Components of the Earth system

Atmosphere

Oceans

Cryosphere

Terrestrial biosphere

Crust and mantle

The oceans

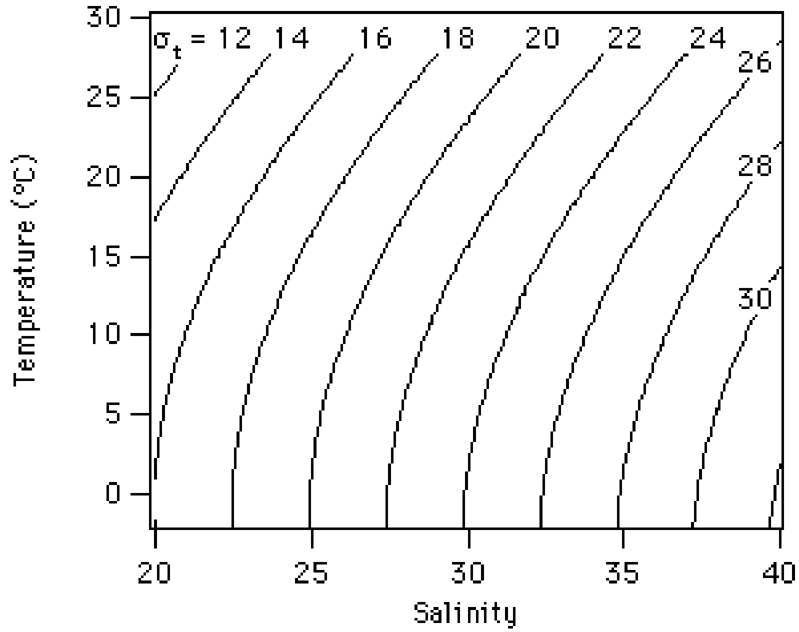
- constituents, equation of state
- vertical structure
- water masses
- wind driven currents
- thermohaline circulation
- the marine biosphere
- role in climate

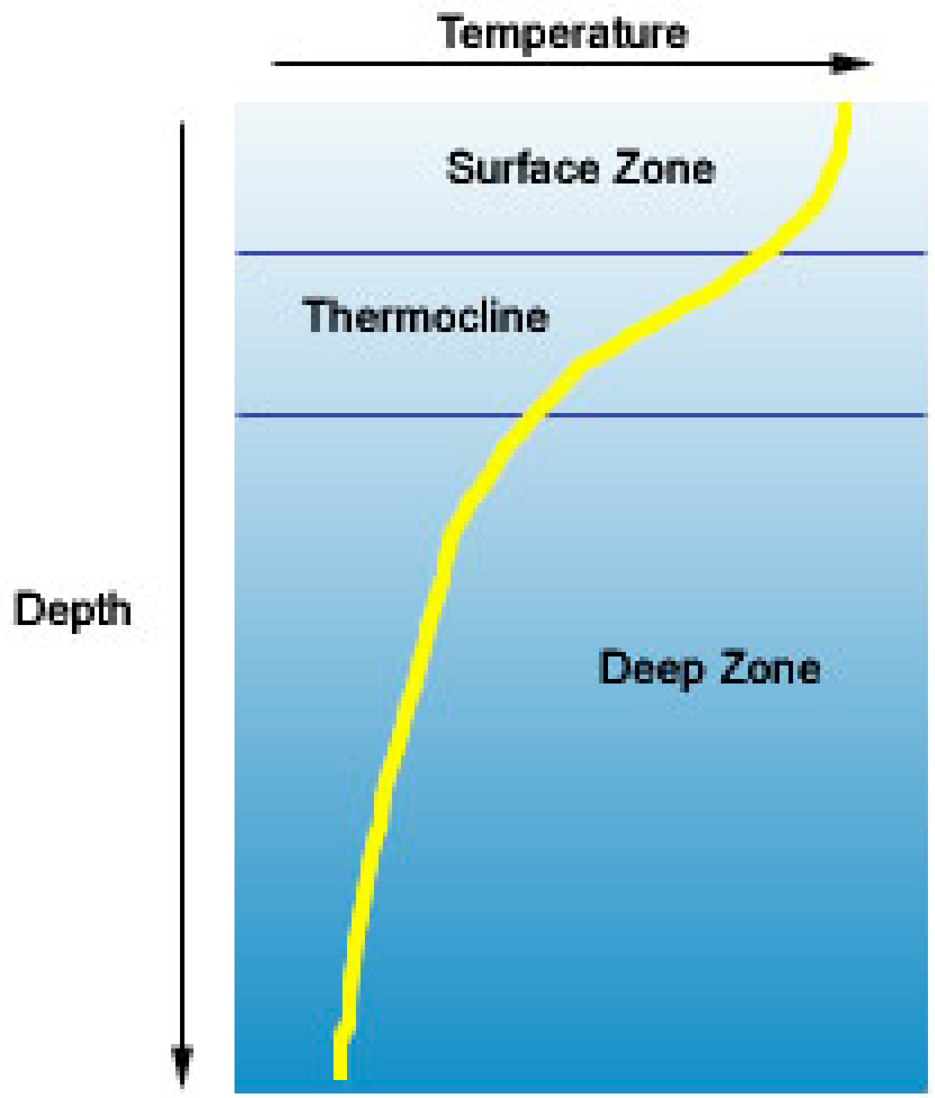
Sea water: equation of state

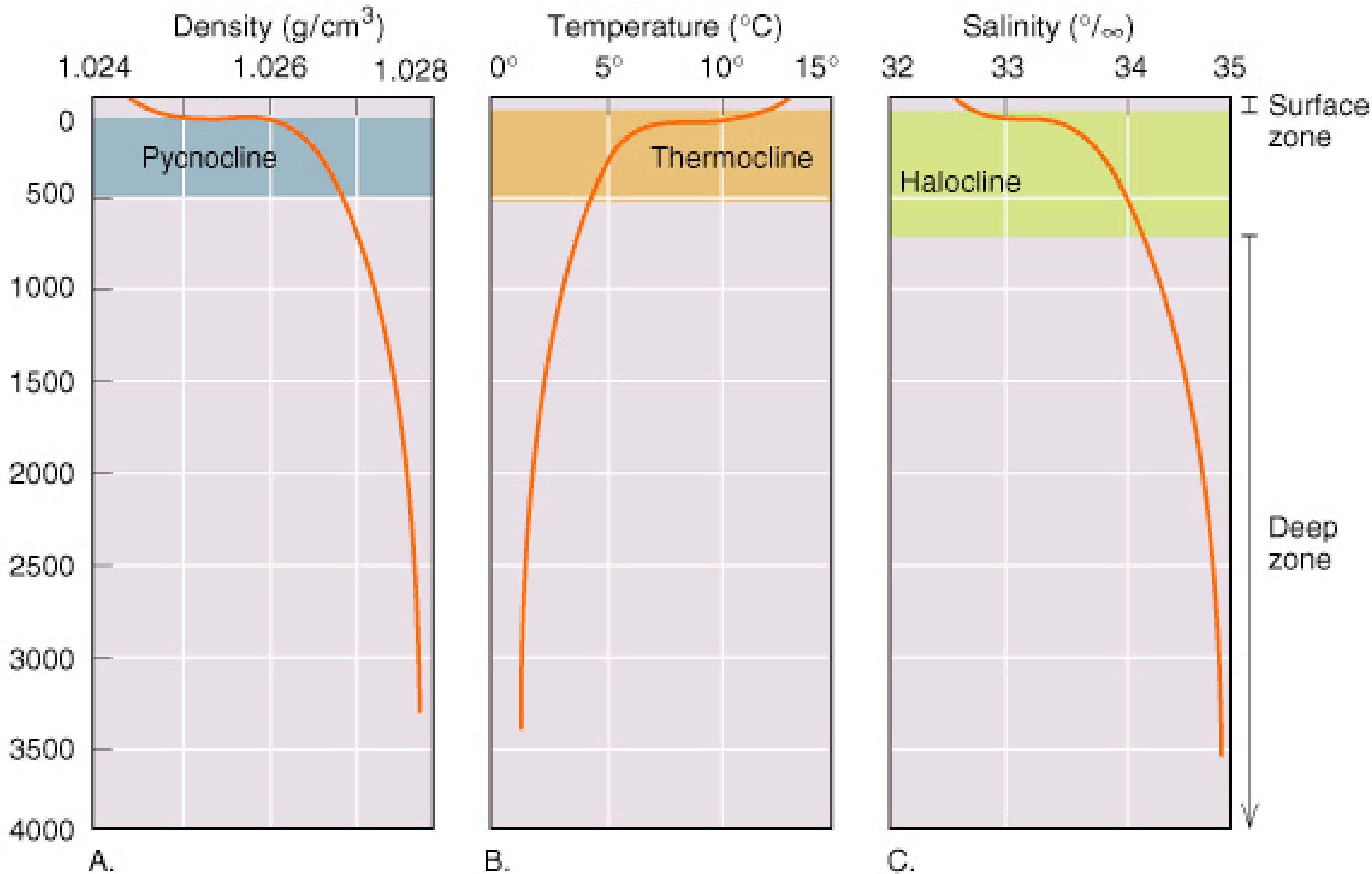
$\sigma_t = (\rho - 1) \times 10^3$

at sea-level

salinity in g/kg □ 1000

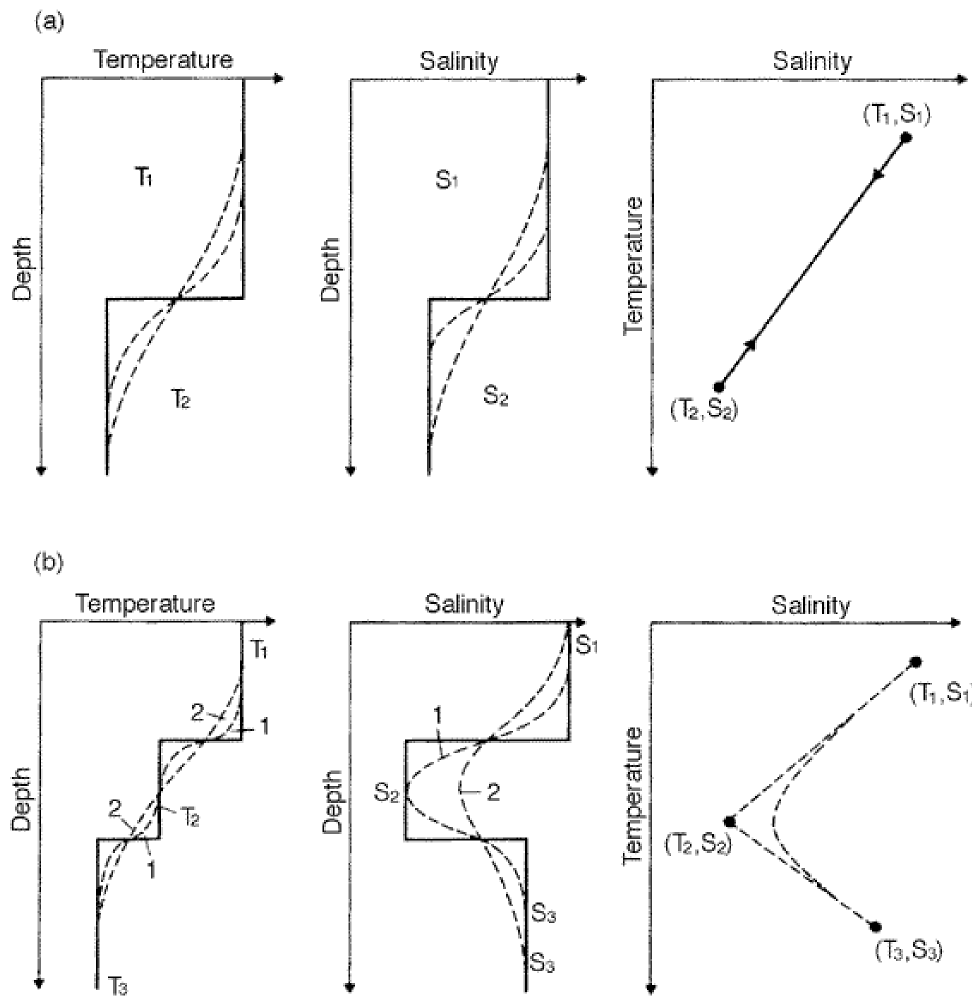



Temperature
Surface Zone
Thermocline
Depth
Deep Zone

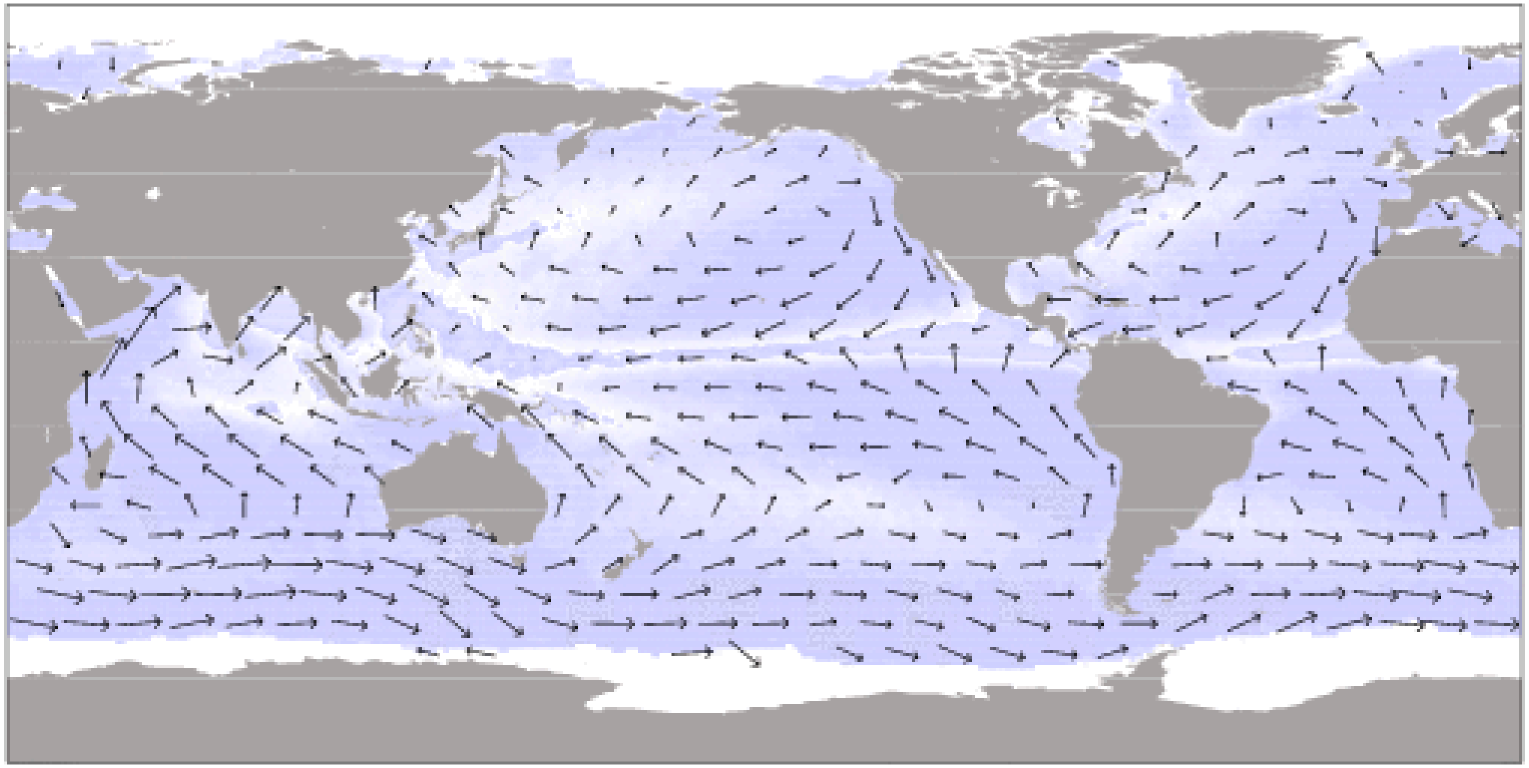


Density (g/cm3)
1.024
1.026
1.028
Temperature (°C)
0°
5°
10°
15°
Salinity (°/∞)
32
33
34
35
0
500
1000
1500
2000
2500
3000
3500
4000
Pycnocline
Thermocline
Halocline
Surface zone
Deep zone
A.
B.
C.

Water masses

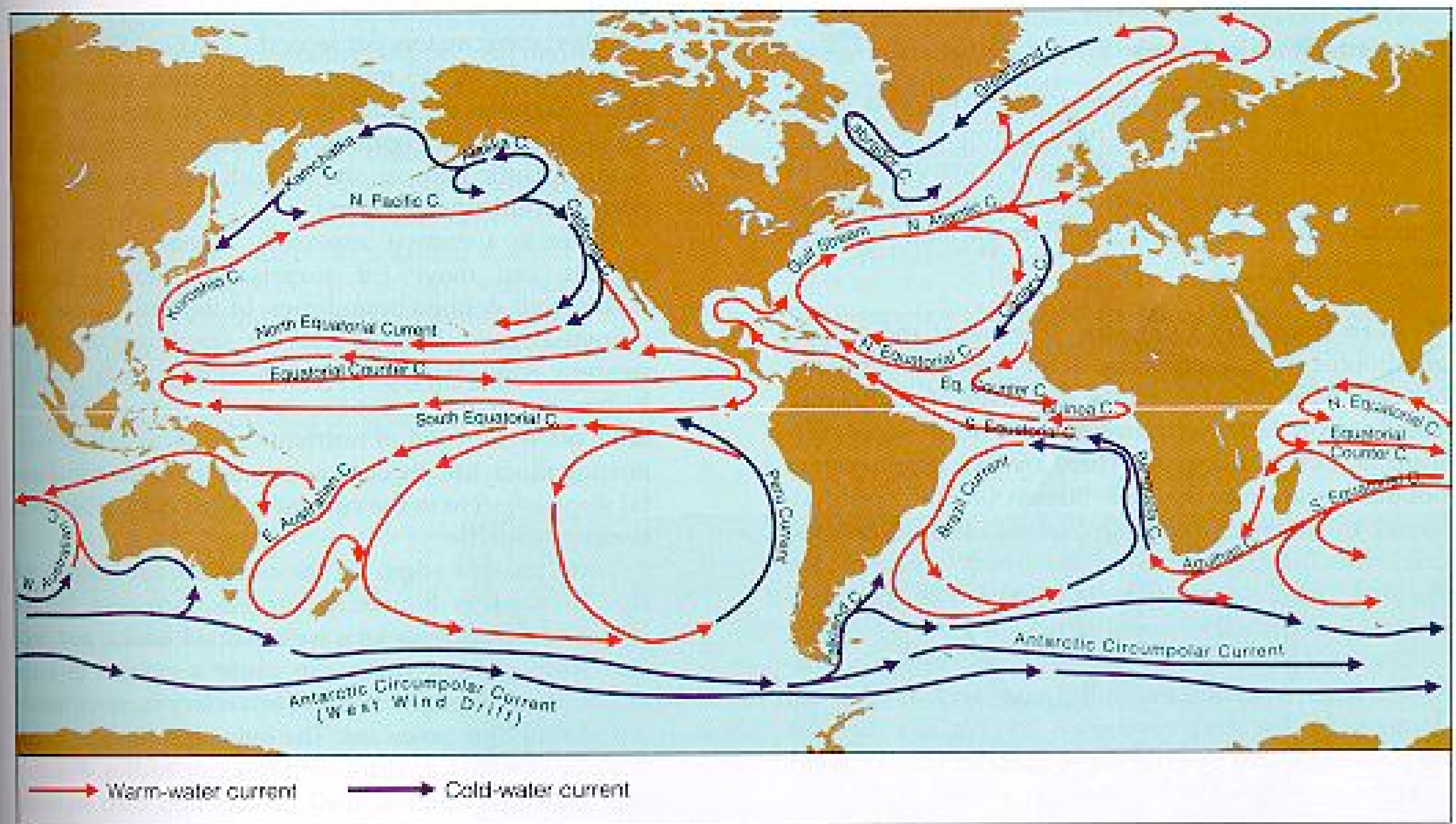


Wind driven ocean circulation



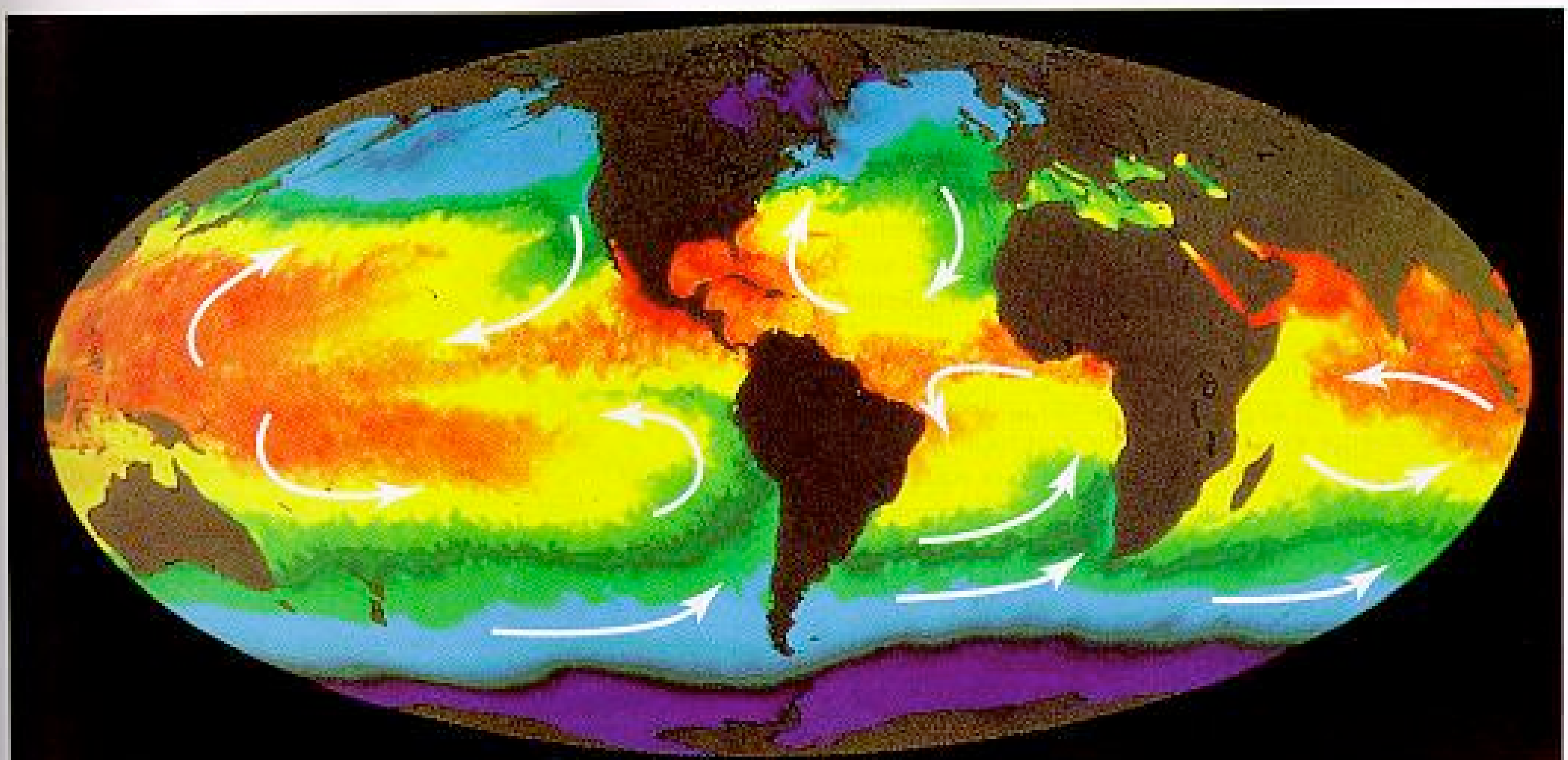
precipitation weighted by 1+abs(sin(latitude))

20 m/s

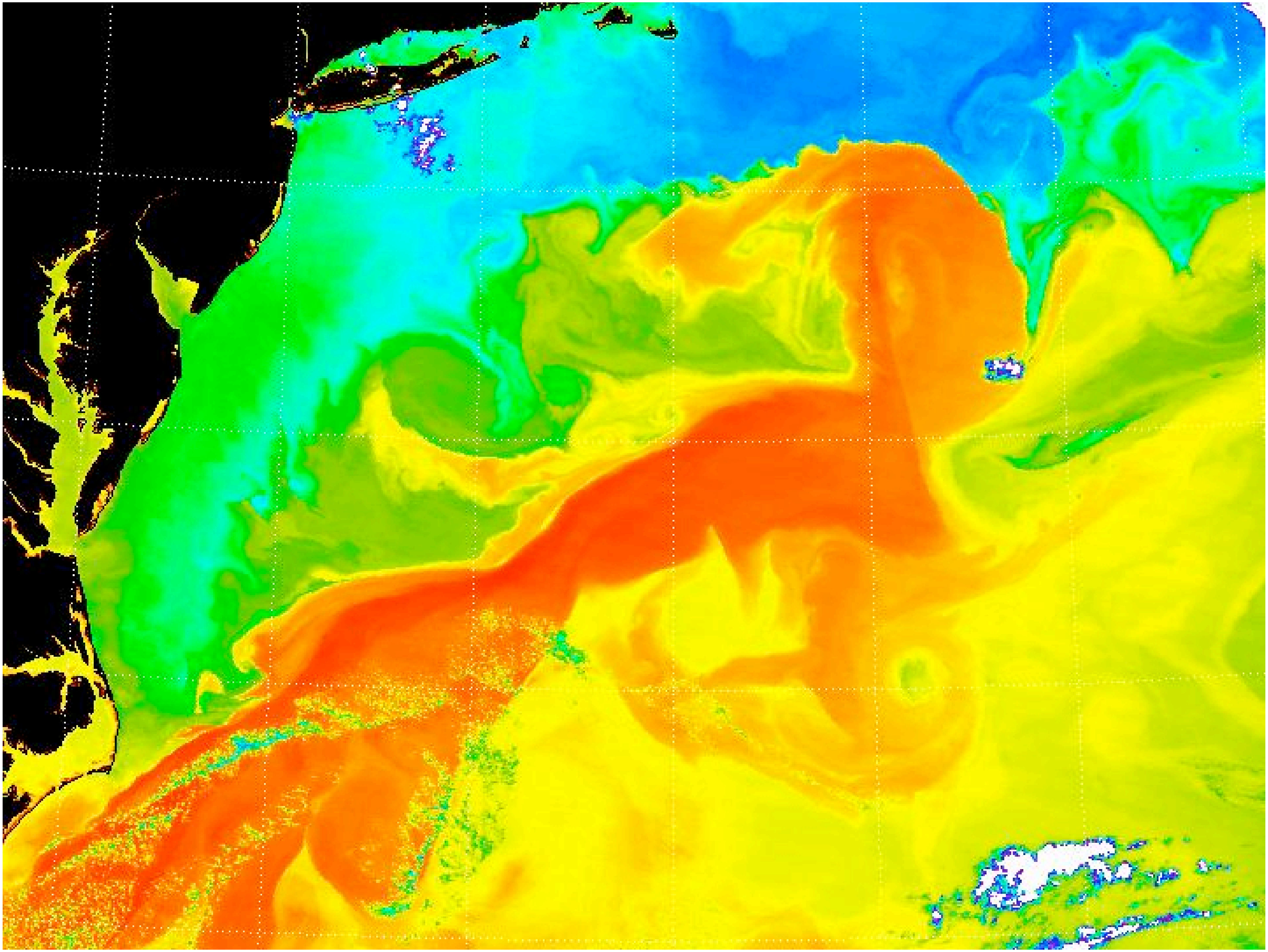


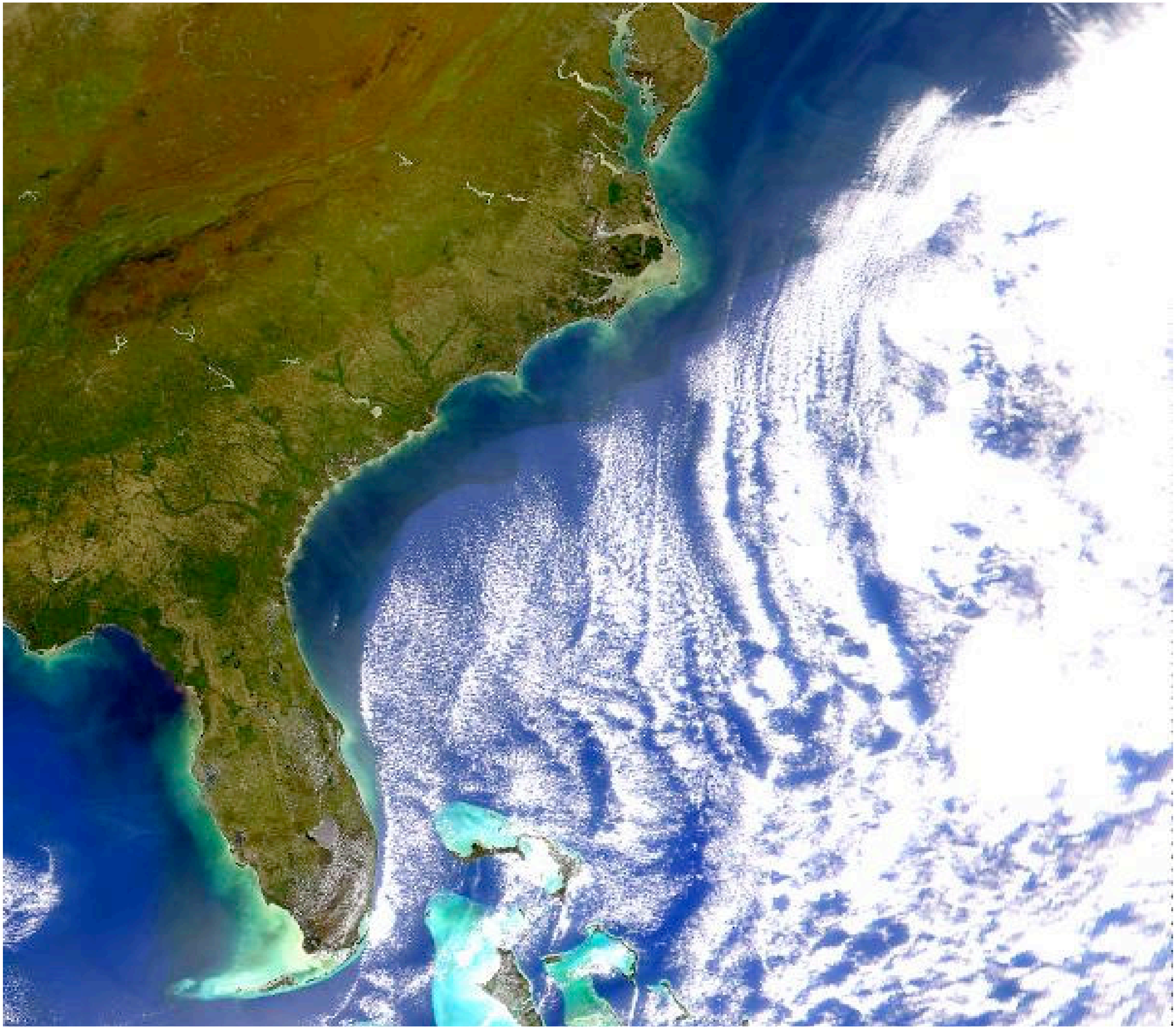
Greenland C.
Labrador C.
Kamchatka C.
Alaska C.
N. Pacific C.
California C.
Kuroshio C.
North Equatorial Current
Equatorial Counter C.
South Equatorial C.
E. Australian C.
W. Australian C.
Peru Current
Gulf Stream
N. Atlantic C.
Canaries C.
N. Equatorial C.
Eq. Counter C.
Guinea C.
S. Equatorial C.
Brazil Current
Benguela C.
Falkland C.
Agulhas C.
N. Equatorial C.
Equatorial Counter C.
S. Equatorial C.
Antarctic Circumpolar Current
Antarctic Circumpolar Current (West Wind Drift)
Warm-water current
Cold-water current

