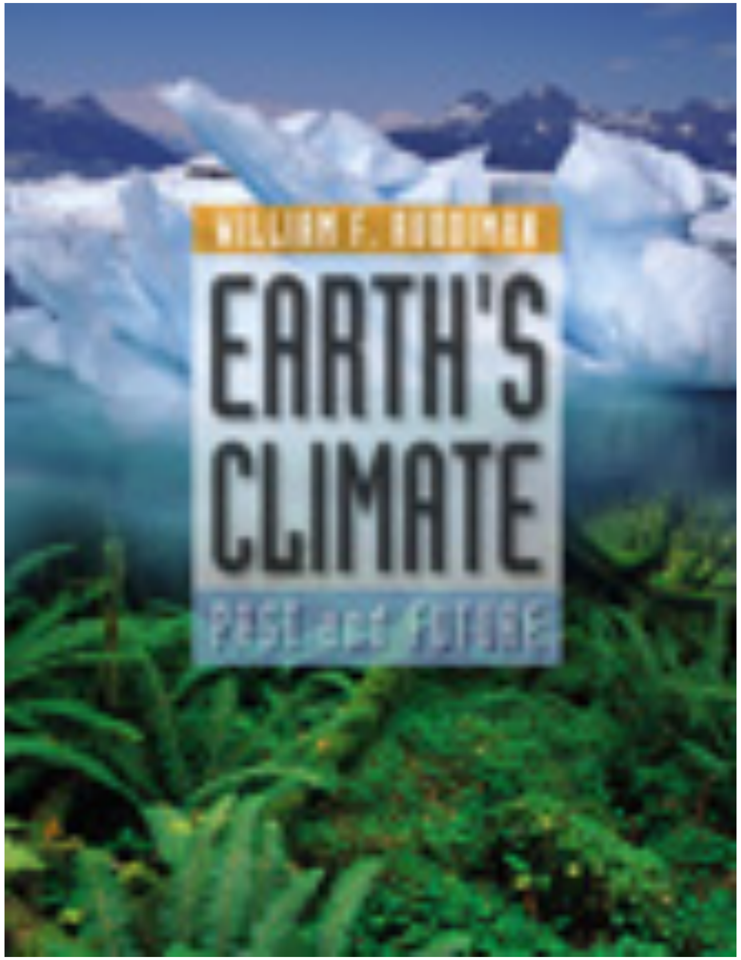
Einführung in die Paläozeanographie


PALEOCEANOGRAPHY


WILLIAM F. RUDDIMAN
EARTH'S CLIMATE
PAST and FUTURE

Klima

Die Synthese des Wetters über einen Zeitraum, der lang genug ist, um dessen statistische Eigenschaften zu bestimmen

KLIMAFAKTOREN:

Prozesse und Zustände, die zur Entstehung, Aufrechterhaltung und Veränderung des Klimas führen.

Sonnenstrahlung (solares Klima)

Strahlungs- und Wärmehaushalt

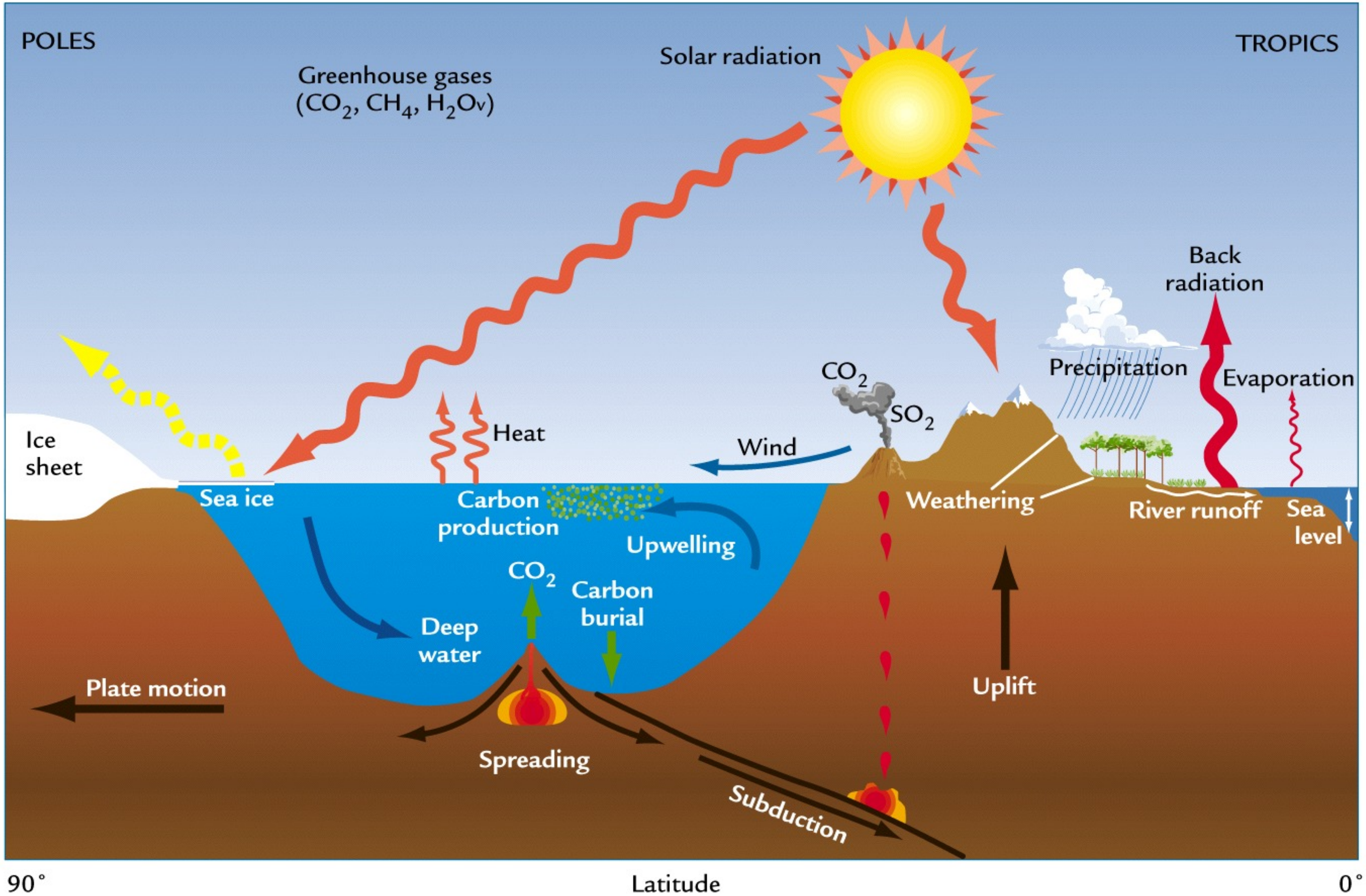
Land- und Meerverteilung (maritimes/kontinentales Klima)

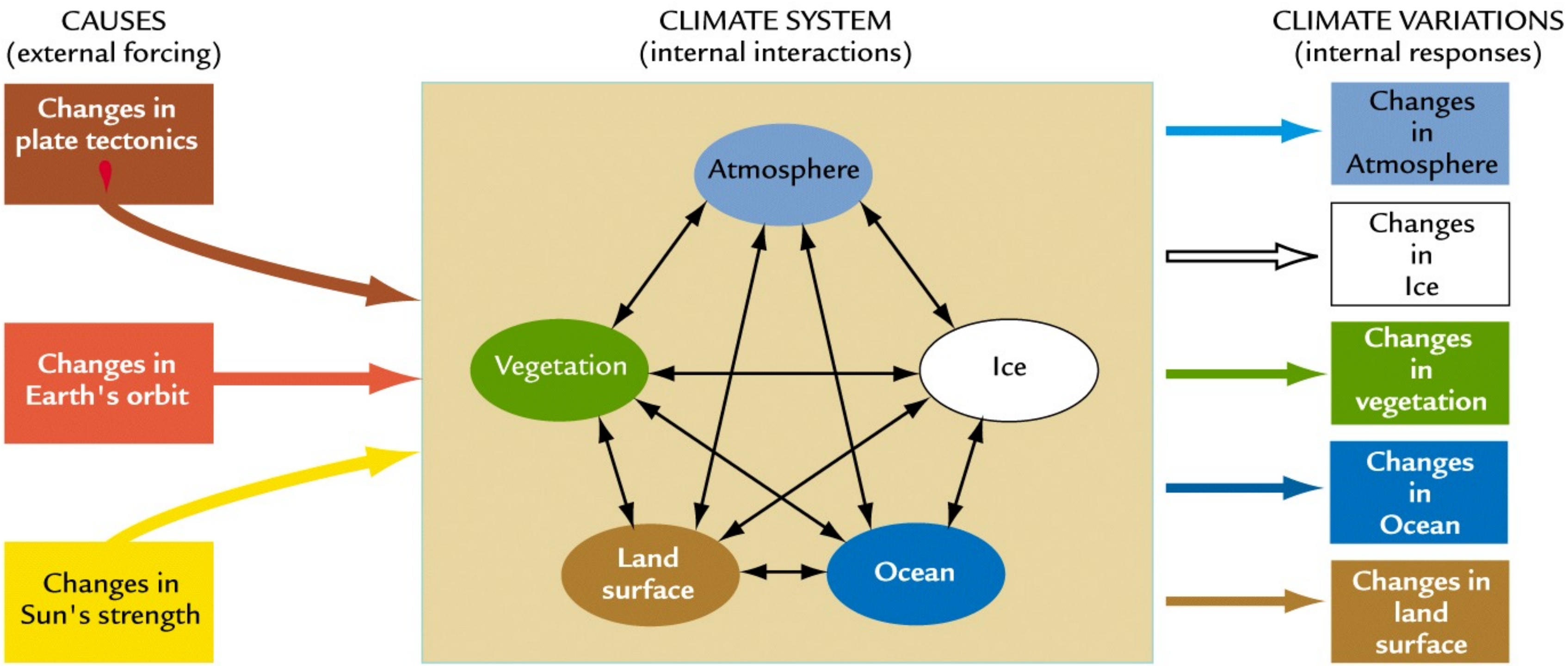
Höhe über NN (Gebirgsklima)

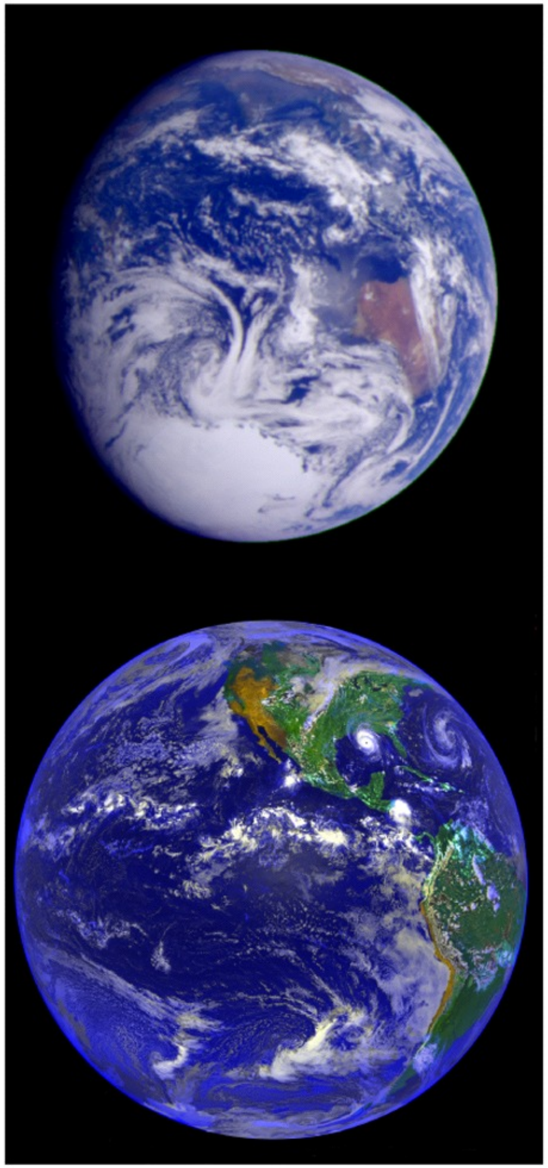
Zusammensetzung der Erdatmosphäre (Spurengase, Aerosole, Wasserdampf)

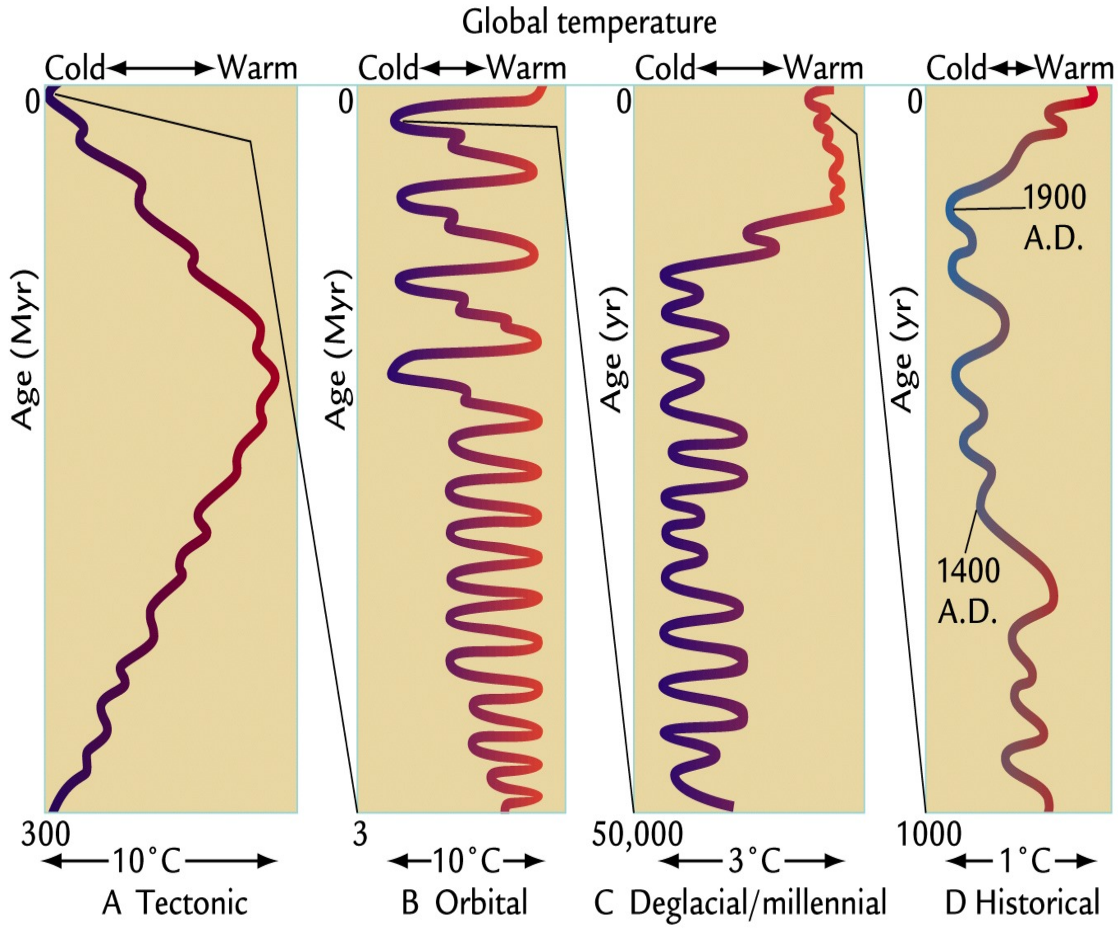
Ozean- und Atmosphärische Zirkulation

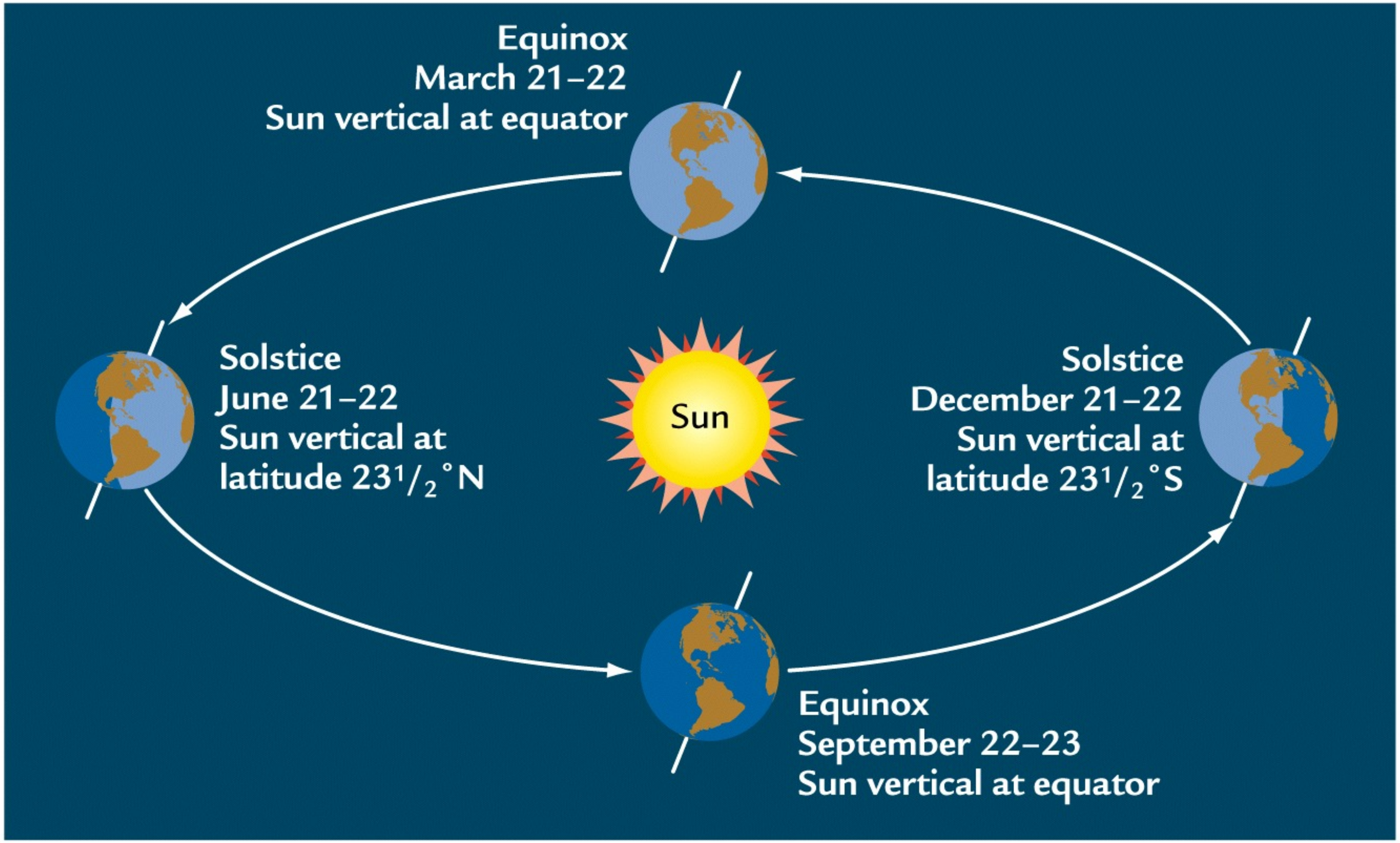
Landvegetation und biologische Produktion


POLES
TROPICS
Solar radiation
Greenhouse gases
(CO_2, CH_4, H_2Ov)
Back
radiation
Precipitation
Evaporation
CO_2
SO_2
Wind
Heat
Ice
sheet
Sea ice
Carbon
production
Upwelling
Weathering
River runoff
Sea
level
CO_2
Carbon
burial
Deep
water
Uplift
Plate motion
Spreading
Subduction
90°
Latitude
0°

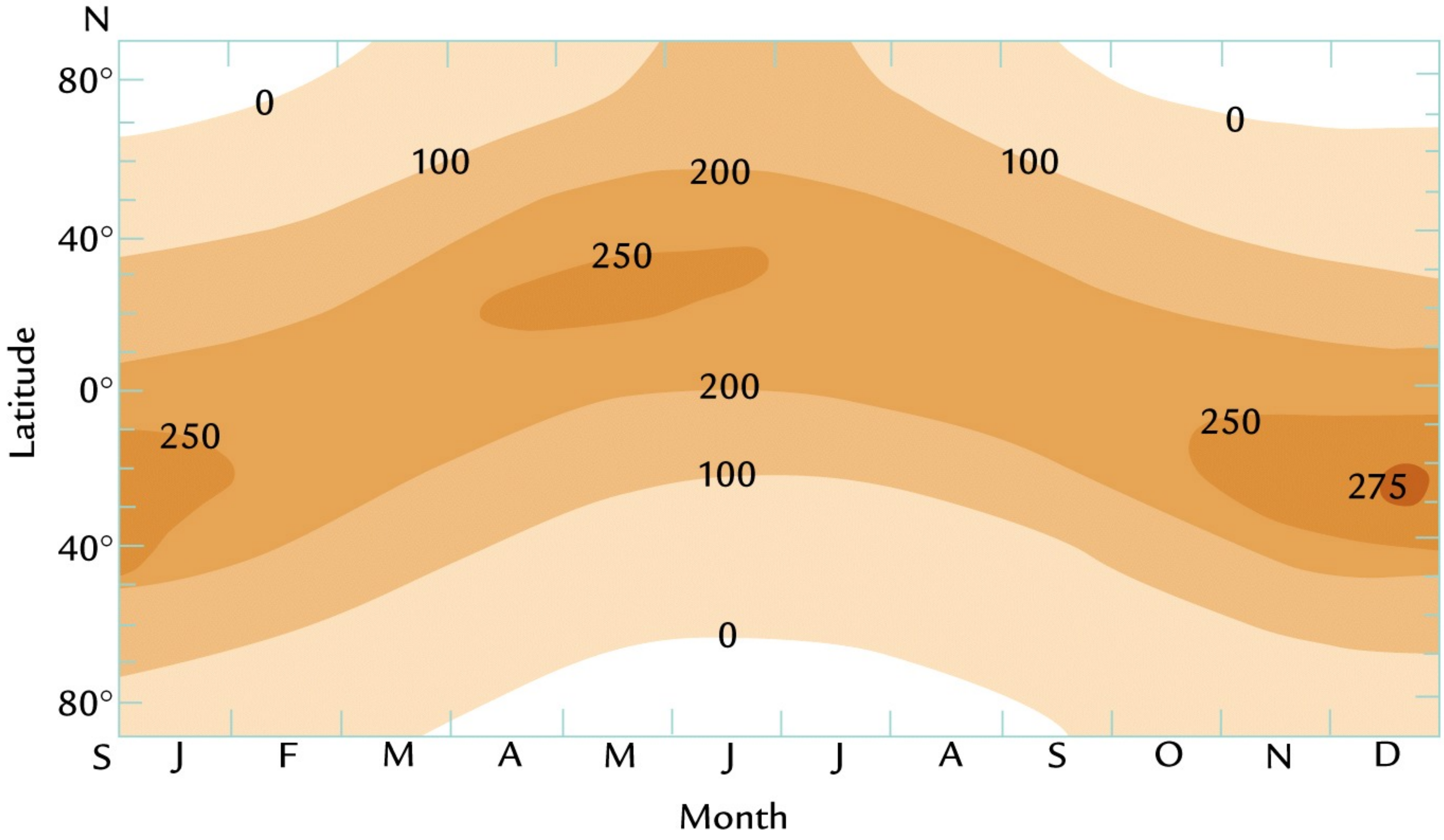

CAUSES
(external forcing)
CLIMATE SYSTEM
(internal interactions)
CLIMATE VARIATIONS
(internal responses)
Changes in plate tectonics
Changes in Earth's orbit
Changes in Sun's strength
Atmosphere
Vegetation
Ice
Land surface
Ocean
Changes in Atmosphere
Changes in Ice
Changes in vegetation
Changes in Ocean
Changes in land surface



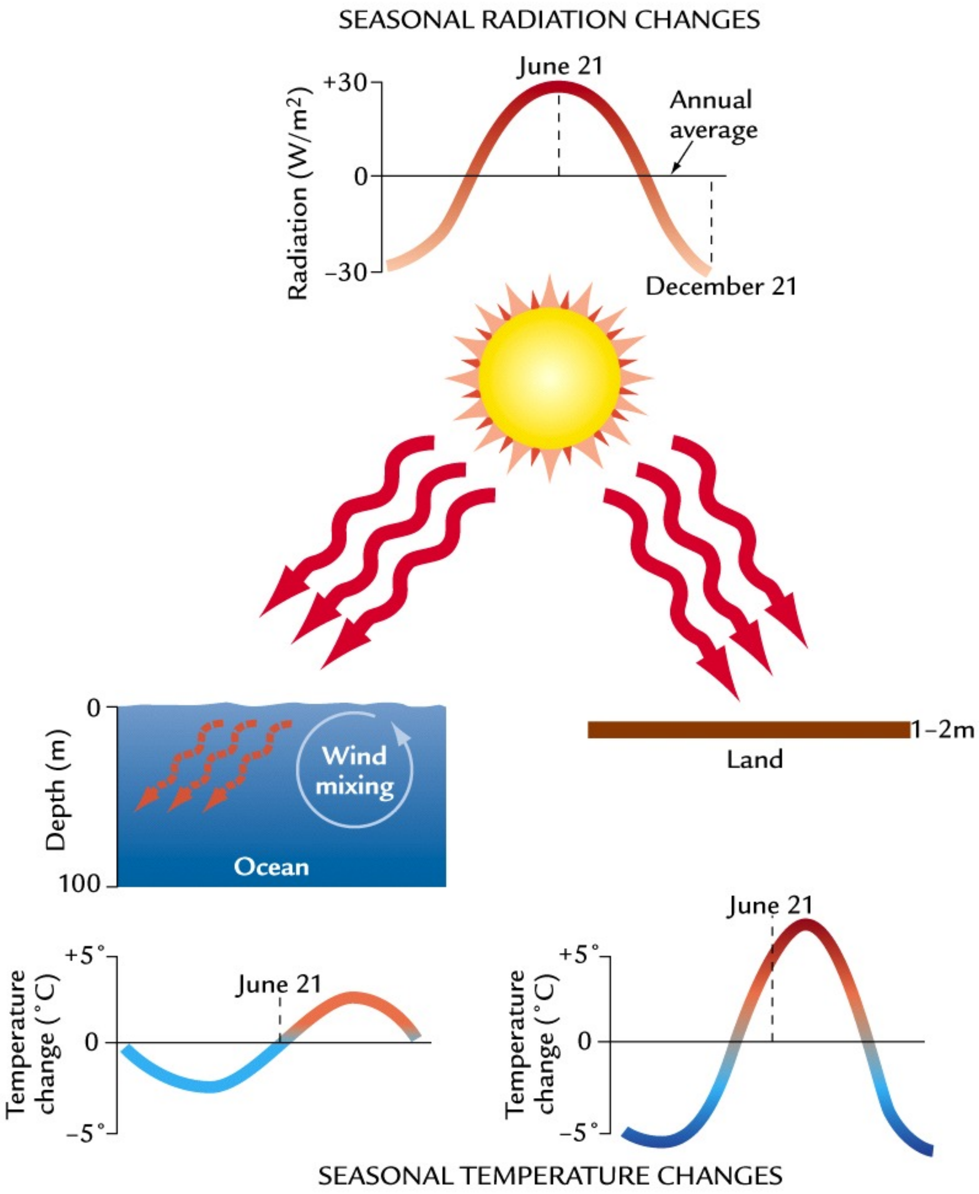

Global temperature
Cold Warm
Cold Warm
Cold Warm
Cold Warm
0
Age (Myr)
300
10°C
A Tectonic
0
Age (Myr)
3
10°C
B Orbital
0
Age (yr)
50,000
3°C
C Deglacial/millennial
0
Age (yr)
1900 A.D.
1400 A.D.
1000
1°C
D Historical



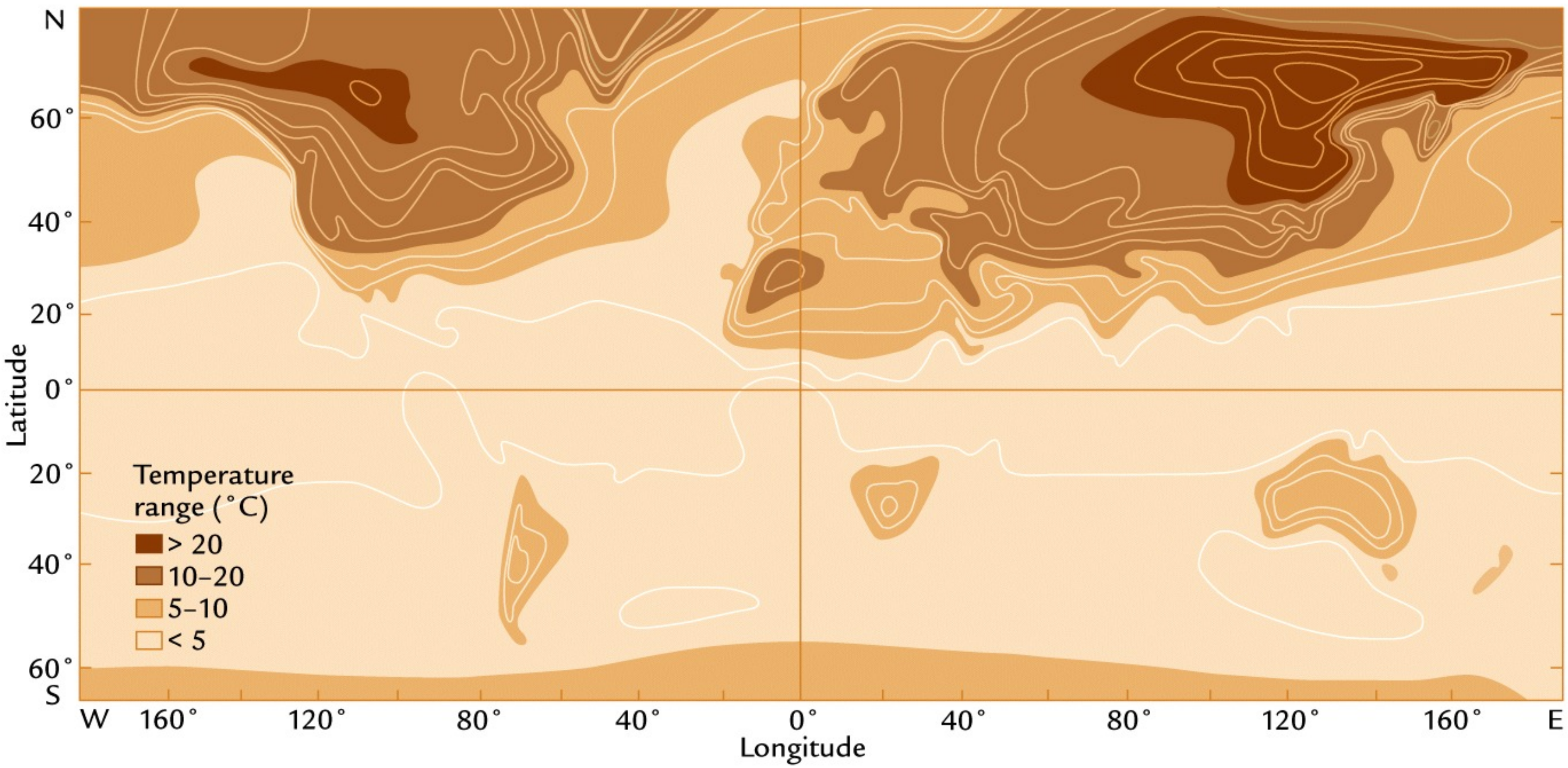
A Earth's orbit



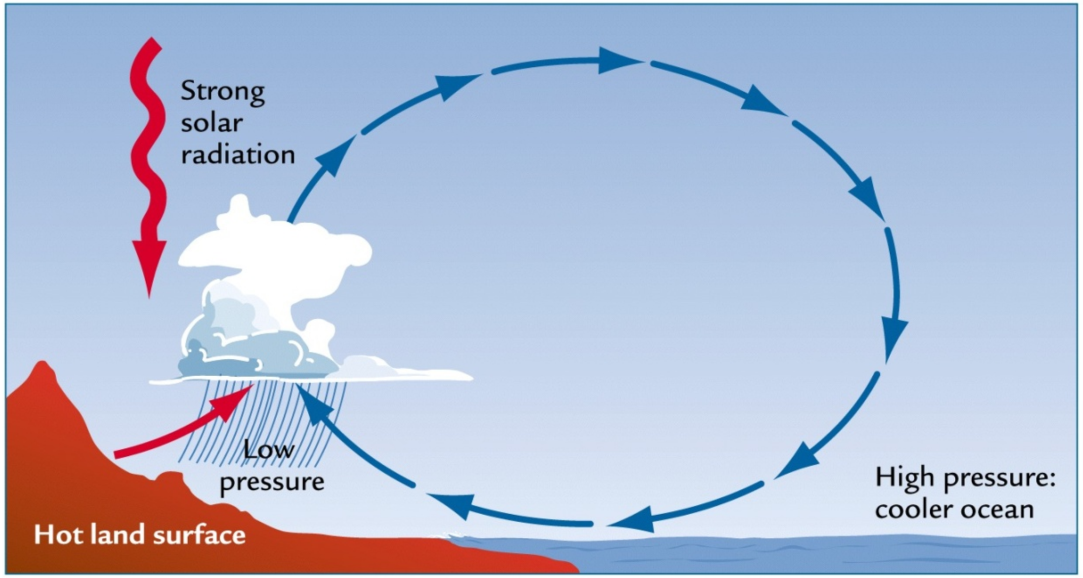
B Seasonal radiation (W/m²)



