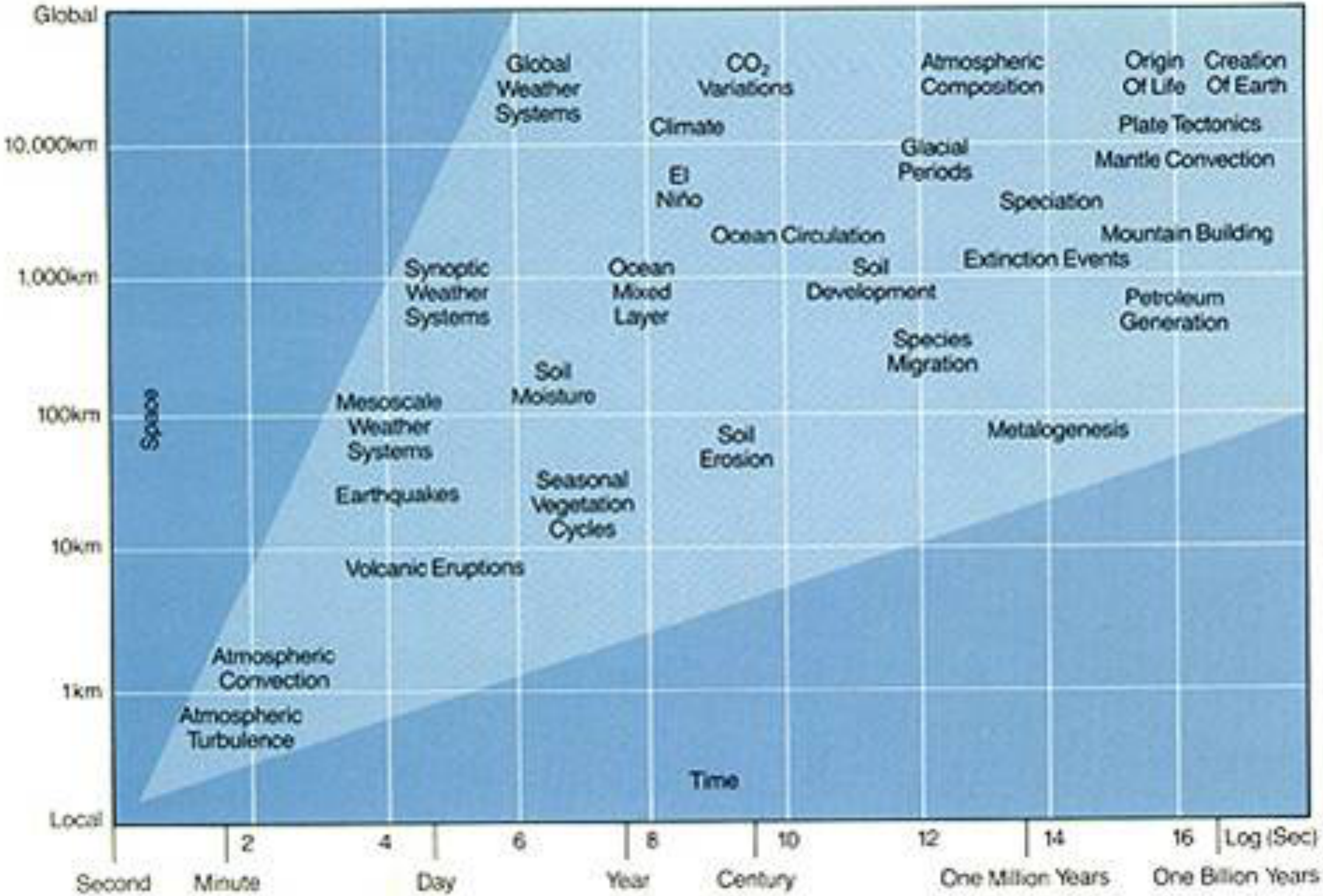
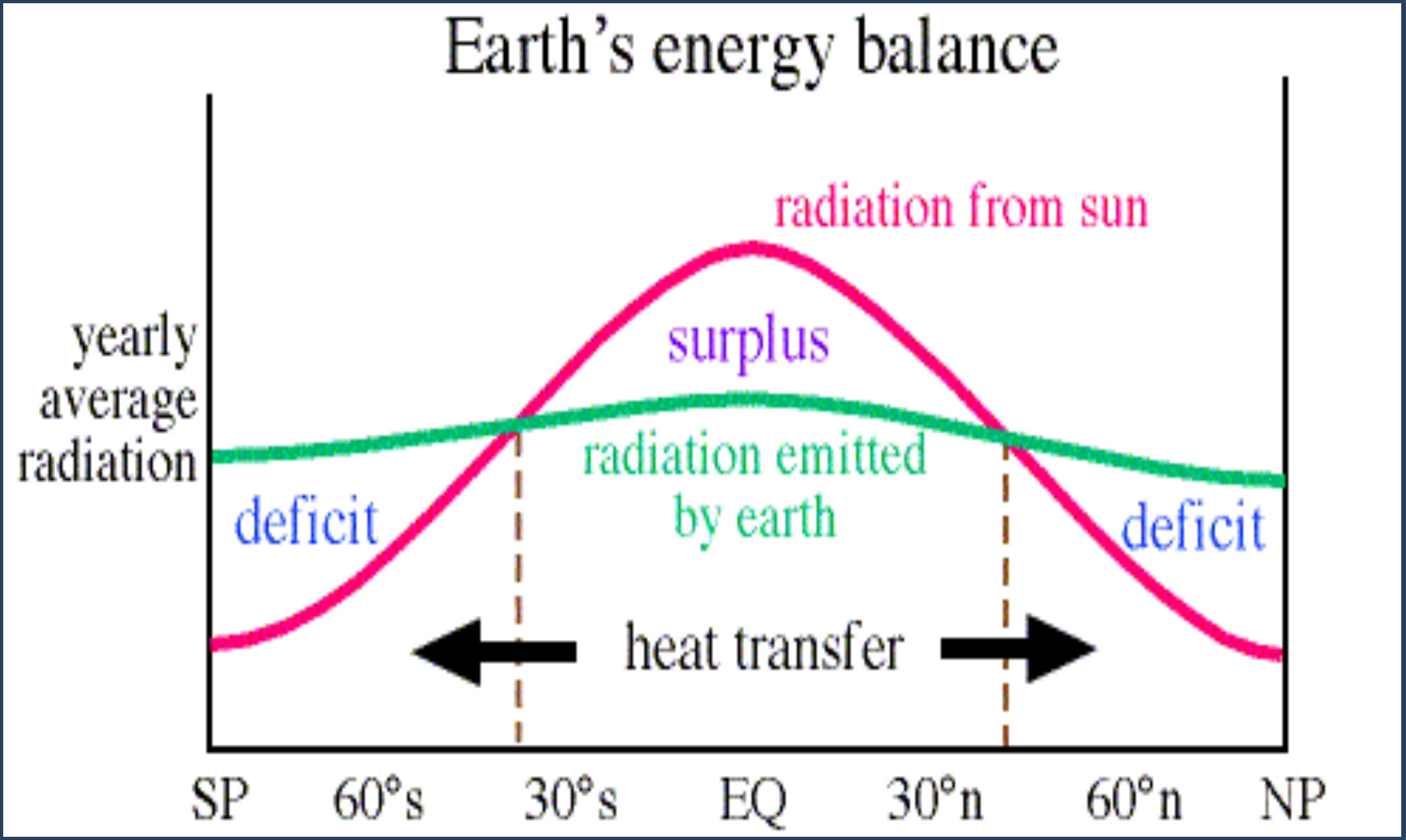
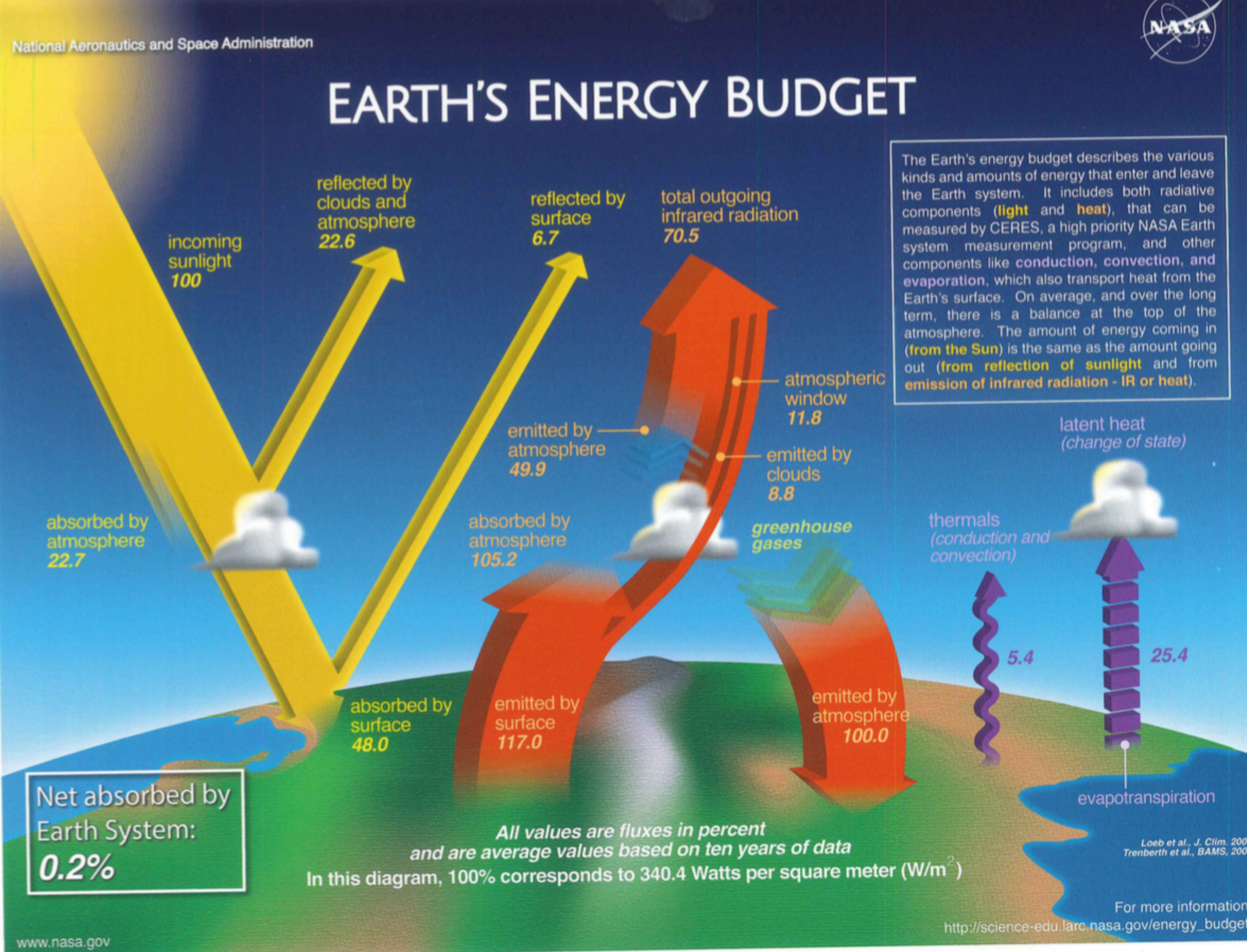
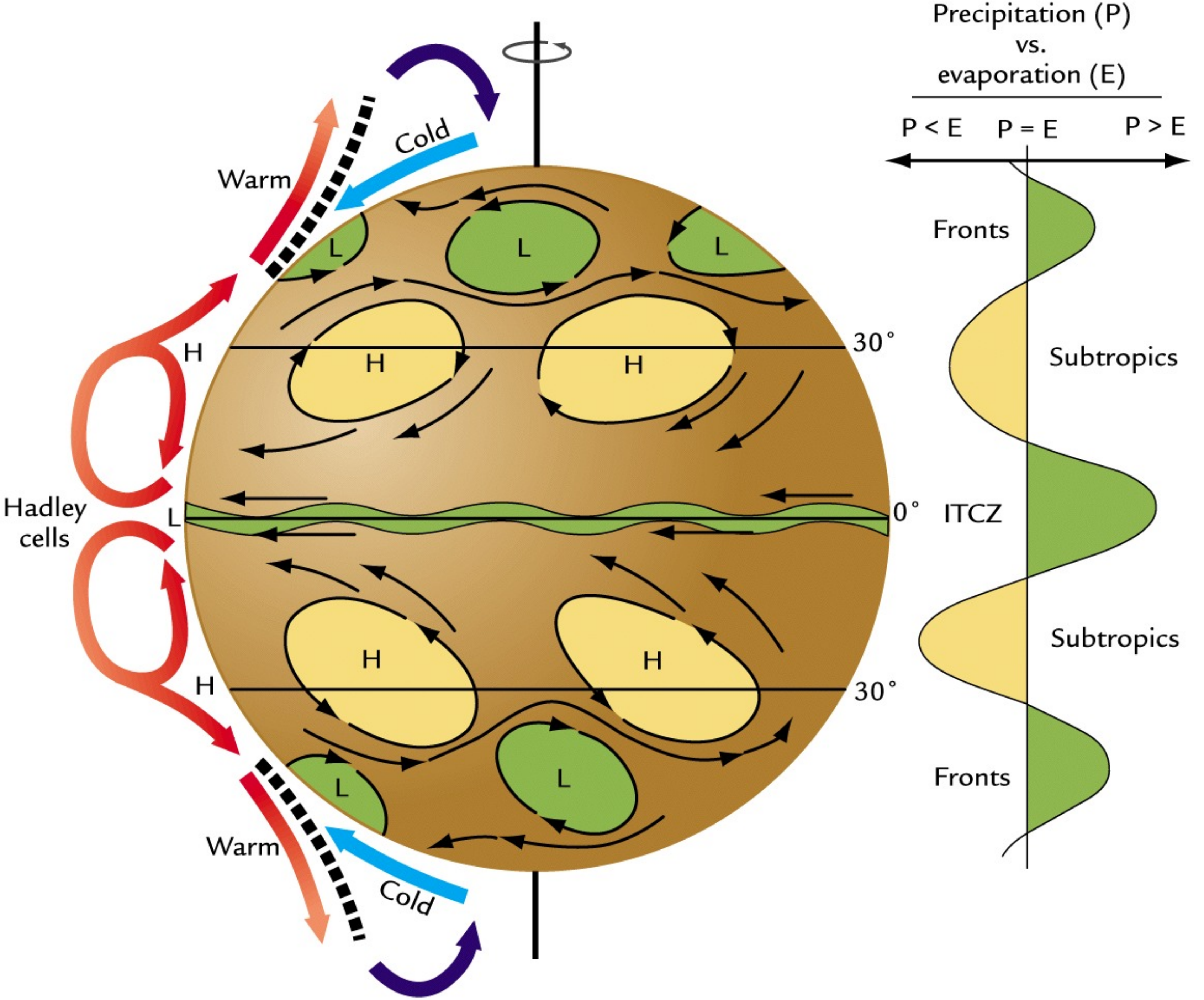
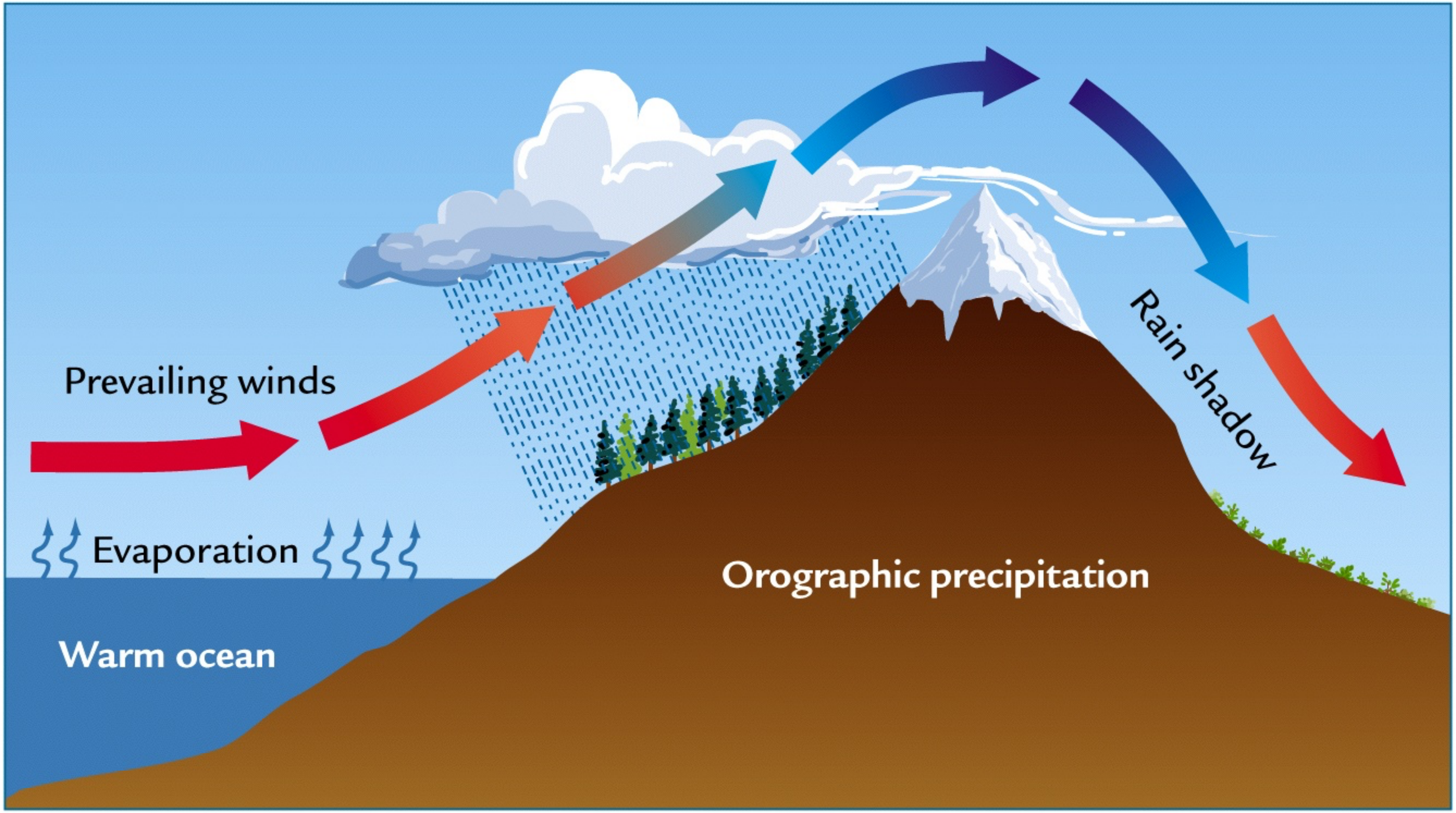