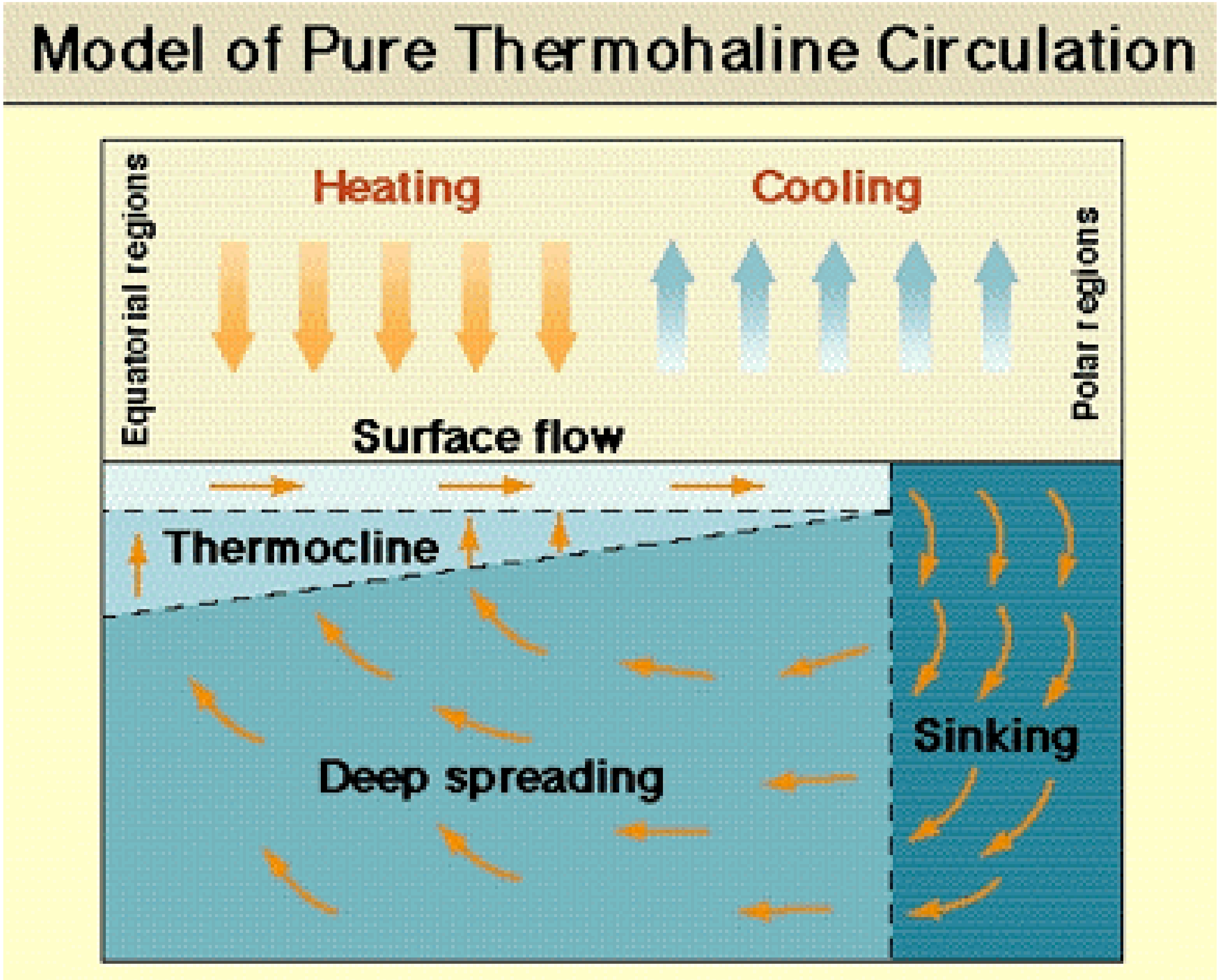
b



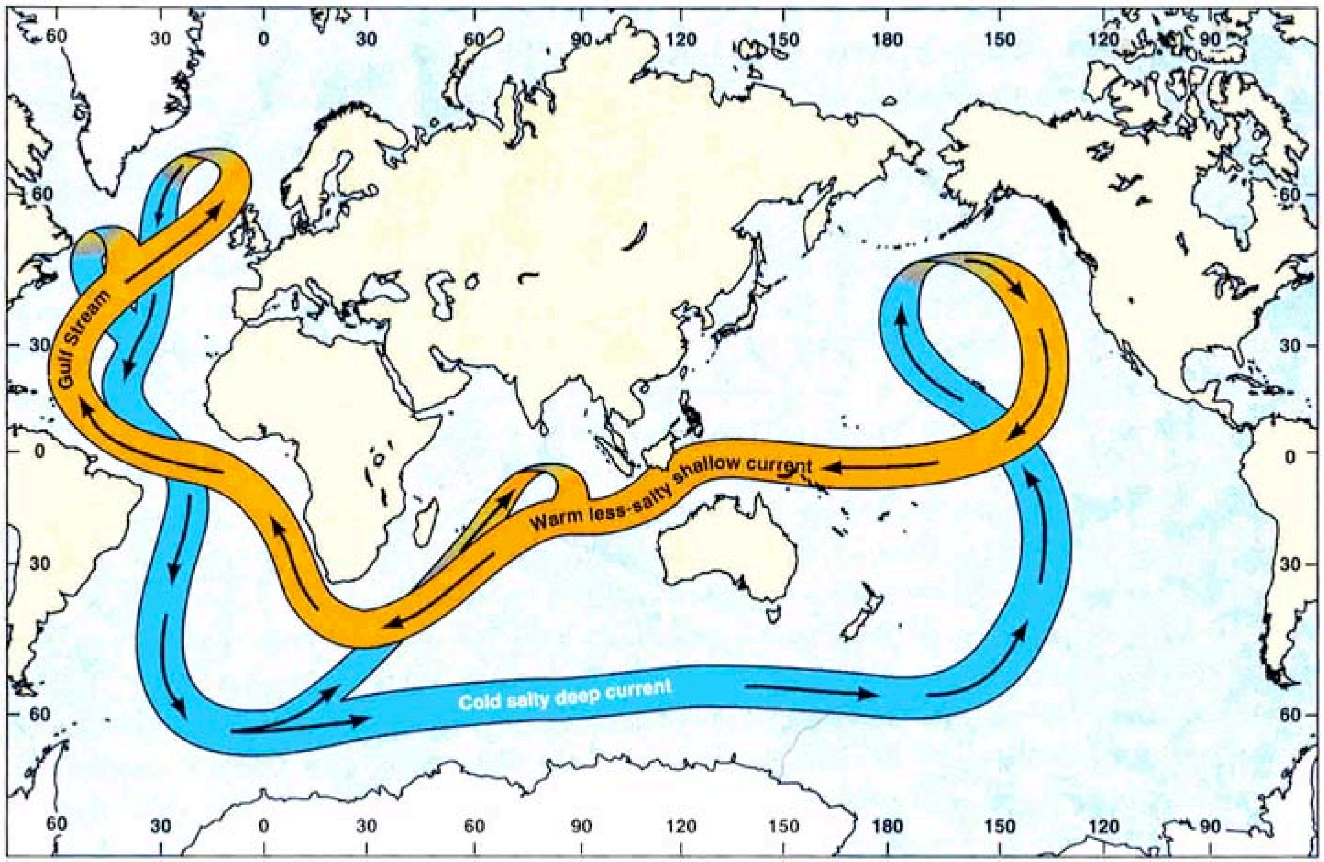
a



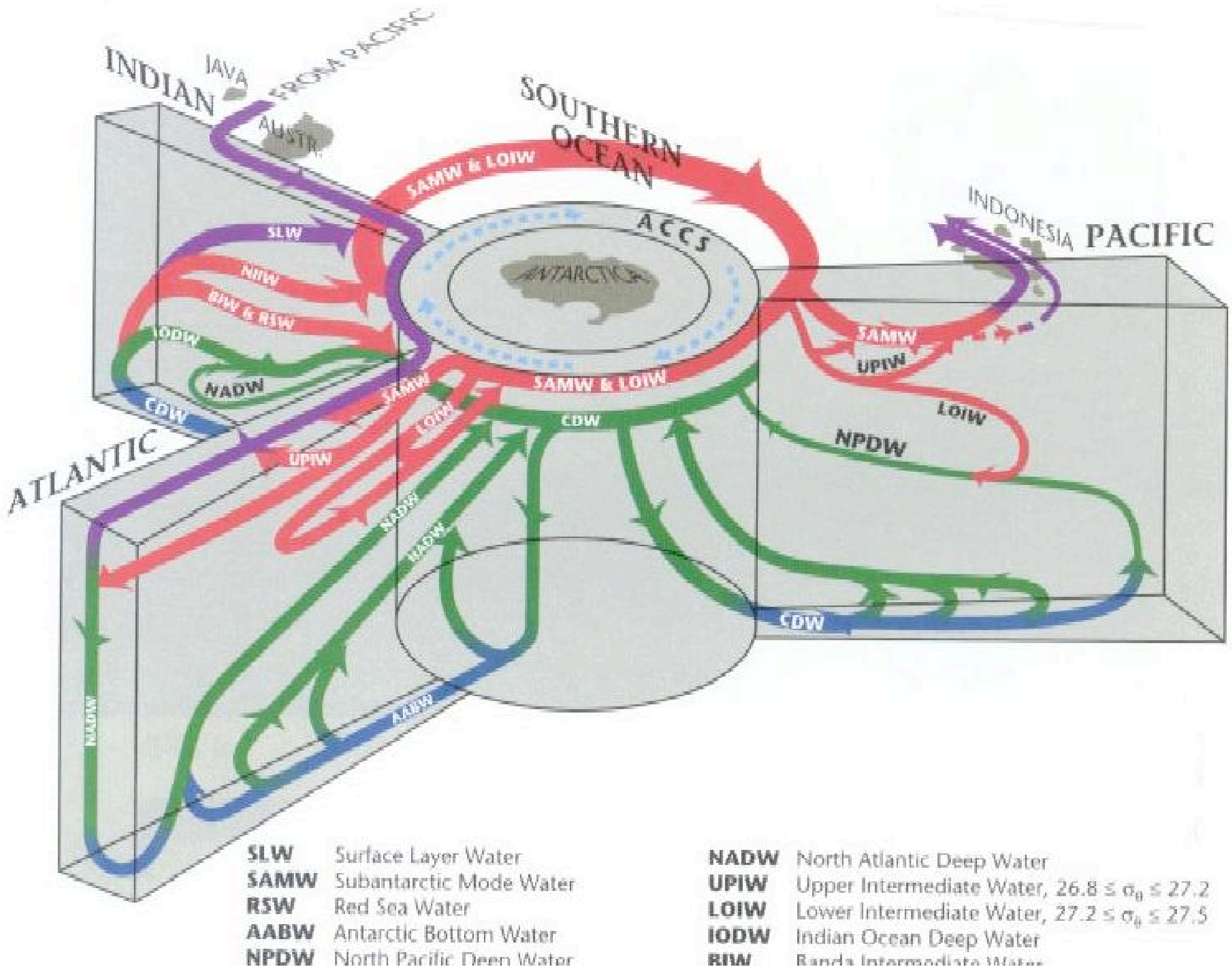


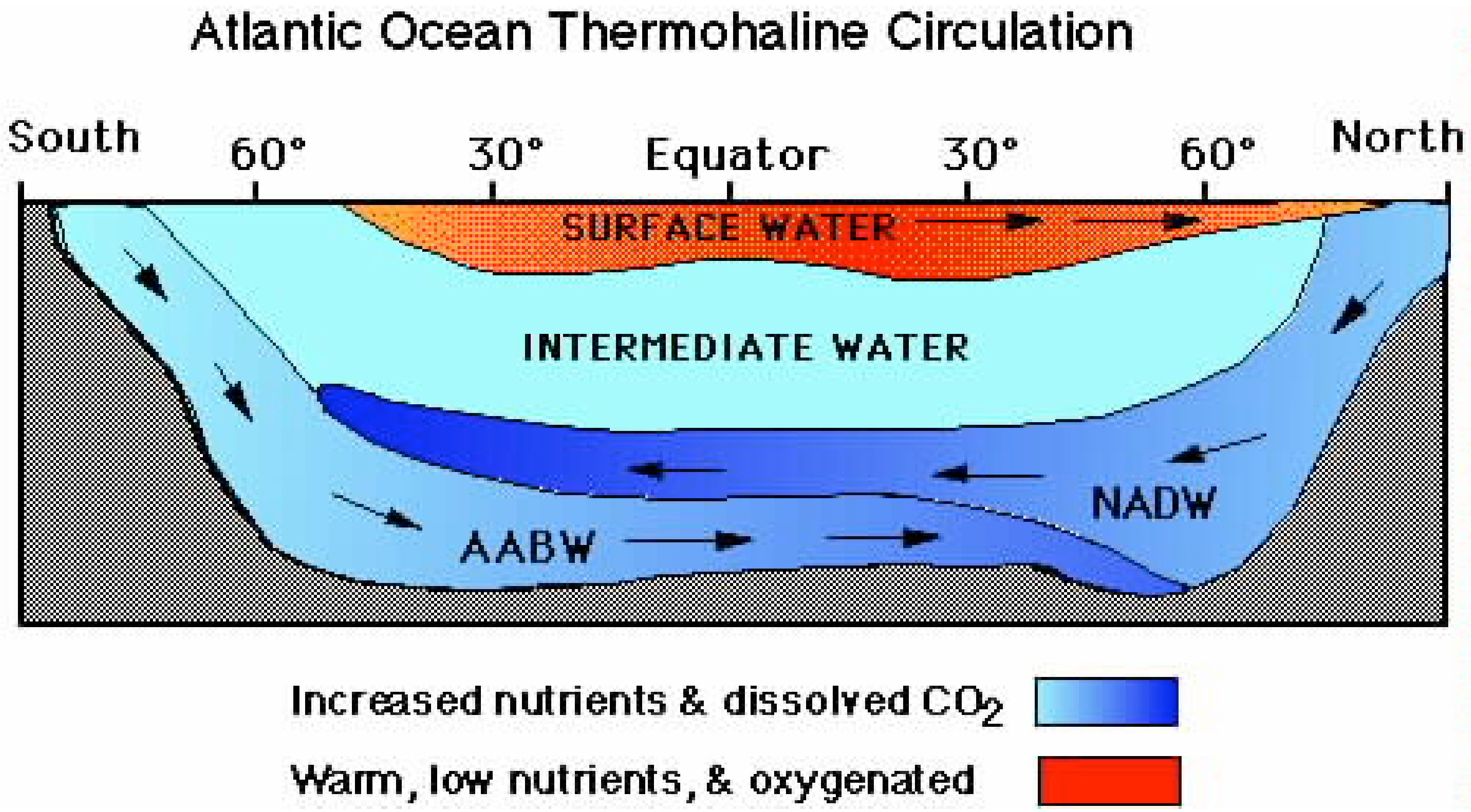

Model of Pure Thermohaline Circulation
Heating
Cooling
Equatorial regions
Polar regions
Surface flow
Thermocline
Sinking
Deep spreading

Broecker's "Conveyor Belt"



“The Mixmaster”





Atlantic Ocean Thermohaline Circulation
South
60°
30°
Equator
30°
60°
North
SURFACE WATER
INTERMEDIATE WATER
NADW
AABW
Increased nutrients & dissolved CO_2
Warm, low nutrients, & oxygenated

Euphotic zone

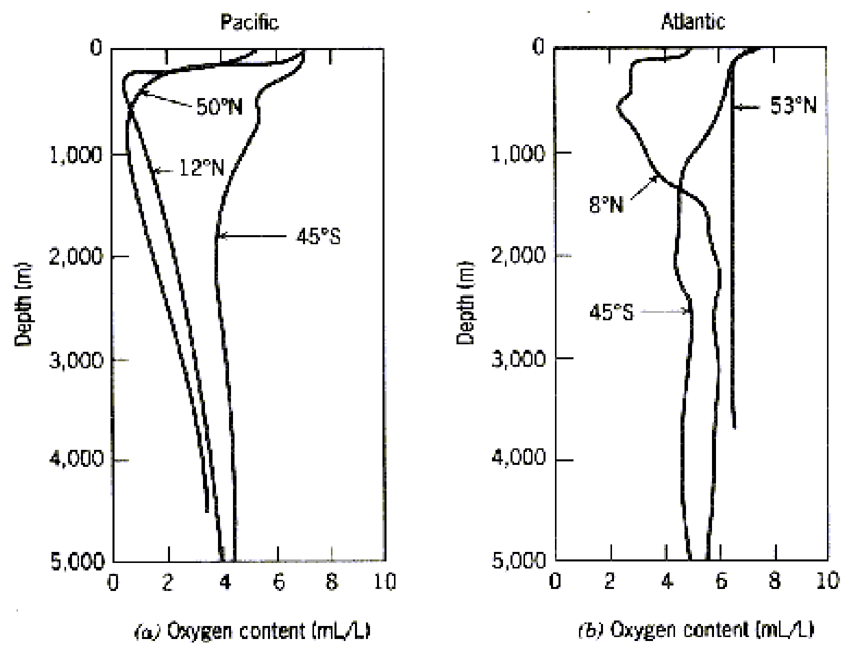


FIGURE 10.2. Depth profiles of oxygen concentrations from (*a*) the Pacific and (*b*) the Atlantic oceans. *Source:* From *Oceanography: An Introduction,* 4th ed., D. E. Ingmanson and W. J. Wallace, copyright © 1989 by Wadsworth, Inc., Belmont, CA, p. 99. Reprinted by permission.

Euphotic zone

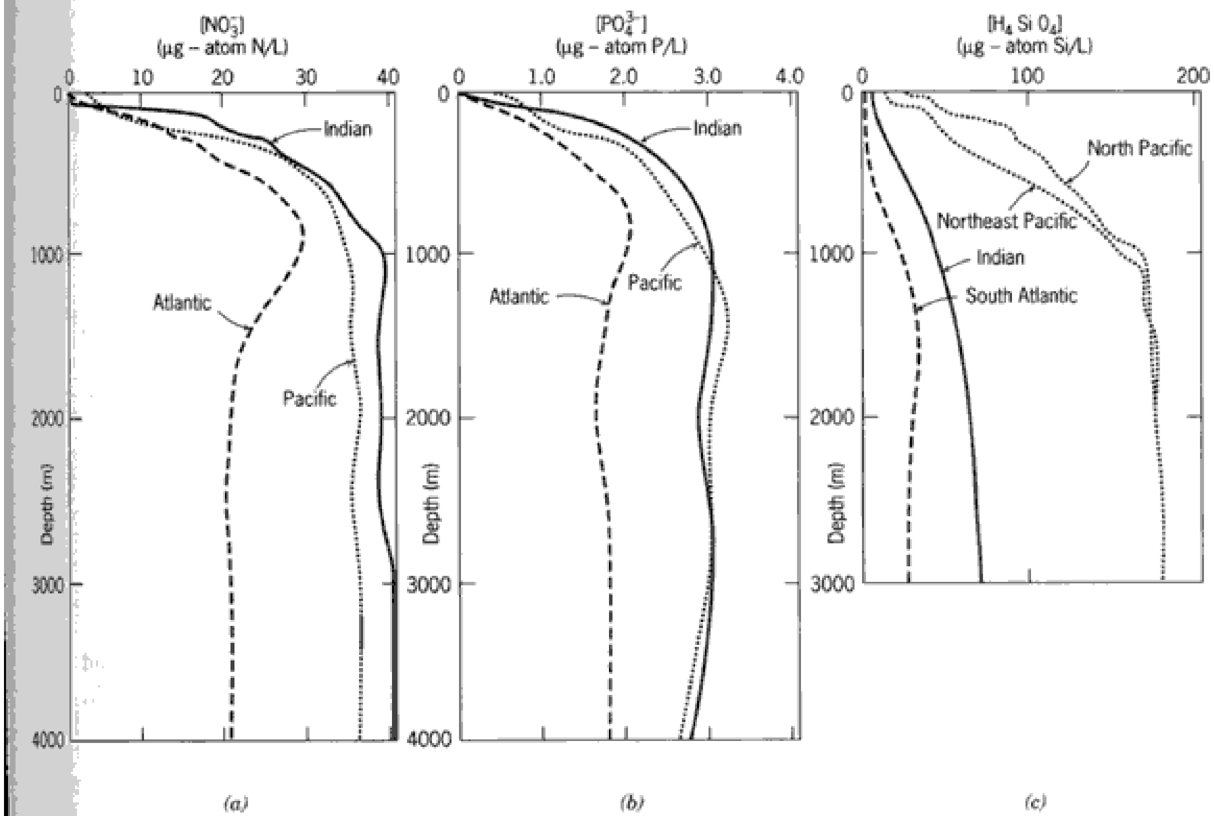
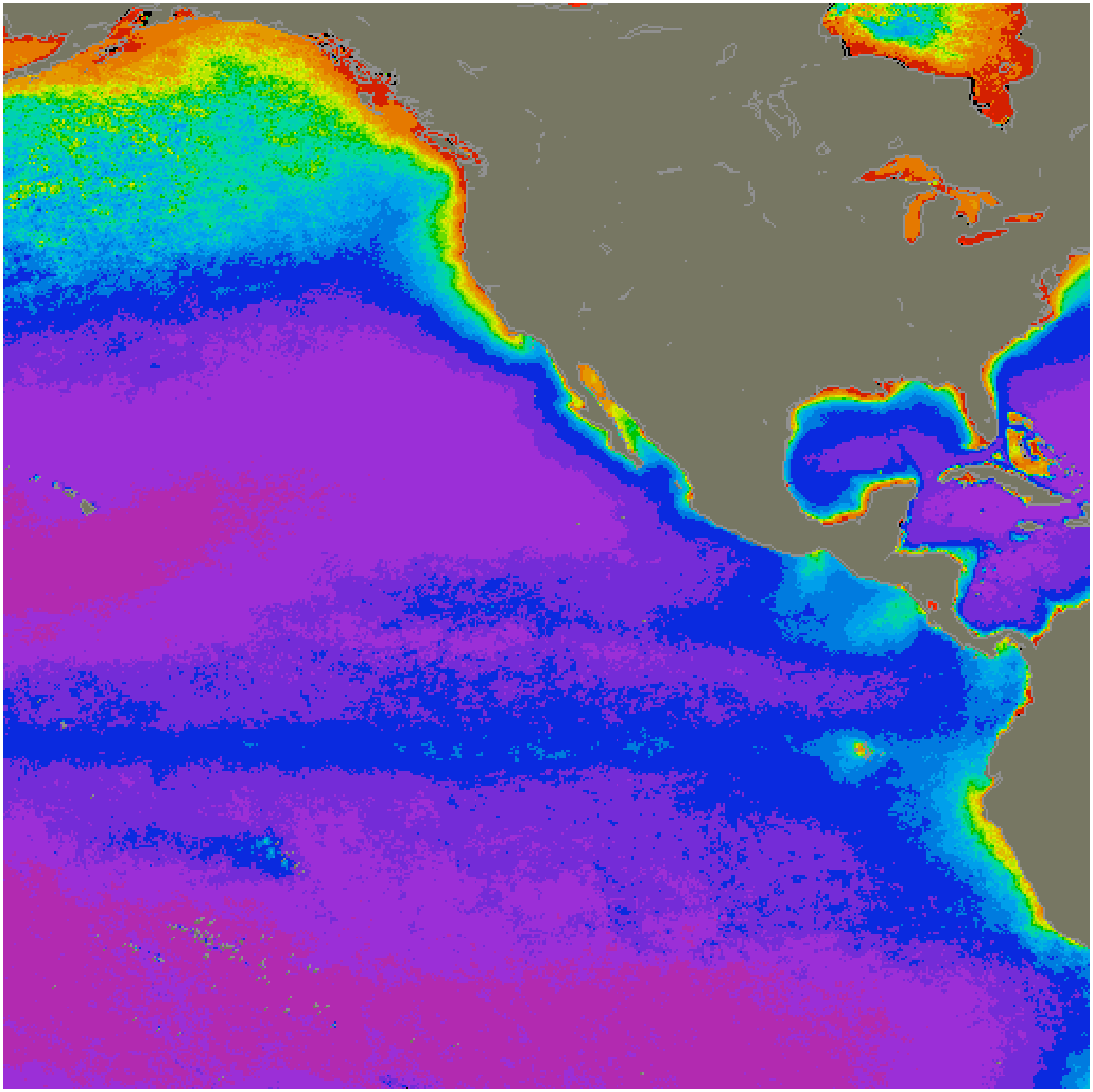
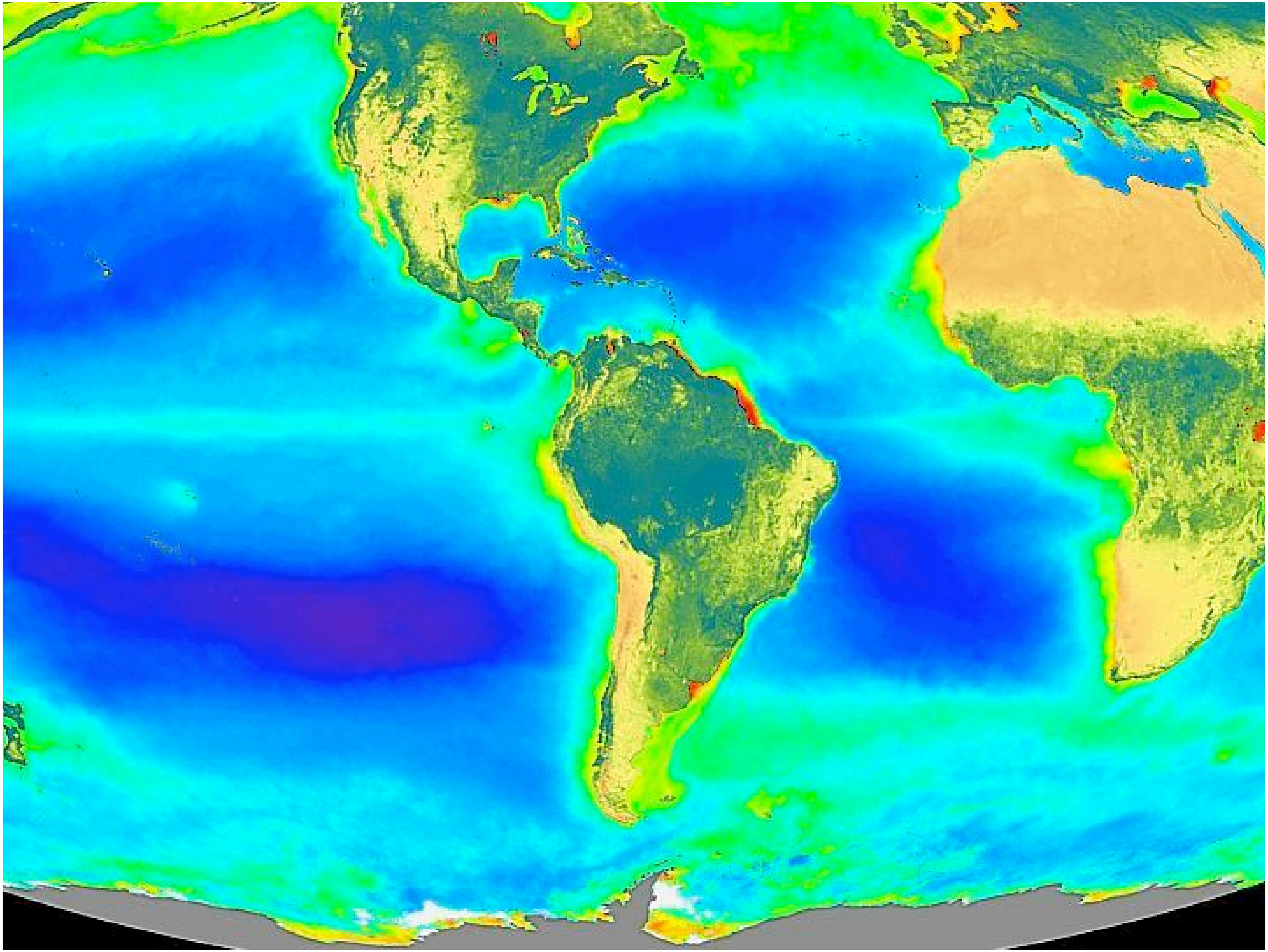


FIGURE 10.1. Vertical distribution of (*a*) nitrate, (*b*) phosphate, and (*c*) dissolved silicon in the Atlantic, Pacific, and Indian oceans. Note that 1 μg-atom/L is equivalent to 1 μM. Thus 1 μg-atom NO_3-N/L is equivalent to 1μmol of dissolved nitrogen (in the form of NO_3^-) per liter of seawater. *Source:* From *The Oceans*, H. U. Sverdrup, M. W. Johnson, and R. H. Fleming, copyright © 1941 by Prentice Hall, Inc., Englewood Cliffs, New Jersey, p. 242. Reprinted by permission. See Sverdrup et al. (1942) for data sources.

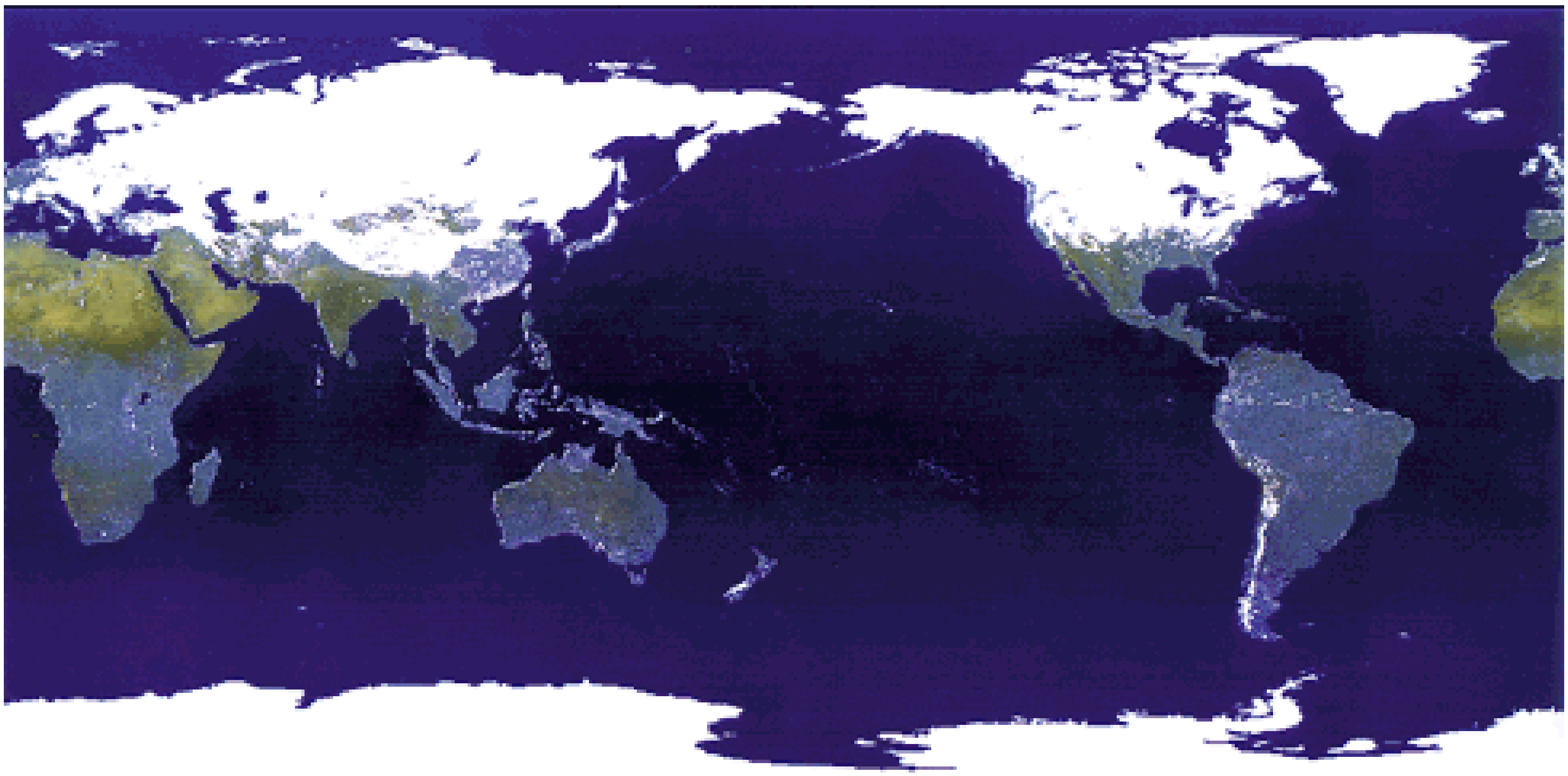




Role of oceans in climate

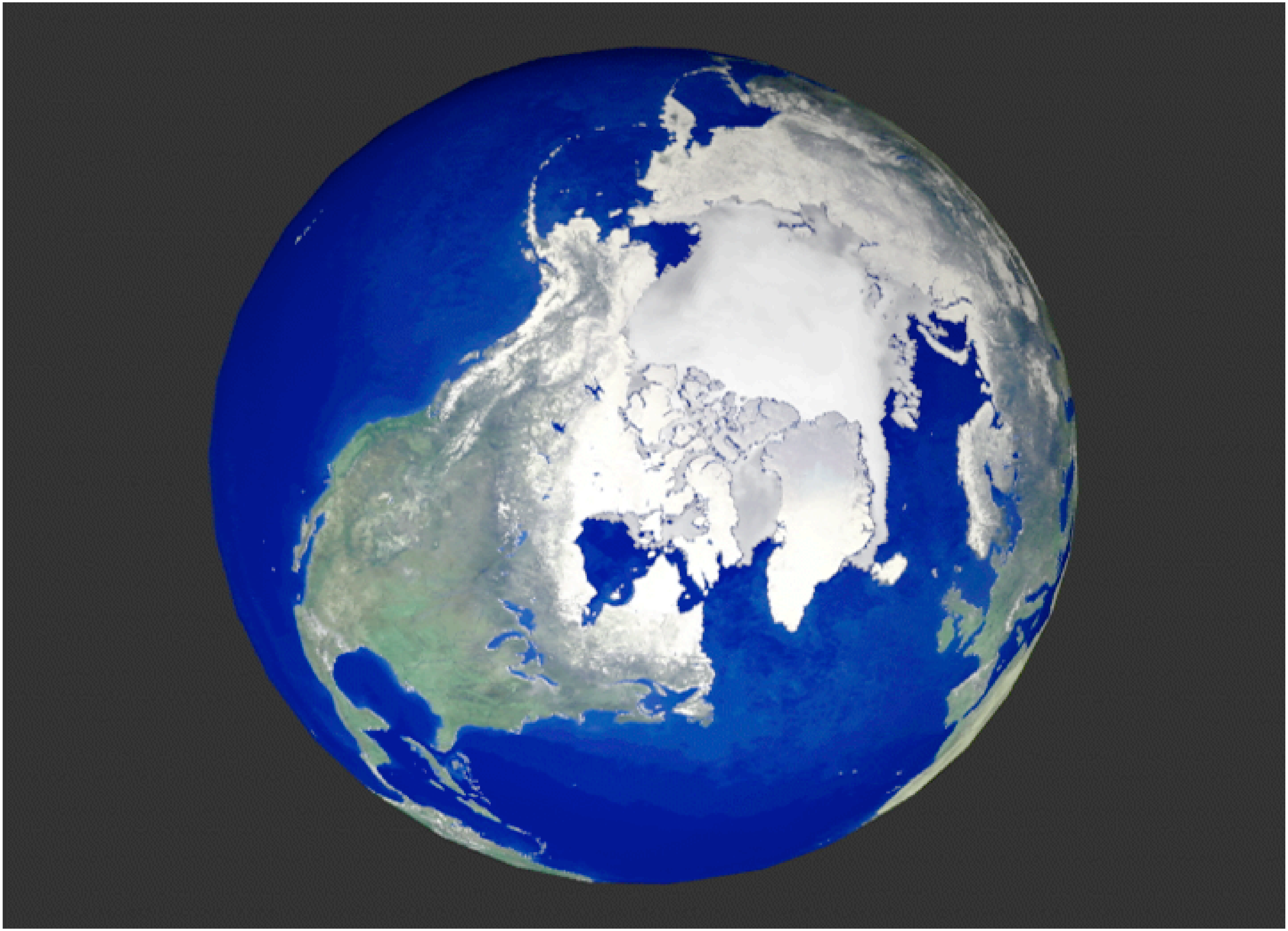
- thermal inertia… seasonal thermocline
- heat transport
- El Niño
- uptake of carbon
- source of trace gases