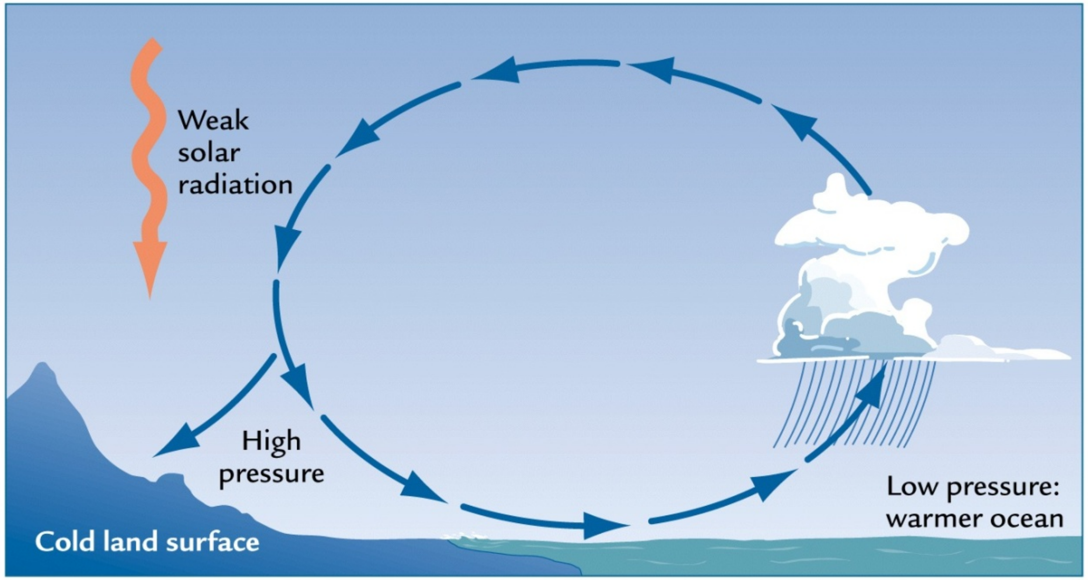
SEASONAL RADIATION CHANGES
June 21
+30
0
−30
Radiation (W/m²)
Annual average
December 21
0
100
Depth (m)
Wind mixing
Ocean
1–2m
Land
June 21
+5°
0
−5°
Temperature change (°C)
June 21
+5°
0
−5°
Temperature change (°C)
SEASONAL TEMPERATURE CHANGES



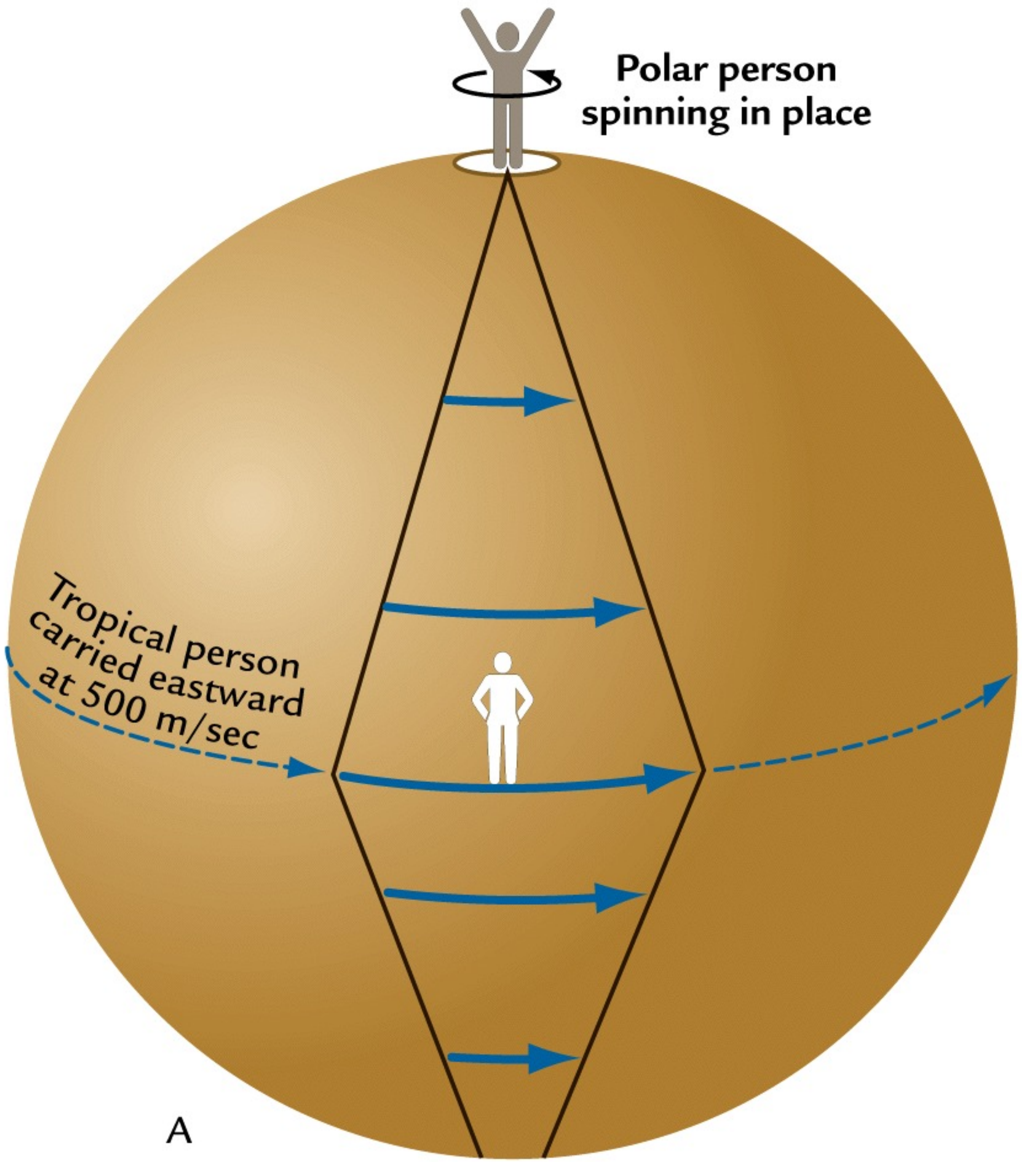
N
60°
40°
20°
0°
20°
40°
60°
S
Latitude
Temperature range (°C)
> 20
10–20
5–10
< 5
W
160°
120°
80°
40°
0°
40°
80°
120°
160°
E
Longitude

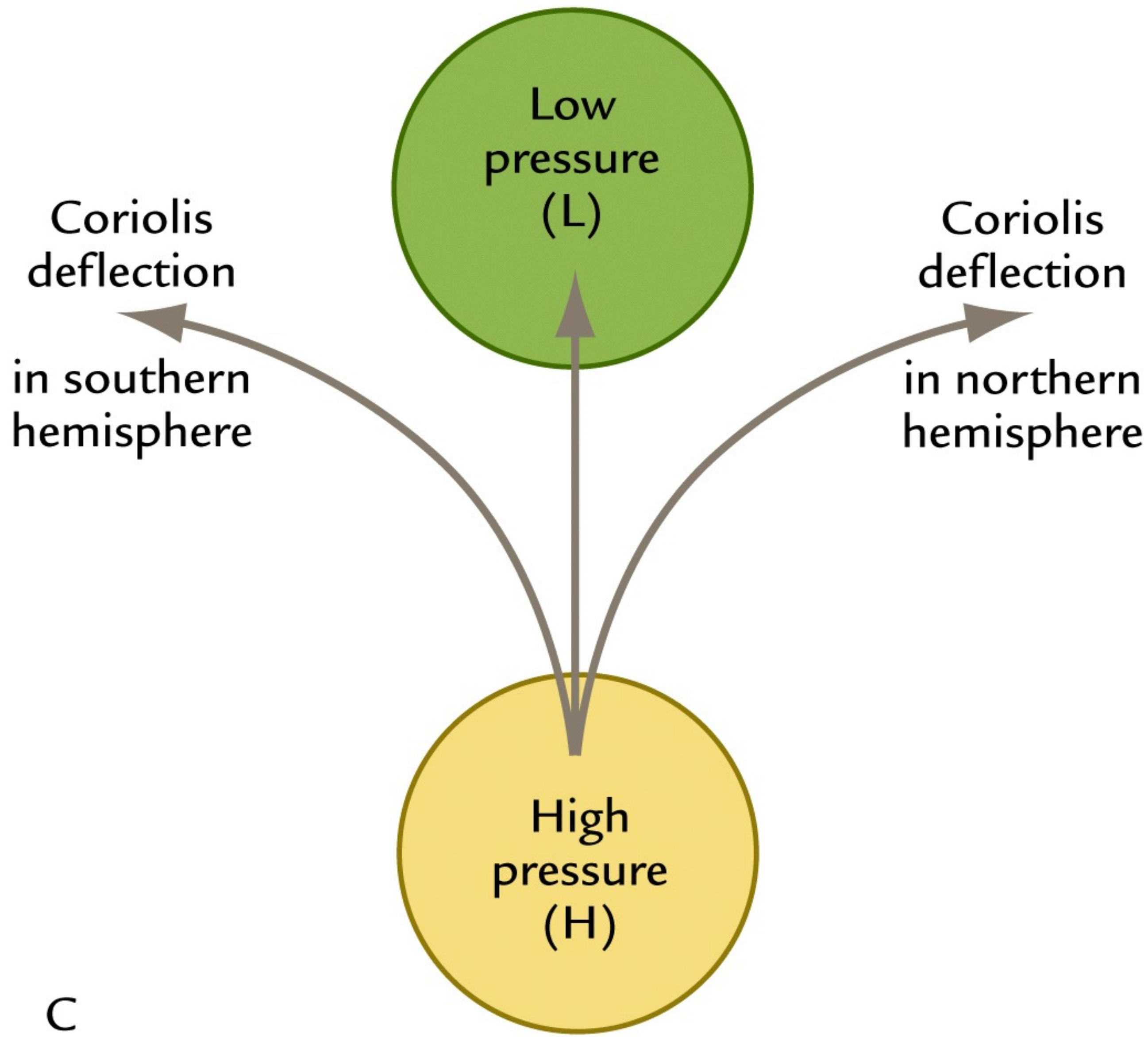


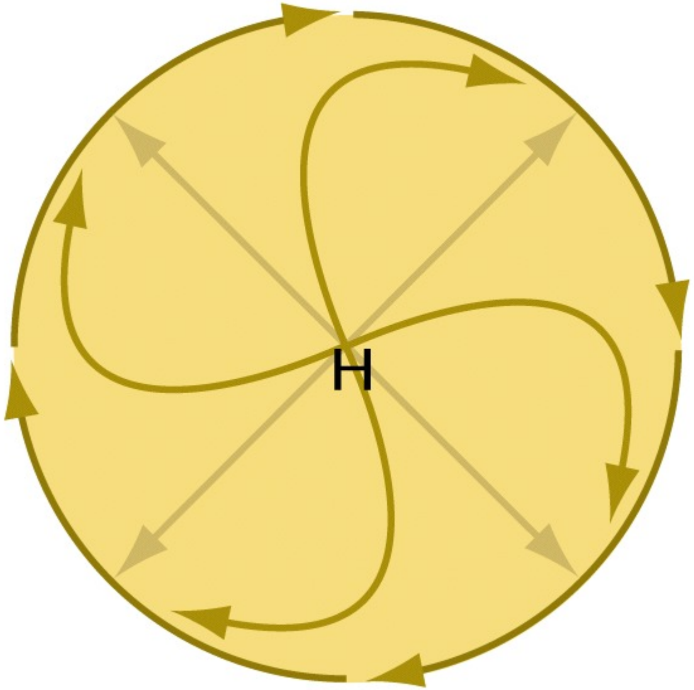
A Summer monsoon



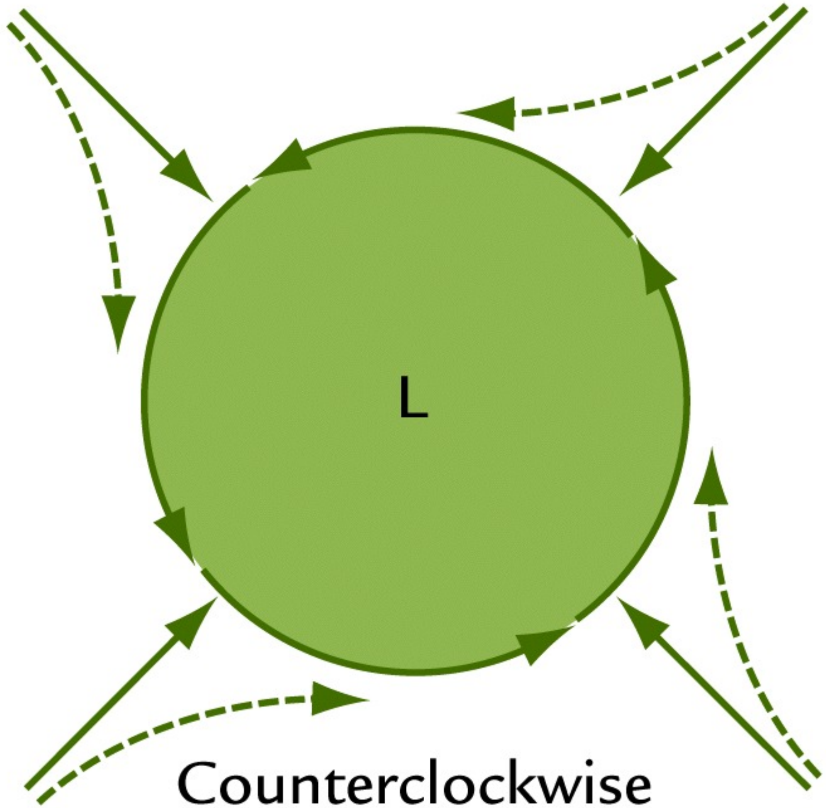
B Winter monsoon


Polar person
spinning in place
Tropical person
carried eastward
at 500 m/sec
A


Low
pressure
(L)
Coriolis
deflection
in southern
hemisphere
Coriolis
deflection
in northern
hemisphere
High
pressure
(H)
C

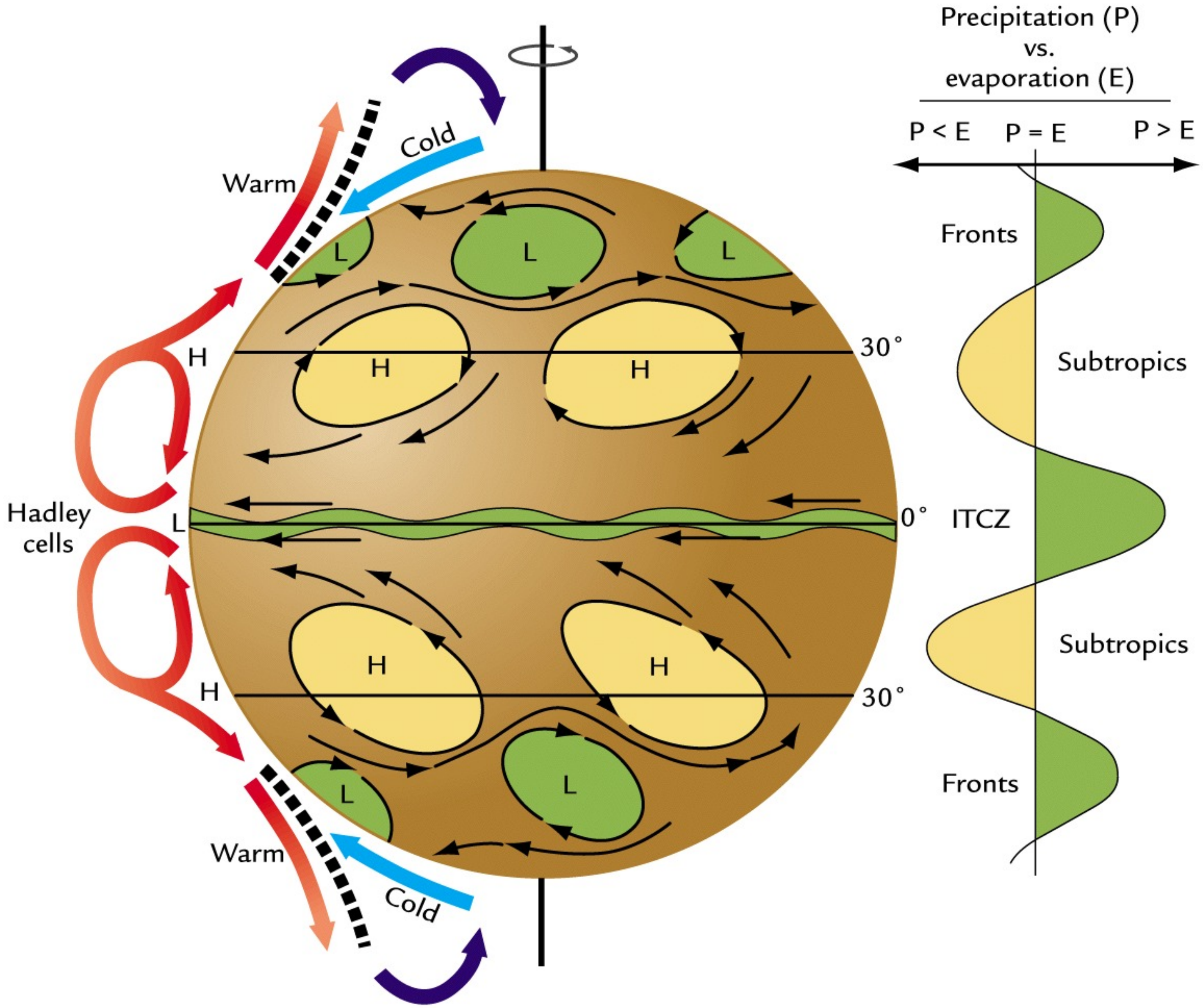


Clockwise circulation coming out of high-pressure regions

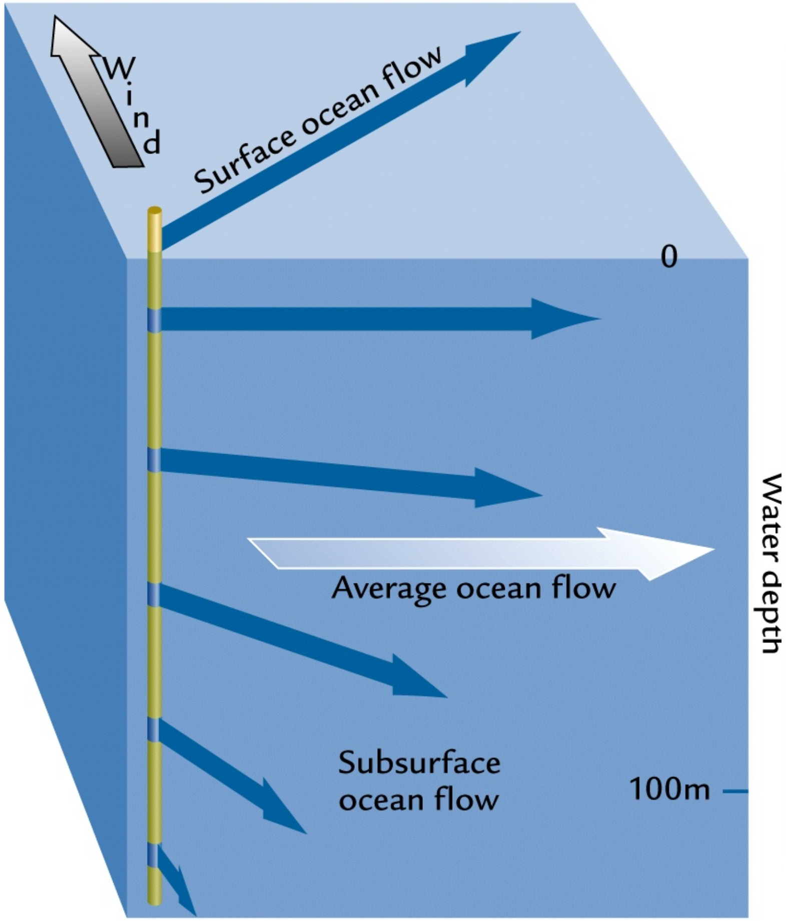


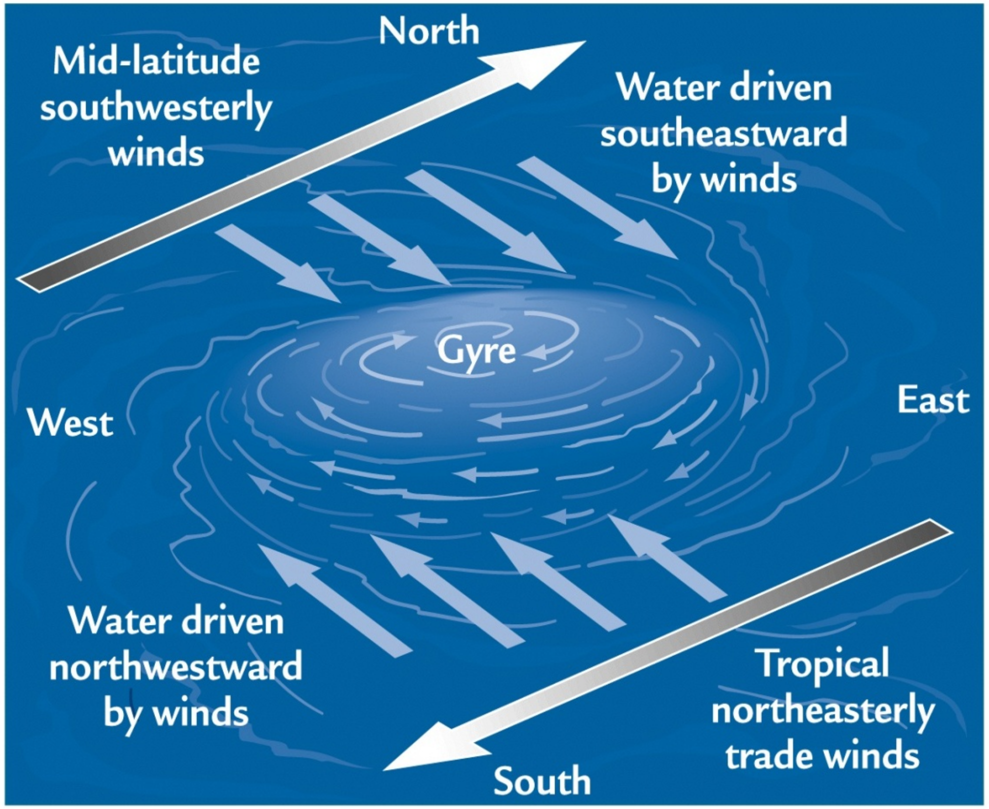
Counterclockwise circulation going into low-pressure regions

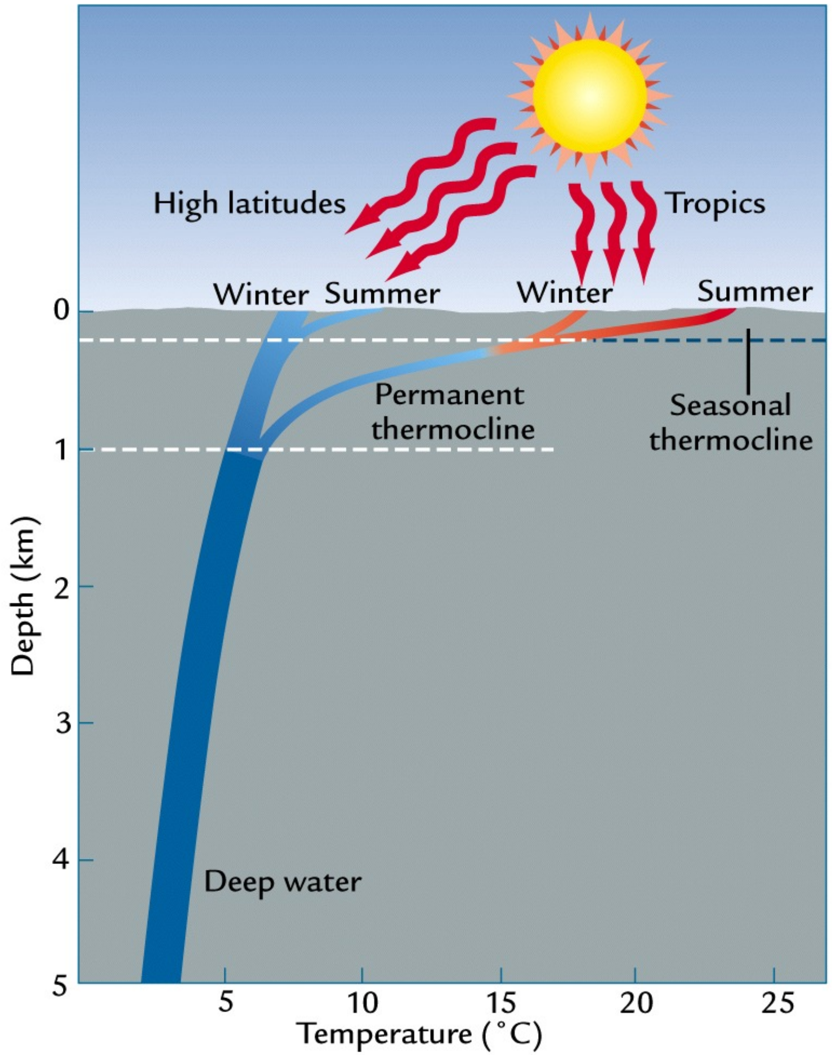
D Northern hemisphere

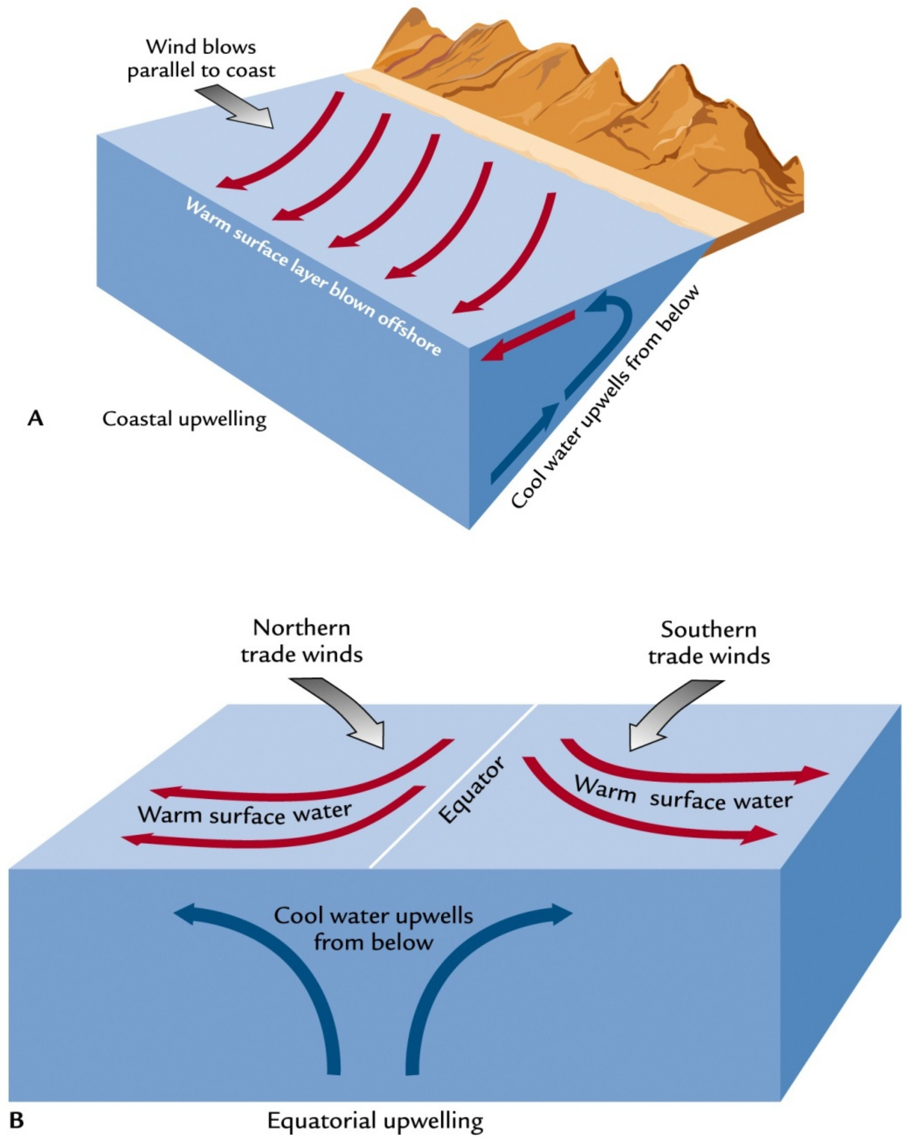


Precipitation (P)
vs.
evaporation (E)
P < E
P = E
P > E
Fronts
Subtropics
ITCZ
Subtropics
Fronts
Cold
Warm
L
L
L
H
H
H
30°
Hadley
cells
L
0°
H
H
H
30°
L
L
Warm
Cold


Wind
Surface ocean flow
0
Average ocean flow
Subsurface ocean flow
100m
Water depth