Global
10,000km
1,000km
100km
10km
1km
Local
Space
Global Weather Systems
CO_2 Variations
Atmospheric Composition
Origin Of Life
Creation Of Earth
Climate
Plate Tectonics
Glacial Periods
Mantle Convection
El Niño
Speciation
Ocean Circulation
Mountain Building
Extinction Events
Synoptic Weather Systems
Ocean Mixed Layer
Soil Development
Petroleum Generation
Species Migration
Soil Moisture
Mesoscale Weather Systems
Metalogenesis
Soil Erosion
Seasonal Vegetation Cycles
Earthquakes
Volcanic Eruptions
Atmospheric Convection
Atmospheric Turbulence
Time
2
4
6
8
10
12
14
16
Log (Sec)
Second
Minute
Day
Year
Century
One Million Years
One Billion Years

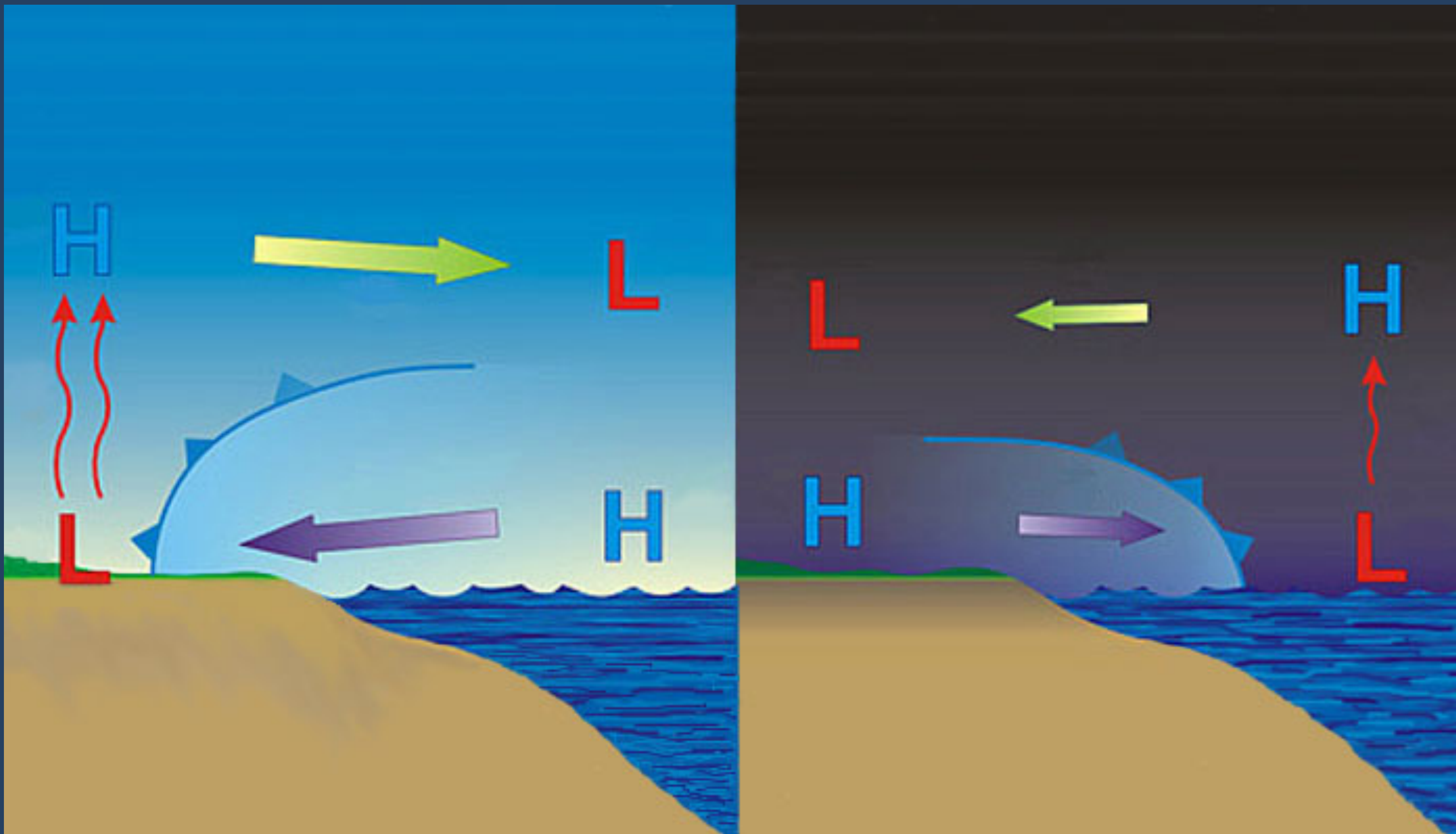

Earth's energy balance
yearly
average
radiation
radiation from sun
surplus
radiation emitted
by earth
deficit
deficit
heat transfer
SP
60°s
30°s
EQ
30°n
60°n
NP


National Aeronautics and Space Administration
NASA
EARTH'S ENERGY BUDGET
The Earth's energy budget describes the various kinds and amounts of energy that enter and leave the Earth system. It includes both radiative components (light and heat), that can be measured by CERES, a high priority NASA Earth system measurement program, and other components like conduction, convection, and evaporation, which also transport heat from the Earth's surface. On average, and over the long term, there is a balance at the top of the atmosphere. The amount of energy coming in (from the Sun) is the same as the amount going out (from reflection of sunlight and from emission of infrared radiation - IR or heat).
incoming sunlight 100
reflected by clouds and atmosphere 22.6
reflected by surface 6.7
total outgoing infrared radiation 70.5
atmospheric window 11.8
emitted by atmosphere 49.9
emitted by clouds 8.8
latent heat (change of state)
absorbed by atmosphere 22.7
absorbed by atmosphere 105.2
greenhouse gases
thermals (conduction and convection)
5.4
25.4
absorbed by surface 48.0
emitted by surface 117.0
emitted by atmosphere 100.0
evapotranspiration
Net absorbed by Earth System: 0.2%
All values are fluxes in percent and are average values based on ten years of data
In this diagram, 100% corresponds to 340.4 Watts per square meter (W/m²)
Loeb et al., J. Clim. 2009
Trenberth et al., BAMS, 2009
For more information: http://science-edu.larc.nasa.gov/energy_budget/
www.nasa.gov

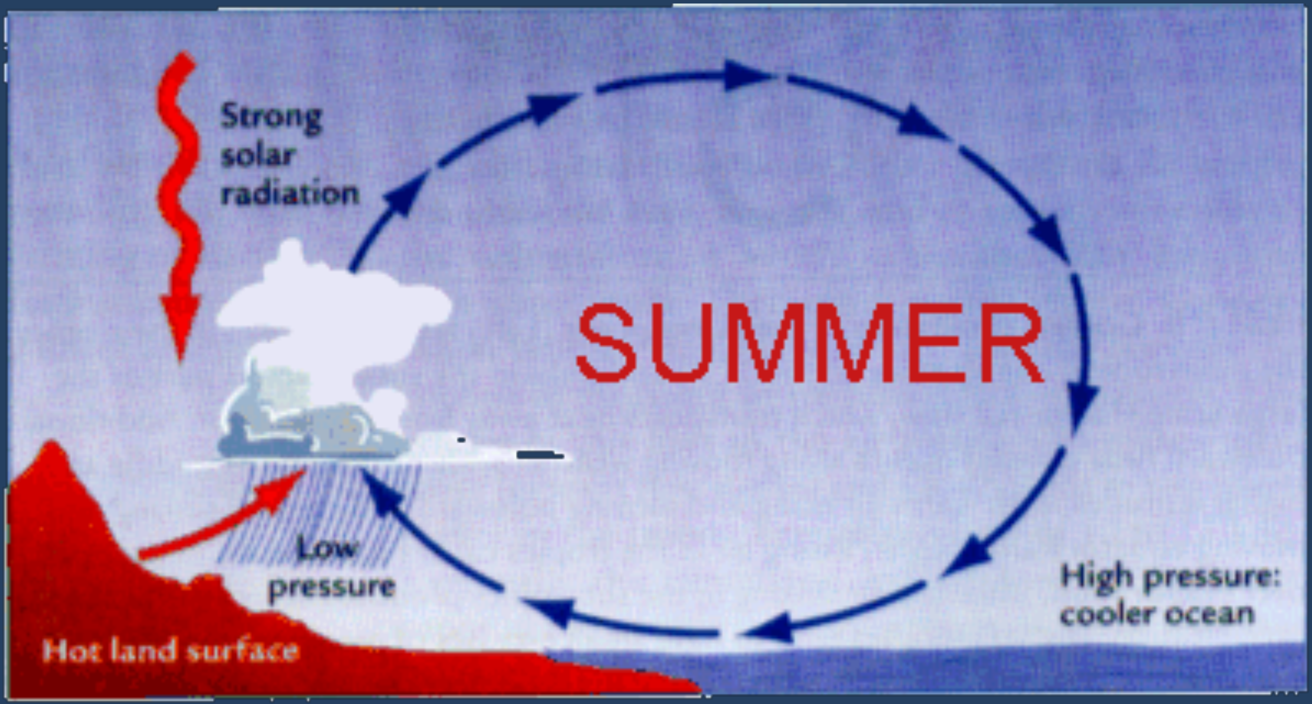


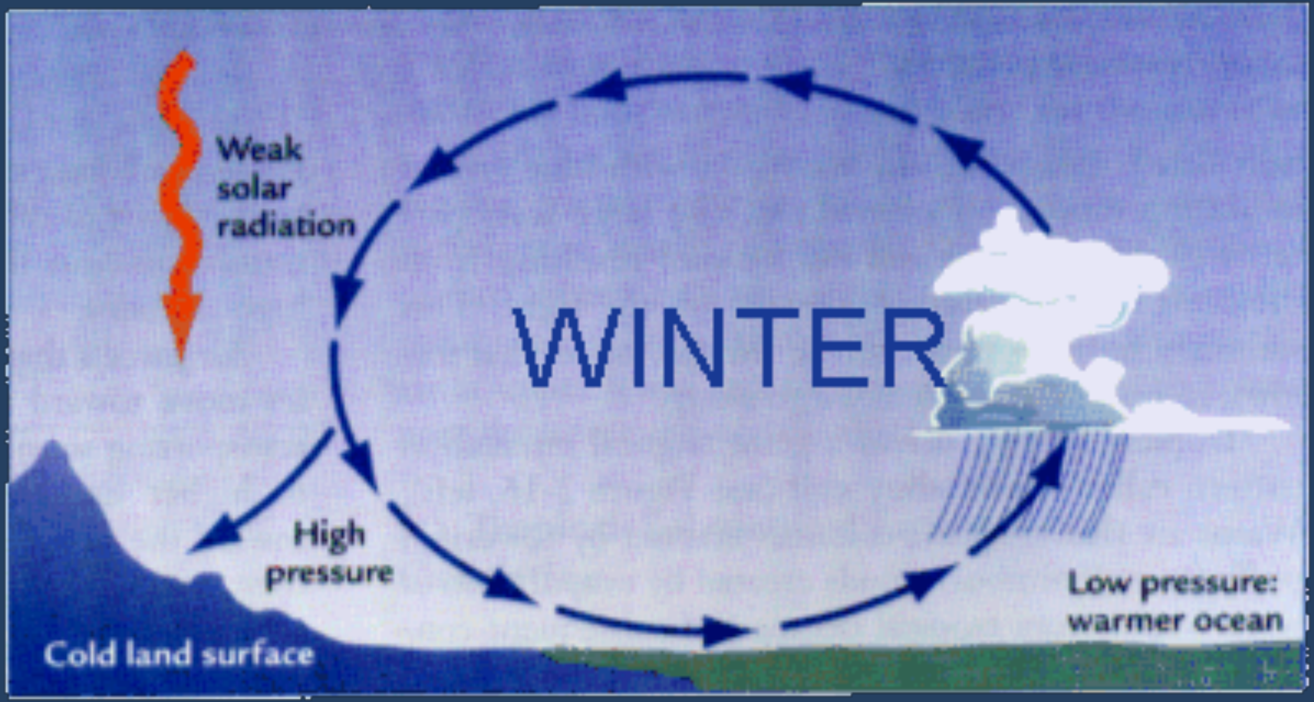
Precipitation (P)
vs.
evaporation (E)
P < E
P = E
P > E
Fronts
Subtropics
ITCZ
Subtropics
Fronts
30°
0°
30°
Cold
Warm
L
L
L
H
H
H
Hadley
cells
L
H
H
H
L
L
Warm
Cold

