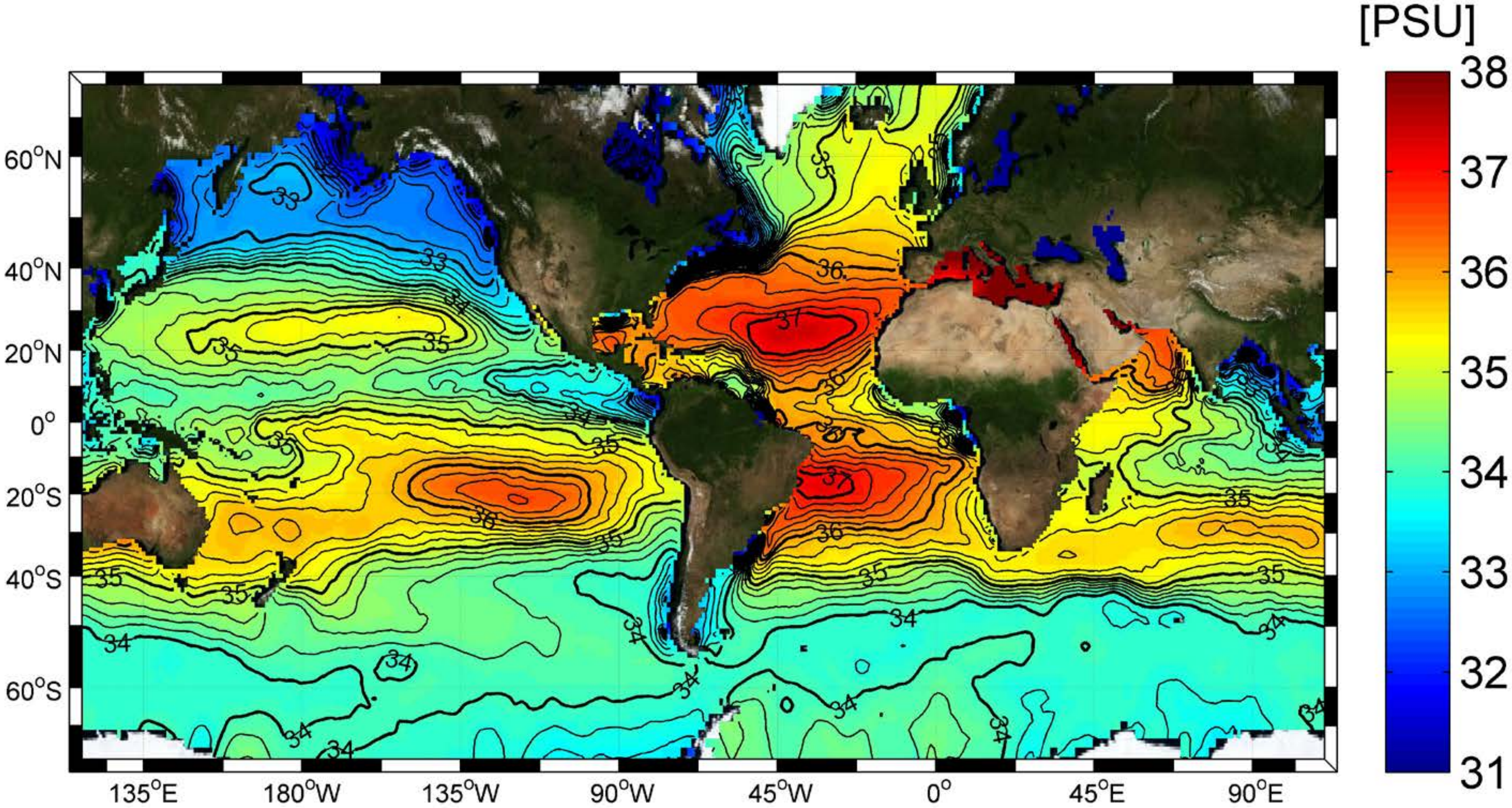
Water budget of the Oceanic basins Nasa

The Atlantic export moisture to the Pacific

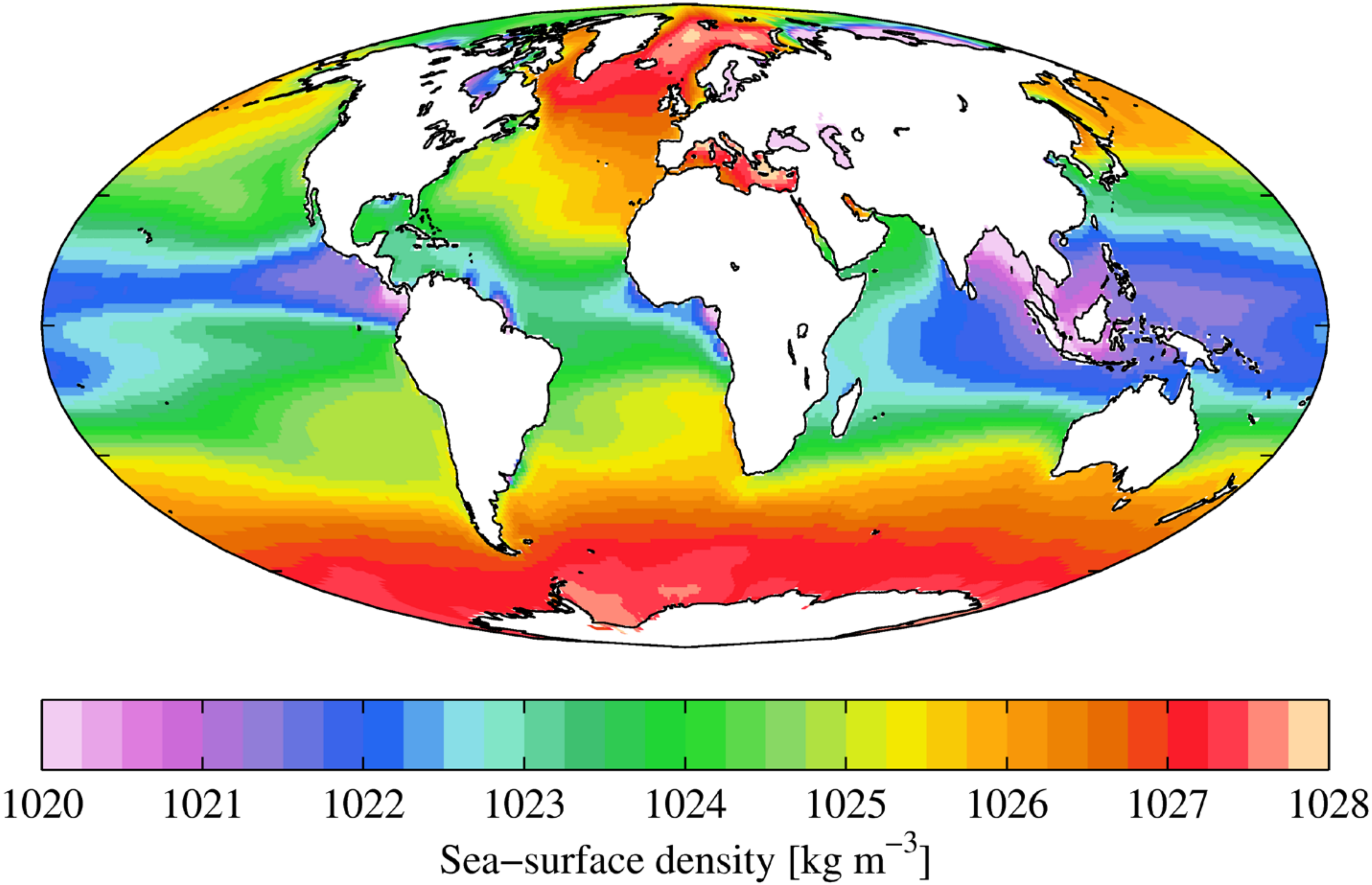


thousand cubic kilometers

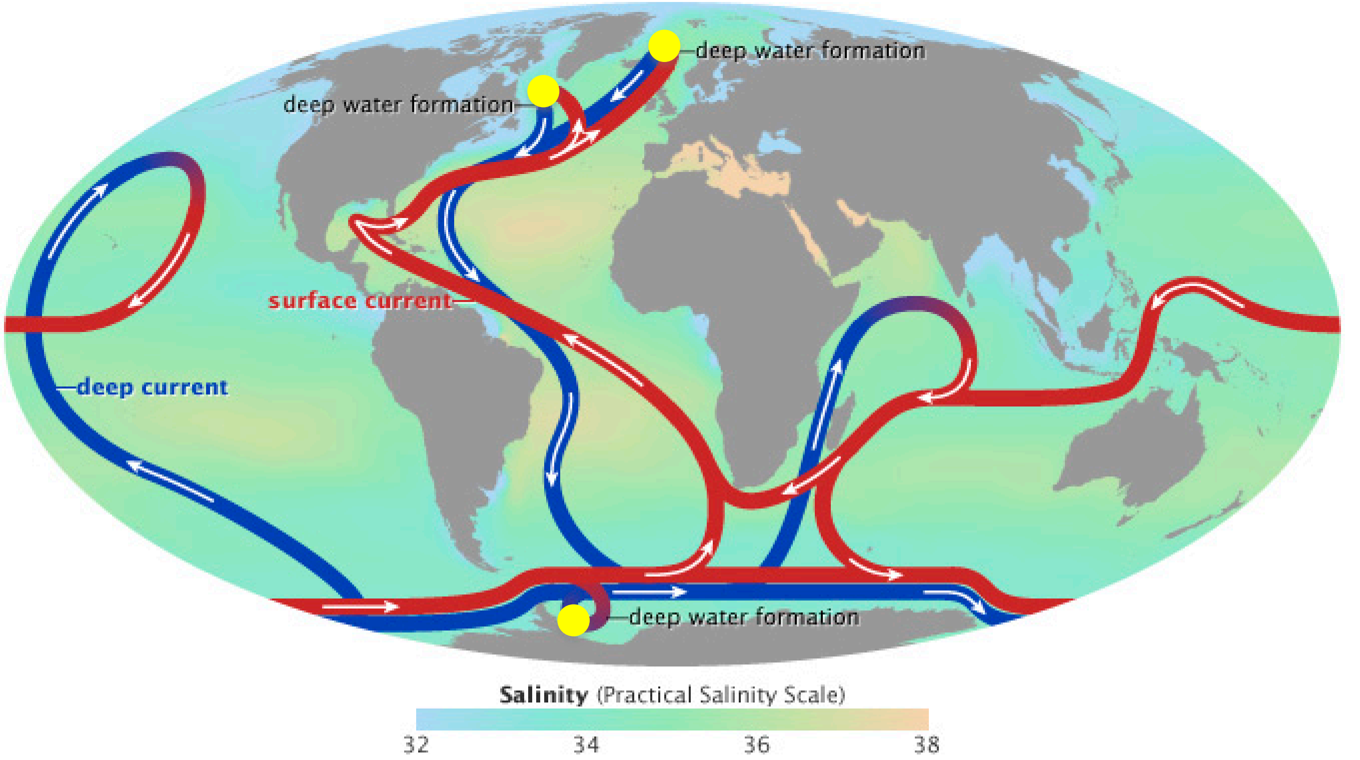
Annual mean sea surface salinity distribution (World Ocean Atlas, 2005)



Te consequence: higher salinities in the Atlantic and lower in the Pacific


1020
1021
1022
1023
1024
1025
1026
1027
1028
Sea–surface density [kg m^{-3}]

The three main sources of deep water formation occurr in the more dense waters of the Atlantic.



Deep water moves from the more dense Atlantic to the less dense Pacific. To balance the mass loss, the Alantic needs to import surface waters from the Pacific.

https://earthobservatory.nasa.gov/features/IceBridge/page4.php

Role of Biosphere

The biosphere regulates the chemistry of the Ocean and the atmosphere, especially the greenhouse gases

Photosynthesis

Solar radiation

$$6CO_2 + 6H_2O + N_{utrients} \rightleftharpoons C_6H_{12}O_6 + 6O_2$$

Respiration
Oxidation

$$CO_2,\ \text{Nutrients} \rightleftharpoons O_2$$

Bio-limiting Nutrients

Macronutrients (main components of cell tissues)

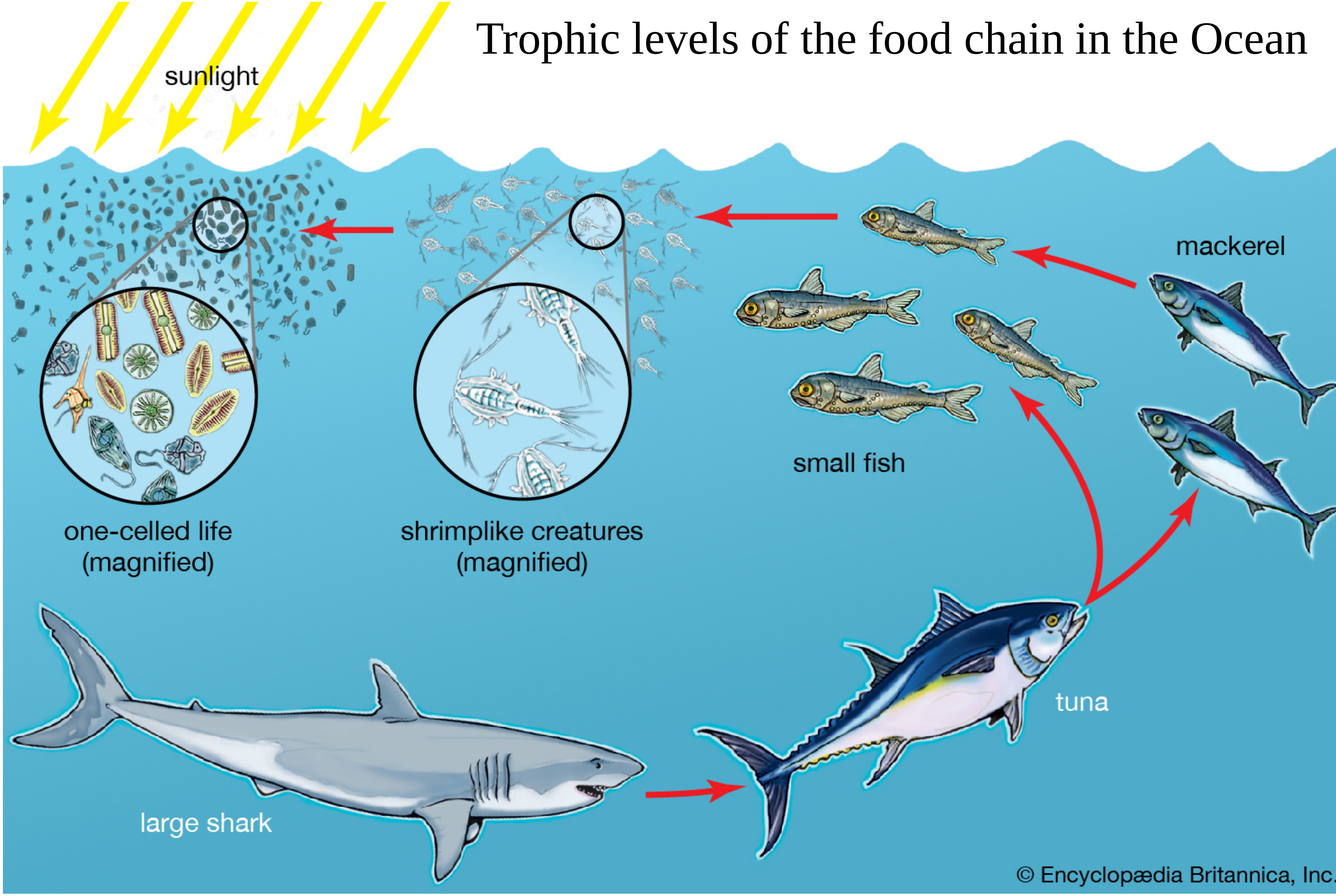
P, C, N, Si, O, H

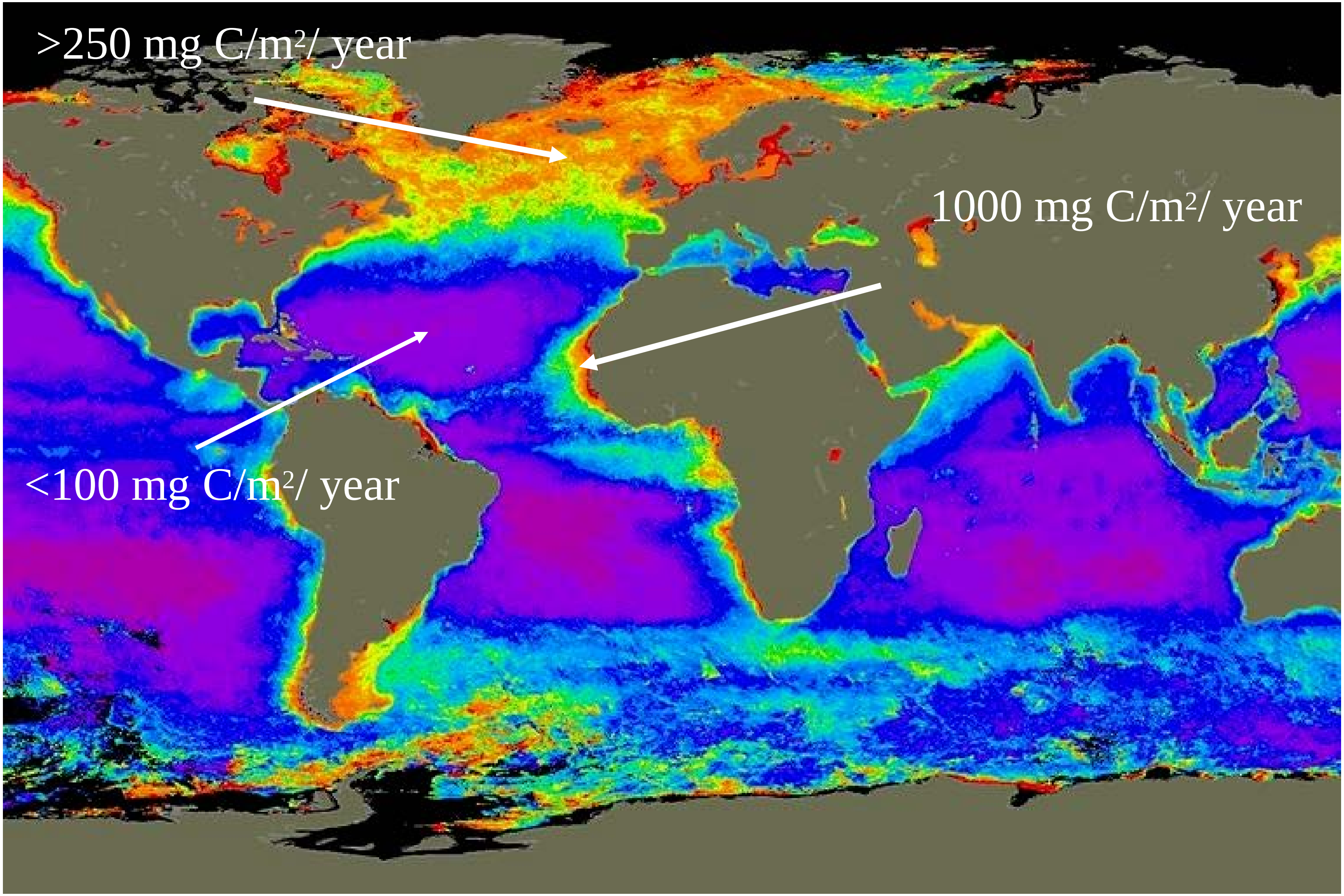
Micronutrients (are needed in trace quantities)