The Cryosphere



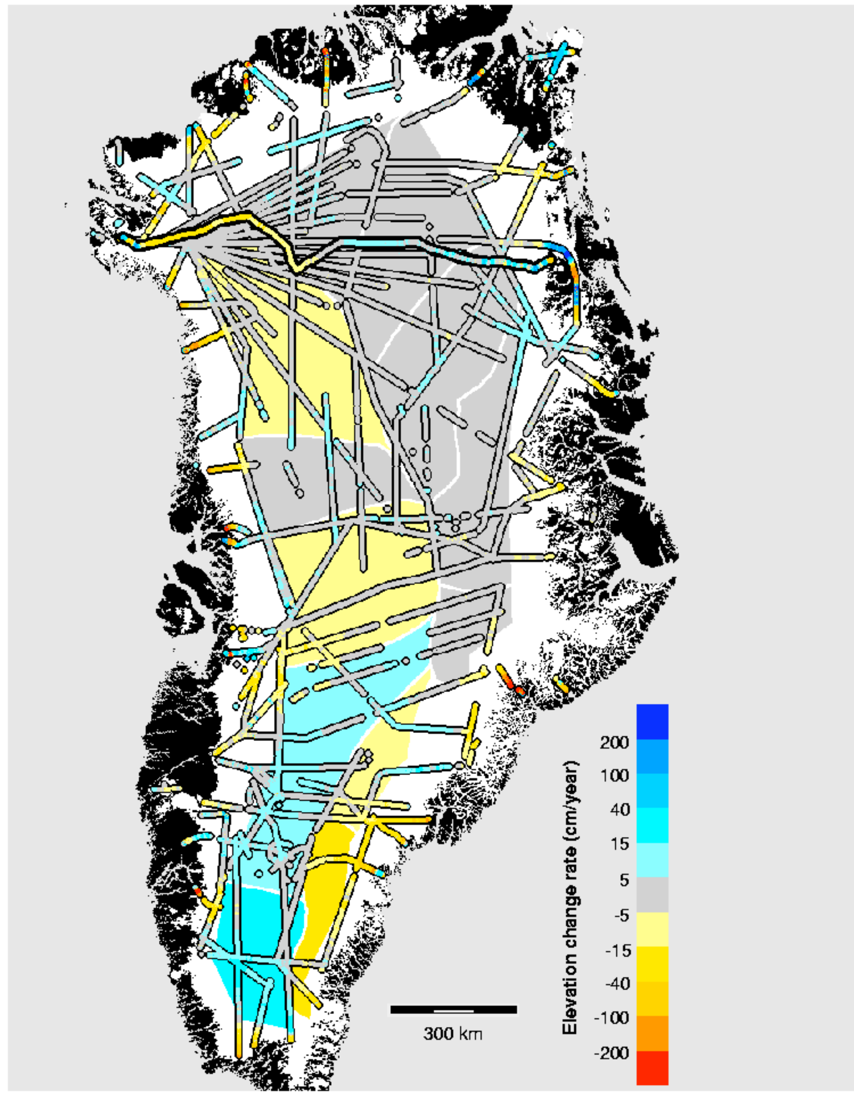
Components of the cryosphere

Cryospheric component	*Area*	*Mass*
Antarctic ice sheet	2.7	53
Greenland ice sheet	0.35	5
Alpine glaciers	0.01	0.2
Sea-ice (in season of max. extent)	7	0.01
Seasonal snow cover	9	<0.01
Permafrost	5	1

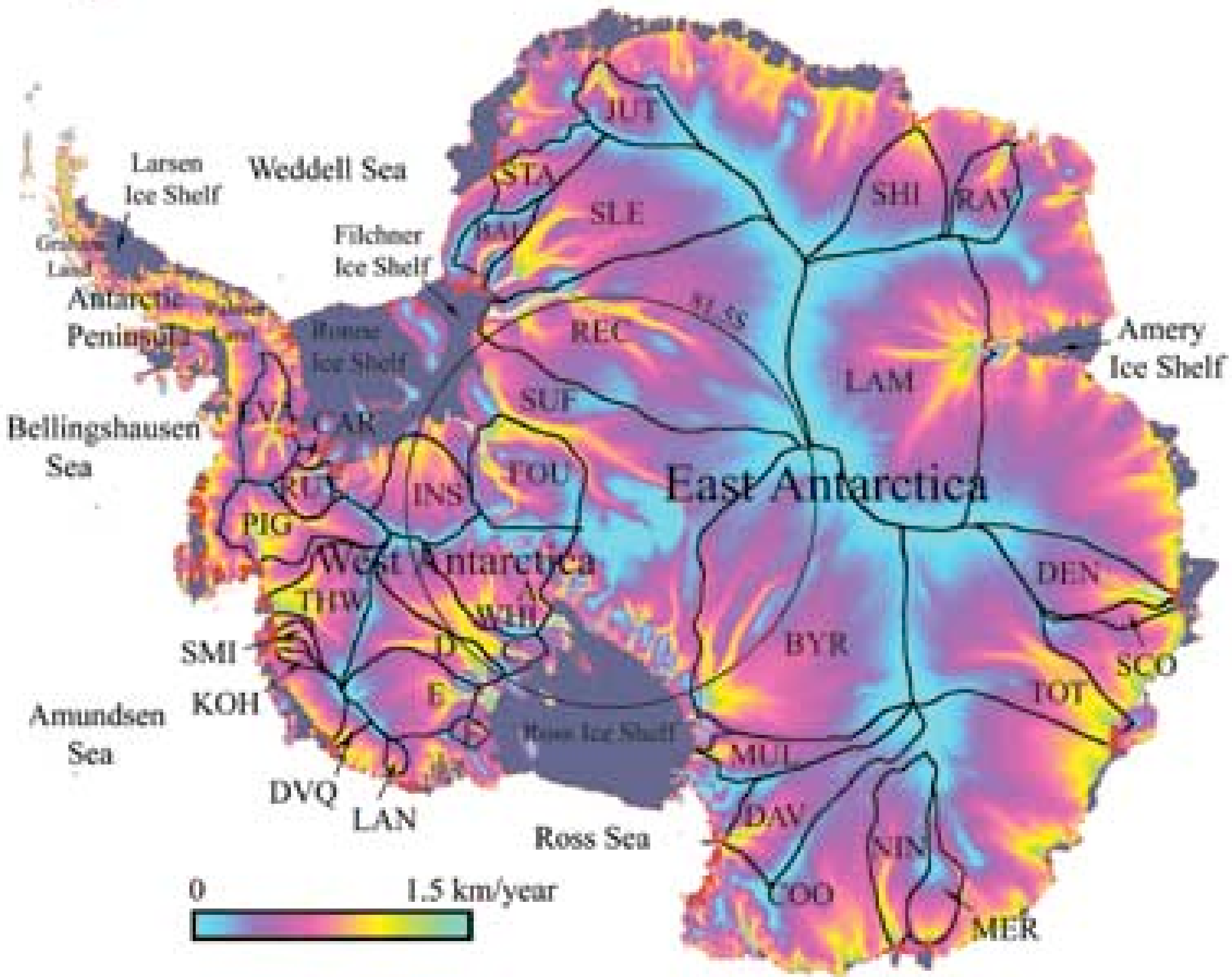


Continental ice sheets

Mass balance



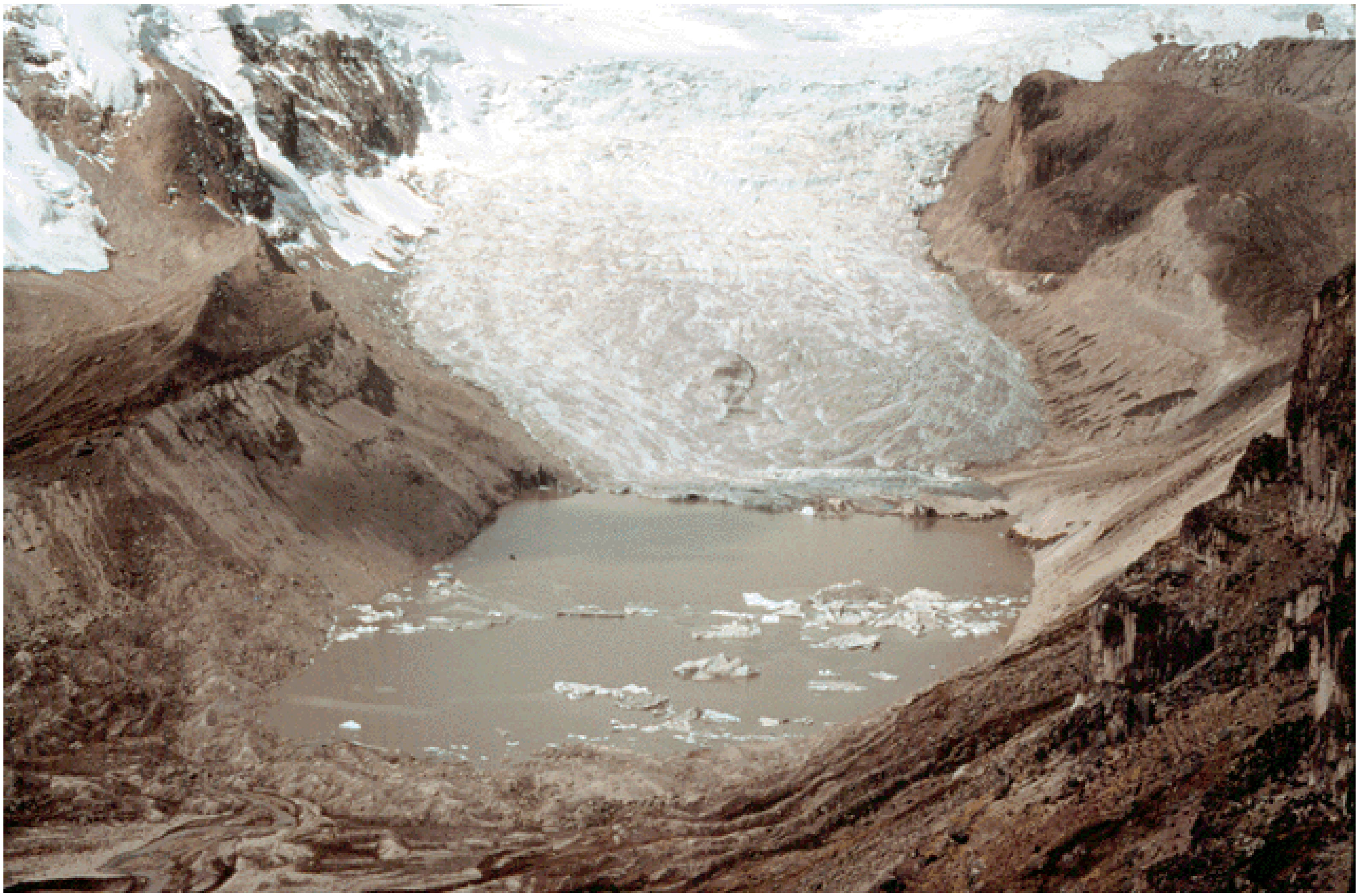
Ice motion


Larsen
Ice Shelf
Weddell Sea
Filchner
Ice Shelf
Antarctic
Peninsula
Ronne
Ice Shelf
Bellingshausen
Sea
Amery
Ice Shelf
JUT
STA
SLE
SHI
RAY
REC
LAM
SUF
CAR
FOU
INS
PIG
East Antarctica
West Antarctica
THW
DEN
SMI
KOH
BYR
SCO
TOT
Amundsen
Sea
Ross Ice Shelf
MUL
DVQ
LAN
DAV
Ross Sea
NIN
COO
MER
0
1.5 km/year

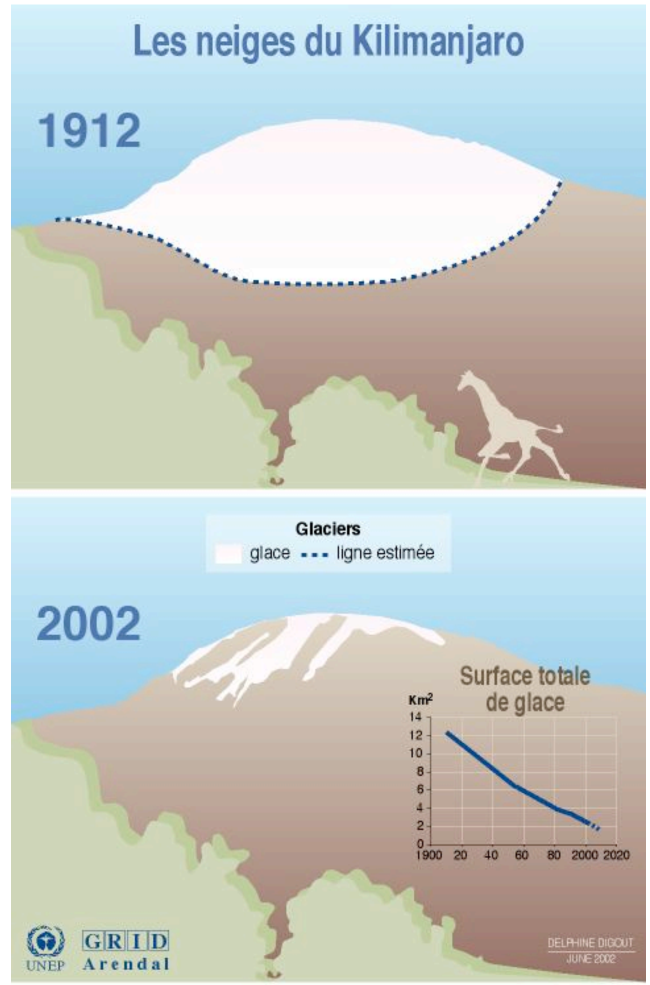
Alpine glaciers

Quelccaya Icecap, Peru 1978

Quelccaya Icecap, Peru 2000



Mt. Kilimanjaro

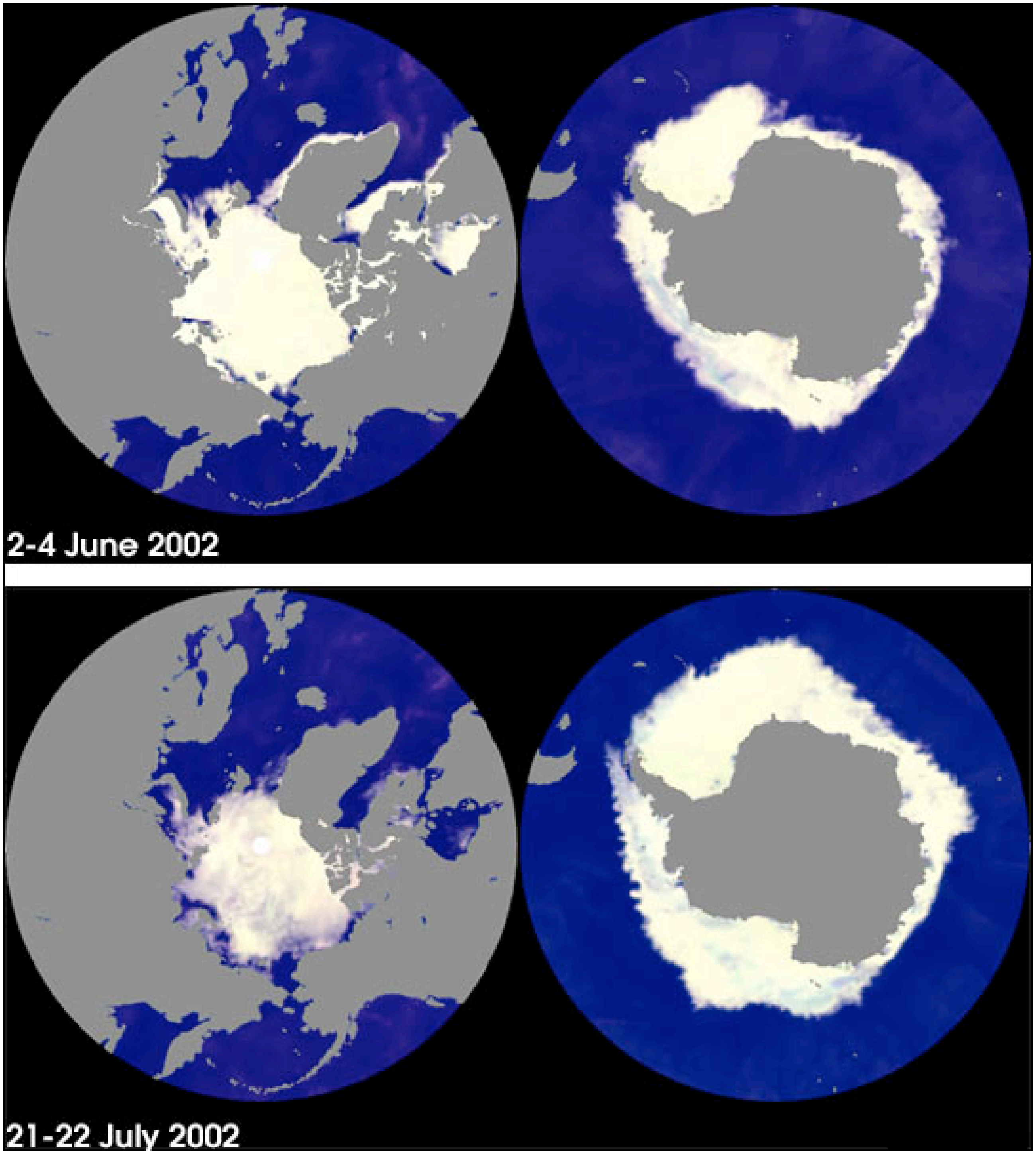


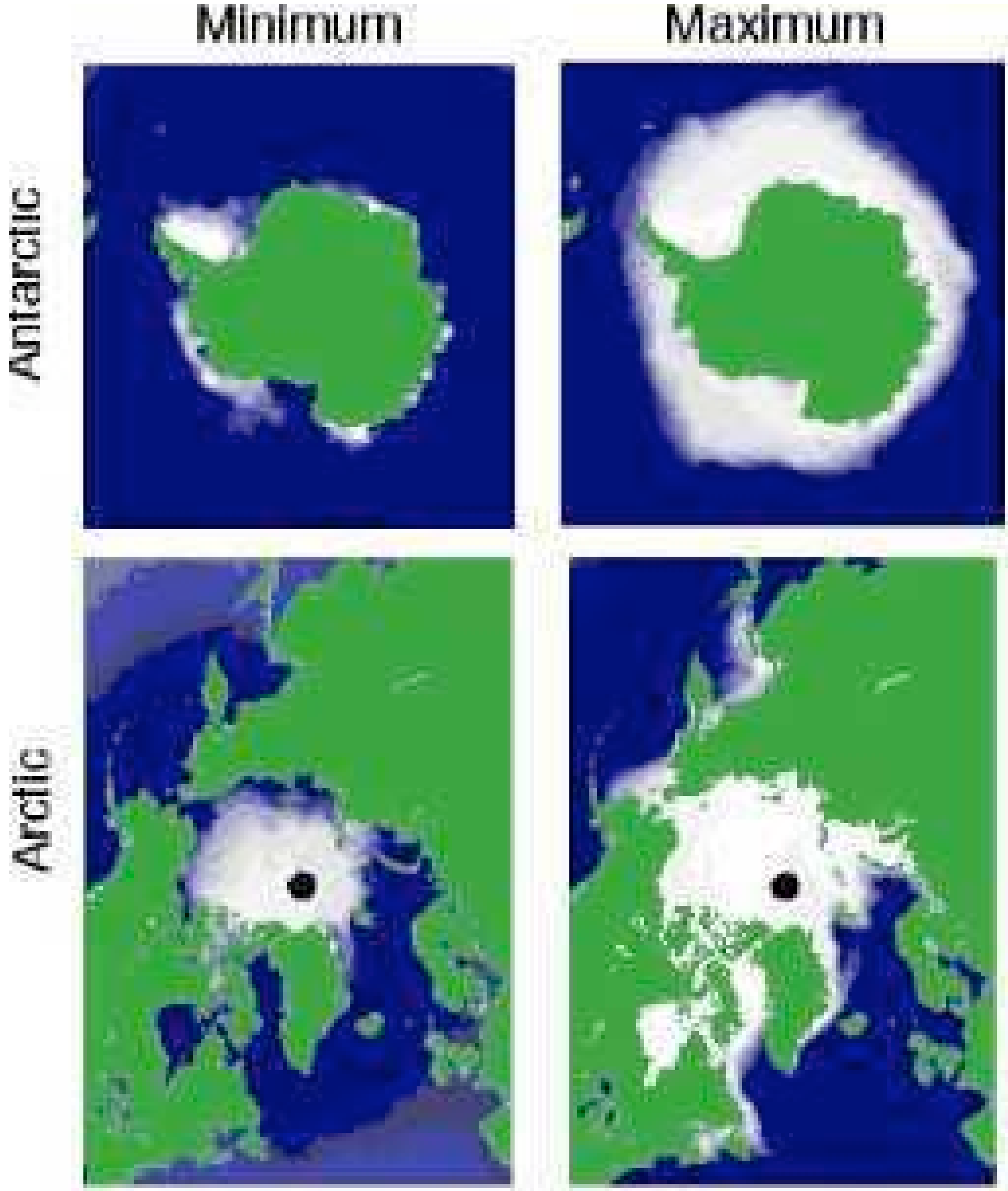
Sources : Réunion de l'Association Américaine pour l'Avancement de la Science (AAAS), Février 2001 ; Earthobservatory.nasa.gov.

Sea-ice

Sea ice

- floats
- covers large areas
- varies seasonally and on longer term
- consists of first year and multi-year ice