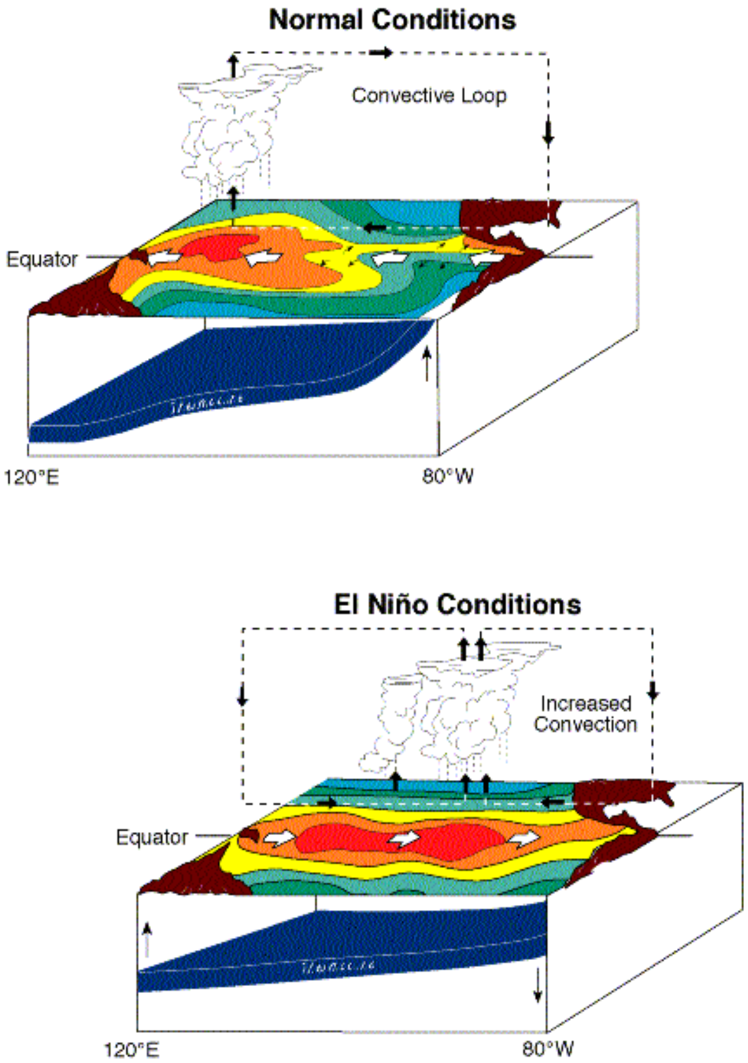

North
Mid-latitude southwesterly winds
Water driven southeastward by winds
Gyre
West
East
Water driven northwestward by winds
Tropical northeasterly trade winds
South


High latitudes
Tropics
Winter
Summer
Winter
Summer
Permanent thermocline
Seasonal thermocline
Deep water
Depth (km)
0
1
2
3
4
5
5
10
15
20
25
Temperature (°C)

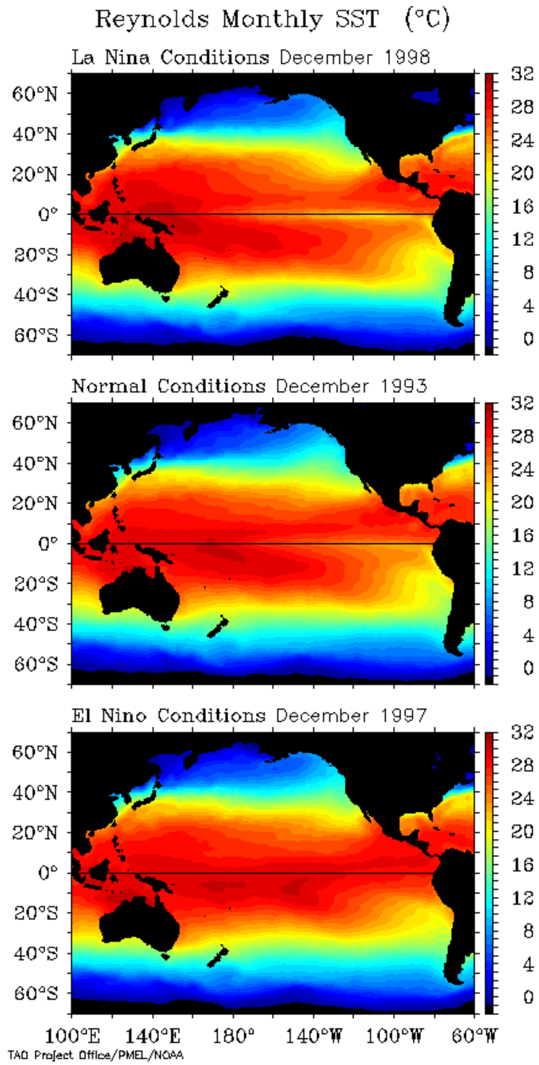

Wind blows parallel to coast
Warm surface layer blown offshore
Cool water upwells from below
A
Coastal upwelling
Northern trade winds
Southern trade winds
Warm surface water
Equator
Warm surface water
Cool water upwells from below
B
Equatorial upwelling

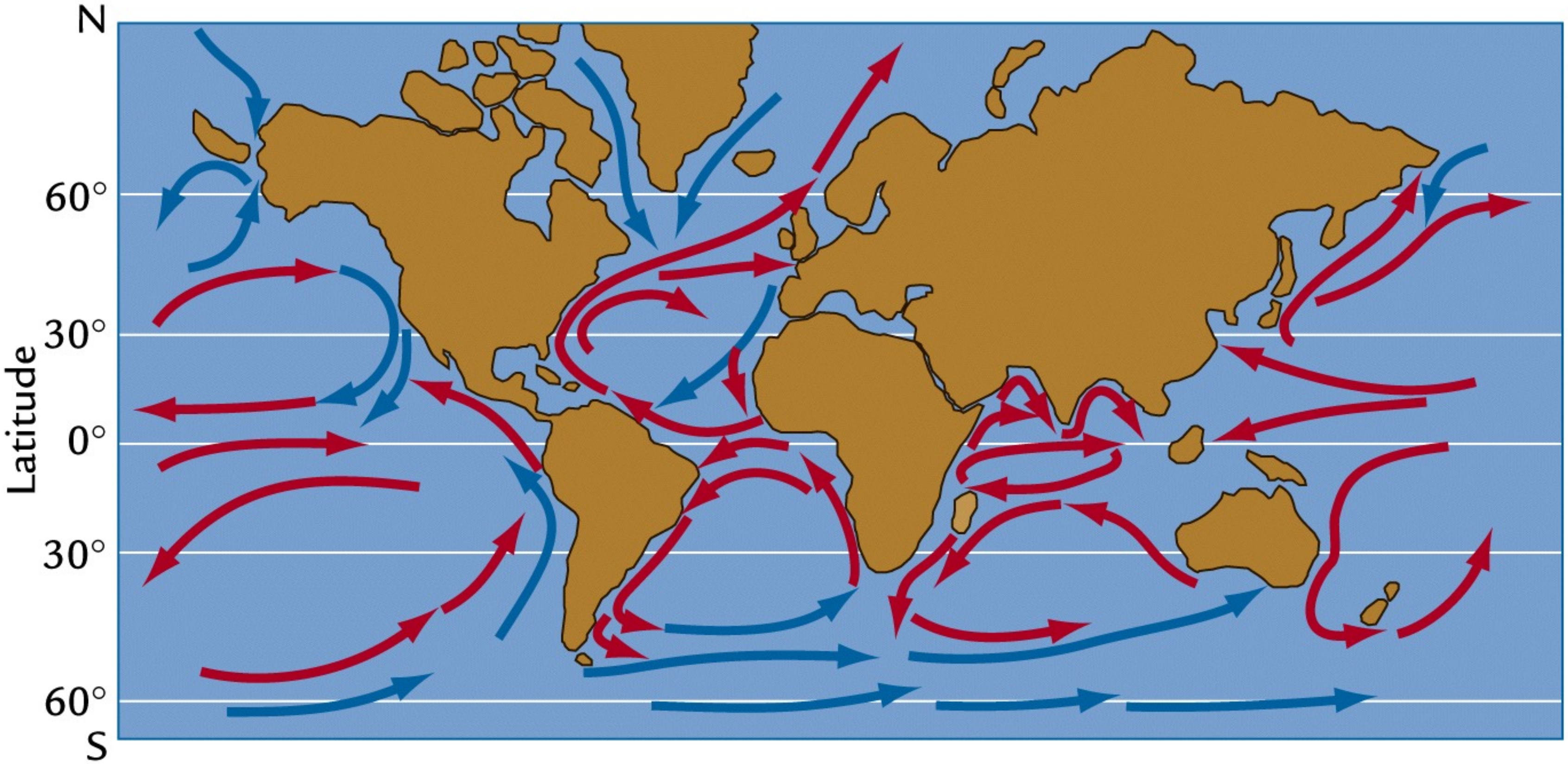
Forcing low latitudes

Cane and Clement (1999) AGU Monograph

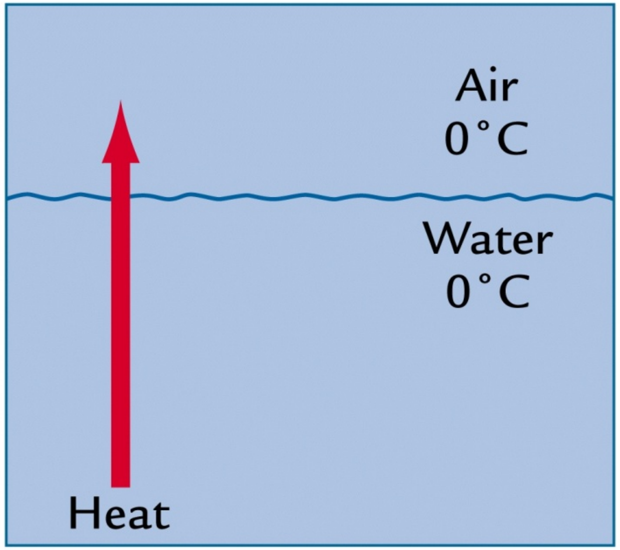


NOAA/PMEL/TAO

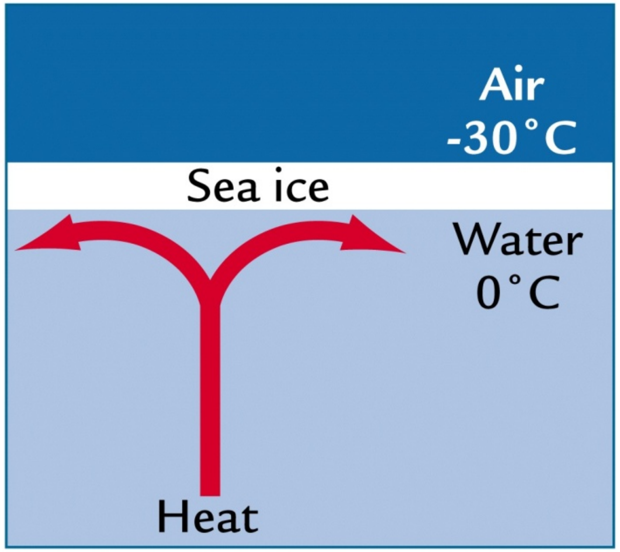



N
60°
30°
Latitude
0°
30°
60°
S

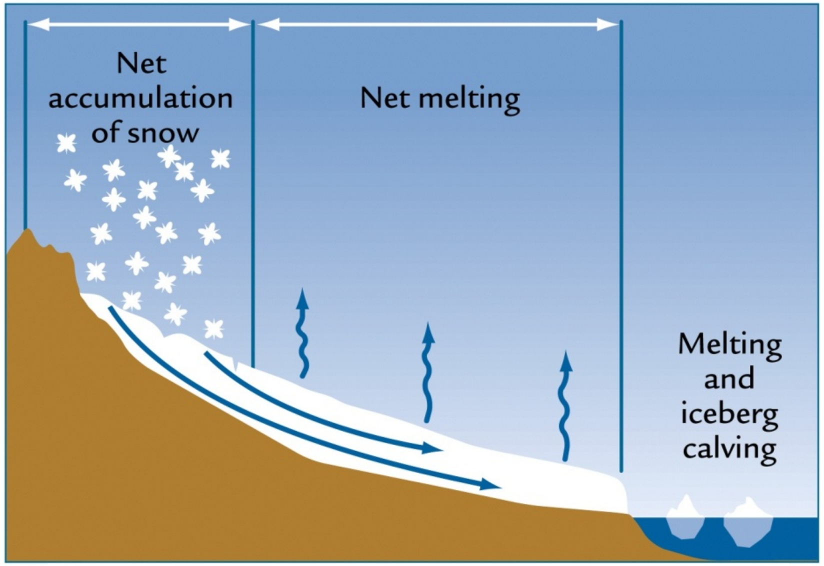

Winter sea ice cover
Gulf Stream
North Atlantic
deep water

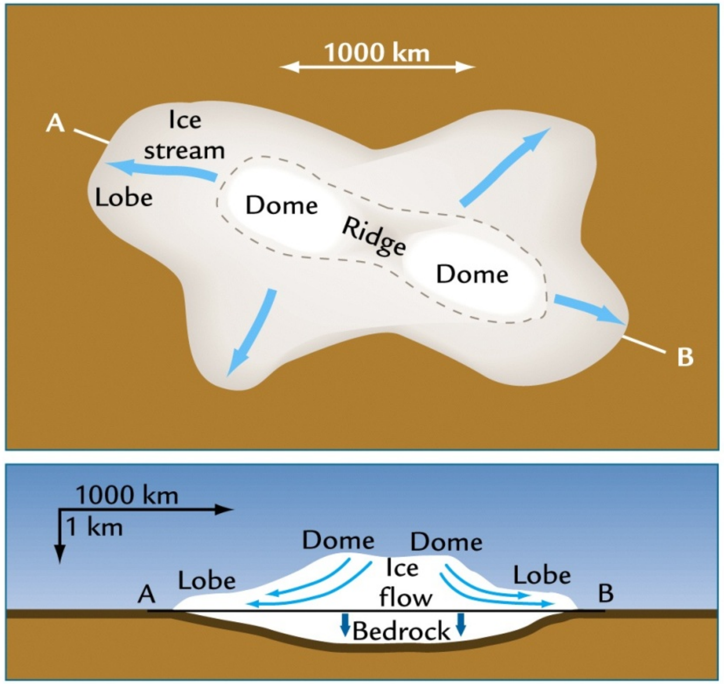


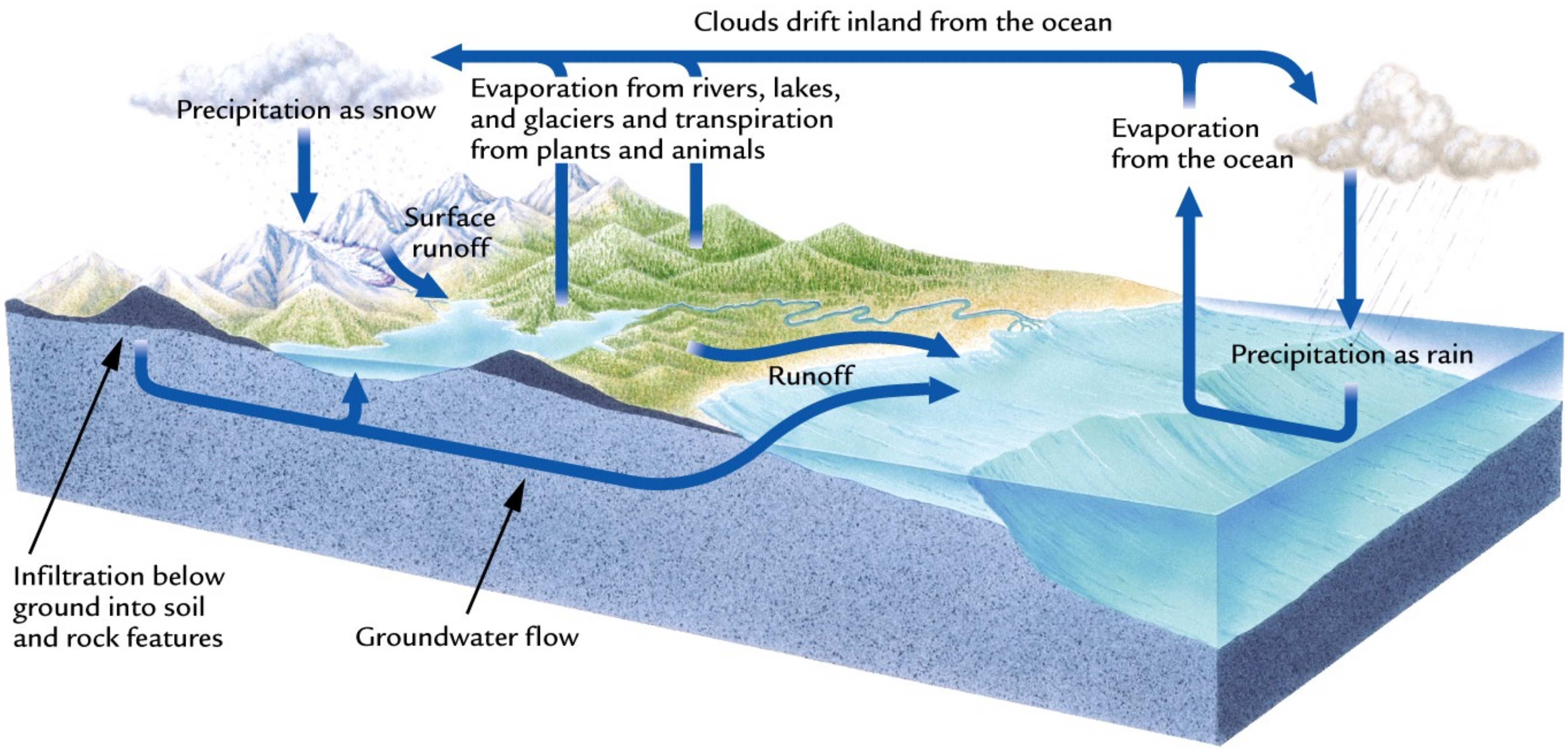
A Without sea ice



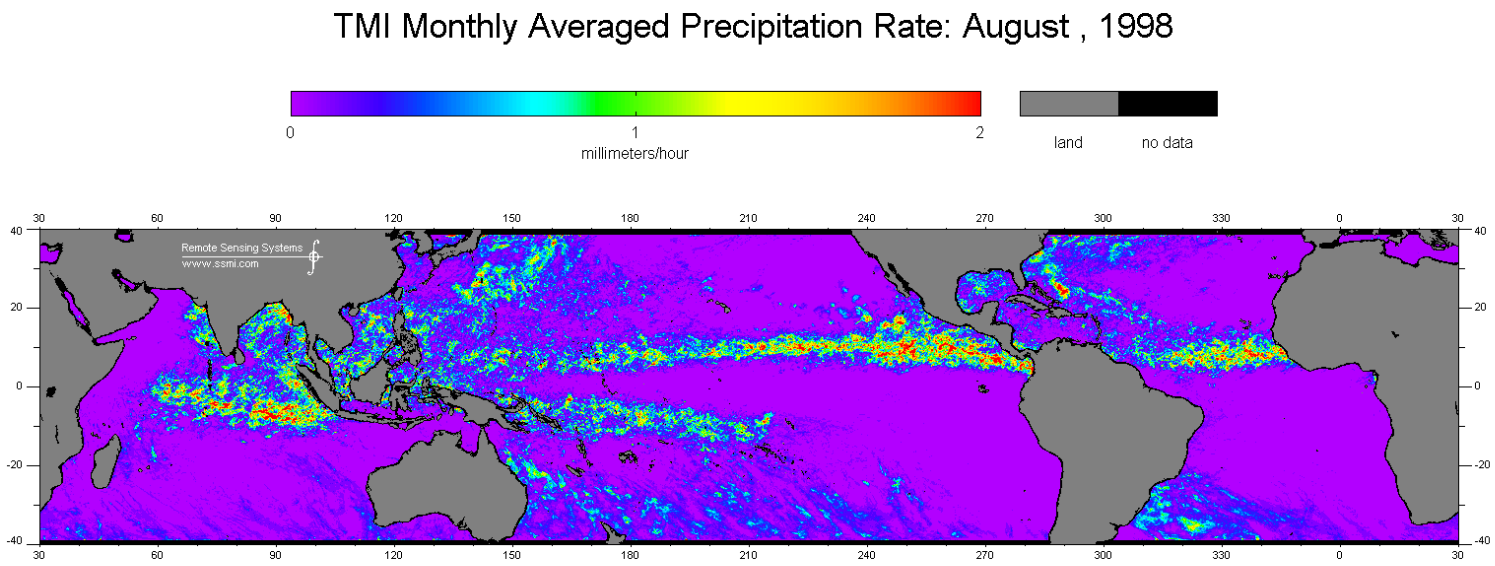
B With sea ice

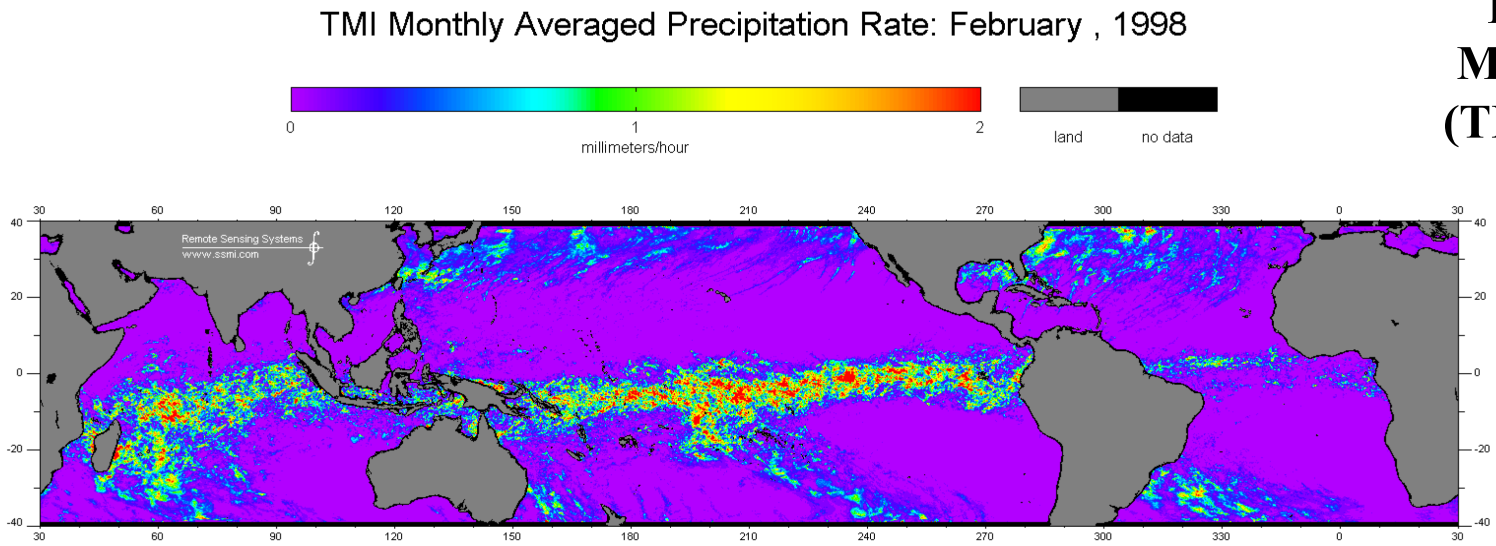




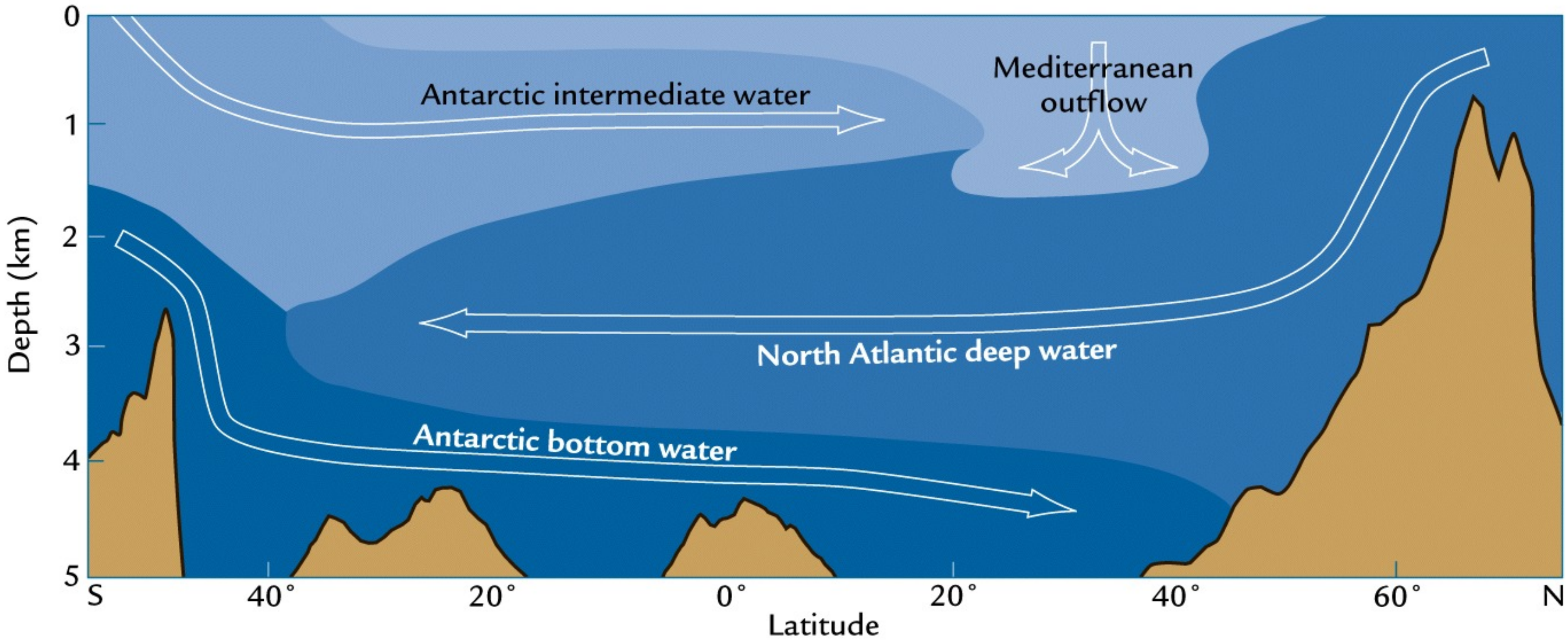

Clouds drift inland from the ocean
Precipitation as snow
Evaporation from rivers, lakes, and glaciers and transpiration from plants and animals
Evaporation from the ocean
Surface runoff
Precipitation as rain
Runoff
Infiltration below ground into soil and rock features
Groundwater flow

Innertropical Convergence Zone



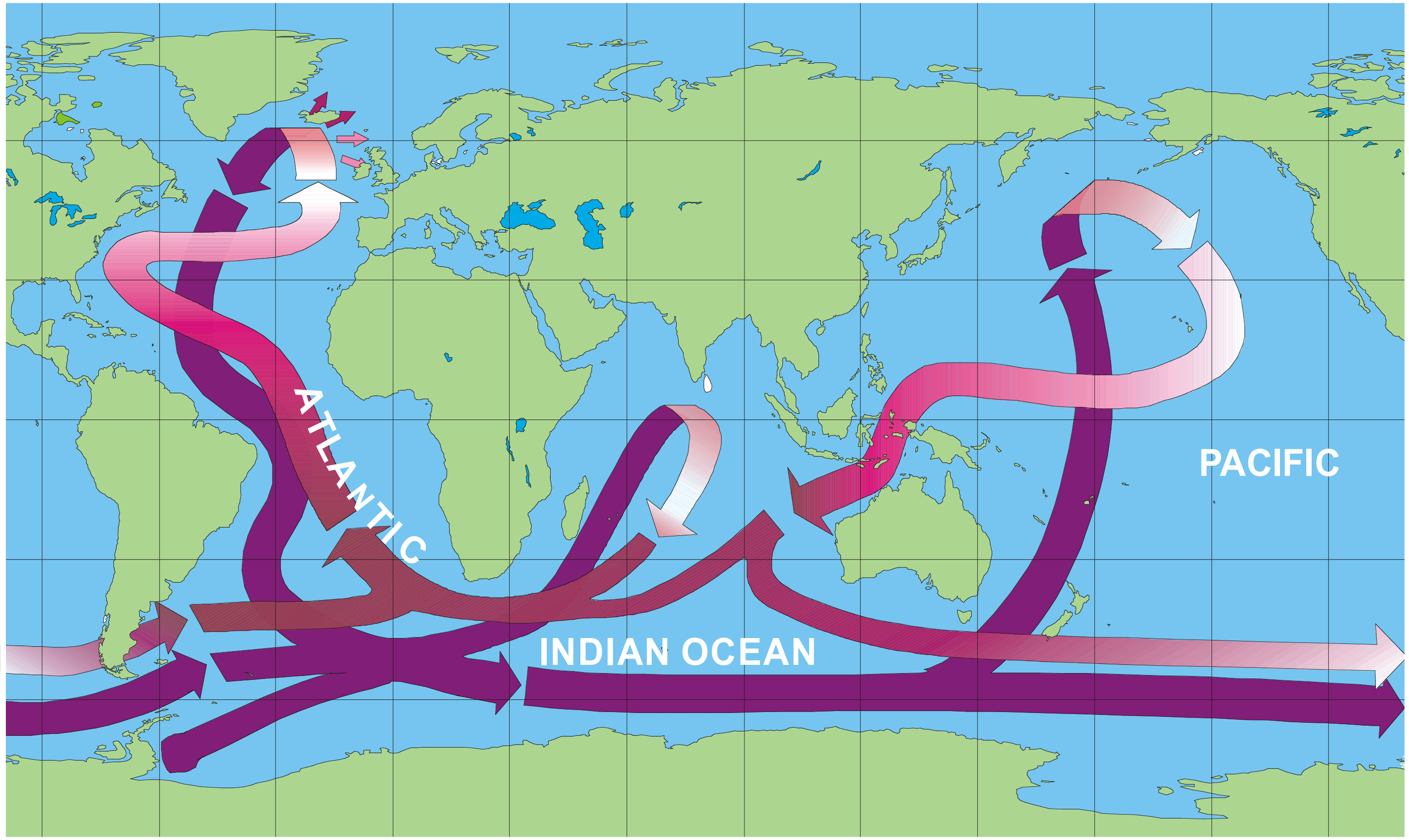


Tropical Rainfall Measuring Mission (TRMM, since 1997)



Antarctic intermediate water
Mediterranean
outflow
North Atlantic deep water
Antarctic bottom water
Depth (km)
0
1
2
3
4
5
S
40°
20°
0°
20°
40°
60°
N
Latitude

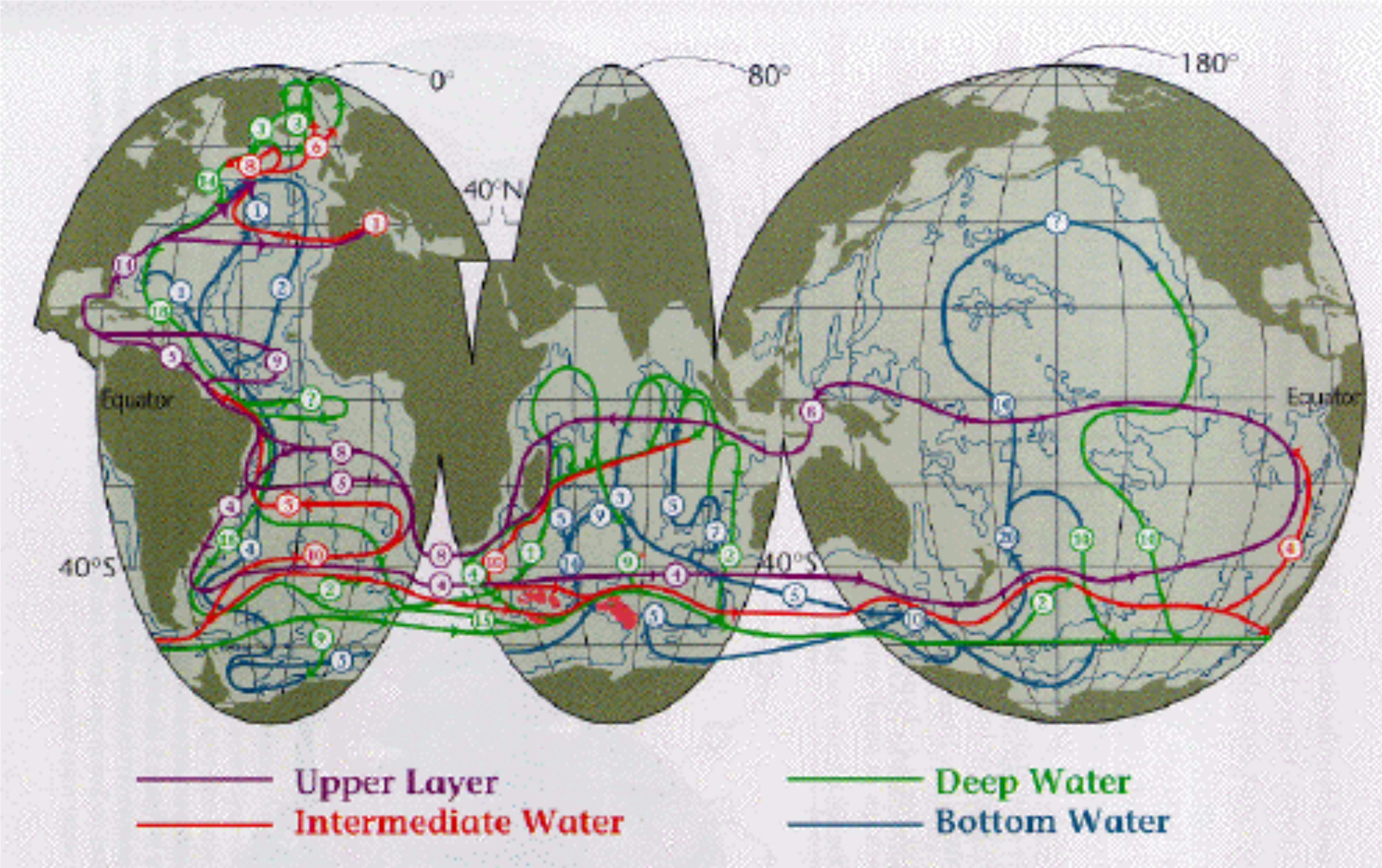
The Thermohaline Circulation



(after W. Broecker, modified after E. Maier-Reimer)