(Fe, Mn, Zn, Co, Cu, Cd, Ni, Se)

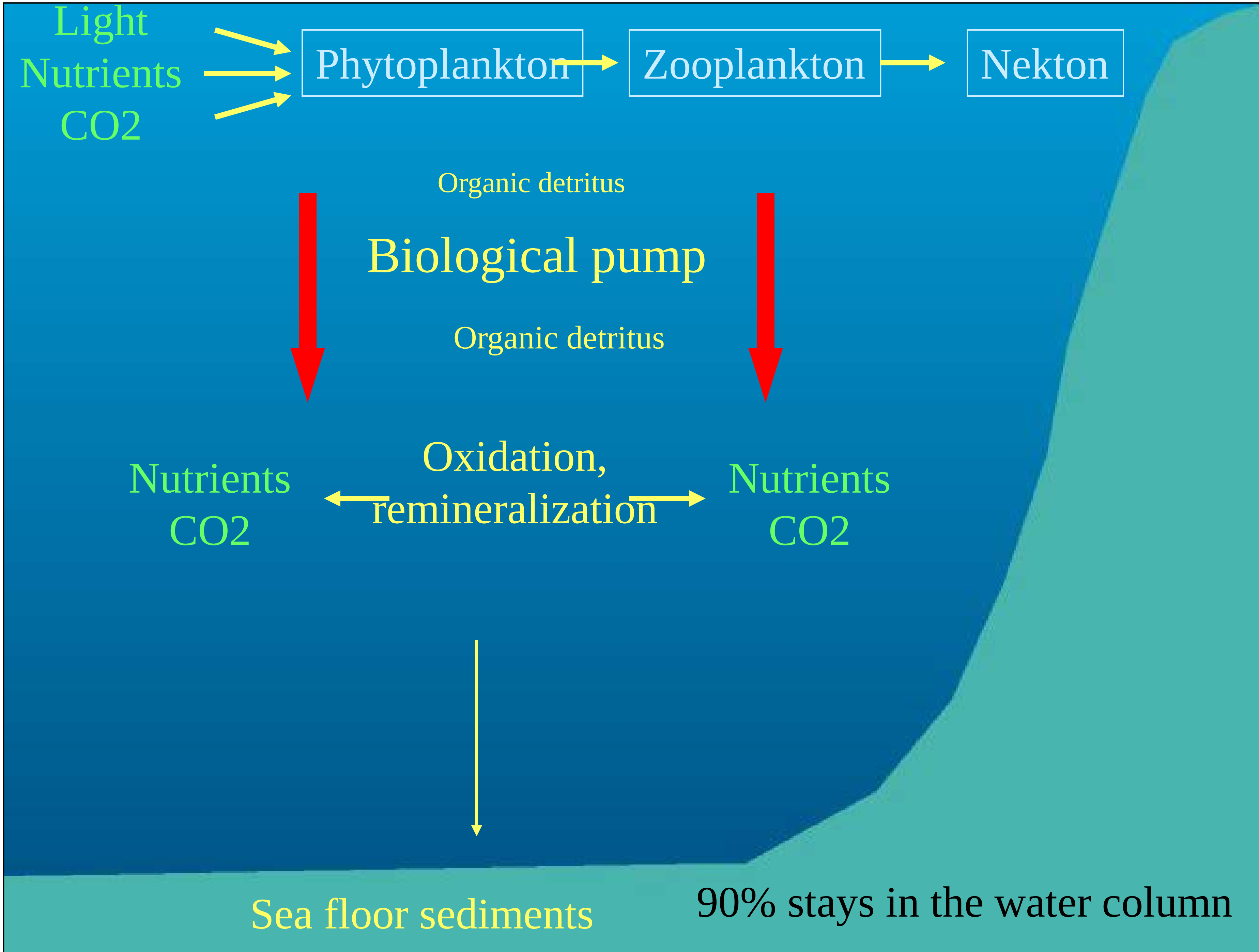
Phytoplankton need micronutrients because they play an important role in their metabolism: for example, Co, Cd and Zn in carbon dioxide acquisition; Fe and Mn in carbon fixation; Zn, Cd and Se in silica uptake; Fe and Mo in N_2 fixation and Fe, Cu and Ni in organic N utilization[3]

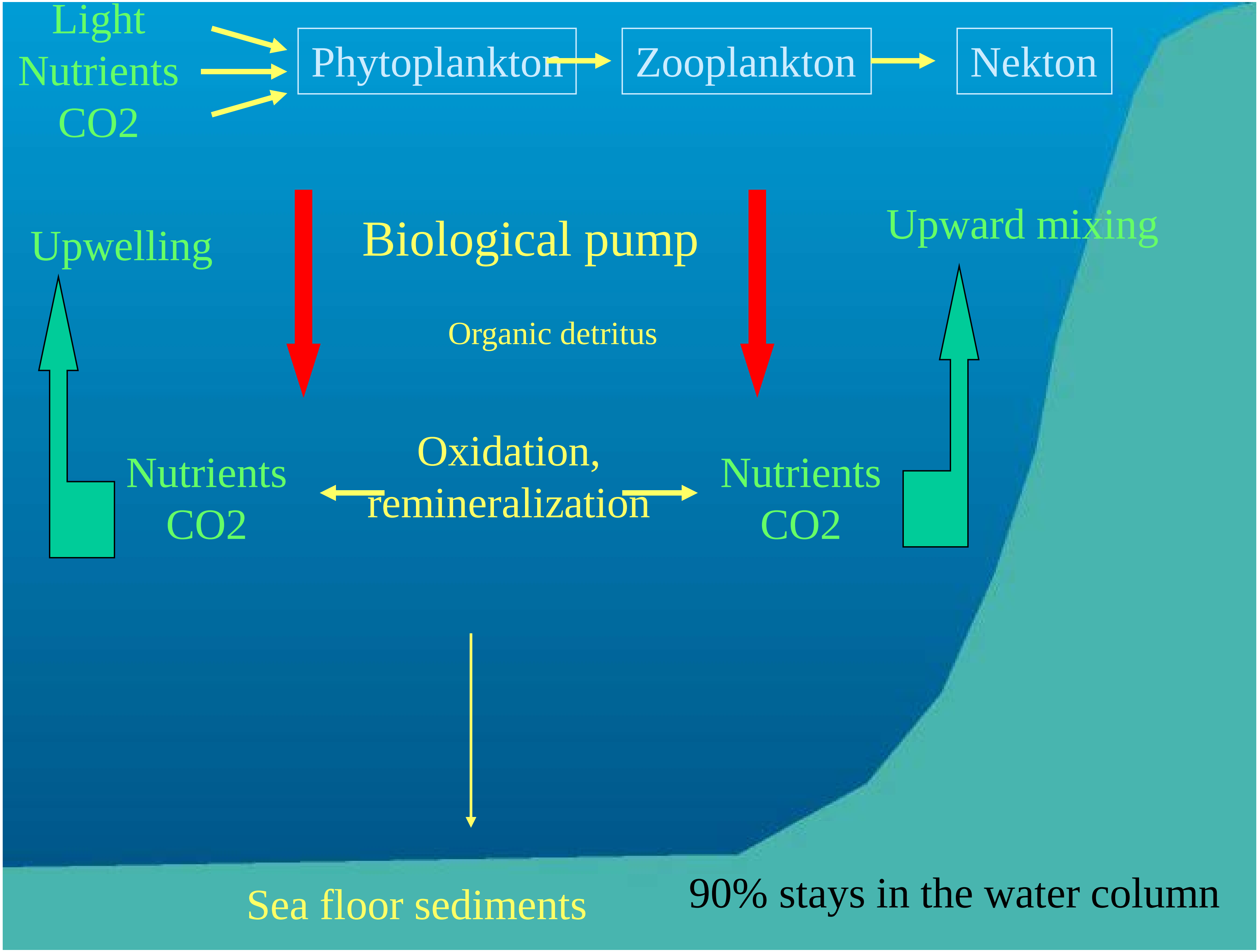
Trophic levels of the food chain in the Ocean

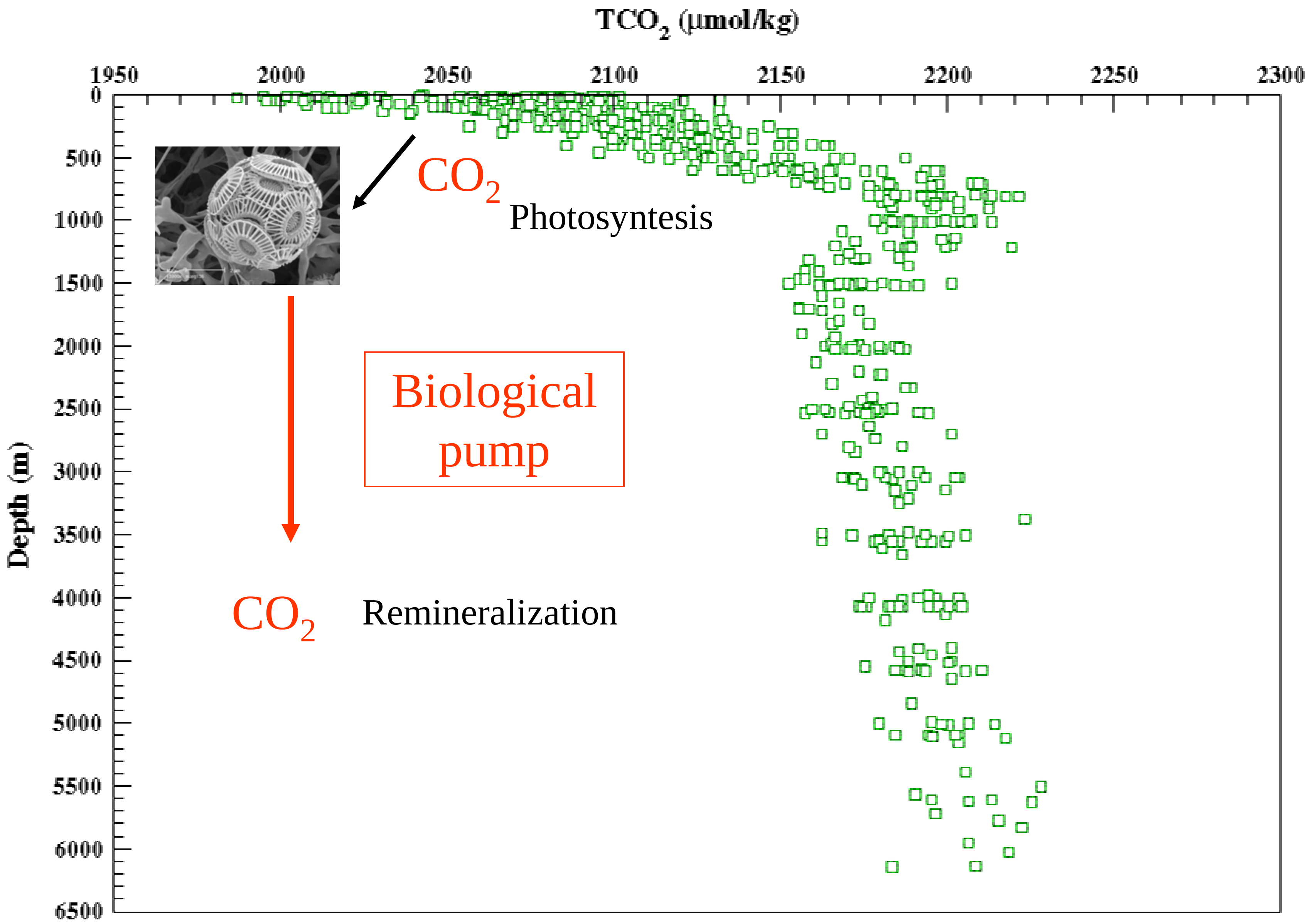




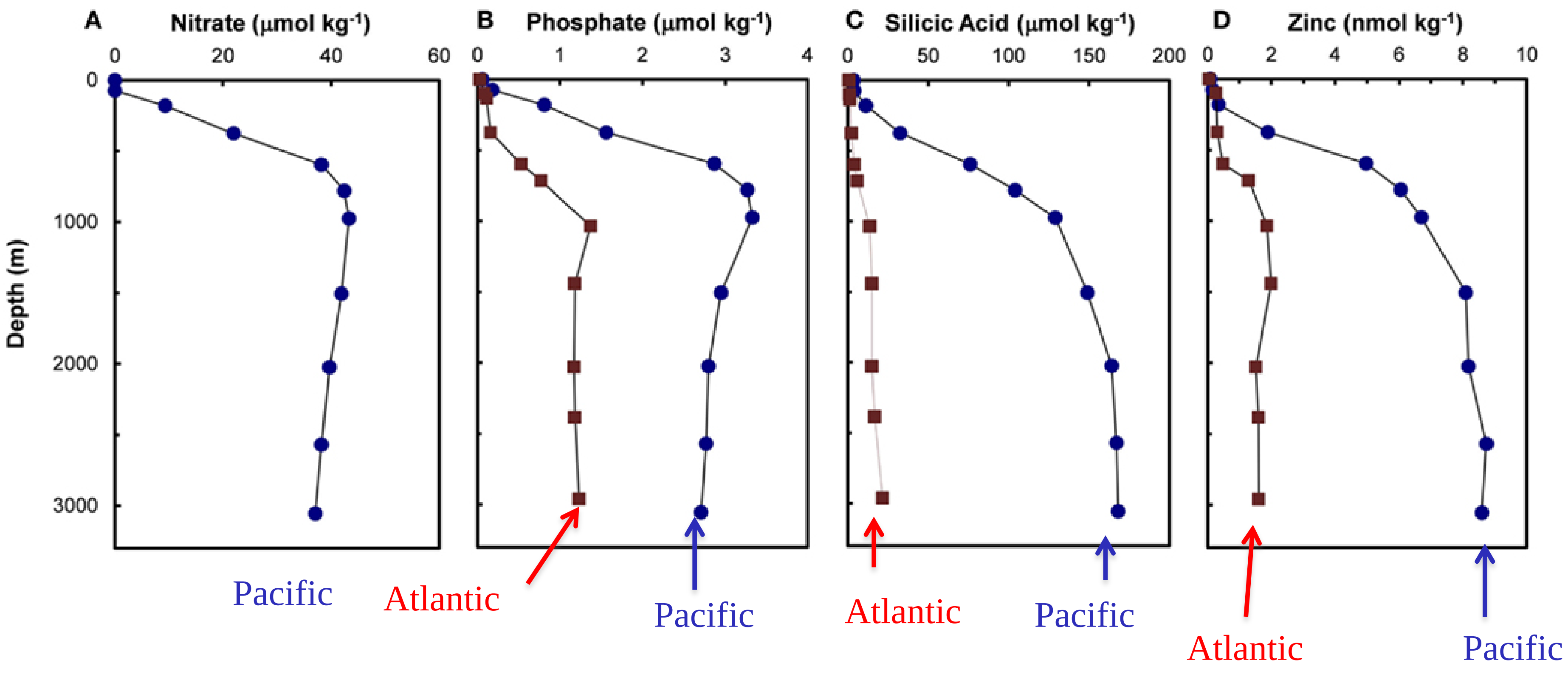
>250 mg C/m2/ year
1000 mg C/m2/ year
<100 mg C/m2/ year


Light
Nutrients
CO2
Phytoplankton
Zooplankton
Nekton
Organic detritus
Biological pump
Organic detritus
Nutrients
CO2
Oxidation,
remineralization
Nutrients
CO2
Sea floor sediments
90% stays in the water column

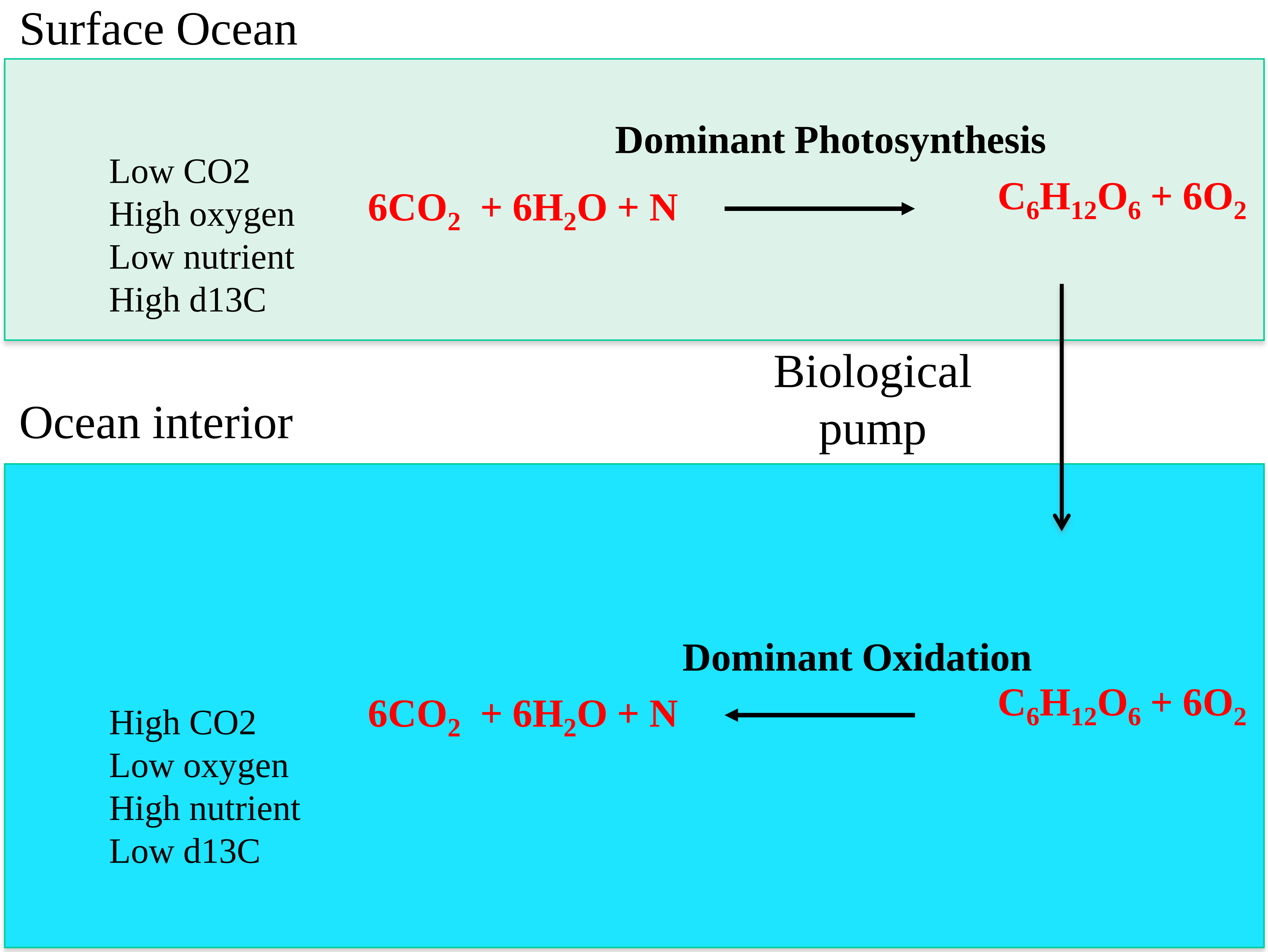

Light
Nutrients
CO2
Phytoplankton
Zooplankton
Nekton
Upwelling
Biological pump
Upward mixing
Organic detritus
Nutrients
CO2
Oxidation, remineralization
Nutrients
CO2
Sea floor sediments
90% stays in the water column