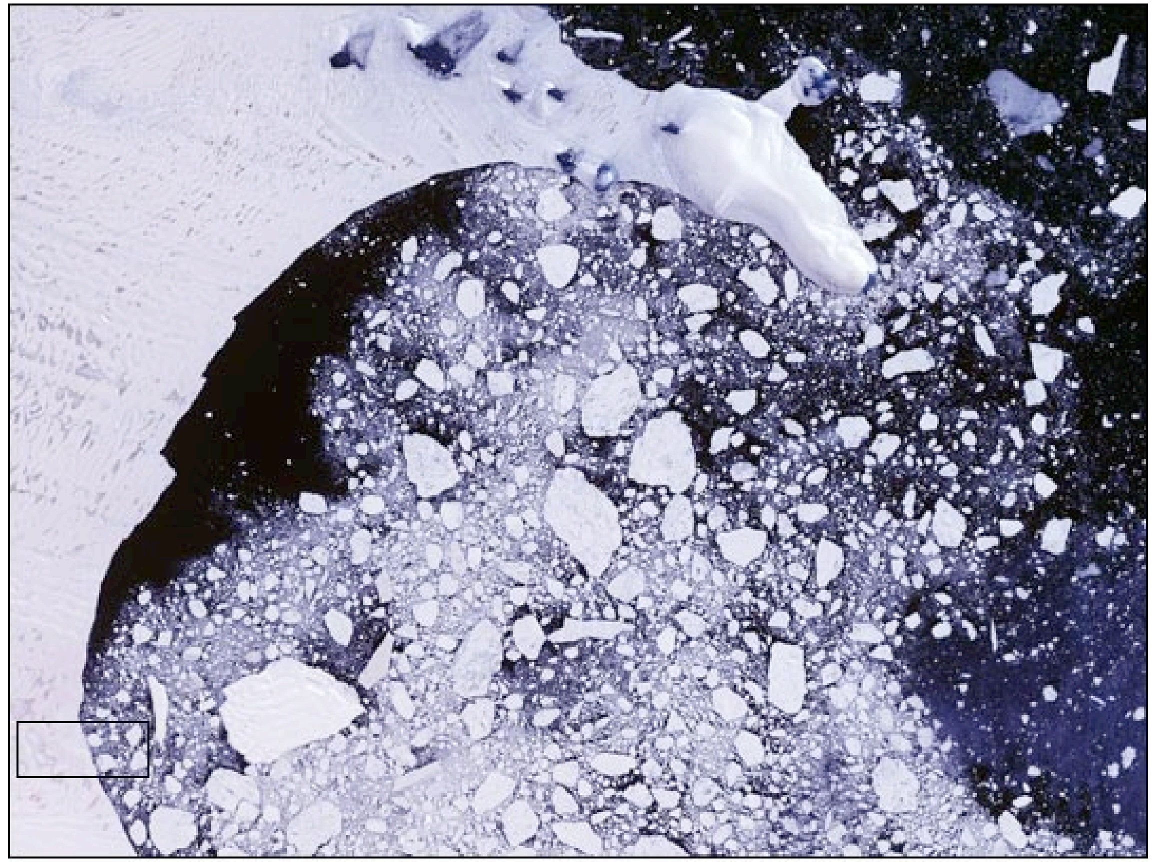

2-4 June 2002
21-22 July 2002

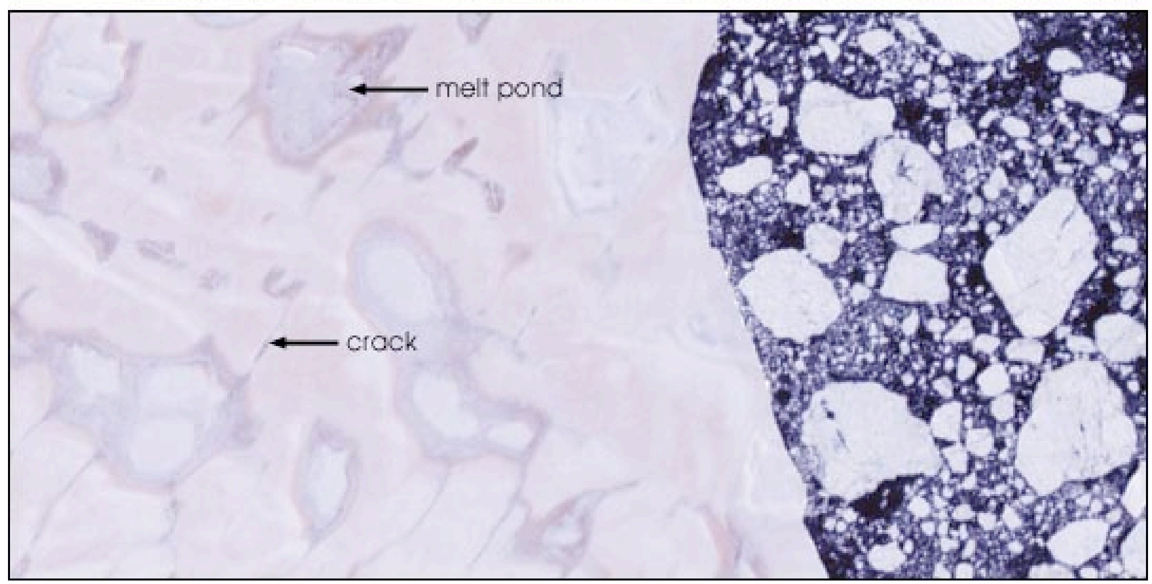


Minimum
Maximum
Antarctic
Arctic

Breakup of Larsen ice shelf

Feb. 2000



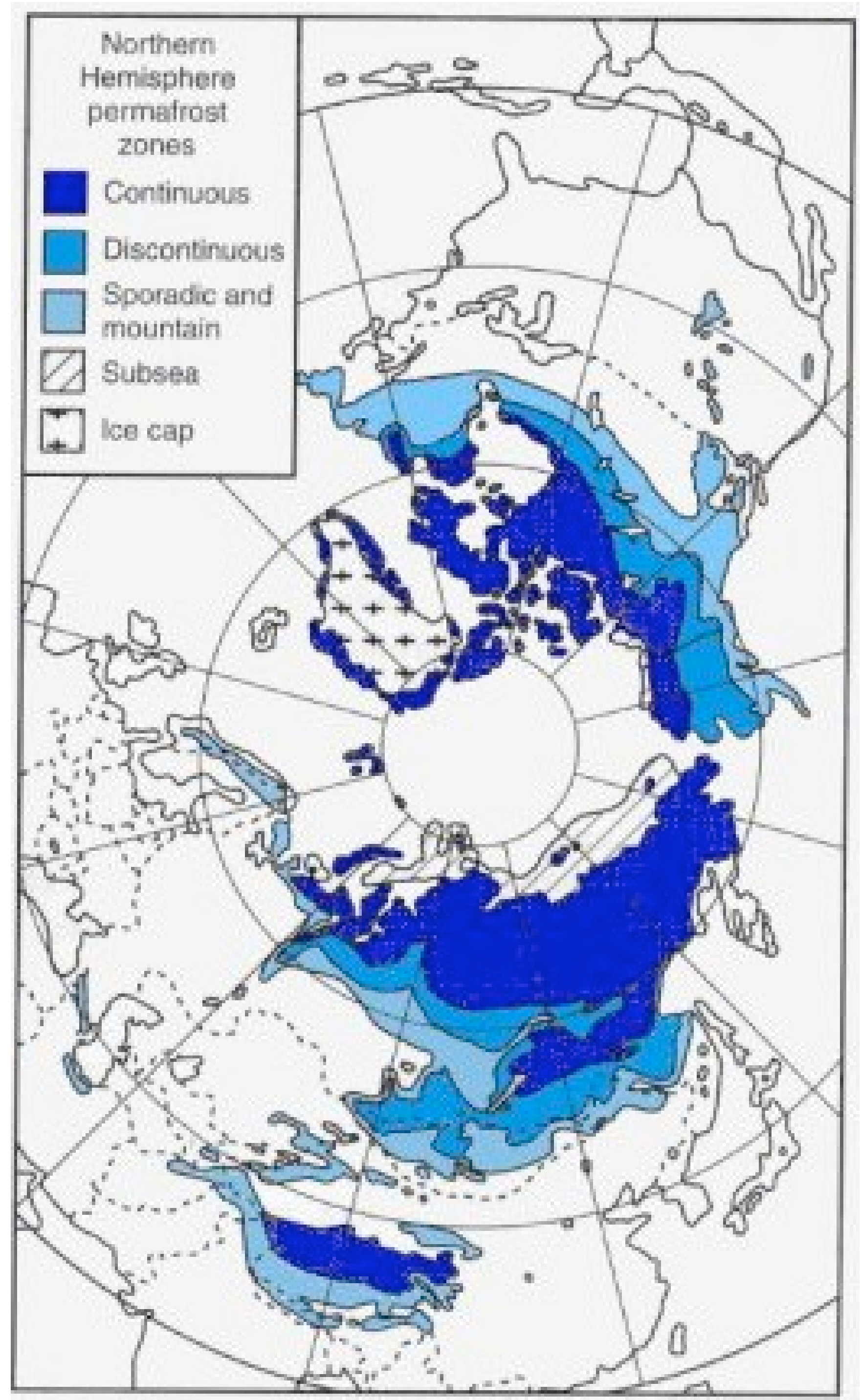


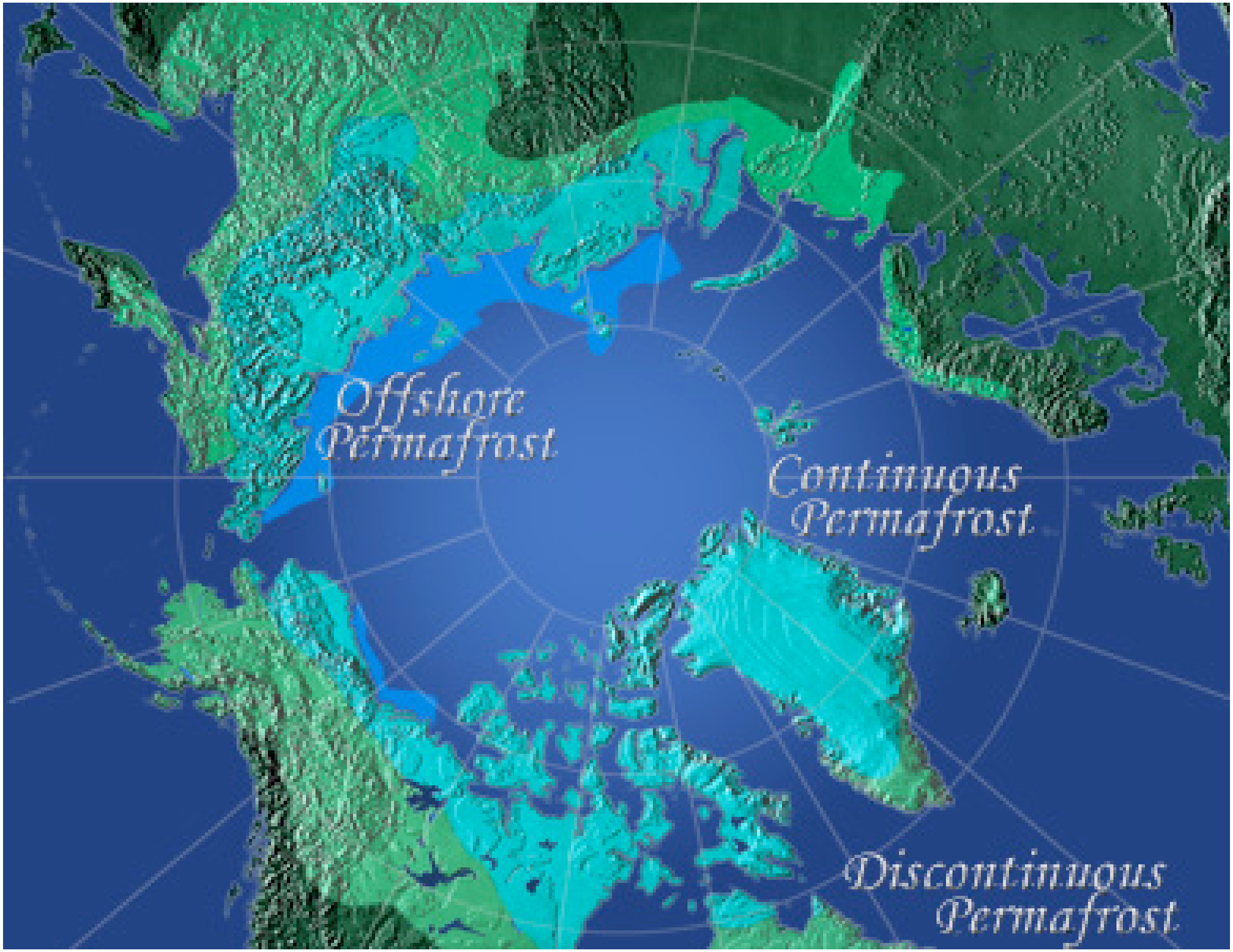
Snow cover

Snow cover

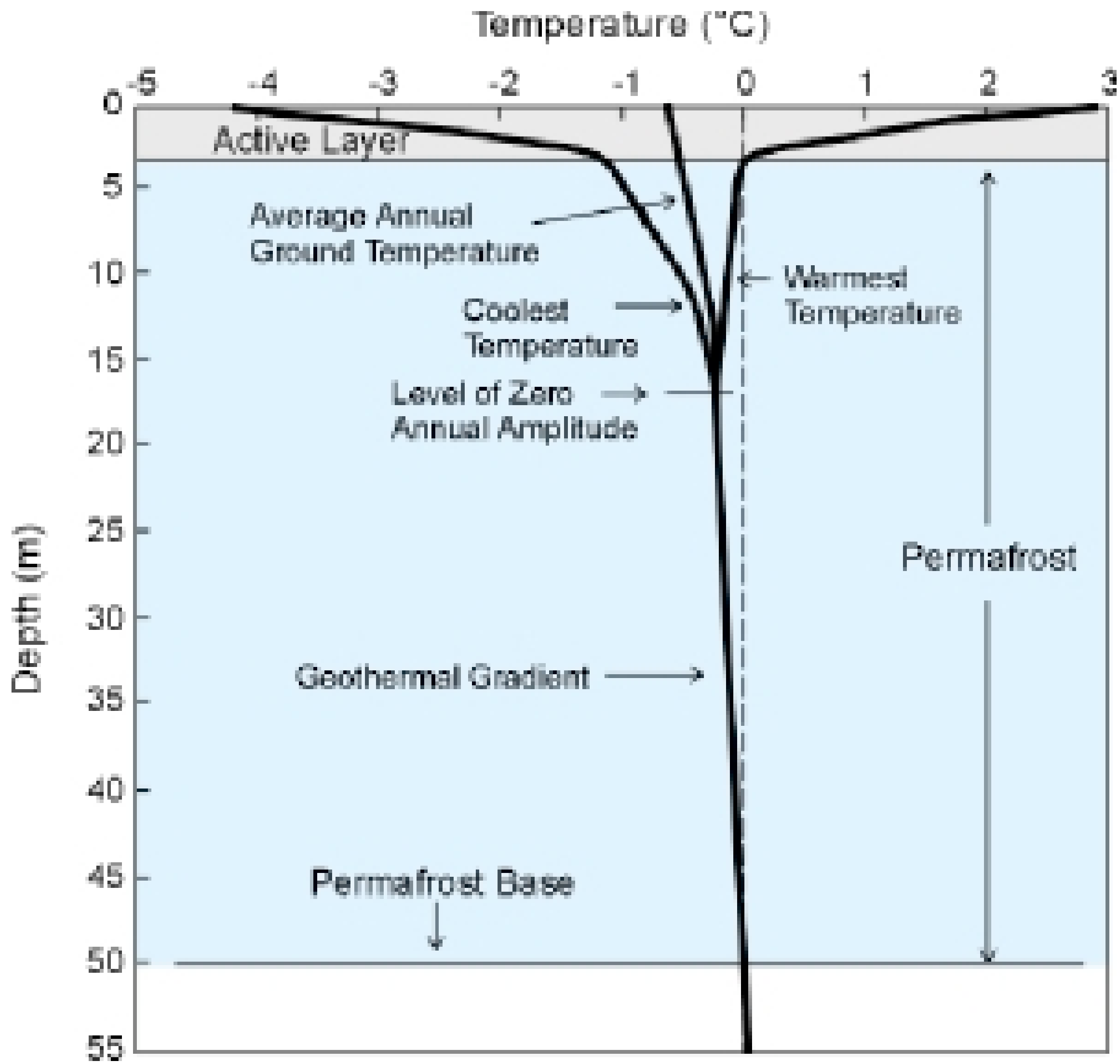
Permafrost

- follows 0°C isotherm
- long response time




Offshore
Permafrost
Continuous
Permafrost
Discontinuous
Permafrost

Karst lakes on permafrost

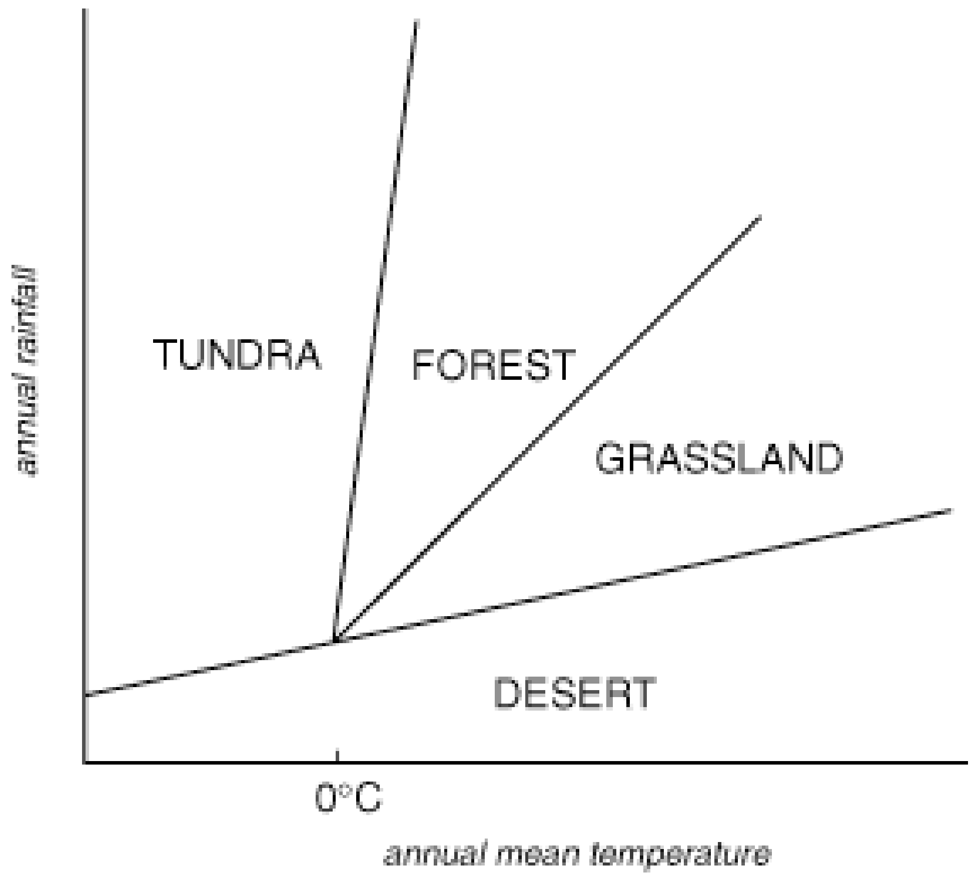


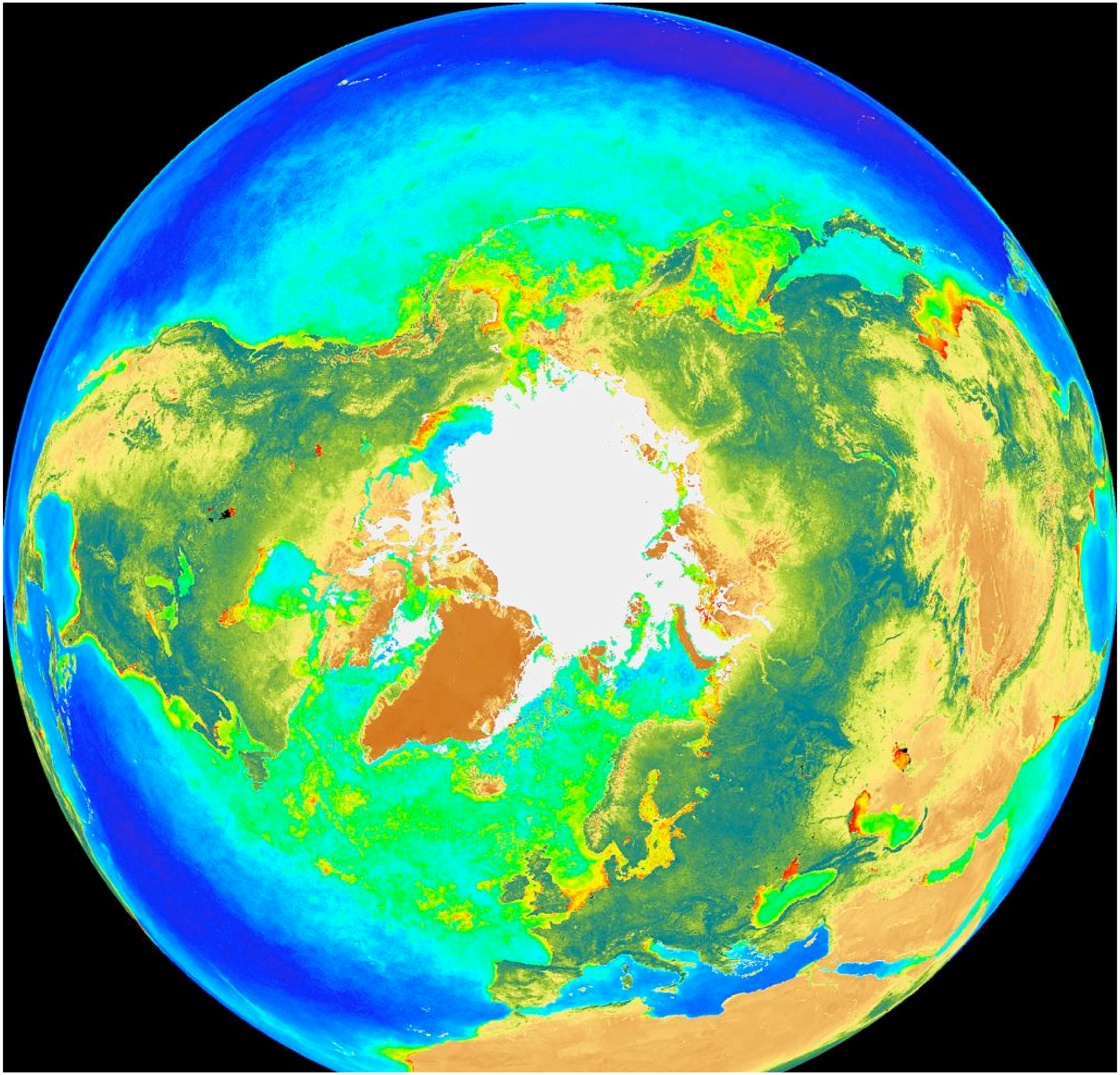
Temperature (°C)
-5
-4
-3
-2
-1
0
1
2
3
0
5
10
15
20
25
30
35
40
45
50
55
Depth (m)
Active Layer
Average Annual
Ground Temperature
Coolest
Temperature
Warmest
Temperature
Level of Zero
Annual Amplitude
Permafrost
Geothermal Gradient
Permafrost Base

Role of the cryosphere

- mediates the earth’s albedo
- damps the seasonal cycle
- keeps high latitudes cold
- records past climate (ice cores)

The terrestrial biosphere

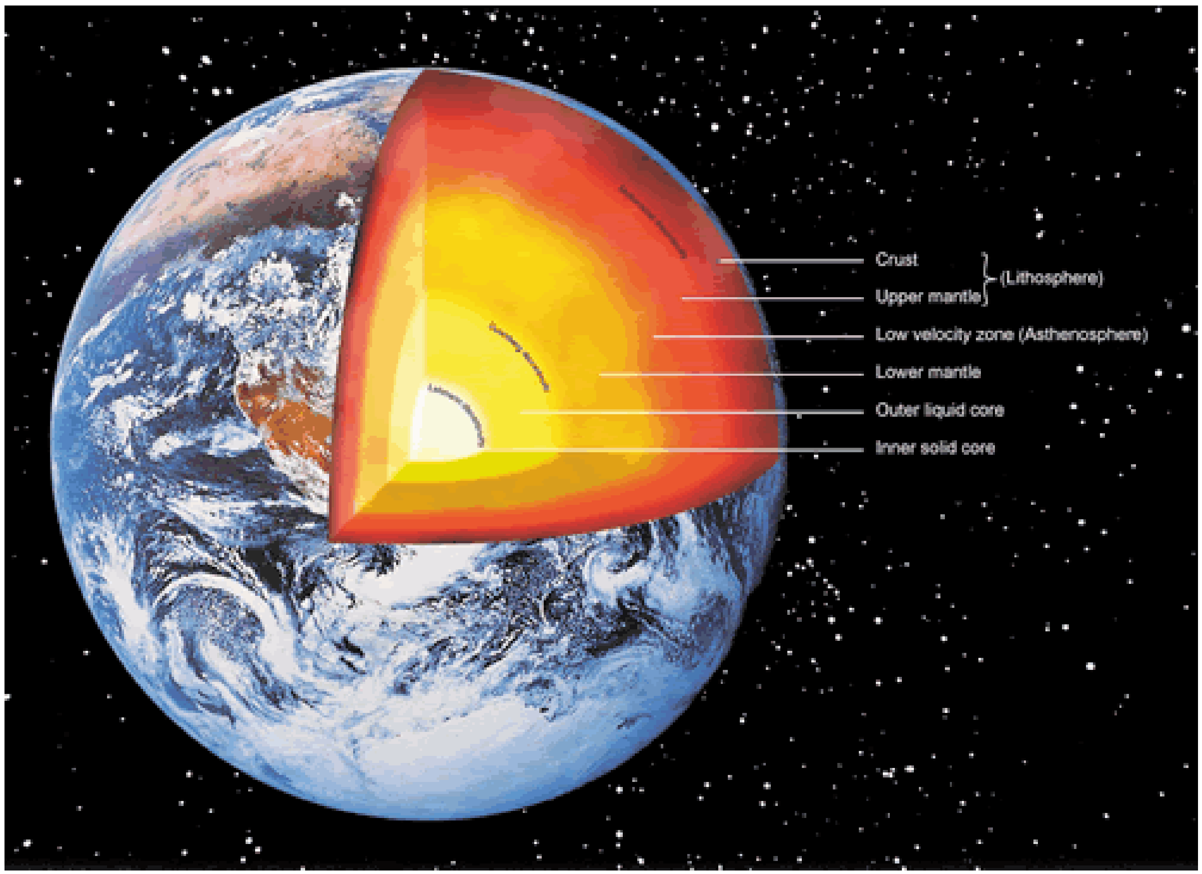


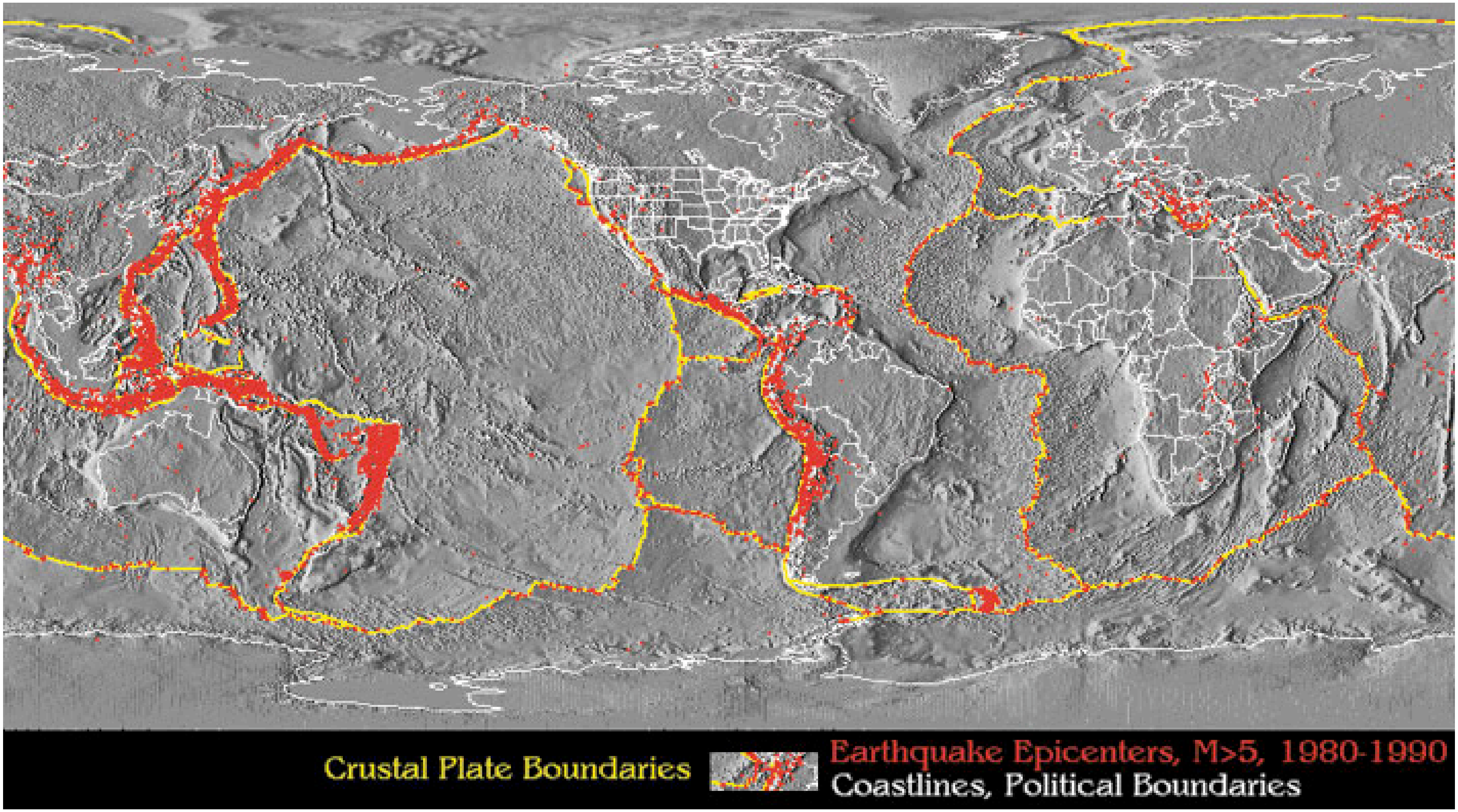


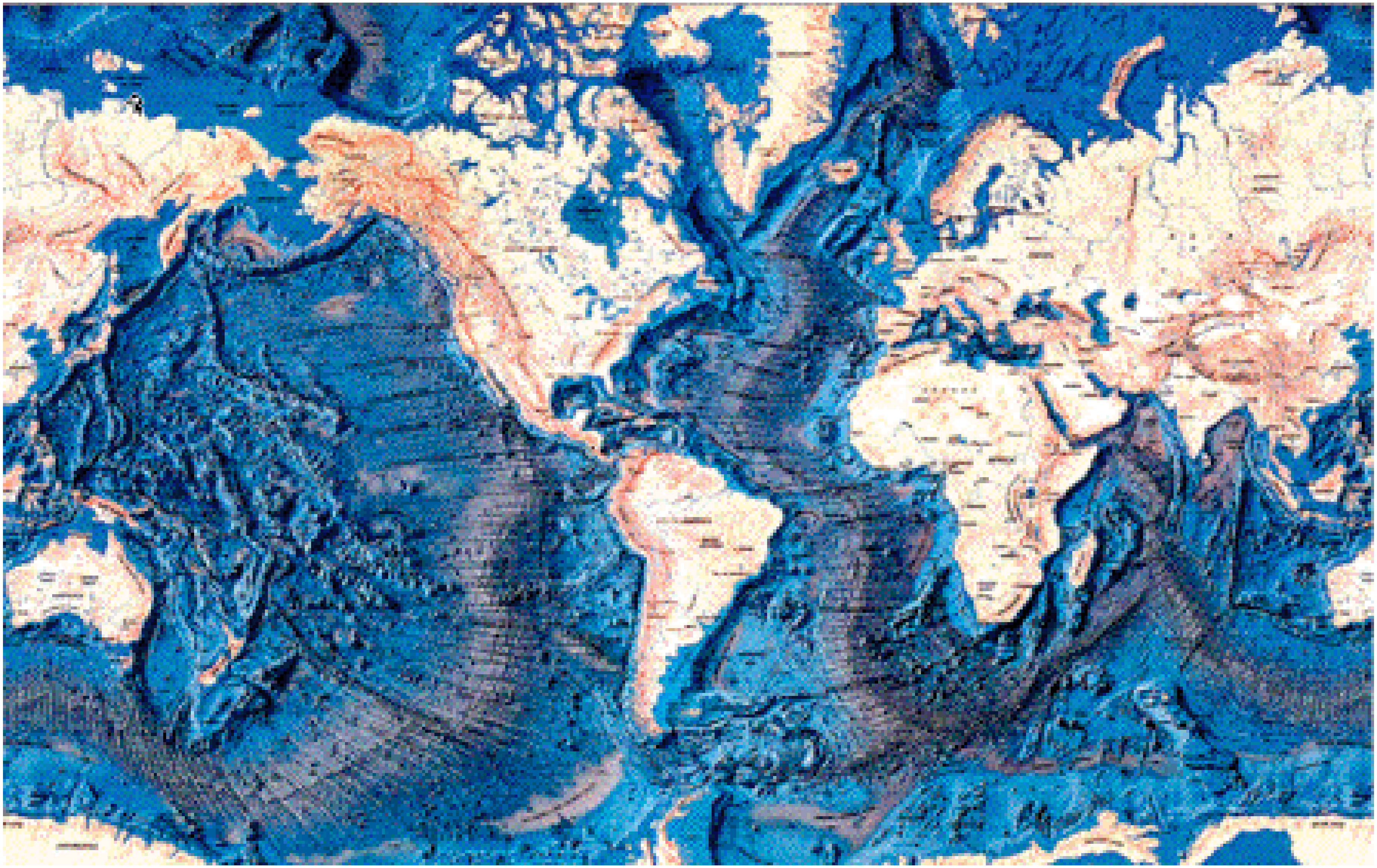
Role of the terrestrial biosphere

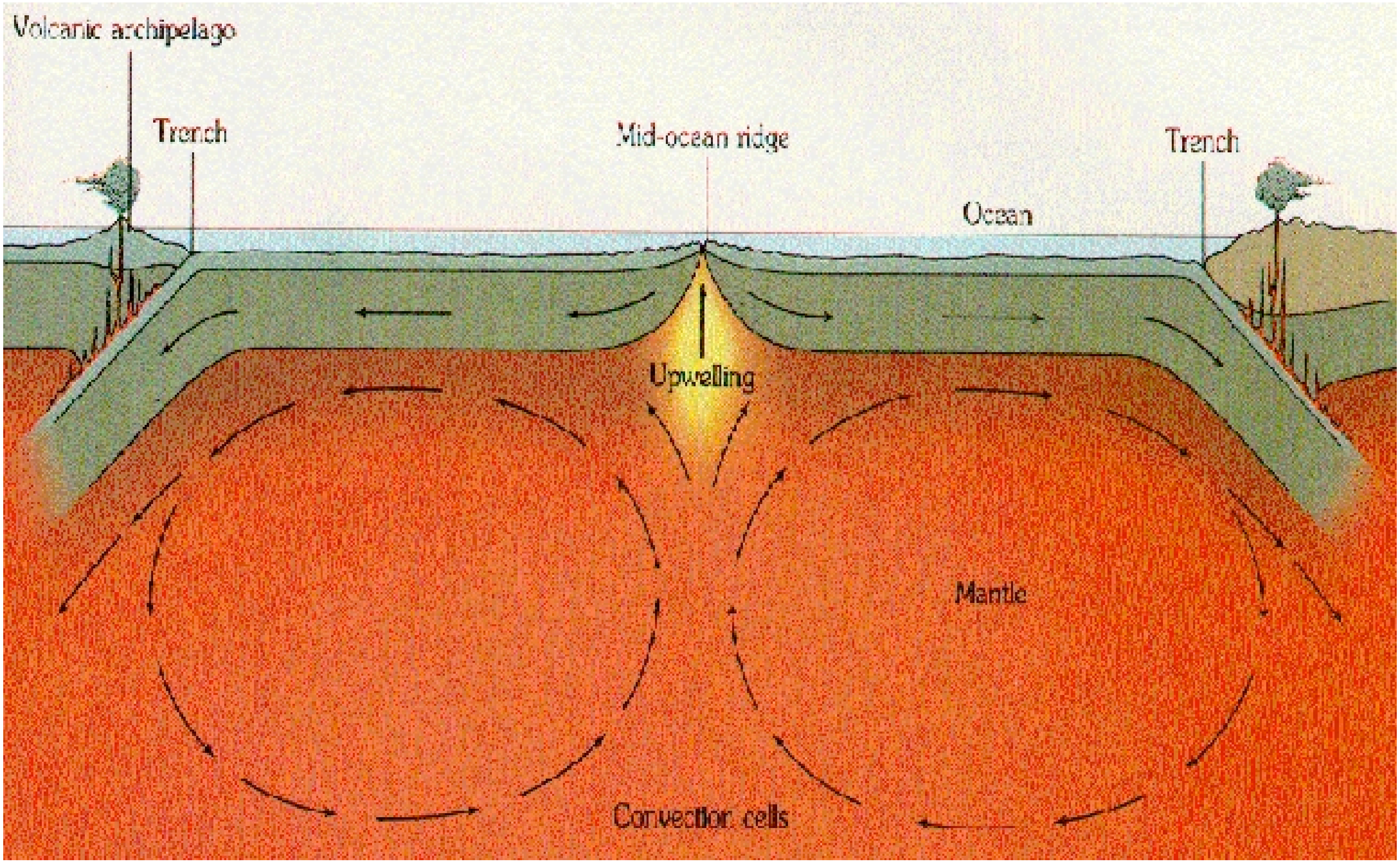
- moisture source
- cools in summer by evapotranspiration
- summer drawdown of carbon dioxide
- source of aerosols and trace gases
- influences albedo

The crust and mantle

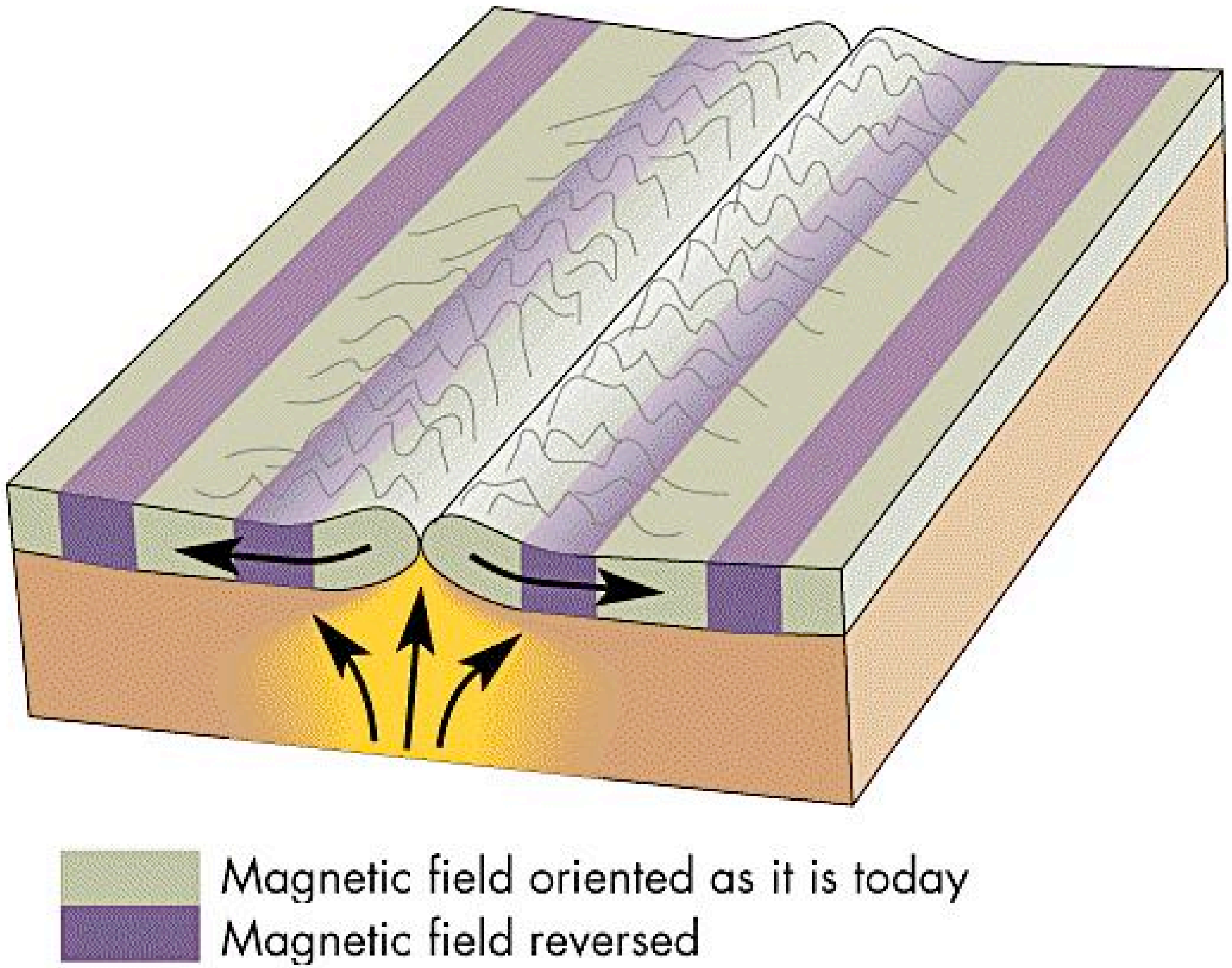


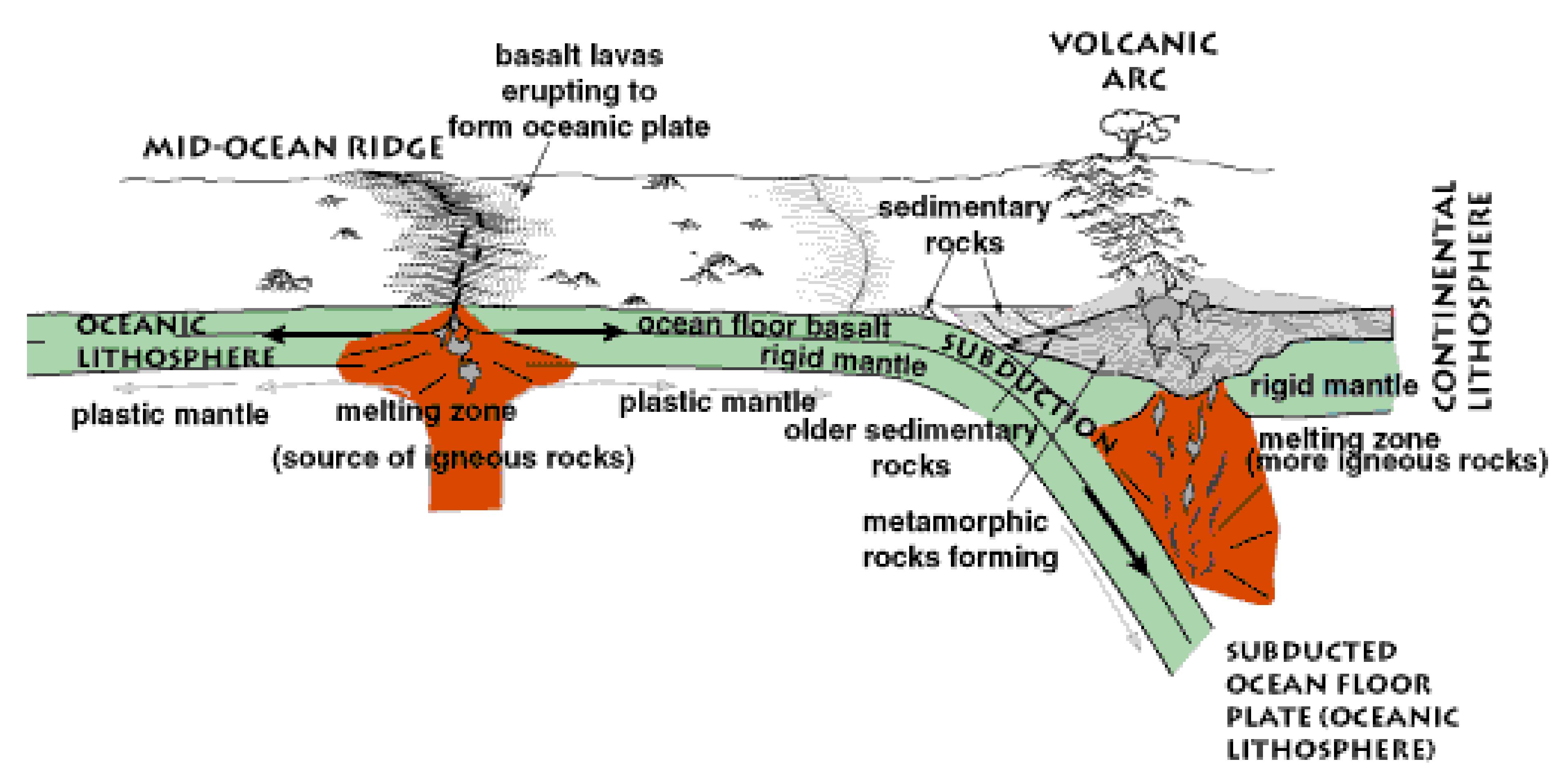

Crustal Plate Boundaries
Earthquake Epicenters, M>5, 1980-1990
Coastlines, Political Boundaries