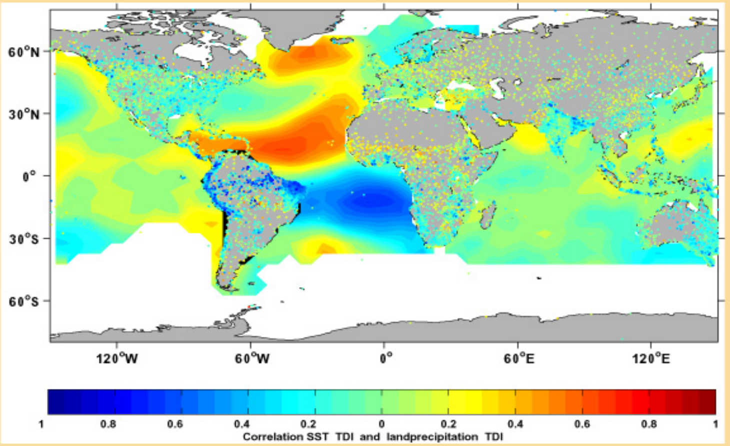
Atmosphere & Ocean Circulation

Schmitz, 1996

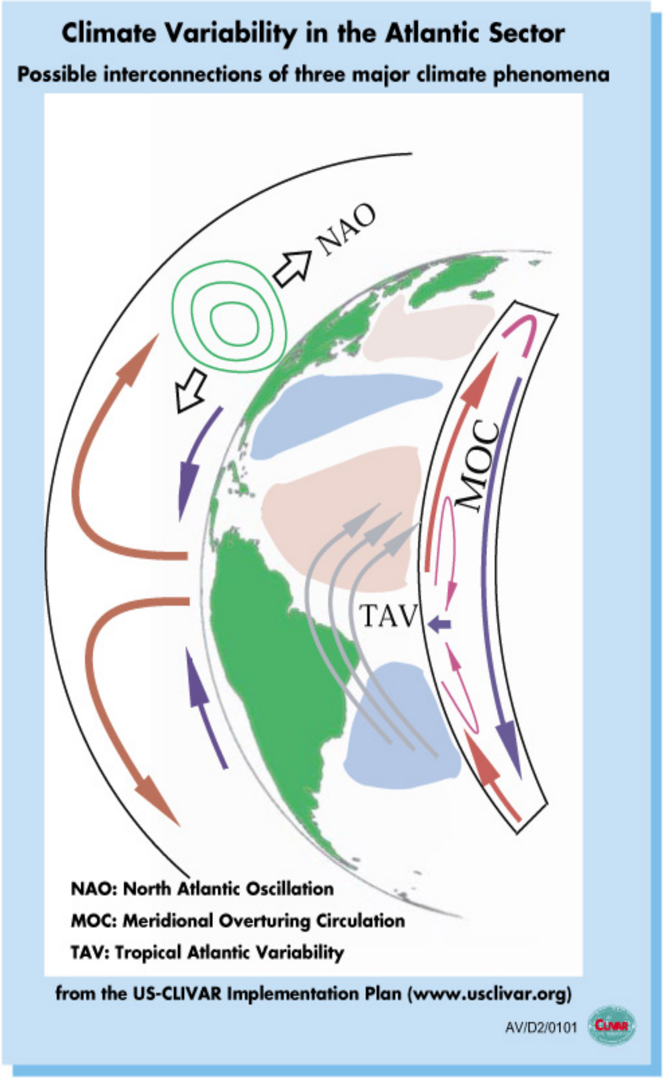


Atmosphere & Ocean Circulation

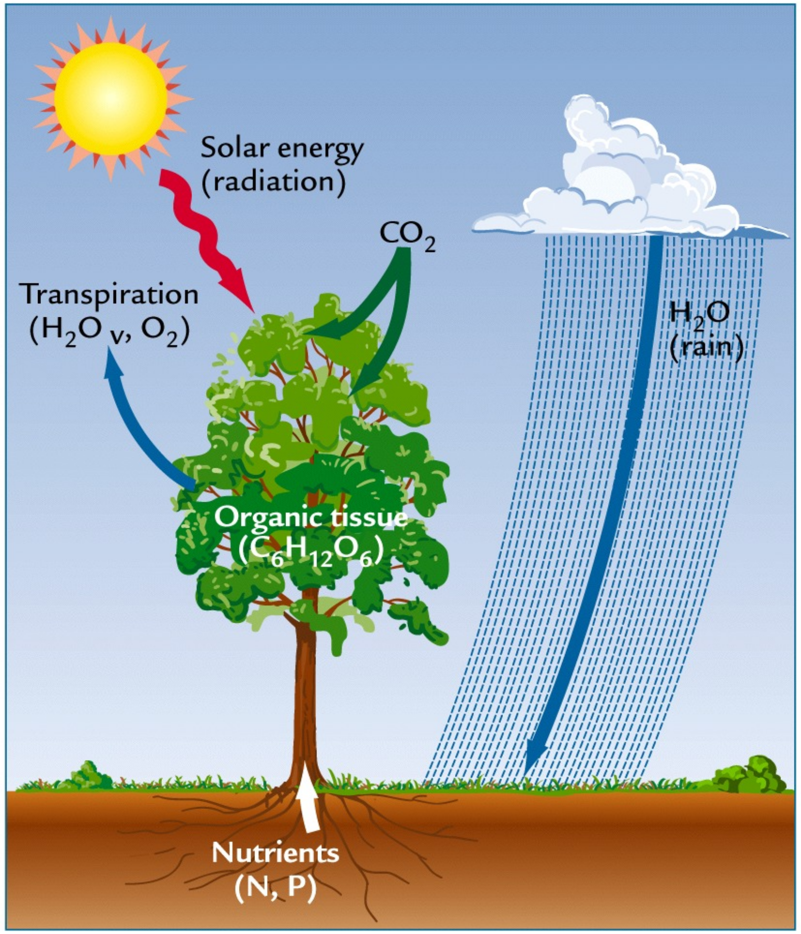
Atlantic SST and Rainfall



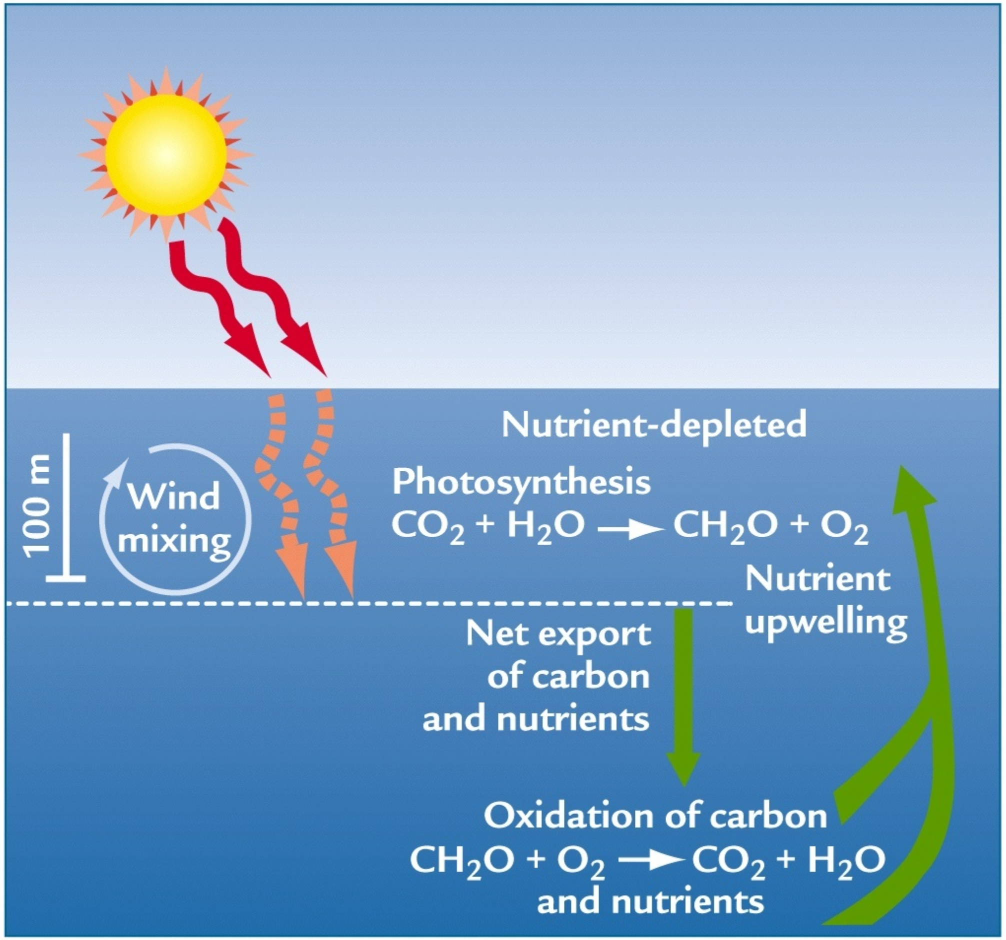
Correlation between the Atlantic cross ITCZ SST difference as defined by Servain (1991, J. Geophys. Res., 15137-15146), and station rainfall. This figure is done for annual averages of both the index and the rainfall data from 47 years. The pattern of the Atlantic SST is very similar to the NAO pattern: i.e. during strong phases of the NAO, there are strong westerlies and north-easterlies, colder SST, and thus the ITCZ is further south. When ITCZ is further south, the correlation with Tropical Dipole Index (TDI) is negative, less precipitation over the Sahel region and more precipitation along the coastline in the Gulf of Guinea, more precipitation in the Nordeste Brazil as well (Y. Kushnir and G. Krahmann, 1998, personal communication).



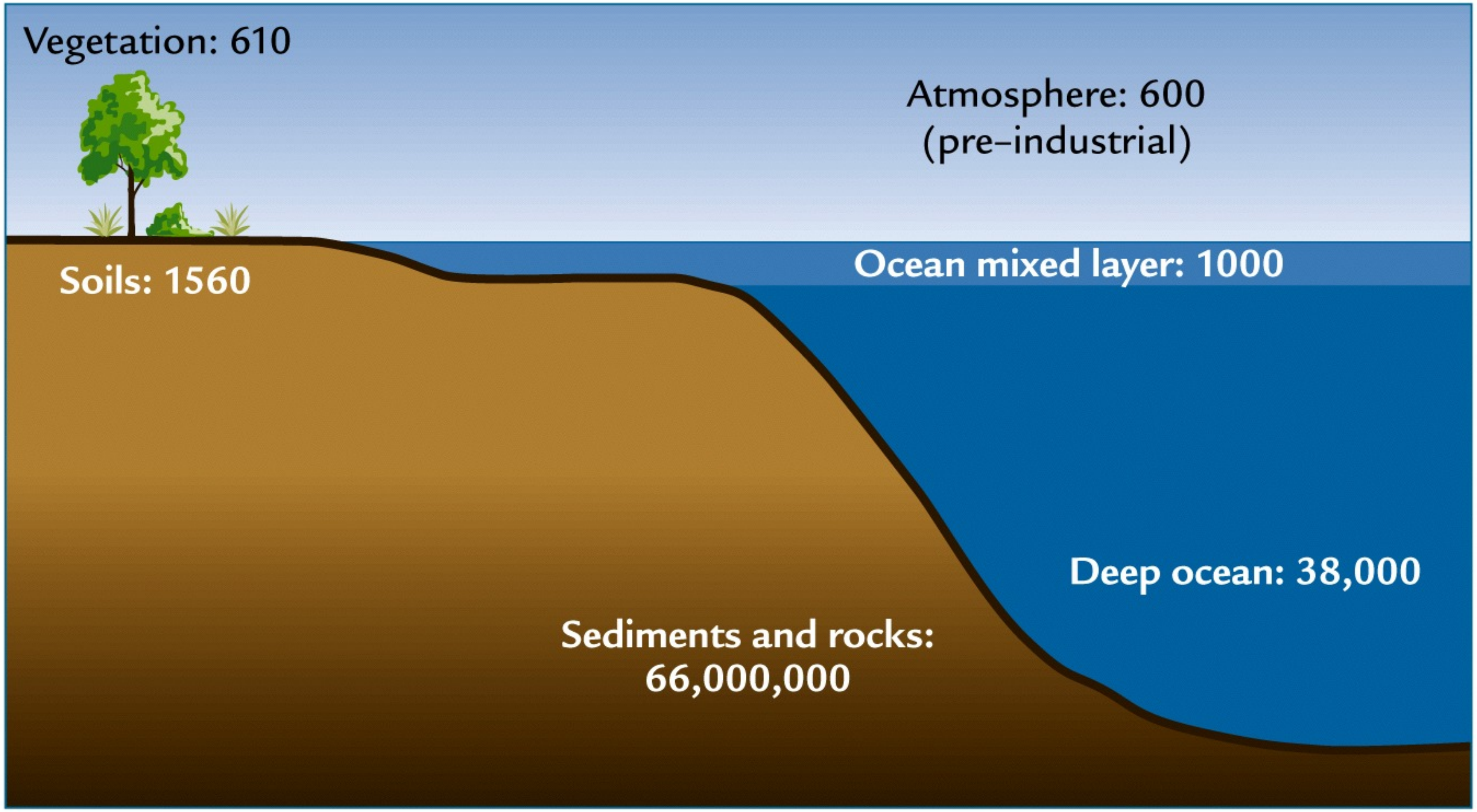
from CLIVAR website



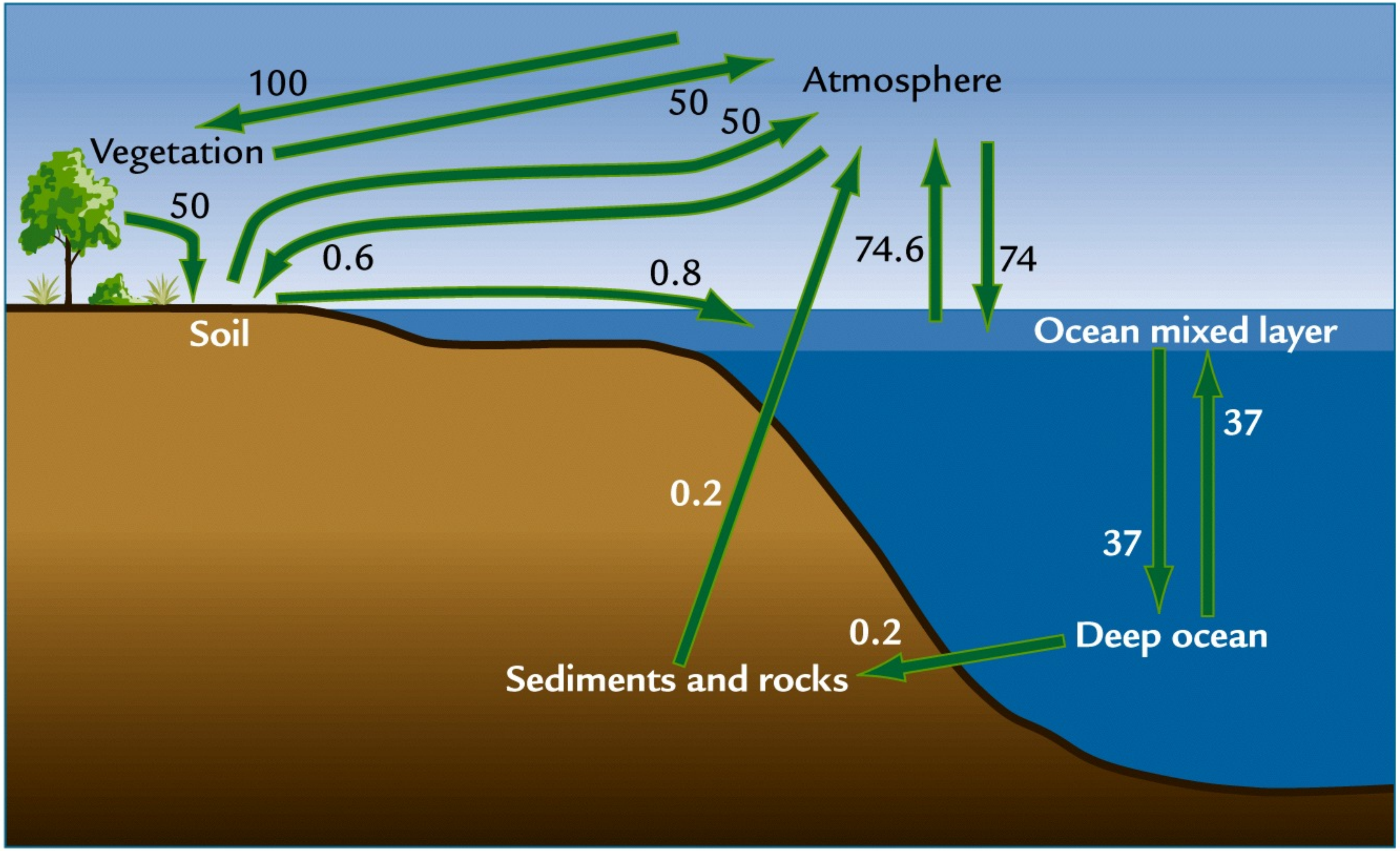
Solar energy
(radiation)
CO2
Transpiration
(H2O v, O2)
H2O
(rain)
Organic tissue
(C6H12O6)
Nutrients
(N, P)



Nutrient-depleted
100 m
Wind
mixing
Photosynthesis
CO2 + H2O → CH2O + O2
Nutrient
upwelling
Net export
of carbon
and nutrients
Oxidation of carbon
CH2O + O2 → CO2 + H2O
and nutrients



A Major carbon reservoirs (gigatons)



B

Carbon exchange rates (gigatons/year)

Paleo-CO_2 and productivity in the ocean

Relation to atmospheric CO_2
Proxies
Problem of Quantification
Late Quaternary Variations

References

Books

Fischer & Wefer 1999, Use of Proxies in Paleoceanography: Examples from the South Atlantic, 546pp, Springer-Verlag, Berlin Heidelberg.

Summerhays, Emeis, Angel, Smith, & Zeitschel 1995, Upwelling in the Ocean: Modern Processes and Ancient Records, 422pp, Dahlem Konferenzen, Wiley, Chichester.

Berger, Smetacek, & Wefer 1989, Productivity in the Ocean: Present and Past, Dahlem Workshop Reports, Life Sciences Research Report 44, John Wiley & Sons, Chichester, New York.

Journals

PALEOCEANOGRAPHY, ORGANIC GEOCHEMISTRY, PALEO3, GEOCHIMICA COSMOCHIMICA ACTA, GLOBAL BIOGEOCHEMICAL CYCLES.

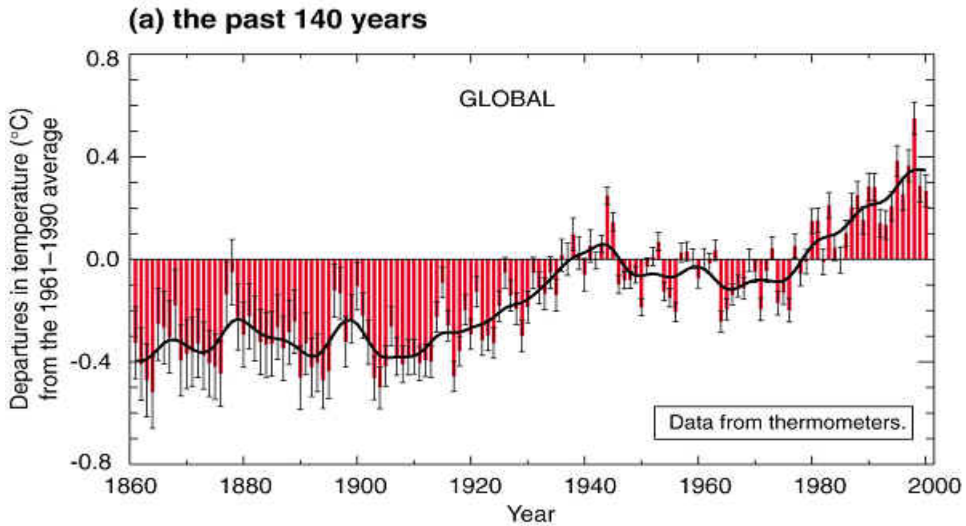
Websites

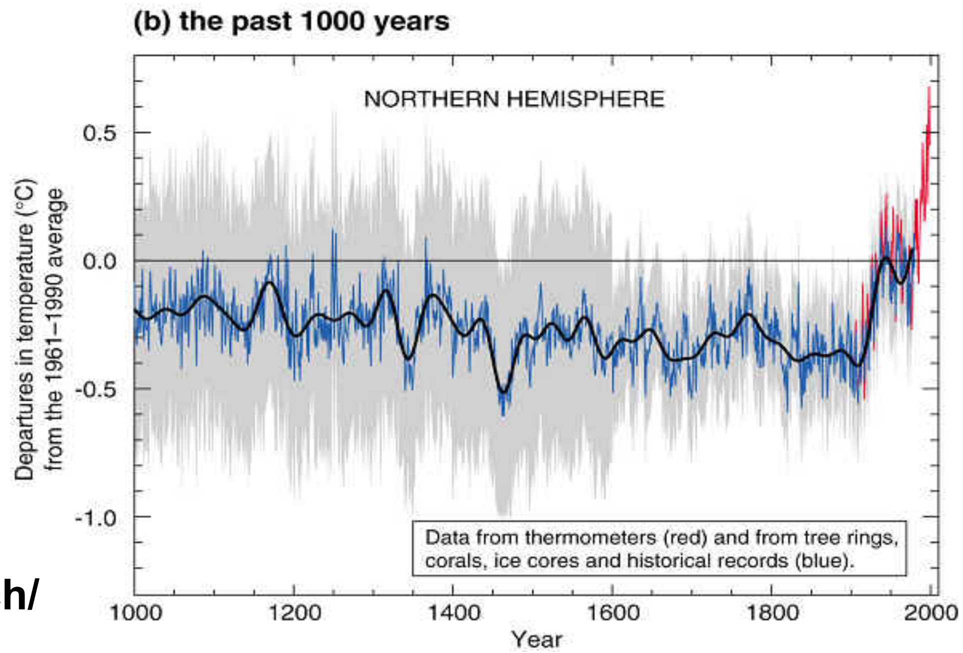
http://usjgofs.whoi.edu/

http://www.obs-vlfr.fr/cd_rom_dmtt/start_france_jgofs.htm

http://seawifs.gsfc.nasa.gov/SEAWIFS.html

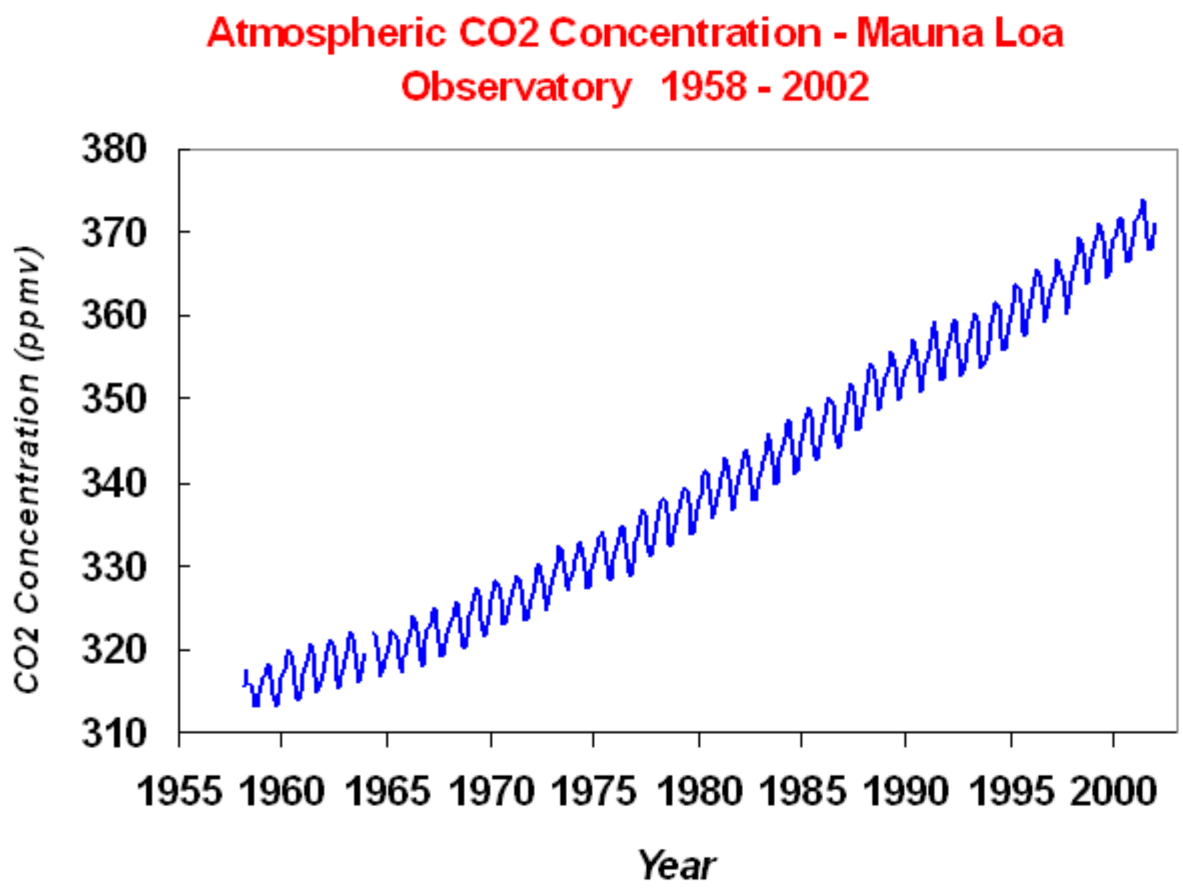
Greenhouse Effect ?





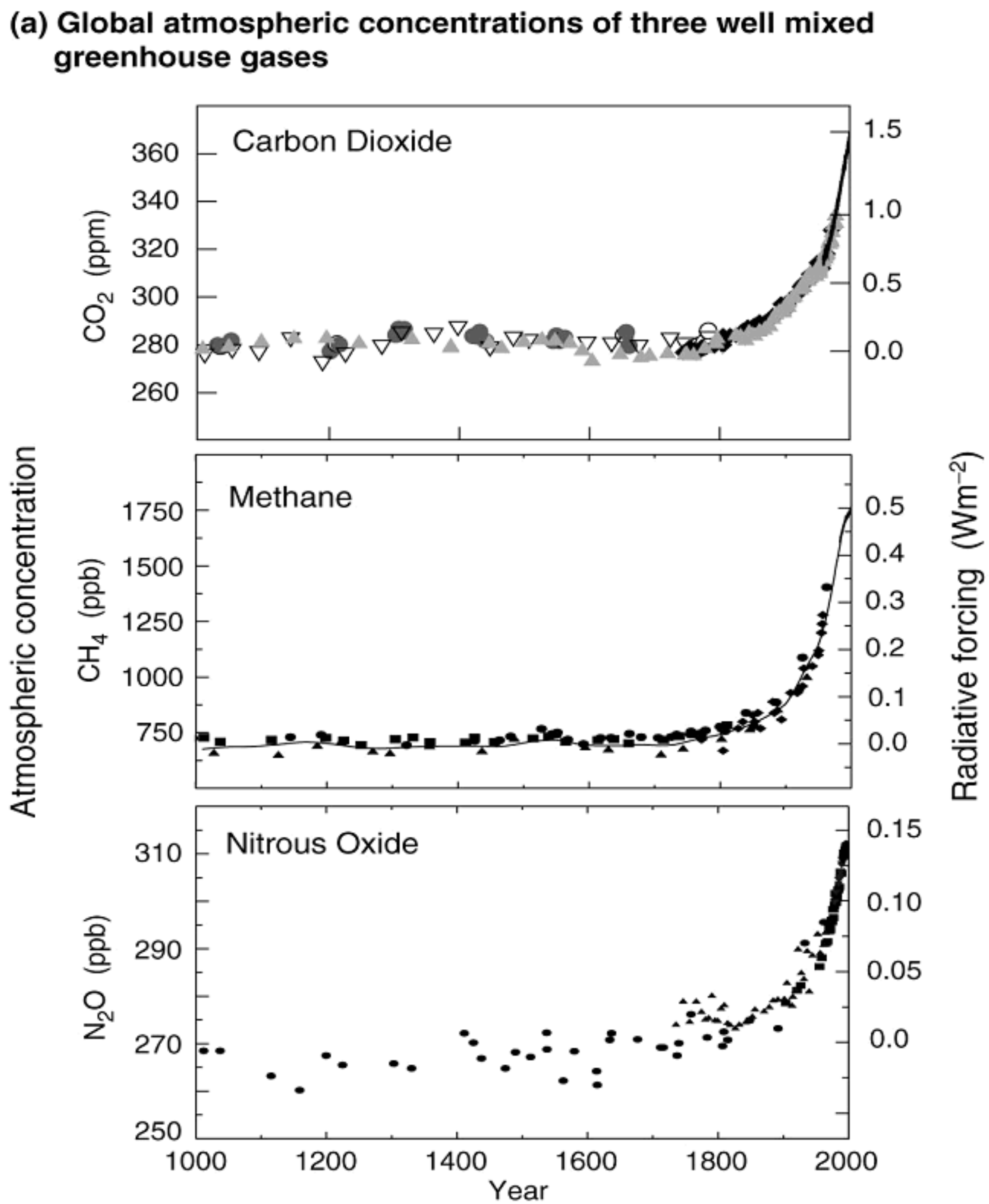
http://www.ipcc.ch/

Greenhouse Effect ?



