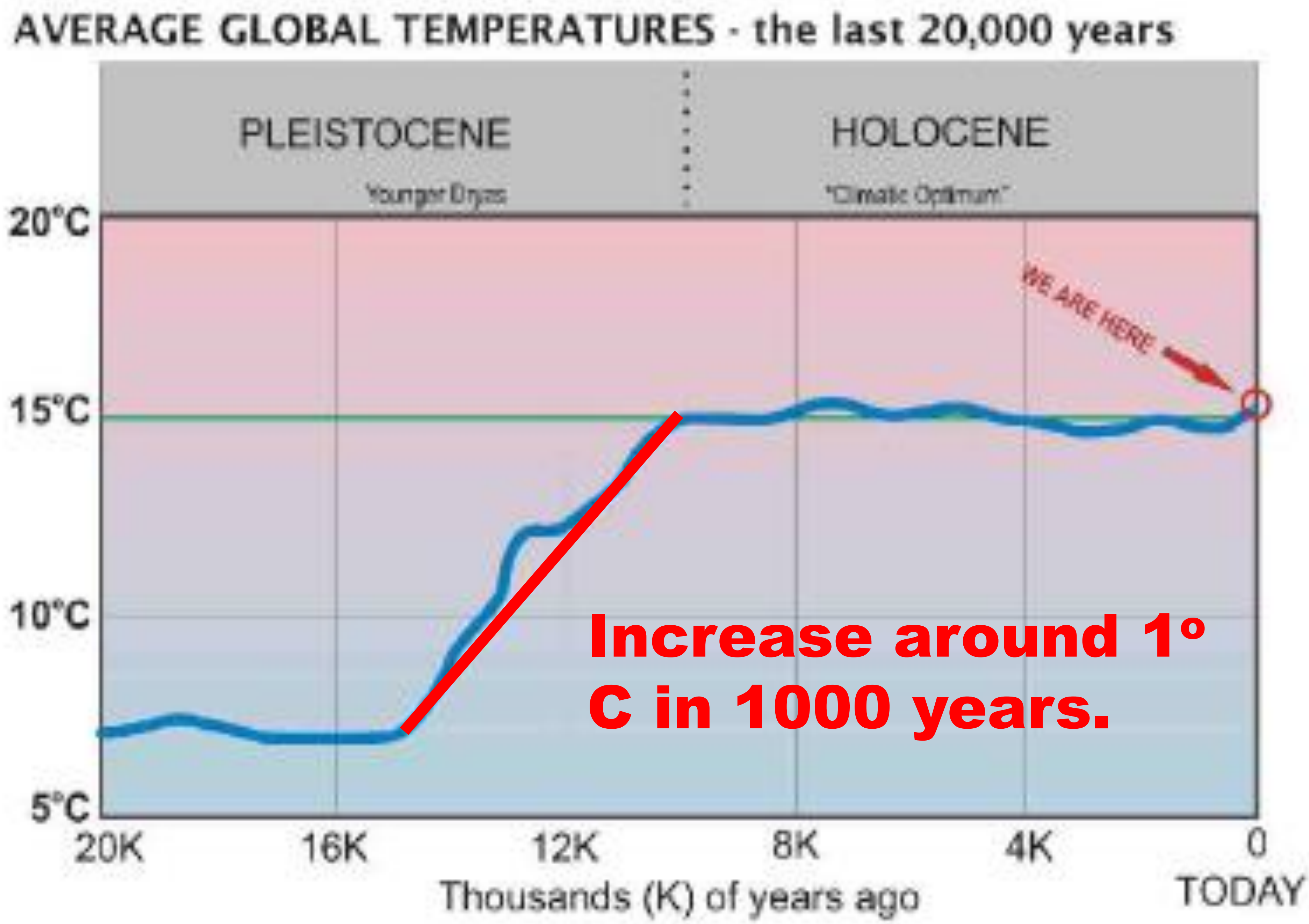
HOW STABLE IS THE EARTH'S CLIMATE?

J.Srinivasan
Divecha Centre for Climate Change
Indian Institute of Science, Bengaluru



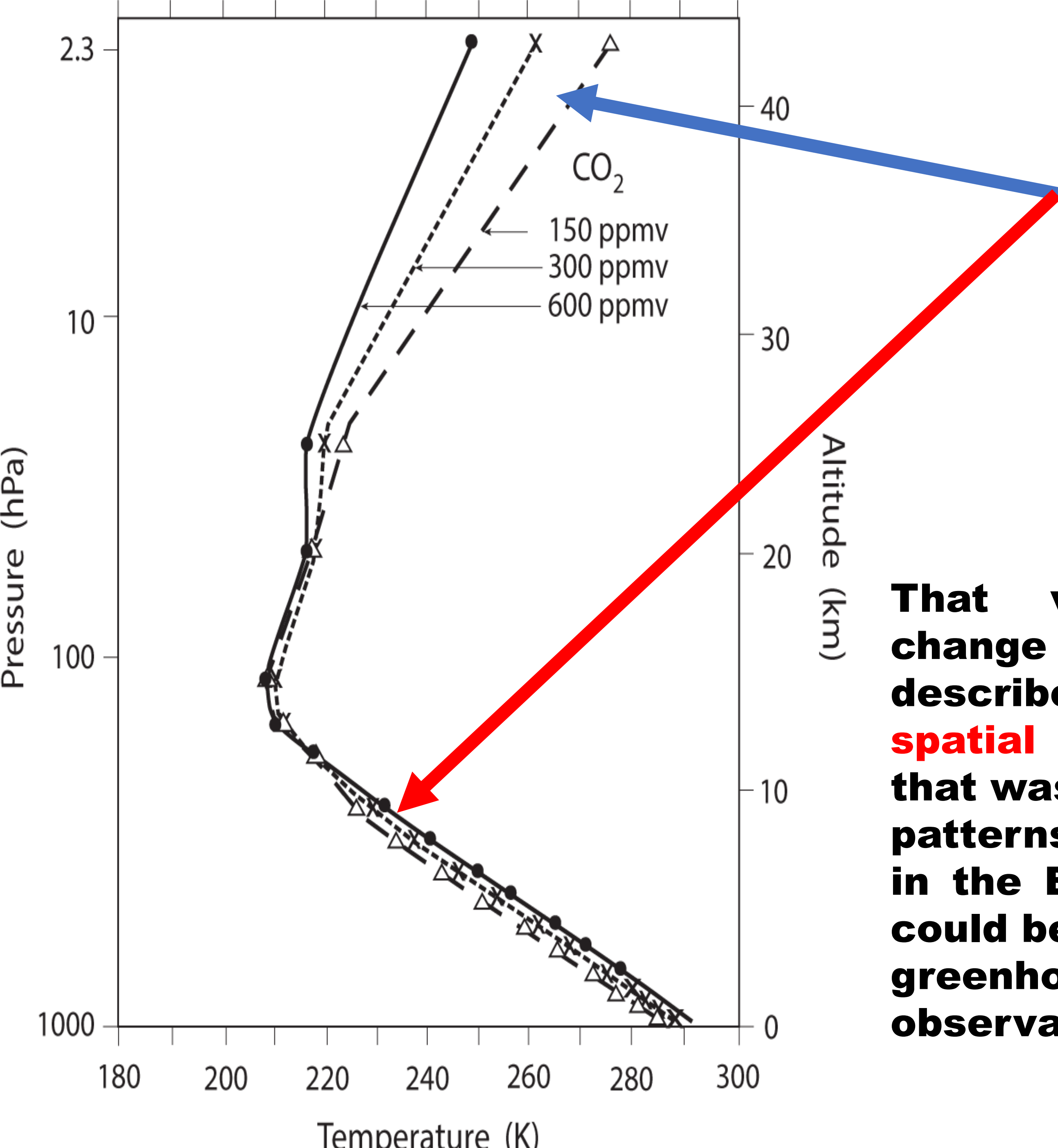
AVERAGE GLOBAL TEMPERATURES - the last 20,000 years
PLEISTOCENE
HOLOCENE
Younger Dryas
"Climatic Optimum"
20°C
15°C
10°C
5°C
WE ARE HERE
Increase around 1° C in 1000 years.
20K
16K
12K
8K
4K
0
TODAY
Thousands (K) of years ago

I was skeptical about climate change. I was cautious about crying wolf...But I'm no longer skeptical

David Attenborough

Klaus Hasslemann **Giorgio Parisi** **Syukuro Manabe**

The Nobel Prize in Physics 2021 was awarded "for ground breaking contributions to our understanding of complex systems" with one half jointly to Syukuro Manabe and Klaus Hasselmann "for the physical modelling of Earth's climate, quantifying variability and reliably predicting global warming"



CO_2 increase causes cooling in the stratosphere and warming in the troposphere

That vertical pattern of change is what Hasselmann described in 1979, as a spatial fingerprint of change that was distinct enough from patterns of internal variability in the Earth's climate that it could be used to detect the greenhouse gas signal in observations.

Noise can lead to periodic fluctuations in the earth's climate !

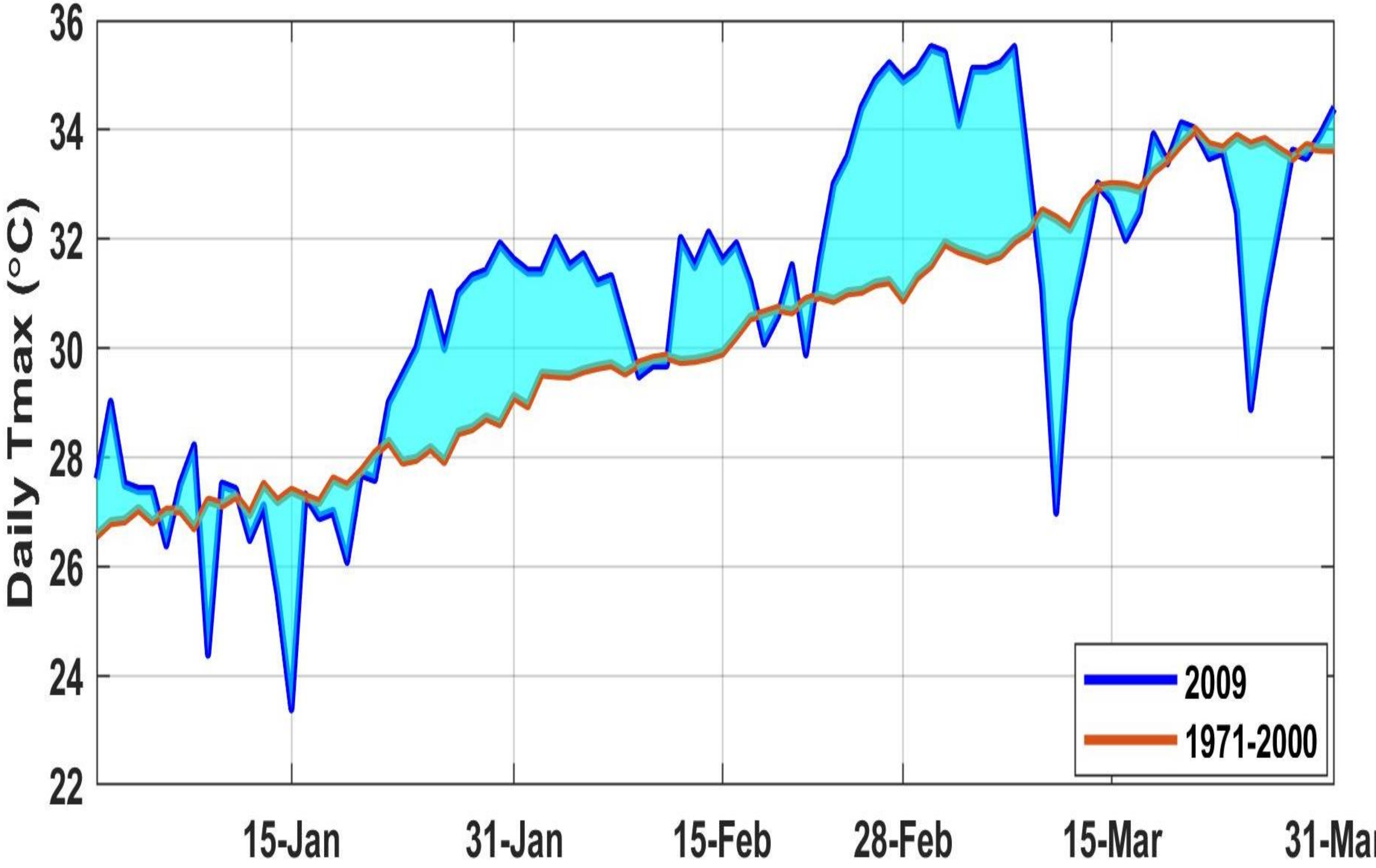
Tellus (1982) *34*, 10–16

Stochastic resonance in climatic change

By ROBERTO BENZI, *Istituto di Fisica dell'Atmosfera, C.N.R., Piazza Luigi Sturzo 31, 00144, Roma, Italy,*
GIORGIO PARISI, *I.N.F.N., Laboratori Nazionali di Frascati, Frascati, Roma, Italy,*
ALFONSO SUTERA, *The Center for the Environment and Man, Hartford, Connecticut 06120, U.S.A.*
and ANGELO VULPIANI, *Istituto di Fisica "G. Marconi", Università di Roma, Italy*