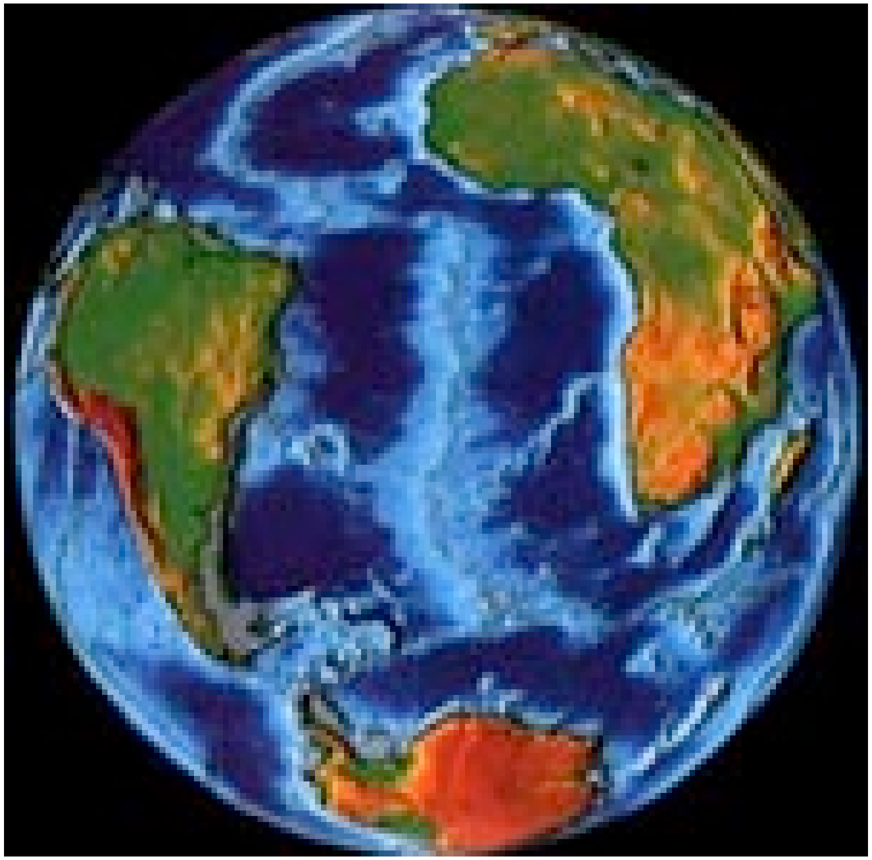


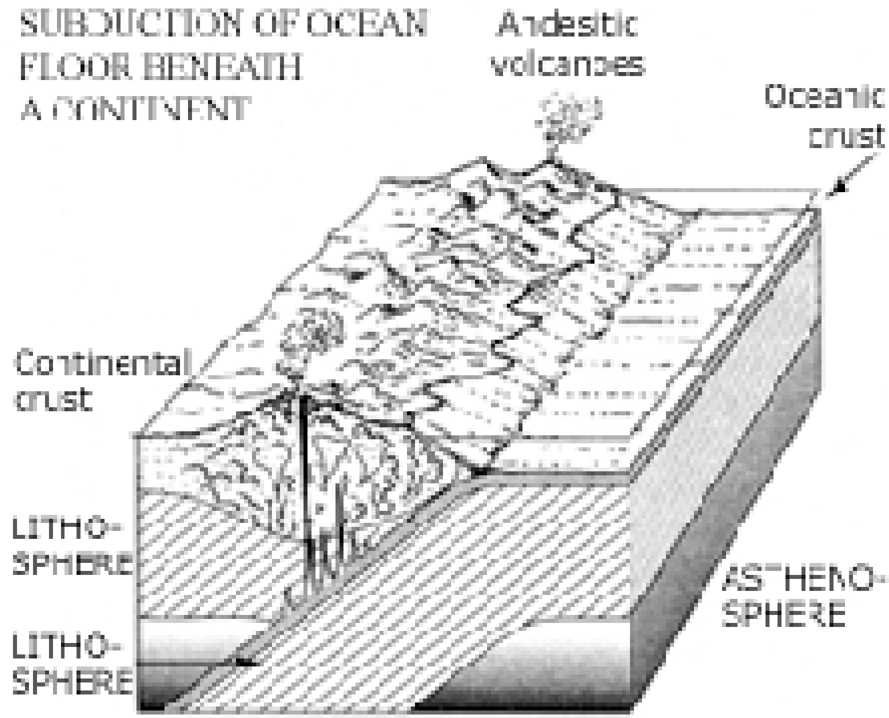
Volcanic archipelago
Trench
Mid-ocean ridge
Trench
Ocean
Upwelling
Mantle
Convection cells

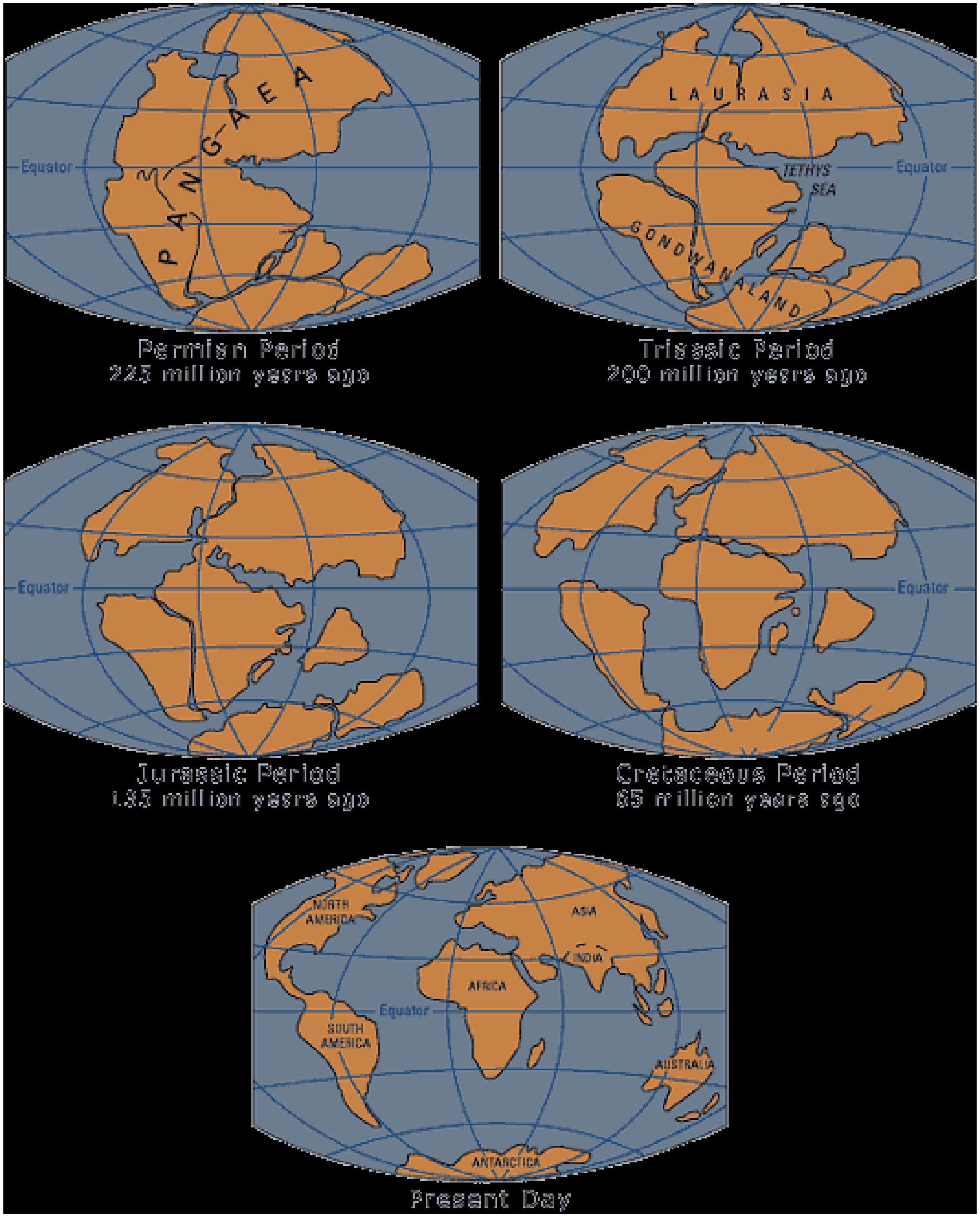

Magnetic field oriented as it is today
Magnetic field reversed



basalt lavas
erupting to
form oceanic plate
MID-OCEAN RIDGE
VOLCANIC
ARC
sedimentary
rocks
CONTINENTAL
LITHOSPHERE
OCEANIC
LITHOSPHERE
ocean floor basalt
rigid mantle
SUBDUCTION
rigid mantle
plastic mantle
melting zone
(source of igneous rocks)
plastic mantle
older sedimentary
rocks
melting zone
(more igneous rocks)
metamorphic
rocks forming
SUBDUCTED
OCEAN FLOOR
PLATE (OCEANIC
LITHOSPHERE)




SUBDUCTION OF OCEAN
FLOOR BENEATH
A CONTINENT
Andesitic
volcanoes
Oceanic
crust
Continental
crust
LITHO-
SPHERE
LITHO-
SPHERE
ASTHENO-
SPHERE


PANGAEA
Equator
Permian Period
225 million years ago
LAURASIA
TETHYS SEA
GONDWANALAND
Equator
Triassic Period
200 million years ago
Equator
Jurassic Period
135 million years ago
Equator
Cretaceous Period
65 million years ago
NORTH AMERICA
ASIA
INDIA
AFRICA
Equator
SOUTH AMERICA
AUSTRALIA
ANTARCTICA
Present Day

Role of crust and mantle

- cycling of carbon
- changing continent configurations
- changing mountain ranges
- changing ocean currents

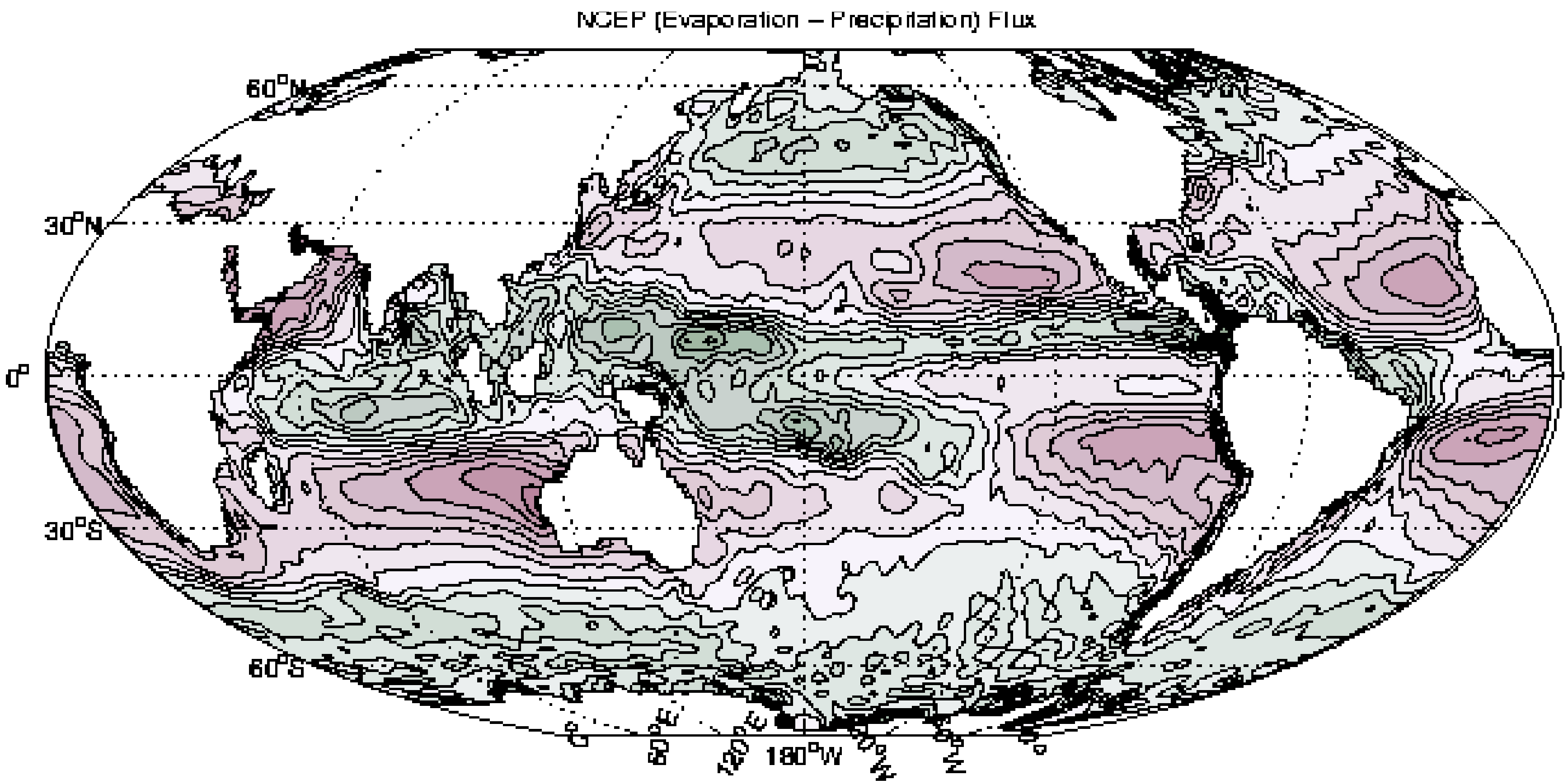
** (on tens of millions of years)

Reservoirs in the hydrologic cycle

Reservoirs of water	*Mass*	*Residence time*
Atmosphere	0.03	10 days
Fresh water	0.6	days to years
Fresh water (underground)	15	up to 10 years
Alpine glaciers	0.2	300 years
Greenland ice sheet	5	15,000 “
Antarctic ice sheet	53	200,000 “
Oceans	2,700	3,000 “
Crust and mantle	20,000	10^{11} “

The Land Bridge

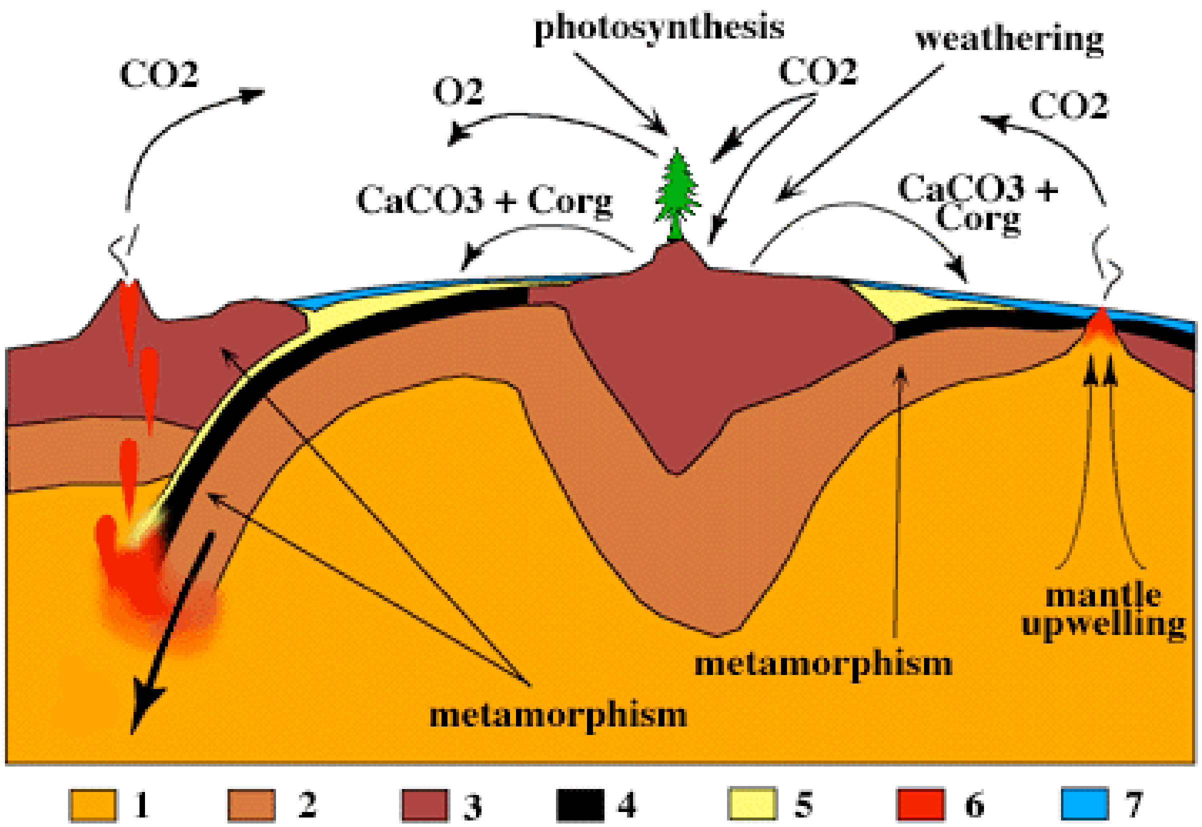
Evaporation minus Precipitation

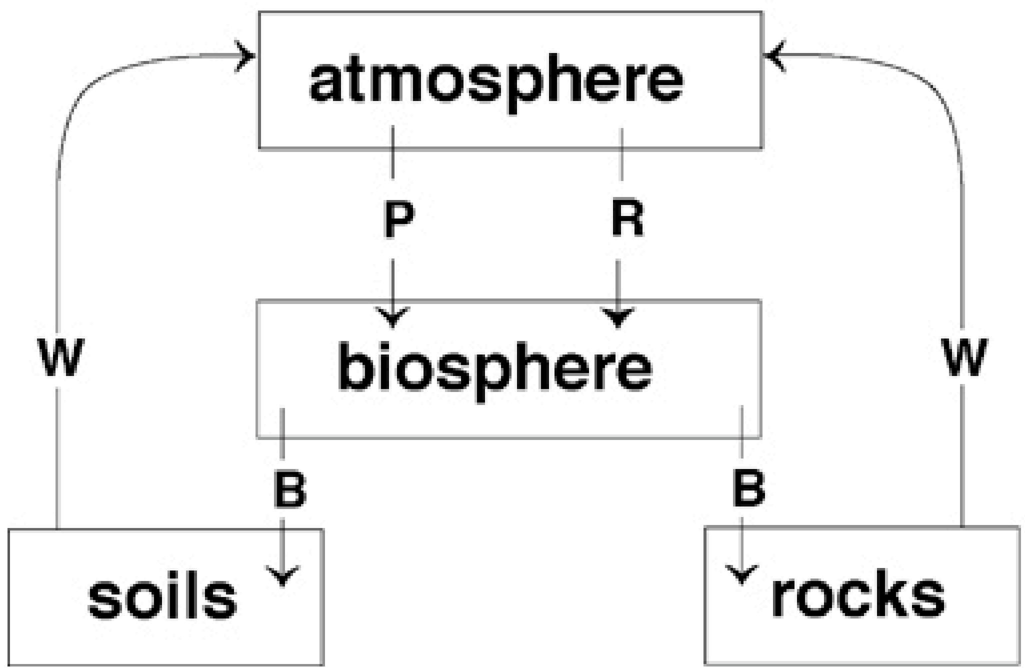


Reservoirs in the carbon cycle

Reservoir	*Capacity*	*Residence time*
Atmospheric CO_	1.6	10 years
Atmospheric CH_	0.02	9 years
Active part of the biosphere	0.1	days to seasons
Tree trunks and roots	1.2	up to centuries
Soils and sediments	3	
Fossil fuels	10	
Organic C in rocks	20,000	
Dissolved carbon dioxide	1.5	
Dissolved carbonates	2.5	
Dissolved bicarbonates	70	
Inorganic C in rocks	80,000	10^8 years

The Carbon Cycle



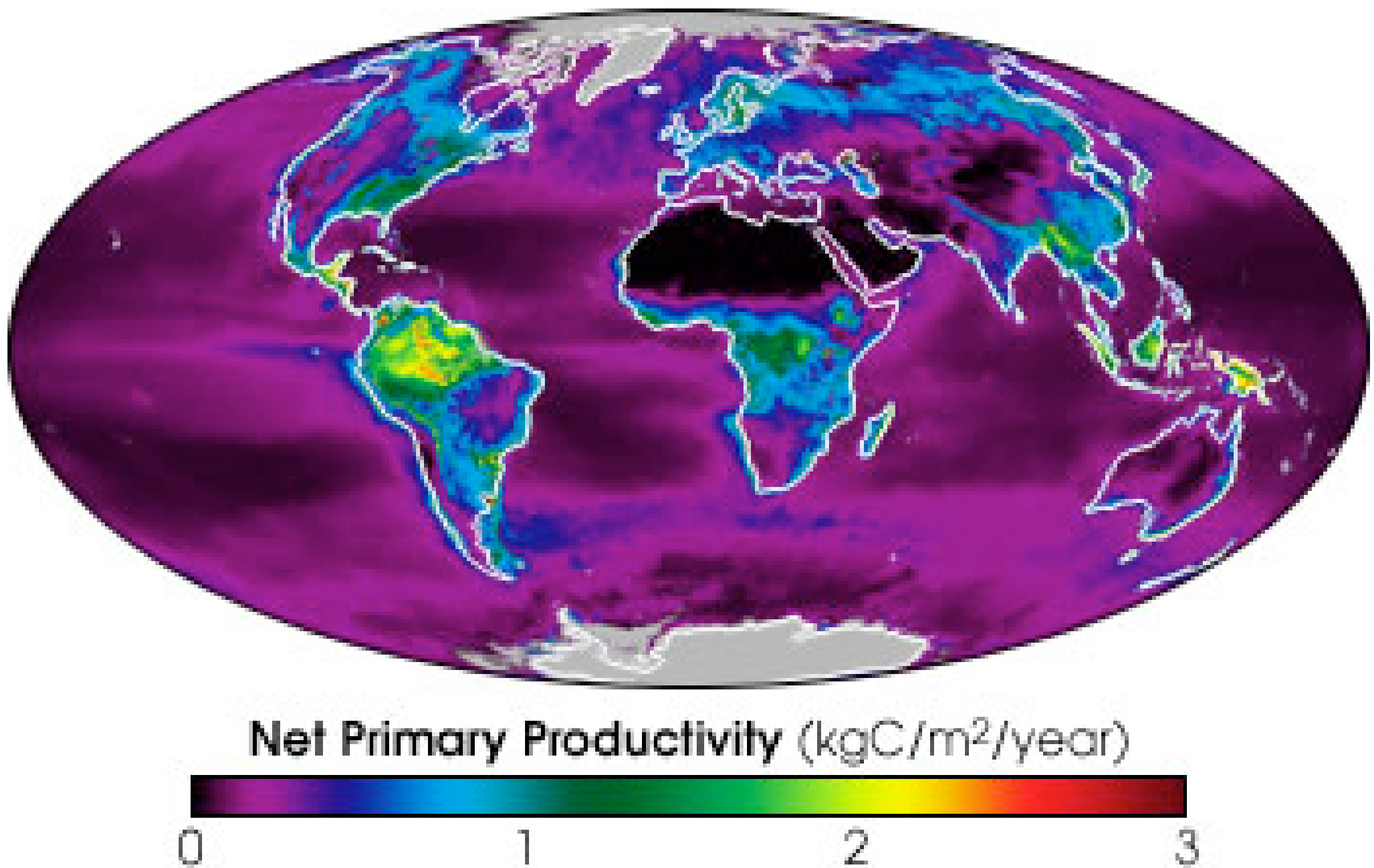

atmosphere
P
R
biosphere
W
W
B
B
soils
rocks

Three carbon cycles

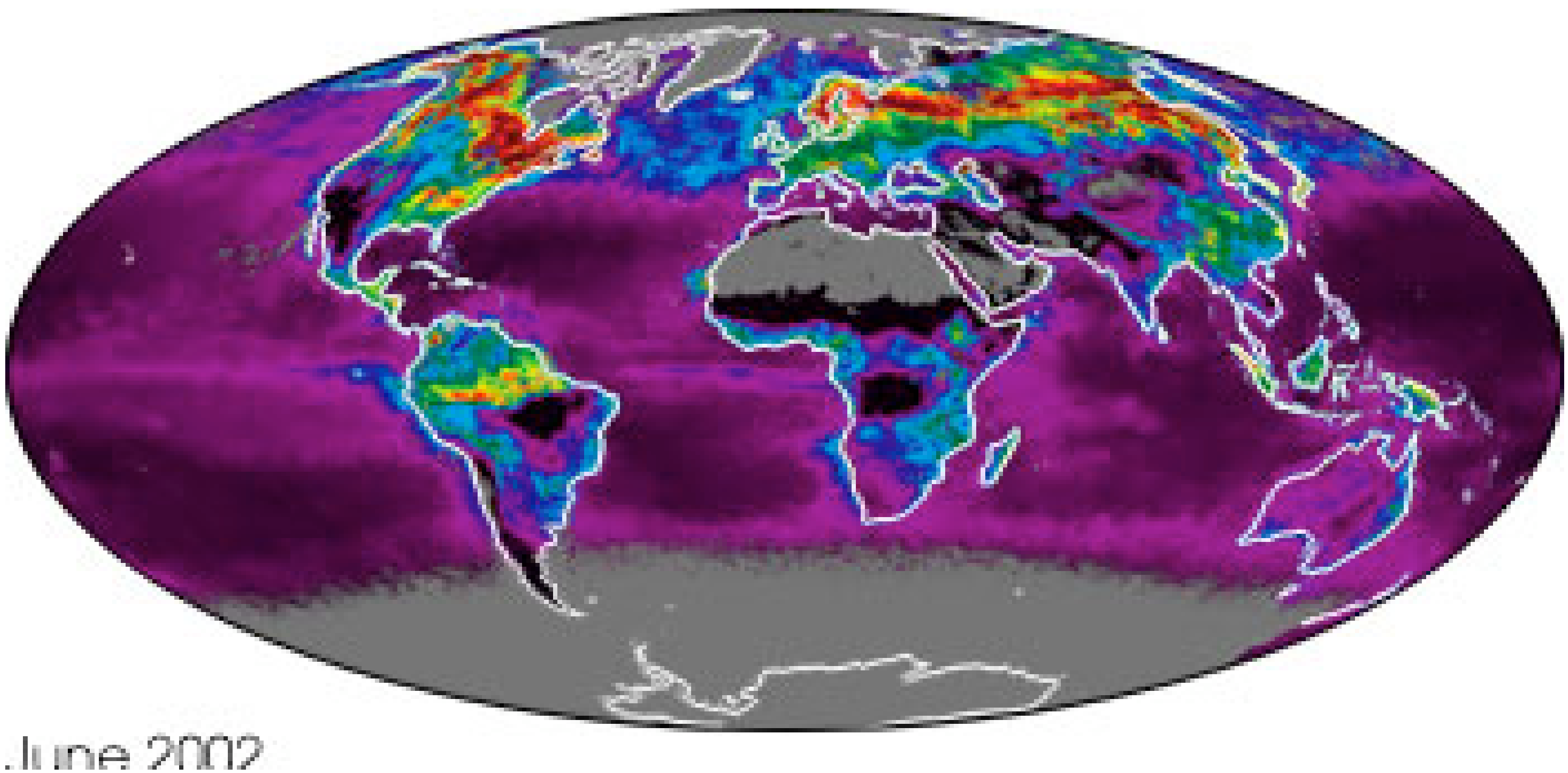
- short term organic
  photosynthesis vs. respiration / decay
- long term organic
  burial, weathering
- long term inorganic
  carbonate sediment formation,
  metamorphosis, weathering