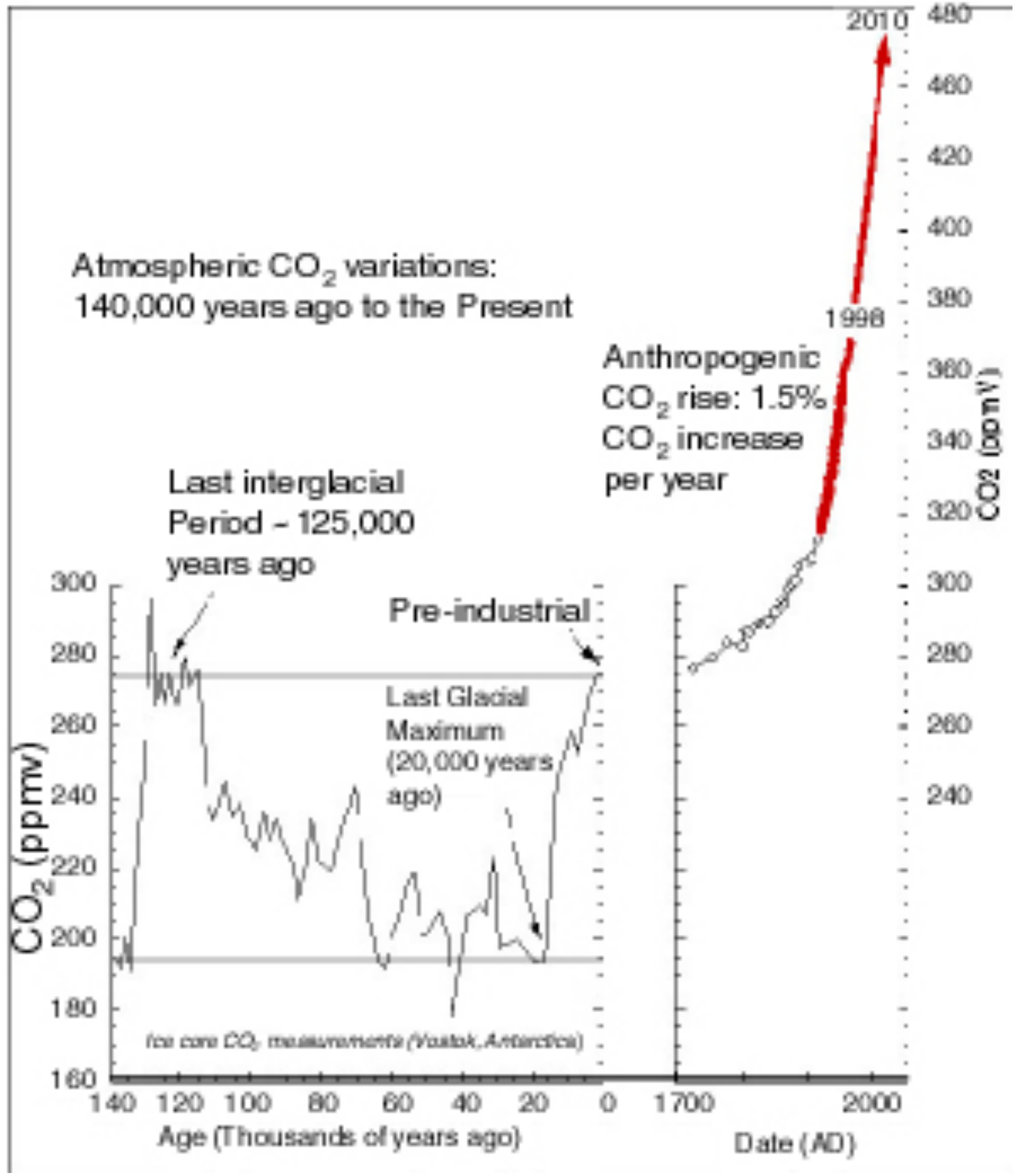
http://www.ipcc.ch/

Greenhouse Effect ?



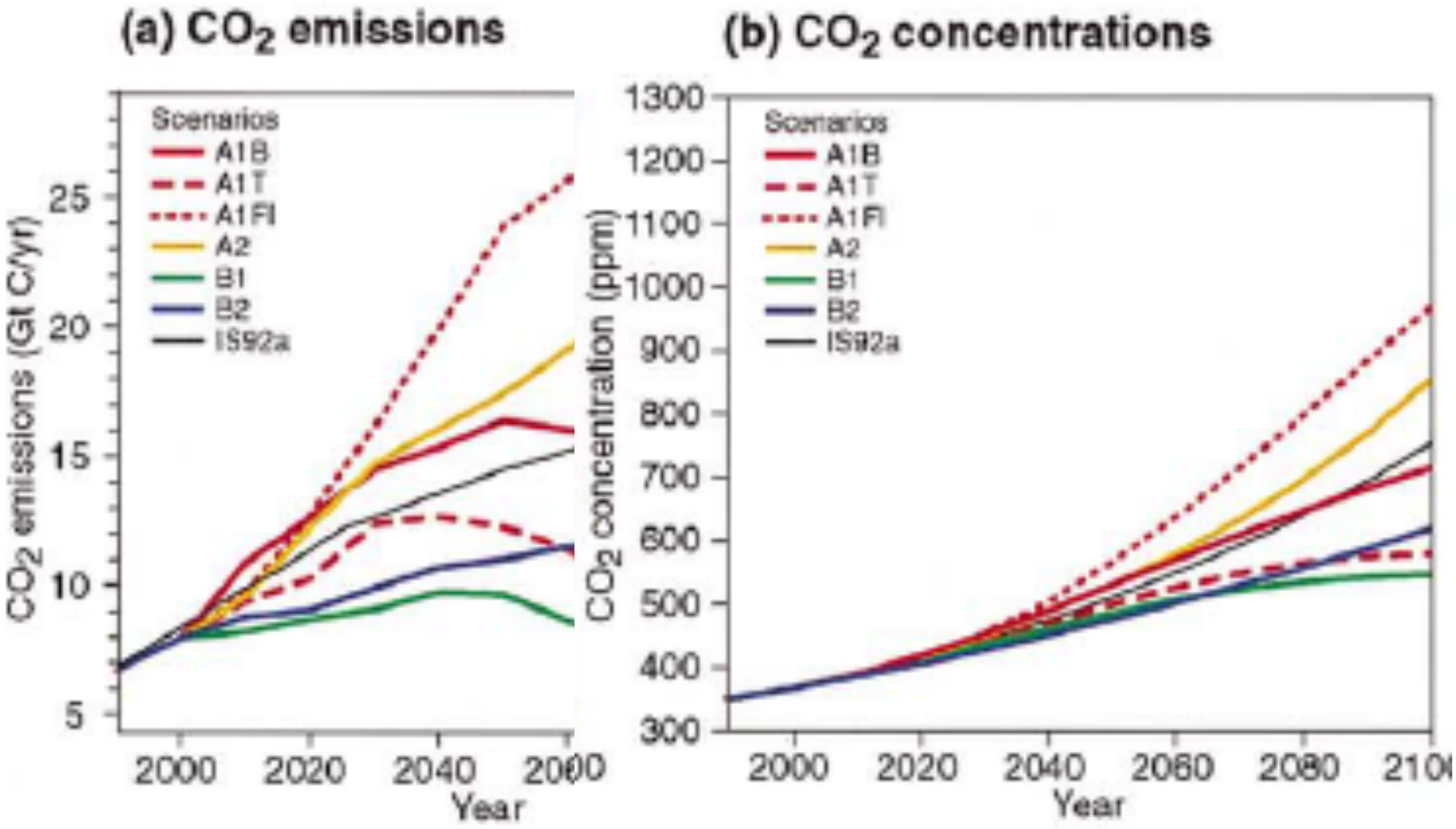
http://www.ipcc.ch/

Greenhouse Effect ?

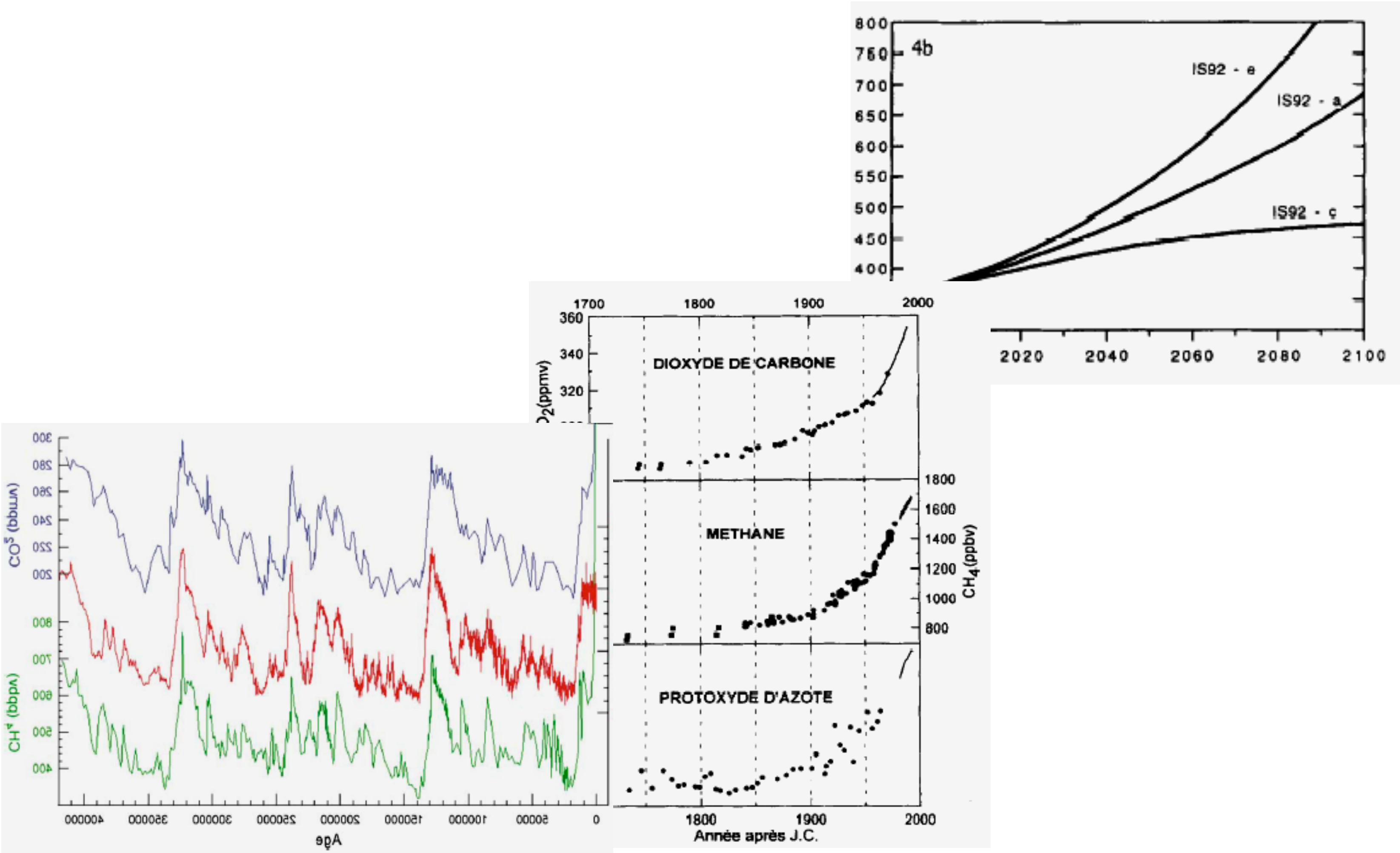


http://www.ipcc.ch/

IPCC Scenarios



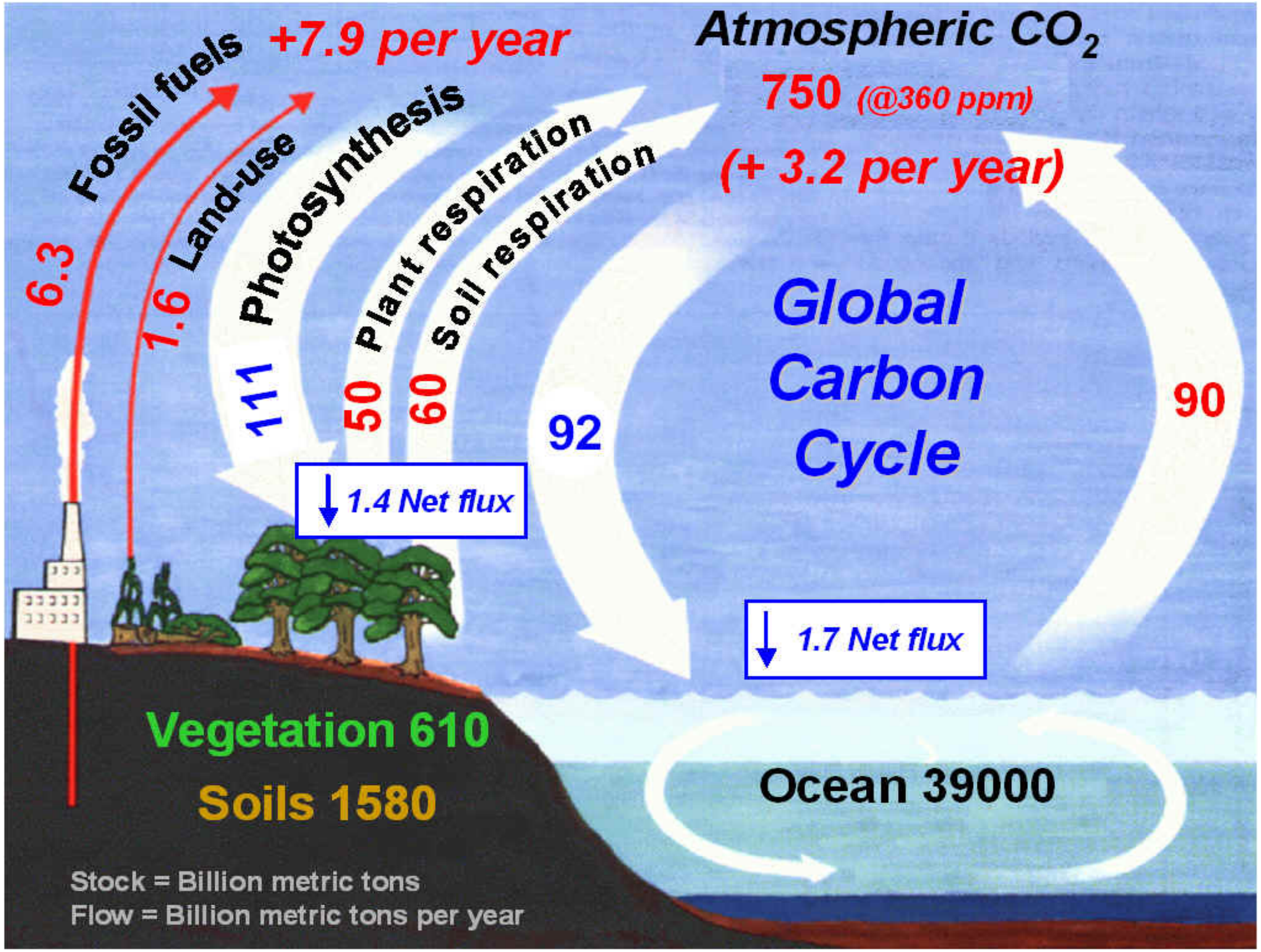
Model results in context with natural variability



Global Carbon Cycle

The table and figure give an accounting of where the different forms of carbon are located on earth ! Note that 10^{15} g = 1 billion tons = 1 gigaton = 1 Pedagram):

In the atmosphere, CO_2 is 99.6% of the total



http://www.visionlearning.com

Global Carbon Cycle

Role of the Ocean

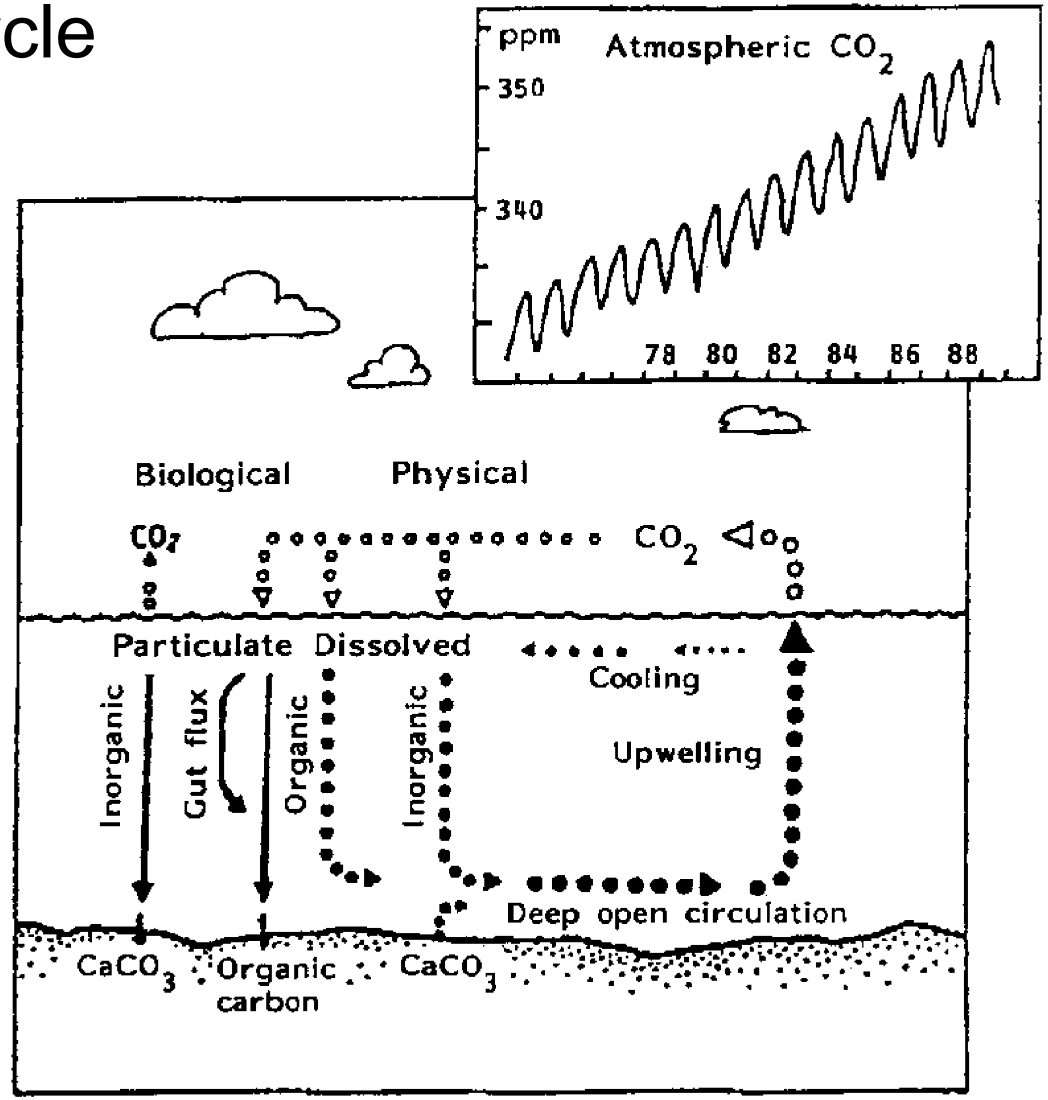


Figure 19.1 Sketch of the natural global carbon cycles (adapted from SCOR 1990).

Type of primary productivity

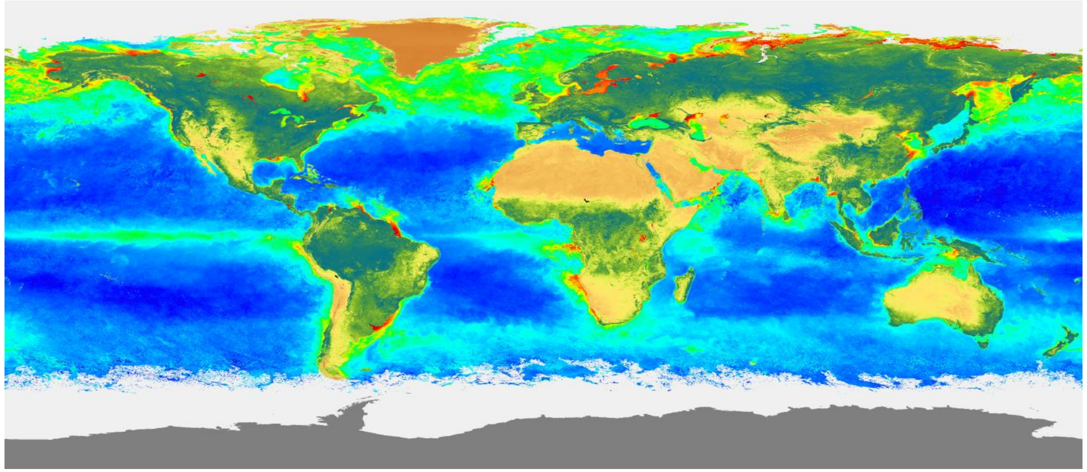
$$Ca^{2+} \; 2HCO_3^- \quad => \quad CaCO_3 + CO_2 + H_20$$

$$H_20 + CO_2 \; =>(\text{Photosynthesis}) \quad CH_2O + O_2$$

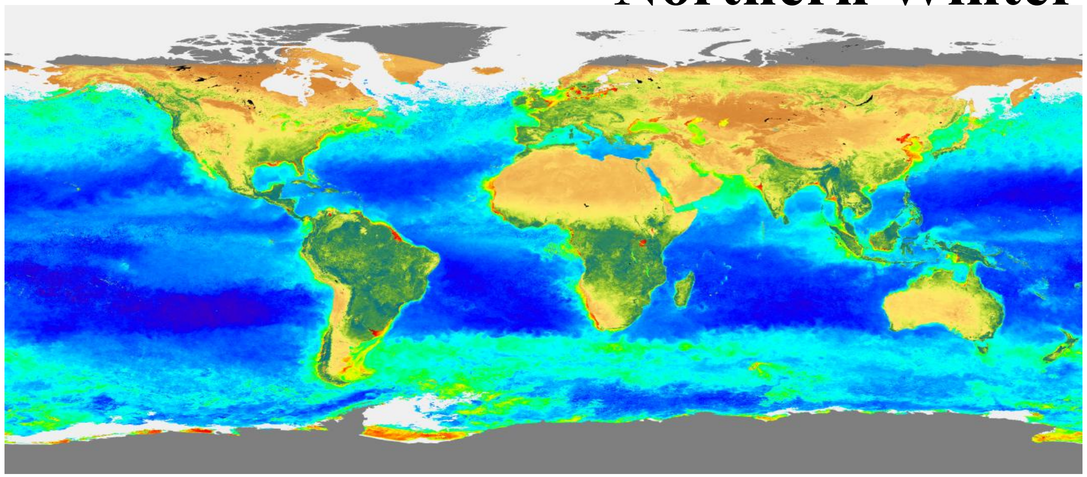
Important: $C_{org}/CaCO_3$ ratio of total PP

Ocean Colour

Northern Summer



Northern Winter



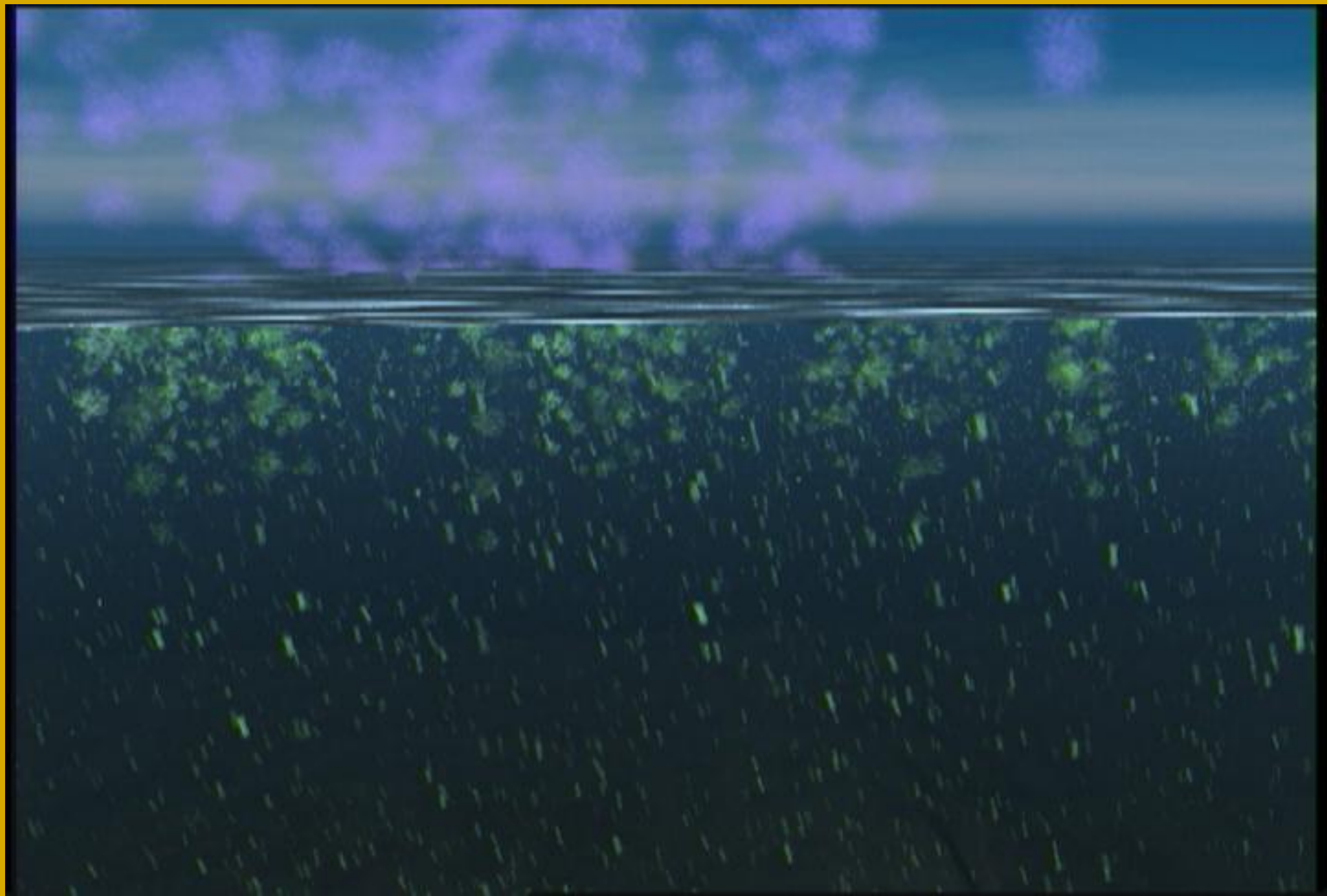
Pigment Concentration

The Global Biosphere Series

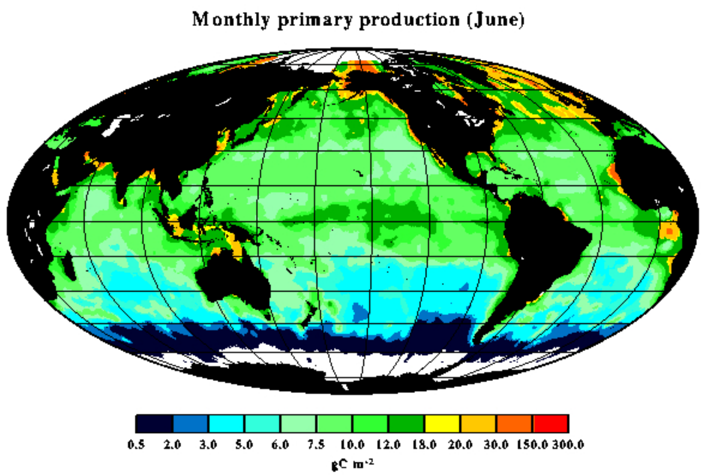
SEAWIFS IMAGE GALLERY

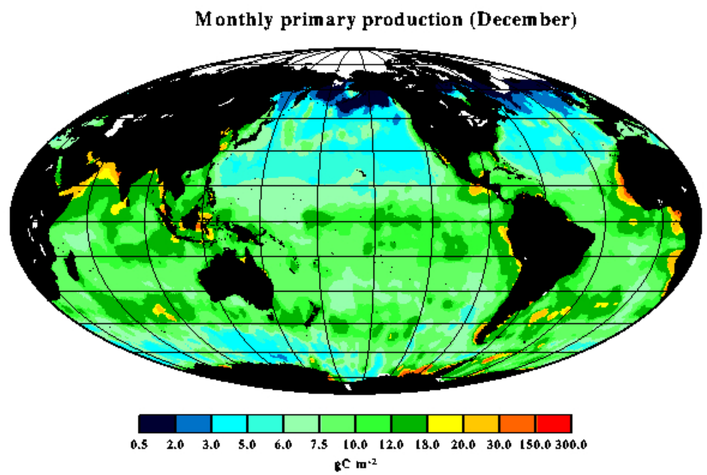
SEAWIFS Project
NASA/Goddard Space Flight Center
and ORBIMAGE

Phytoplankton



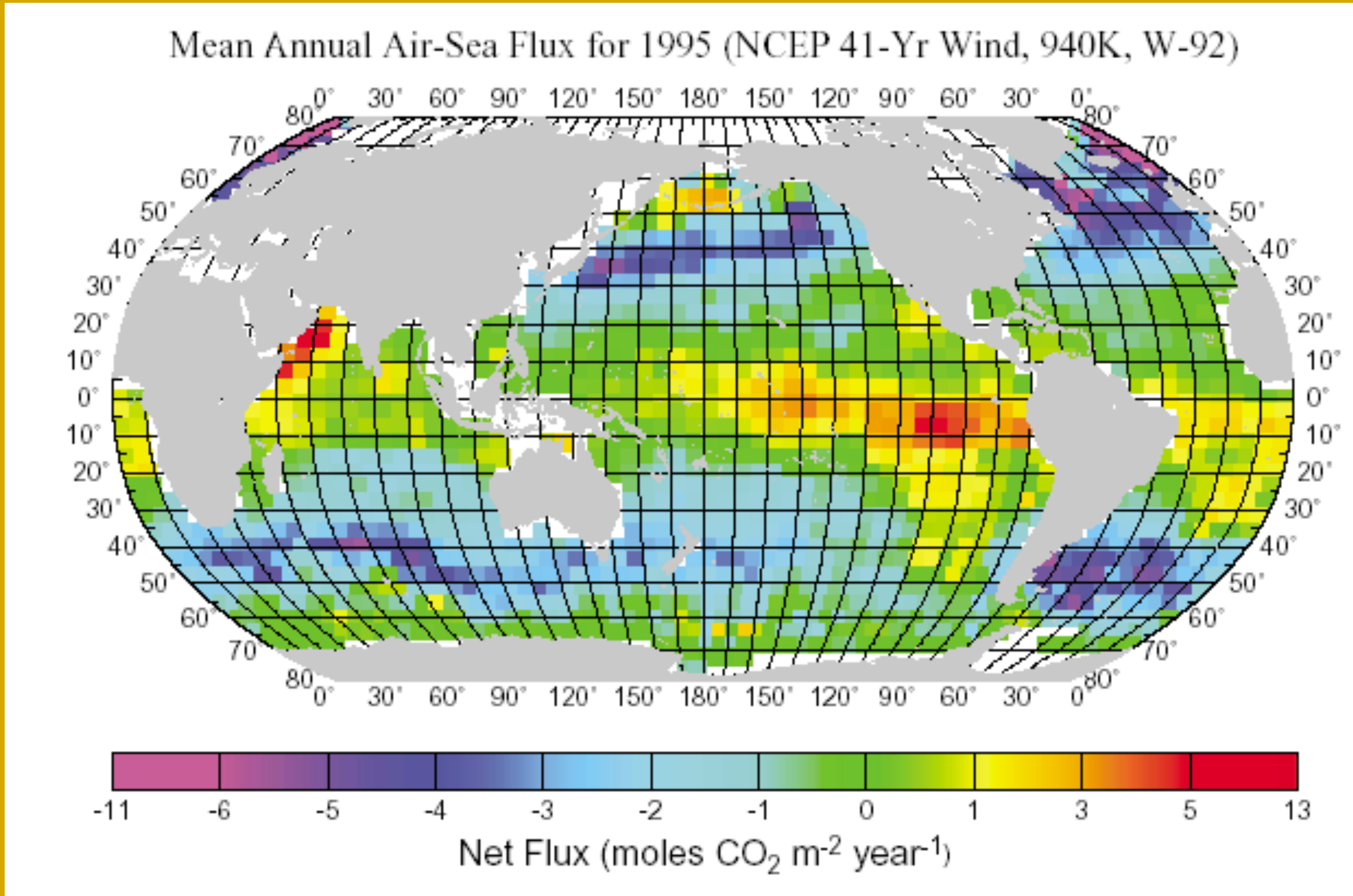
Primary Productivity (gC m^{-2})