- **Fluctuations in weather**
- **Natural climate Variability**
- **Anthropogenic Climate change**

Maximum temperature: Bengaluru



CLIMATE IS DIFFERENT FROM WEATHER

WEATHER

- TIME SCALE
  - HOURS-DAYS
- SPATIAL SCALE
  - REGIONAL
- MAIN COMPONENTS
  - ATMOSPHERE

CLIMATE

- TIME SCALE

30 YEARS &BEYOND

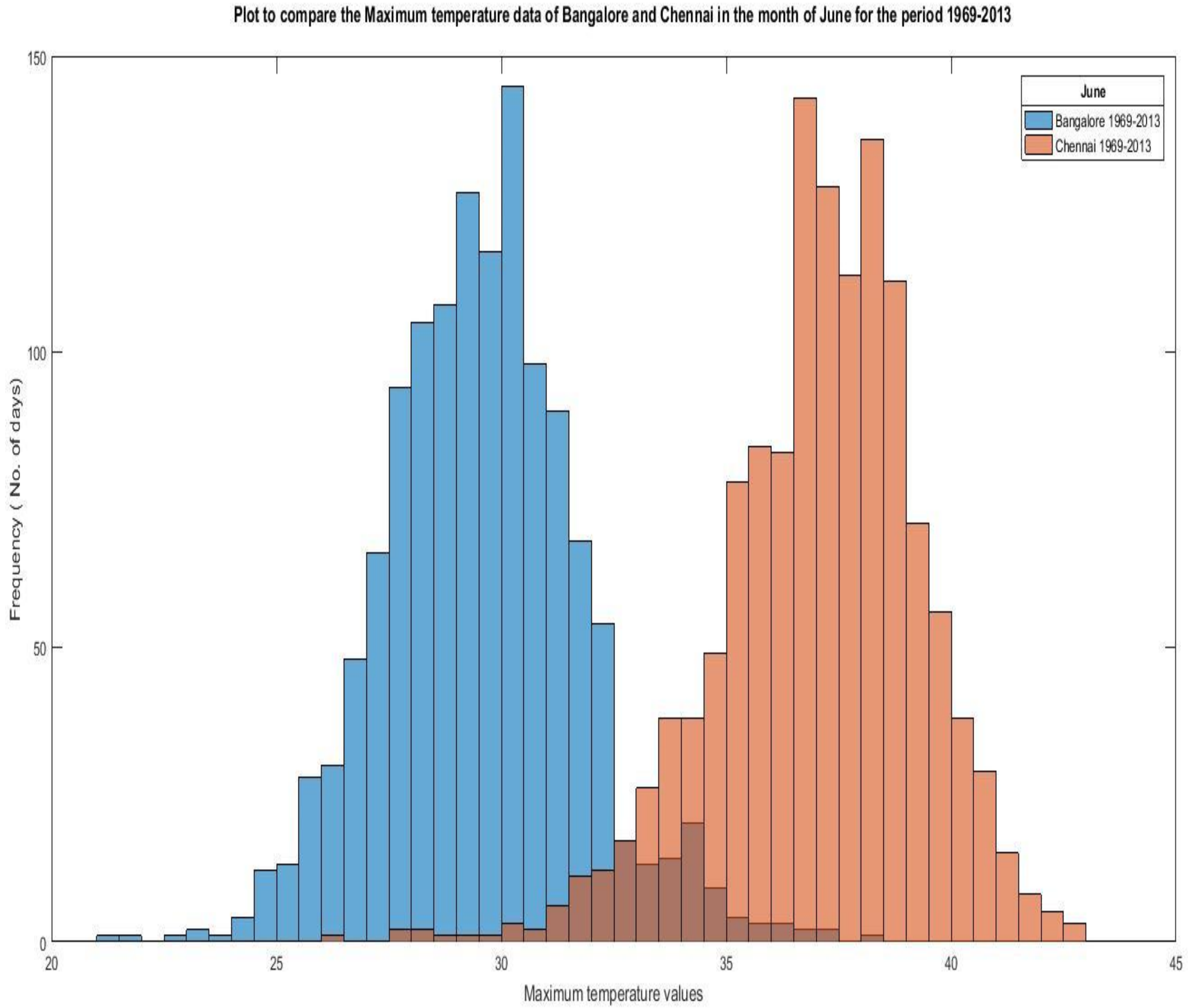
- SPATIAL SCALE

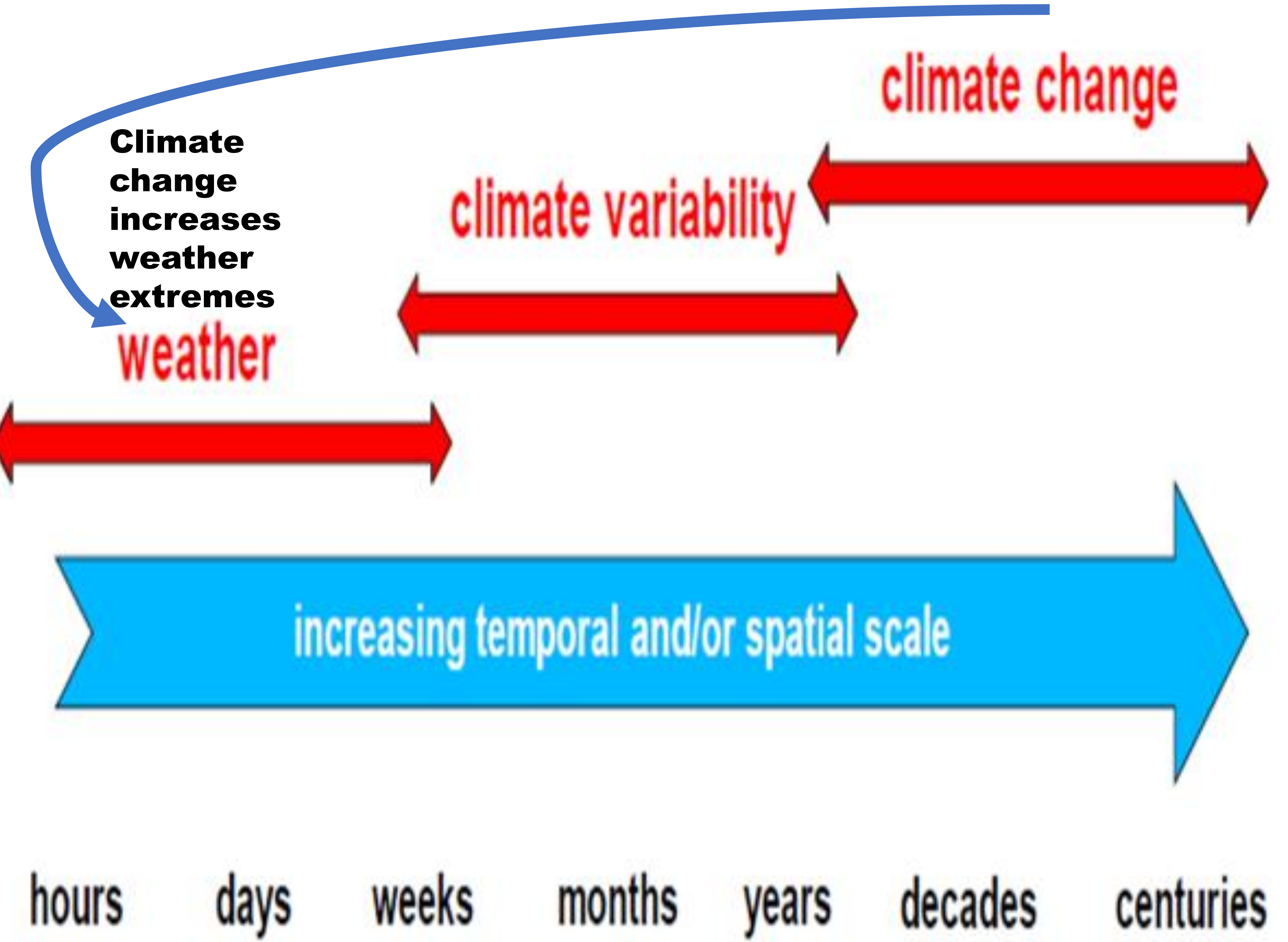
REGIONAL-GLOBAL

- MAIN COMPONENTS

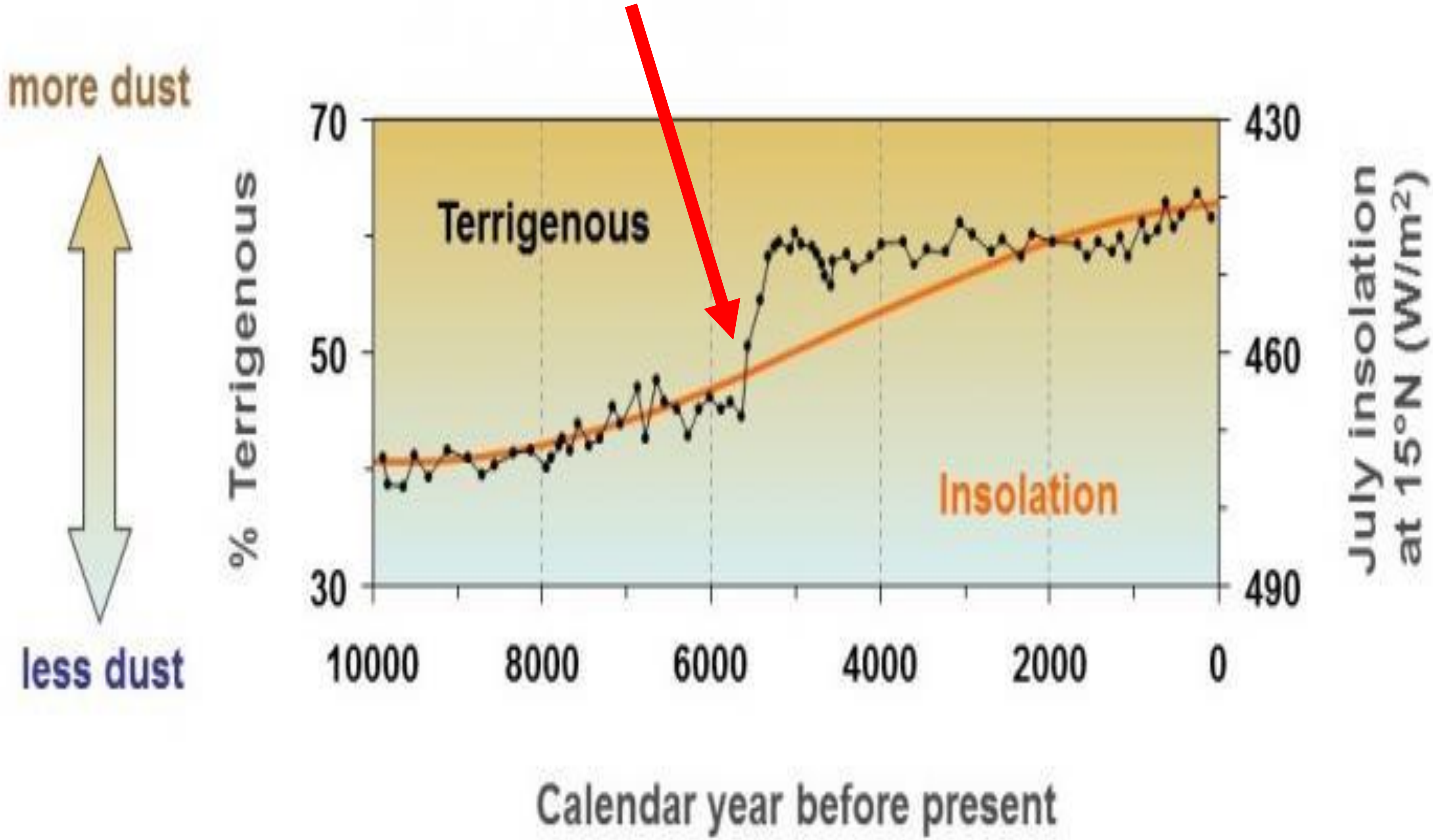
ATMOSPHERE, OCEAN, LAND... HUMANS

CLIMATE IS THE STATISTICS OF WEATHER AVERAGED OVER TIME


Plot to compare the Maximum temperature data of Bangalore and Chennai in the month of June for the period 1969-2013
June
Bangalore 1969-2013
Chennai 1969-2013
Frequency (No. of days)
150
100
50
0
20
25
30
35
40
45
Maximum temperature values