Short term organic carbon cycle

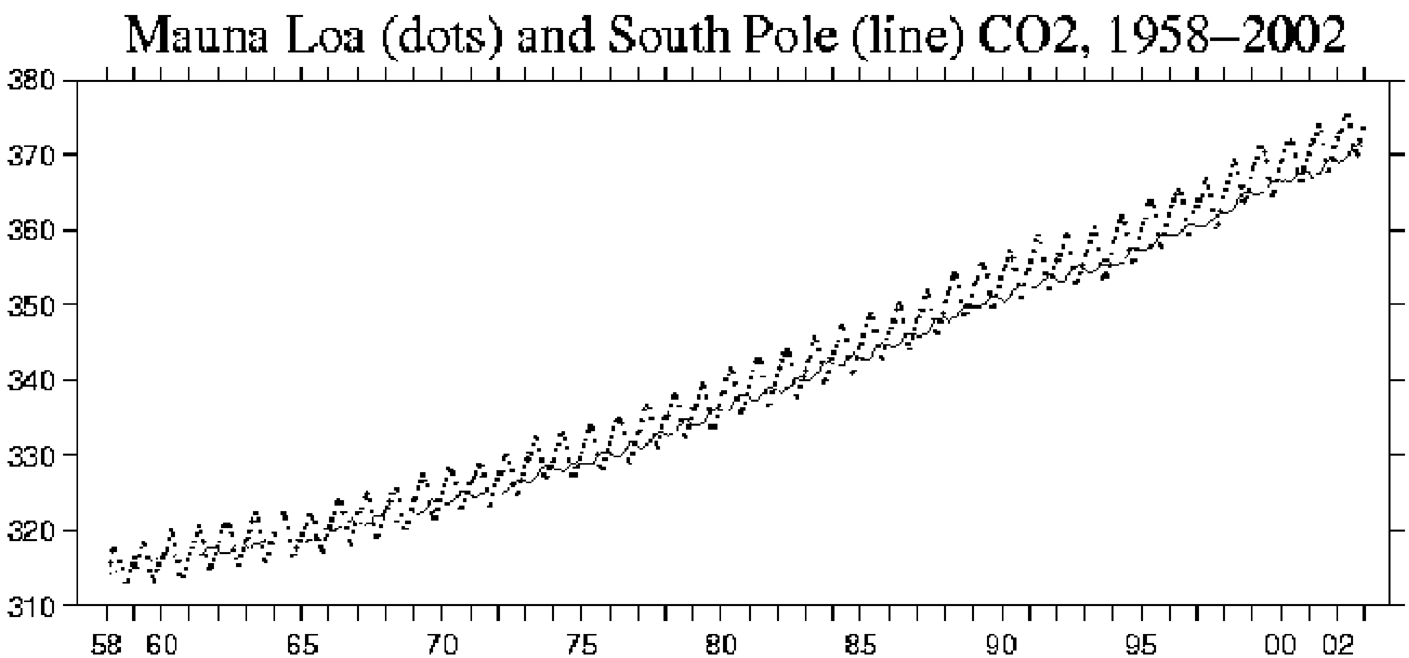
Annual mean NPP



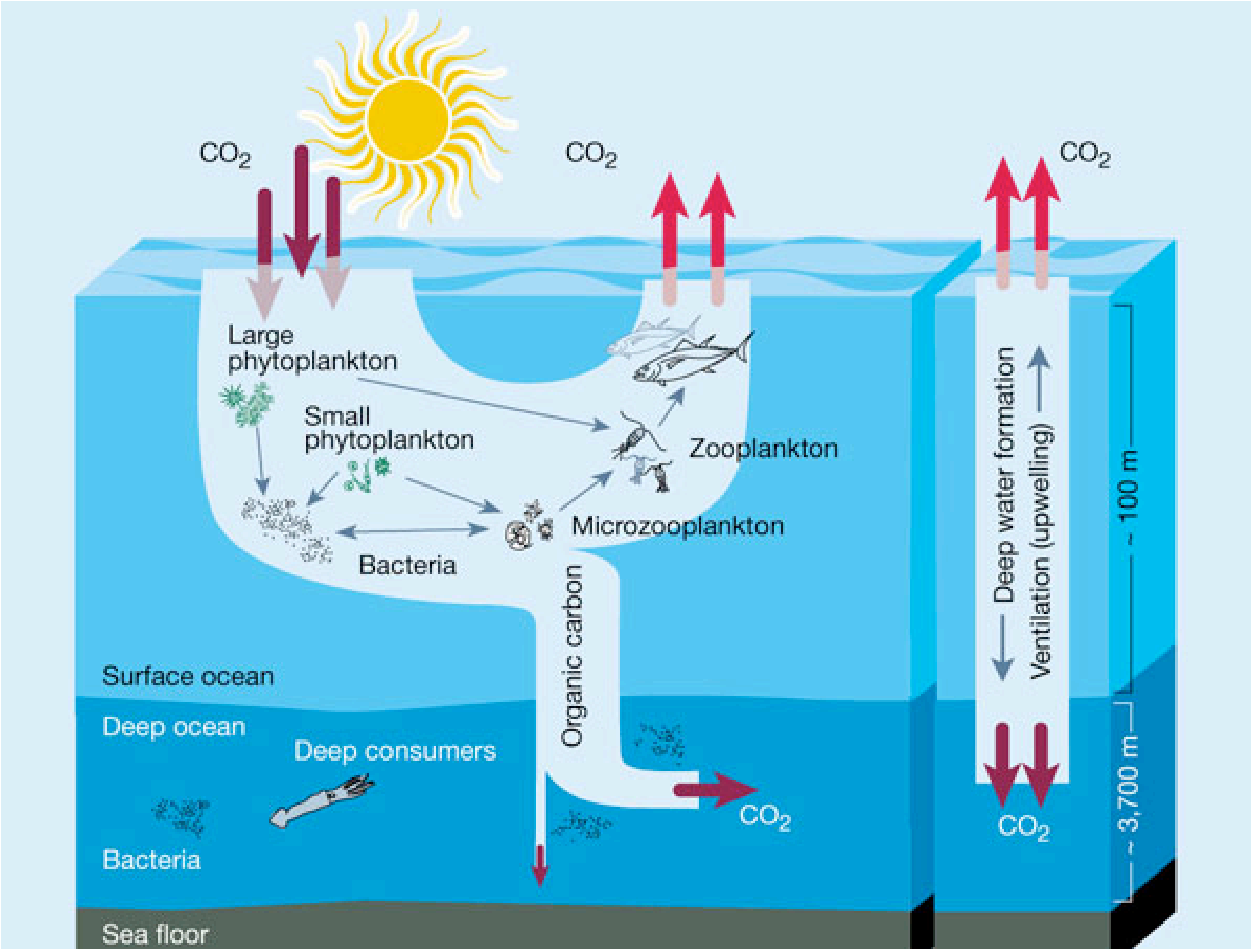
June NPP



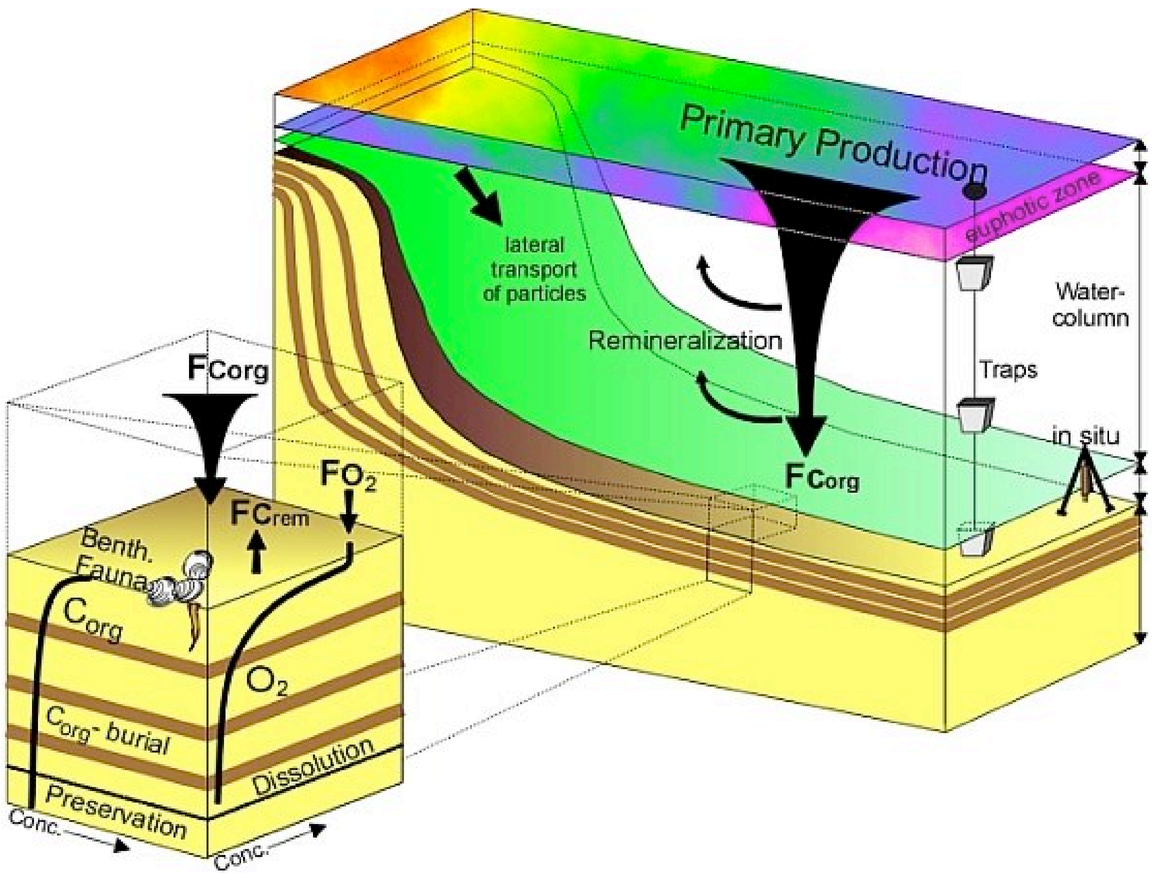
Summer drawdown of CO_2



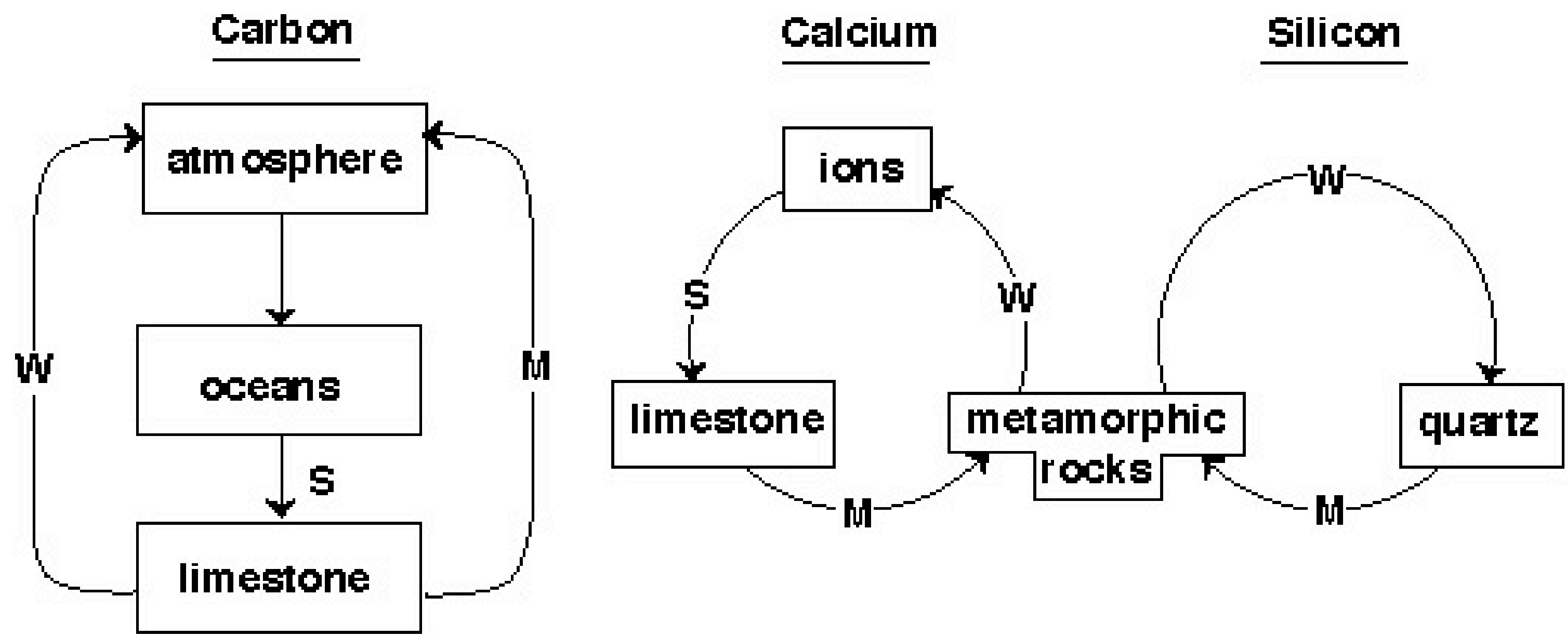
The biological pump



Long term organic carbon cycle



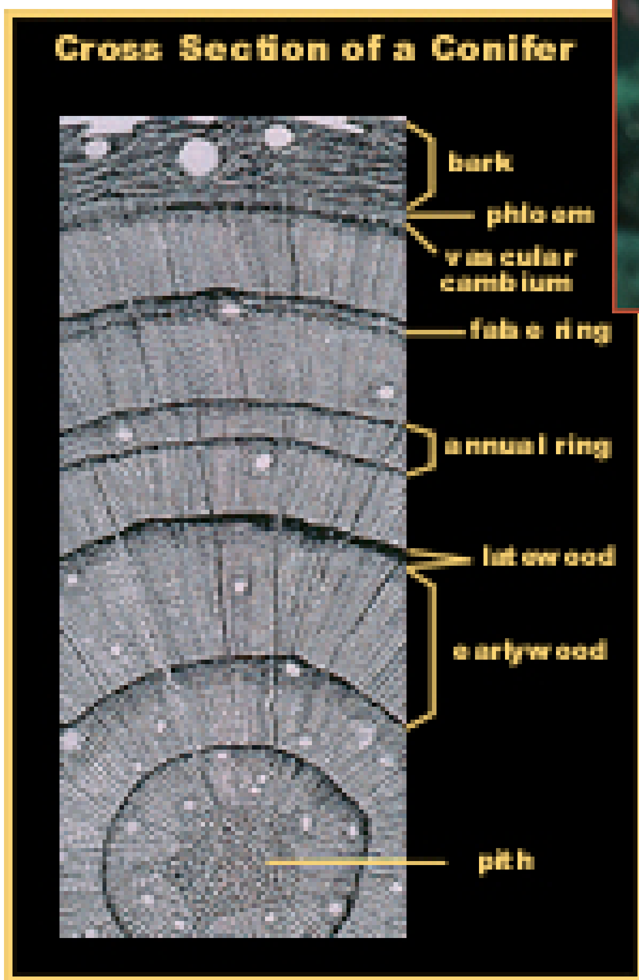
Inorganic carbon cycle

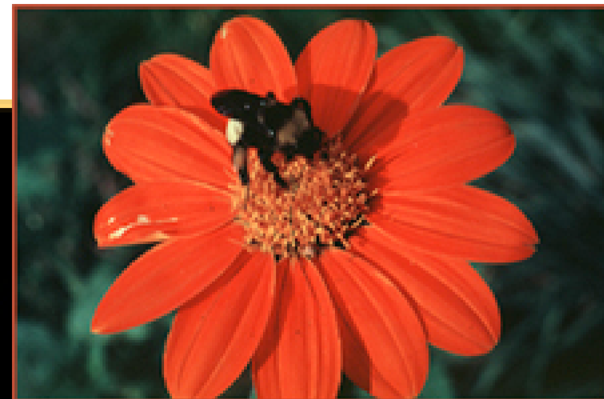


Oxygen inventory

Atmosphere	2.353 kg m^{-3}
Oceans and sediments	31
Crust (ferric iron)	>100
Crust (carbonates)	>100
Crust (other)	>100
Mantle (ferric iron)	>100

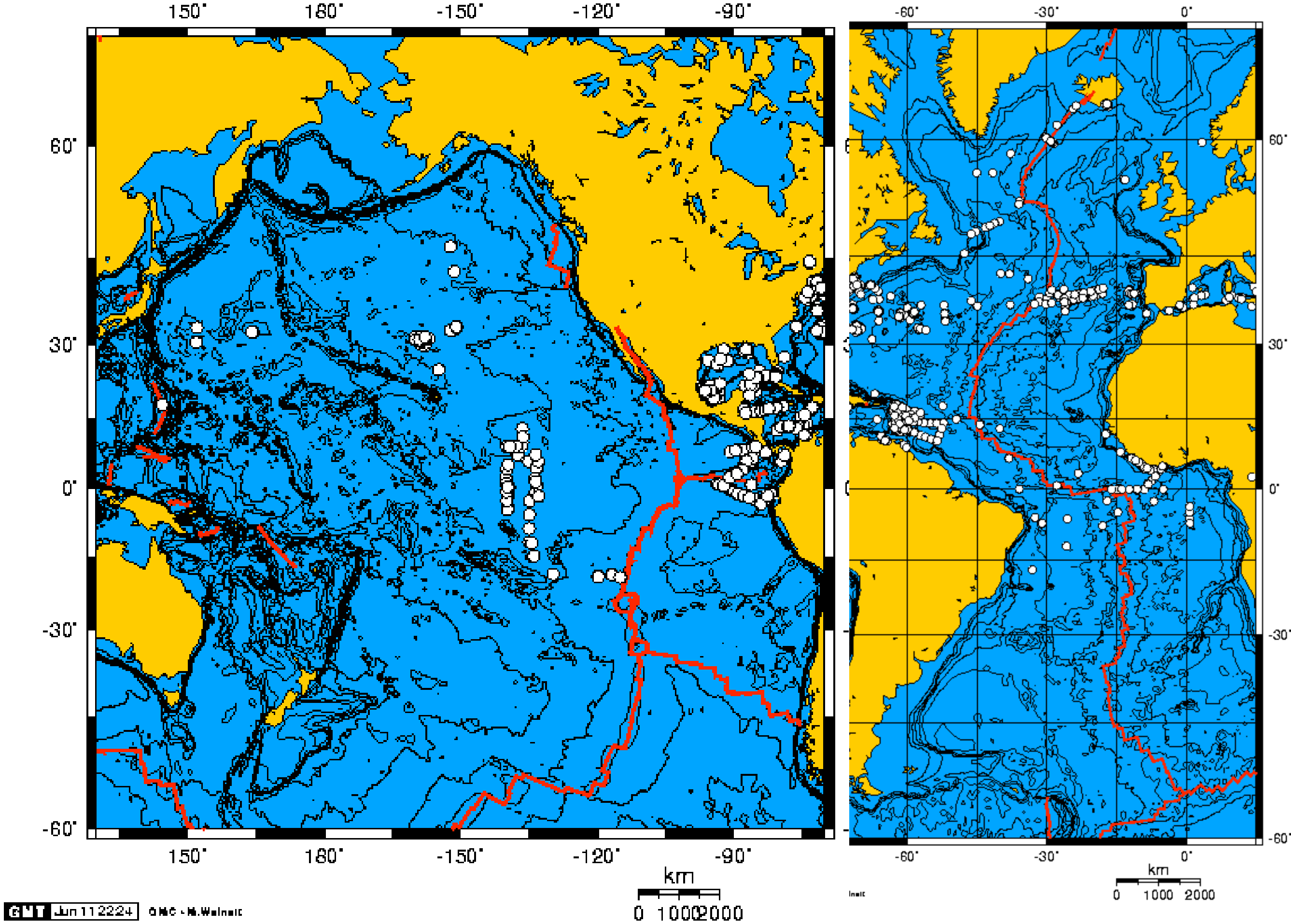
Proxy evidence of past climate





Ice cores

Sediment cores



Isotopes

- Deuterium in snow samples (temperature)
- Oxygen 18 in sediment cores (temperature)
- Carbon-13 in fossils (ambient CO2)
- Carbon-13 in air (biospheric sources)
- Carbon 14 in fossils (radiocarbon dating)

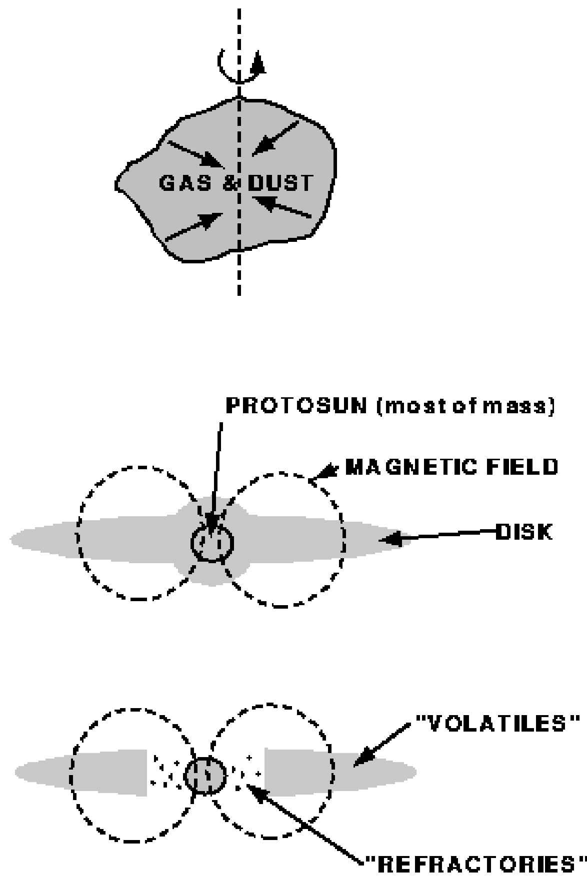
A brief history of the earth system

- lifetime of solar system (4.5 billion years)
- past 100 million years (since the Cretaceous)
- past 1-2 million years (Quaternary)
- past 20,000 years (Younger Dryas, Holocene)
- past 1,000 years (MWP, “Little Ice Age”

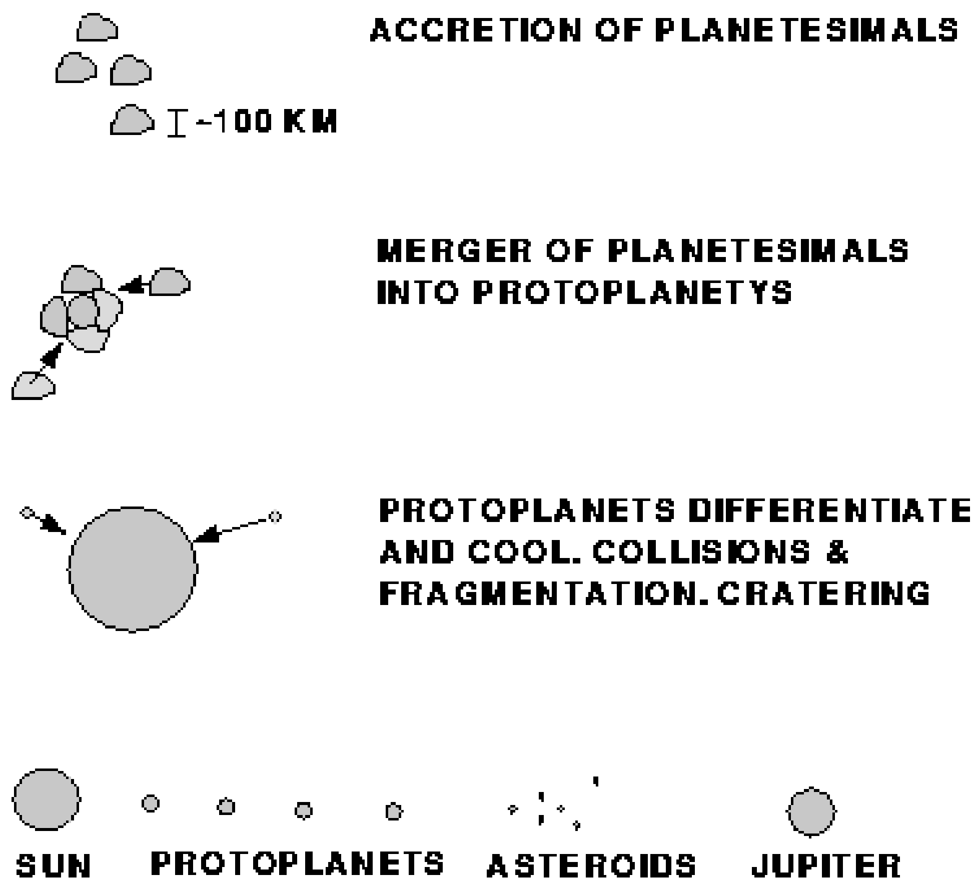
Early history of Earth

- accreted from planetesimals
- bombardment (Hadean epoch)
- evolution of the Sun
- cyanobacteria produce O_2 from 3.0 -3.8bya
- large methane concentrations?
- loss of hydrogen
- abrupt rise of oxygen 2 billion years ago
- major glaciations

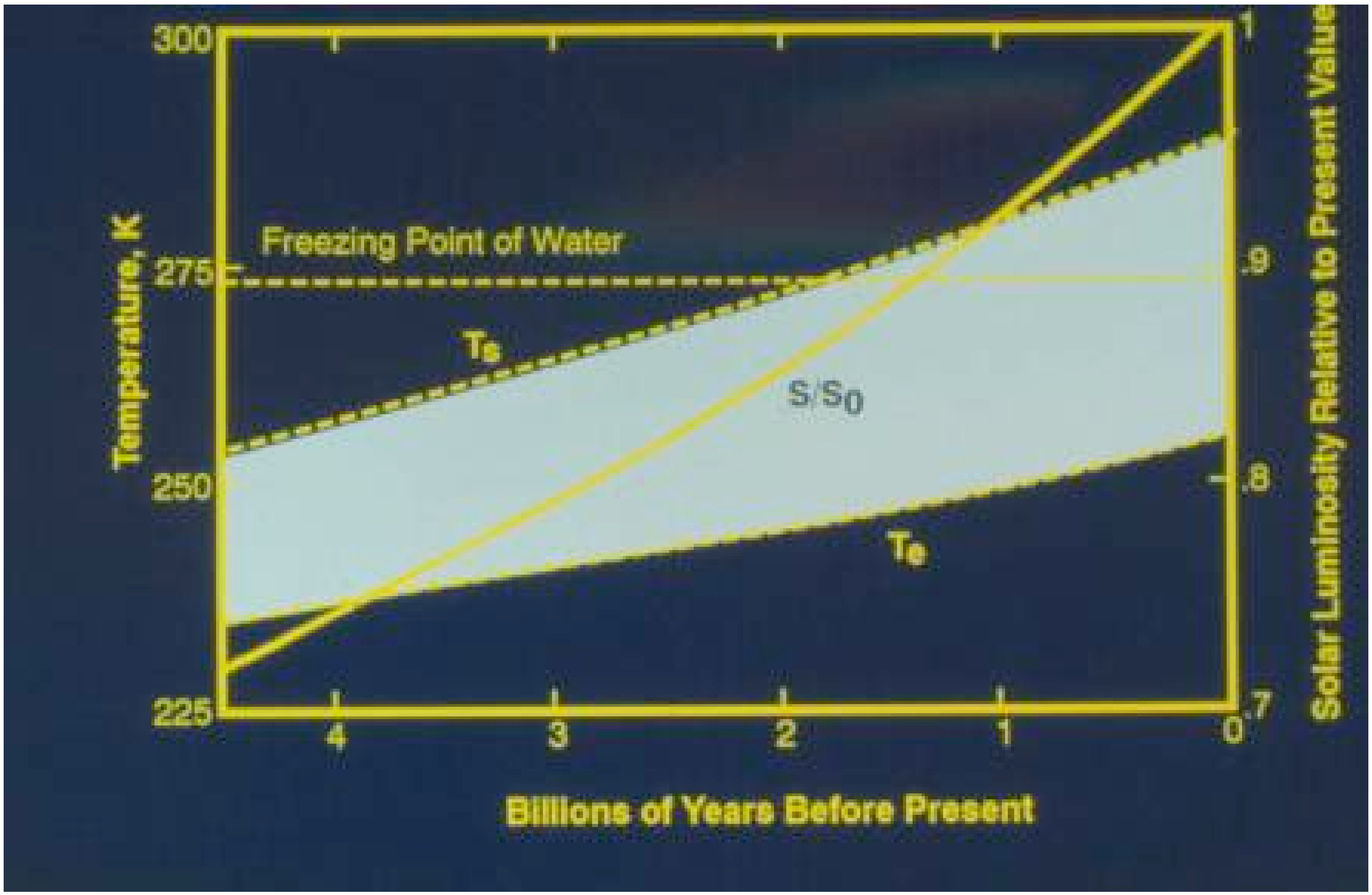
Formation of solar system

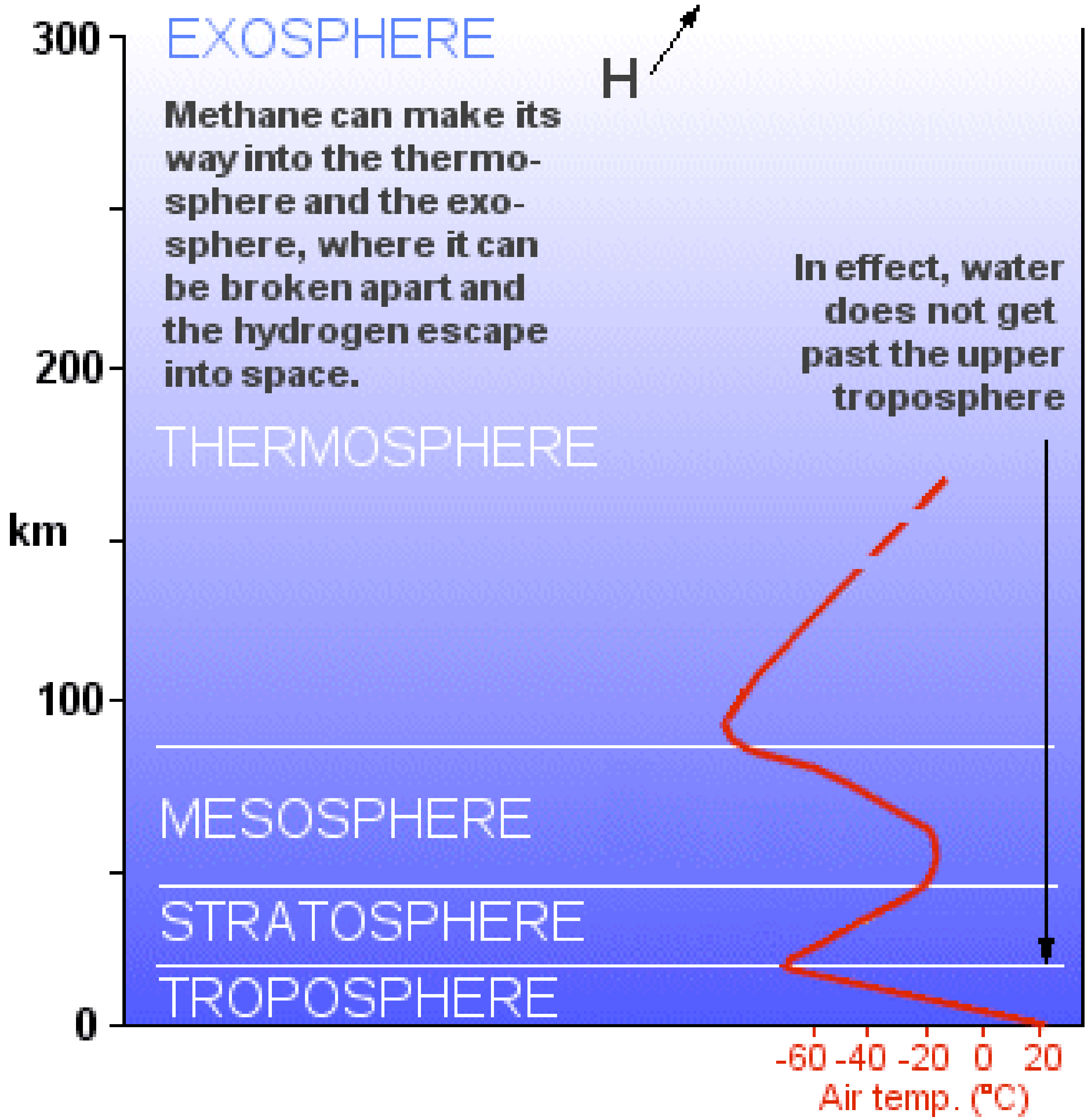


Formation of solar system



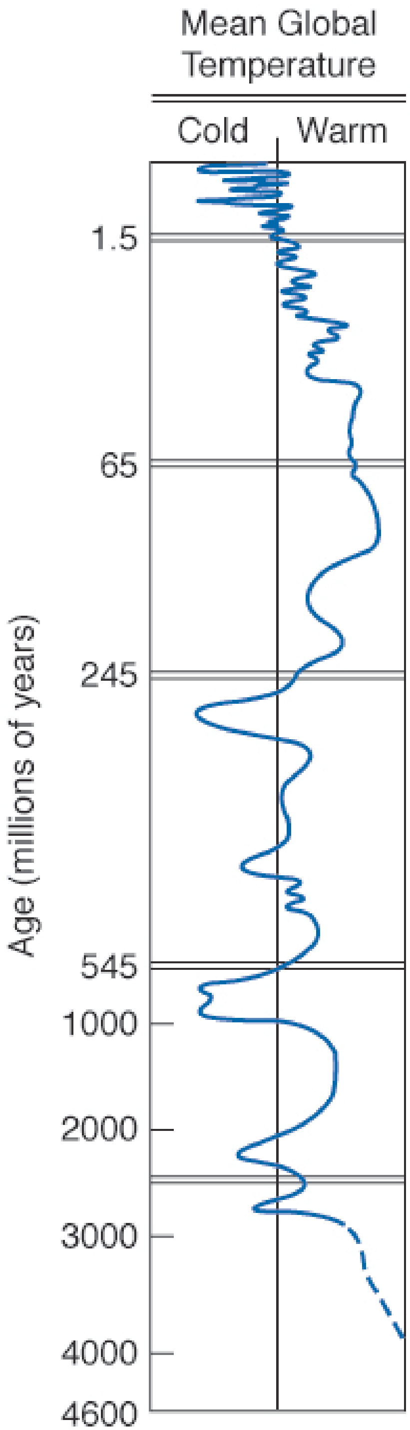
Faint young sun paradox

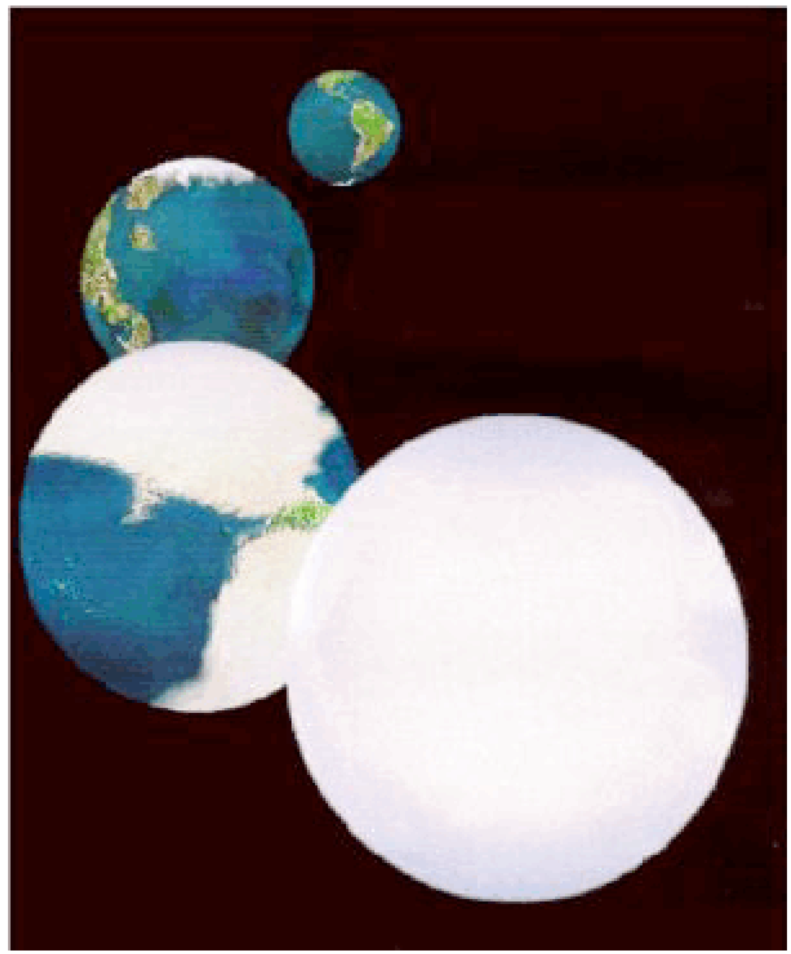




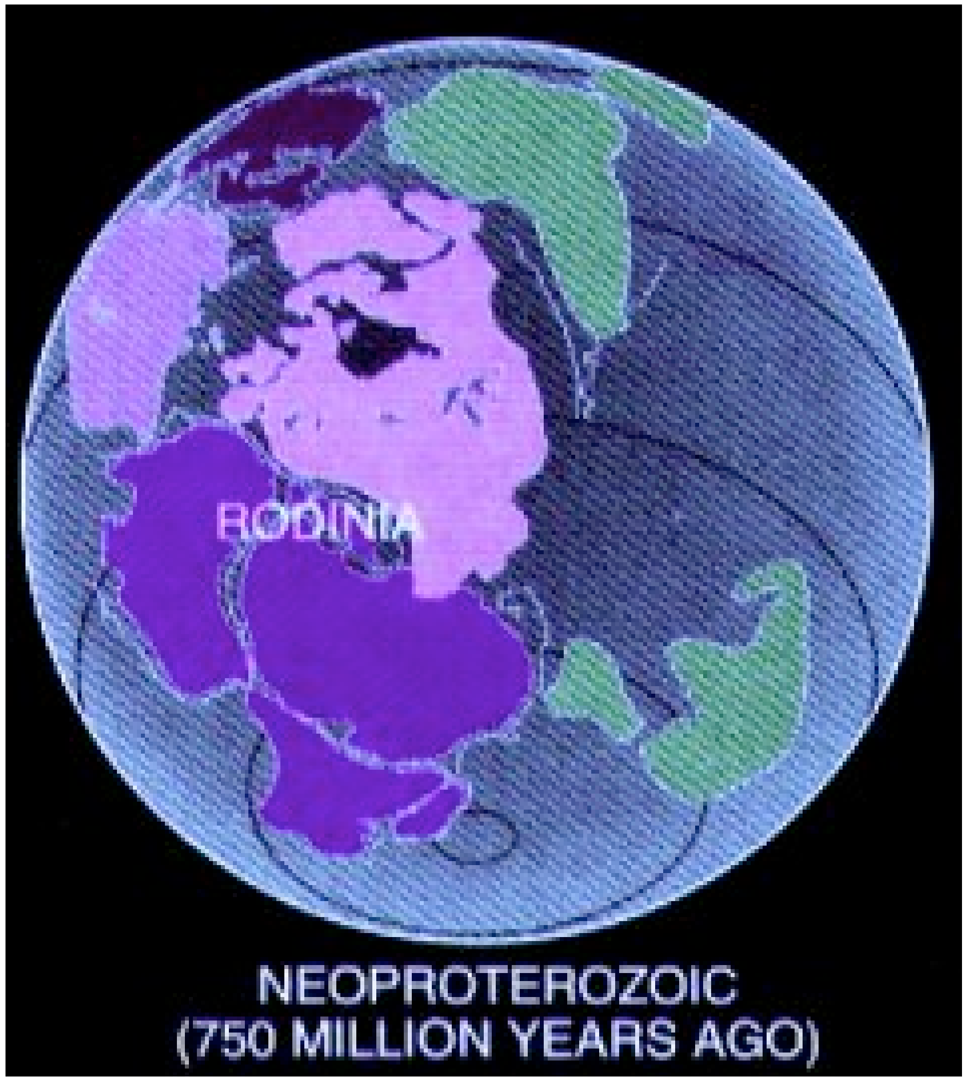
300
200
km
100
0
EXOSPHERE
H
Methane can make its way into the thermo-sphere and the exo-sphere, where it can be broken apart and the hydrogen escape into space.
In effect, water does not get past the upper troposphere
THERMOSPHERE
MESOSPHERE
STRATOSPHERE
TROPOSPHERE
-60 -40 -20 0 20
Air temp. (°C)

"Snowball Earth"





Tropical glaciation

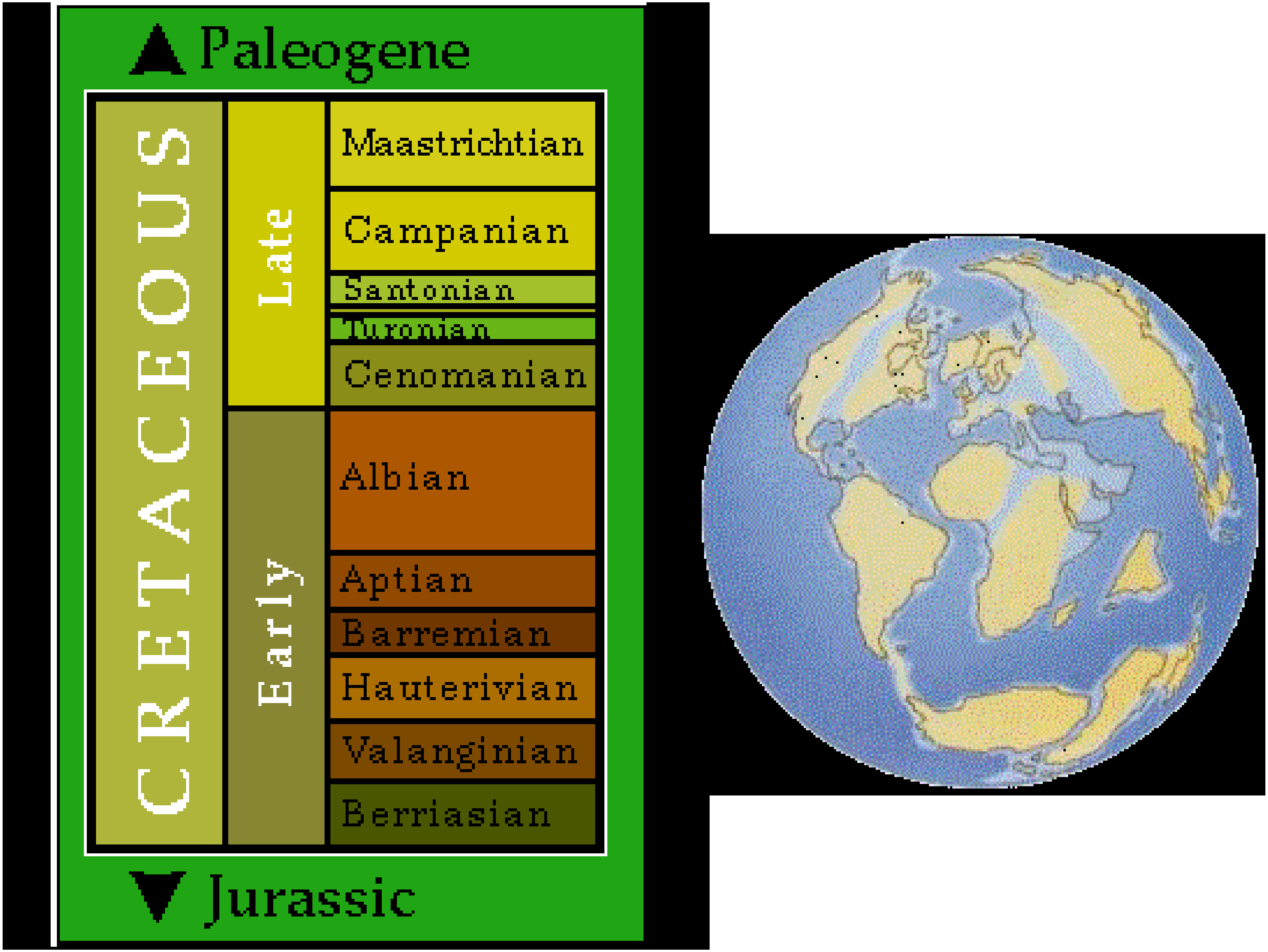


“Snowball Earth” scenario

- cooling phase with + ice-albedo feedback
- frozen phase: CO_2 builds up in atmosphere for lack of any removal mechanism
- abrupt regime shift to ice free state
- hothouse phase: gradually decreasing CO_2