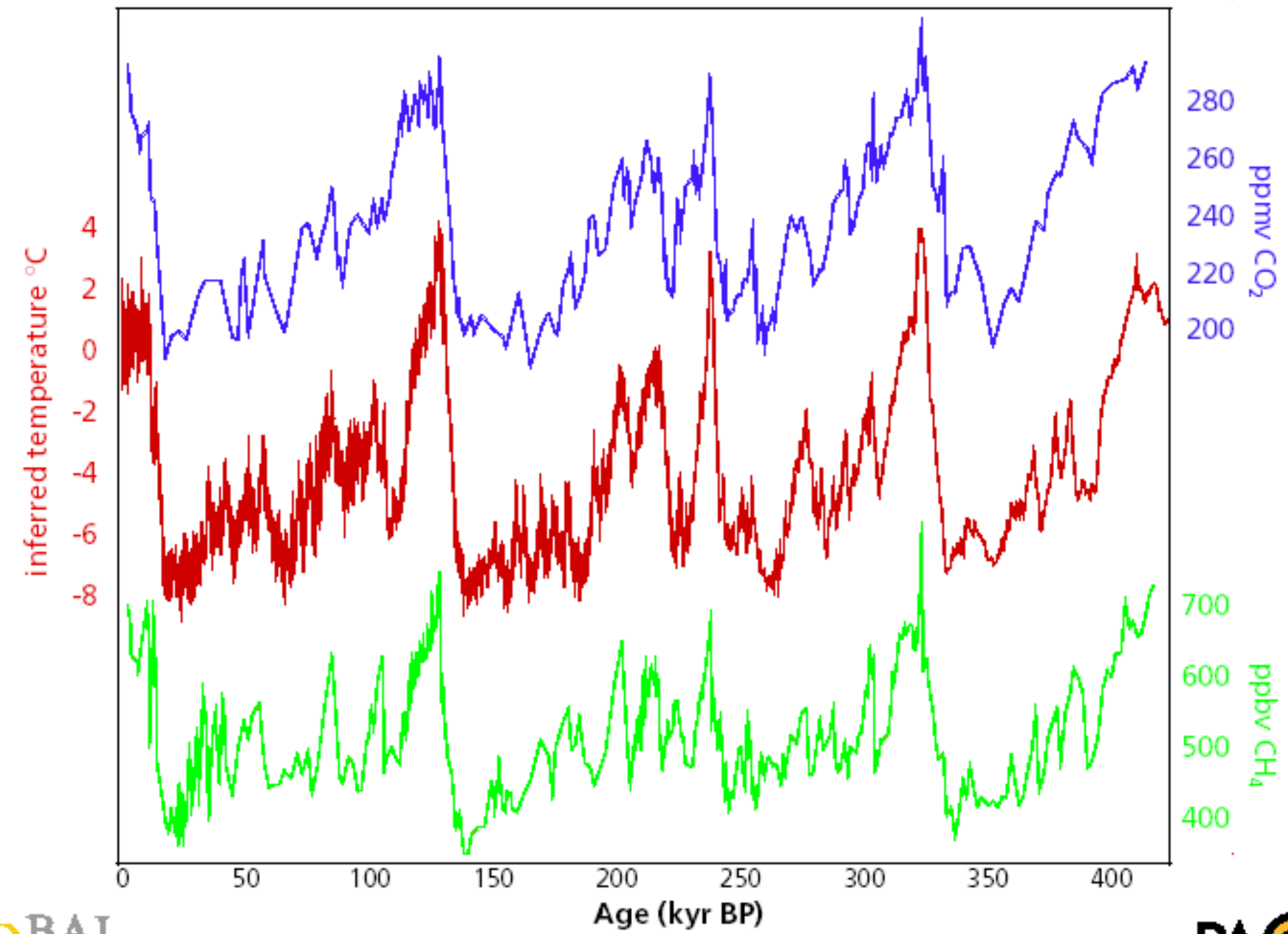
Antoine et al. 1996

Atmosphere - Ocean CO_2 exchange



Takahashi et al. 2002

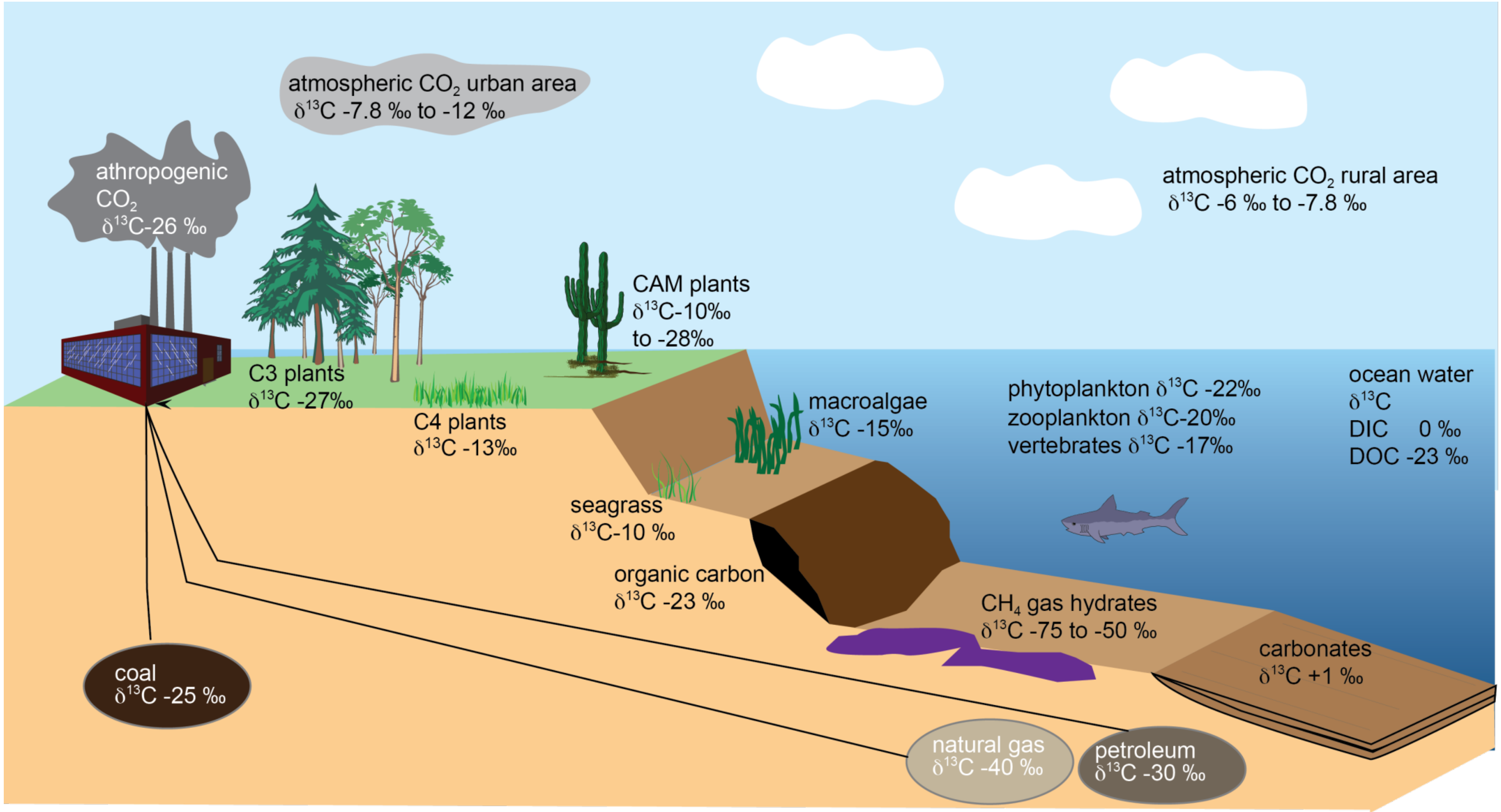
4 glacial cycles recorded in the Vostok ice core



GLOBAL IGBP CHANGE

J.R. Petit et al., *Nature,* **399**, 429–36, 1999.

PAGES PAST GLOBAL CHANGES



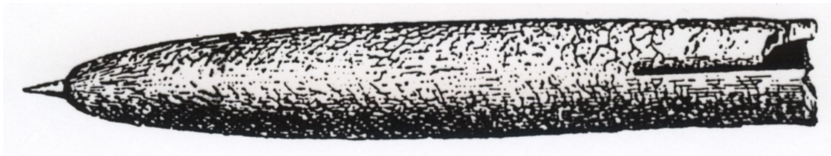
modified after http:// homepage.mac.com/uriarte/carbon13.html and iae.org

Der delta-Wert

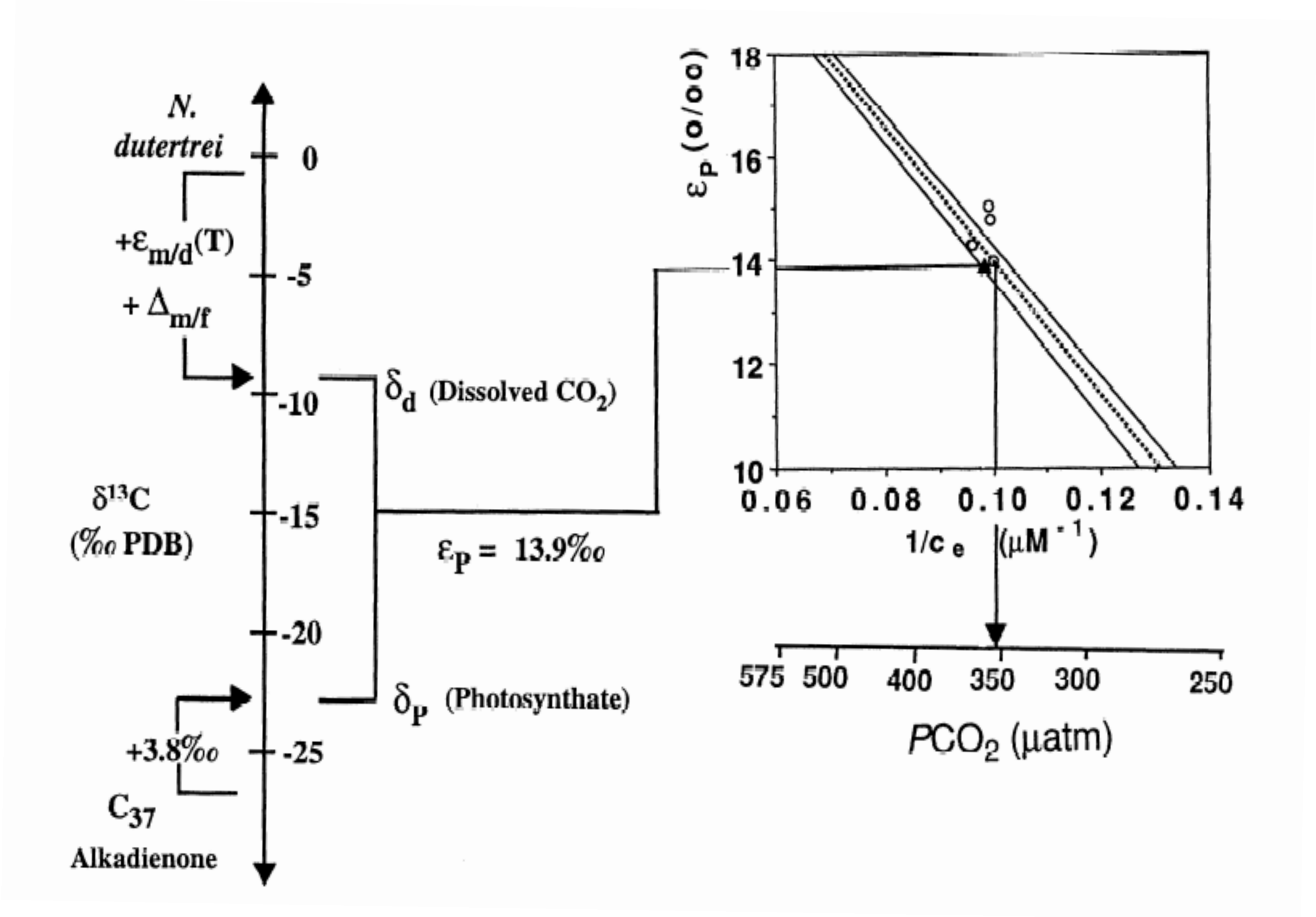
$$\delta^{18}O\ ‰ = \left[\frac{(^{18}O/^{16}O)_{Sa} - (^{18}O/^{16}O)_{Std}}{(^{18}O/^{16}O)_{Std}} \right] x\ 1000$$

$$\delta^{13}C\ ‰ = \left[\frac{(^{13}C/^{12}C)_{Sa} - (^{13}C/^{12}C)_{Std}}{(^{13}C/^{12}C)_{Std}} \right] x\ 1000$$

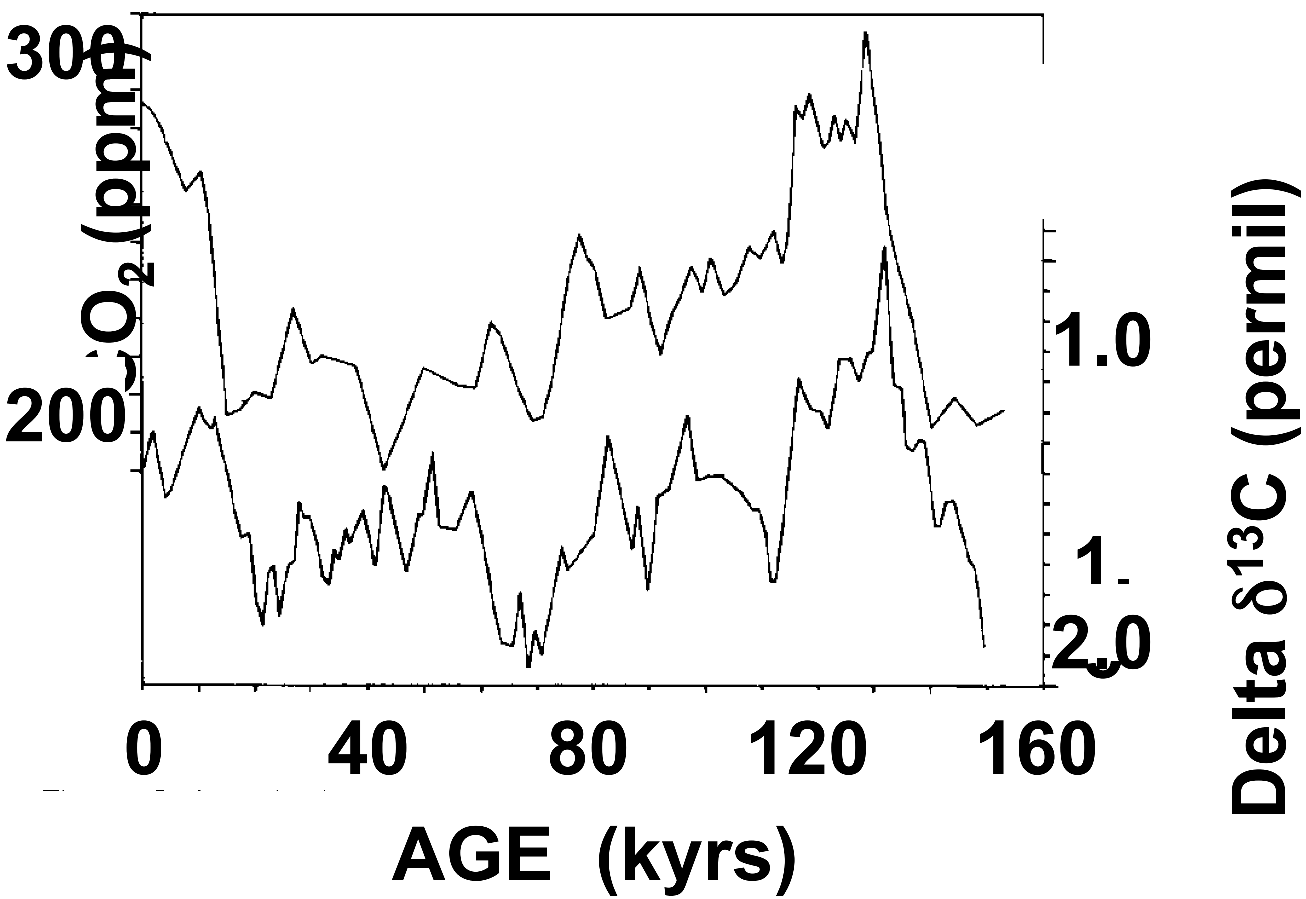
Internationale Standards für Isotopen-Zusammensetzungen von H, C, O, S, N

Standard	Standard	Element
PDB	*Belemnitella americana* aus der Peedee Formation der Kreide South Carolina 	C, O
SMOW	Standard Mean Ocean Water	H, O
CD	Troilit (FeS) Eisenmeteorit aus dem Diabolo Canyon	S
N_2 (Luft)	Luft	N

Calculation of paleo PCO_2 in the ocean



Biological Pump Effect



Berger et al. 1989

RADIOCARBON DATING

Method, Instruments, Calibration,

and Application in the Marine Environment

References

Books

Libby 1955 (2nd edition), Radiocarbon Dating, University of Chicago Press, Chicago.

Bard & Broecker 1992, The Last Deglaciation: Absolute and Radiocarbon Chronologies, NATO ASI Series I, Springer Verlag, Berlin, Heidelberg, New York.

Bradley 1992 (2nd edition), Quaternary Paleoclimatology, Methods of Paleoclimatic Reconstruction, Chapman & Hall, London.

Faure 1977, Principles of Isotope Geology, John Wiley & Sons, New York

Journal

RADIOCARBON

Websites

http://www.radiocarbon.com/

http://www.c14dating.com/

Radiocarbon Method

The radiocarbon dating method was developed by a team of scientists led by the late Professor Willard F. Libby of the University of Chicago between 1947 and 1952.

Libby later received the Nobel Prize in Chemistry in 1960:

"for his method to use Carbon-14 for age determinations in archaeology, geology, geophysics, and other branches of science."

"Seldom has a single discovery in chemistry had such an impact on the thinking of so many fields of human endeavour. Seldom has a single discovery generated such wide public interest."

Today, there are over **130** **radiocarbon dating laboratories** around the world producing radiocarbon assays for scientific fields including hydrology, atmospheric science, oceanography, geology, palaeoclimatology, archaeology and biomedicine.

Radiocarbon Method

There are three principal isotopes of carbon which occur naturally - C12, C13 (both stable) and C14 (unstable or radioactive). These isotopes are present in the following amounts C12 - 98.89%, C13 - 1.11% and C14 - 0.00000000010%. Thus, one carbon 14 atom exists in nature for every 1,000,000,000,000 C12 atoms in living material. The radiocarbon method is based on the rate of decay of the radioactive or unstable carbon isotope 14 (14C), which is formed in the upper atmosphere through the effect of cosmic ray neutrons upon nitrogen 14. The reaction is:

14N + n => 14C + p (Where n is a neutron and p is a proton).

The 14C formed is rapidly oxidised to 14CO2 and enters the earth's plant and animal lifeways through photosynthesis and the food chain. The rapidity of the dispersal of C14 into the atmosphere has been demonstrated by measurements of radioactive carbon produced from thermonuclear bomb testing. 14C also enters the Earth's oceans in an atmospheric exchange and as dissolved carbonate (the entire 14C inventory is termed the **carbon exchange reservoir** (Aitken, 1990)). Plants and animals which utilise carbon in biological foodchains take up 14C during their lifetimes. They exist in equilibrium with the C14 concentration of the atmosphere, that is, the numbers of C14 atoms and non-radioactive carbon atoms stays approximately the same over time. As soon as a plant or animal dies, they cease the metabolic function of carbon uptake; there is no replenishment of radioactive carbon, only decay.

Libby, Anderson and Arnold (1949) first discovered that this decay occurs at a constant rate. They found that after 5568 years, half the C14 in the original sample will have decayed and after another 5568 years, half of that remaining material will have decayed, and so on (see figure 1 below). The **half-life** (*t* 1/2) is the name given to this value which Libby measured at 5568±30 years. This became known as the **Libby half-life**. After 10 half-lives, there is a very small amount of radioactive carbon present in a sample. At about 50 - 60 000 years, then, the limit of the technique is reached (beyond this time, other radiometric techniques must be used for dating). By measuring the C14 concentration or residual radioactivity of a sample whose age is not known, it is possible to obtain the countrate or number of decay events per gram of Carbon. By comparing this with modern levels of activity (1890 wood corrected for decay to 1950 AD) and using the measured half-life it becomes possible to calculate a date for the death of the sample.
As 14C decays it emits a weak beta particle (*b*), or electron, which possesses an average energy of 160keV. The decay can be shown: **14C => 14N + *b***

Thus, the 14C decays back to 14N. There is a quantitative relationship between the decay of 14C and the production of a beta particle. The decay is constant but spontaneous. That is, the probability of decay for an atom of 14C in a discrete sample is constant, thereby requiring the application of statistical methods for the analysis of counting data.

Natural Carbon Isotopes

^{12}C ~ 98.89 % of total

^{13}C ~ 1.11 % of total

^{14}C ~ 0.00000000010 % of total (1 part per Trillion)

Radionuclides	Half-life (years)
^{10}Be	1,500,000
^{14}C	5,730
^{26}Al	730,000
^{36}Cl	301,000
^{41}Ca	100,000
^{129}I	16,000,000

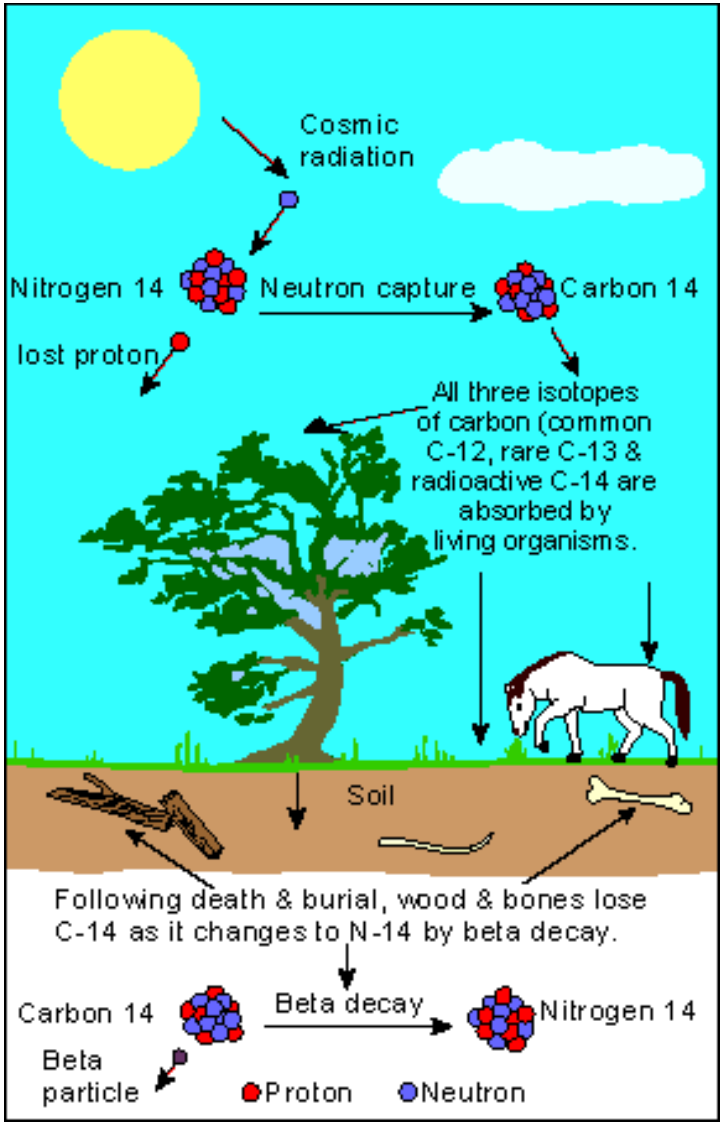
!! Libby´s half-life time is used by convention !!

^{14}C	5,558 ±30

Cosmogenic nuclides

Cosmogenic nuclides are isotopes that are produced by interaction of cosmic rays with the nucleus of the atom. Shown are radioactive isotopes of the elements beryllium, carbon, aluminum, chlorine, calcium, and iodine. The lifetimes range from thousands to millions of years. They are produced in meteorites and other extraterrestrial materials, in the Earth's atmosphere, and on the solid surface of the earth.

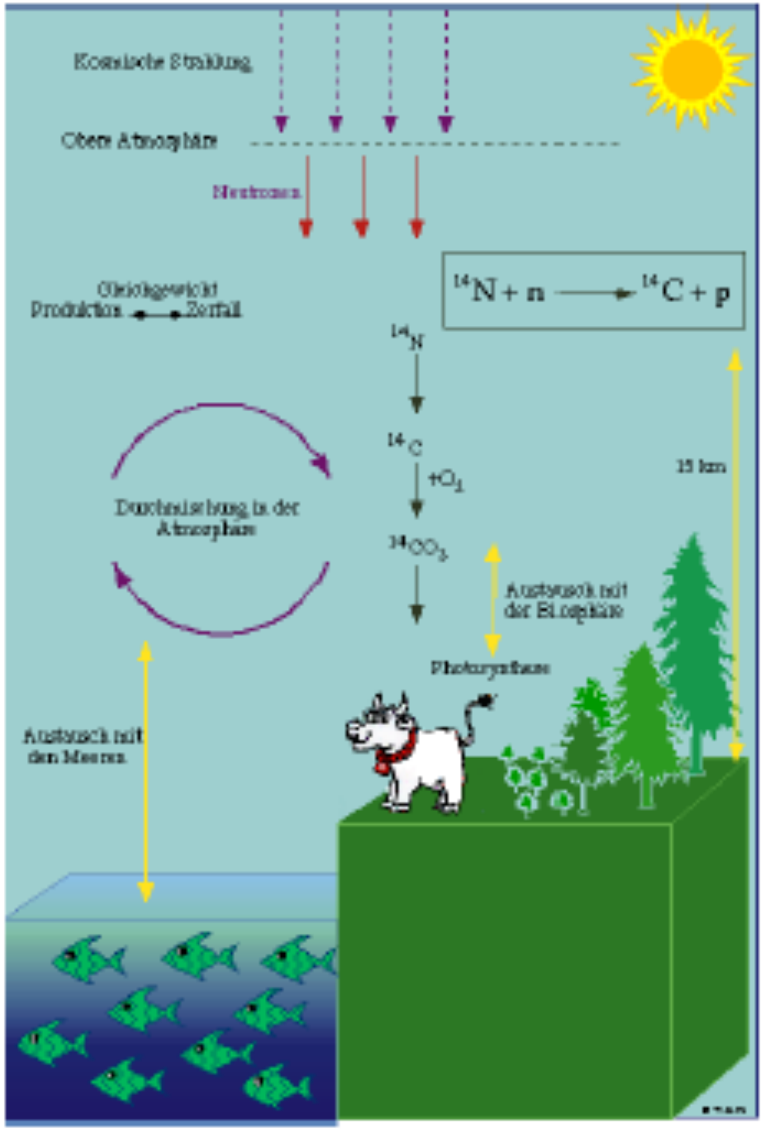
Natural Distribution



Production

^{14}C **Incorporation**

Decay



Production and Decay

$$^{1}_{0}n + ^{14}_{7}N \longrightarrow ^{14}_{6}C + ^{1}_{1}H$$

$$^{14}_{6}C \longrightarrow ^{14}_{7}N + \beta^{-} \; \textit{(160 keV)}$$

Atmosphere, Biosphere, and Oceans contain about:
42 x 10^{12} tons of ^{12}C
47 x 10^{10} tons of ^{13}C
but only 62 tons of ^{14}C

The estimated ^{14}C production rate of 7.5 kg/year is assumed to be by the annual global decay to keep the global ^{14}C budget constant

Law of Decay

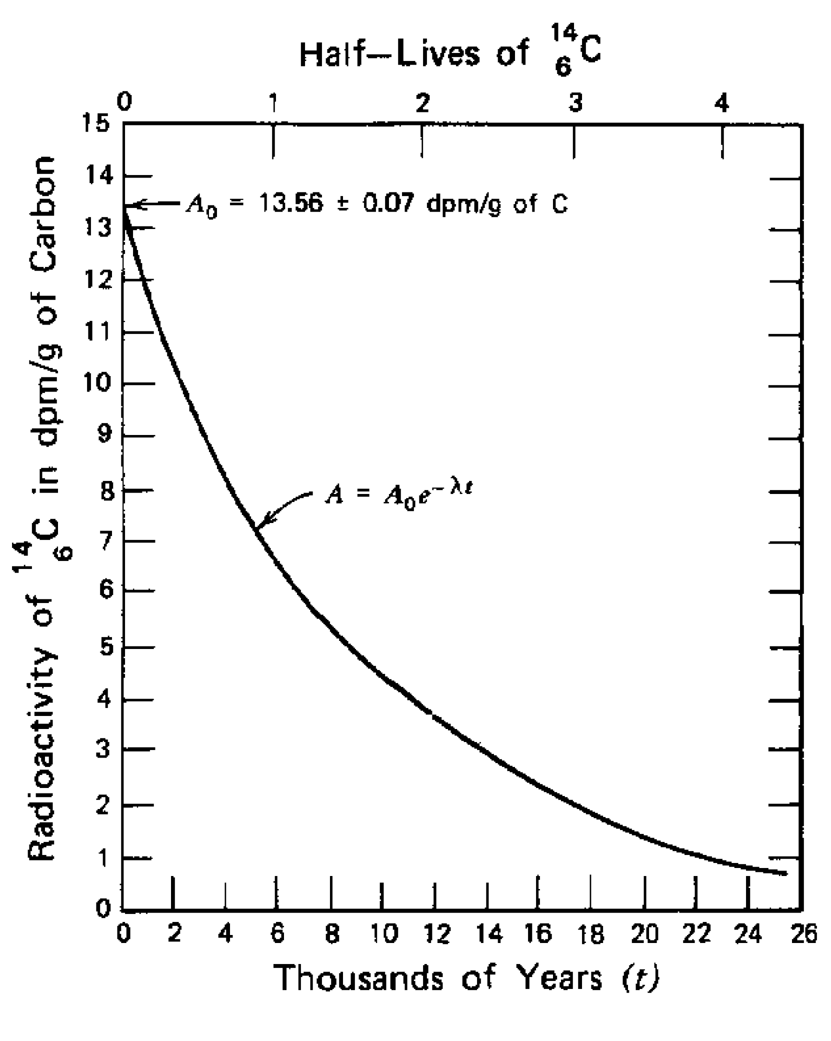
$$A = A_0 \, e^{-\lambda t}$$

$$\ln (A/A_0) = -\lambda t \;\Rightarrow\; t = 1/\lambda \, \ln(A_0/A)$$

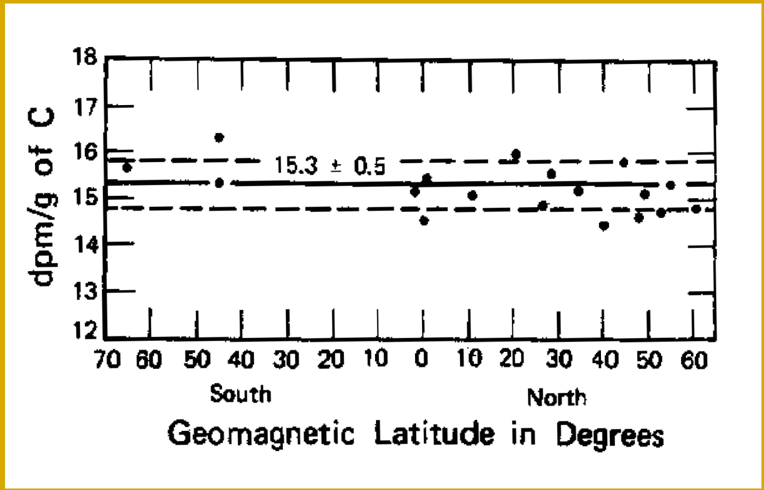
A: measured ^{14}C activity, e.g., in dpm/gC
A_0: natural ^{14}C activity at the time of incorporation
λ : half-life time ($t_{1/2}$), t : time passed

http://vcourseware4.calstatela.edu/VirtualDating/files/RC_2.html
http://staff.gc.maricopa.edu/~mvillarb/SyRIS/lawdecay.htm