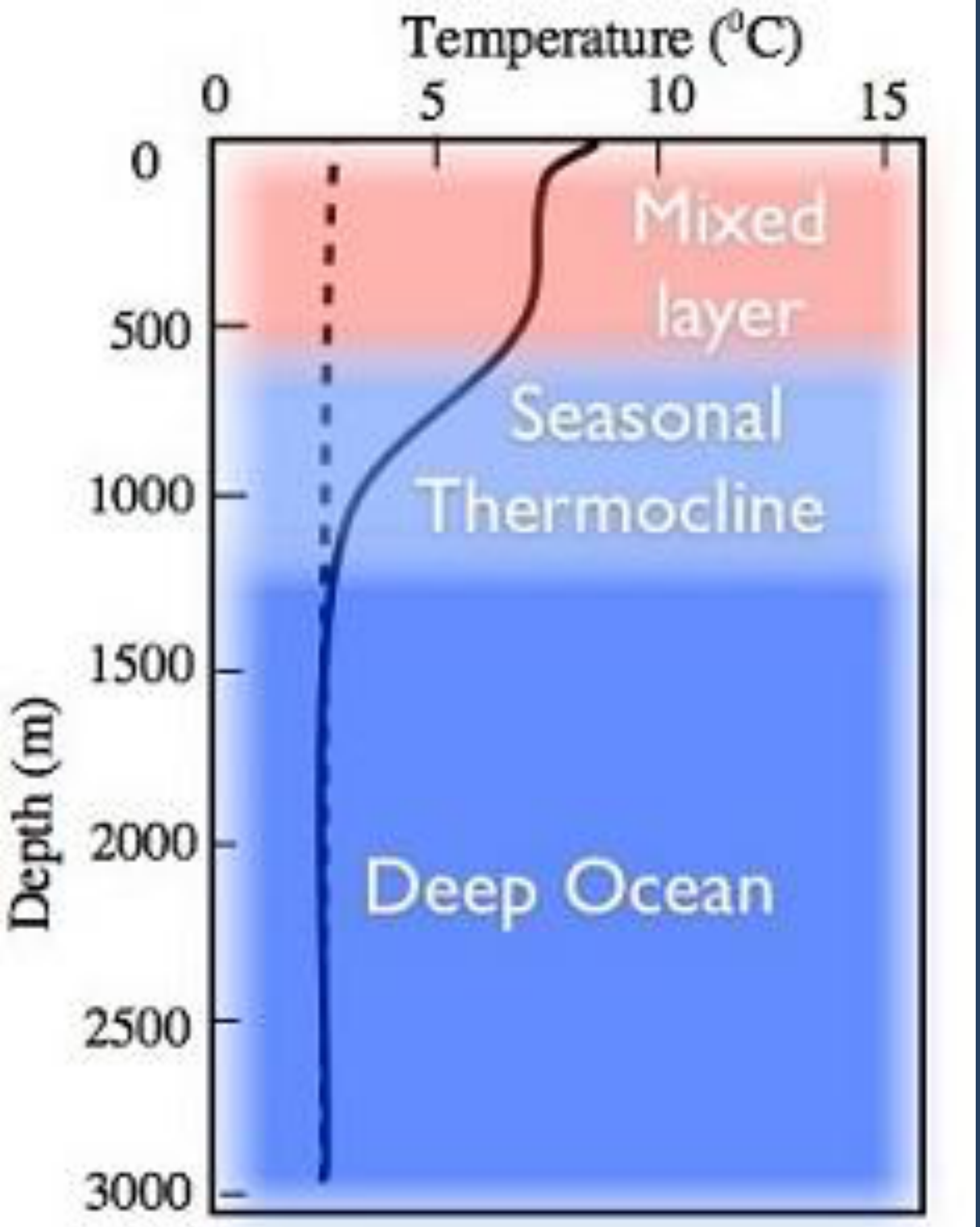

Prevailing winds
Evaporation
Warm ocean
Orographic precipitation
Rain shadow



H
L
L
H
L
H
H
L


Strong
solar
radiation
SUMMER
Low
pressure
High pressure:
cooler ocean
Hot land surface

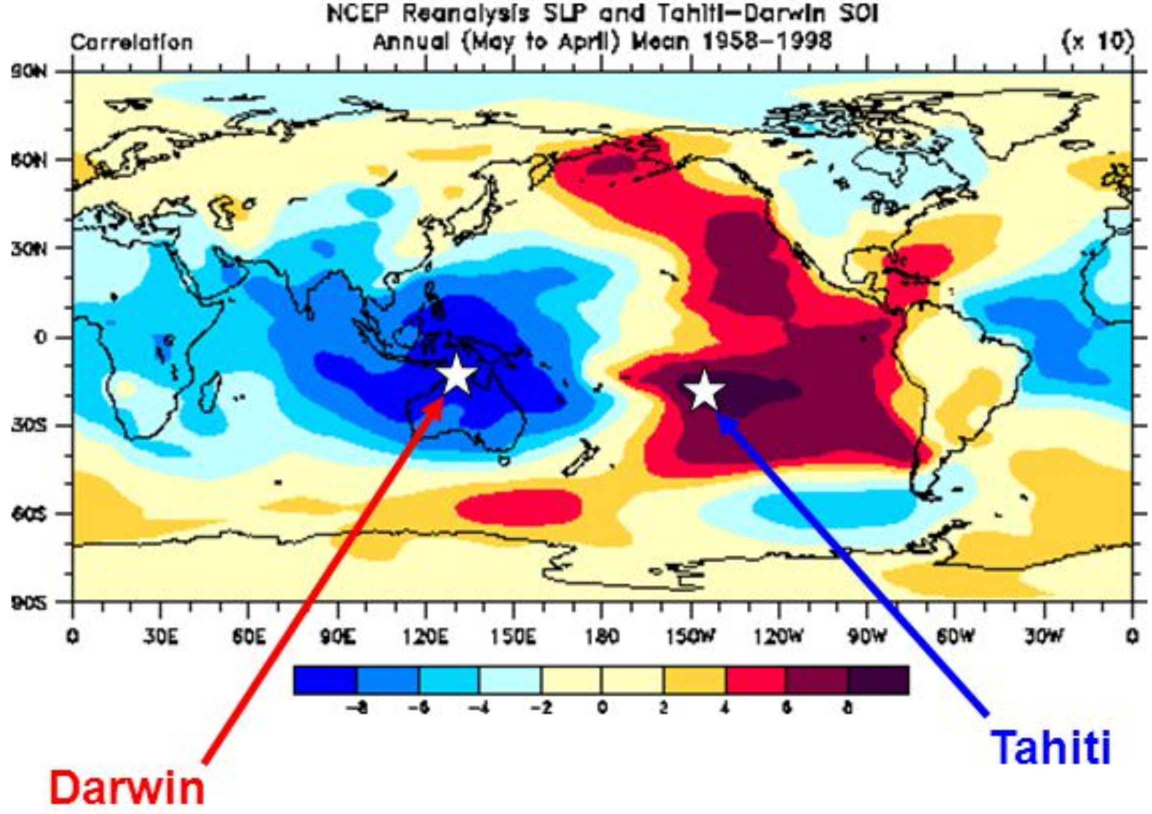

Weak
solar
radiation
WINTER
High
pressure
Low pressure:
warmer ocean
Cold land surface



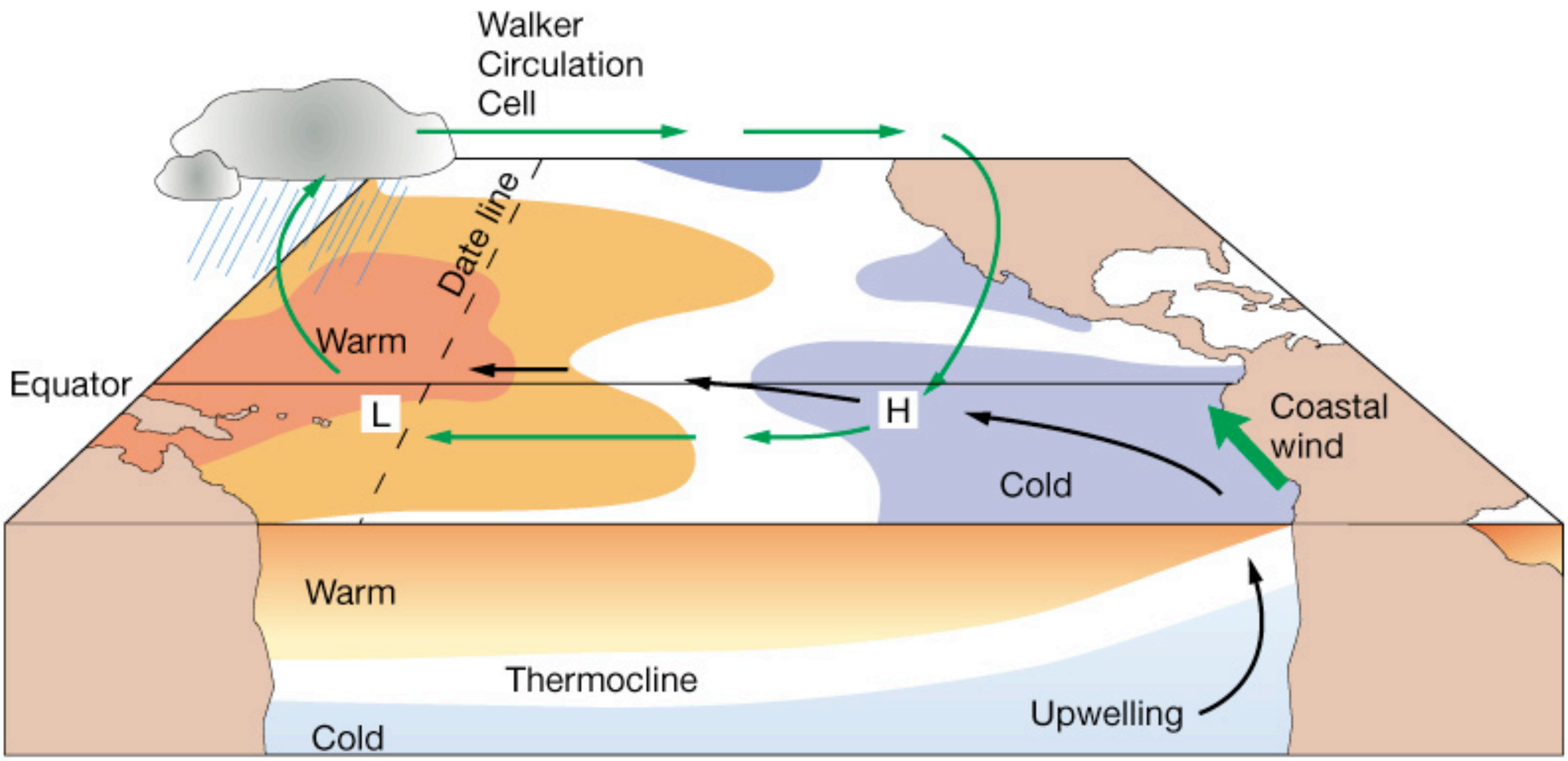
Temperature (°C)
0
5
10
15
0
500
1000
1500
2000
2500
3000
Depth (m)
Mixed layer
Seasonal Thermocline
Deep Ocean

The Southern Oscillation

Sir Gilbert Walker
(1868-1958)

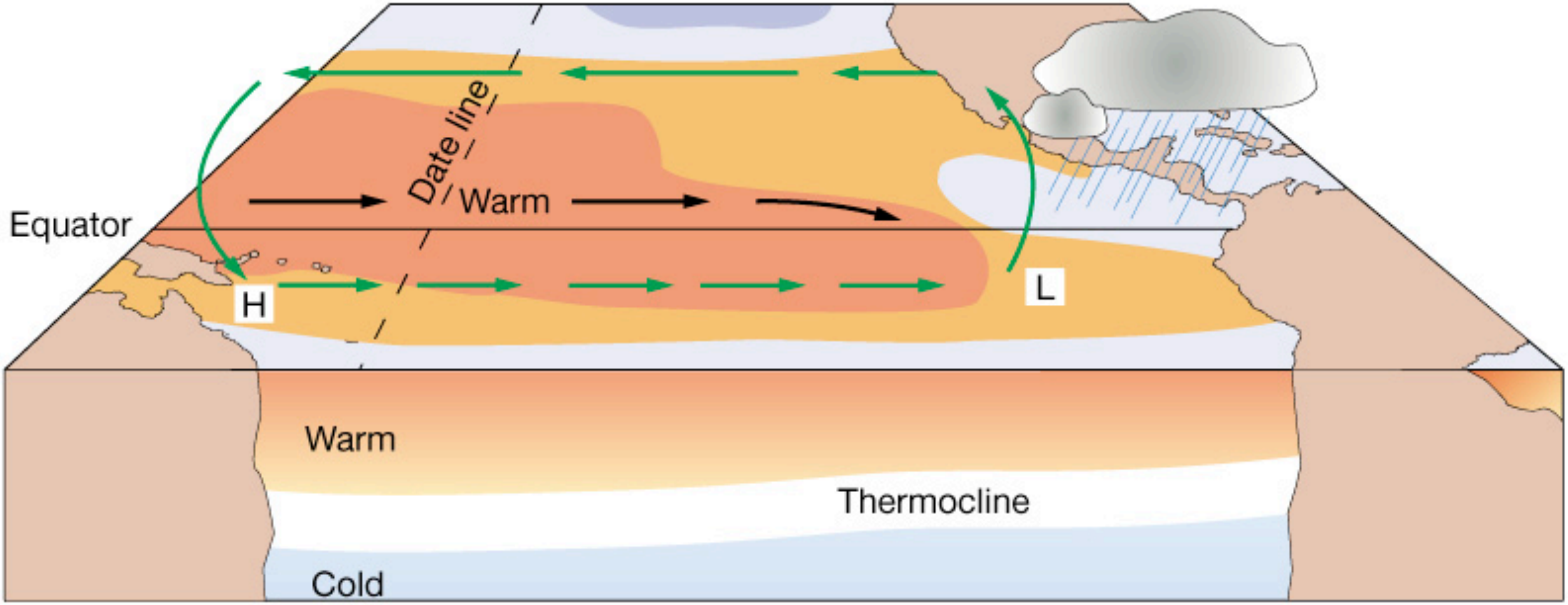


Normal conditions in the Pacific Ocean



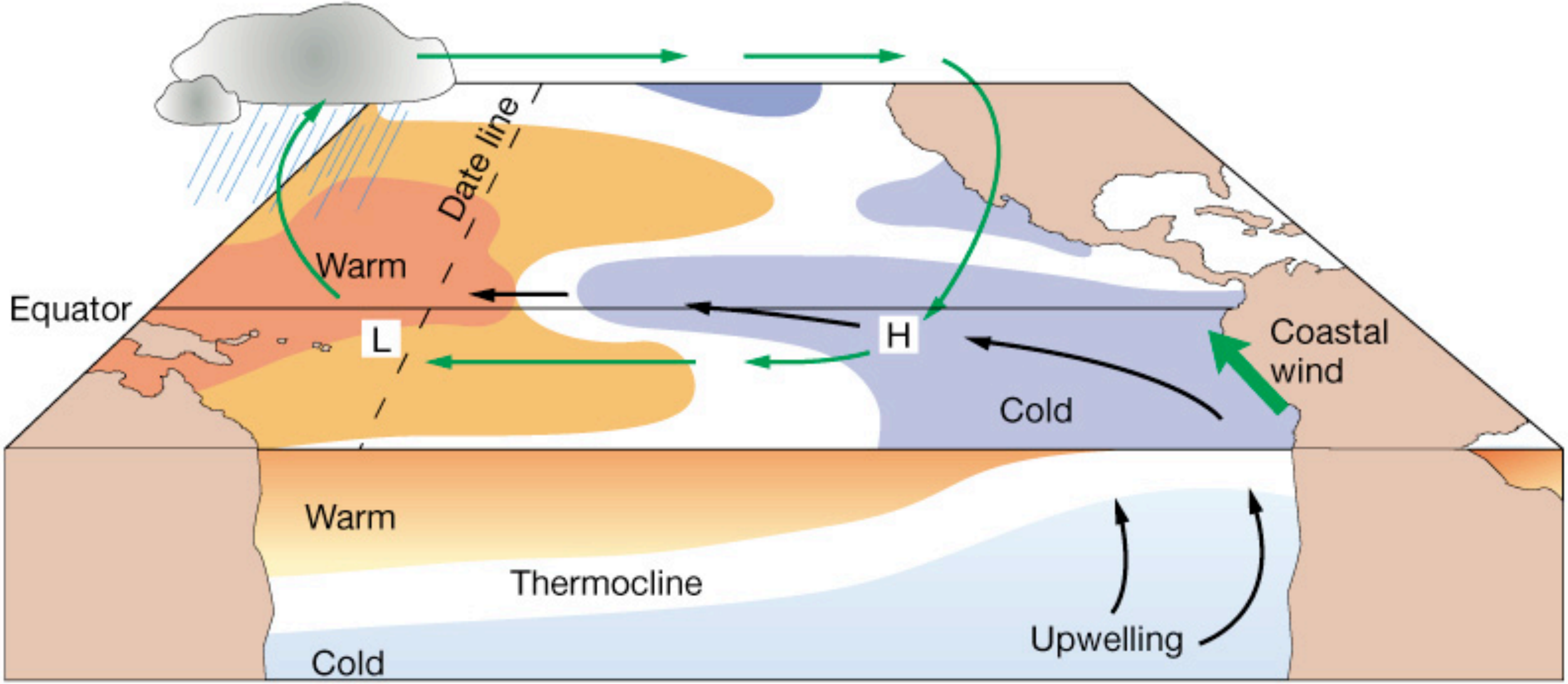
(a) Normal conditions

El Niño conditions (ENSO warm phase)