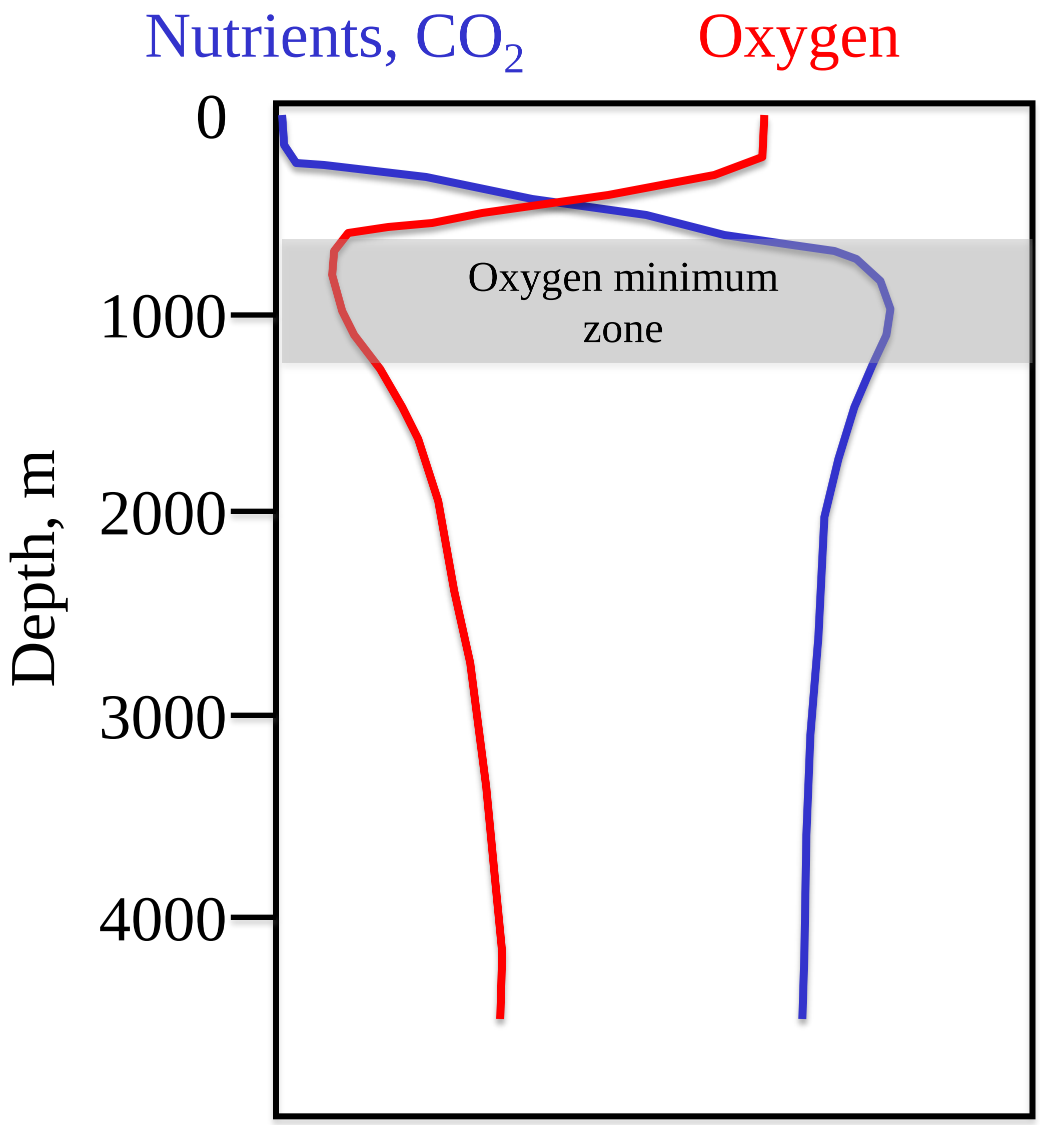

TCO2 (µmol/kg)
1950
2000
2050
2100
2150
2200
2250
2300
Depth (m)
0
500
1000
1500
2000
2500
3000
3500
4000
4500
5000
5500
6000
6500
CO2
Photosyntesis
Biological pump
CO2
Remineralization

Depth profiles for major nutrients

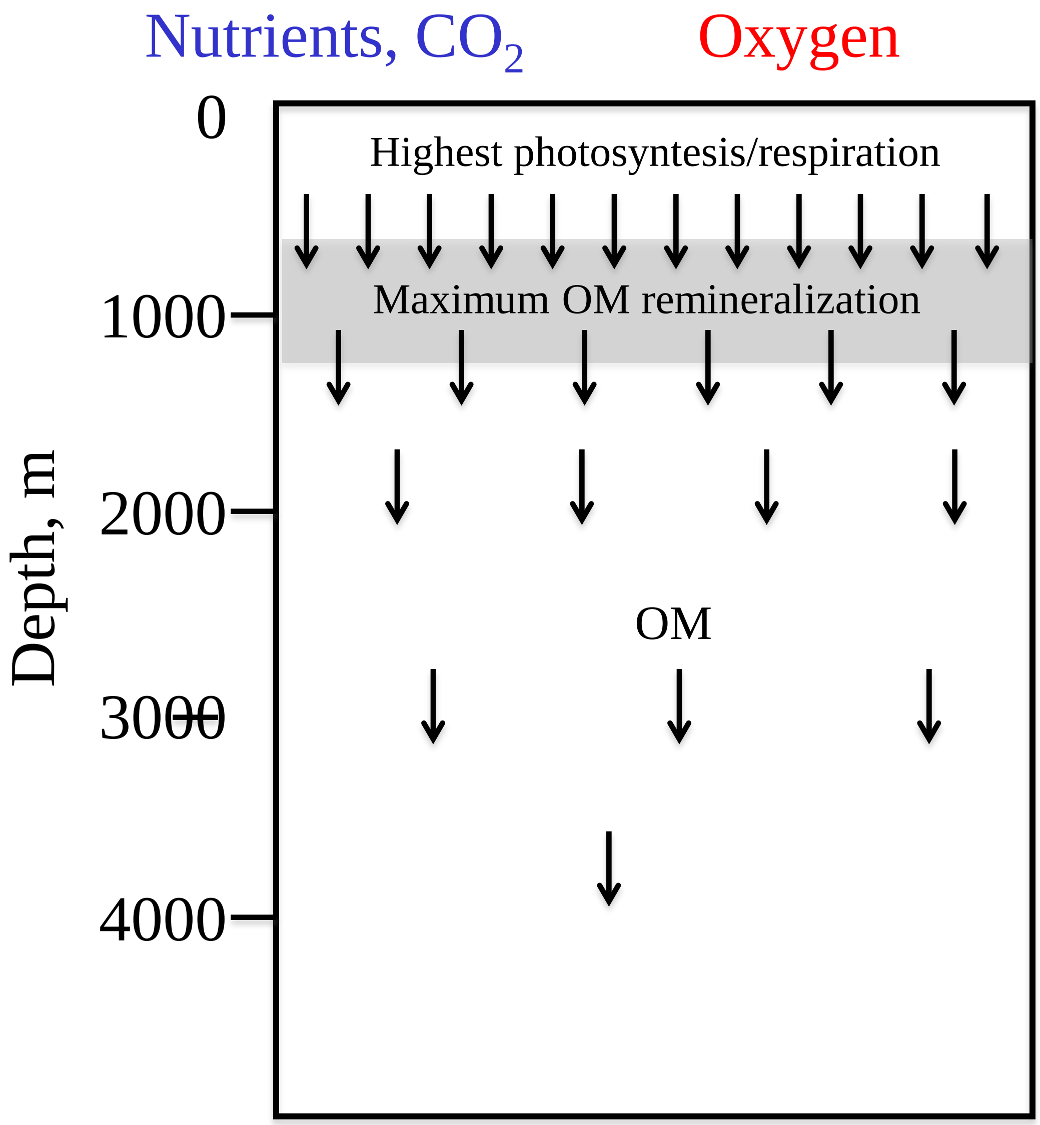


Bruland and Franks 1983

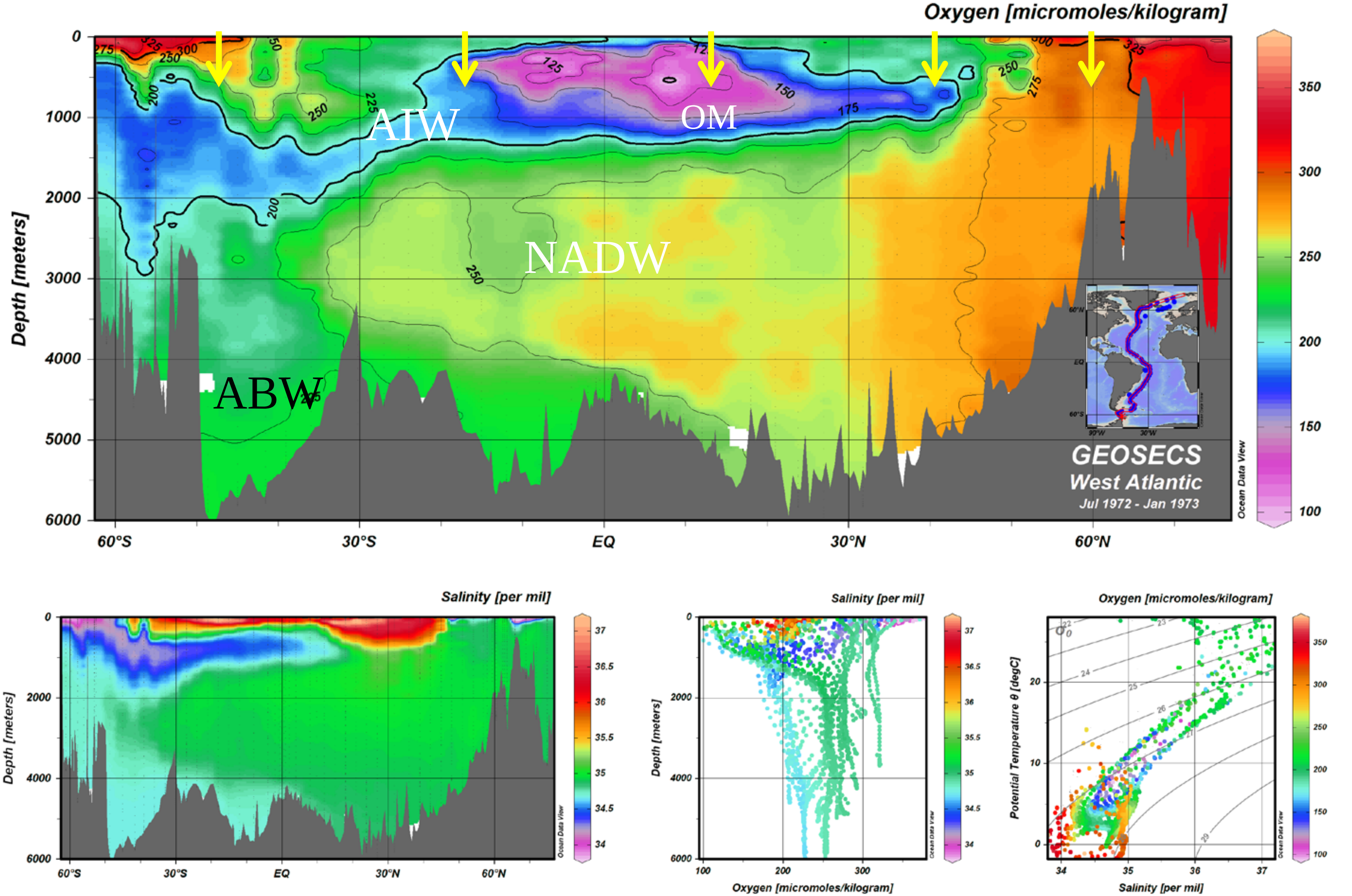

Surface Ocean
Low CO2
High oxygen
Low nutrient
High d13C
Dominant Photosynthesis
$6CO_2 + 6H_2O + N \rightarrow C_6H_{12}O_6 + 6O_2$
Biological pump
Ocean interior
High CO2
Low oxygen
High nutrient
Low d13C
Dominant Oxidation
$6CO_2 + 6H_2O + N \leftarrow C_6H_{12}O_6 + 6O_2$

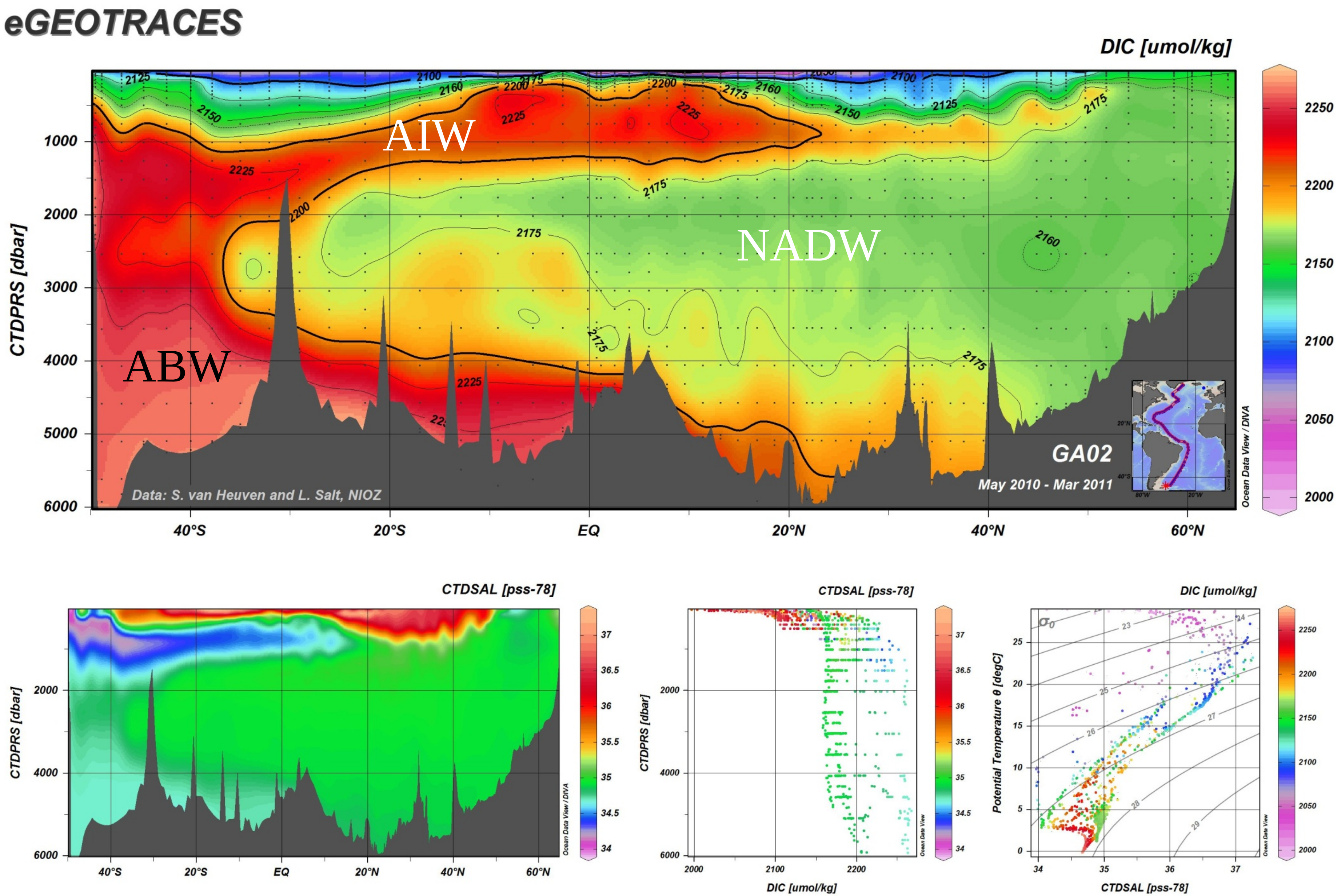


In the euphotic zone photosynthesis dominates over oxidation, consuming CO_2 and nutrients, but in the Ocean interior oxidation and respiration dominates over photosynthesis, consuming oxygen and releasing CO_2 and nutrients to the water.

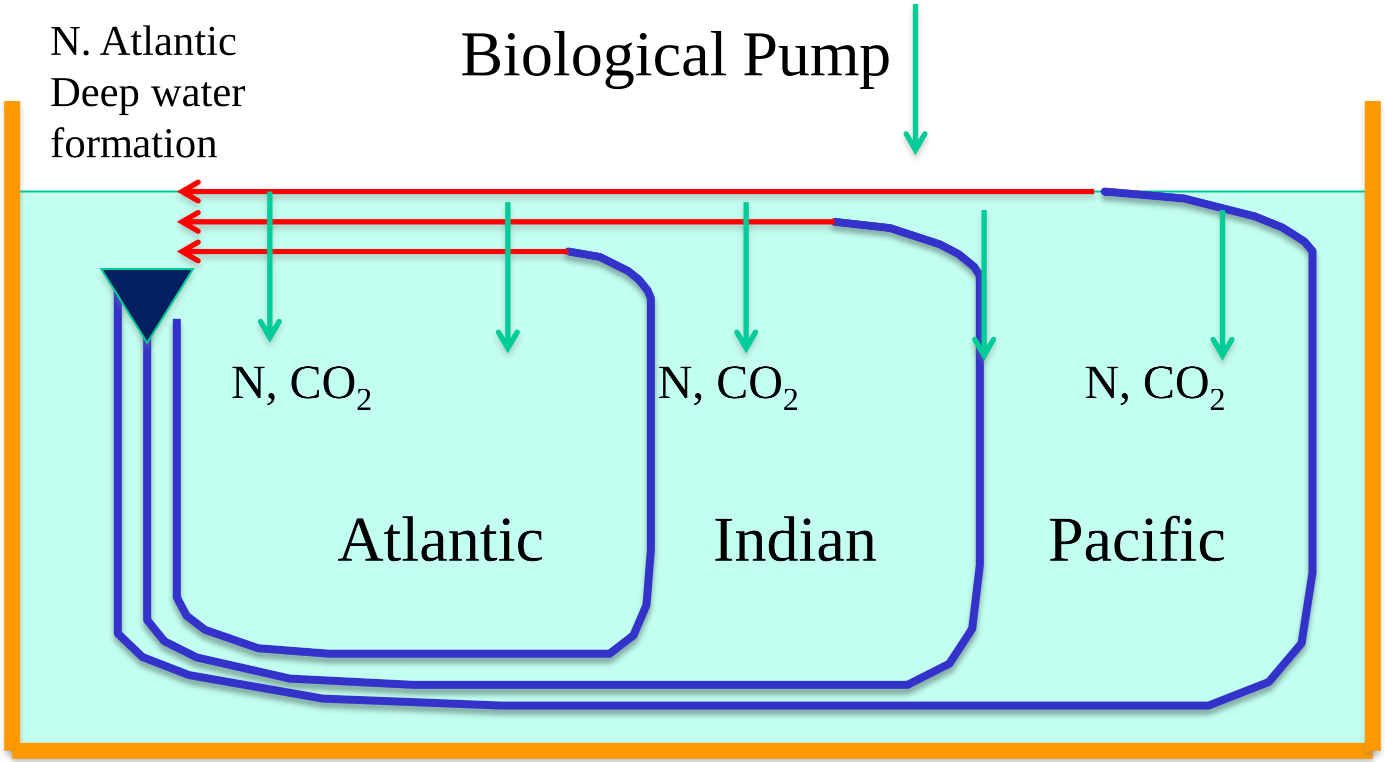


In the euphotic zone photosynthesis dominates over oxidation, consuming CO_2 and nutrients, but in the Ocean interior oxidation and respiration dominates over photosynthesis, consuming oxygen and releasing CO_2 and nutrients to the water.