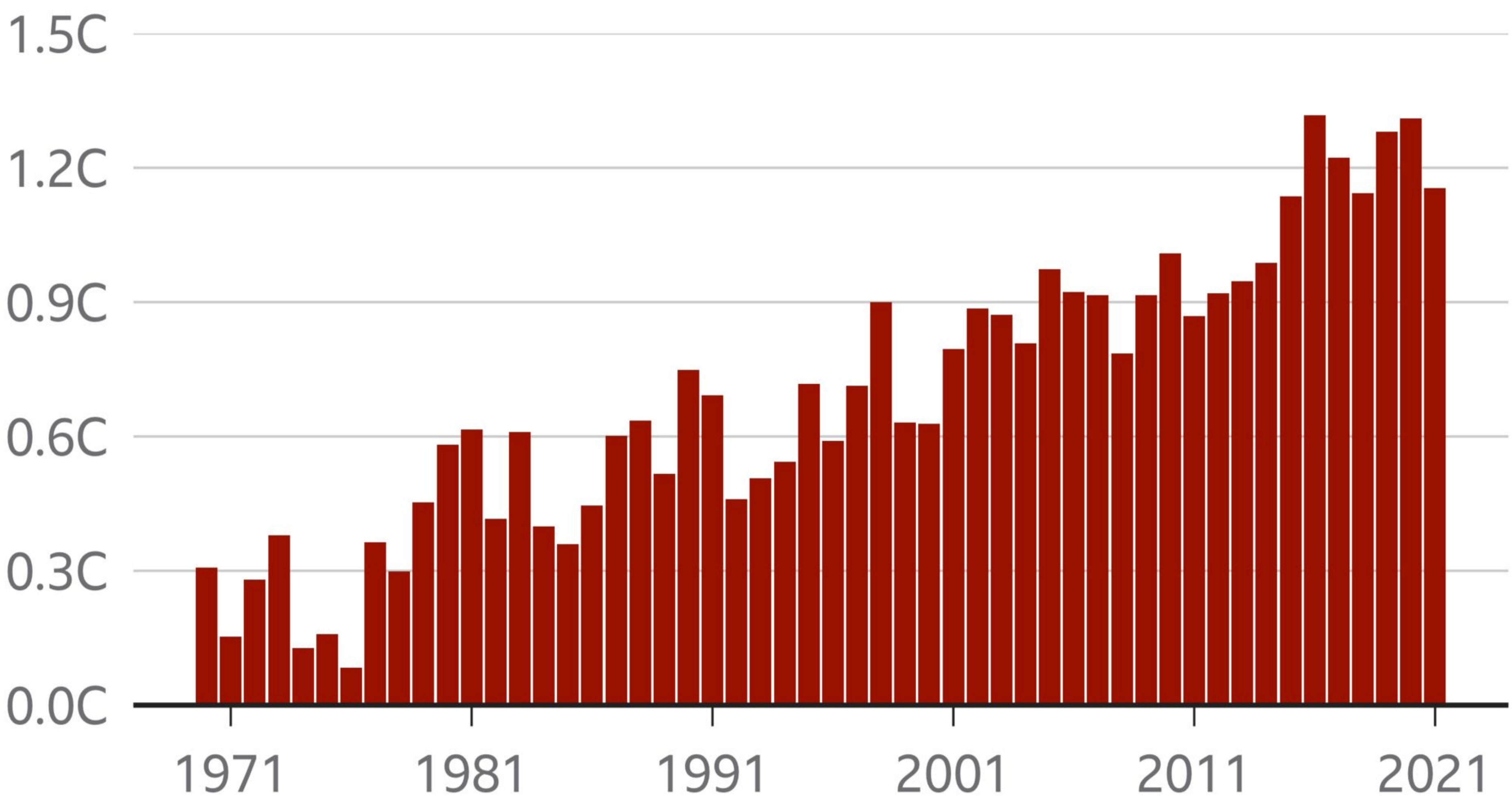

climate change
Climate change increases weather extremes
climate variability
weather
increasing temporal and/or spatial scale
hours
days
weeks
months
years
decades
centuries

RAPID CLIMATE CHANGE FROM GREEN SAHARA TO A DESERT

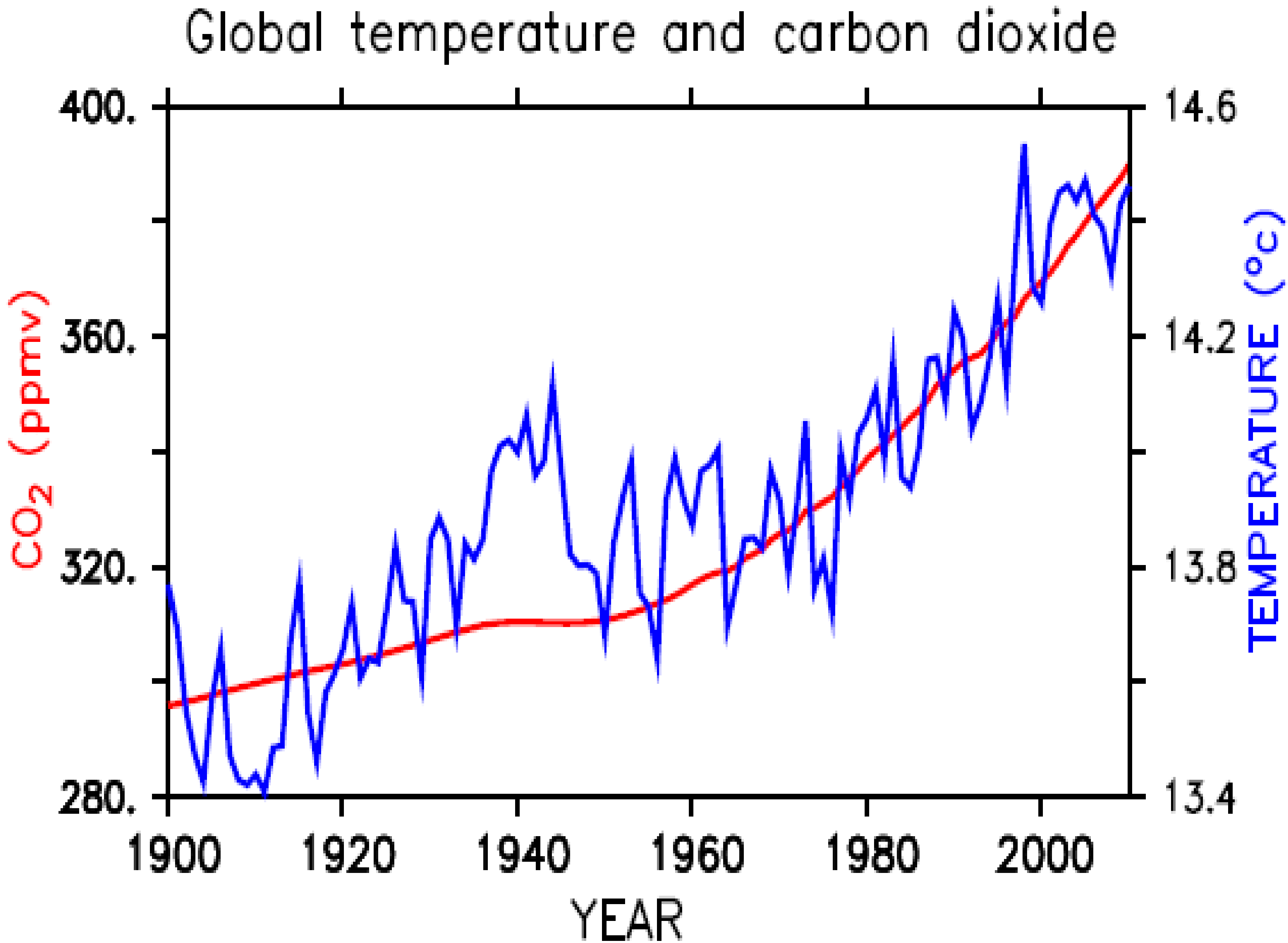


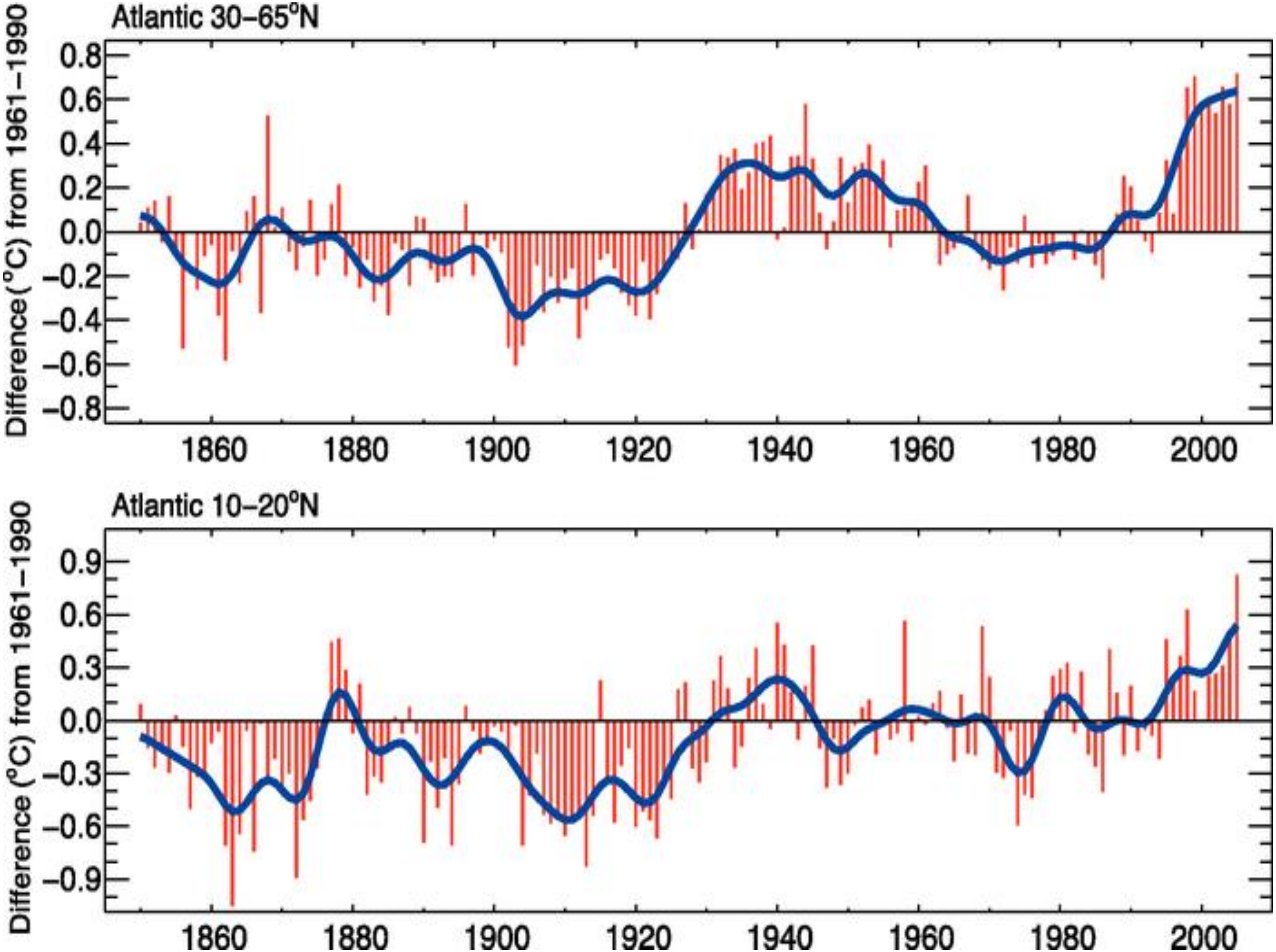
2021 was the fifth warmest year on record

Annual global-average temperature increase (degrees C) above pre-industrial level