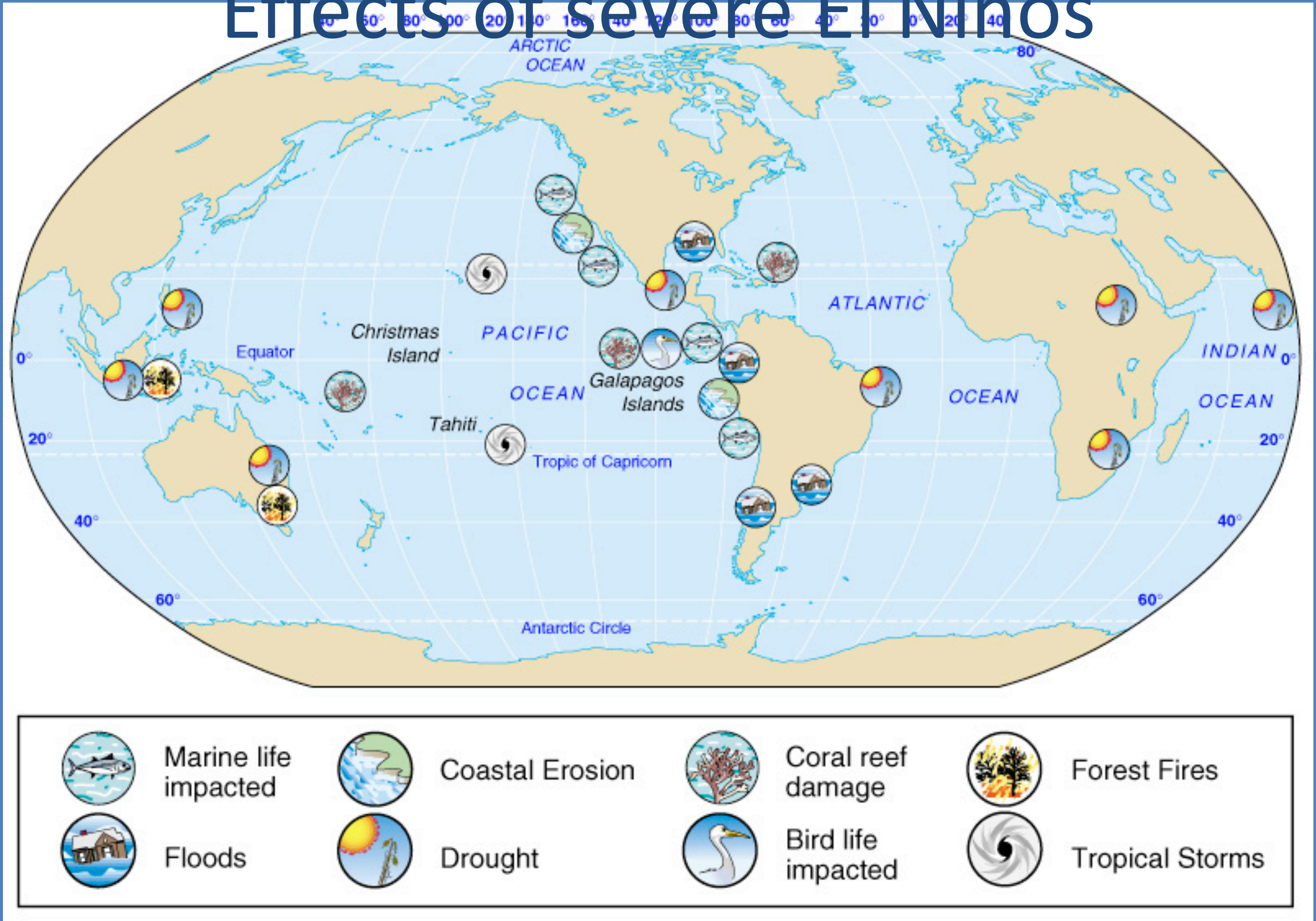
(b) El Niño conditions

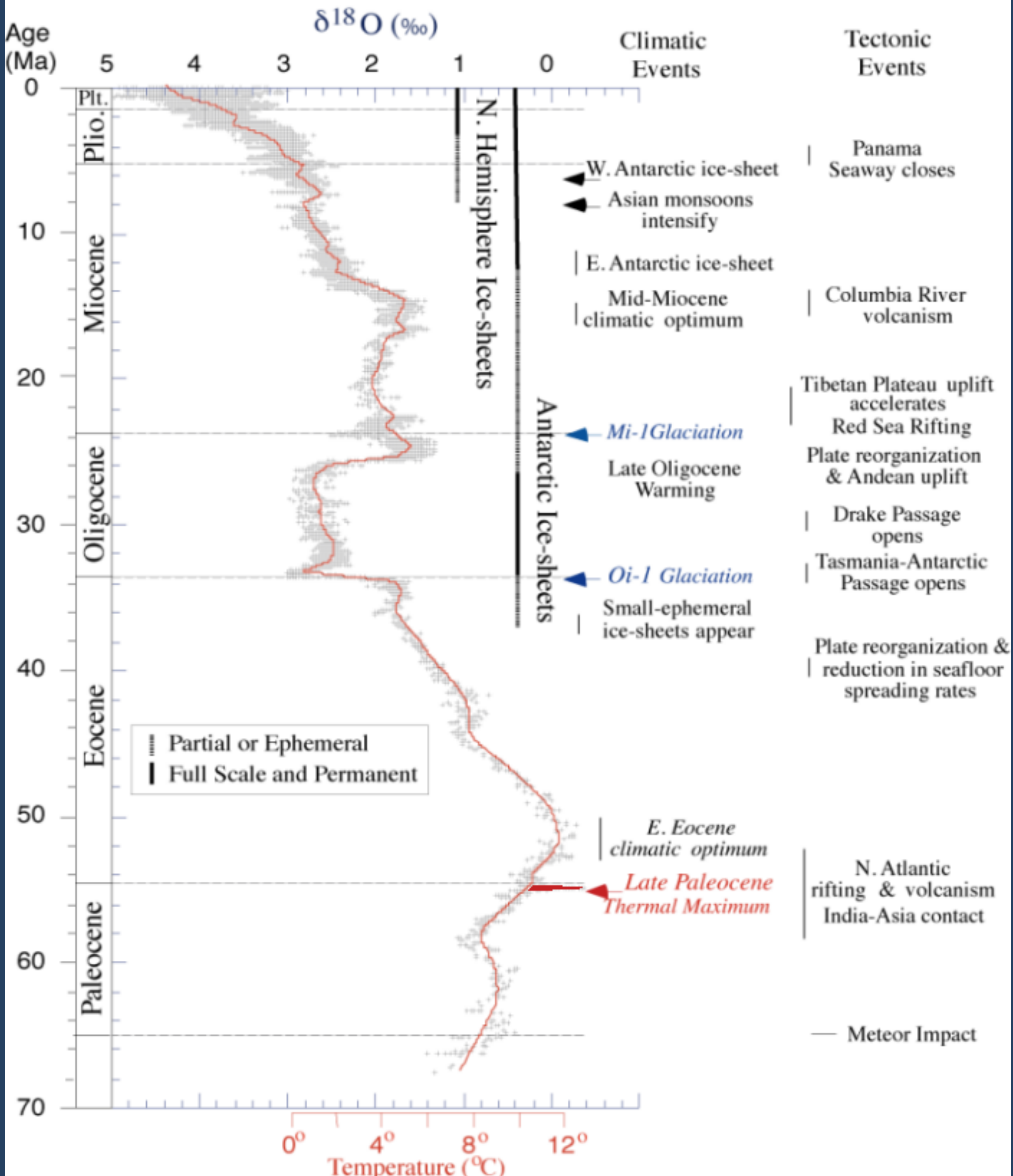
La Niña conditions
(cool phase; opposite of El Niño)



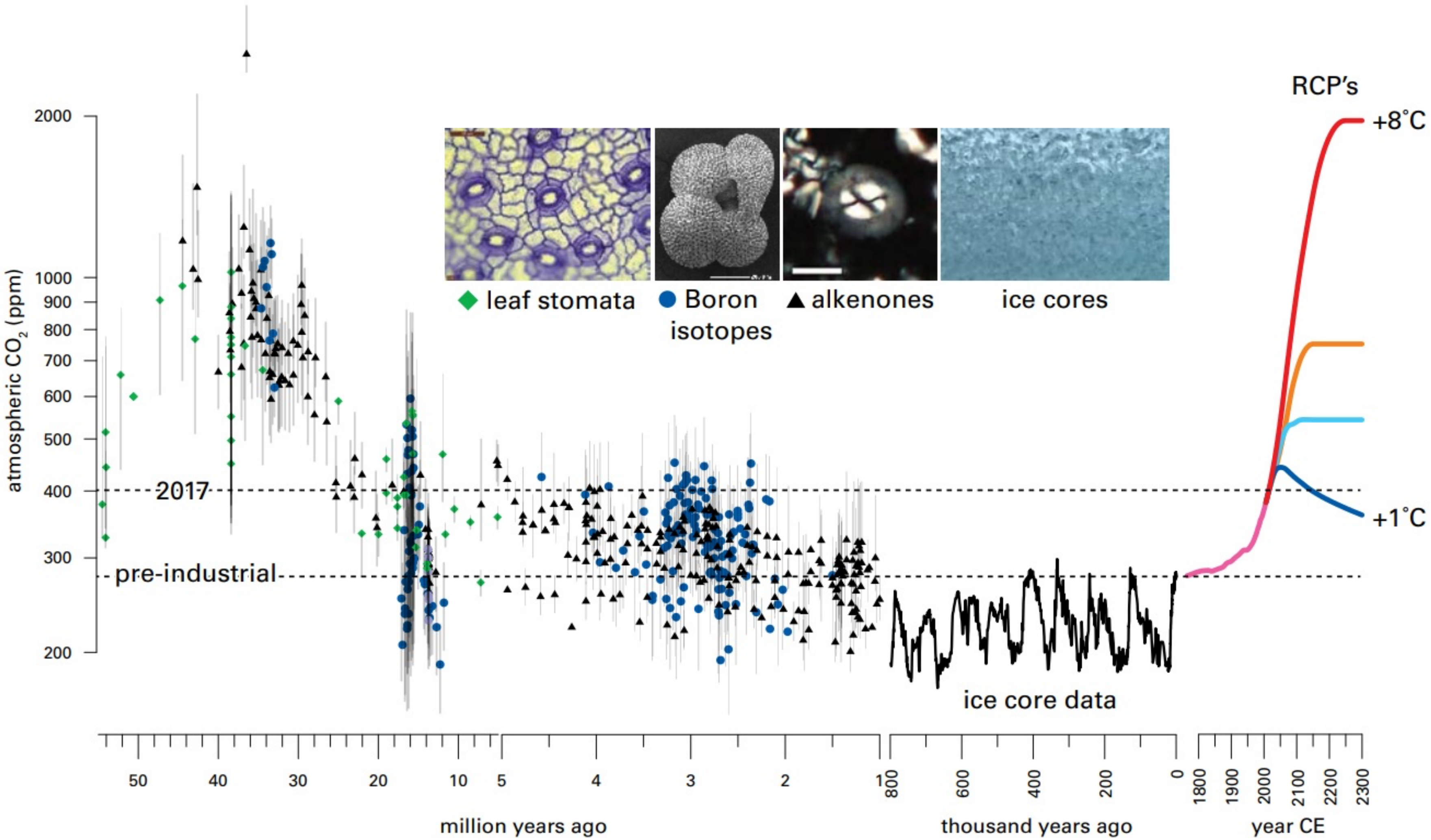
(c) La Niña conditions

Effects of severe El Niños



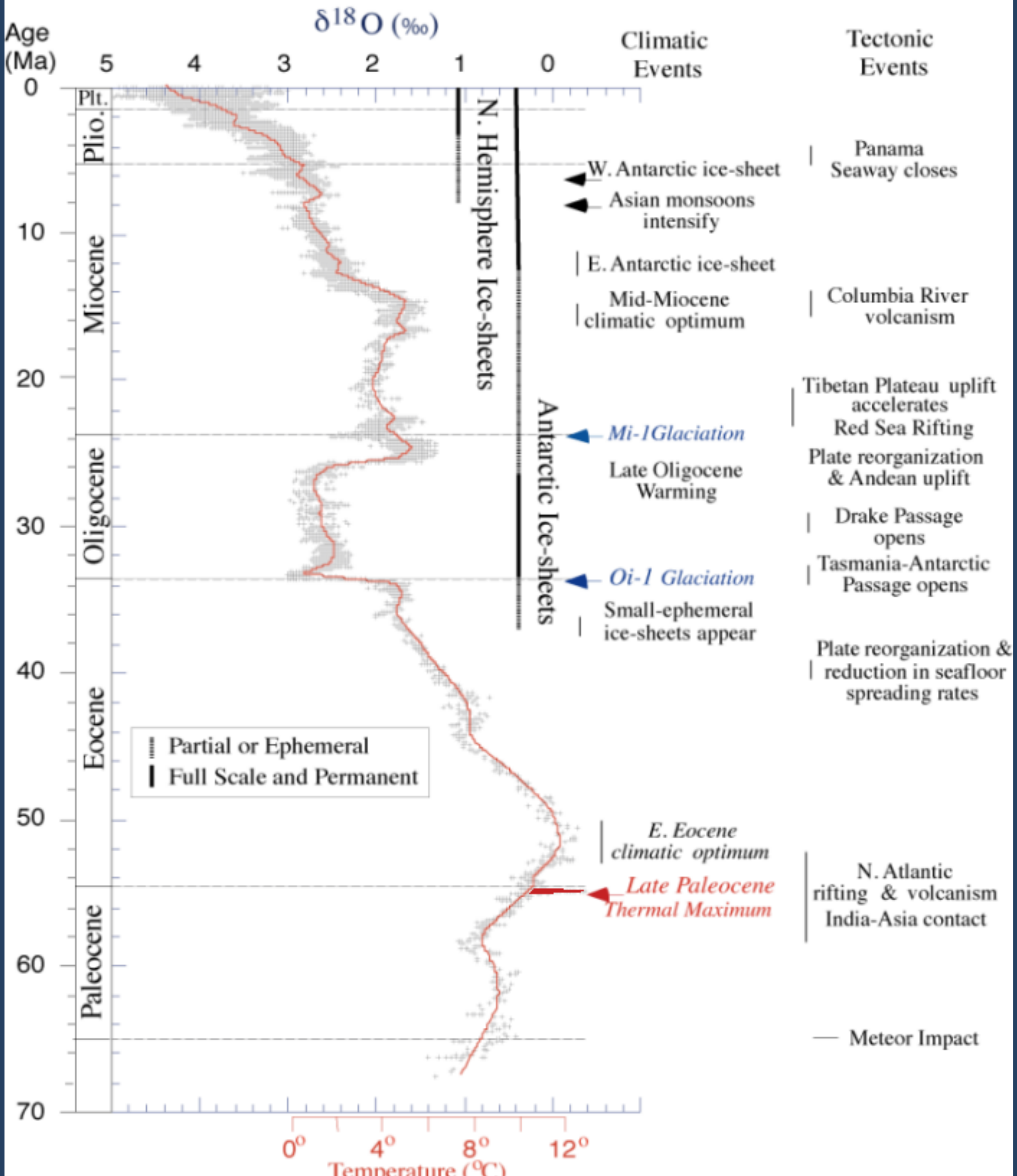


Age (Ma)
δ18O (‰)
5 4 3 2 1 0
Climatic Events
Tectonic Events
Plt.
Plio.
Miocene
Oligocene
Eocene
Paleocene
N. Hemisphere Ice-sheets
Antarctic Ice-sheets
W. Antarctic ice-sheet
Asian monsoons intensify
E. Antarctic ice-sheet
Mid-Miocene climatic optimum
Mi-1Glaciation
Late Oligocene Warming
Oi-1 Glaciation
Small-ephemeral ice-sheets appear
E. Eocene climatic optimum
Late Paleocene Thermal Maximum
Panama Seaway closes
Columbia River volcanism
Tibetan Plateau uplift accelerates
Red Sea Rifting
Plate reorganization & Andean uplift
Drake Passage opens
Tasmania-Antarctic Passage opens
Plate reorganization & reduction in seafloor spreading rates
N. Atlantic rifting & volcanism
India-Asia contact
Meteor Impact
Partial or Ephemeral
Full Scale and Permanent
0 10 20 30 40 50 60 70
0° 4° 8° 12°
Temperature (°C)