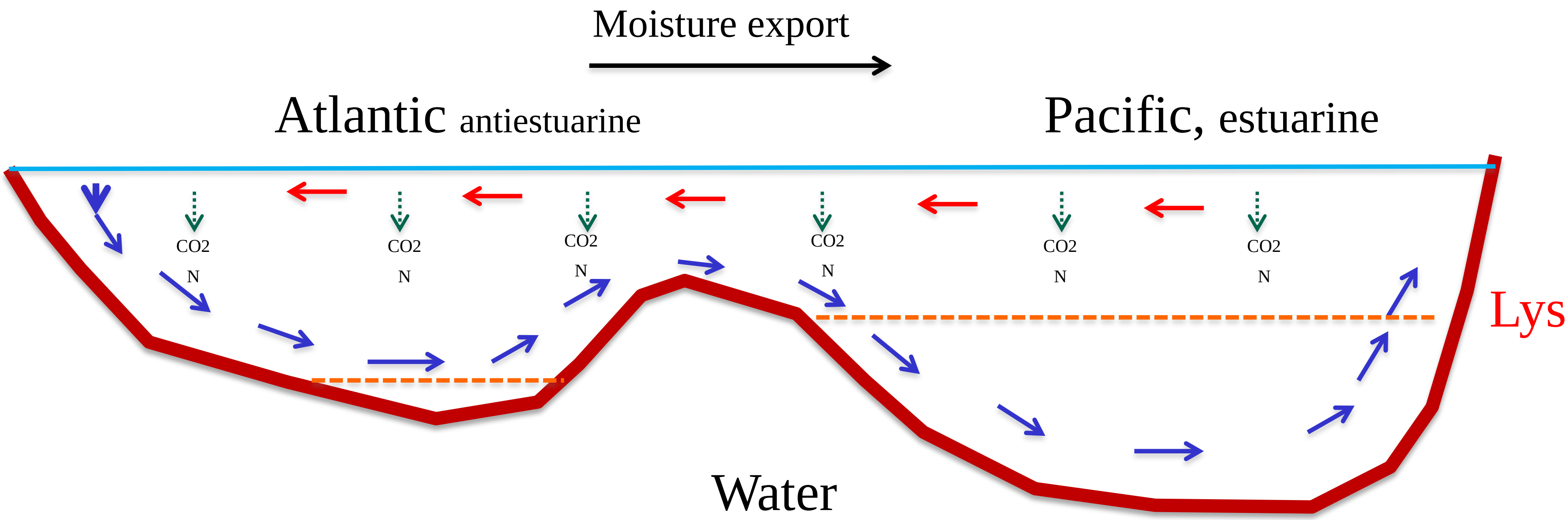

Oxygen [micromoles/kilogram]
Depth [meters]
AIW
OM
NADW
ABW
60°S
30°S
EQ
30°N
60°N
GEOSECS
West Atlantic
Jul 1972 - Jan 1973
Ocean Data View
Salinity [per mil]
Depth [meters]
Salinity [per mil]
Oxygen [micromoles/kilogram]
Oxygen [micromoles/kilogram]
Potential Temperature θ [degC]
Salinity [per mil]


eGEOTRACES
DIC [umol/kg]
AIW
NADW
ABW
CTDPRS [dbar]
GA02
May 2010 - Mar 2011
Data: S. van Heuven and L. Salt, NIOZ
40°S
20°S
EQ
20°N
40°N
60°N
CTDSAL [pss-78]
DIC [umol/kg]
Potential Temperature θ [degC]
Ocean Data View / DIVA

Global conveyor circulation moves CO_2 and nutrients from the Atlantic to the Indian and Pacific Oceans



Residence time



Water

Low nutrients
Low CO_2
High O_2

High nutrients
High CO_2
Low O_2

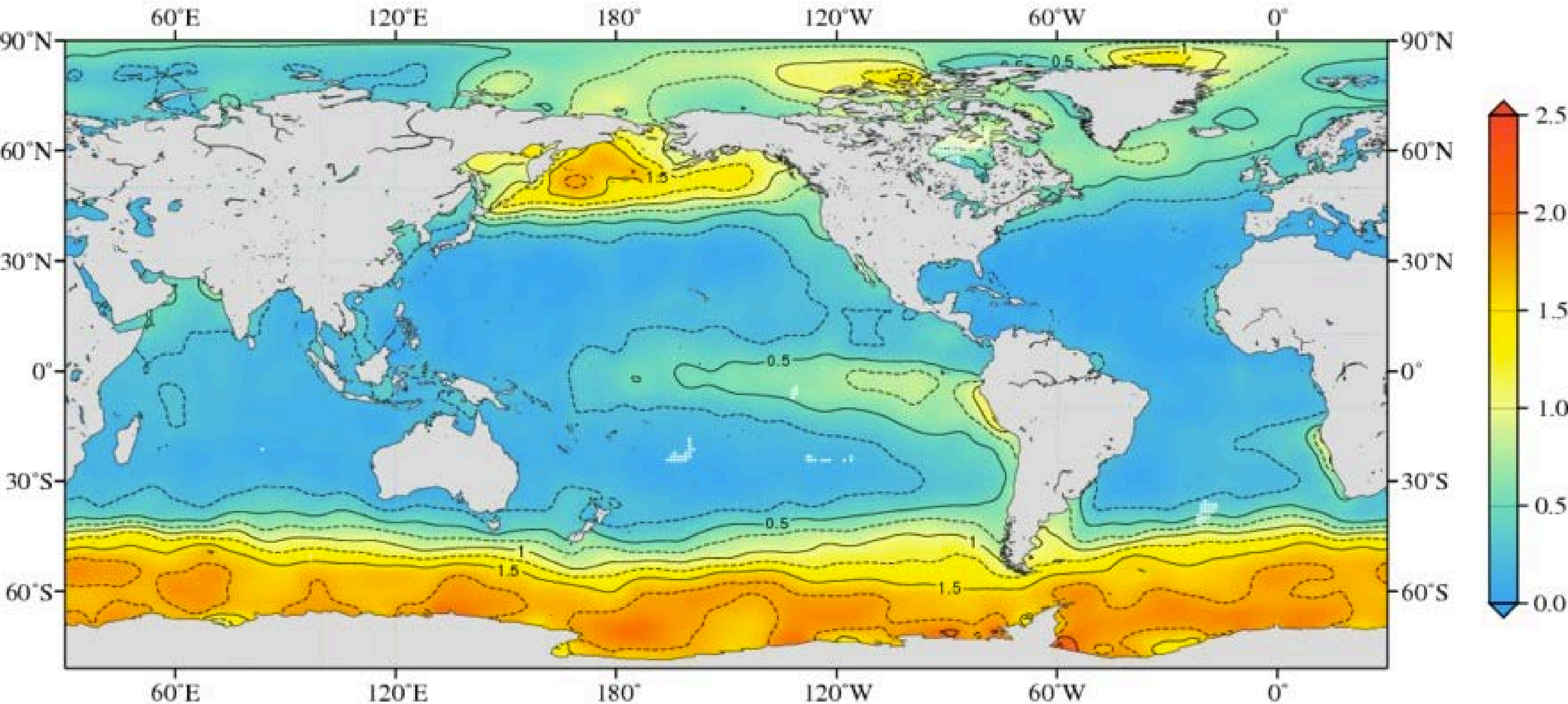
Sediments

High carbonate
Low $Si0_2$
Low TOC

Low carbonate
High $Si0_2$
High TOC

World Ocean Atlas Climatology

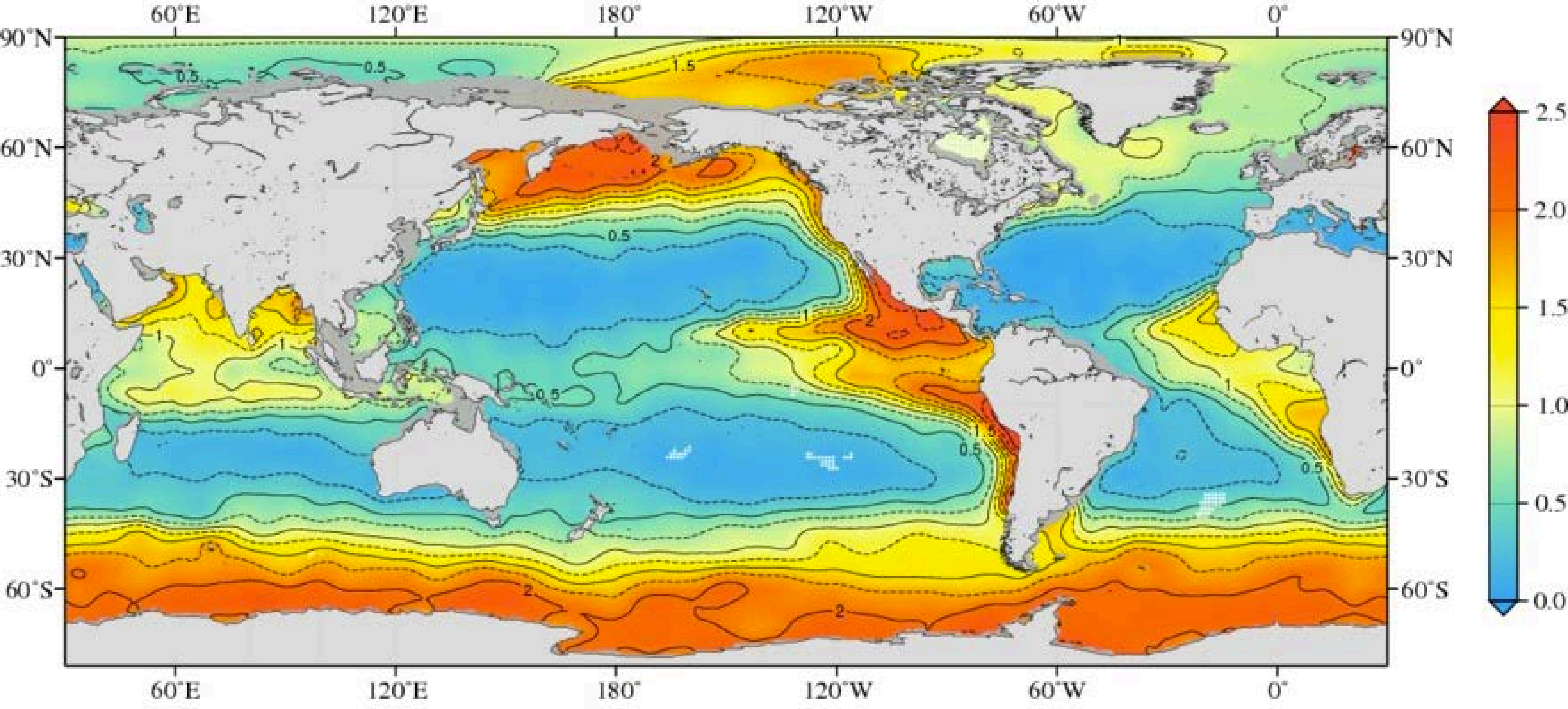
Contour Interval=0.25



Annual phosphate [umol/kg] at the surface (one-degree grid)

World Ocean Atlas Climatology

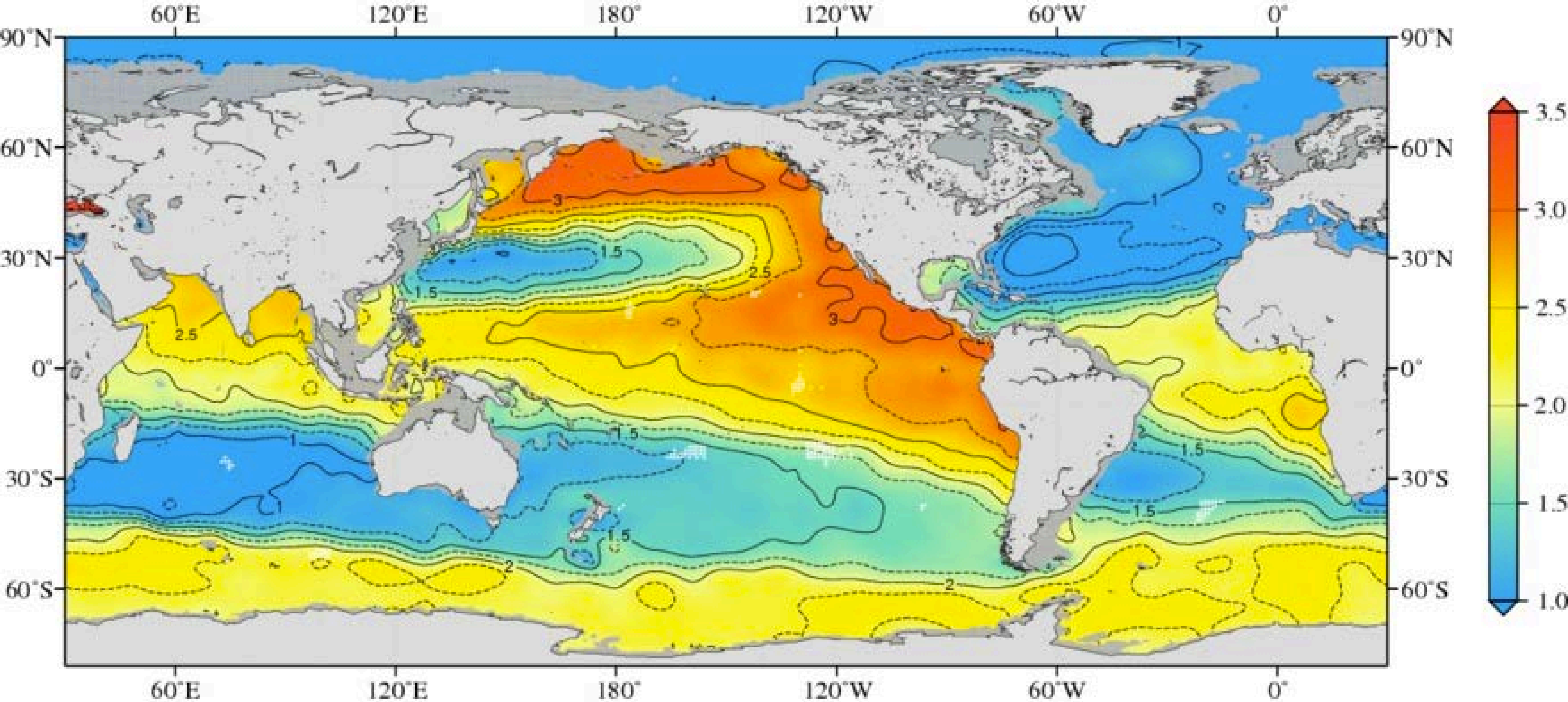
Contour Interval=0.25



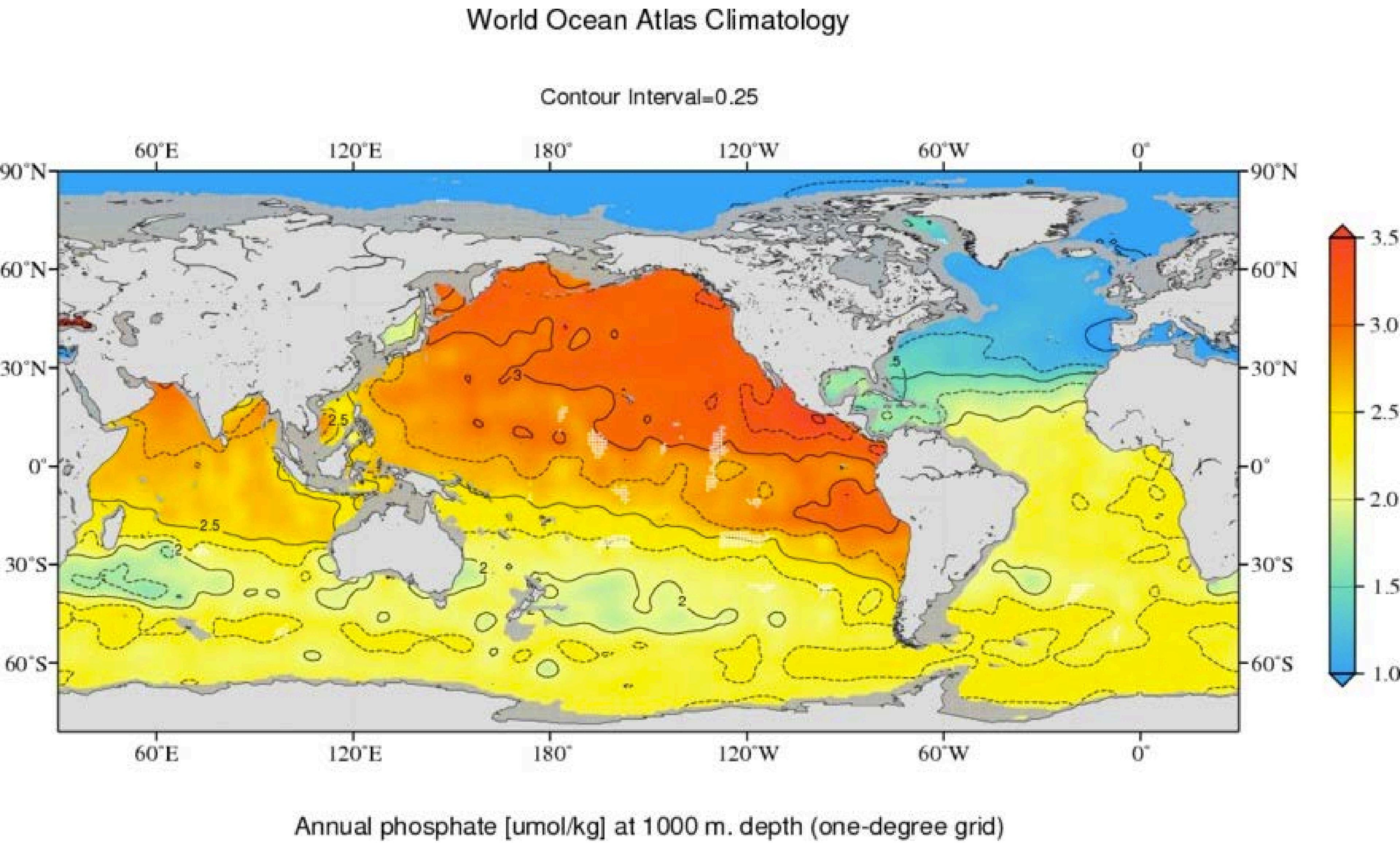
Annual phosphate [umol/kg] at 100 m. depth (one-degree grid)