Source: ERA5, Copernicus Climate Change Service


Global temperature and carbon dioxide
400.
360.
320.
280.
14.6
14.2
13.8
13.4
CO_2 (ppmv)
TEMPERATURE (°c)
1900
1920
1940
1960
1980
2000
YEAR



Atlantic 30–65°N
Difference (°C) from 1961–1990
0.8
0.6
0.4
0.2
0.0
−0.2
−0.4
−0.6
−0.8
1860
1880
1900
1920
1940
1960
1980
2000
Atlantic 10–20°N
Difference (°C) from 1961–1990
0.9
0.6
0.3
0.0
−0.3
−0.6
−0.9
1860
1880
1900
1920
1940
1960
1980
2000

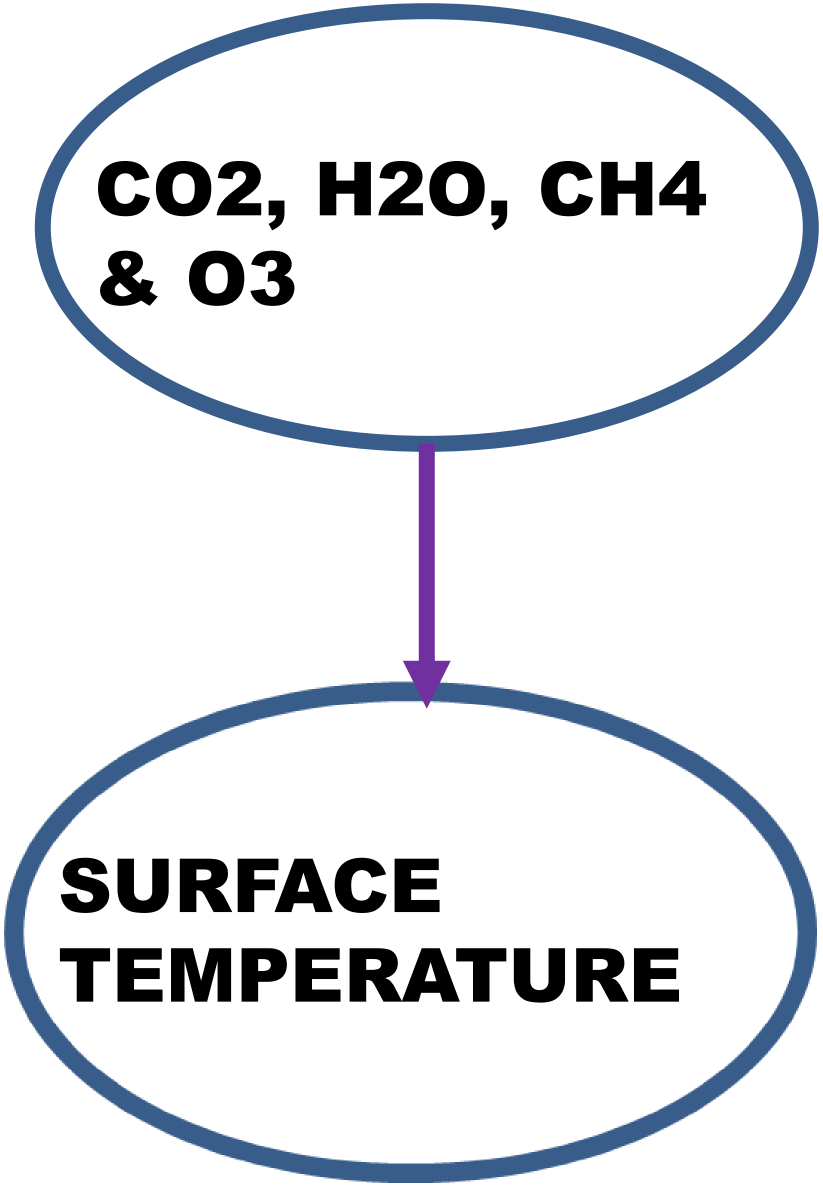
SIMPLE CLIMATE MODELS

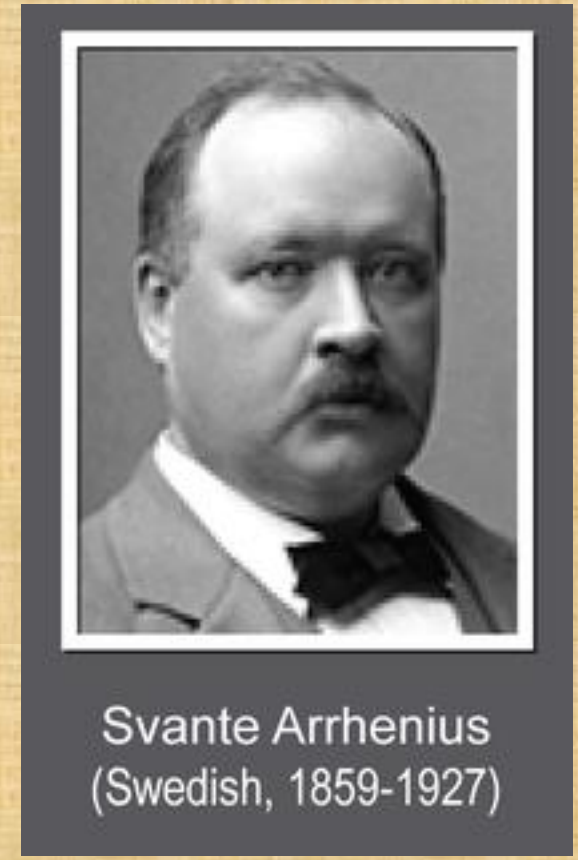
The global mean temperature is determined by the delicate balance between absorbed solar radiation and emitted earth's radiation

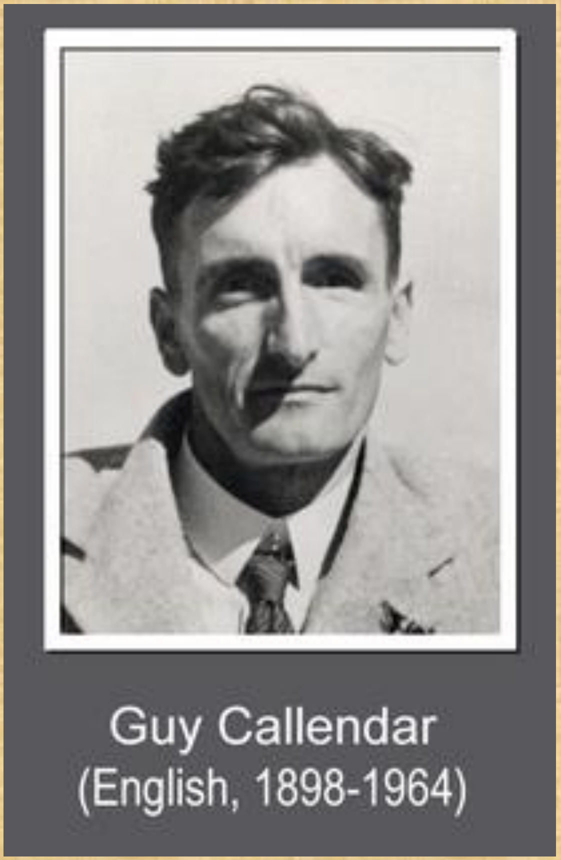
absorption of solar radiation(a function of temperature)

= earth's emission to space (a function of Temp)

Four minor gases (CO_2, H_2O, CH_4 & O_3) control the earth's surface temperature by reducing the amount of radiation that can emitted to space







Svante Arrhenius calculated that emissions from industry might someday warm the earth. In 1939, G.S.Callendar argued that carbon dioxide causes global warming. Arrhenius and Callendar thought that global warming will be beneficial !