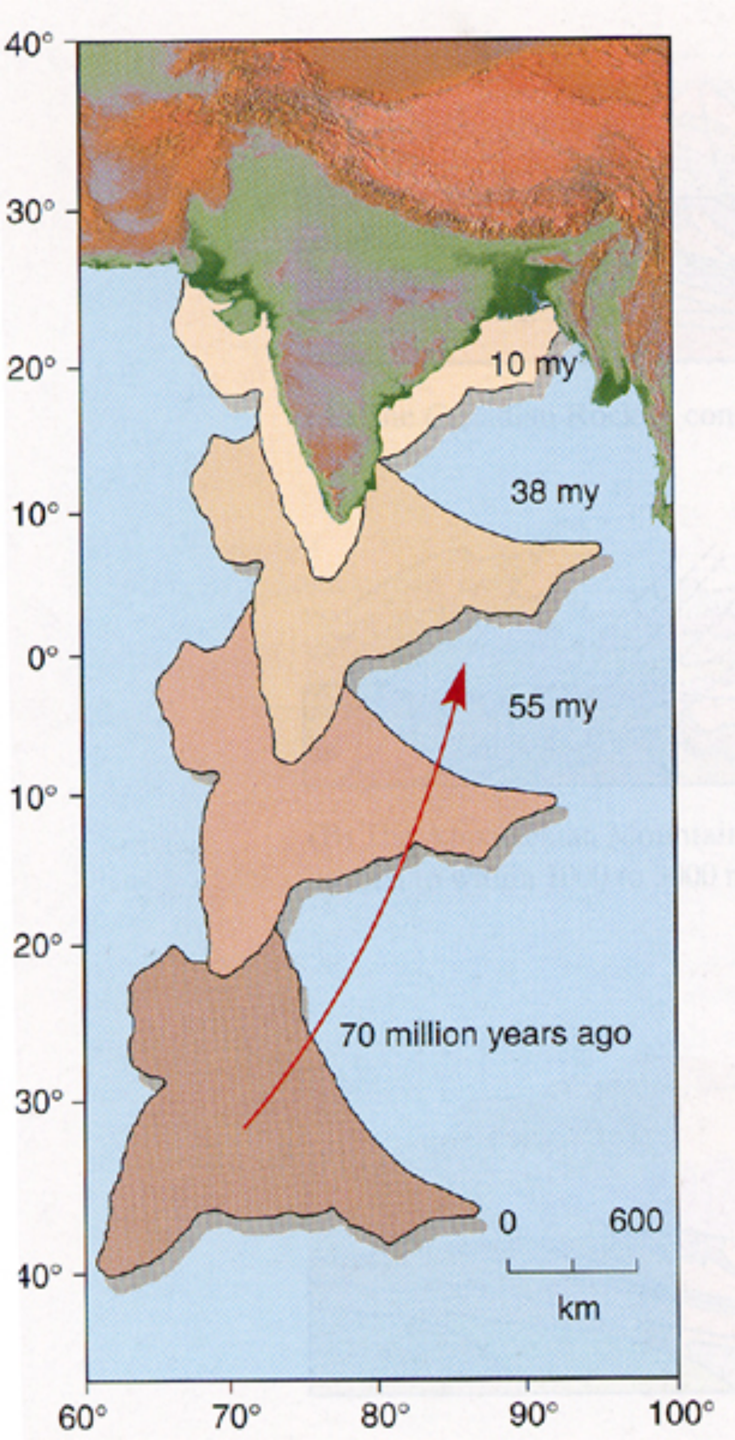


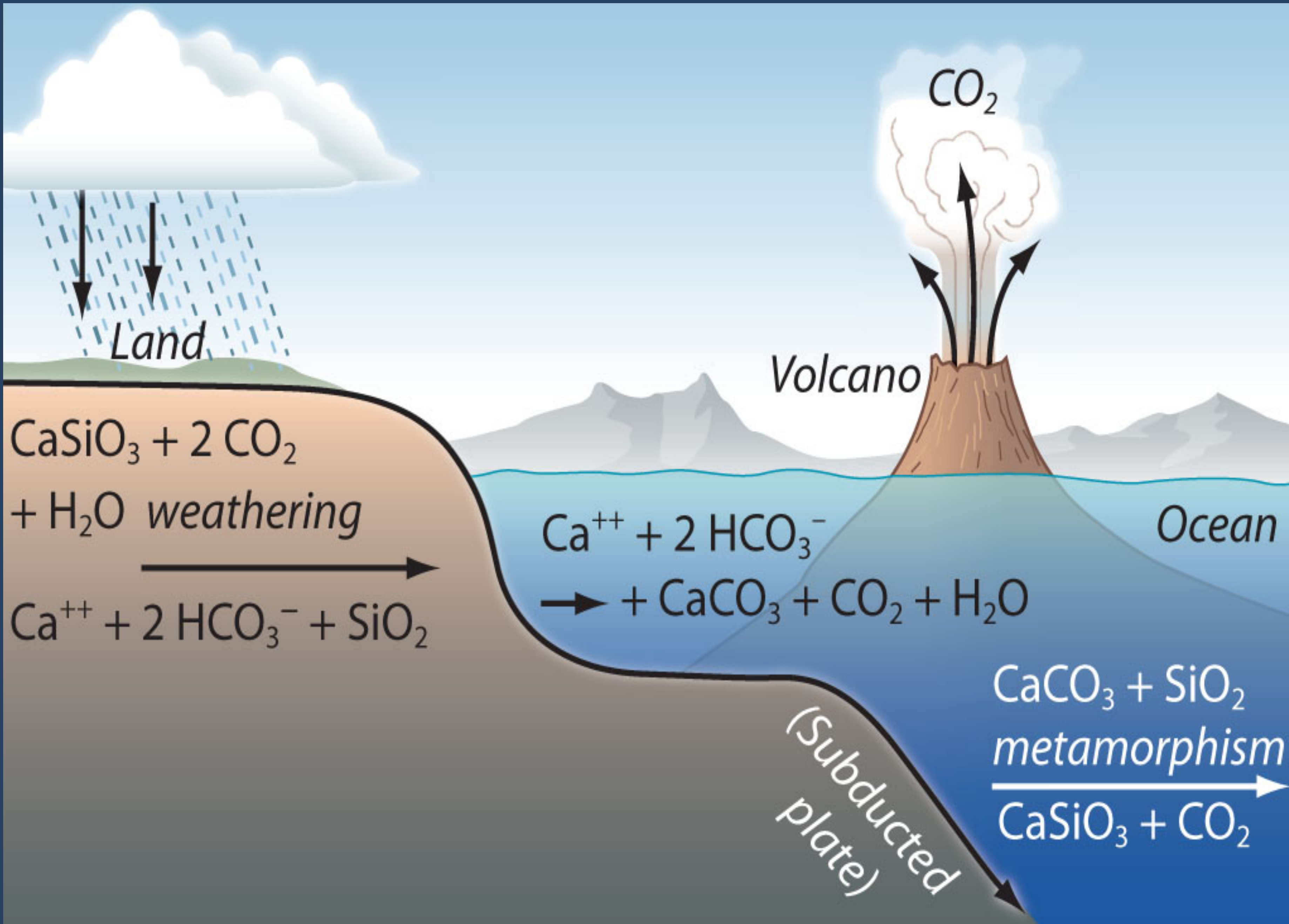
RCP's
+8°C
+1°C
2000
1000
900
800
700
600
500
400
300
200
atmospheric CO2 (ppm)
leaf stomata
Boron isotopes
alkenones
ice cores
2017
pre-industrial
ice core data
50
40
30
20
10
5
4
3
2
1
800
600
400
200
0
1800
1900
2000
2100
2200
2300
million years ago
thousand years ago
year CE


GLOMAR CHALLENGER
8



Age (Ma)
δ18O (‰)
5
4
3
2
1
0
Climatic Events
Tectonic Events
Plt.
Plio.
Miocene
Oligocene
Eocene
Paleocene
N. Hemisphere Ice-sheets
Antarctic Ice-sheets
W. Antarctic ice-sheet
Asian monsoons intensify
E. Antarctic ice-sheet
Mid-Miocene climatic optimum
Mi-1Glaciation
Late Oligocene Warming
Oi-1 Glaciation
Small-ephemeral ice-sheets appear
E. Eocene climatic optimum
Late Paleocene Thermal Maximum
Panama Seaway closes
Columbia River volcanism
Tibetan Plateau uplift accelerates
Red Sea Rifting
Plate reorganization & Andean uplift
Drake Passage opens
Tasmania-Antarctic Passage opens
Plate reorganization & reduction in seafloor spreading rates
N. Atlantic rifting & volcanism
India-Asia contact
Meteor Impact
Partial or Ephemeral
Full Scale and Permanent
0
10
20
30
40
50
60
70
0°
4°
8°
12°
Temperature (°C)

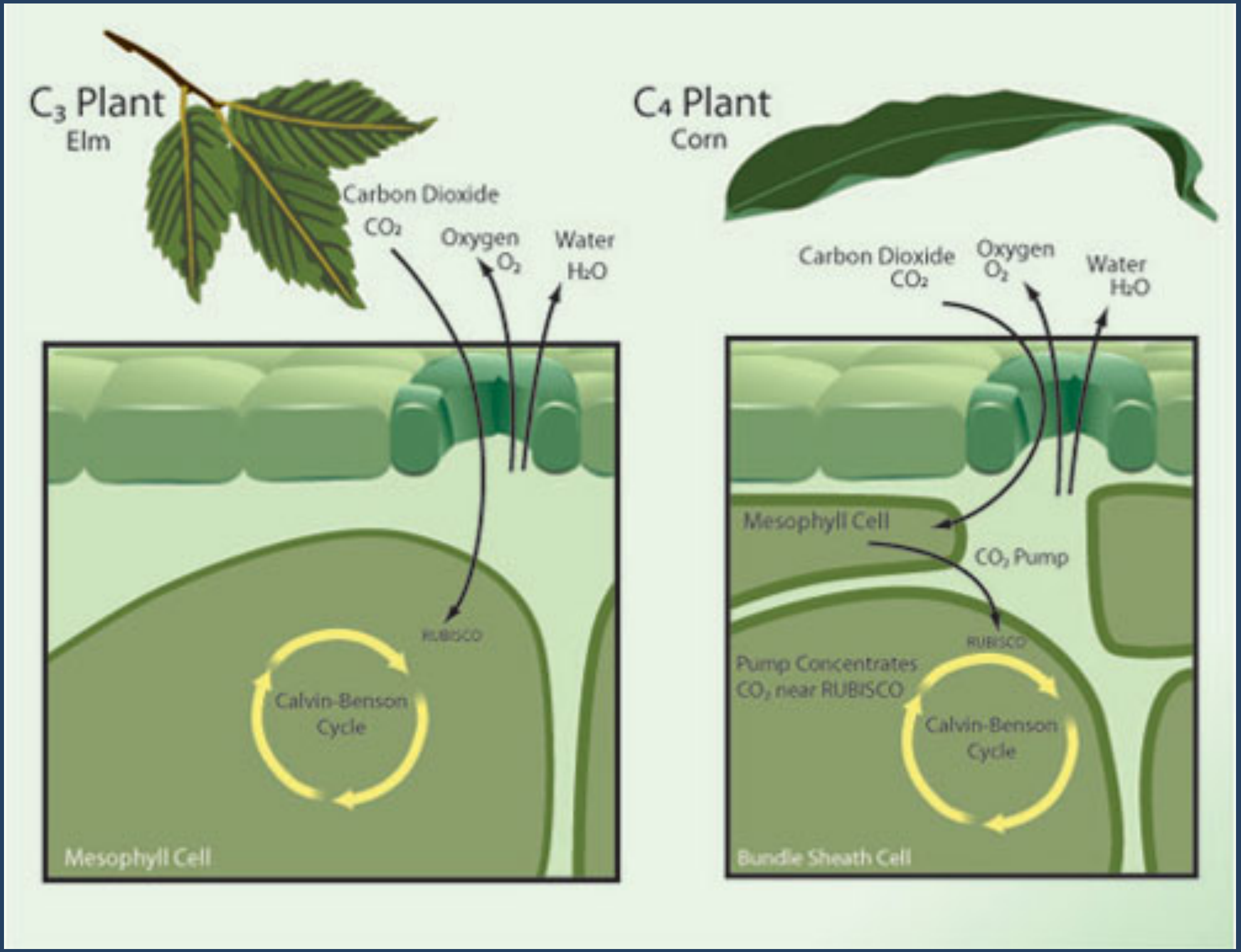

40°
30°
20°
10°
0°
10°
20°
30°
40°
10 my
38 my
55 my
70 million years ago
0
600
km
60°
70°
80°
90°
100°

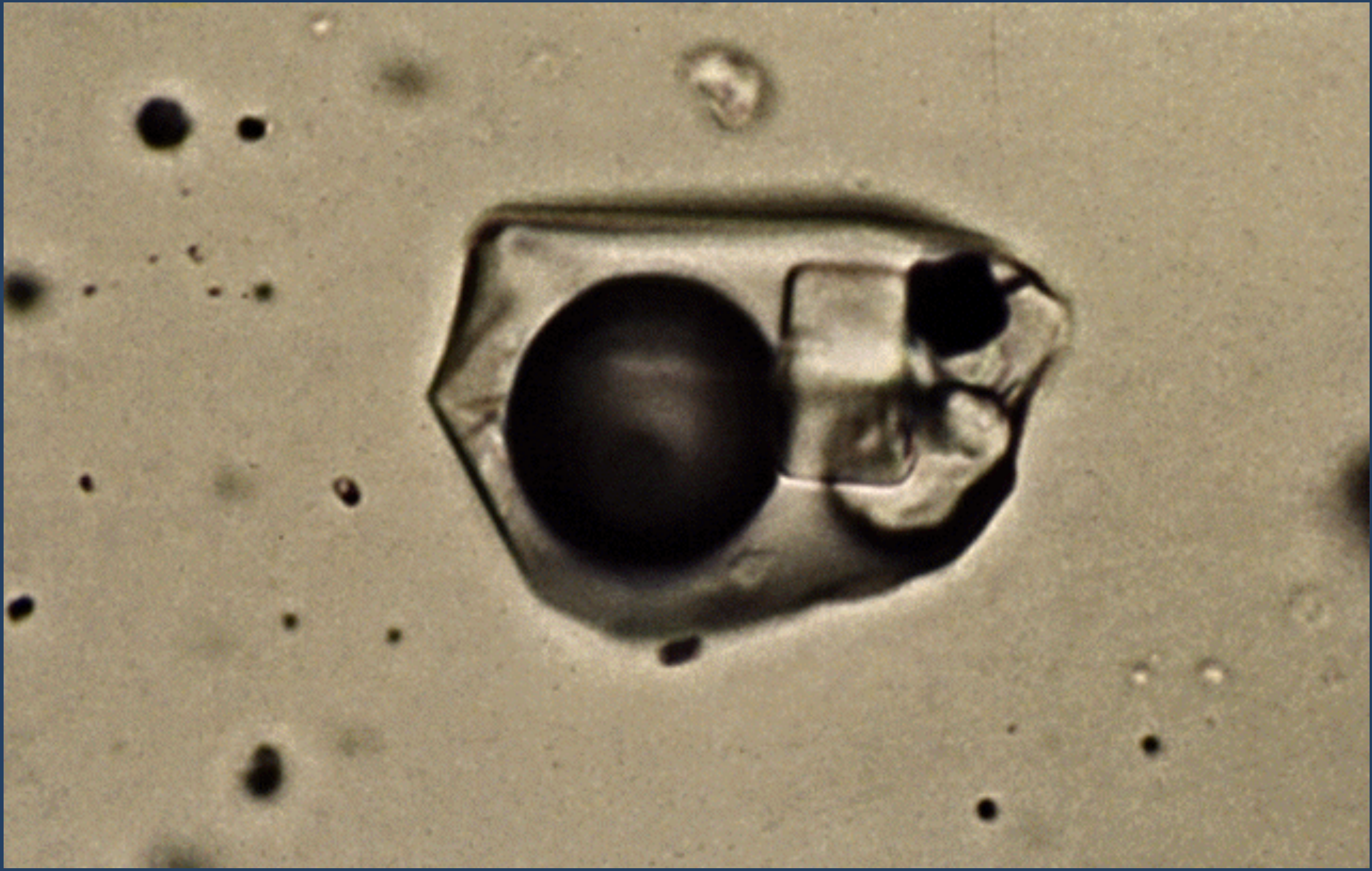


Land
$CaSiO_3 + 2\ CO_2$
$+ H_2O$ *weathering*
$Ca^{++} + 2\ HCO_3^- + SiO_2$
CO_2
Volcano
$Ca^{++} + 2\ HCO_3^-$
$\rightarrow + CaCO_3 + CO_2 + H_2O$
Ocean
$CaCO_3 + SiO_2$
metamorphism
$CaSiO_3 + CO_2$
(Subducted plate)