World Ocean Atlas Climatology

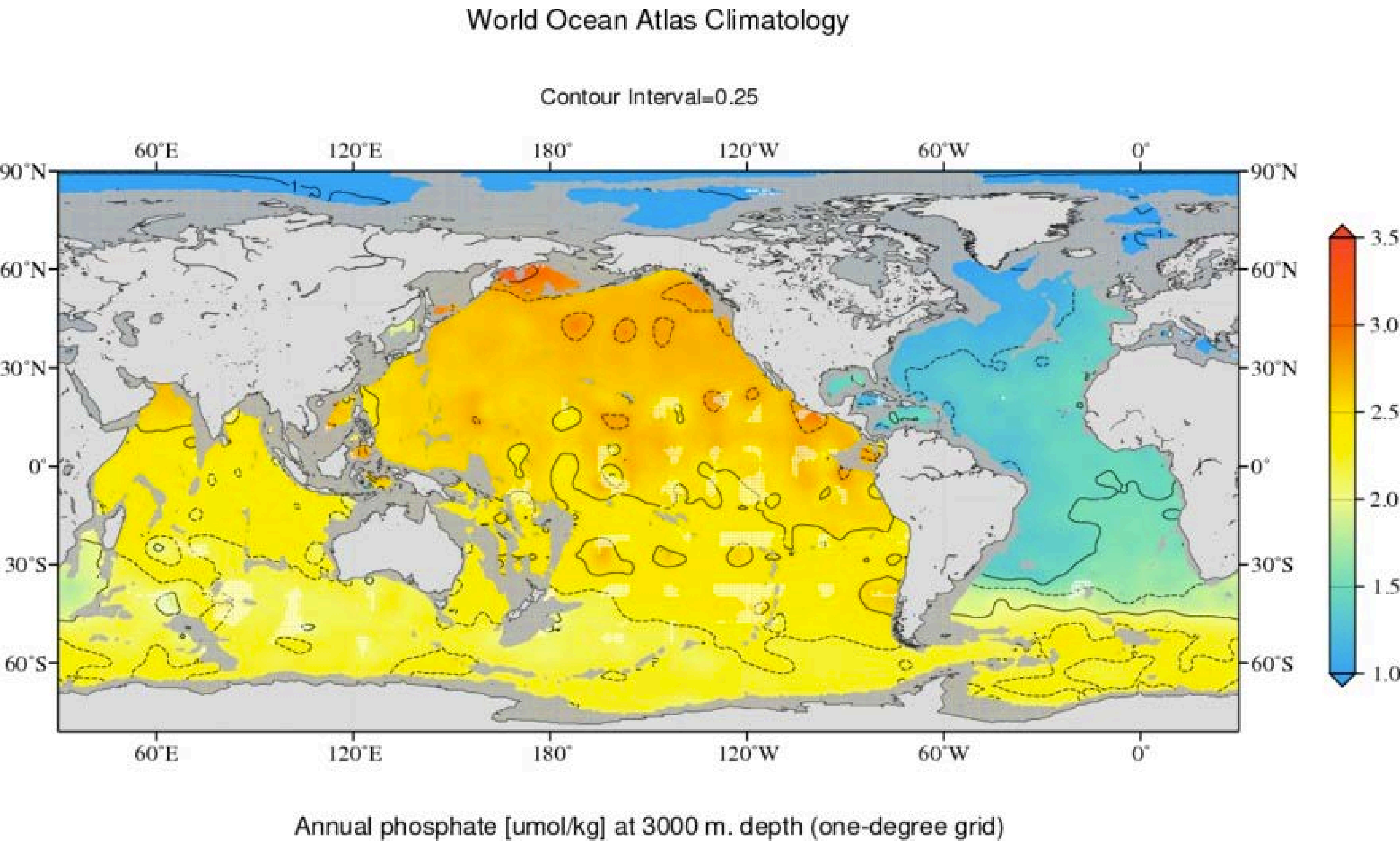
Contour Interval=0.25



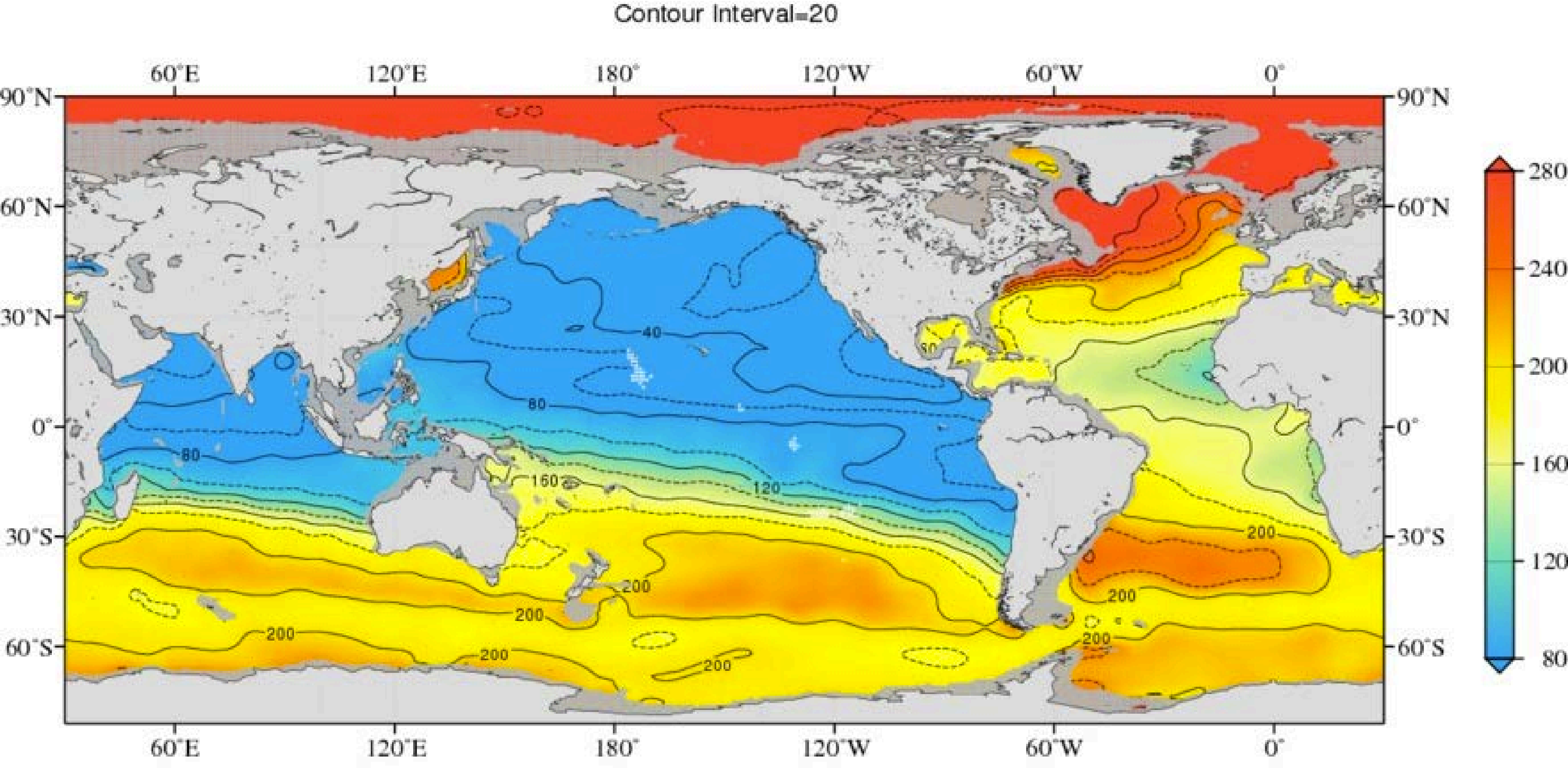
Annual phosphate [umol/kg] at 500 m. depth (one-degree grid)



World Ocean Atlas Climatology
Contour Interval=0.25
60°E
120°E
180°
120°W
60°W
0°
90°N
60°N
30°N
0°
30°S
60°S
3.5
3.0
2.5
2.0
1.5
1.0
Annual phosphate [umol/kg] at 1000 m. depth (one-degree grid)


World Ocean Atlas Climatology
Contour Interval=0.25
60°E
120°E
180°
120°W
60°W
0°
90°N
60°N
30°N
0°
30°S
60°S
3.5
3.0
2.5
2.0
1.5
1.0
Annual phosphate [umol/kg] at 3000 m. depth (one-degree grid)

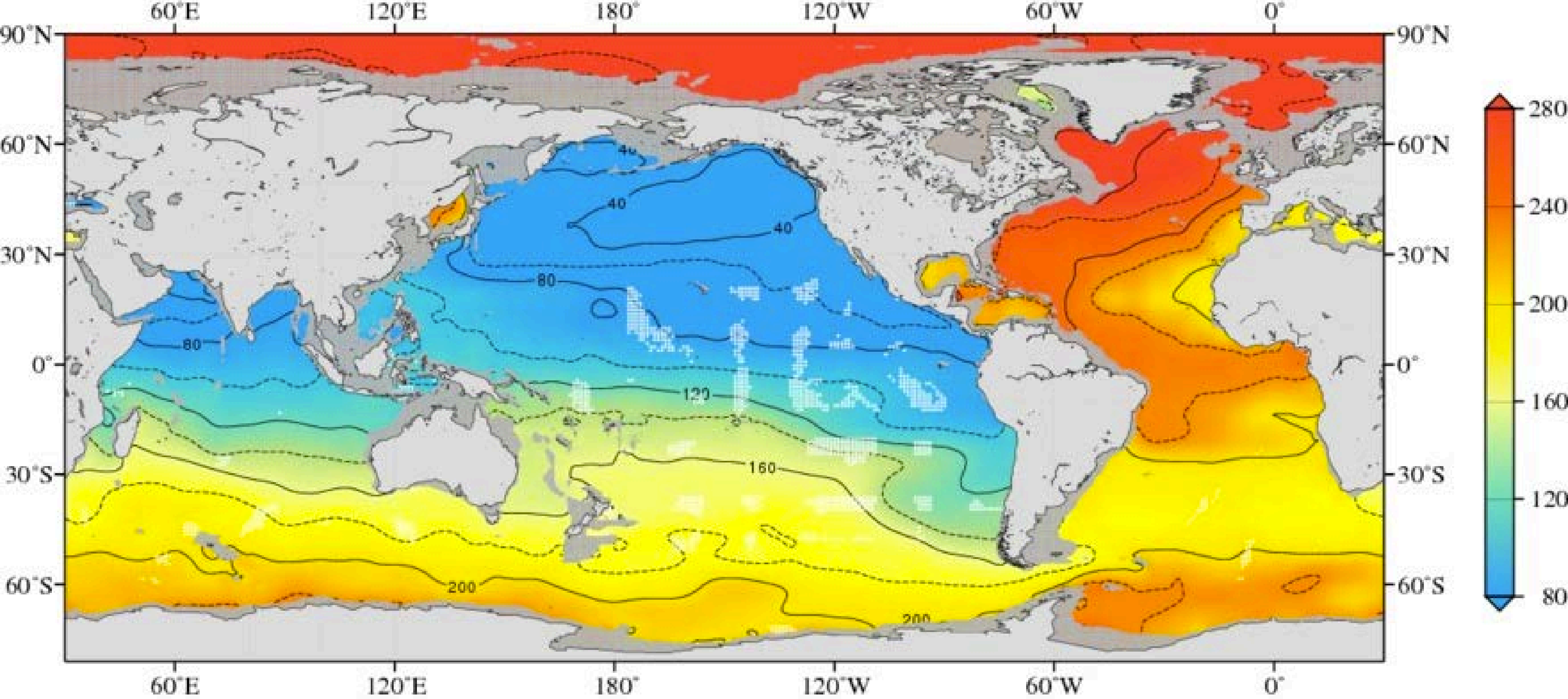
World Ocean Atlas Climatology



Annual oxygen [umol/kg] at 1000 m. depth (one-degree grid)

World Ocean Atlas Climatology

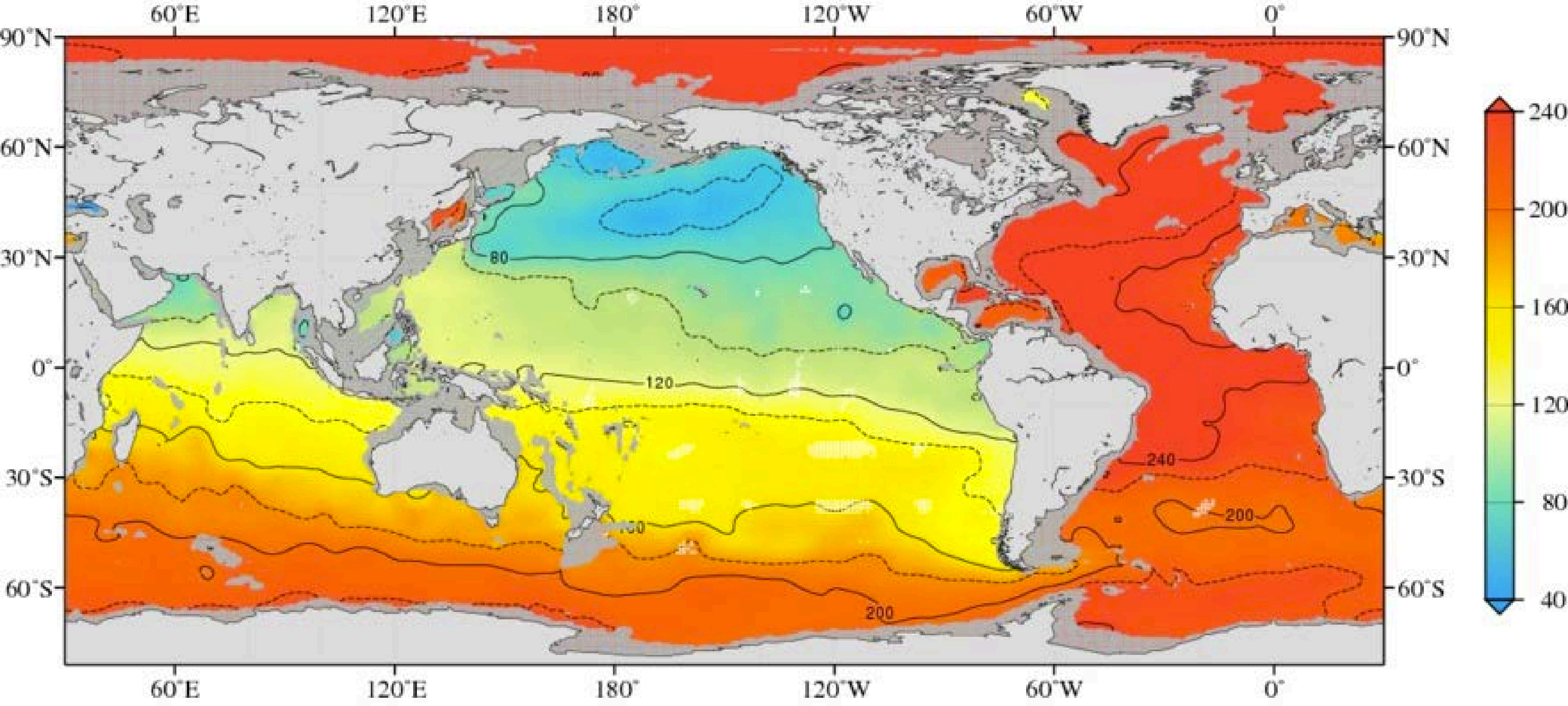
Contour Interval=20



Annual oxygen [umol/kg] at 1500 m. depth (one-degree grid)

World Ocean Atlas Climatology

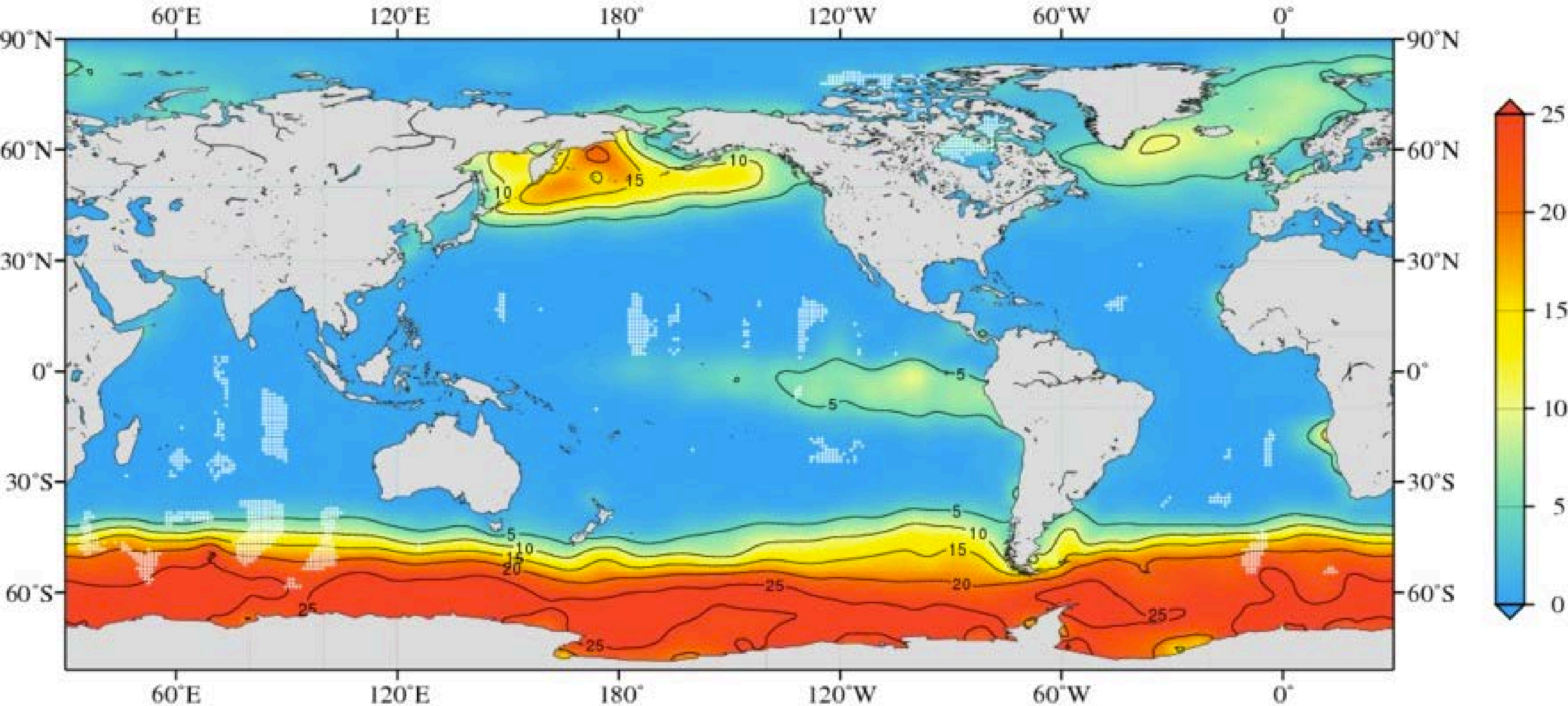
Contour Interval=20



Annual oxygen [umol/kg] at 2000 m. depth (one-degree grid)