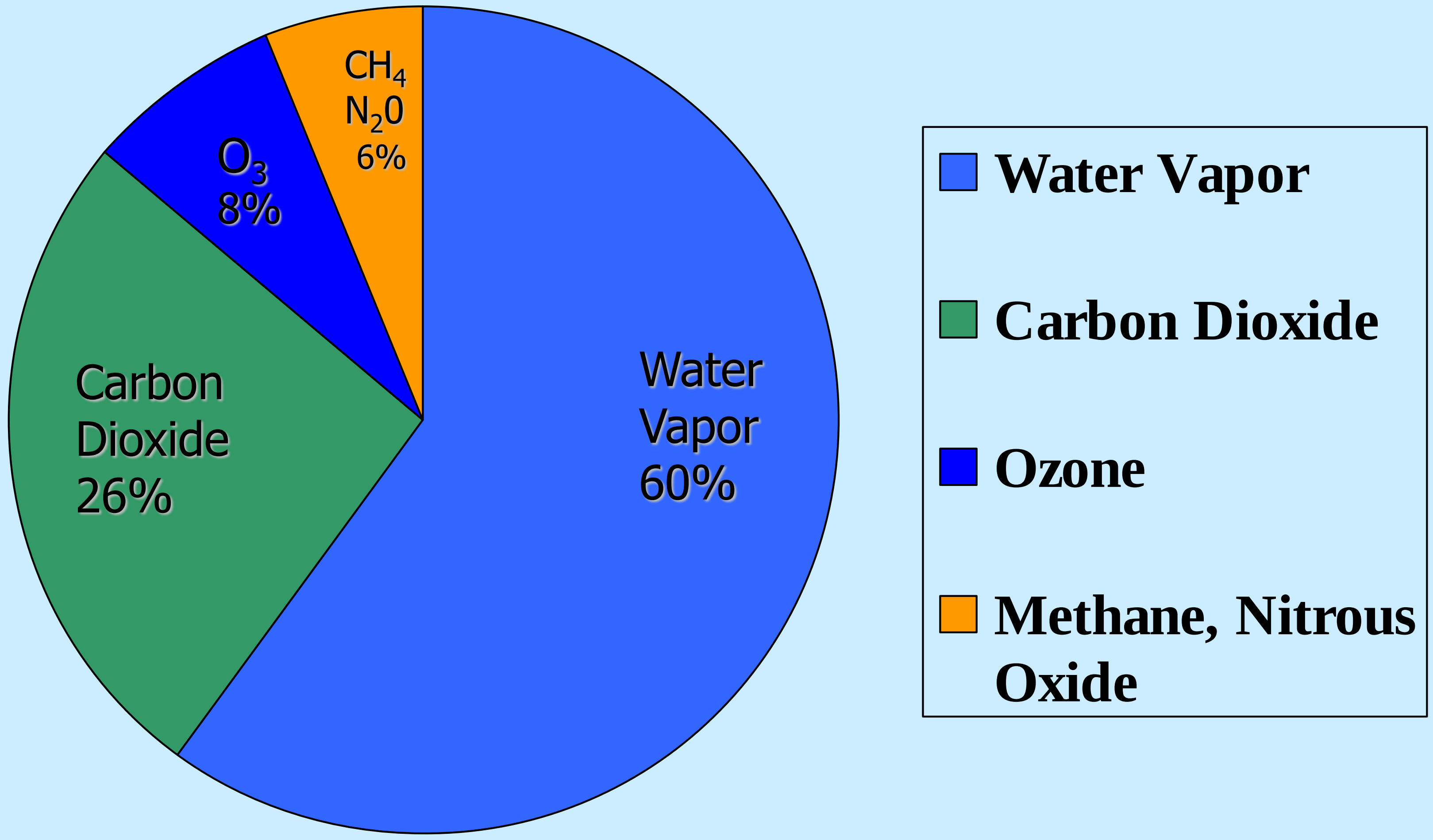
GREENHOUSE EFFECT

GHE = RADIATION EMITTED BY PLANET'S SURFACE – RADIATION LEAVING THE PLANET

EARTH = 390 -240 =150 W/m^2

VENUS=16100-200=15,900 W/m^2

The Greenhouse Effect: clear sky



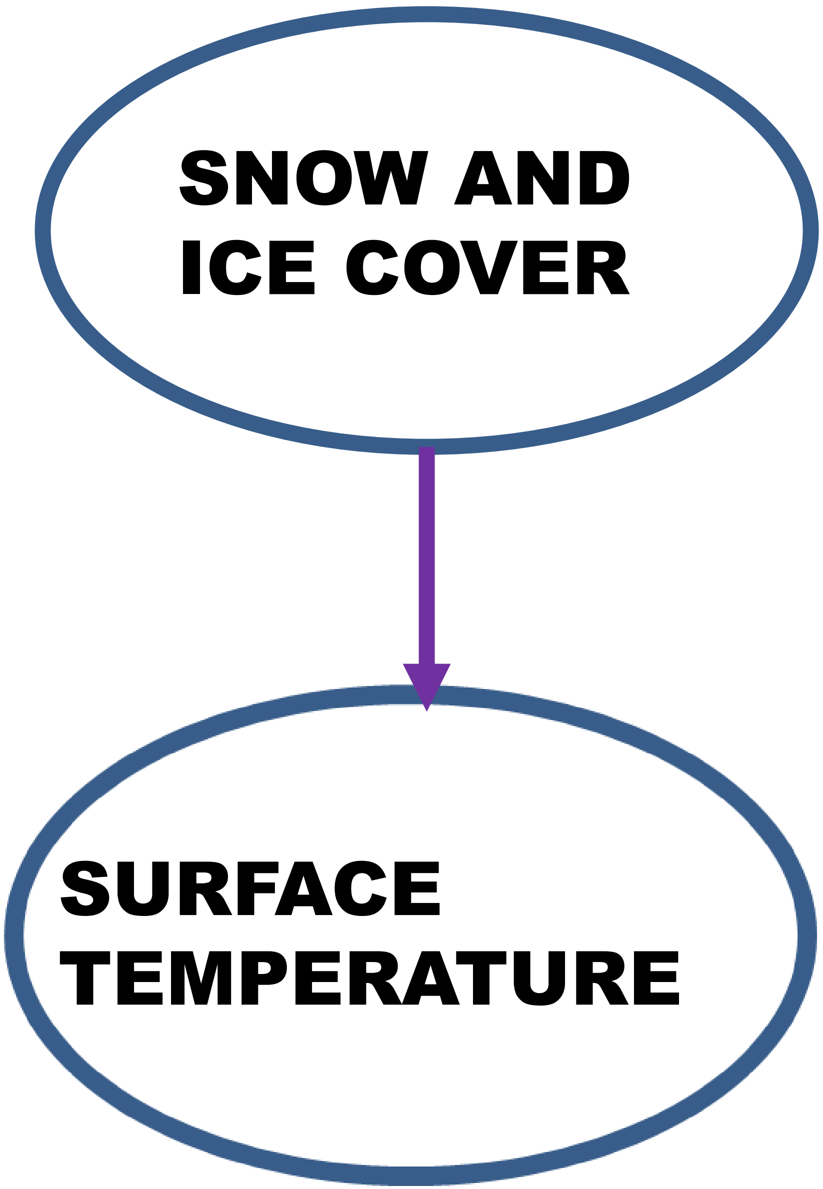
WATER VAPOR CONSIDERED AS A FEEDBACK

Kiehl and Trenberth 1997

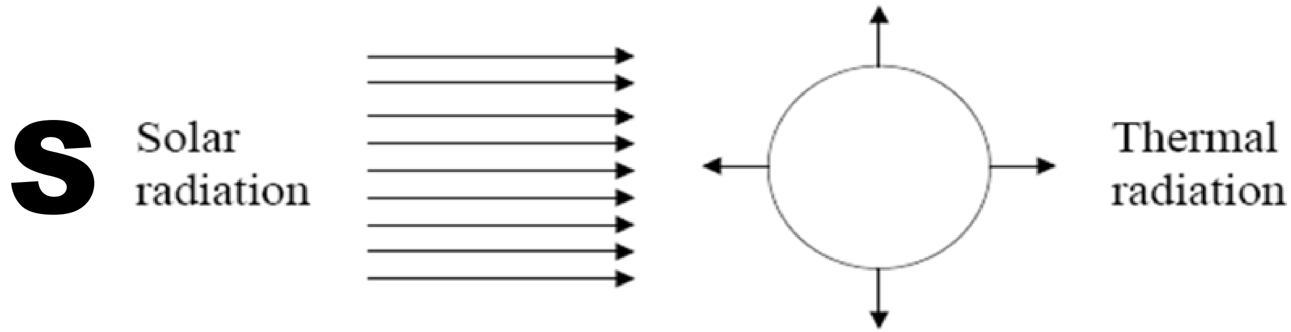
Global mean temperature is controlled mainly by carbon dioxide (With water vapor acting as a powerful amplifier)

Amount of water vapor on earth is controlled by CO_2 through its impact on global mean temperature.

Snow and ice covered area control the earth's surface temperature by altering the amount of solar radiation reflected to space



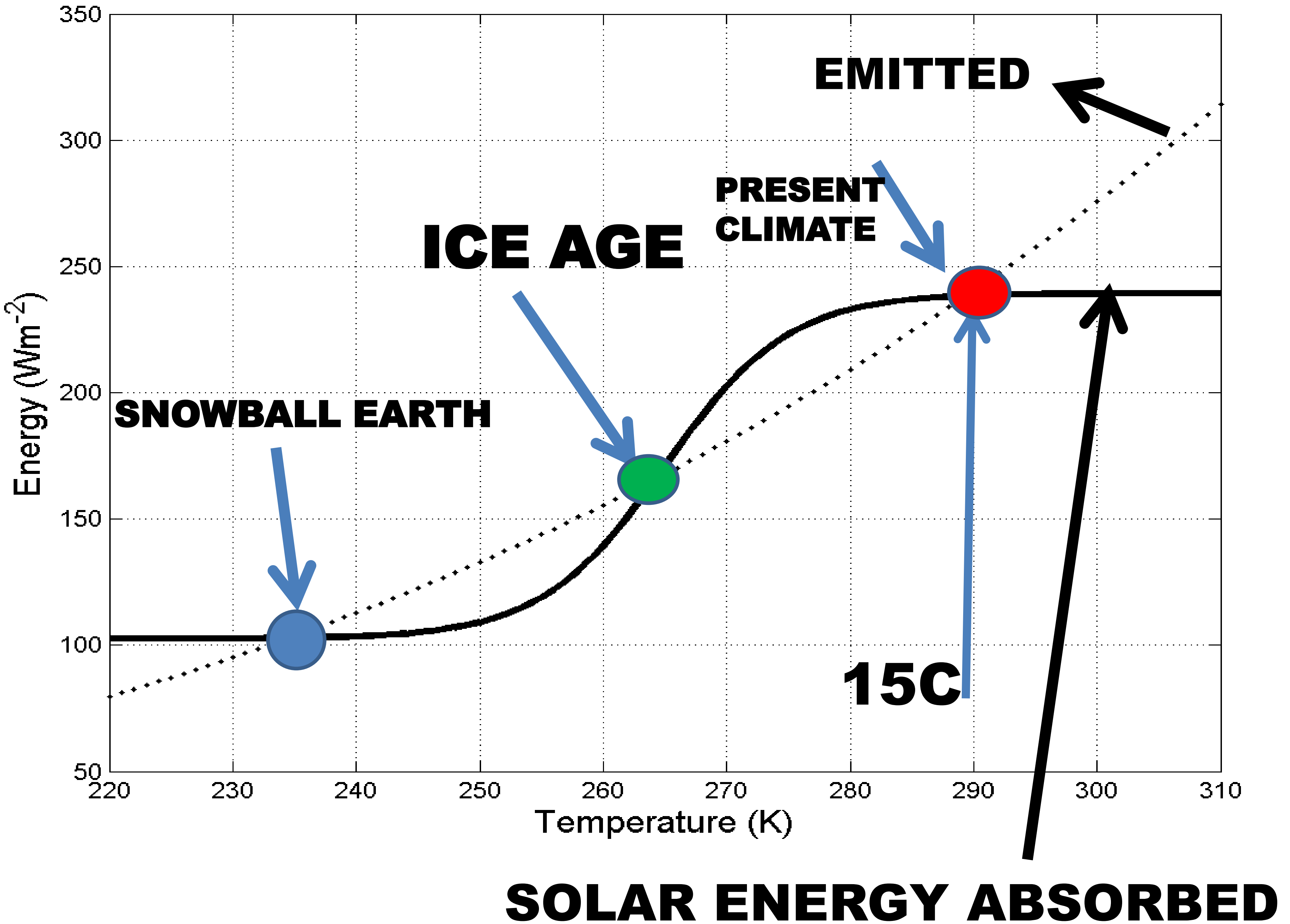
Overall energy balance of the Earth



Absorbed solar= emitted by earth-atmos

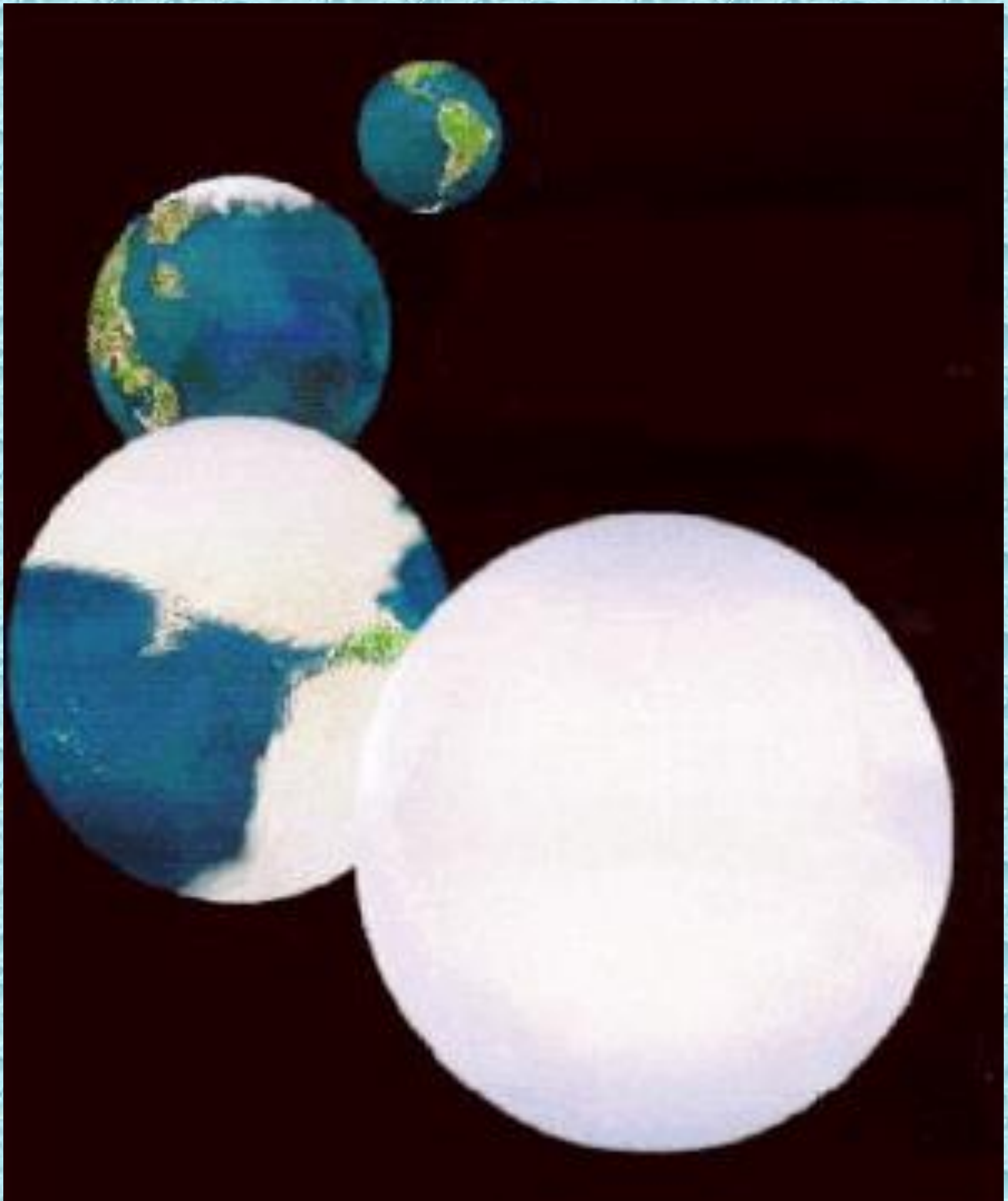
$$S/4\,\{1-\rho(T)\} = \text{Emission}\,(T, \text{GHG})$$

ρ=Reflection of solar rad (called albedo) is a function of temperature T



EMITTED
PRESENT
CLIMATE
ICE AGE
SNOWBALL EARTH
15C
Energy (Wm-2)
Temperature (K)
350
300
250
200
150
100
50
220
230
240
250
260
270
280
290
300
310
SOLAR ENERGY ABSORBED