Law of Decay

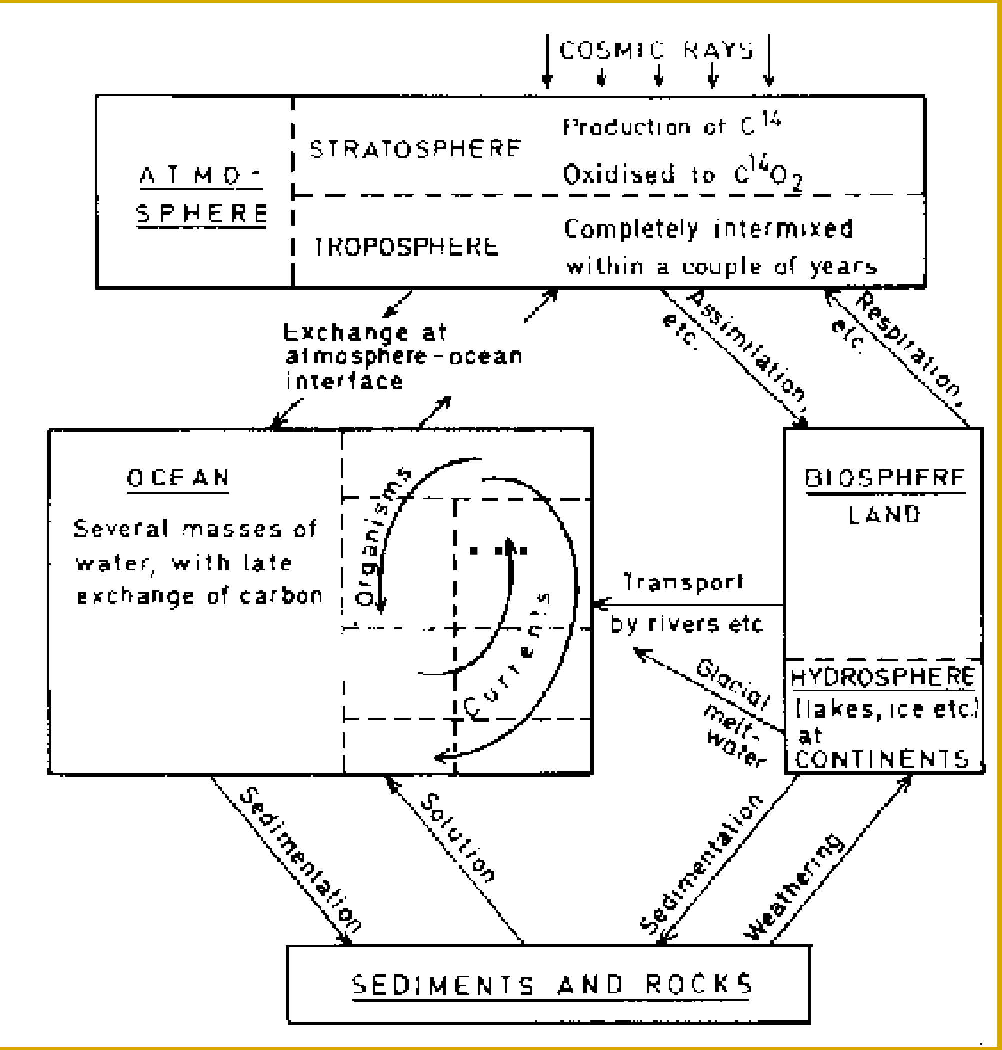


Half–Lives of $^{14}_{6}C$
A_0 = 13.56 ± 0.07 dpm/g of C
$A = A_0 e^{-\lambda t}$
Radioactivity of $^{14}_{6}C$ in dpm/g of Carbon
Thousands of Years (t)

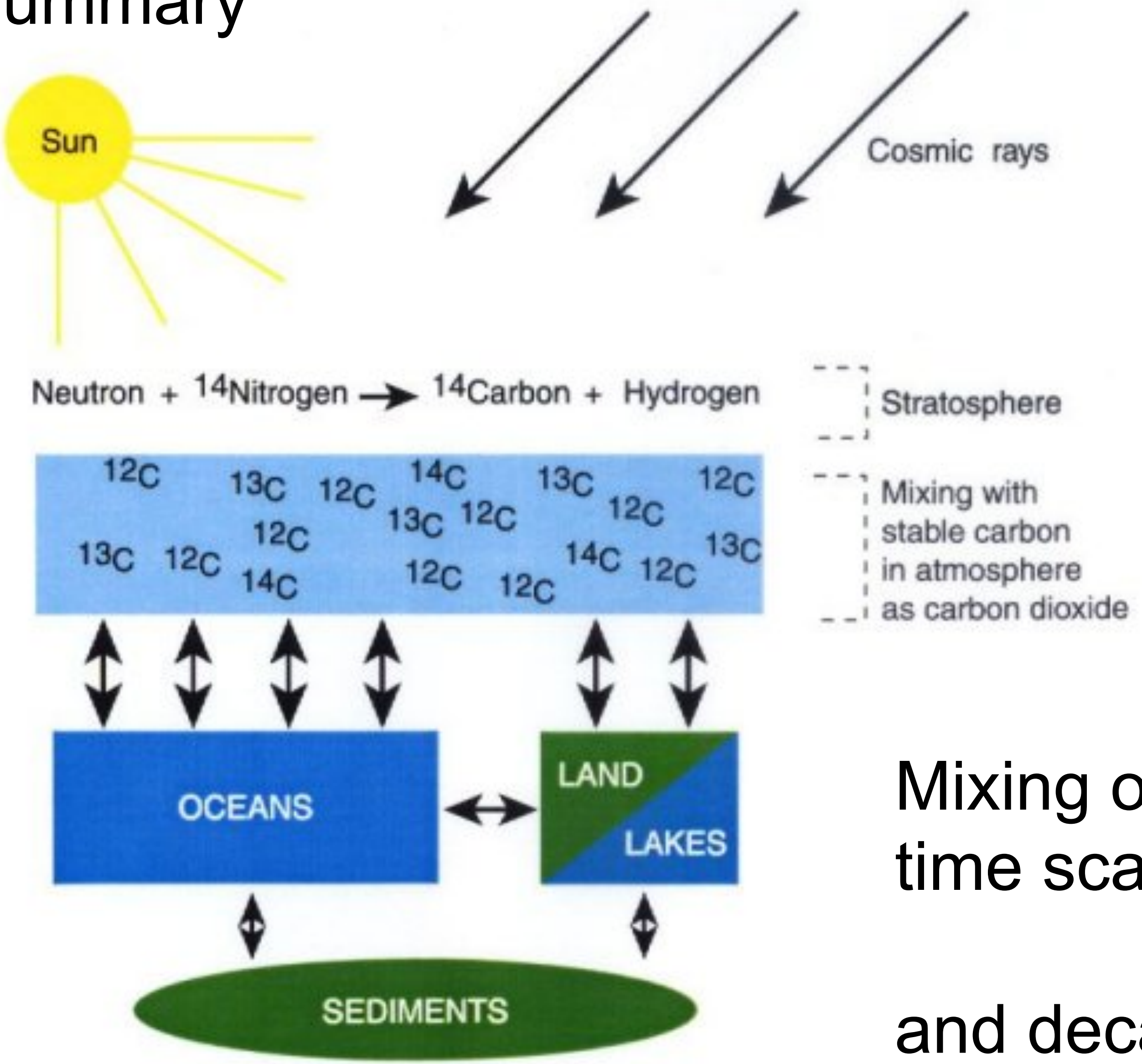


15.3 ± 0.5
dpm/g of C
South
North
Geomagnetic Latitude in Degrees

Summary


COSMIC RAYS
ATMOSPHERE
STRATOSPHERE
Production of C^{14}
Oxidised to $C^{14}O_2$
TROPOSPHERE
Completely intermixed within a couple of years
Exchange at atmosphere - ocean interface
Assimilation, etc.
Respiration, etc.
OCEAN
Several masses of water, with late exchange of carbon
Organisms
Currents
BIOSPHERE
LAND
Transport by rivers etc
Glacial melt-water
HYDROSPHERE
(lakes, ice etc.) at CONTINENTS
Sedimentation
Solution
Sedimentation
Weathering
SEDIMENTS AND ROCKS

Summary



Mixing on longer time scales!

and decay

Terrestrial Archives

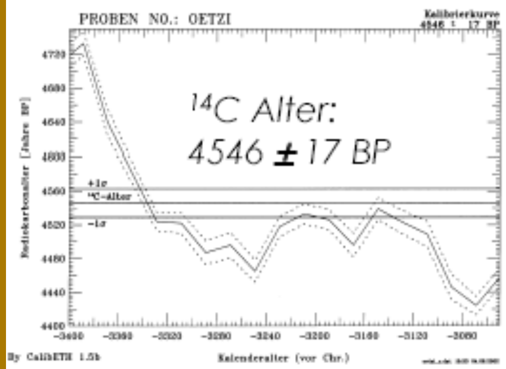
Archaeological Sites

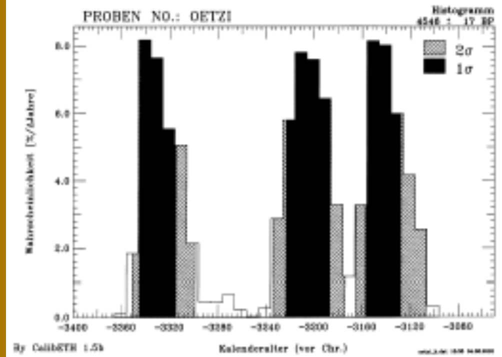
http://www.ipp.phys.ethz.ch/research/experiments/tandem/posters/

Terrestrial Archives

19.9.1991

1992





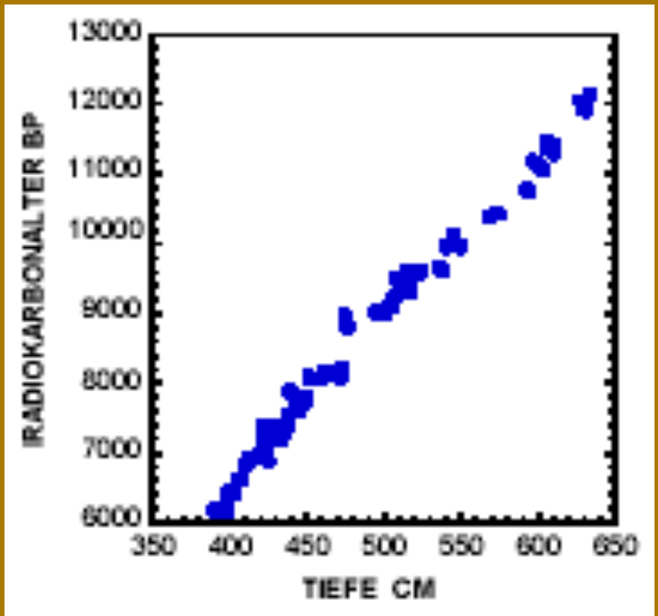
Kalenderalter:
3350 bis 3110 vor Chr.

http://www.ipp.phys.ethz.ch/research/experiments/tandem/posters/

Terrestrial Archives

Lake Soppensee, Luzern, Switzerland

6'000 bis 13'000 BP



14'190 ± 120 BP

http://www.ipp.phys.ethz.ch/research/experiments/tandem/posters/

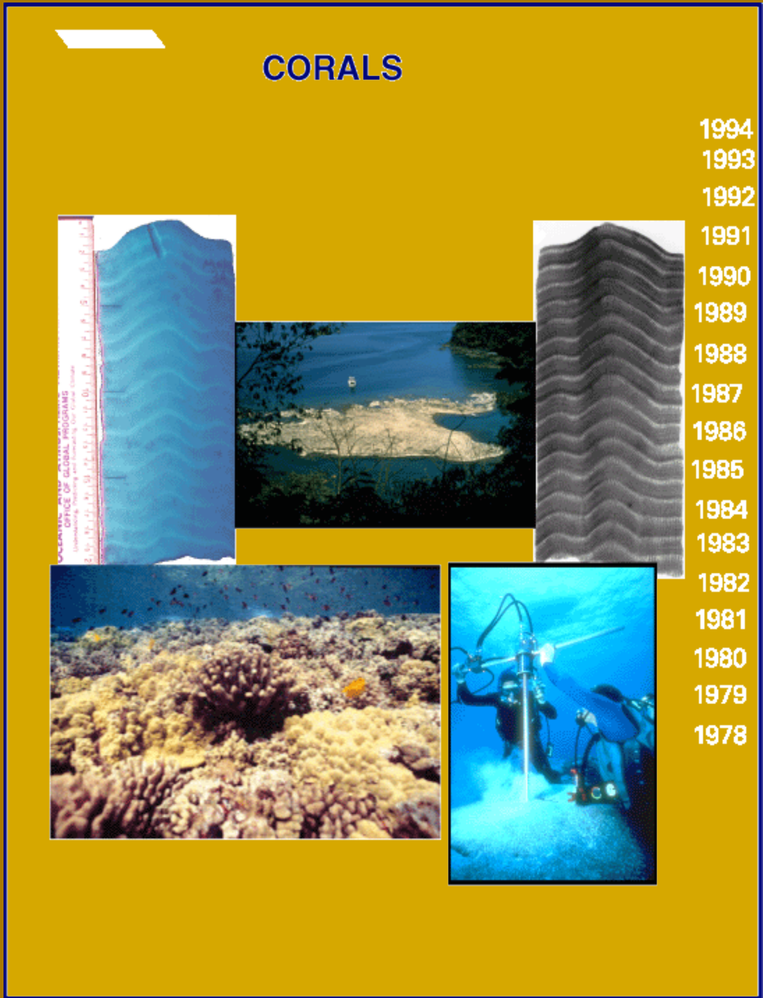
Terrestrial Archives

TREE RINGS

ICE CORES AND GLACIERS

IGBP-PAGES website

Marine Archives

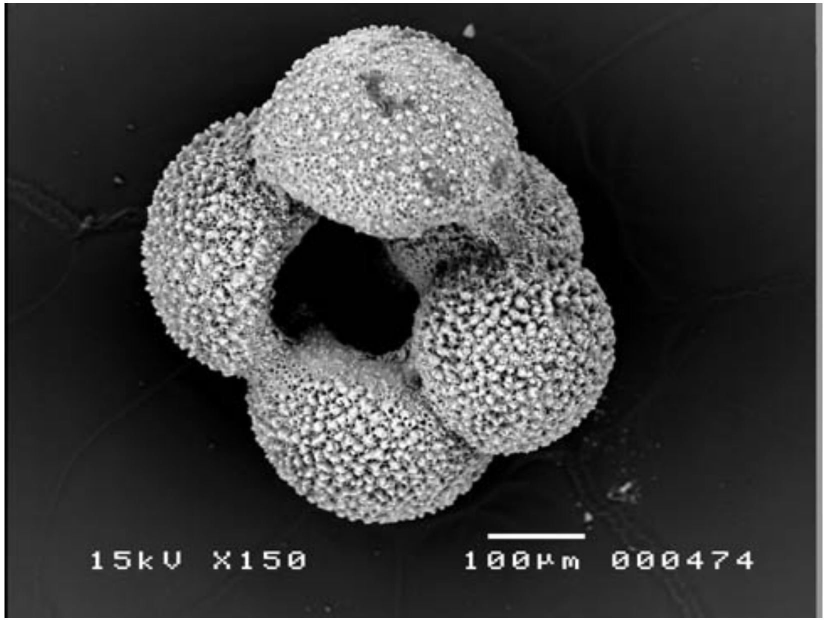


IGBP-PAGES website **Institut fuer Umweltphysik, Uni Heidelberg**

Marine Archives

Planktonic Foraminifera/
Mediterranean/ Levantine Basin/

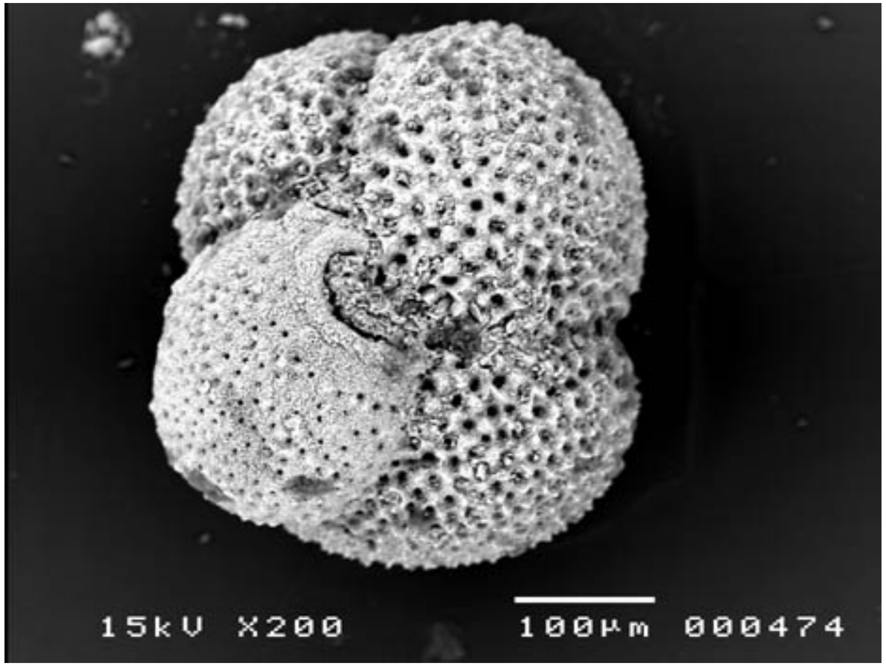
Globigerina bulloides



Globerinoides ruber

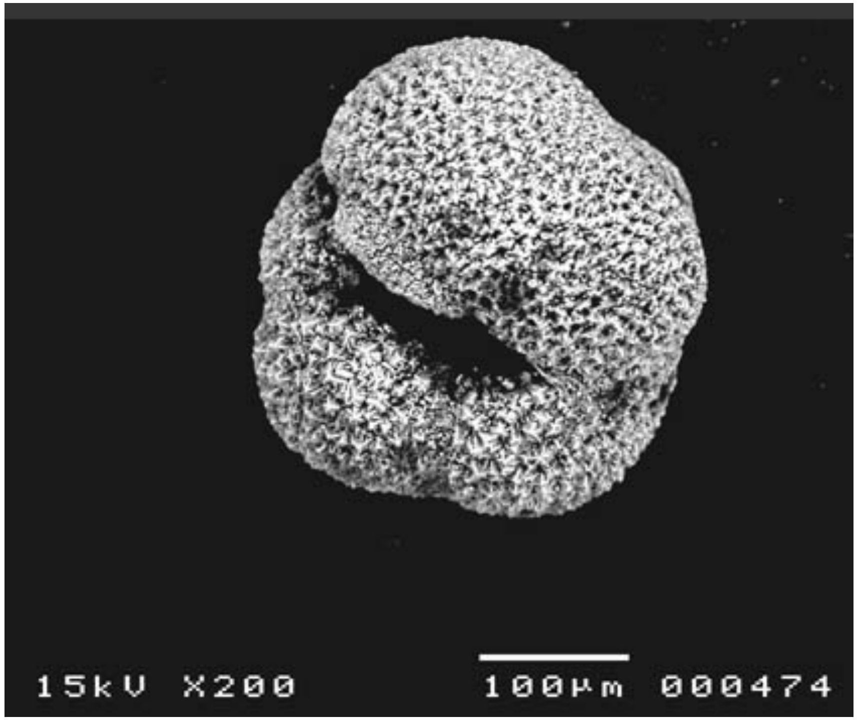
Images from a thesis by Jens Kallmayer (yr. 1998
SOCRATES visitor from Bremen)
For more information about these research projects
contact Dr.Eelco.J.Rohling
(Pages created and maintained by Barry Marsh

SOES)

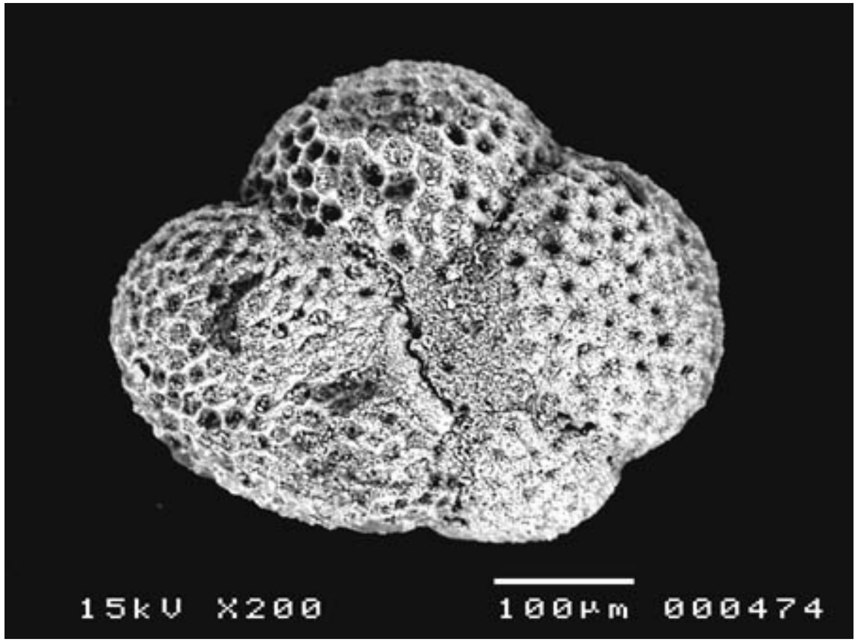


Marine Archives

Neogloboquadrina pachyderma **(right coiling)**



Globigerinoides sacculifera



Counting techniques

β^- DECAY in dpm per g C

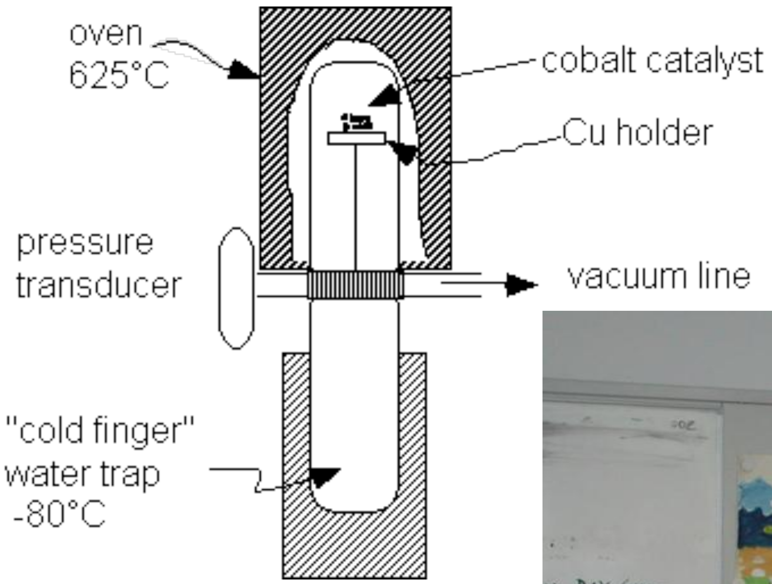
in gas counters (Geiger principle) C is converted to CH_4, CO_2 or Acetylene and electron emmission is measured by voltage

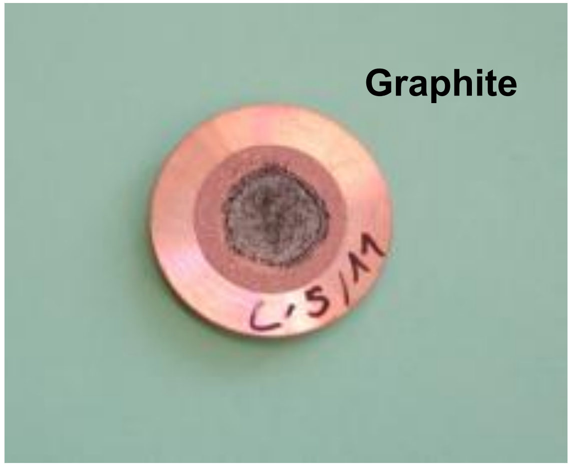
with liquid scintillation with conversion of C into an organic liquid (e.g., Benzene) and photochemical reaction (flashes of light) in the liquid

PROBLEMS:
Large samples needed, grams of pure C
Long measure times of hours to days for old samples
Shielding of instruments against natural background radioactivity

➔ **AMS ^{14}C Measurements**

Sample Preparation

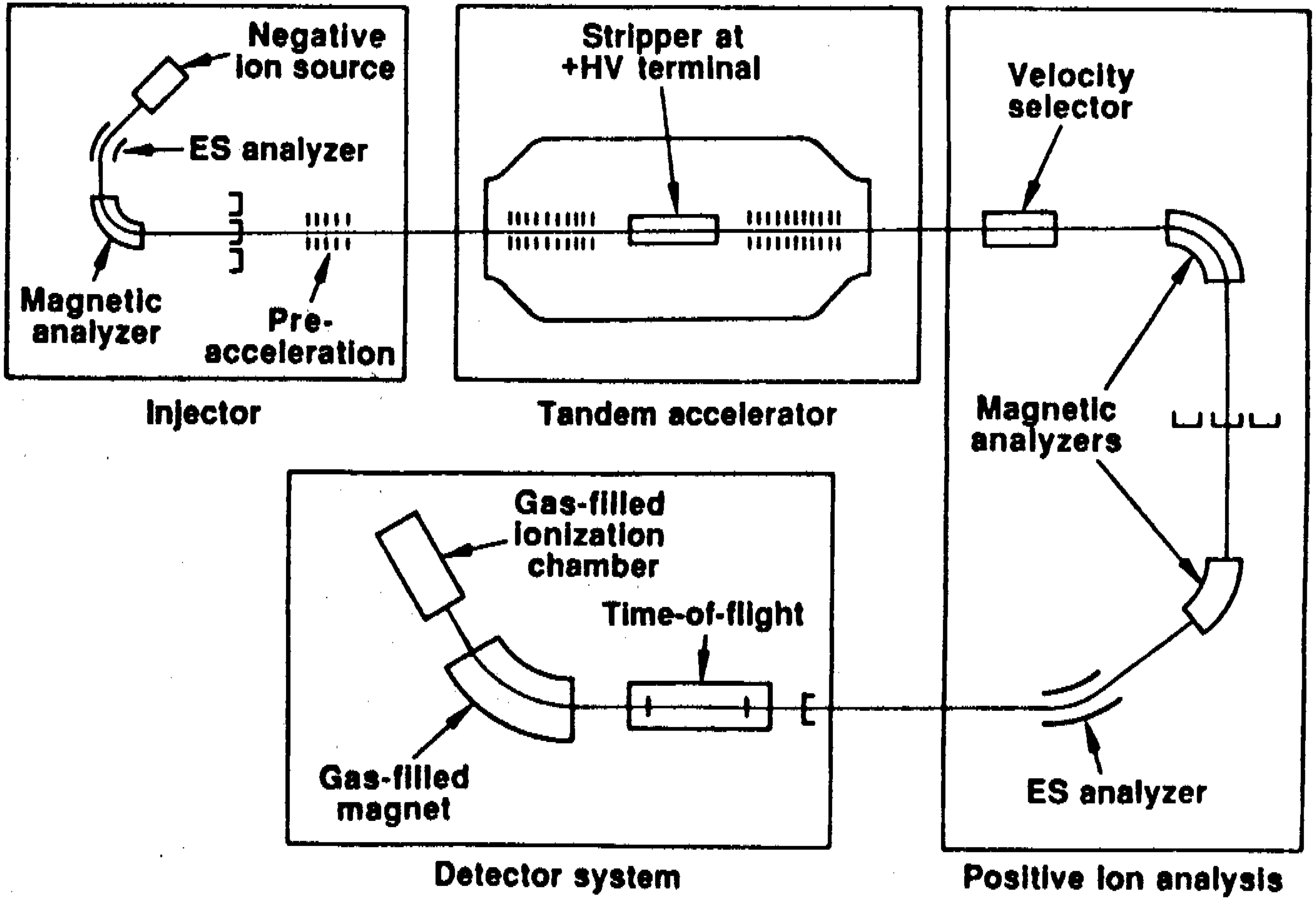




Large reaction chamber

ETH Zürich Website

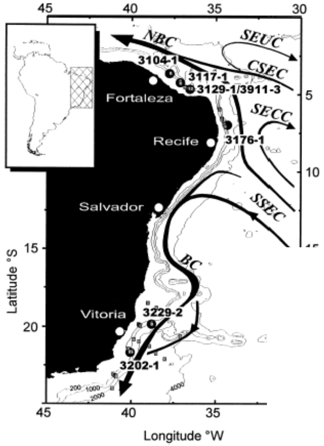
Principle Accelerator Mass-Spectrometer



Accelerator Mass-Spectrometer „mini version“

ETH Zürich Website

Examples Marine Records



Arz et al. 1999

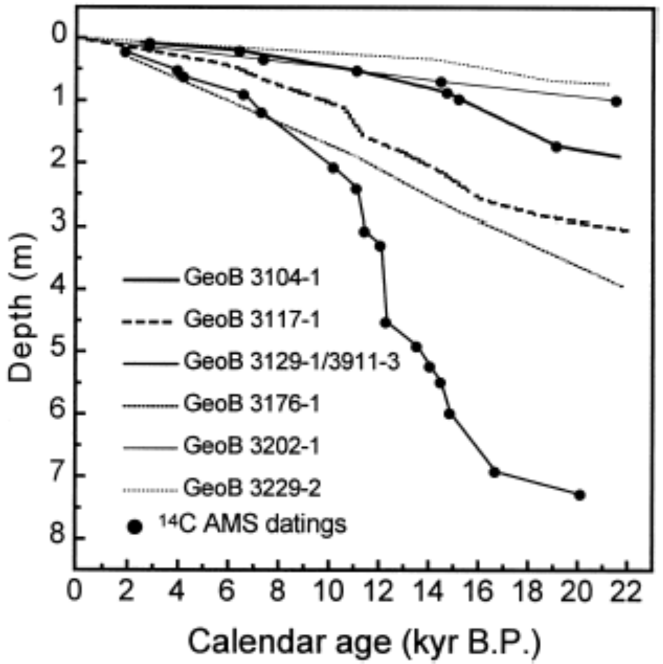


Fig. 3. Age models for the sediment cores GeoB 3104-1, 3129-1/3911-3, and 3202-2, derived from linearly interpolated and calibrated ^{14}C AMS dates. The cores GeoB 3117-1, 3176-1, and 3229-2 were linked to the established stratigraphies correlating various sediment parameters.