World Ocean Atlas Climatology

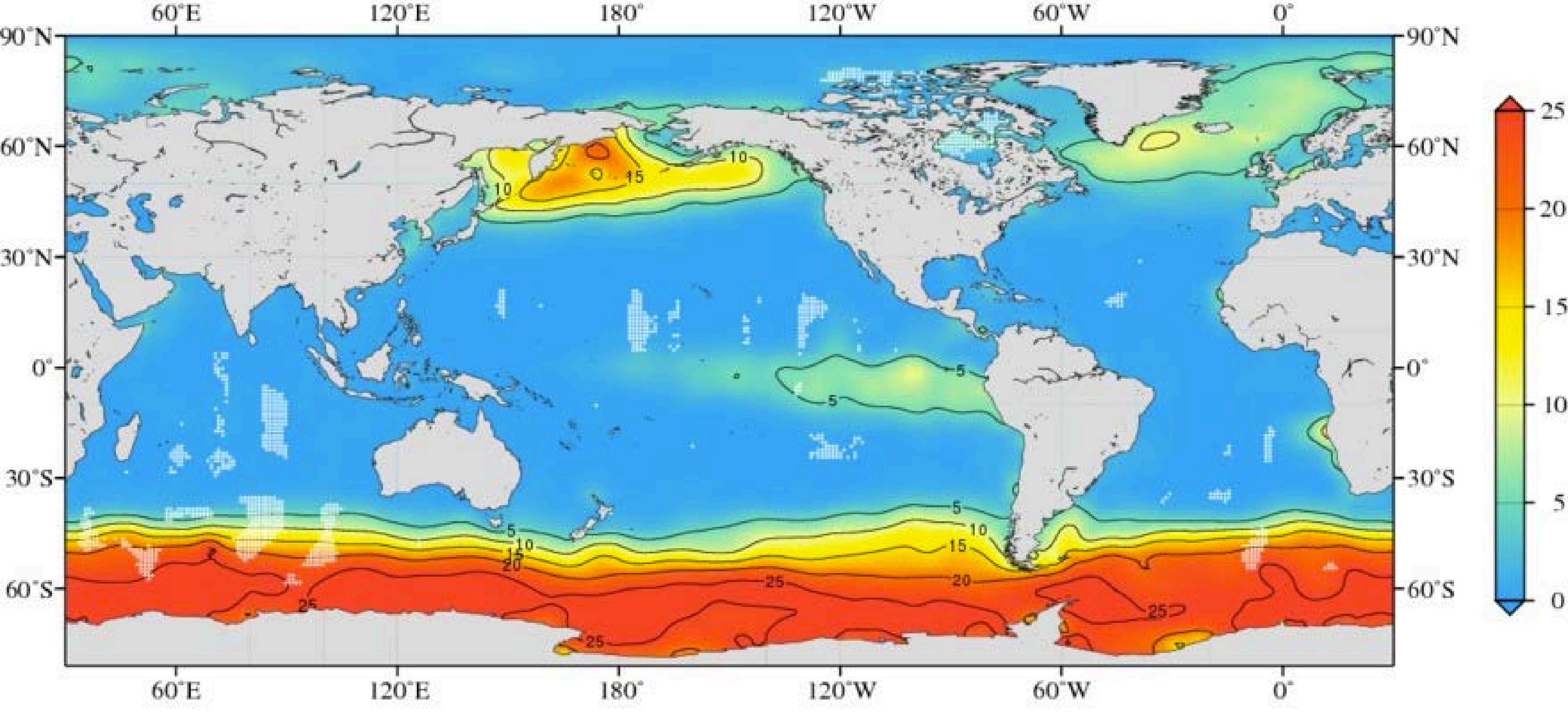
Contour Interval=5



Annual nitrate [umol/kg] at the surface (one-degree grid)

World Ocean Atlas Climatology

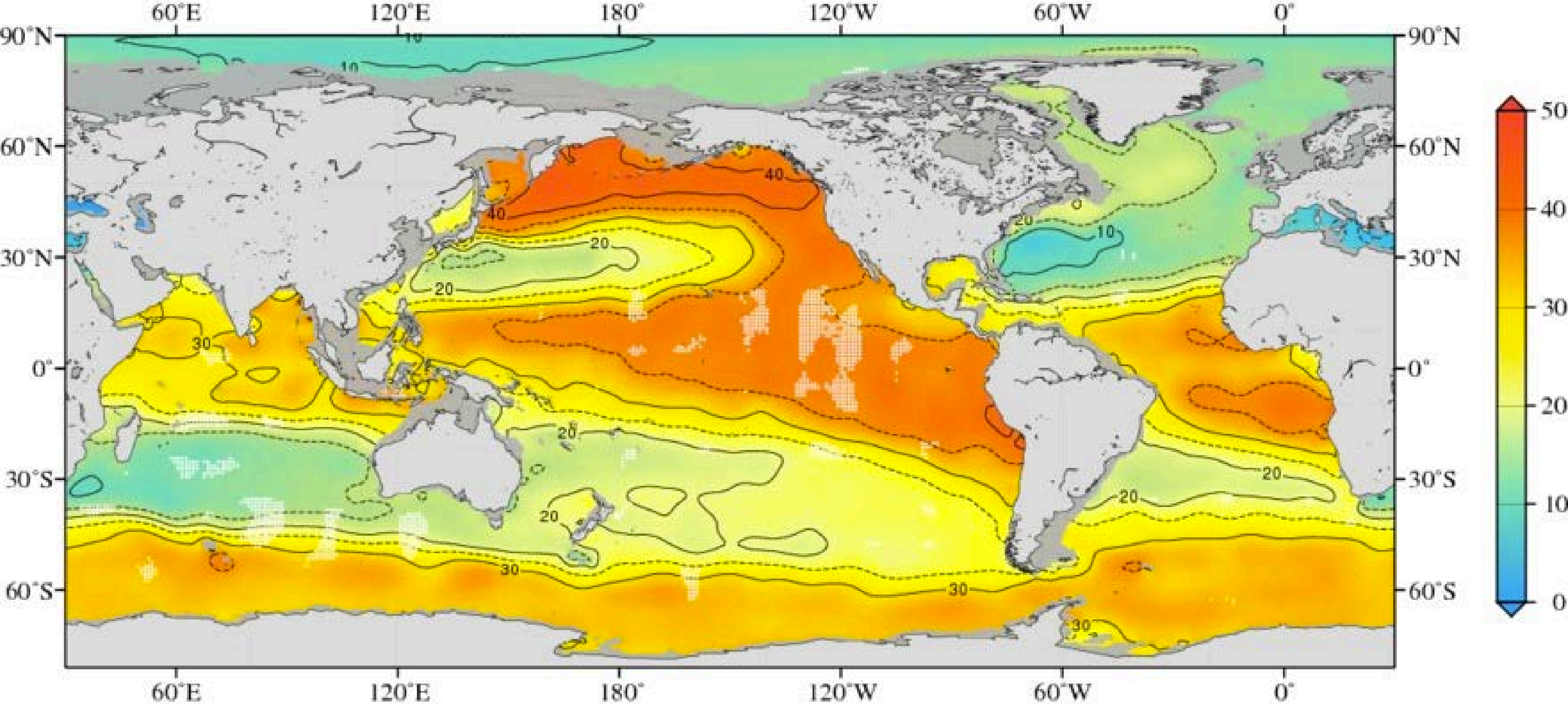
Contour Interval=5



Annual nitrate [umol/kg] at the surface (one-degree grid)

World Ocean Atlas Climatology

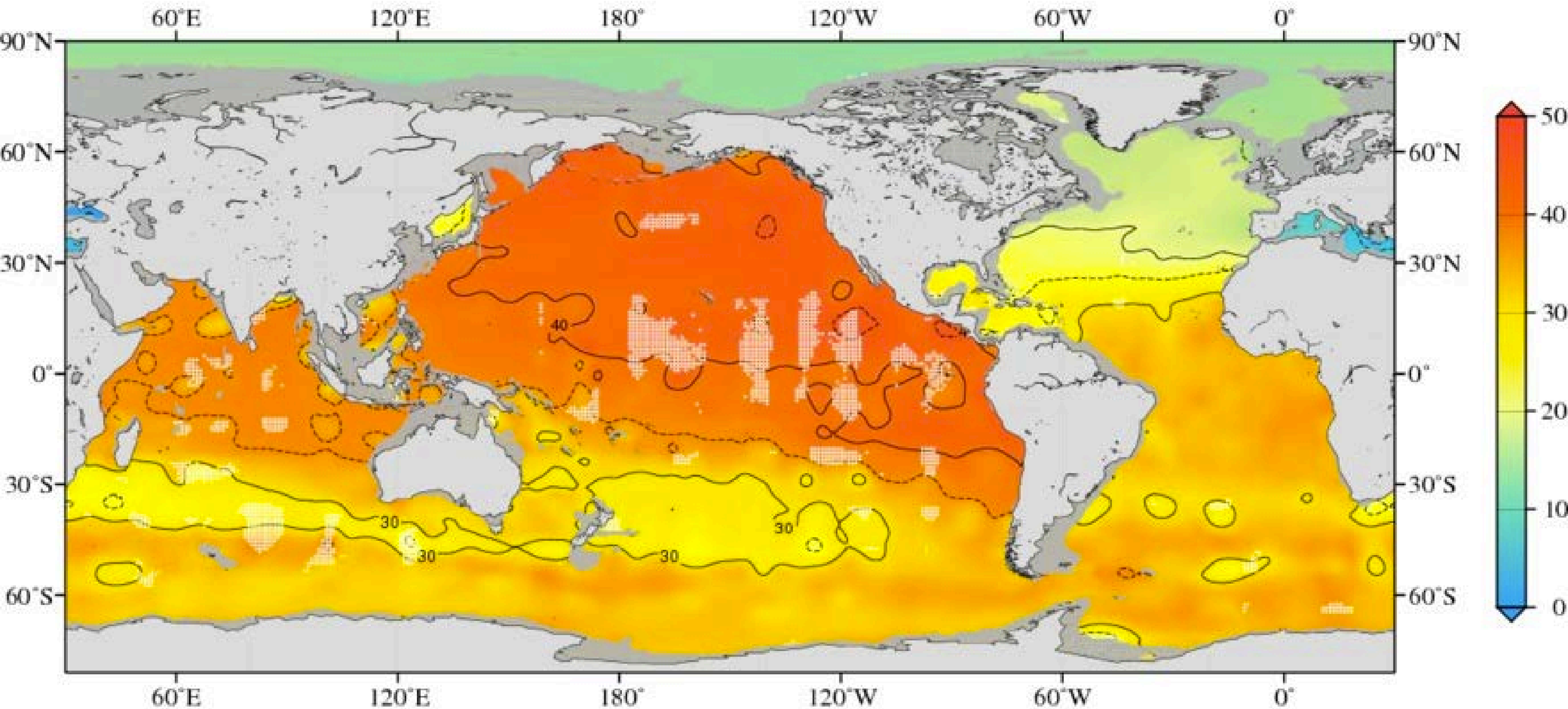
Contour Interval=5



Annual nitrate [umol/kg] at 500 m. depth (one-degree grid)

World Ocean Atlas Climatology

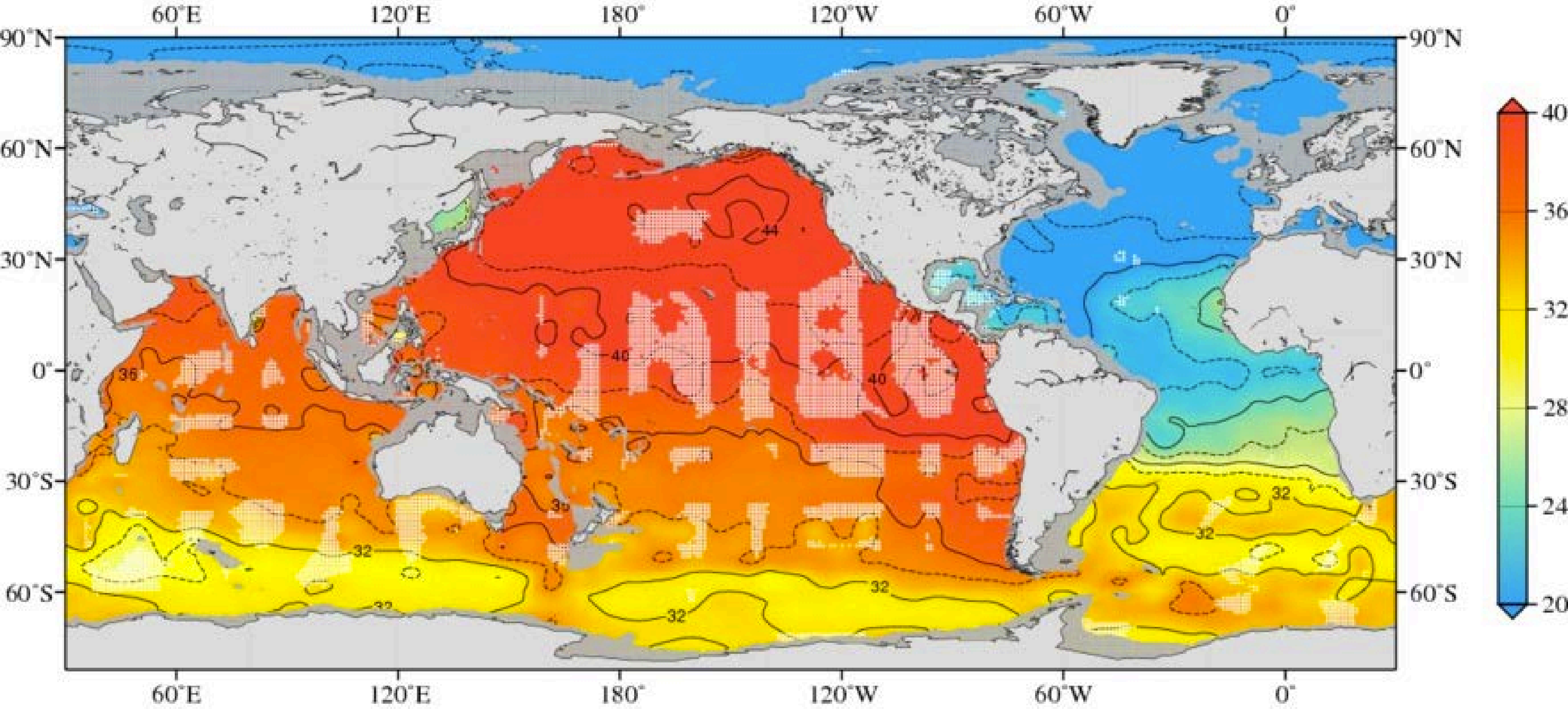
Contour Interval=5



Annual nitrate [umol/kg] at 1000 m. depth (one-degree grid)

World Ocean Atlas Climatology

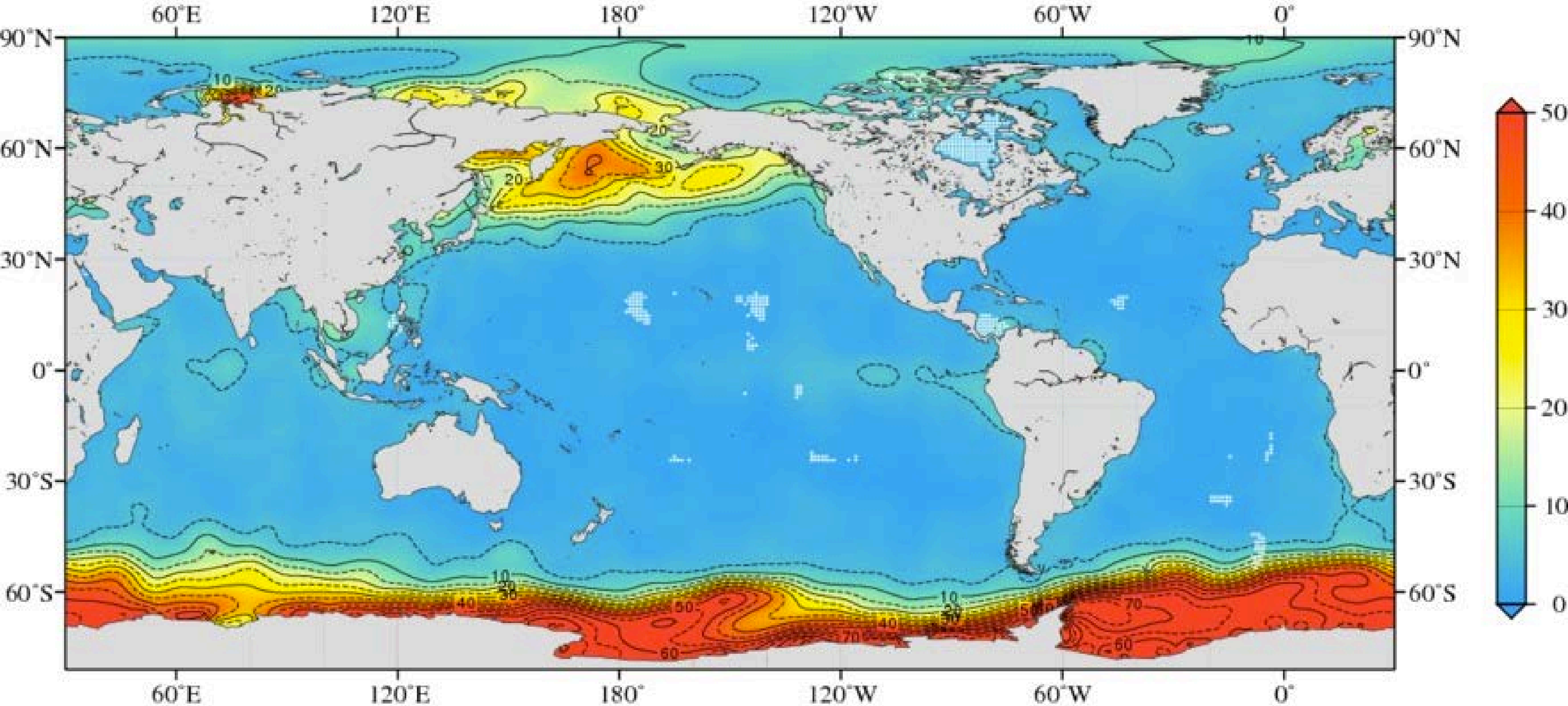
Contour Interval=2



Annual nitrate [umol/kg] at 1500 m. depth (one-degree grid)