Natural climate change



Oscillations between ice-free and ice-covered earth

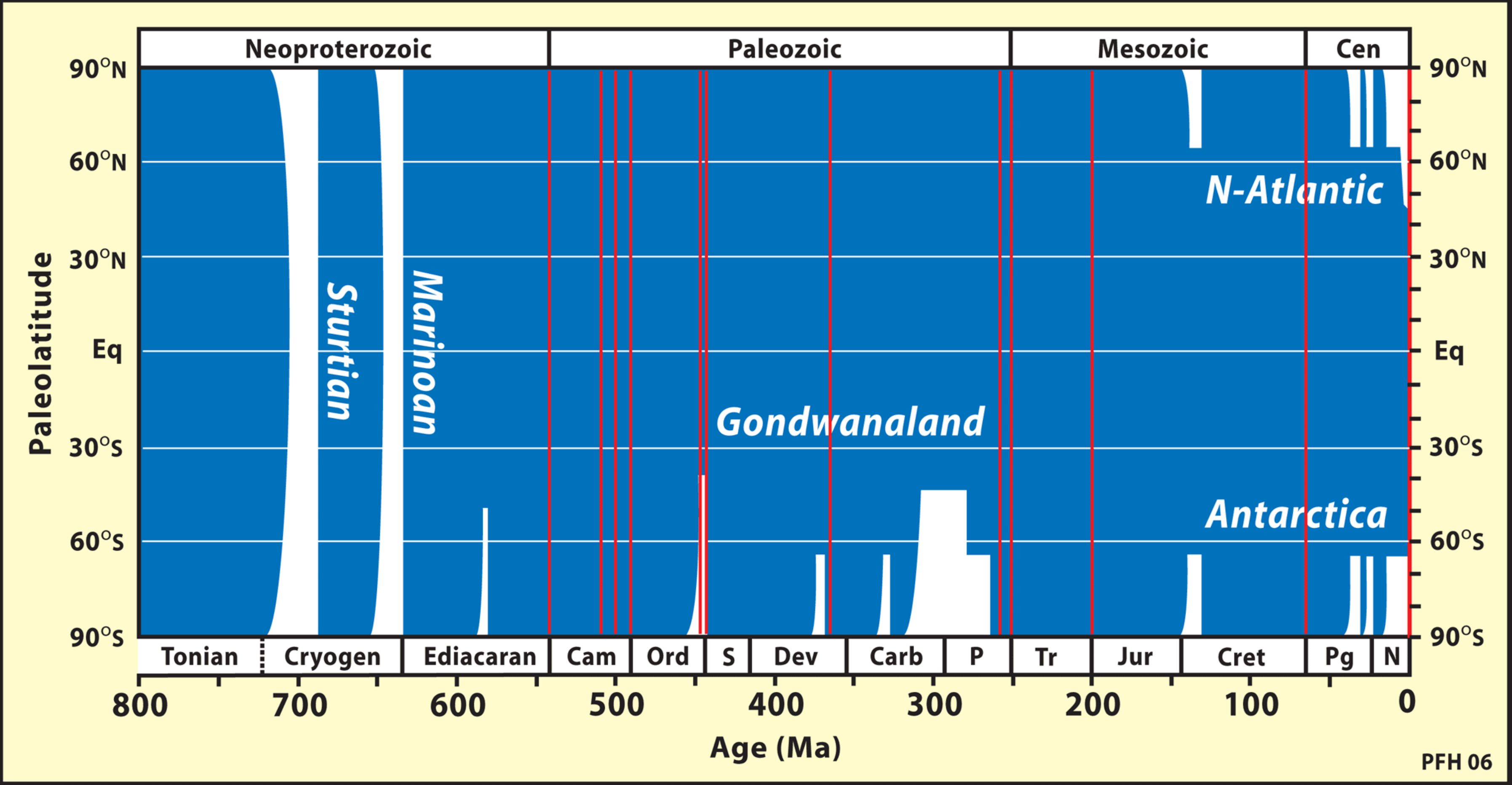
SNOWBALL EARTH

The Story of a Maverick Scientist and His Theory of the Global Catastrophe That Spawned Life As We Know It

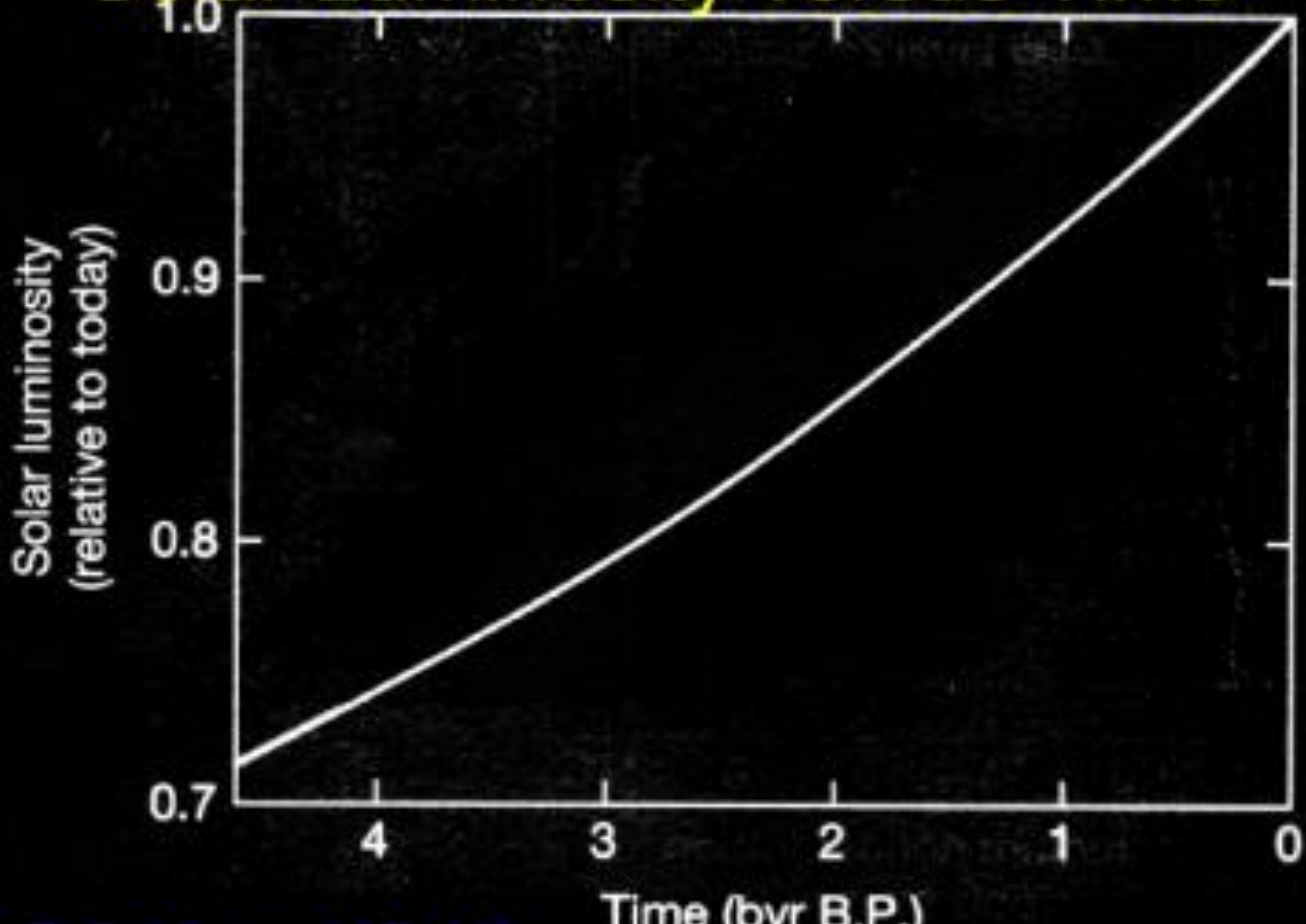
Gabrielle Walker

Paul Hoffman

Paleogeographic extent of continental ice sheets and permanent sea ice over the last 800 Myr (red lines indicate major mass extinctions)



Solar Luminosity versus Time



The Earth System, ed. 2 Fig. 1.12

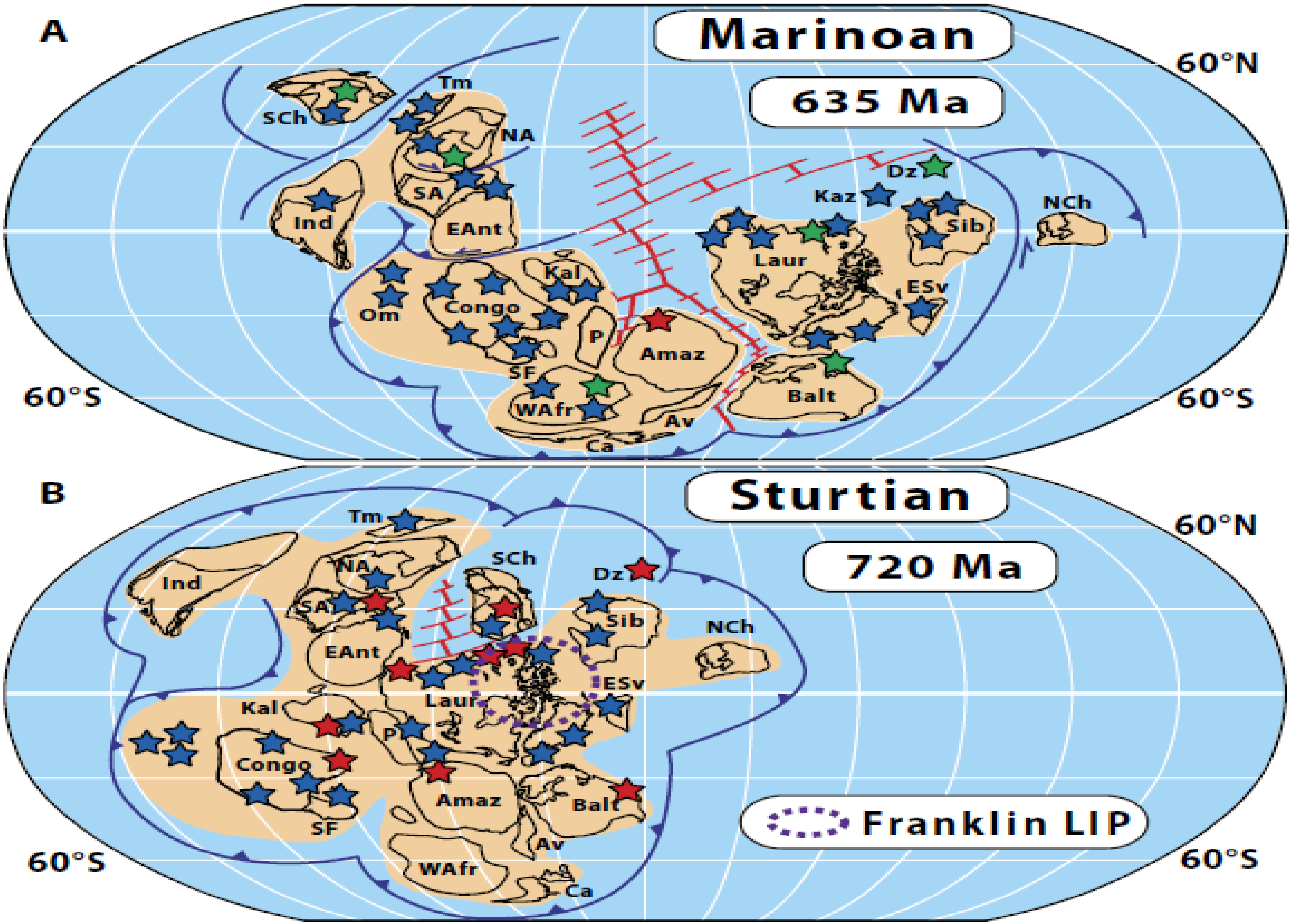
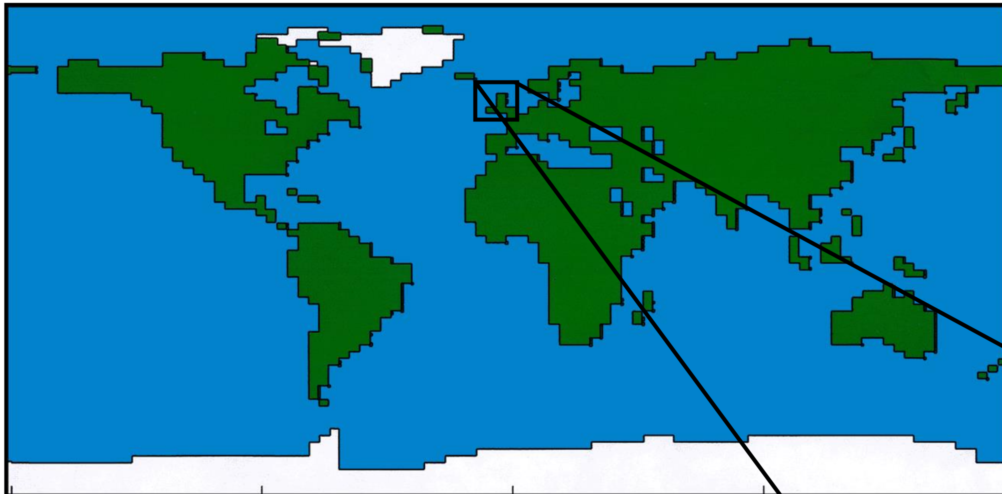