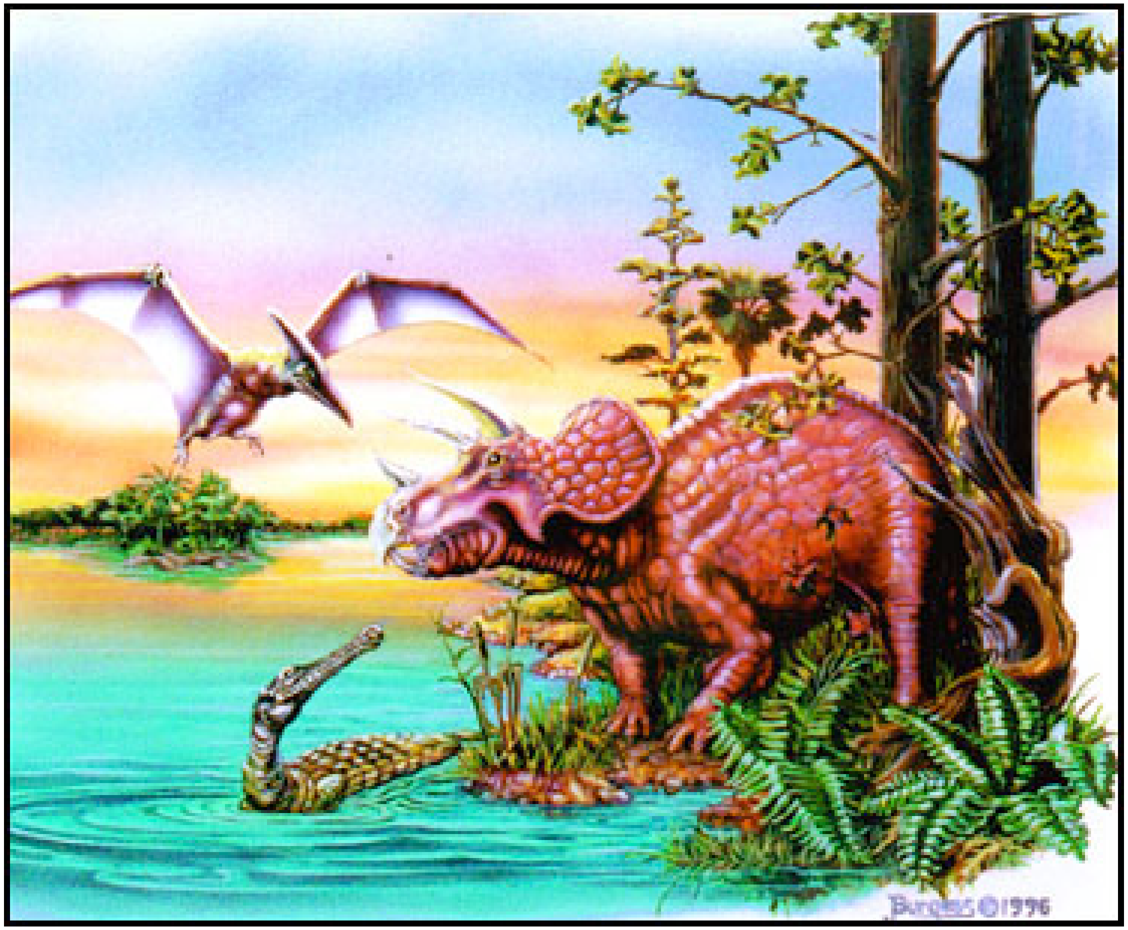
The past 100 million years

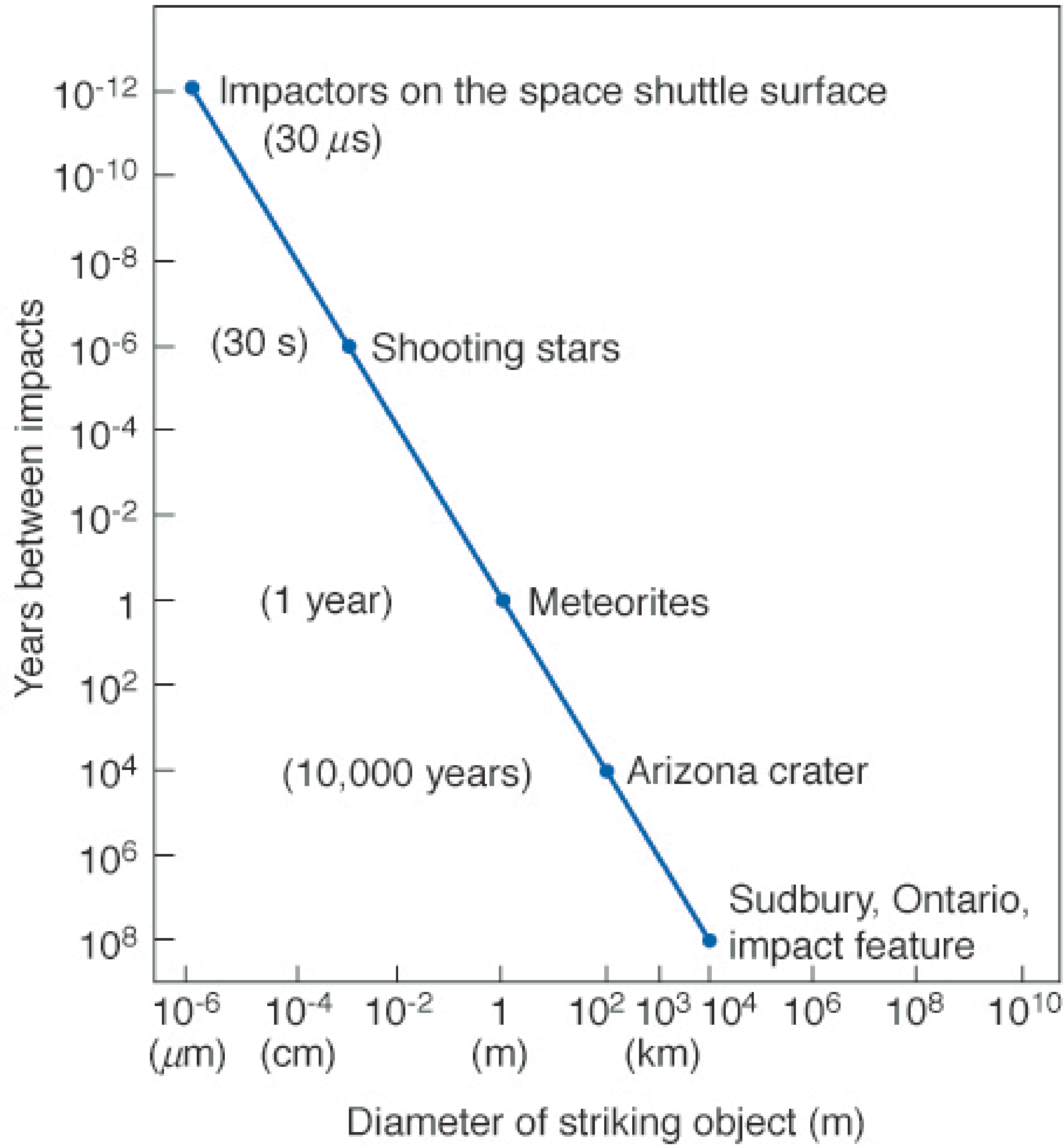
- the K-T extinction
- decline in atmospheric CO_2
- India collides with the Asian plate
- uplift of Himalayas and Rockies
  - increased weathering
- Antarctica goes south, becomes glaciated
- Drake Passage opens, Panamanian Isthmus closes
  - changes in ocean circulation



Paleogene
CRETACEOUS
Late
Early
Maastrichtian
Campanian
Santonian
Turonian
Cenomanian
Albian
Aptian
Barremian
Hauterivian
Valanginian
Berriasian
Jurassic

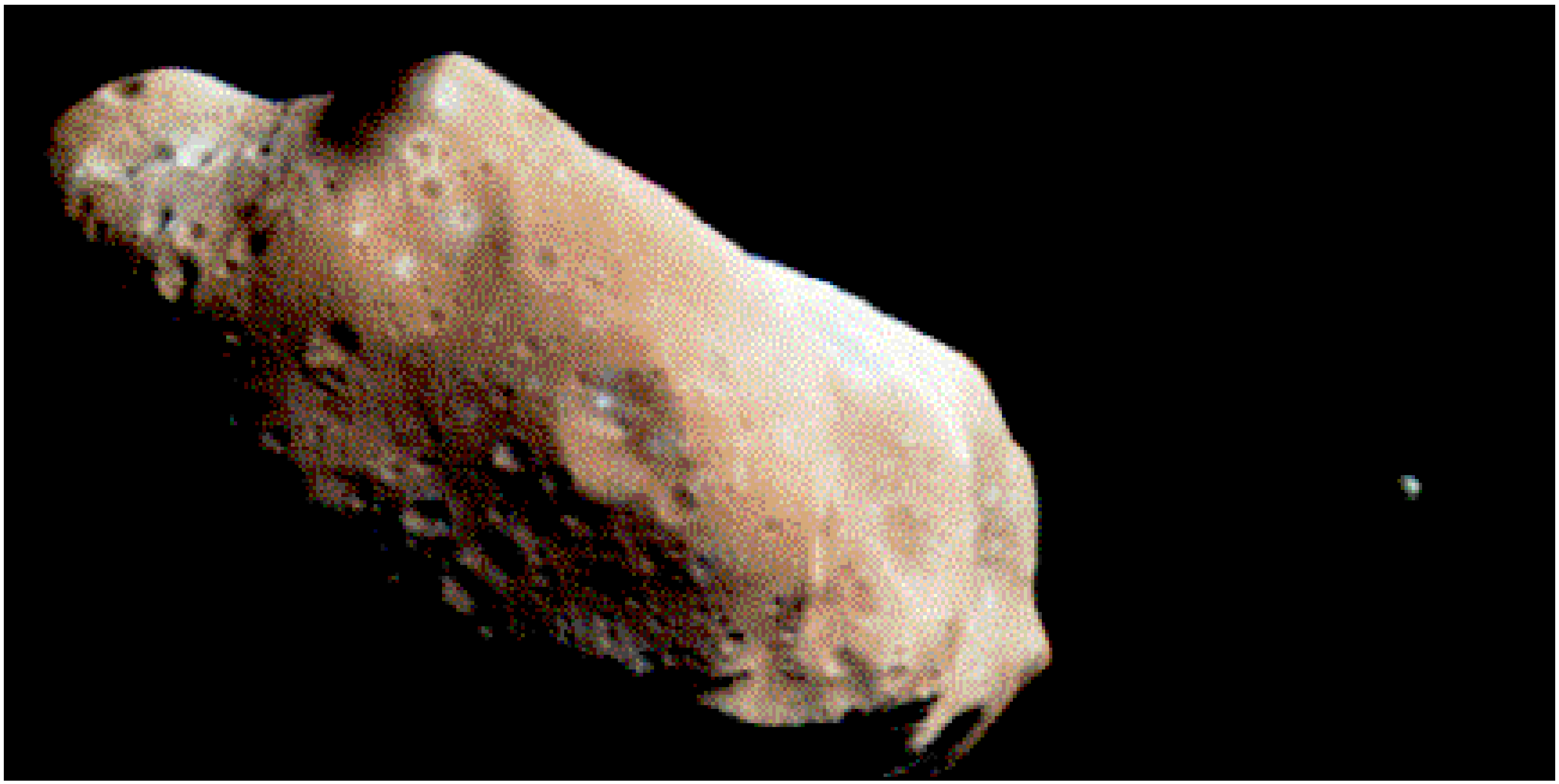
The K-T Extinction





Years between impacts
10^{-12}
10^{-10}
10^{-8}
10^{-6}
10^{-4}
10^{-2}
1
10^{2}
10^{4}
10^{6}
10^{8}
Impactors on the space shuttle surface
(30 μs)
(30 s)
Shooting stars
(1 year)
Meteorites
(10,000 years)
Arizona crater
Sudbury, Ontario, impact feature
10^{-6} (μm)
10^{-4} (cm)
10^{-2}
1 (m)
10^{2}
10^{3} (km)
10^{4}
10^{6}
10^{8}
10^{10}
Diameter of striking object (m)

Asteroid “Ida” and its moon



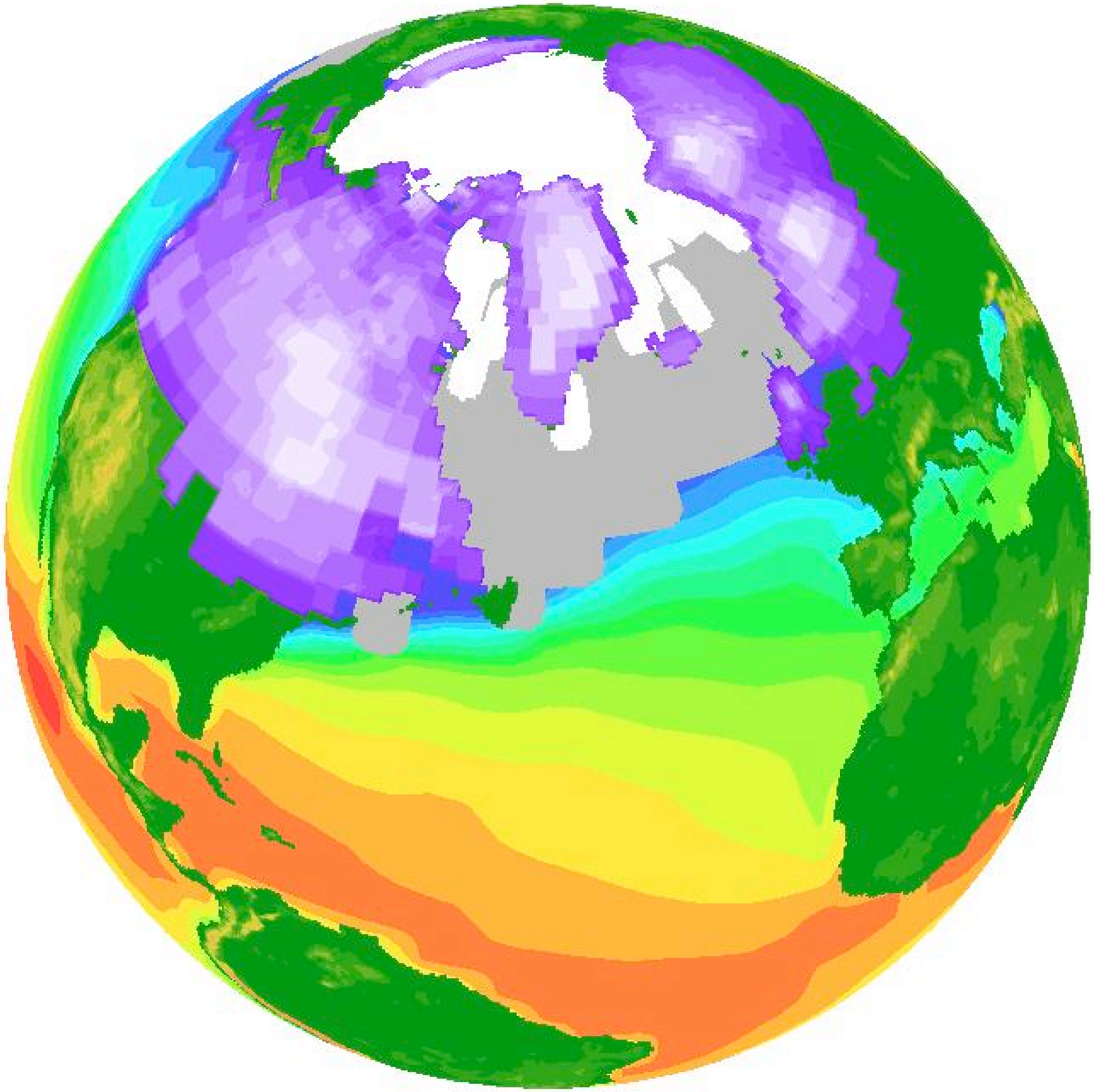
Comet Hale-Bopp

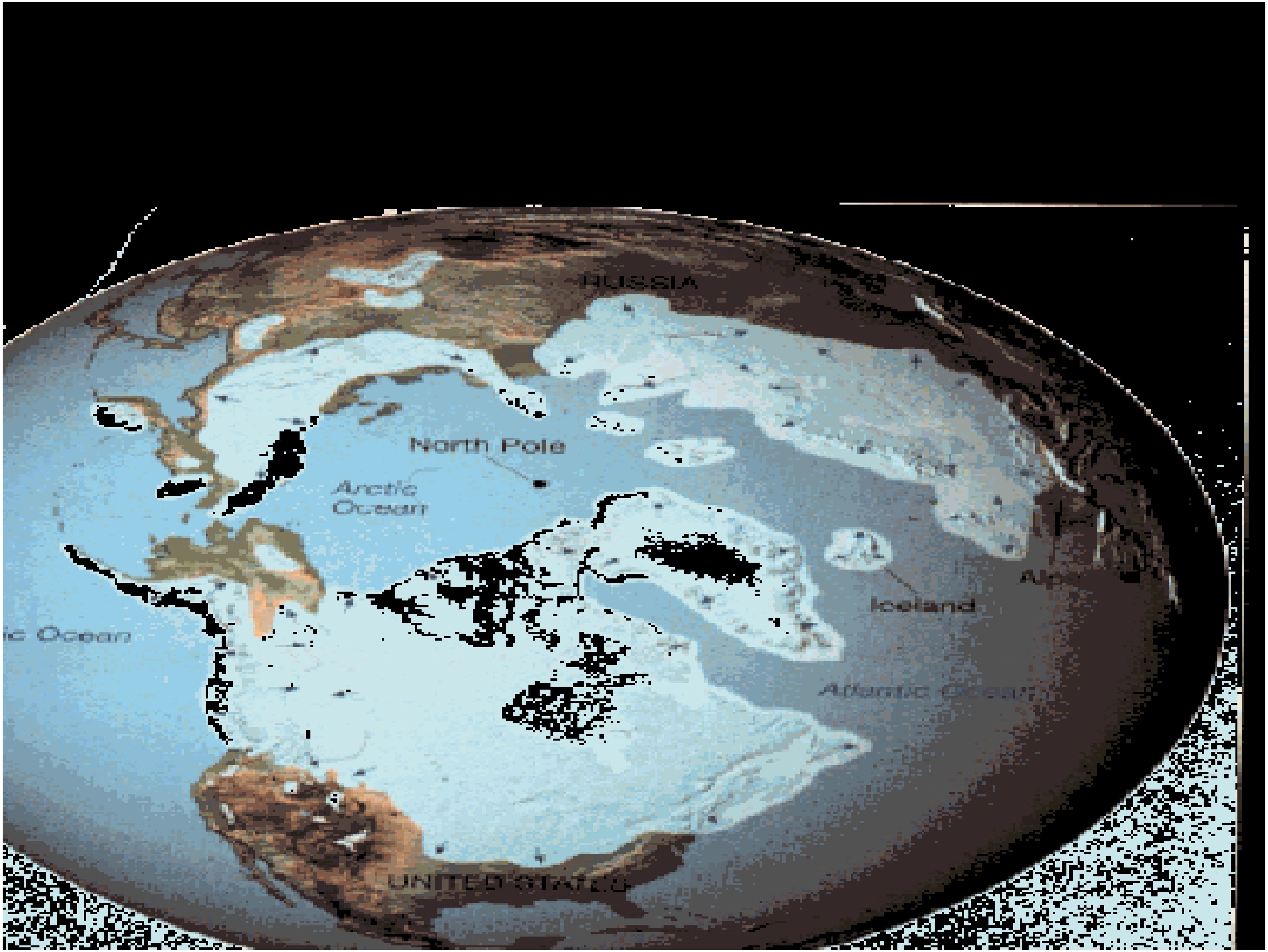
The Quaternary epoch

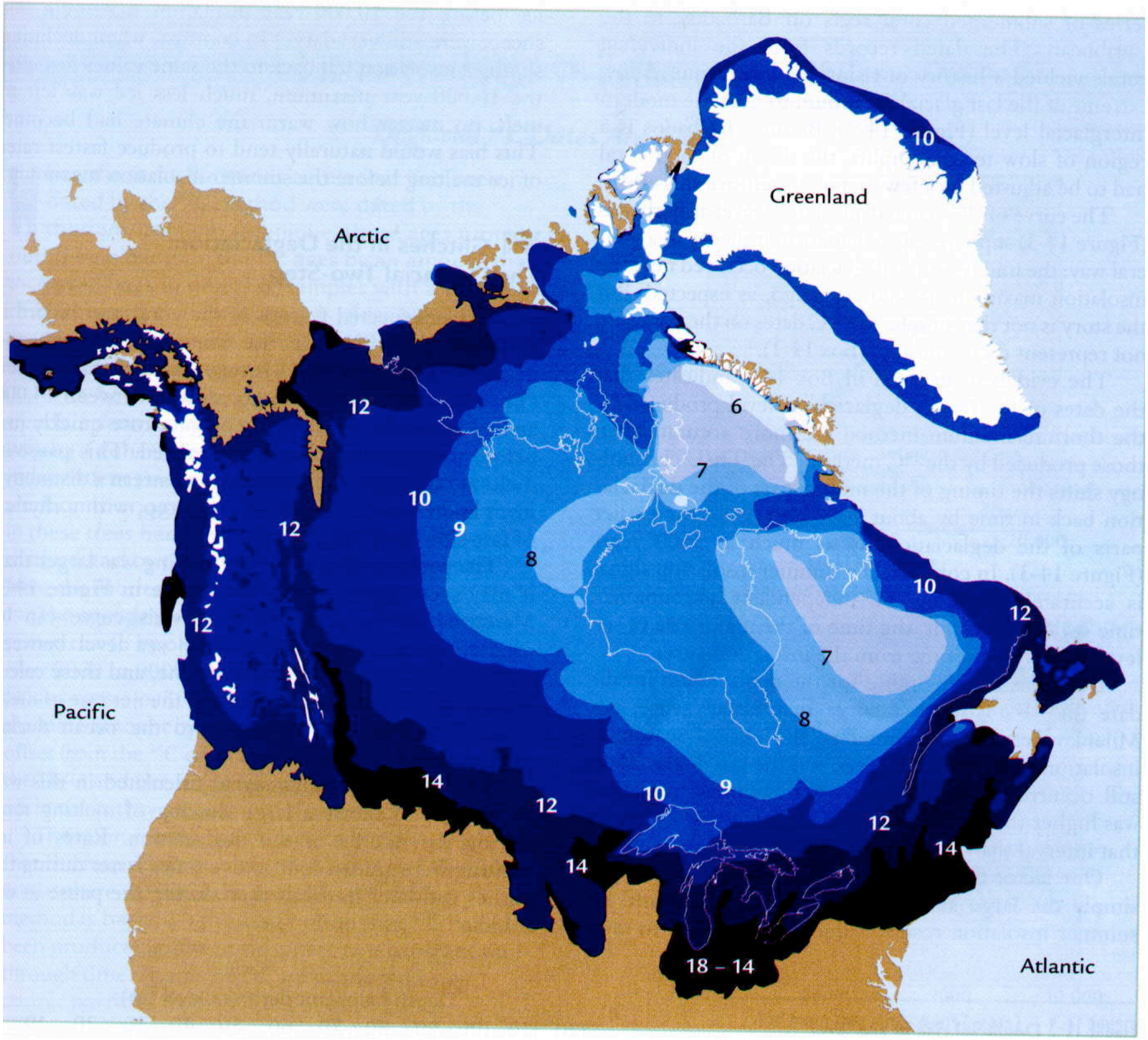
Episodic Northern Hemisphere glaciations

- cold glacial epochs, warmer interglacials
- global in extent
- evident in CO_2, methane, dust
- related to orbital variations (Milankovitch)
- triggered by variations in NH summer insolation

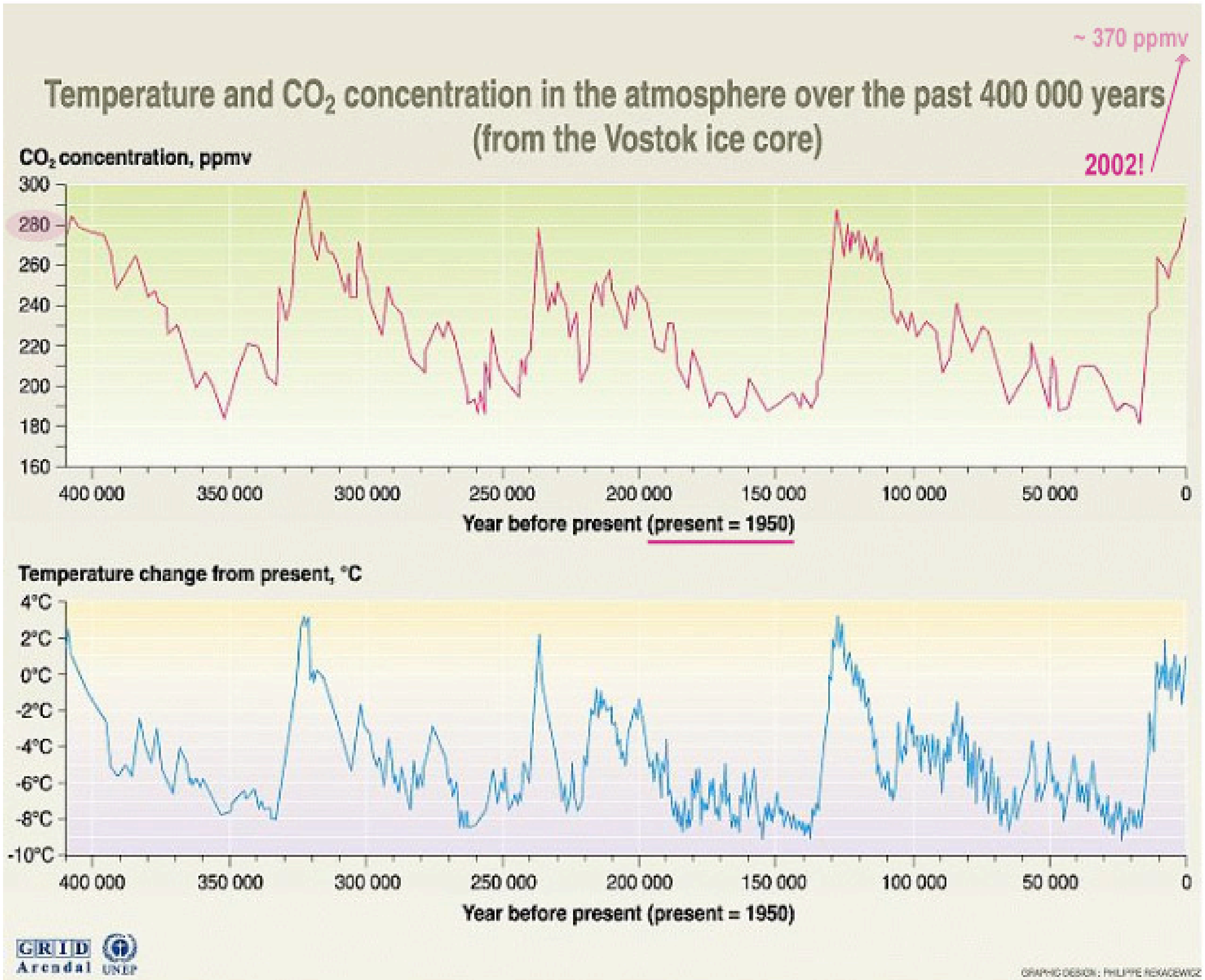
LGM Ice Extent and SST




RUSSIA
North Pole
Arctic Ocean
Iceland
Atlantic Ocean
UNITED STATES


Greenland
10
Arctic
6
7
12
10
12
9
8
10
12
12
7
Pacific
8
14
12
10
9
12
14
14
18 – 14
Atlantic

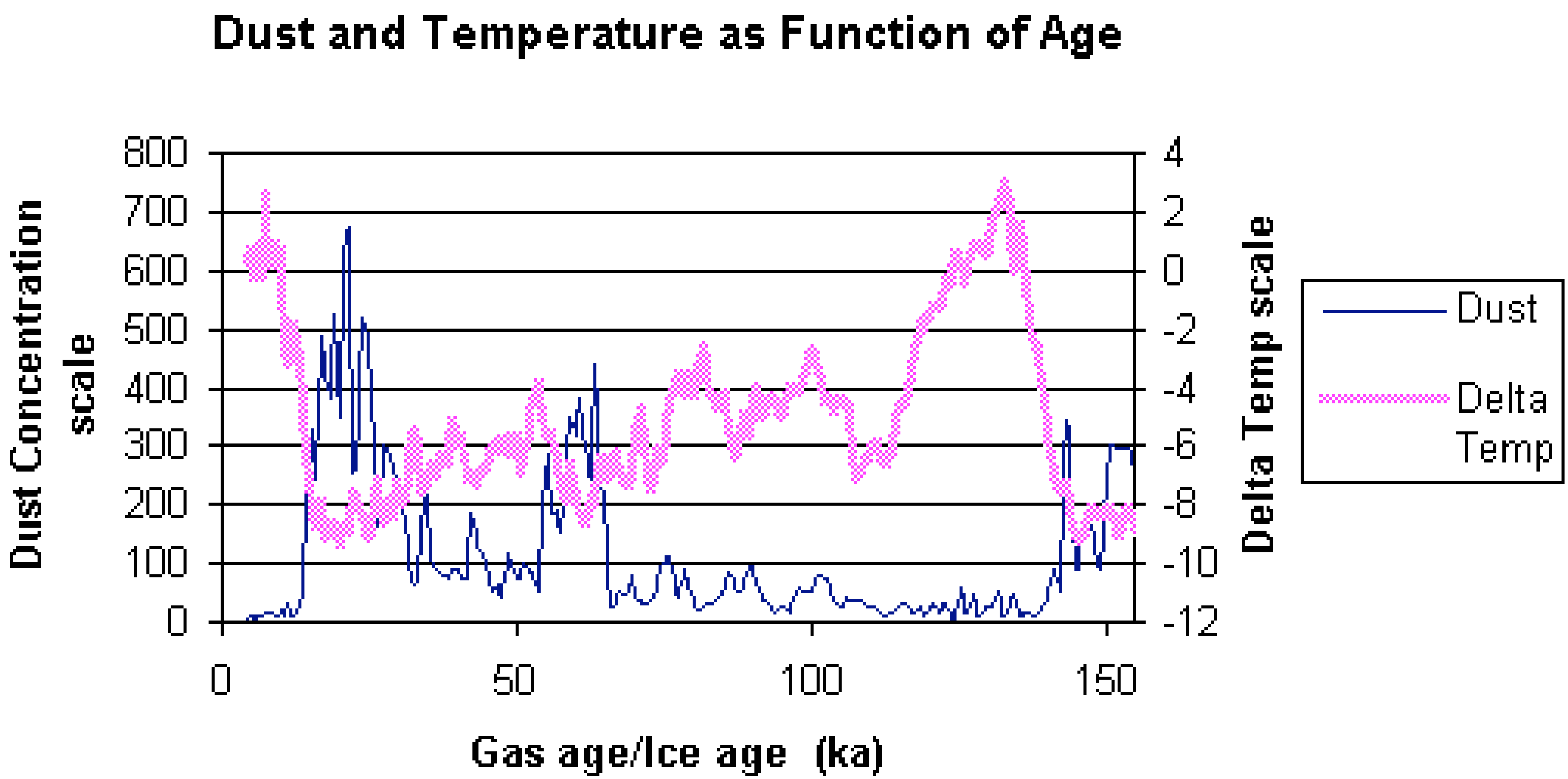
Vostok ice core



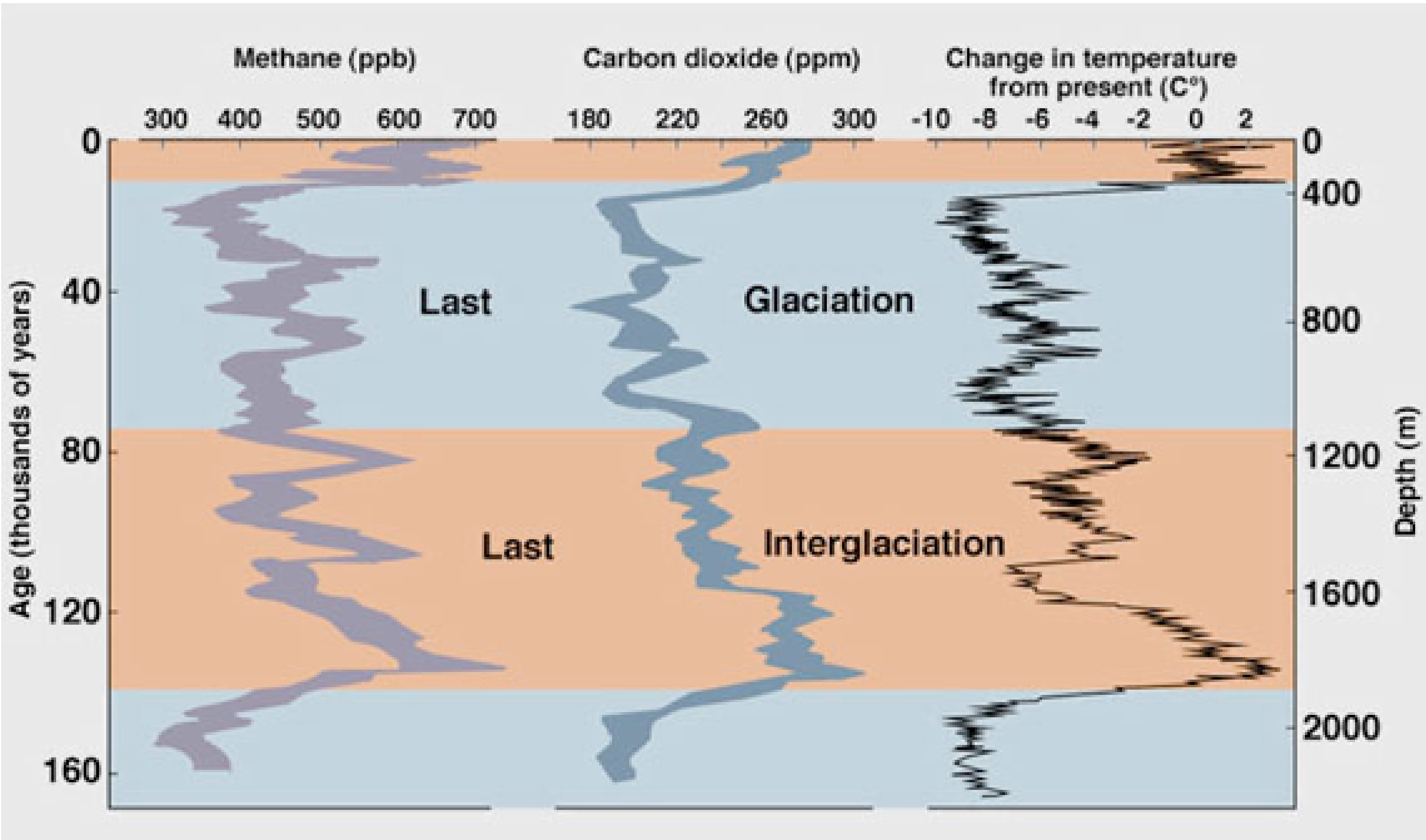
Source: J.R. Petit, J. Jouzel, et al. Climate and atmospheric history of the past 420 000 years from the Vostok ice core in Antarctica, Nature 399 (3JUne), pp 429-436, 1999.