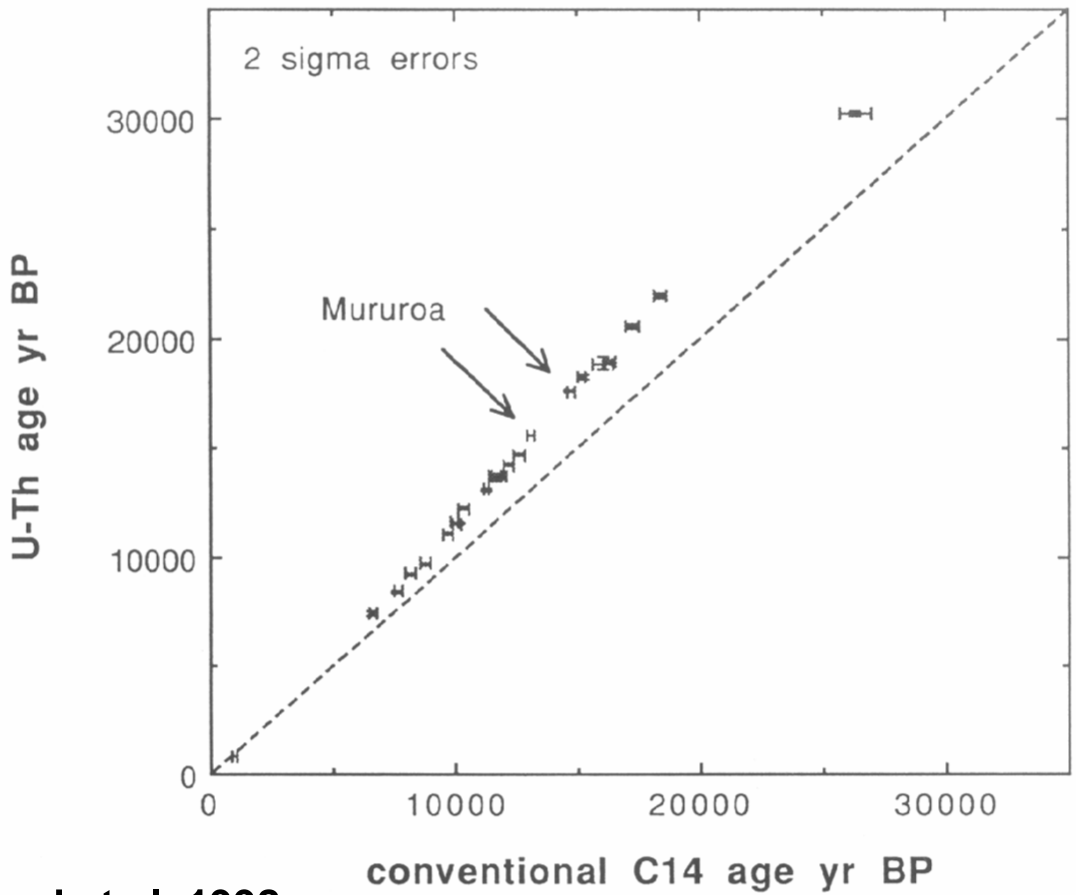
Table 2
^{14}C Ages obtained by accelerator mass spectrometry (AMS) dating of monospecific samples [a]

Lab. ID	Core depth (cm)	^{14}C AMS age (yr B.P.)	± Error (yr)	Calibrated age (cal. yr B.P.)
GeoB 3104-1				
KIA 653	8	2660	±50	2880
KIA 1857	20	5740	±60	6450
KIA 1856	52	9660	±50	11140
GrA 3719	87	12580	±100	14760
KIA 1855	97	12960	±90	15230
GrA 3720	172	16120	±160	19150
KIA 651	209	20540	+350/−330	24280
GeoB 3129-1 and 3911-3				
KIA 2576	22	1830	±30	1910
KIA 2575	52	3610	±50	3980
KIA 2574	62	3820	±30	4230
KIA 2573	90	5880	±40	6610
KIA 655	119	6510	±60	7330
KIA 654	207	9160	±80	10200
KIA 1872	241	9650	±60	11130
KIA 1871	307	9910	±60	11450
KIA 1861	329	10430	±60	12090
KIA 1860	452	10610	±70	12320
KIA 1859	491	11600	±70	13540
KIA 2614	523	12040	±70	14090
KIA 2612	548	12380	±50	14510
KIA 2613	543*	12680	±80	14880
KIA 2611	648*	14160	±110	16720
KIA 1858	665*	16920	±90	20140
GeoB 3202-1				
KIA1850	14	3010	±30	3280
KIA1849	34	6420	±40	7230
KIA1848	69	12400	±70	14540
KIA1847	99	18090	±100	21590

[a] *G. sacculifer* in the fraction of 250–500 μm, analyses performed at the Leibniz-Labor AMS facility in Kiel, Germany [37] and the Center for Isotope Research, Groningen, Netherlands. GrA = Groningen; KIA = Kiel. The ^{14}C ages were corrected for a reservoir effect of 400 years [38] and transformed into calendar years [40].
* Samples from core GeoB 3911-3.

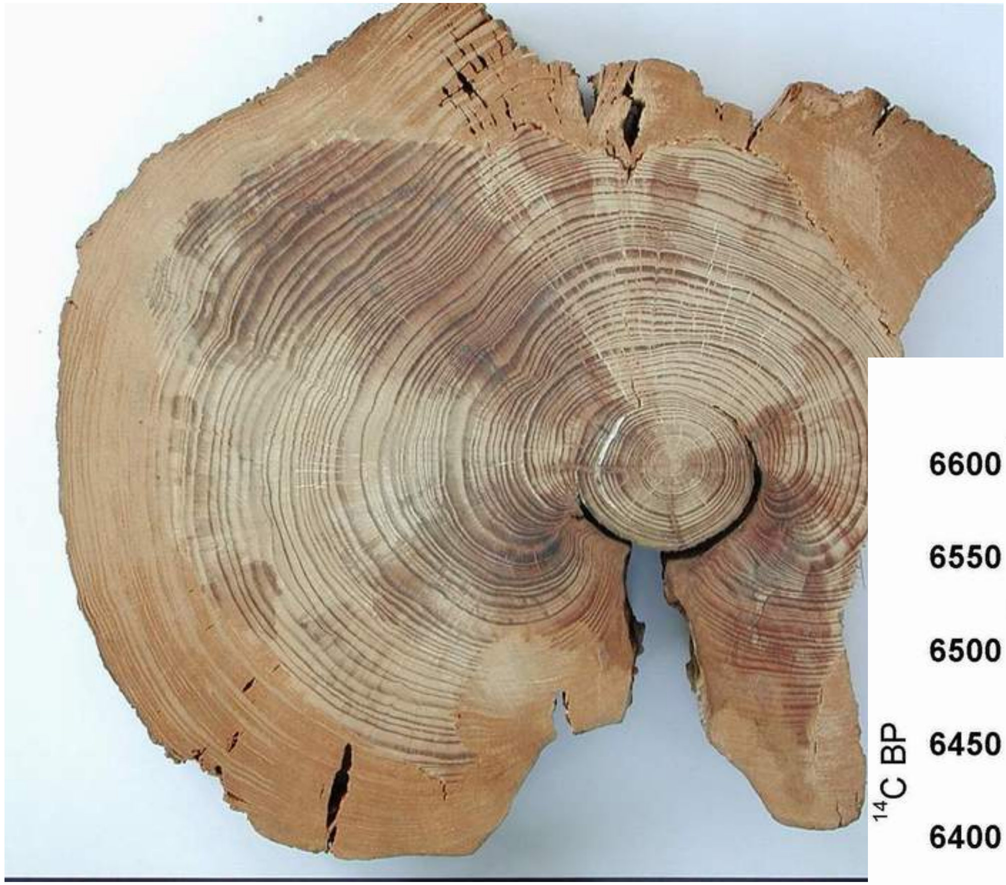
Calibration: Marine Environment

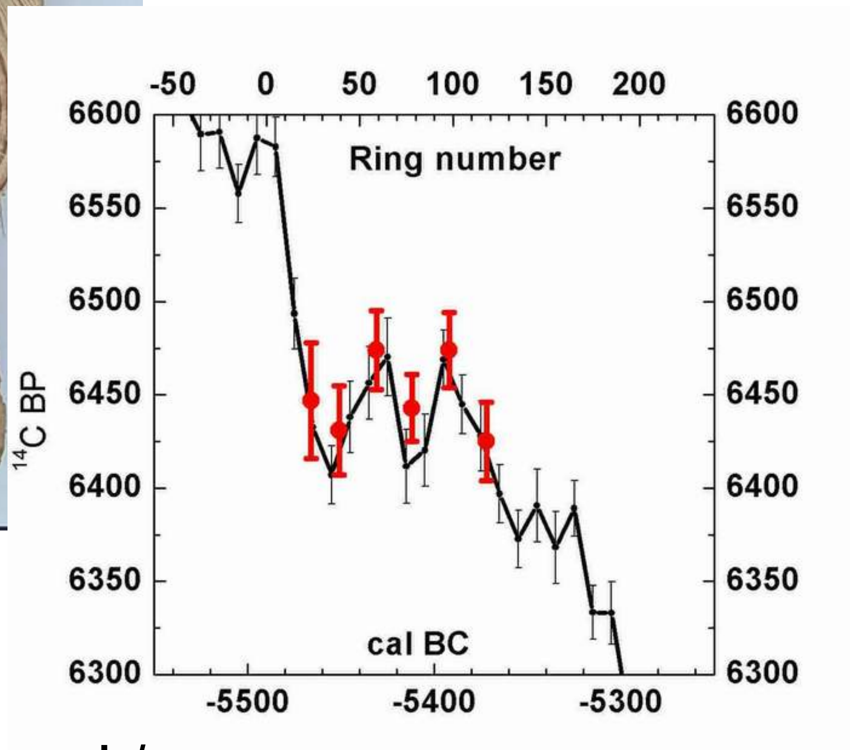
^{14}C versus $^{230}Th/^{234}U$ in the same coral sample



Bard et al. 1992

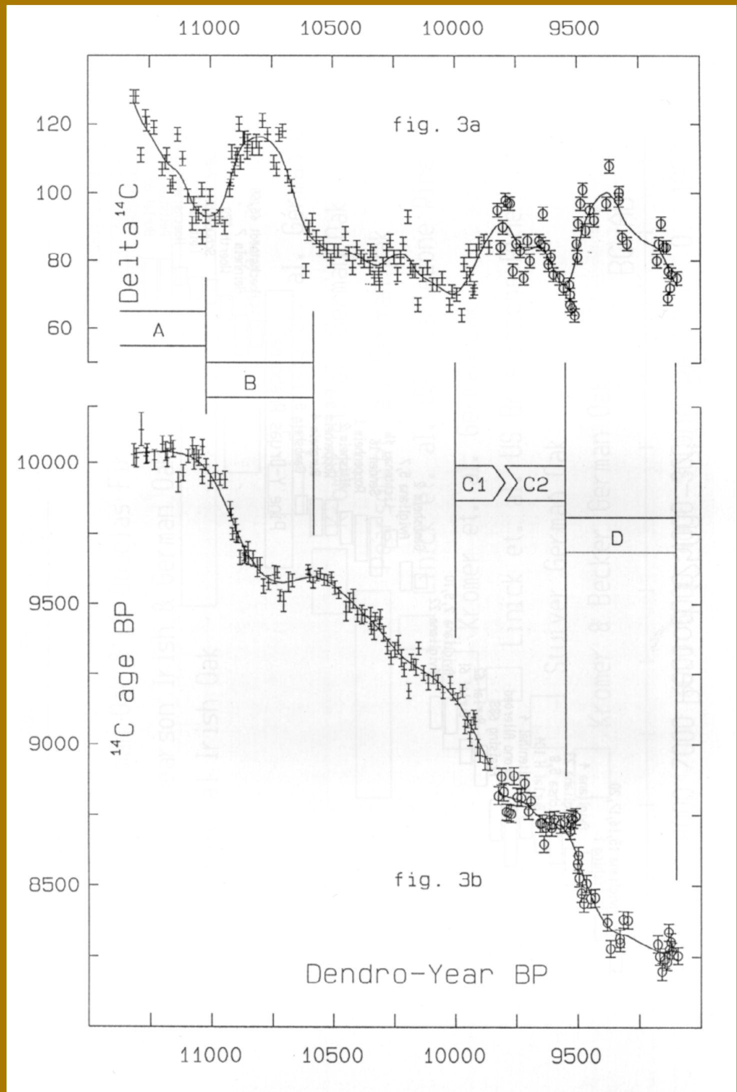
Calibration by tree rings „Dendrochronologie“





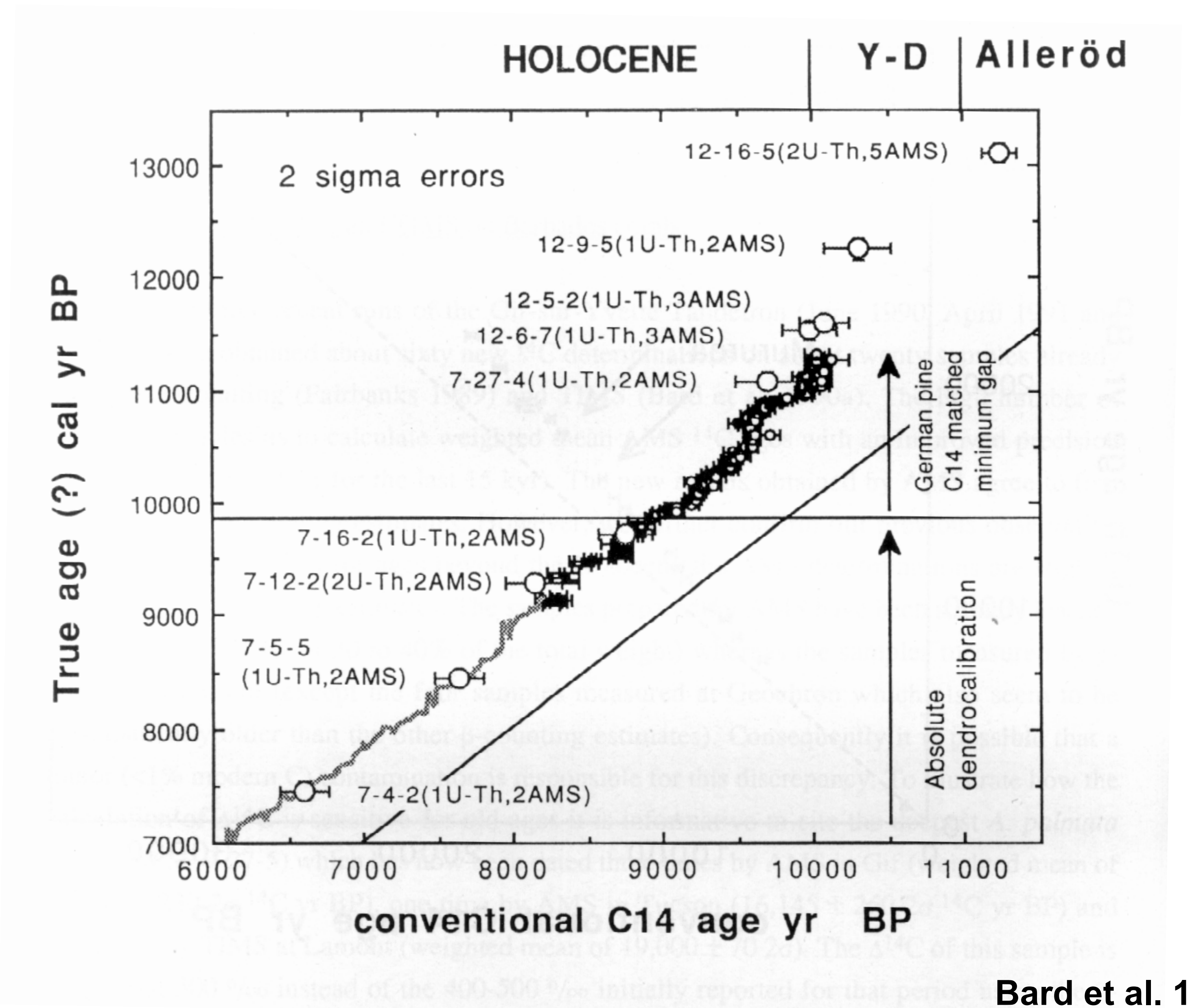
http://www.umweltphysik.uni-heidelberg.de/

Calibration by tree rings „Dendrochronologie“



! Delta ^{14}C !

Kromer & Becker 1992



Bard et al. 1992

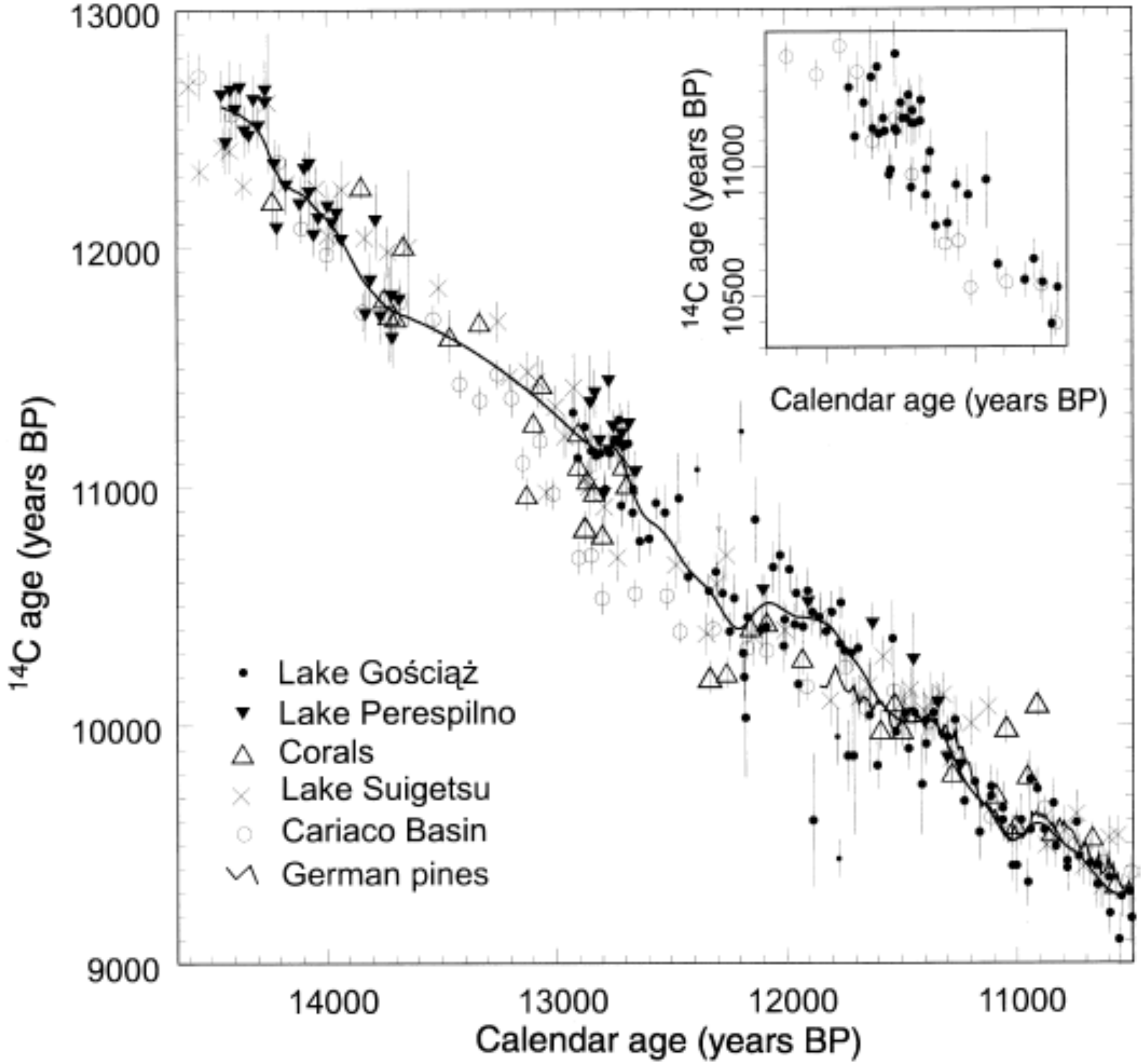
Causes for
deviations of radiocarbon ages from calendaric ages

1. Variations in the rate of ^{14}C production in the atmosphere
   # Variations in cosmic ray flux due to solar activity
   # Variations in cosmic ray flux due to changes in the geomagnetic field
   # 14C production by nuclear weapon testing and nuclear techniques

2. Variations in the rate of exchange of ^{14}C between various reservoirs and changes in the relative CO_2 content between reservoirs
   # Changes in CO2 solubility and dissolution, atmosphere-ocean
   # Changes in terrestrial biosphere (biomass), humidity, human activity
   # Ocean productivity and upwelling, and deep circulation

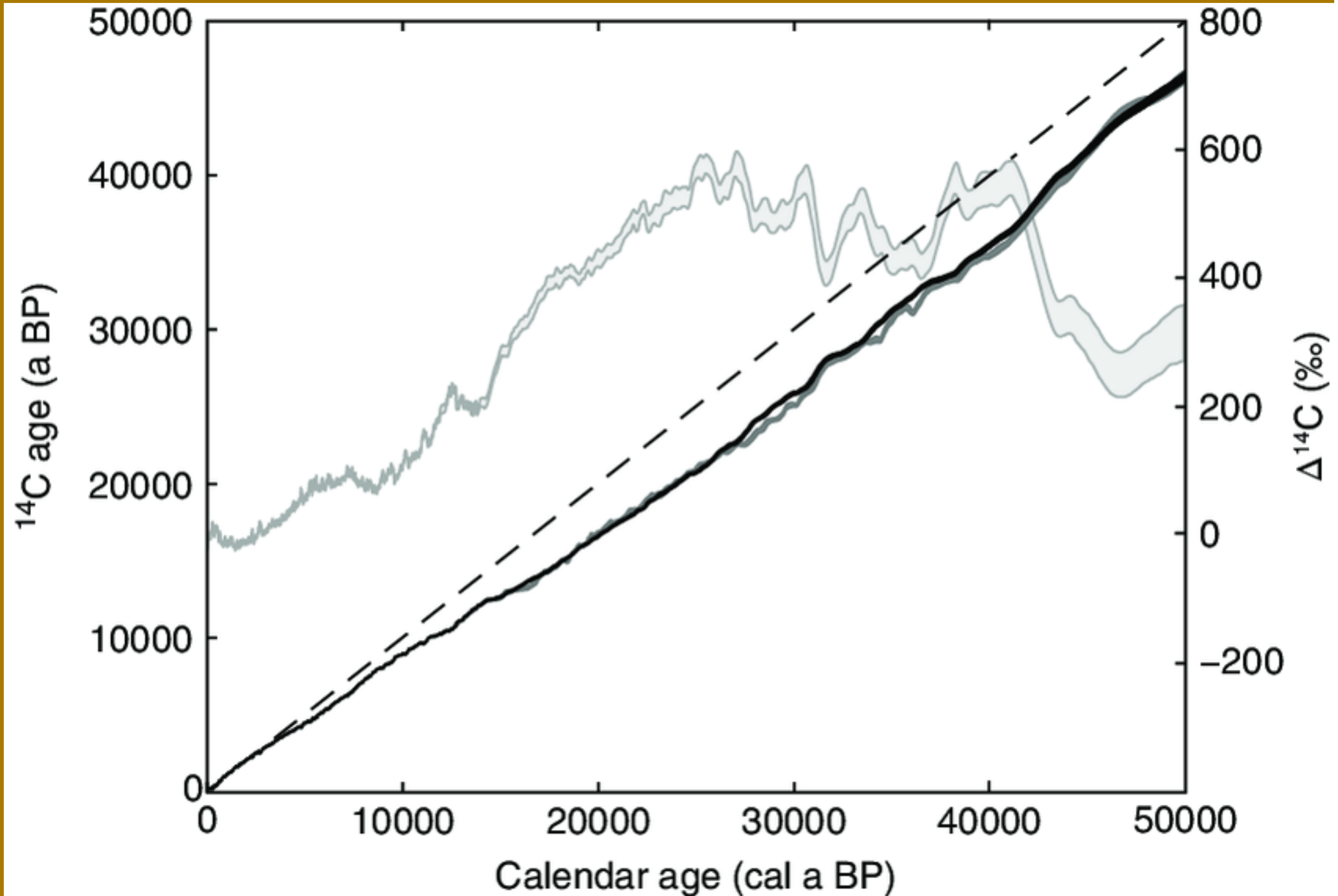
3. Variations in the total amount of CO_2 in the atmosphere, biosphere, and hydrosphere
   # Volcanism and other mechanisms of CO_2 lithosphere degassing
   # Release or burial in sedimentary reservoirs
   # Combustions of fossil fuels

Warved lake sediments in Poland



Goslar et al. 2000

IntCal13



Reimer et al. 2013

IntCal13

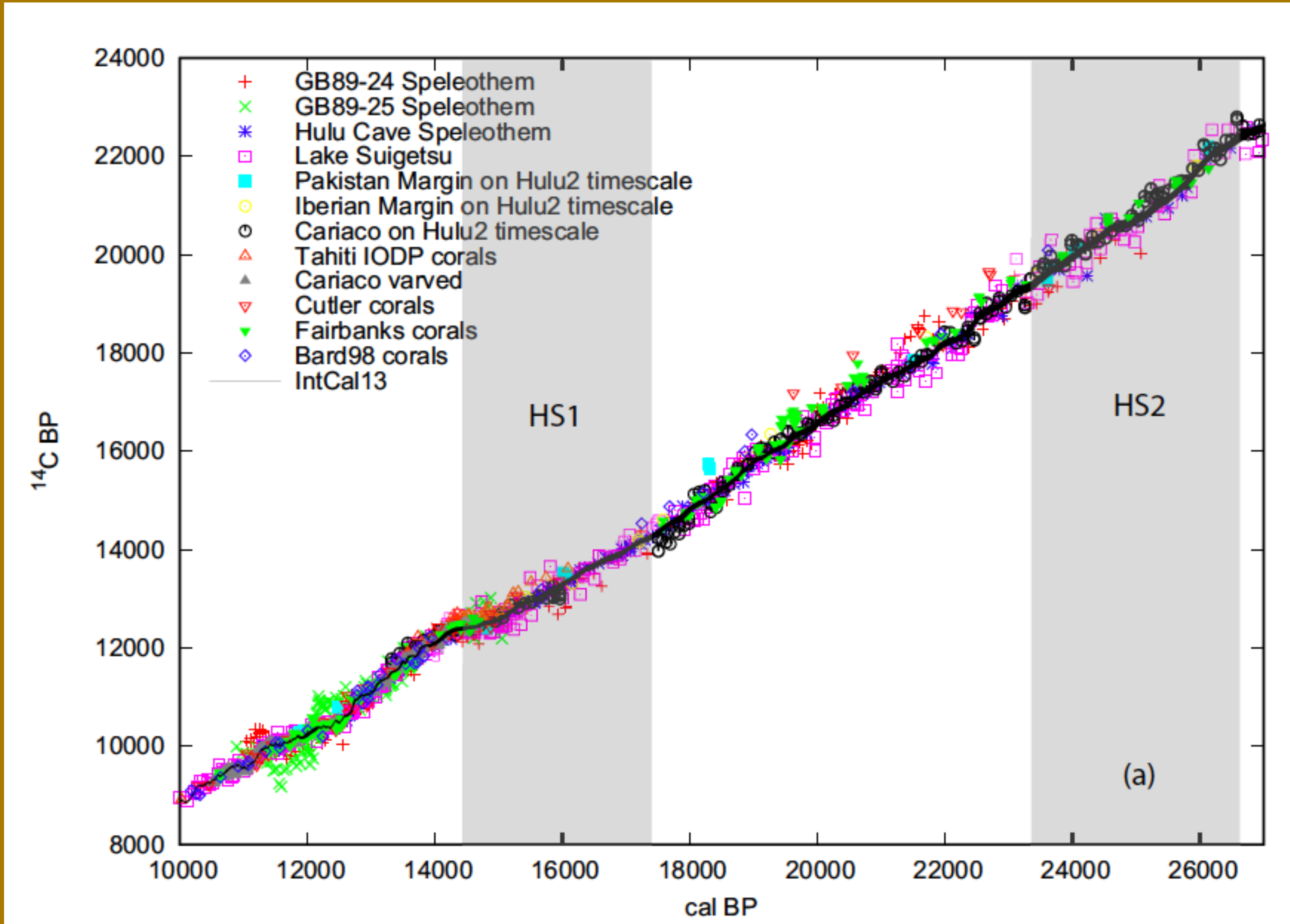
RADIOCARBON, Vol 55, Nr 4, 2013, p 1869–1887

INTCAL13 AND MARINE13 RADIOCARBON AGE CALIBRATION CURVES 0–50,000 YEARS CAL BP

Paula J Reimer[1,2] • Edouard Bard[3] • Alex Bayliss[4] • J Warren Beck[5] • Paul G Blackwell[6] • Christopher Bronk Ramsey[7] • Caitlin E Buck[6] • Hai Cheng[8,9‡] • R Lawrence Edwards[8] • Michael Friedrich[10,11] • Pieter M Grootes[12] • Thomas P Guilderson[13,14] • Haflidi Haflidason[15†] • Irka Hajdas[16] • Christine Hatté[17†] • Timothy J Heaton[6] • Dirk L Hoffmann[18‡] • Alan G Hogg[19] • Konrad A Hughen[20] • K Felix Kaiser[21,22*] • Bernd Kromer[11] • Sturt W Manning[23] • Mu Niu[6] • Ron W Reimer[1] • David A Richards[24] • E Marian Scott[25†] • John R Southon[26] • Richard A Staff[7‡] • Christian S M Turney[27] • Johannes van der Plicht[28,29]

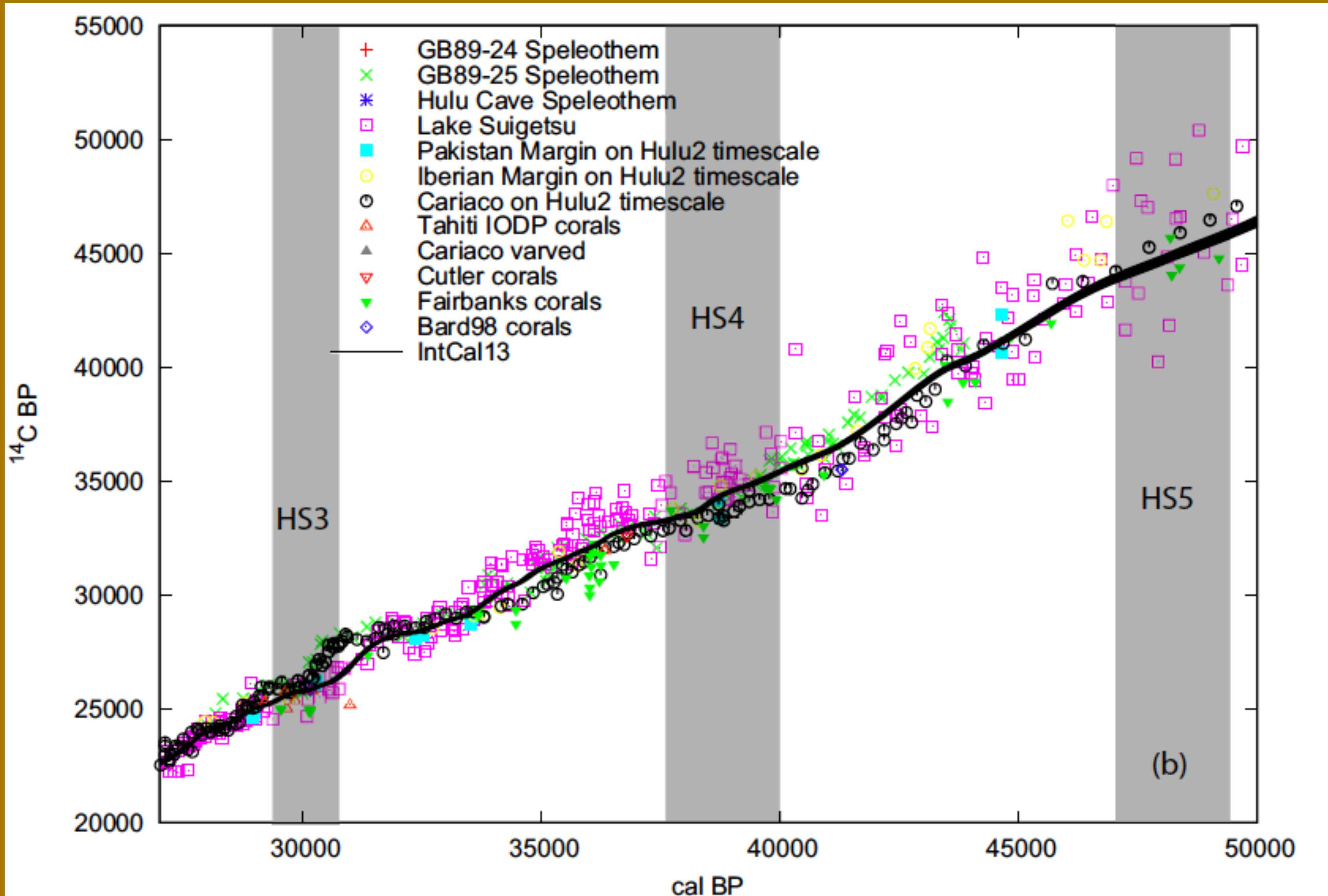
Reimer et al. 2013

IntCal13



Reimer et al. 2013

IntCal13



Reimer et al. 2013