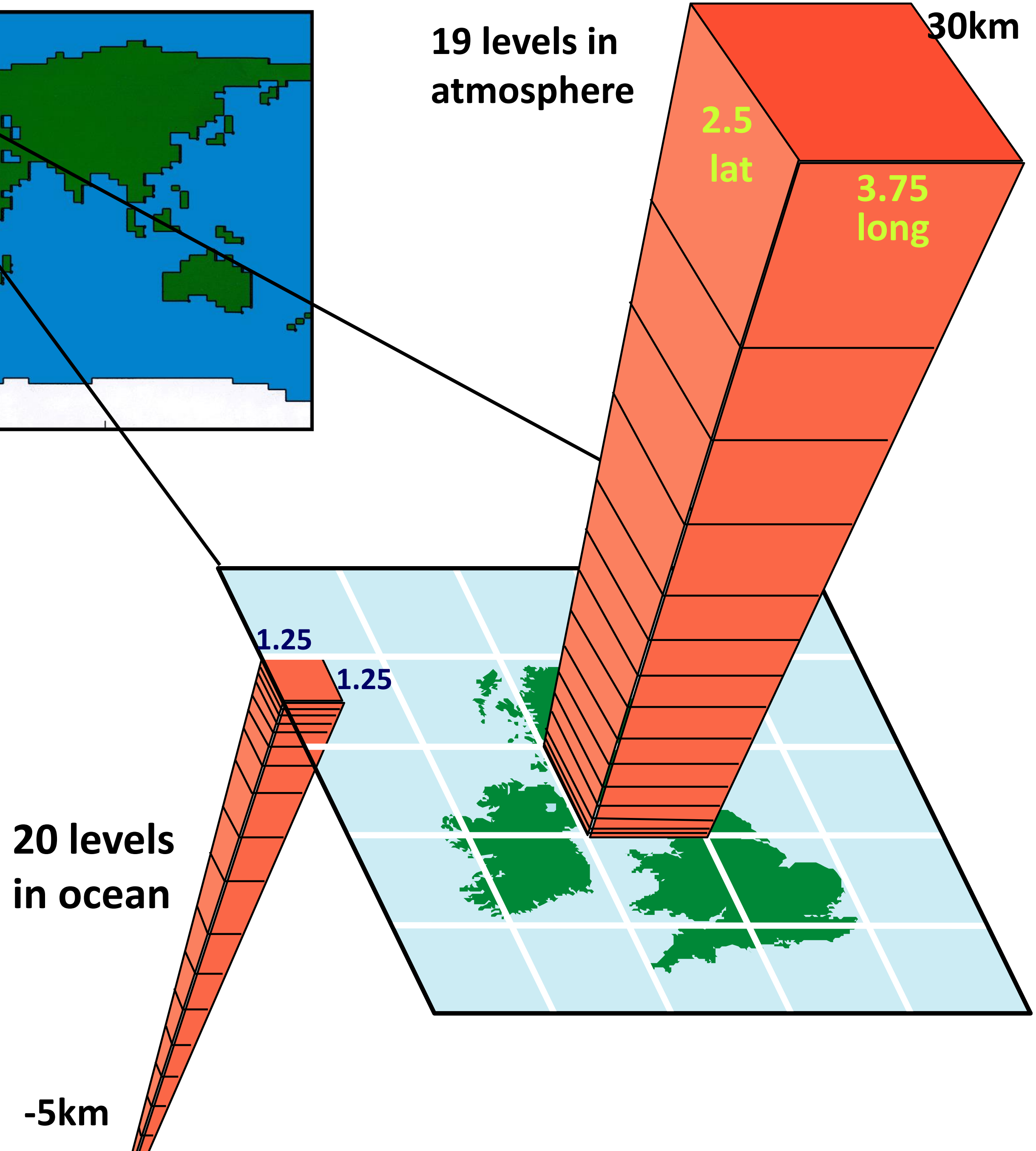
Fig. 5. Cryogenian paleogeography and the breakup of Rodinia. Global paleo-

COMPLEX CLIMATE MODELS



THE HADLEY CENTRE THIRD COUPLED MODEL - HadCM3

no flux adjustments



Conservation equations for gridbox-mean quantities in a model

- Mass

$$\nabla \cdot (\rho \bar{\mathbf{u}}) = 0$$

- Thermodynamic energy

$$\frac{D\bar{\theta}}{Dt} = F_\theta$$

- Radiation
- Latent heat release
- *Transport by turbulence*
- *Transport by deep convection*

- Water vapour

$$\frac{D\bar{q}}{Dt} = F_q$$

- Condensation/evaporation
- Precipitation
- *Transport by turbulence*
- *Transport by deep convection*

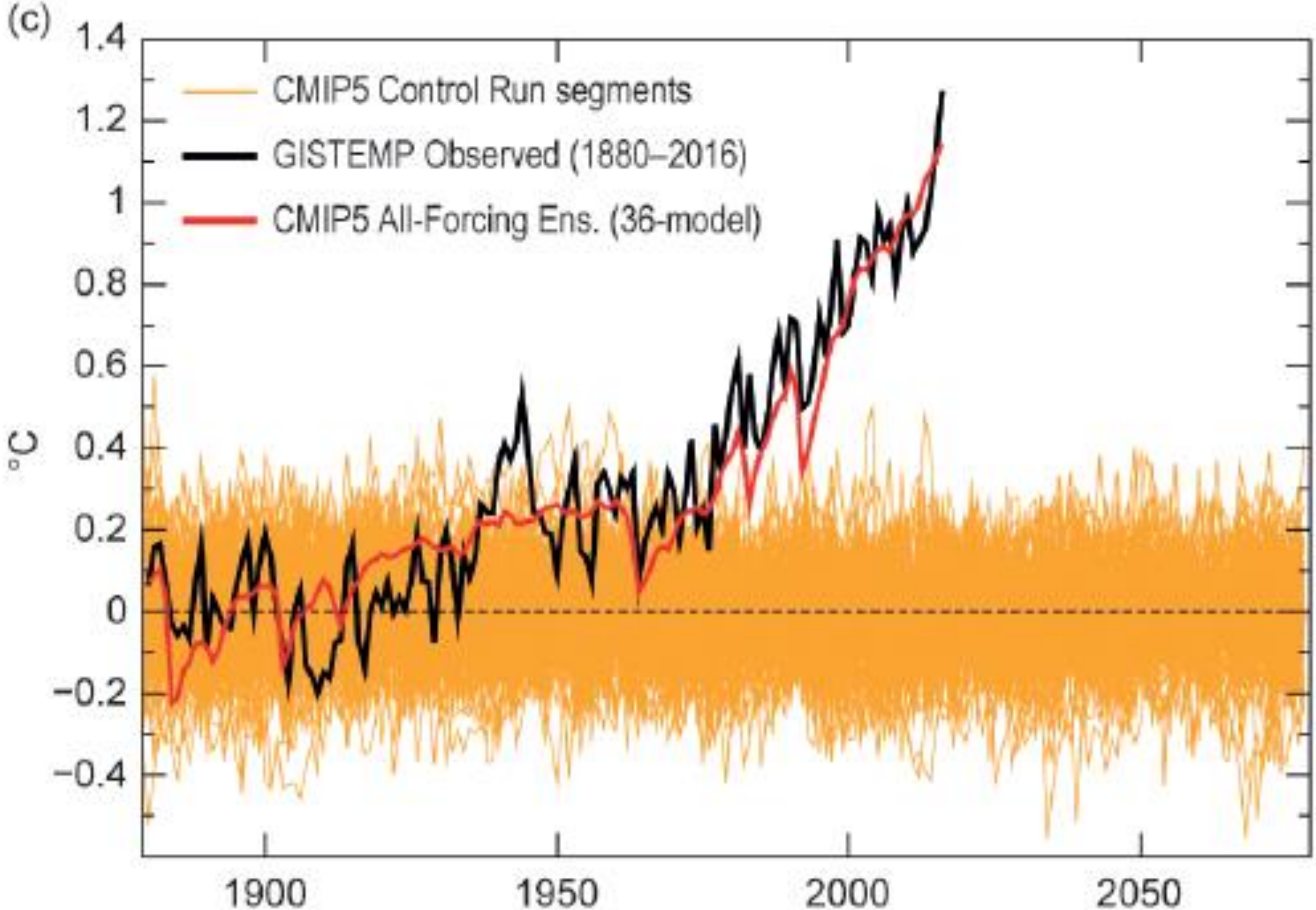
- Momentum (acceleration = force per unit mass)

$$\frac{D\bar{\mathbf{u}}}{Dt} + f\hat{\mathbf{k}} \times \bar{\mathbf{u}} + \frac{1}{\rho}\nabla p + \hat{\mathbf{k}}g = \mathbf{F}_\mathbf{u}$$

- *Gravity wave drag*
- *Transport by turbulence*
- *Transport by deep convection*

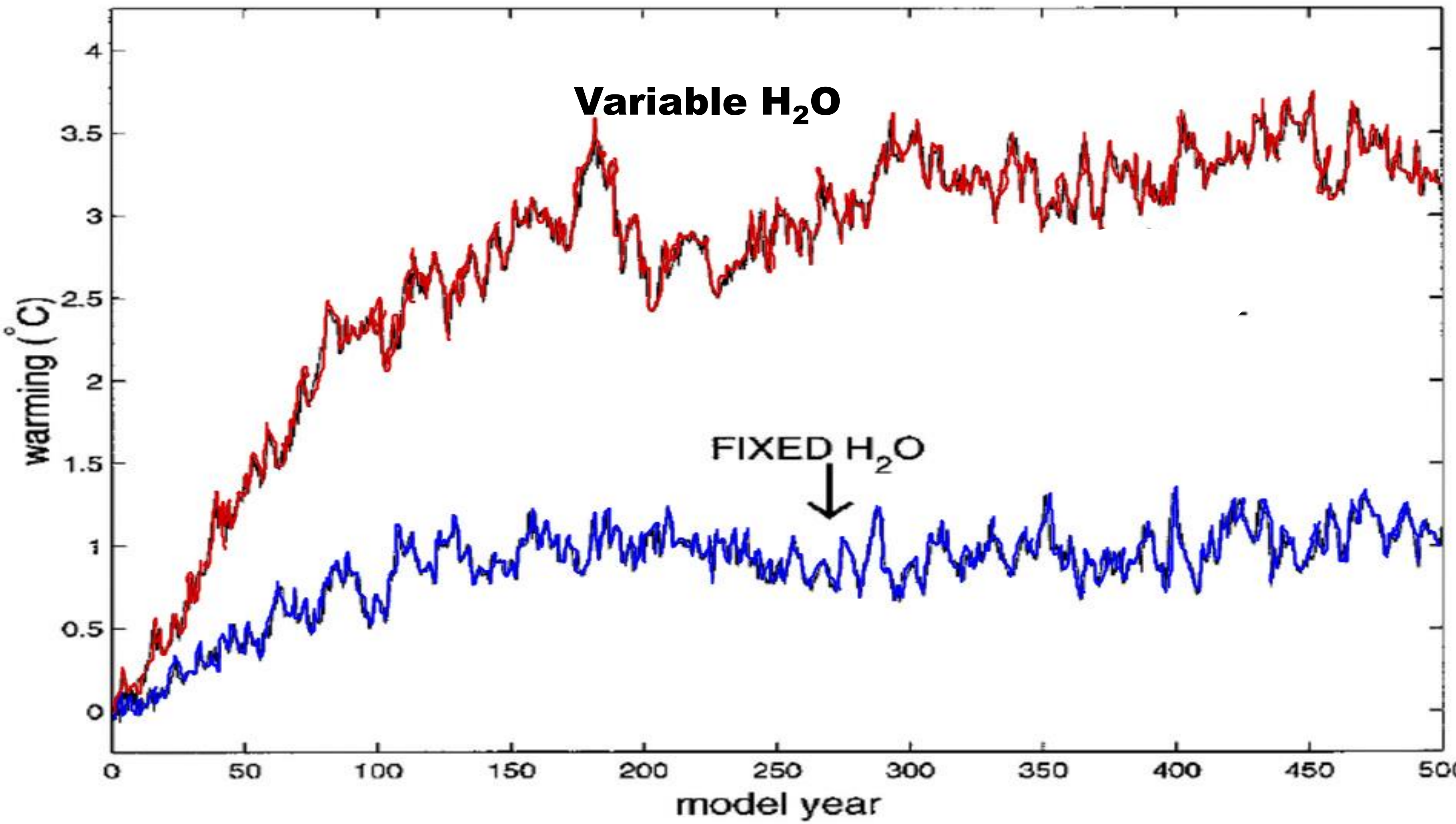
Old fashioned division: terms on the left are "dynamics", terms on the right are "physics"