Grasses: a new type of photosynthesis

C4 plants evolved in the Oligocene as a response to lowering CO_2 levels, drought conditions and other environmental stresses. Arose in many families of plants simultaneously; a good example of convergent evolution





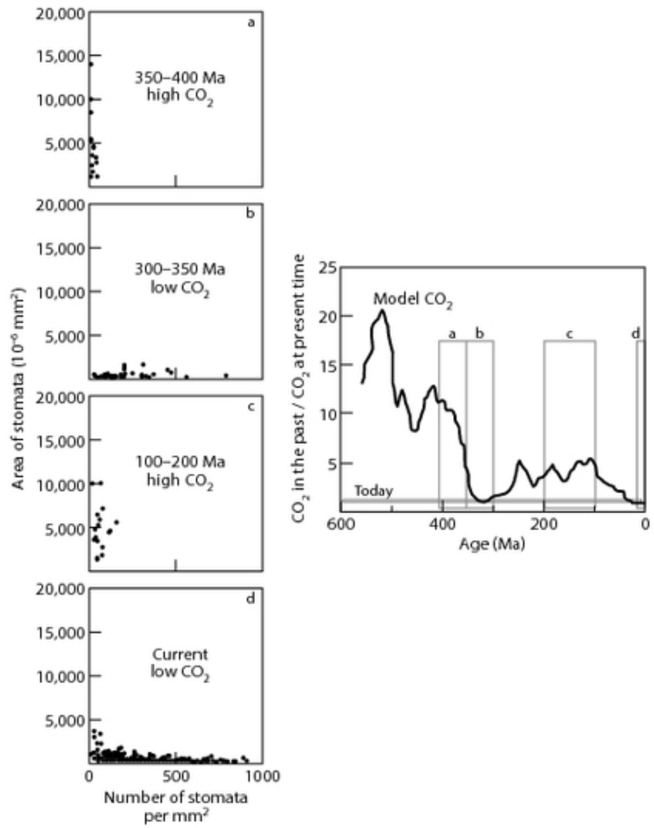
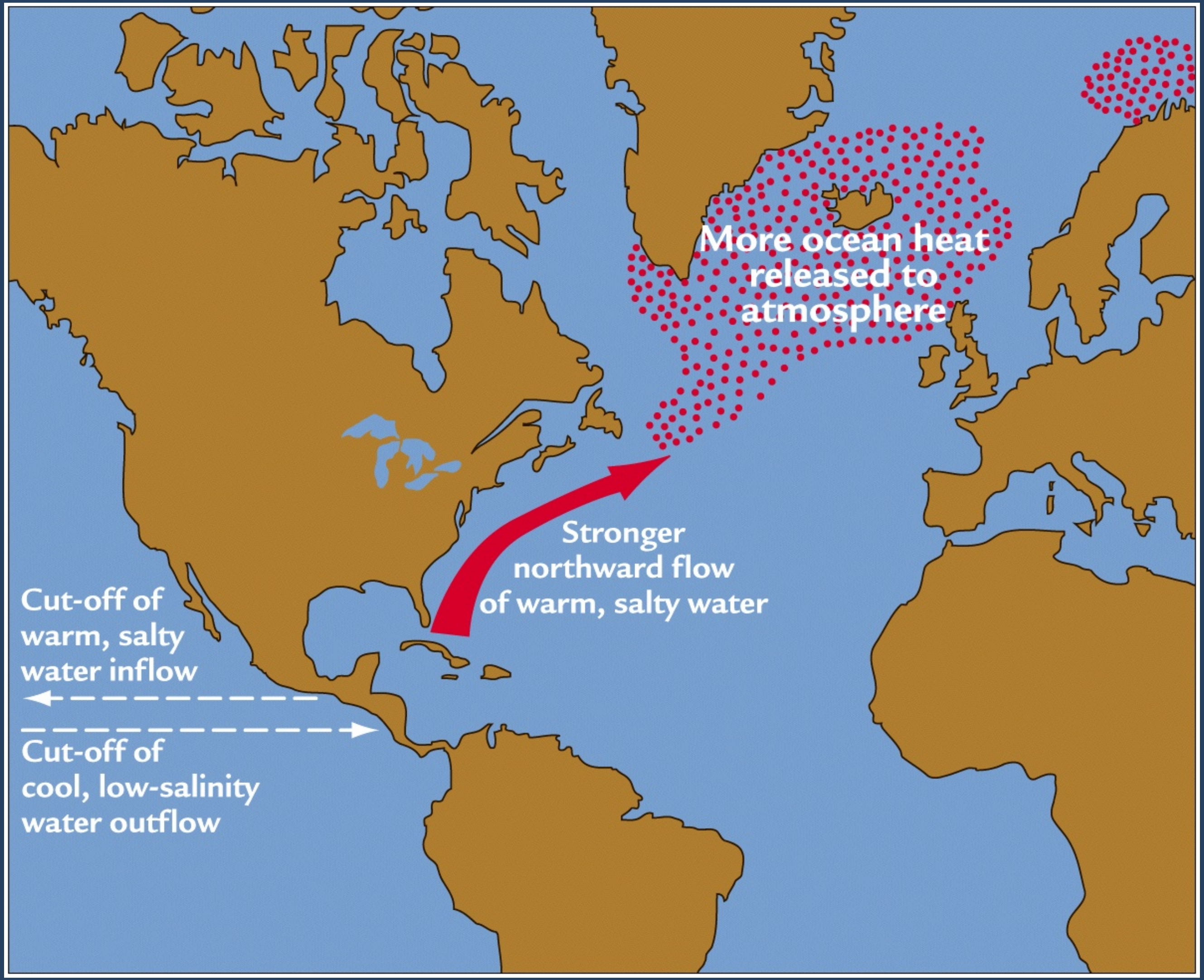
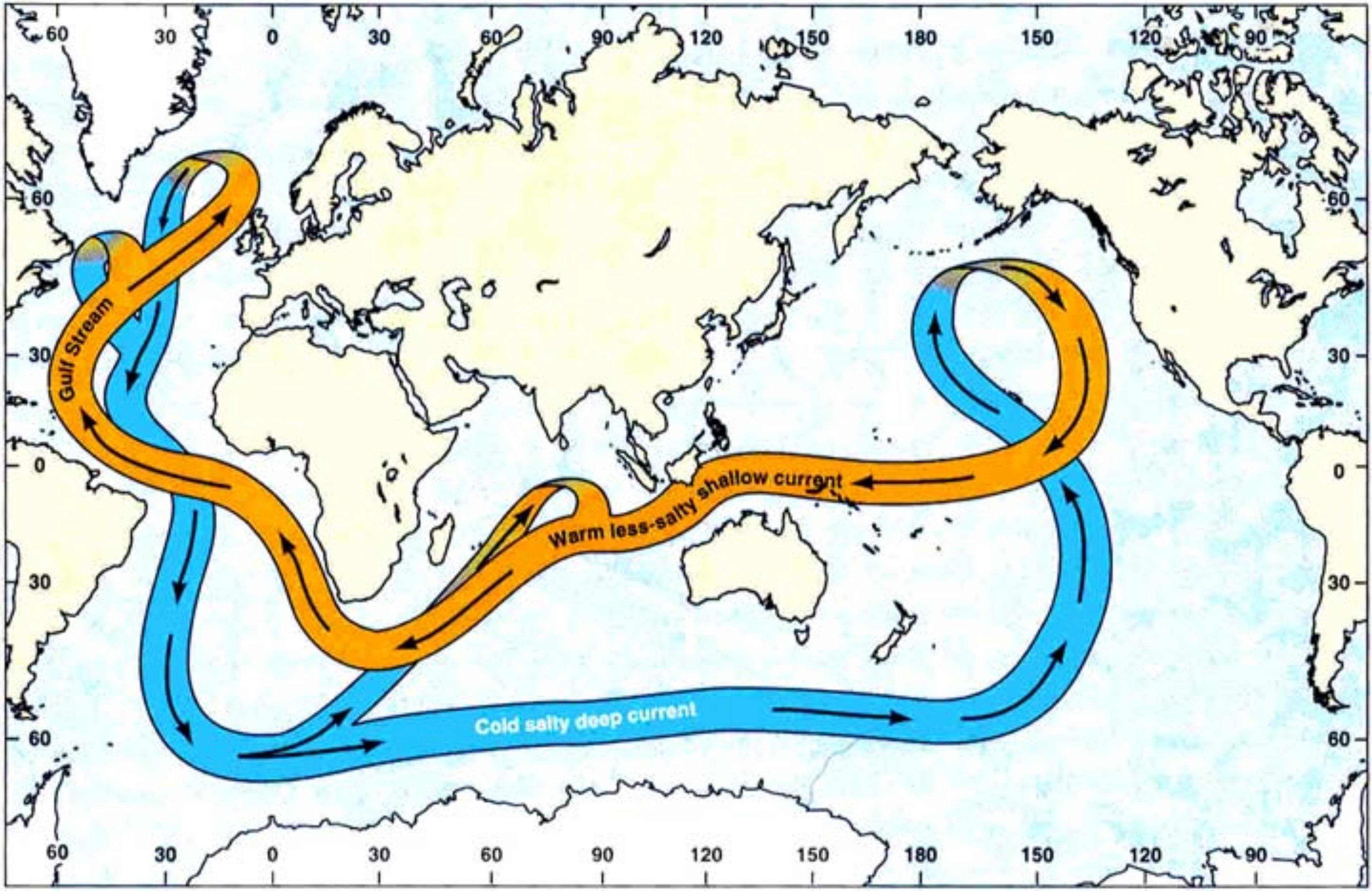


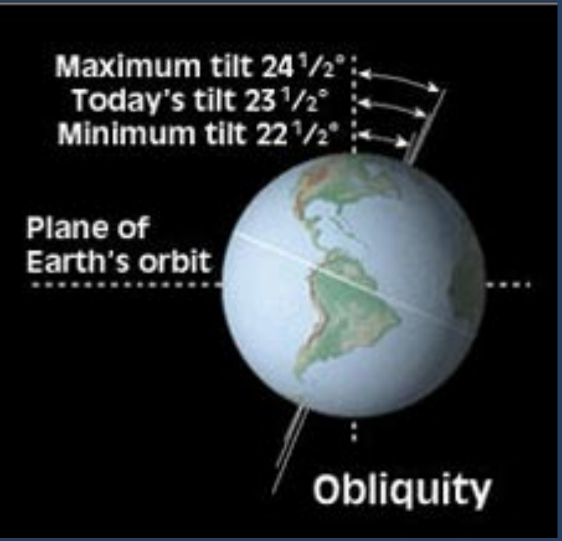
Fig. 4.2. Simulated values of the atmospheric CO_2 concentration during the Phanerozoic, and implications for the atmospheric CO_2 level from the size and abundance of stomata in fossil leaves. *Right*: Atmospheric CO_2 concentration versus time over the Phanerozoic, as simulated by the Geocarbsulf model of Berner (2006). The boxes labeled a–d mark the times corresponding to the panels on the *left*. *Other 4 panels*: Area of stomata versus number density of stomata for leaves from four time intervals. Large numbers of small stomata


More ocean heat released to atmosphere
Stronger northward flow of warm, salty water
Cut-off of warm, salty water inflow
Cut-off of cool, low-salinity water outflow

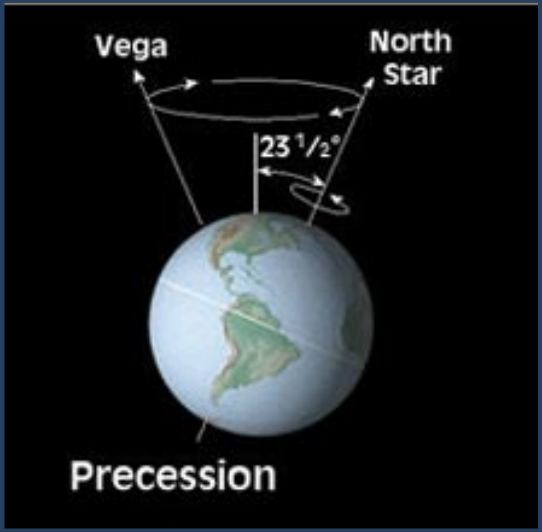

Gulf Stream
Warm less-salty shallow current
Cold salty deep current
60
30
0
30
60
90
120
150
180
150
120
90
60
30
0
30
60