(Note: 2002 information added to diagram)

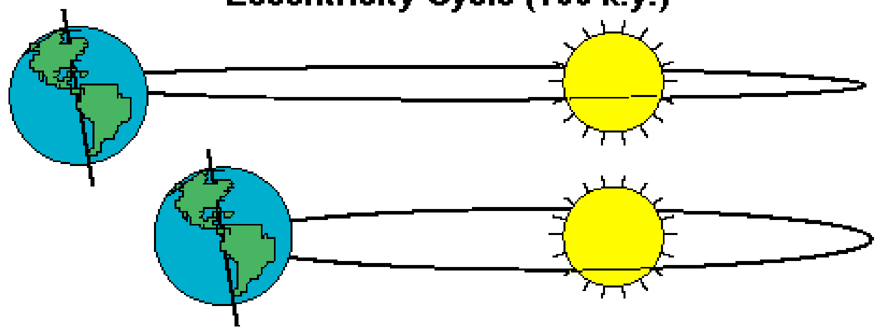
Vostok ice core



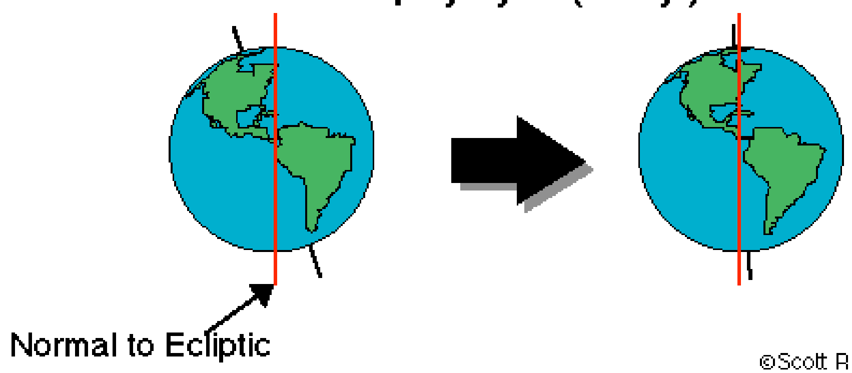
Vostok ice core



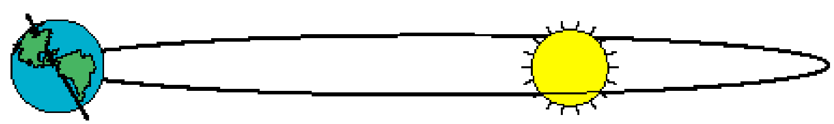
Eccentricity Cycle (100 k.y.)



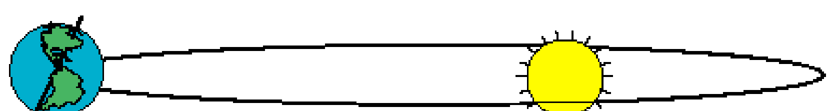
Obliquity Cycle (41 k.y.)



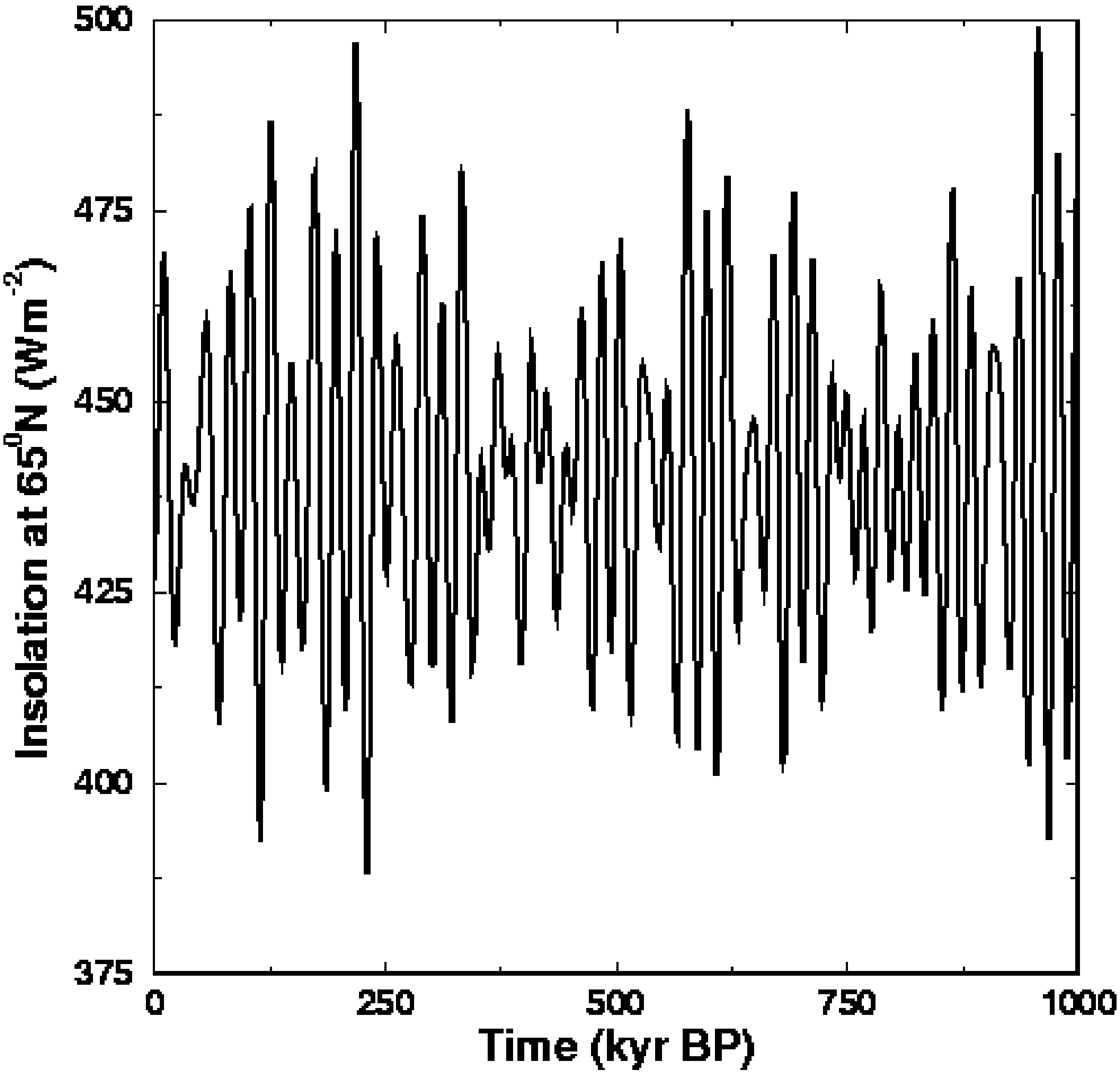
Precession of the Equinoxes (19 and 23 k.y.)



Northern Hemisphere tilted away from the sun at aphelion.



Northern hemisphere tilted toward the sun at aphelion.



500
475
450
425
400
375
Insolation at 65°N (Wm⁻²)
0
250
500
750
1000
Time (kyr BP)

The past 20,000 years

- transition to current interglacial
- The Younger Dryas event

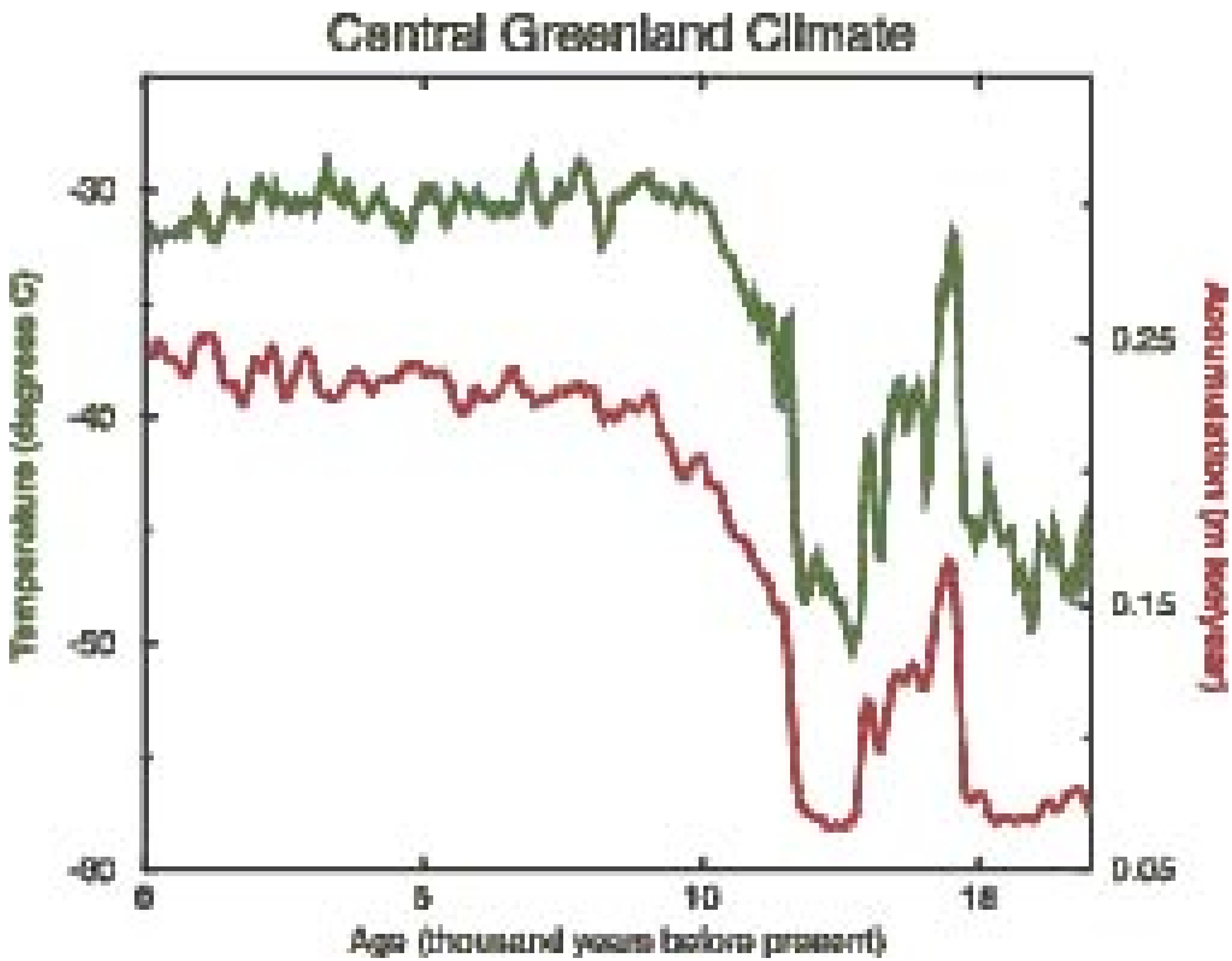
  most clearly apparent in NH high latitudes

  ended abruptly 11,700 ybp
- the Holocene

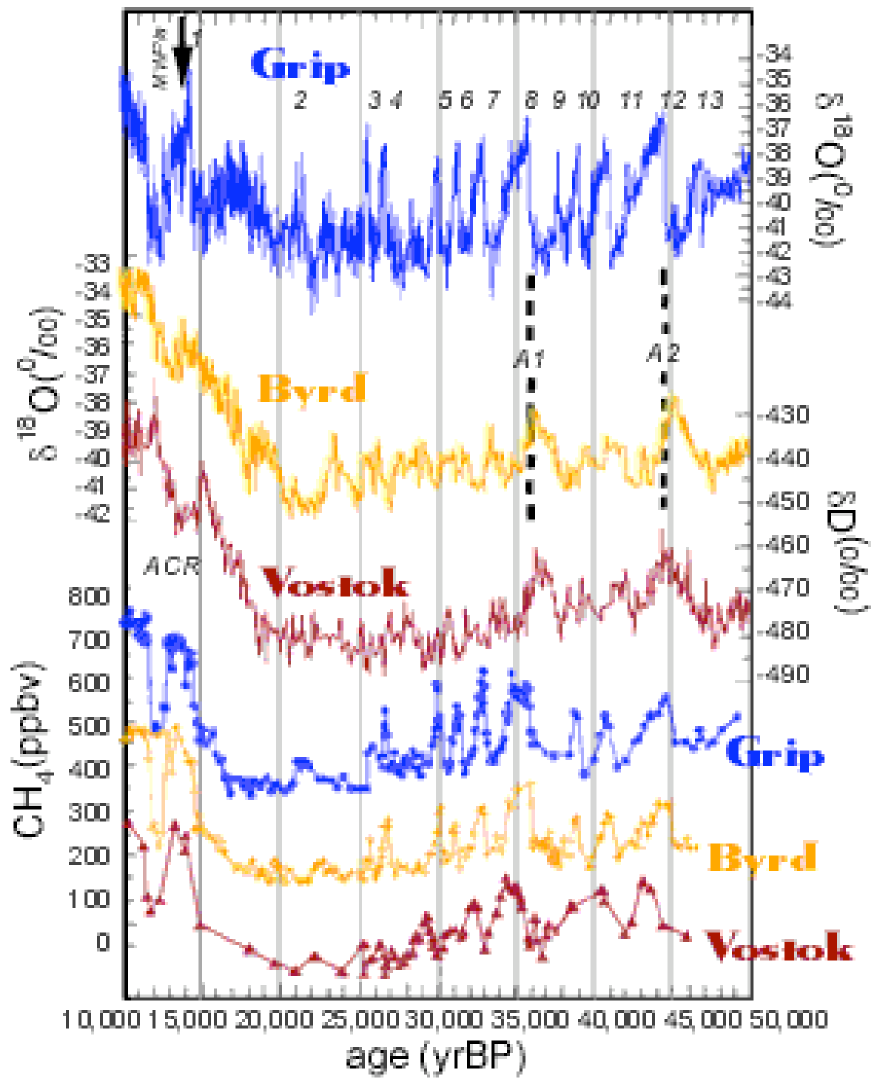
  "relatively" uneventful

  NH subtropical dry belt was wetter 6,000 ybp

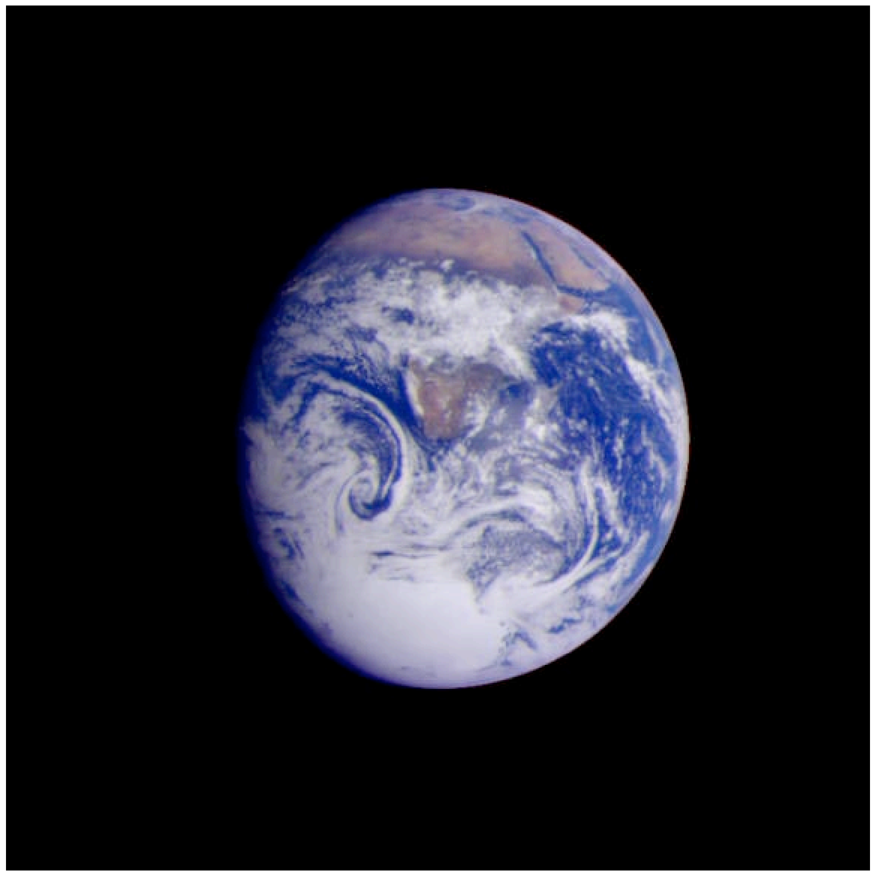
Greenland ice core

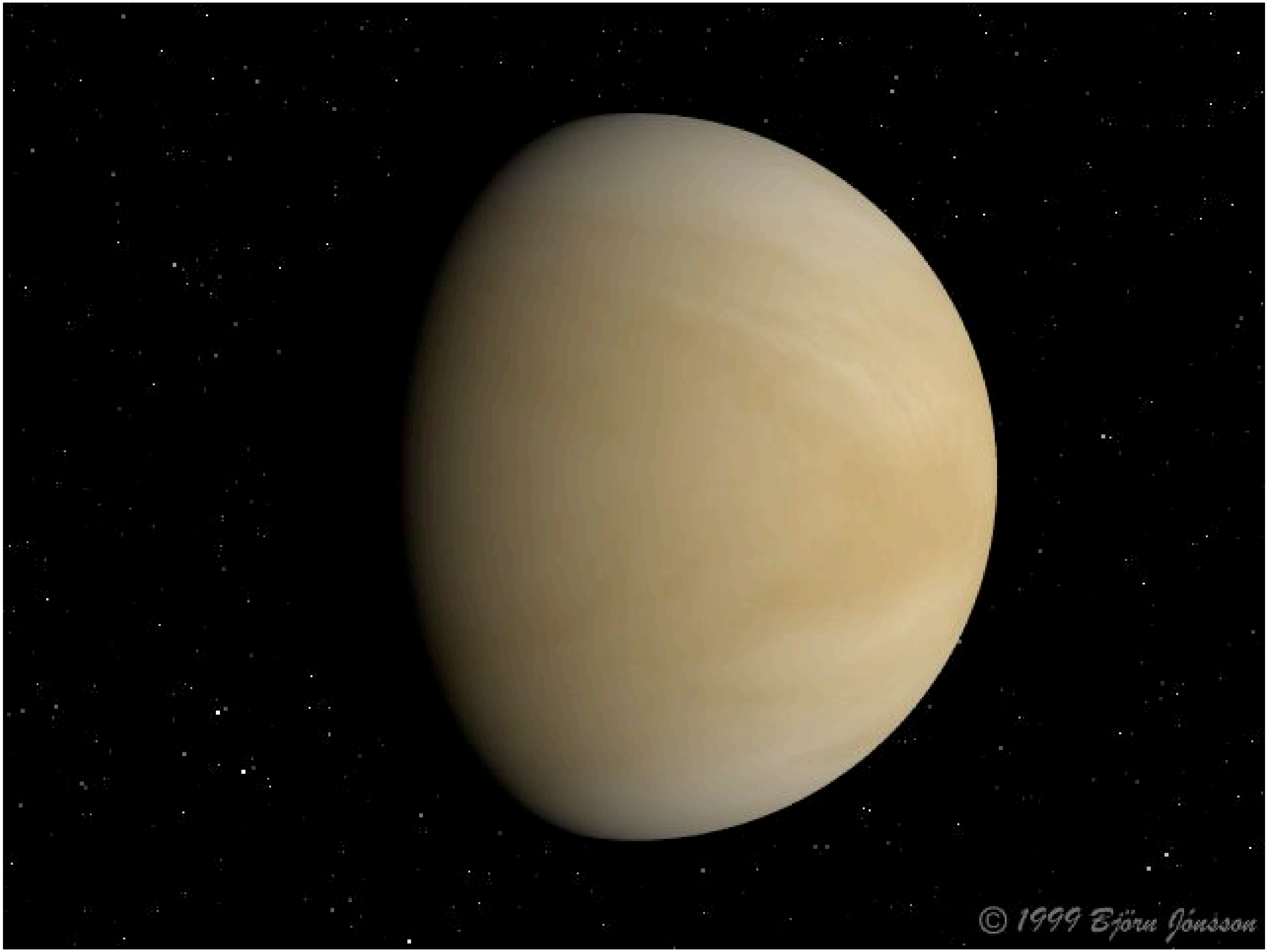


Greenland vs. Antarctica



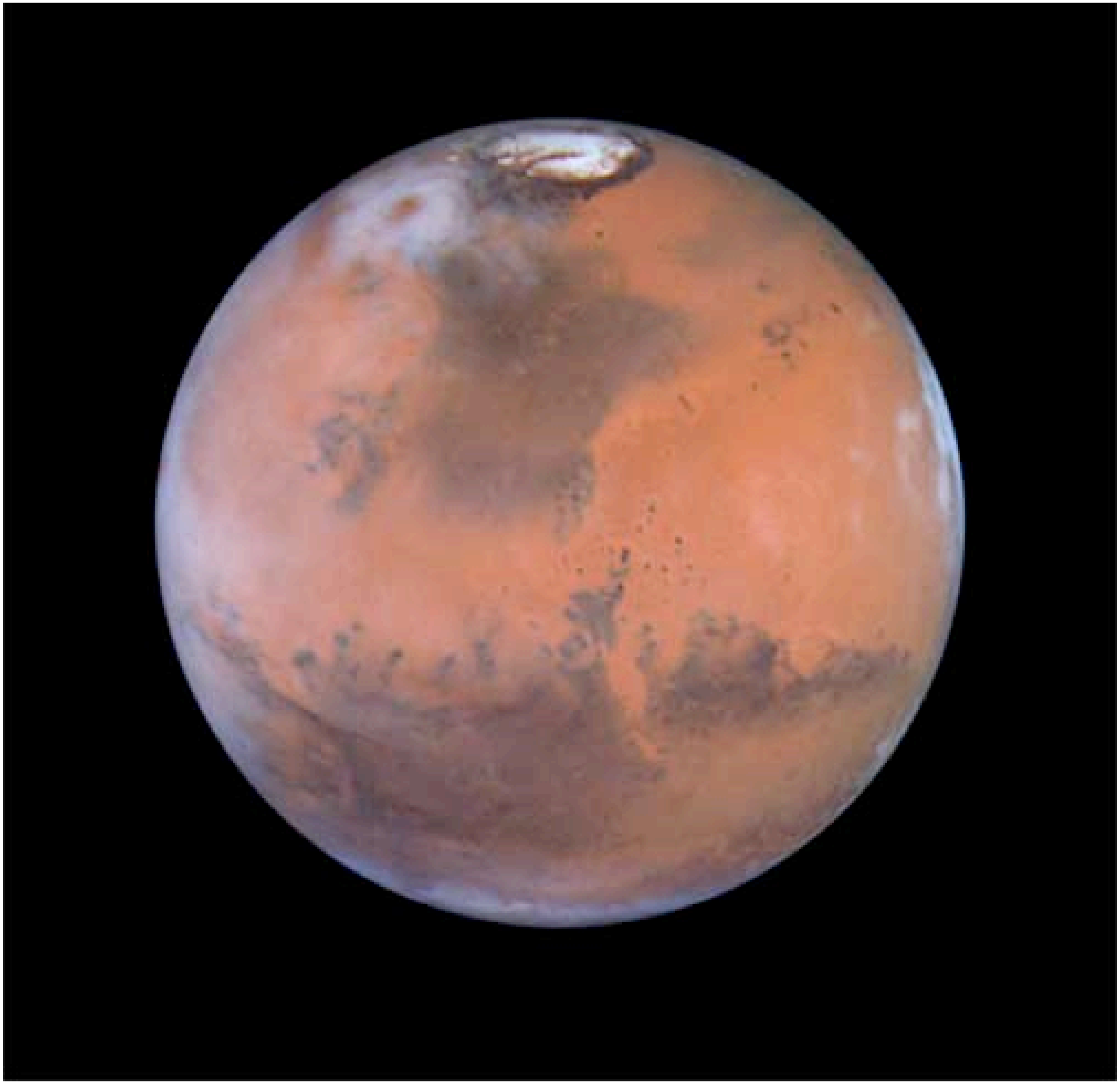
Earth the Habitable Planet

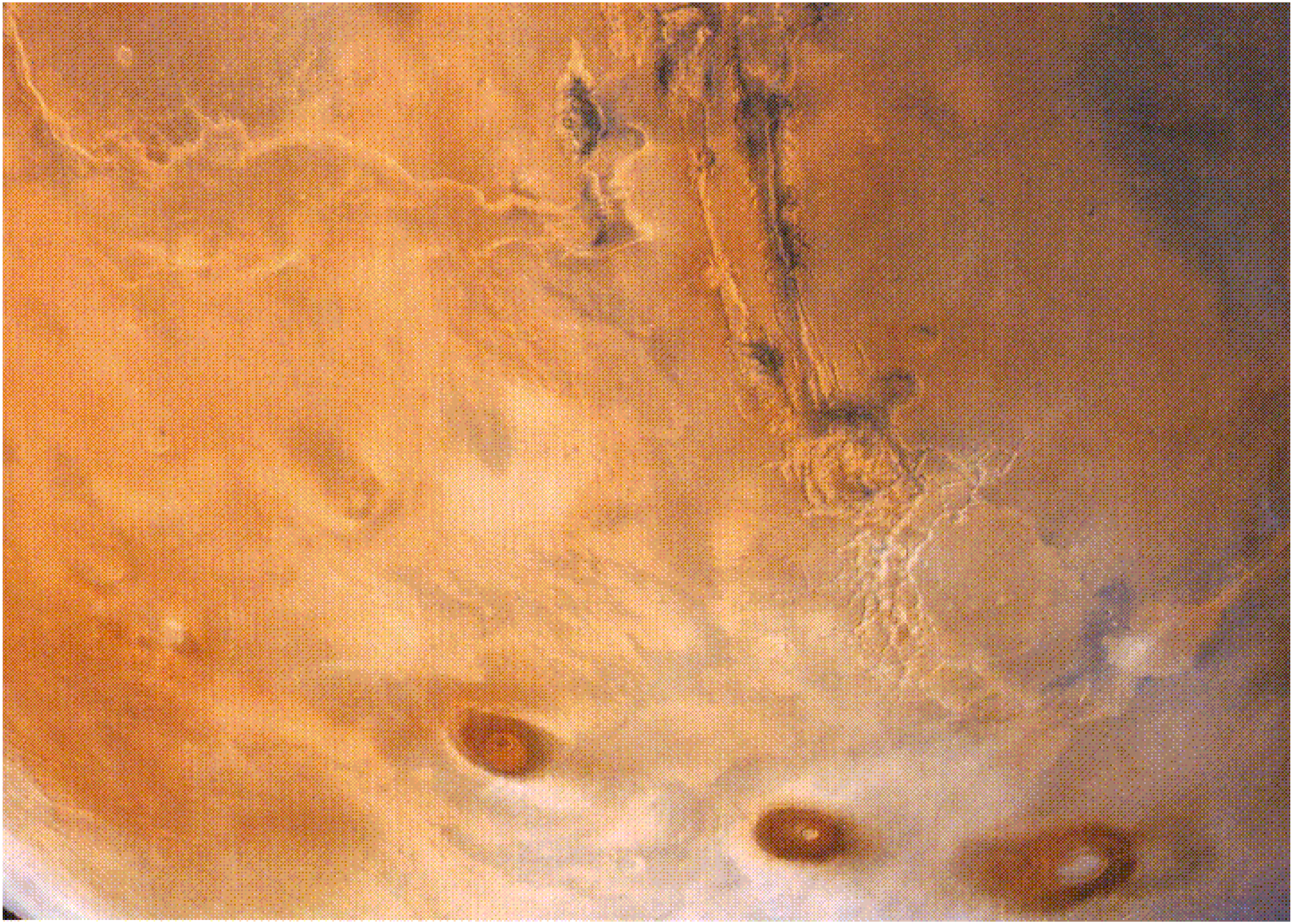


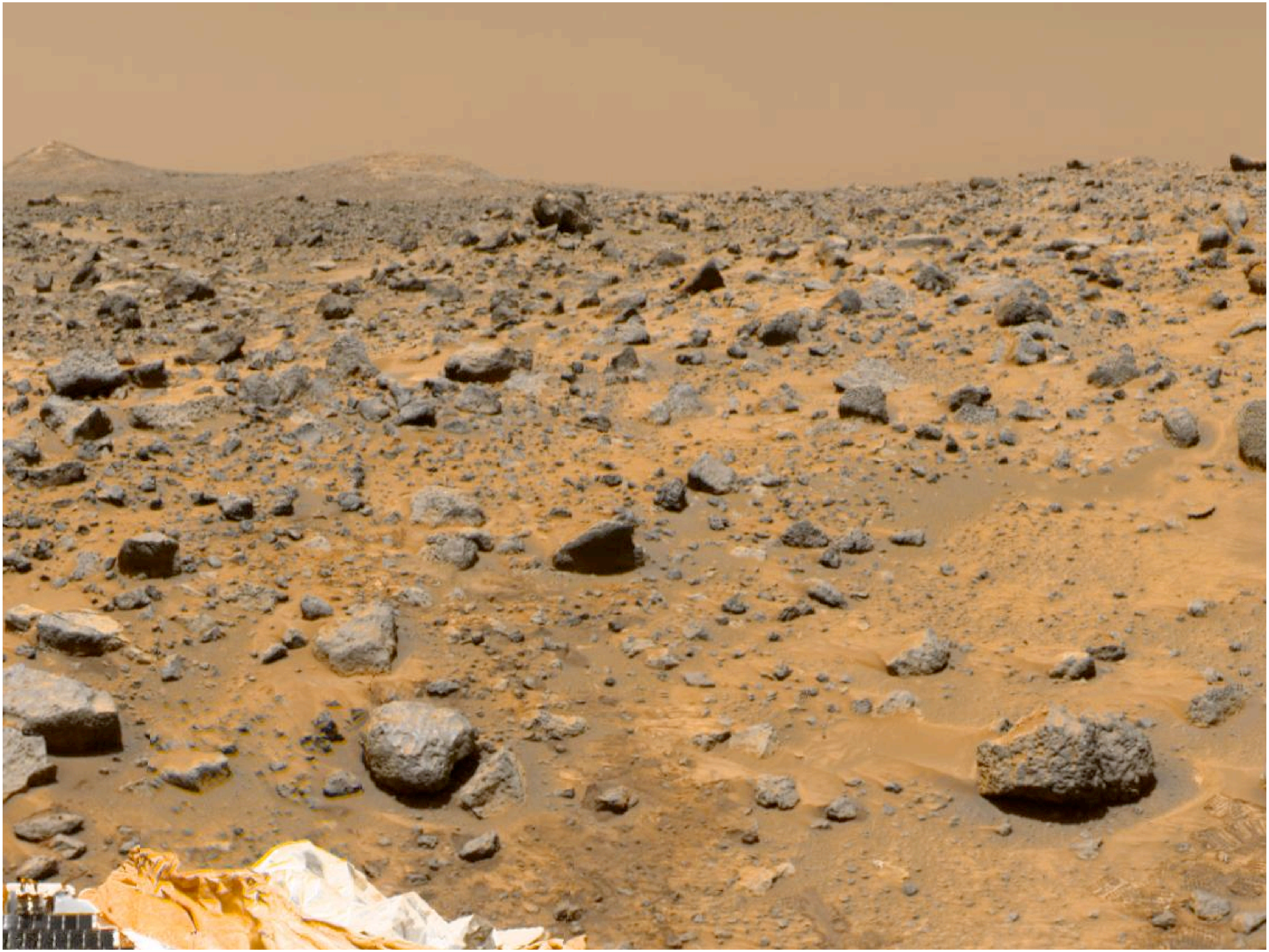

© 1999 Björn Jónsson

Venus

- active plate tectonics
- massive atmosphere (nearly 100 x Earth)
- high planetary albedo
- 96.5% CO_2, 3.5% N_2; absence of hydrogen
- surface temperature 737 K
  super greenhouse
- very slow rotation rate







Mars

- vulcanism has ended
- composition much like Venus
- eccentric orbit
- surface pressure 7-9 hPa
- global dust storms
- short radiative time scale
- strong tidal motions, baroclinic waves
- evidence of water erosion?

Jupiter

- abundance of hydrogen and helium
- deep atmosphere
- rapid (10 hr) rotation, long lived features
- emits more radiation than it absorbs
- its moons have interesting atmospheres

Earth the habitable planet

- Temperatures amenable for liquid water
- escape of hydrogen
- active plate tectonics
- active hydrologic cycle
- massive outer planets
- large moon
- rotation