World Ocean Atlas Climatology

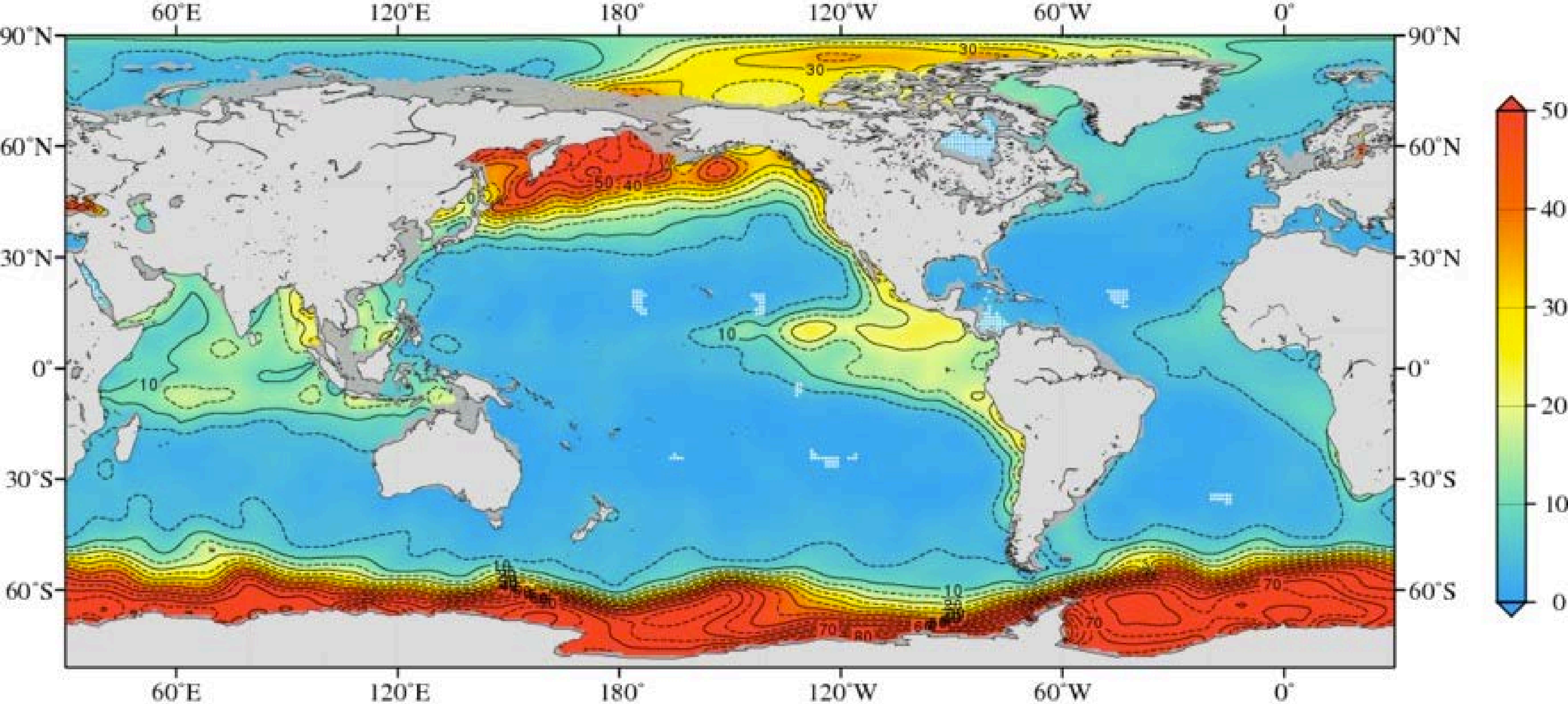
Contour Interval=5



Annual silicate [umol/kg] at the surface (one-degree grid)

World Ocean Atlas Climatology

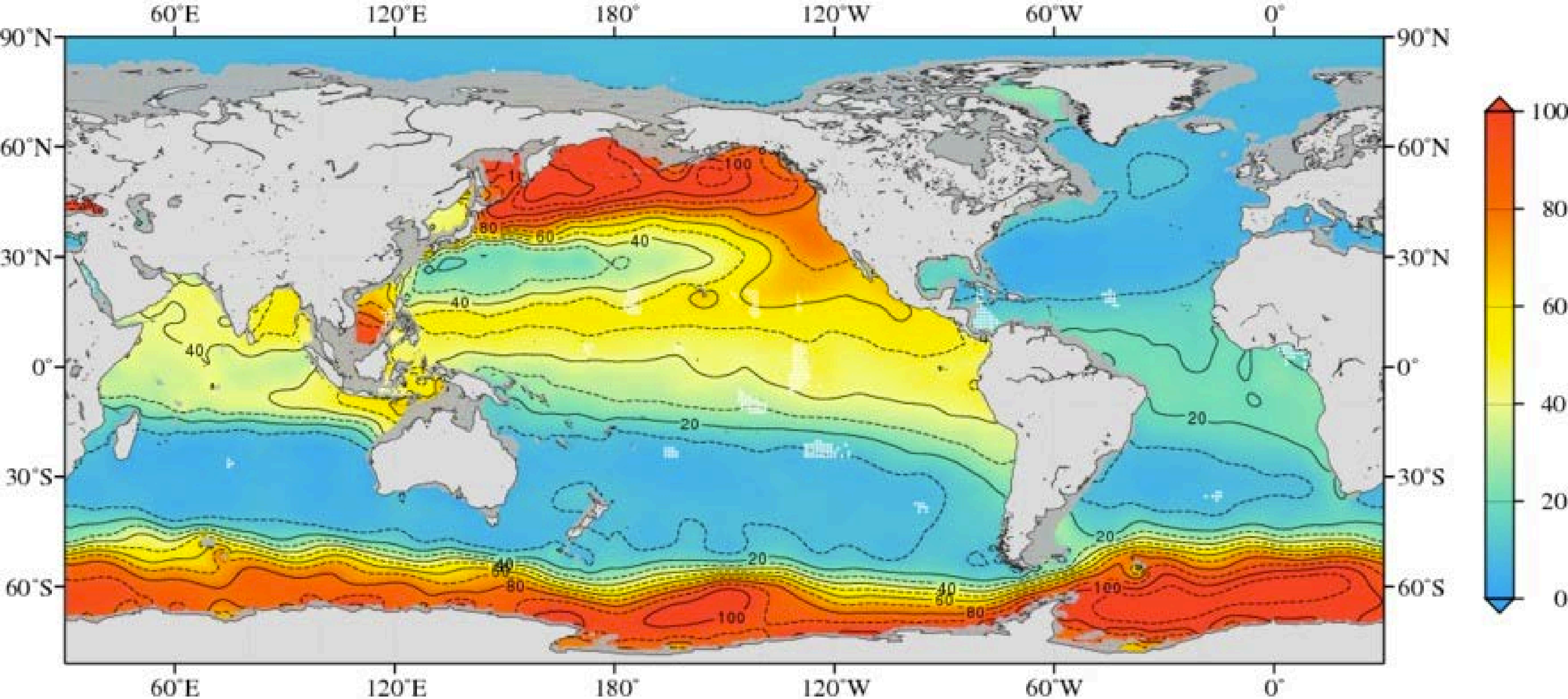
Contour Interval=5



Annual silicate [umol/kg] at 100 m. depth (one-degree grid)

World Ocean Atlas Climatology

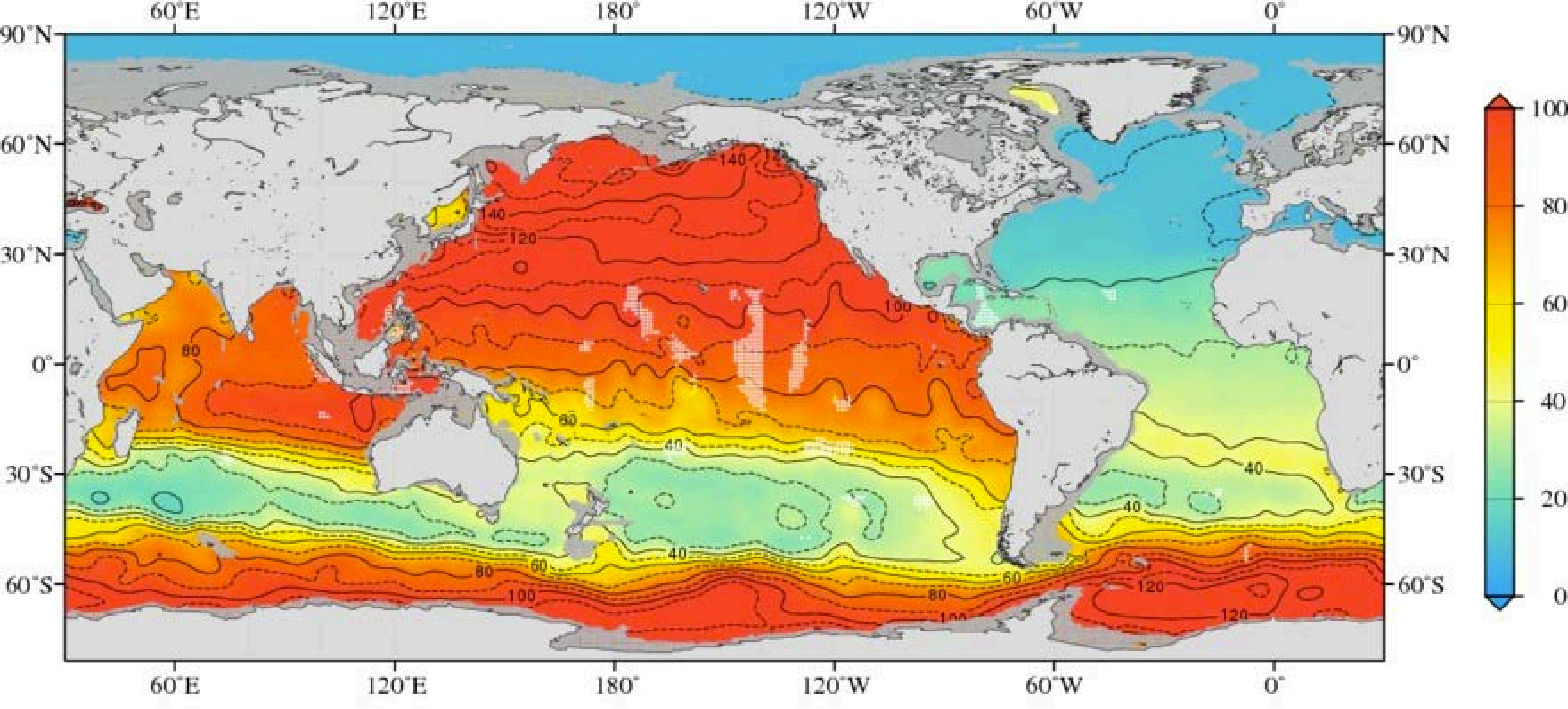
Contour Interval=10



Annual silicate [umol/kg] at 500 m. depth (one-degree grid)

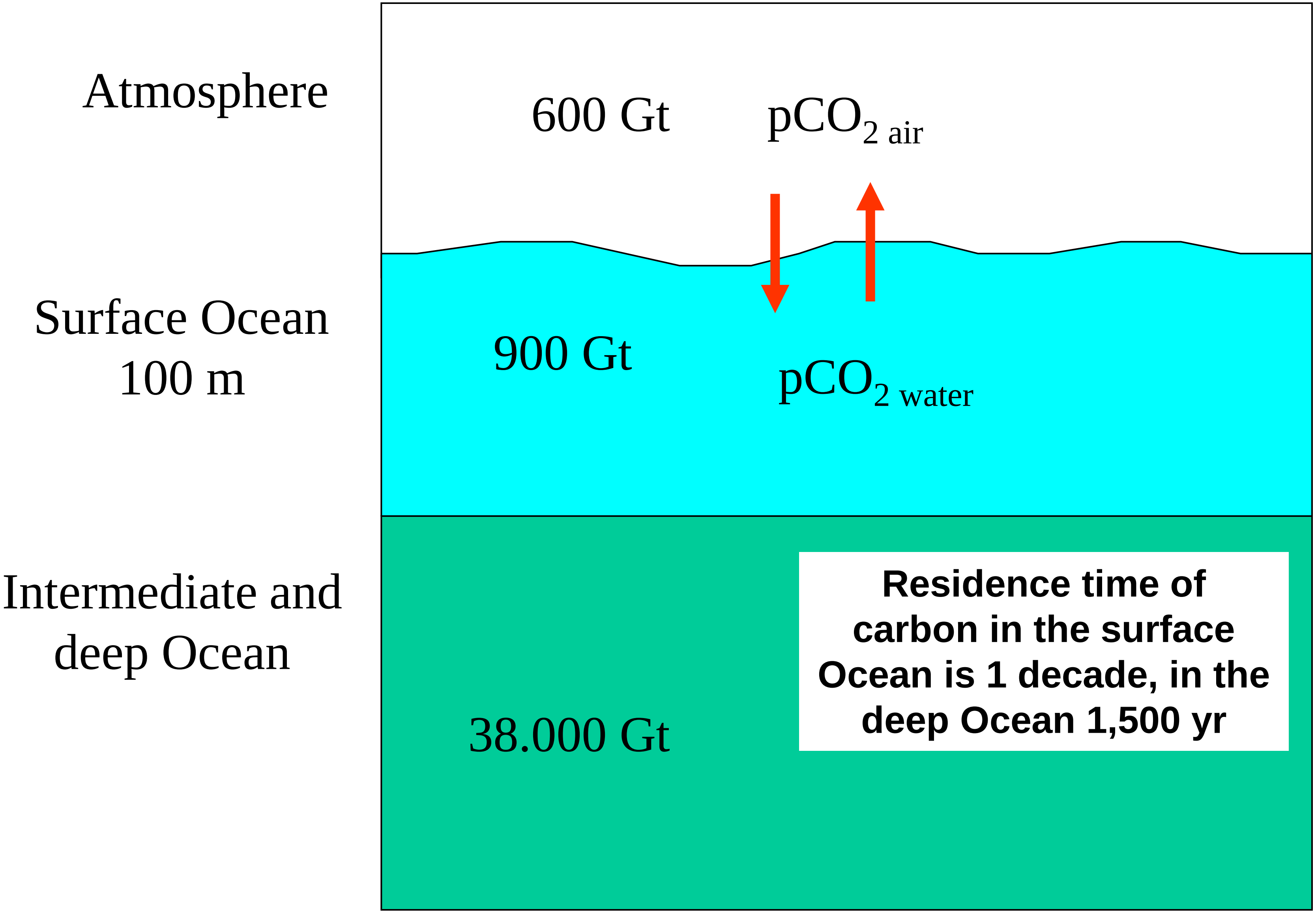
World Ocean Atlas Climatology

Contour Interval=10



Annual silicate [umol/kg] at 1000 m. depth (one-degree grid)