Milankovitch Cycles

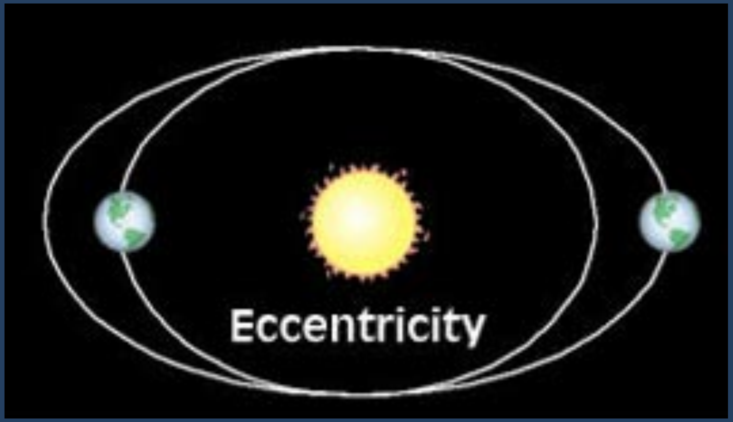
Earth's wobble, tilt, and orbit



Obliquity

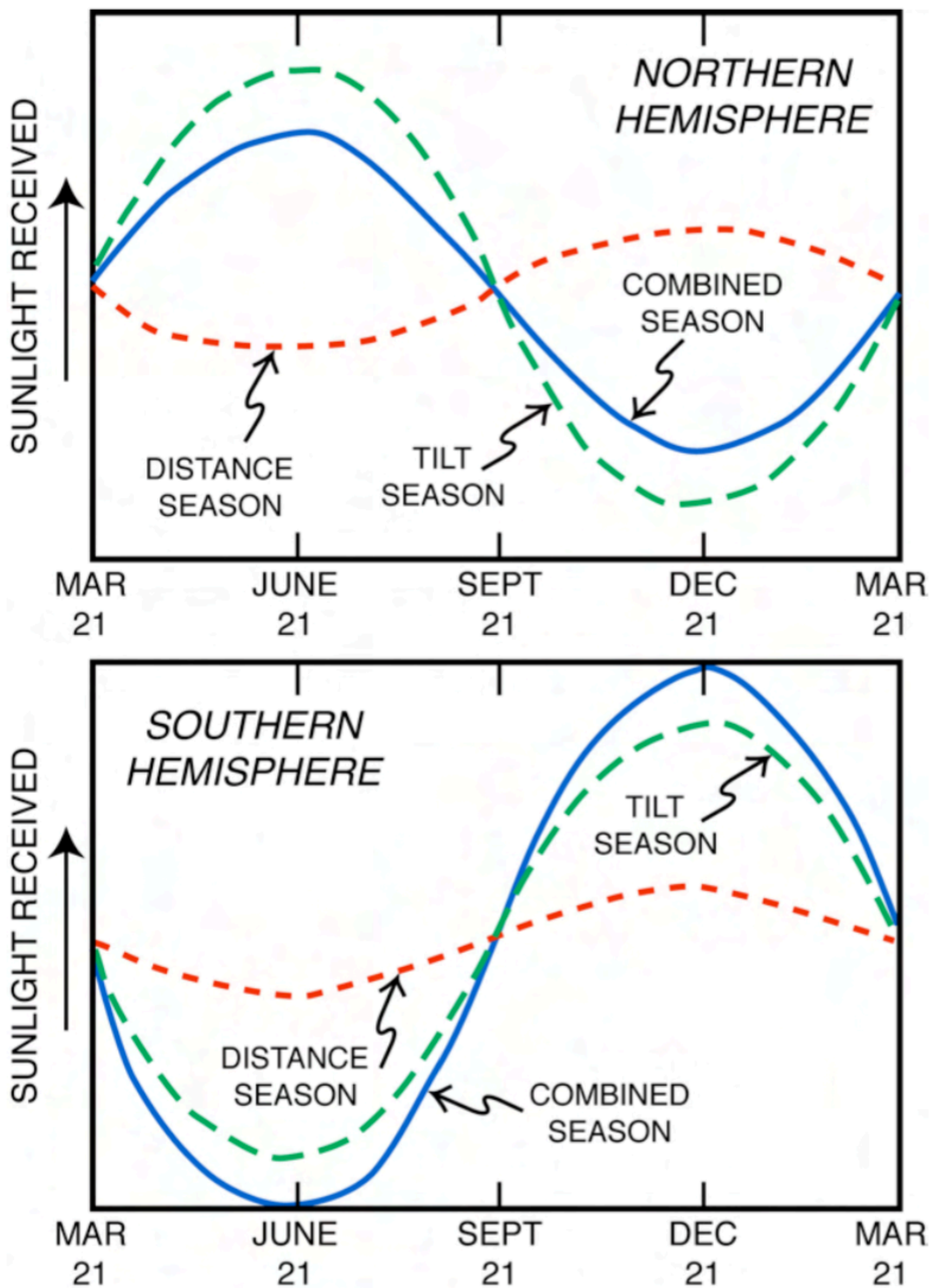


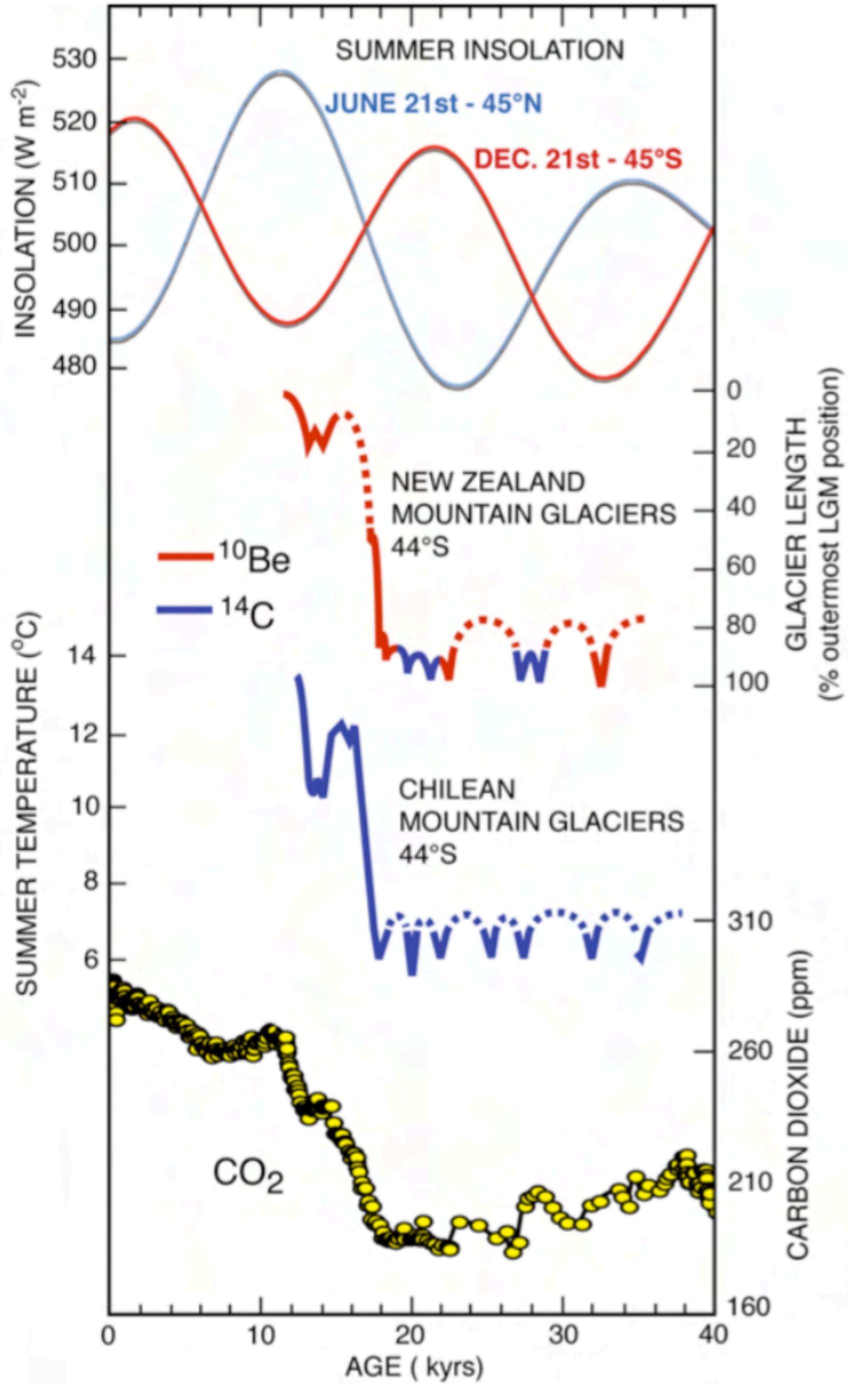
Precession



Eccentricity

Changing Seasonality

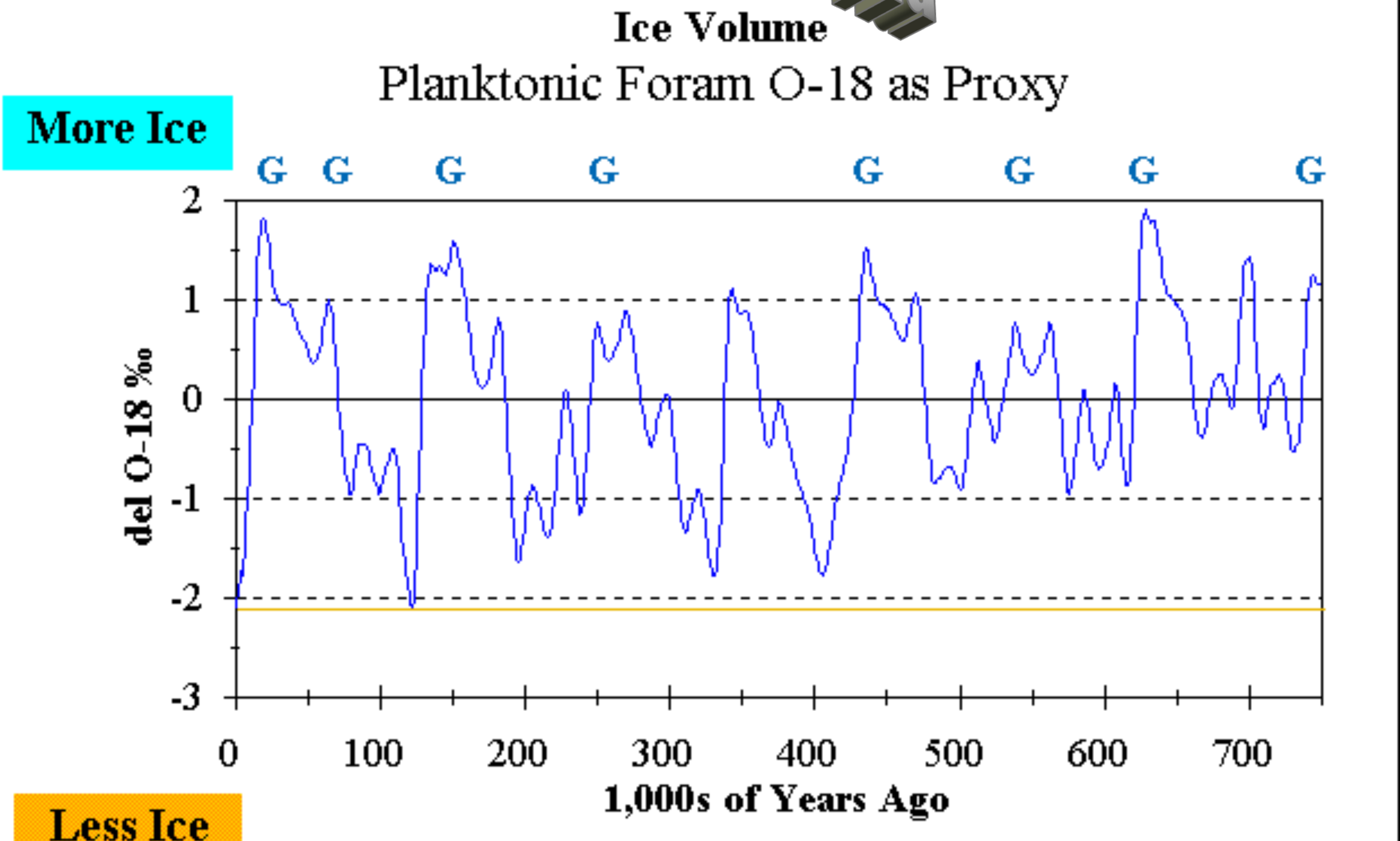


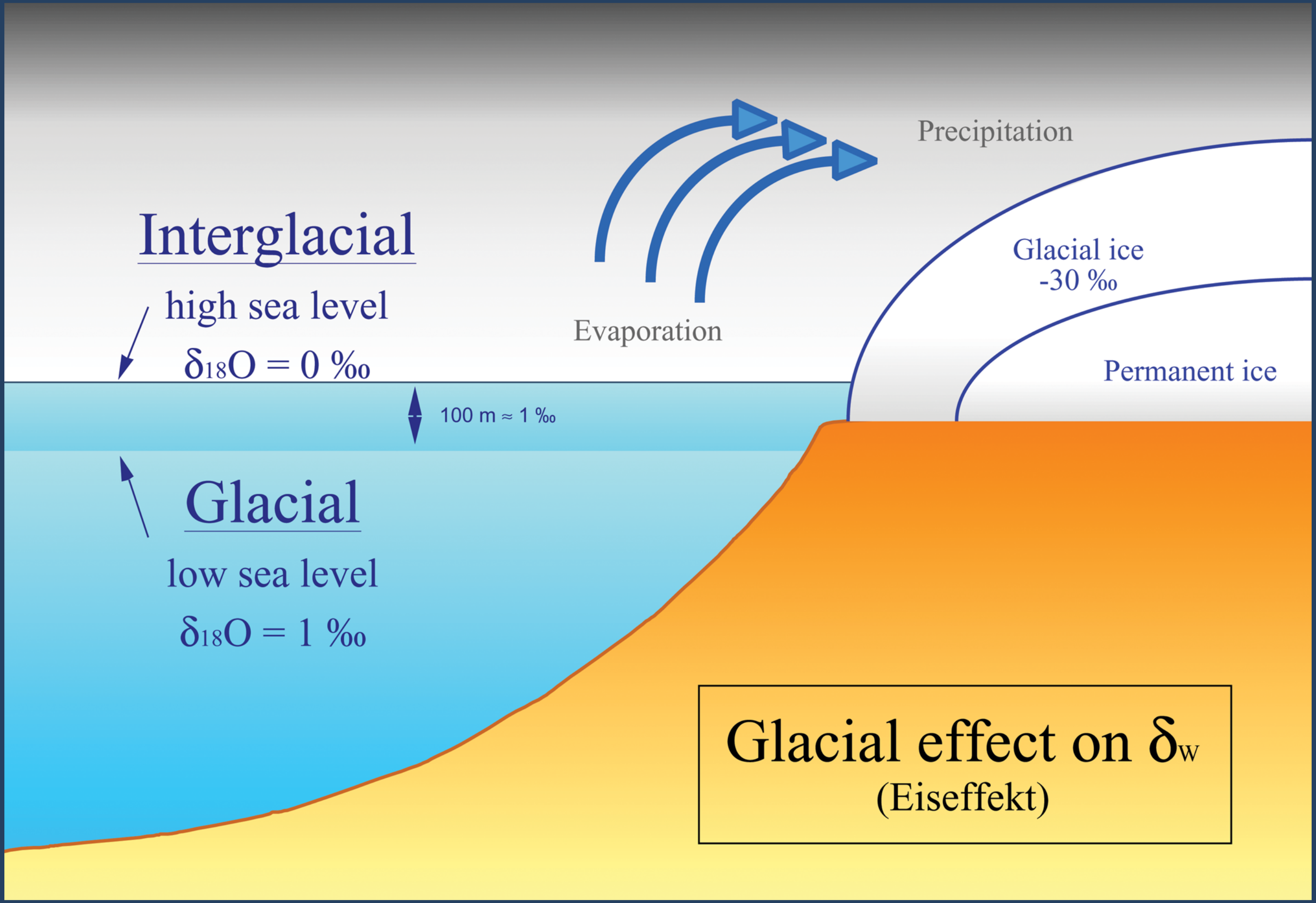


This shows us that the
Northern Hemisphere
And Southern Hemisphere
Glaciations should occur at
the different times –
Millankovitch
would predict they would be
out of phase