Ocean role on atmospheric CO2 concentration

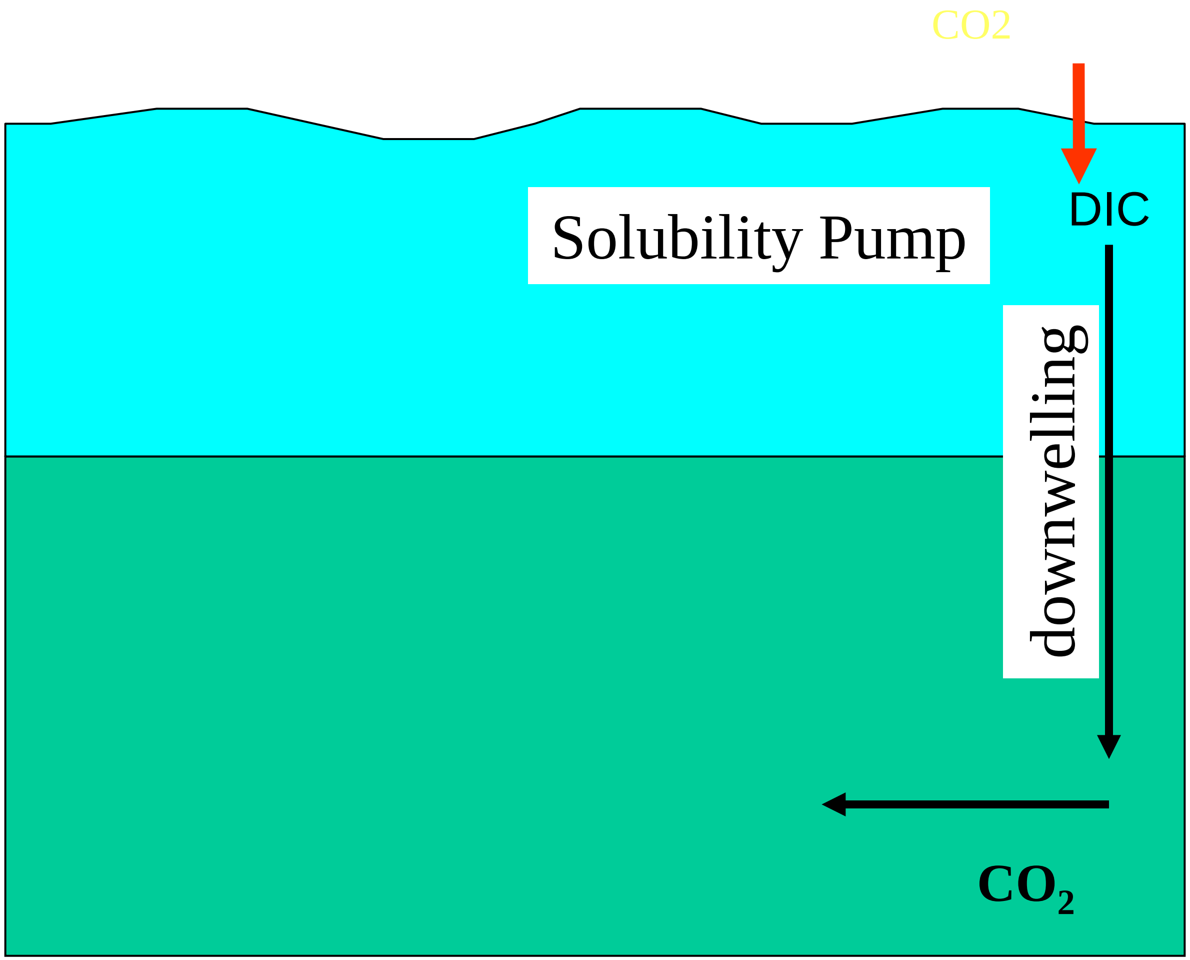


Solubility Pump

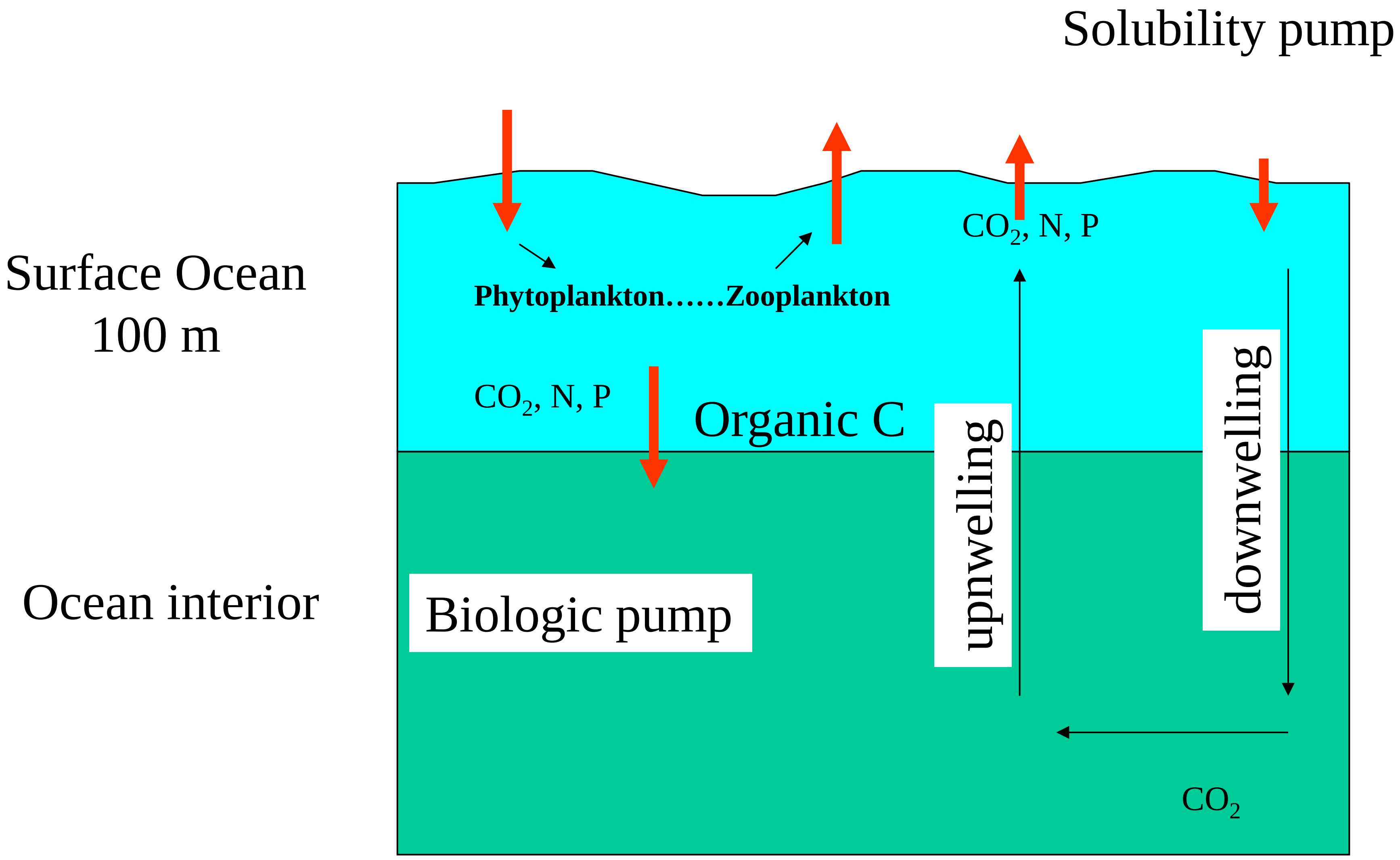
Te solubility of CO_2 in seawater is a function of temperature. Solubility is higher in colder seawater and the pressure of CO_2 decreases.

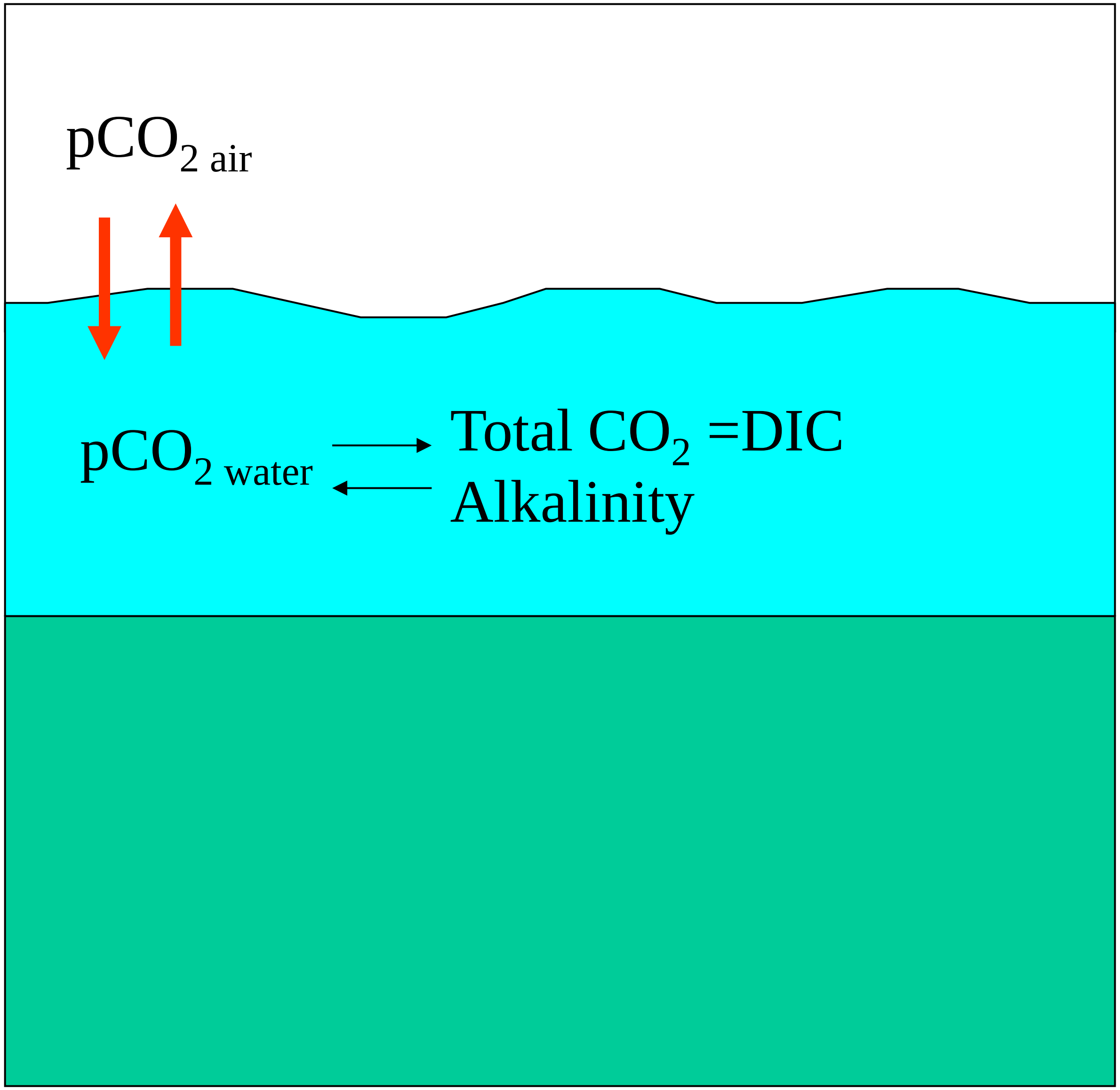
Solubility increases with hydrostatic pressure. Deep Ocean is undersaturated in CO_2.

Solubility pump

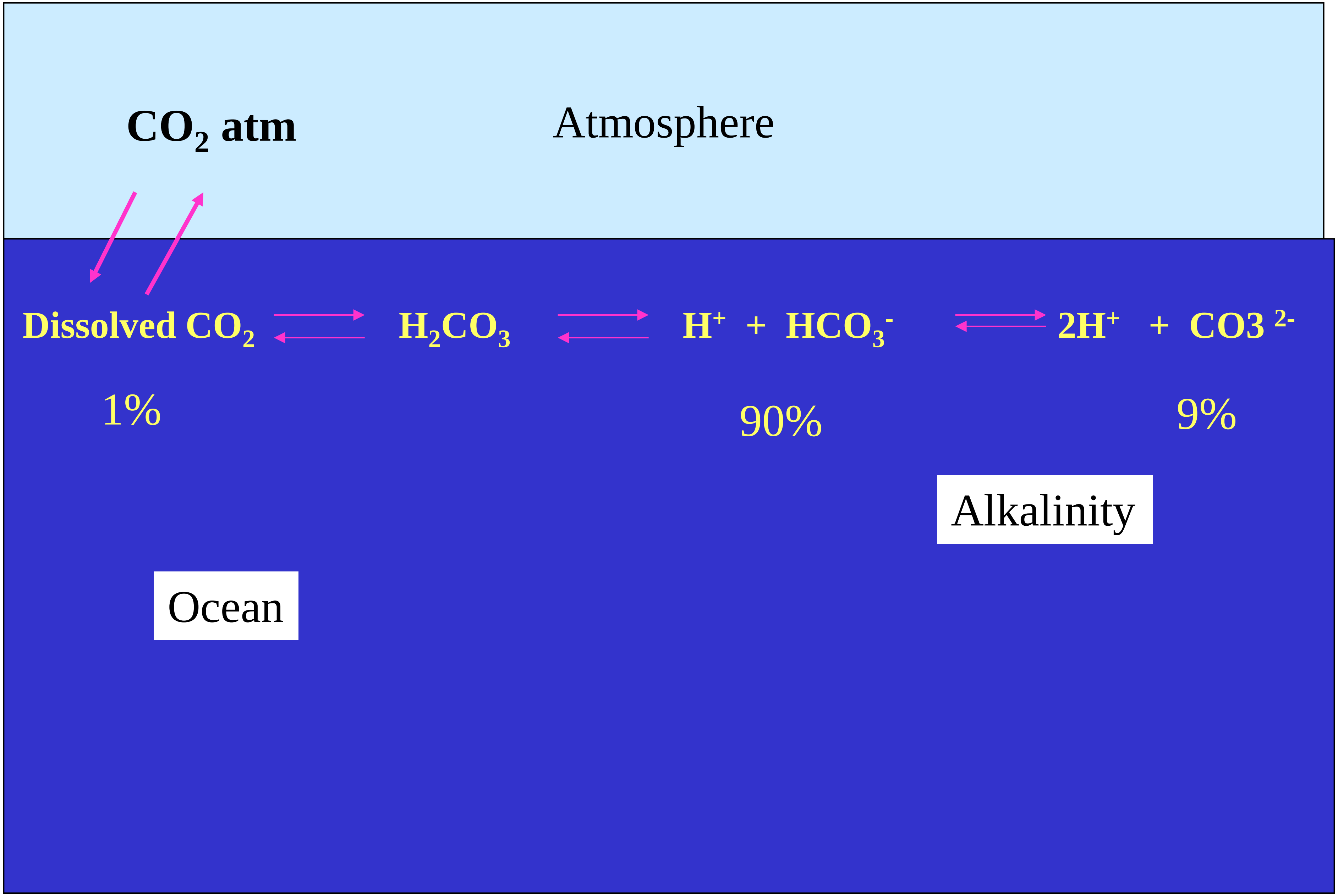


Solubility Pump

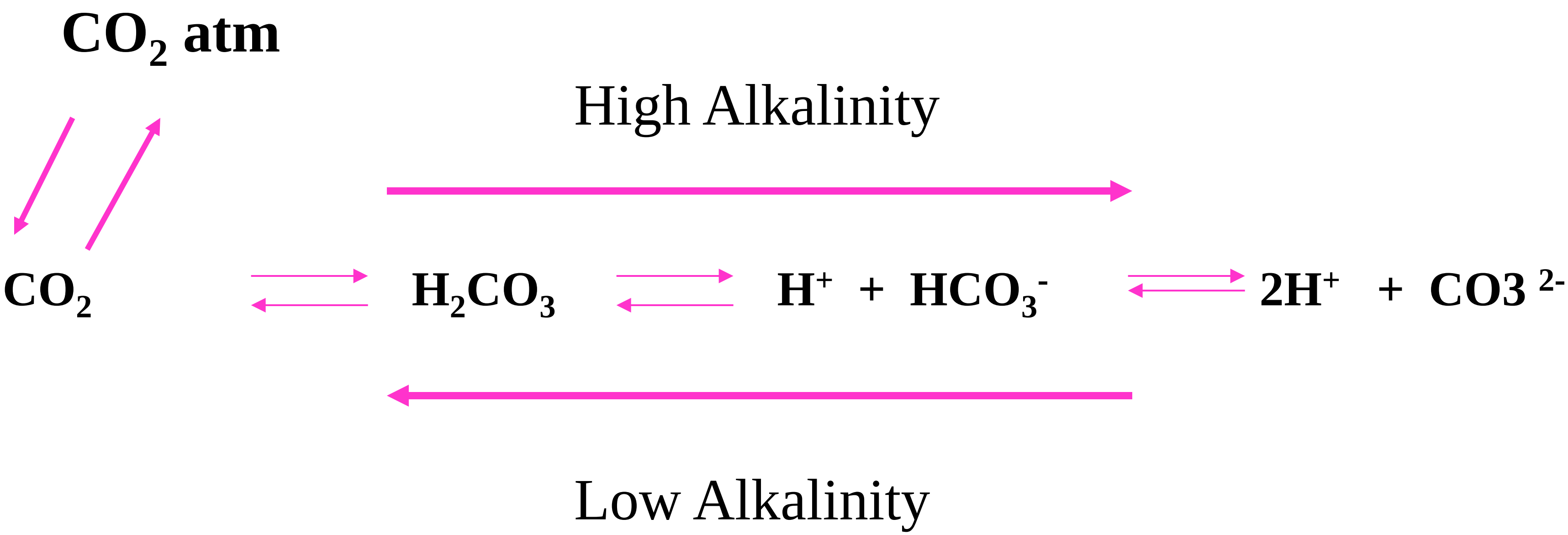




$pCO_{2\ air}$
$pCO_{2\ water}$
Total CO_2 =DIC
Alkalinity



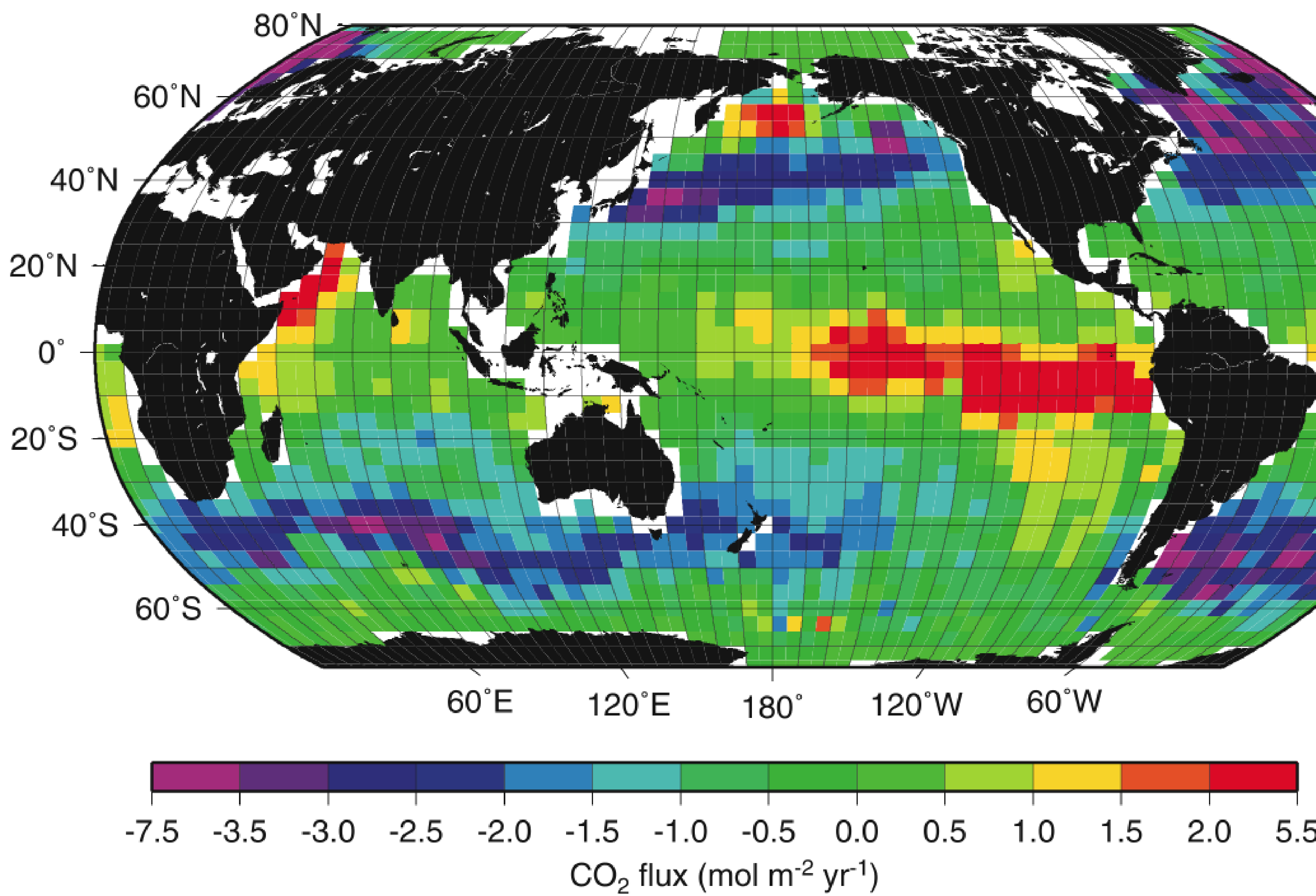
CO_2 atm
Atmosphere
Dissolved CO_2 ⇌ H_2CO_3 ⇌ H^+ + HCO_3^- ⇌ $2H^+$ + CO3 $^{2-}$
1%
90%
9%
Alkalinity
Ocean


CO_2 atm
High Alkalinity
CO_2
H_2CO_3
$H^+ + HCO_3^-$
$2H^+ + CO3^{2-}$
Low Alkalinity

Alkalinity in Ocean is controlled by Ca^{2+}

Alkalinity sinks in Ocean.
Carbonate production and burial by Coccolithophores, foraminifers, corals, etc reduces ocean alkalinity by removing Ca^{2+} from seawater

Alkalinity sources in Ocean:
River supply
Carbonate dissolution in the deep sea


80°N
60°N
40°N
20°N
0°
20°S
40°S
60°S
60°E
120°E
180°
120°W
60°W
-7.5
-3.5
-3.0
-2.5
-2.0
-1.5
-1.0
-0.5
0.0
0.5
1.0
1.5
2.0
5.5
CO2 flux (mol m-2 yr-1)

Glacial interglacial changes in CO2