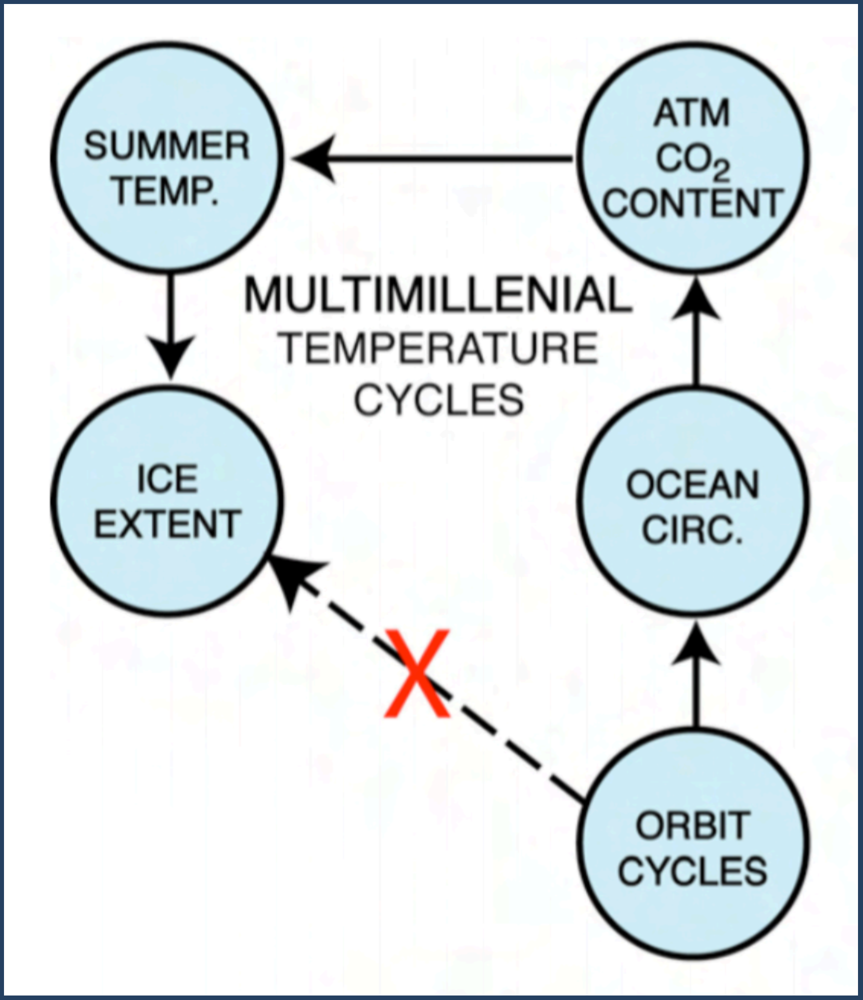
They are in phase

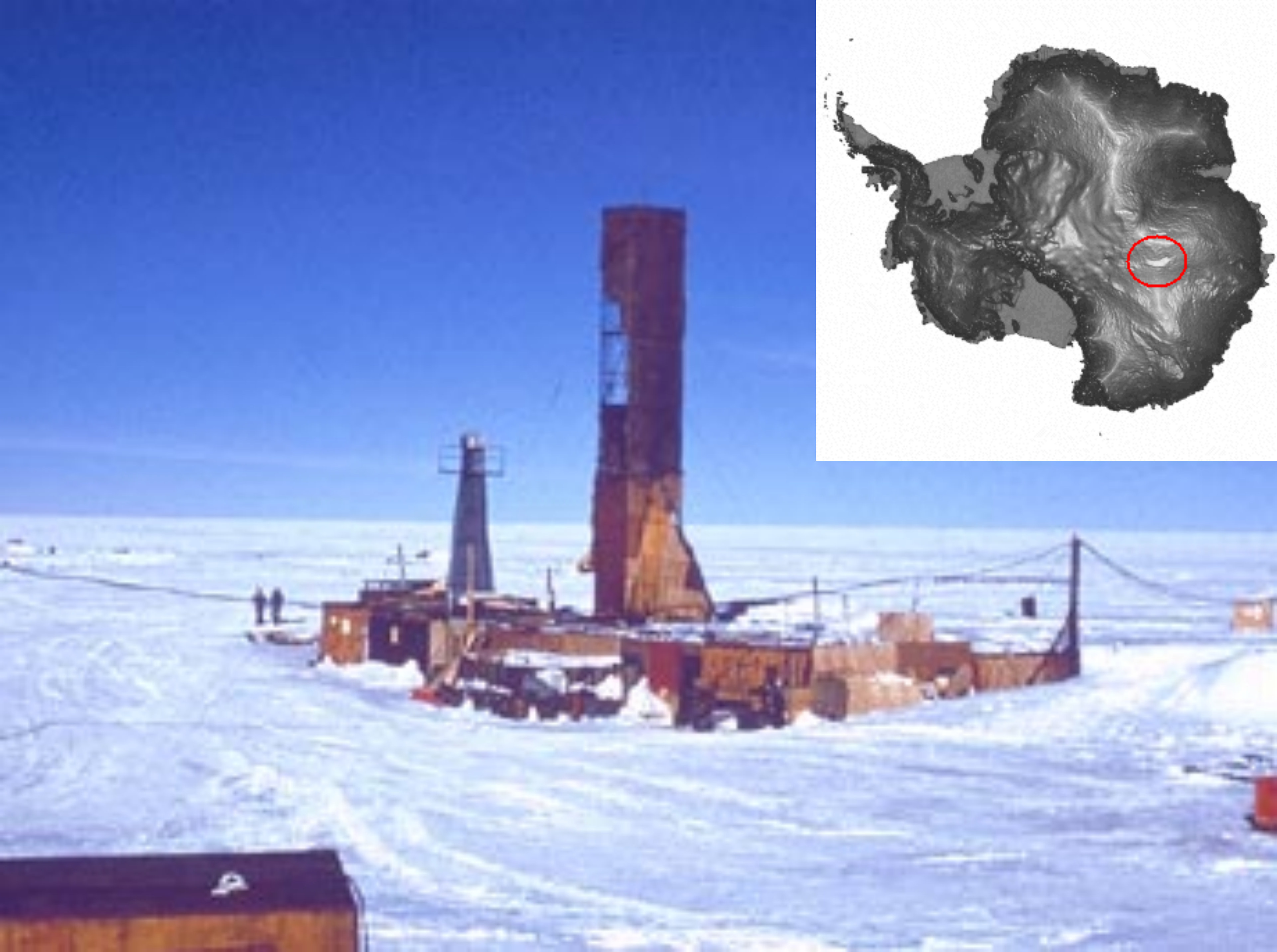
Ice Age World

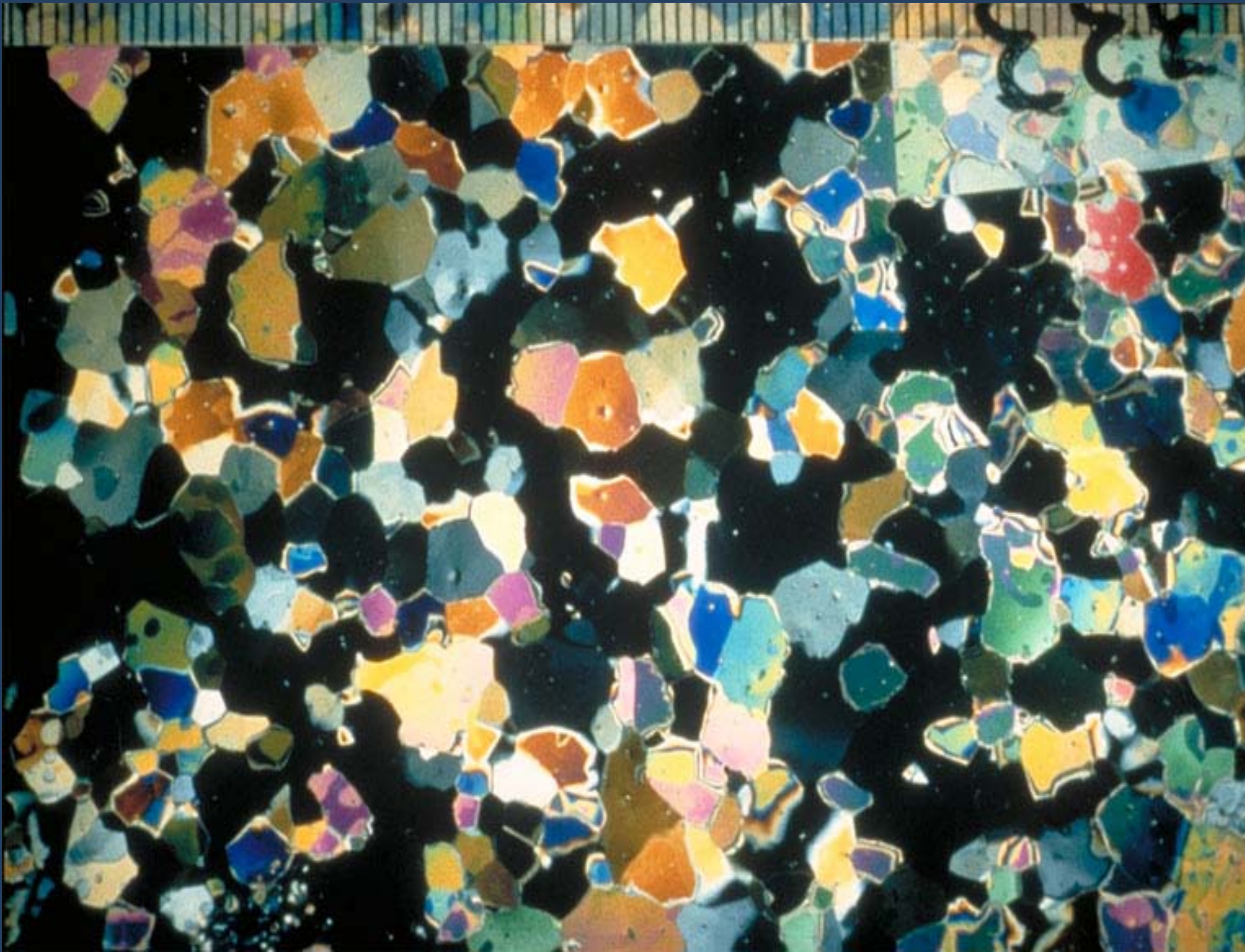


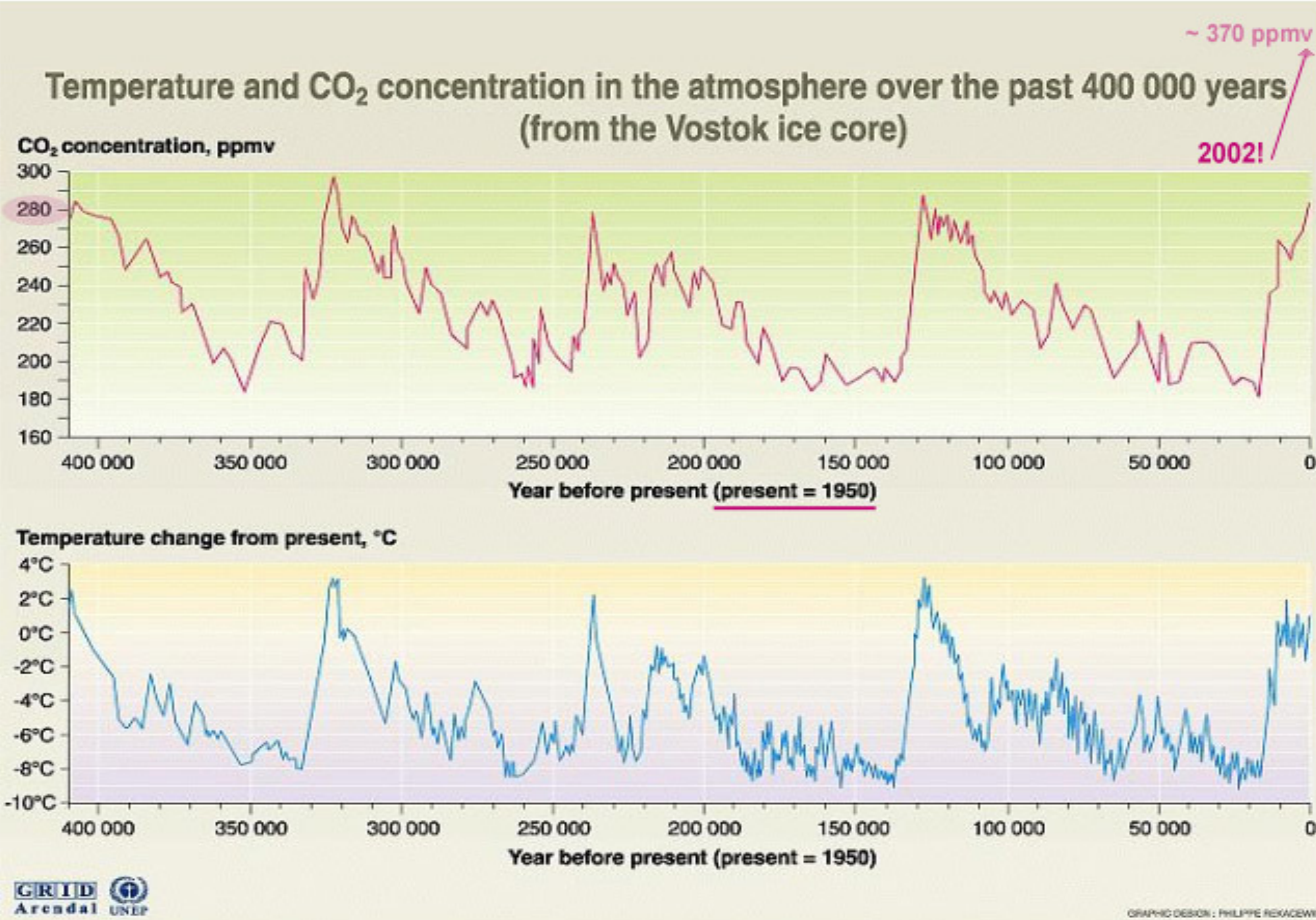


$$\delta^{18}O = \frac{(^{18}O/^{16}O)_{sample} - (^{18}O/^{16}O)_{SMOW}}{(^{18}O/^{16}O)_{SMOW}} \times 1000$$


SUMMER TEMP.
ATM CO_2 CONTENT
MULTIMILLENIAL TEMPERATURE CYCLES
ICE EXTENT
OCEAN CIRC.
X
ORBIT CYCLES

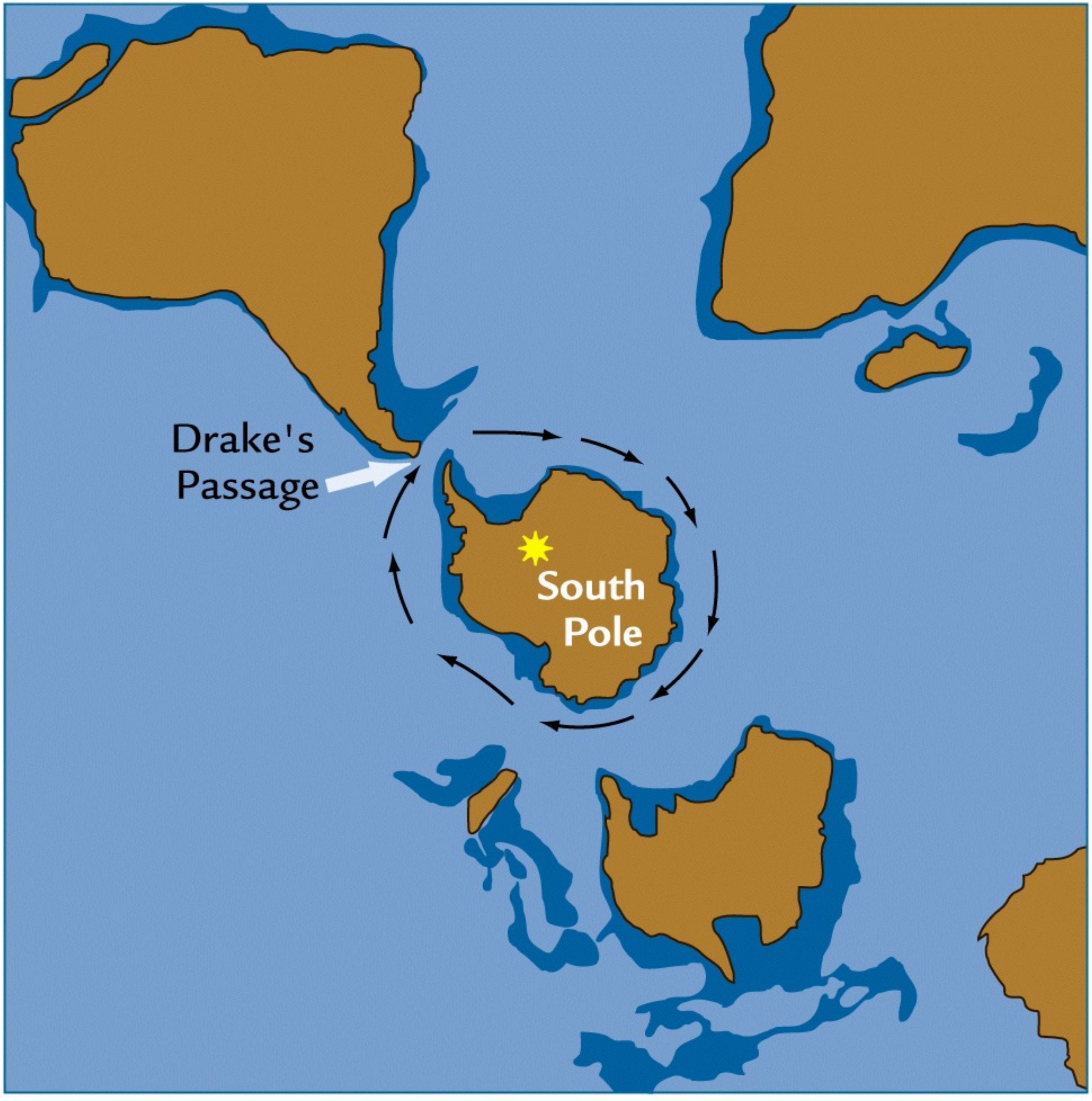






Source: J.R. Petit, J. Jouzel, et al. Climate and atmospheric history of the past 420 000 years from the Vostok ice core in Antarctica, Nature 399 (3JUne), pp 429-436, 1999.

(Note: 2002 information added to diagram)


Drake's
Passage
South
Pole

Latest CO_2 reading
January 09, 2019

410.51 ppm

Carbon dioxide concentration at Mauna Loa Observatory