Processes in italics are purely due to unresolved processes: would be unnecessary in a high resolution model (e.g. 100 m)



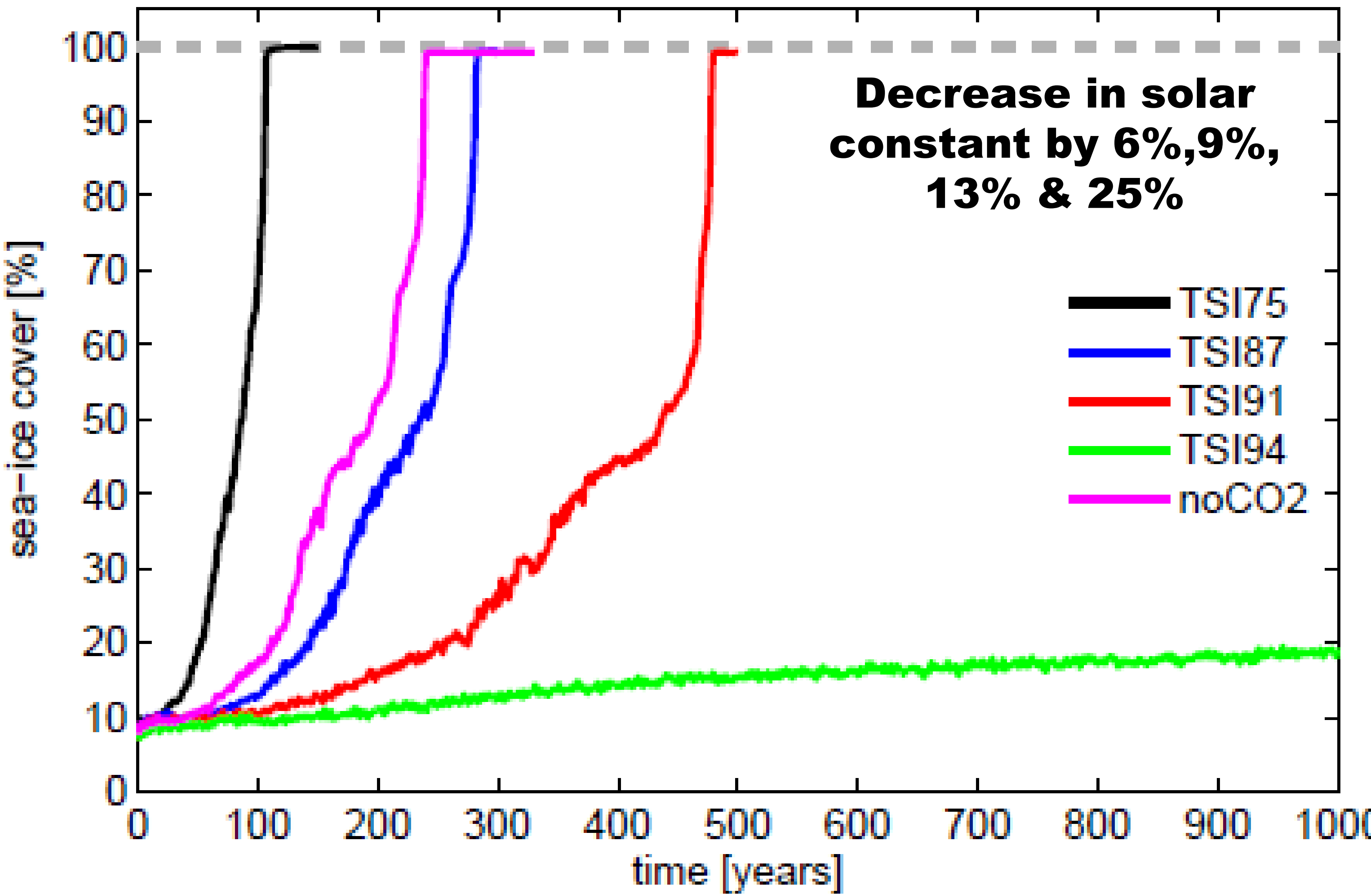
Knutson et al., Bulletin of the American Meteorological Society, December 2017

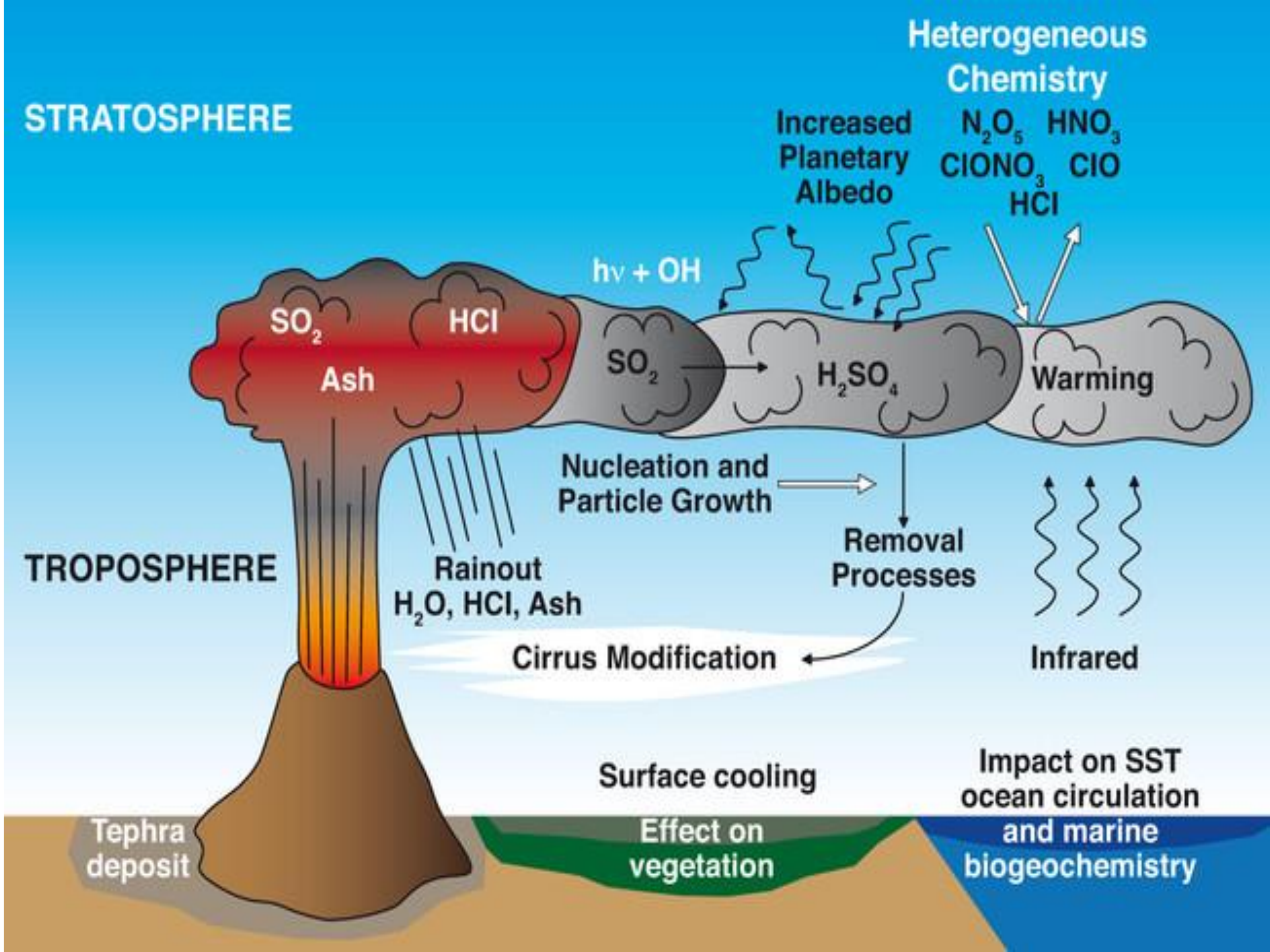
Hall and Manabe ,Journal of Climate,1999



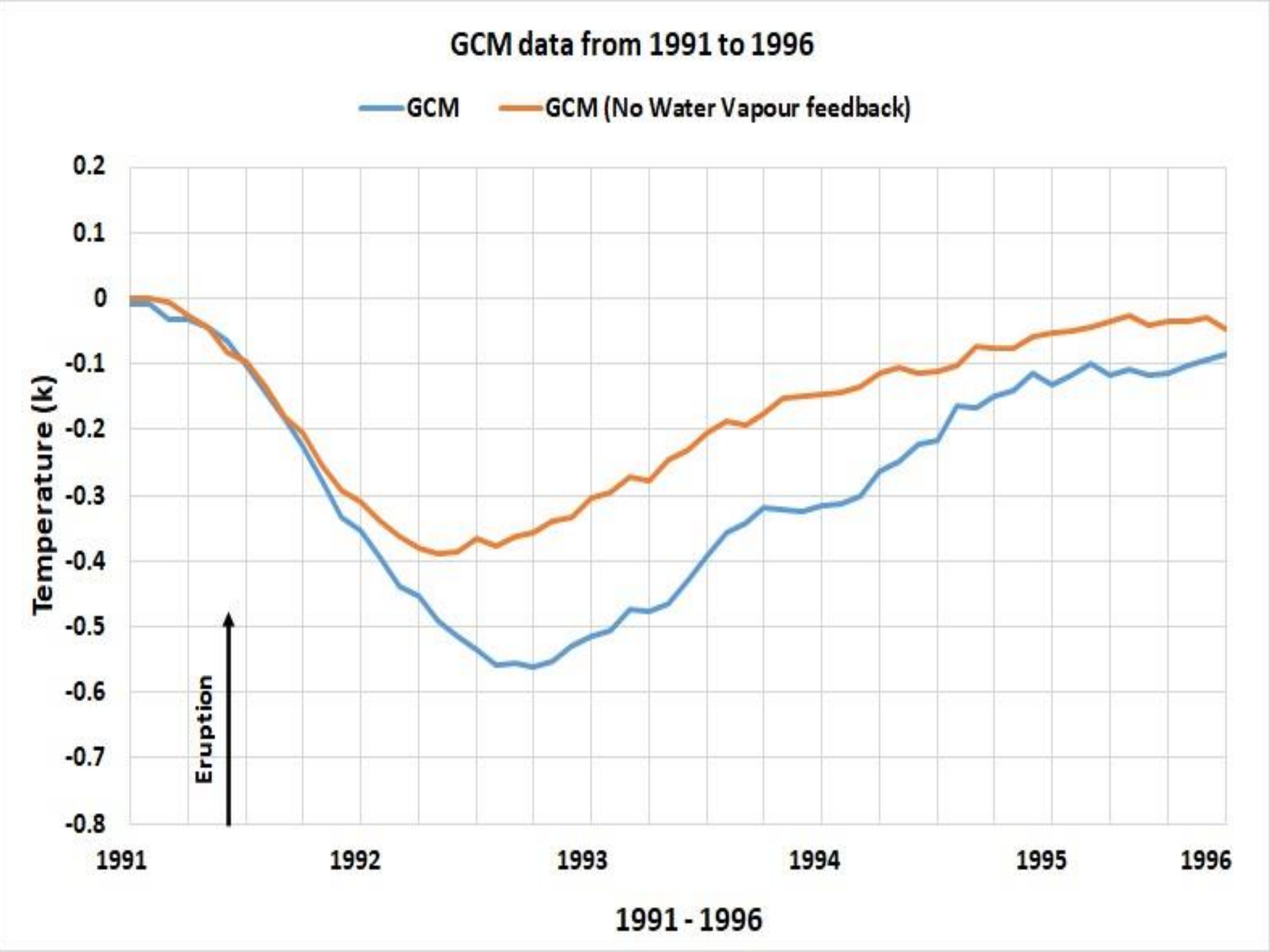
The 500-yr annual-mean time series of the global-mean surface temperature change in the integrations where CO2 is doubled to 720 ppm relative to the unperturbed variability experiments, where CO2 is fixed at 360 ppm.

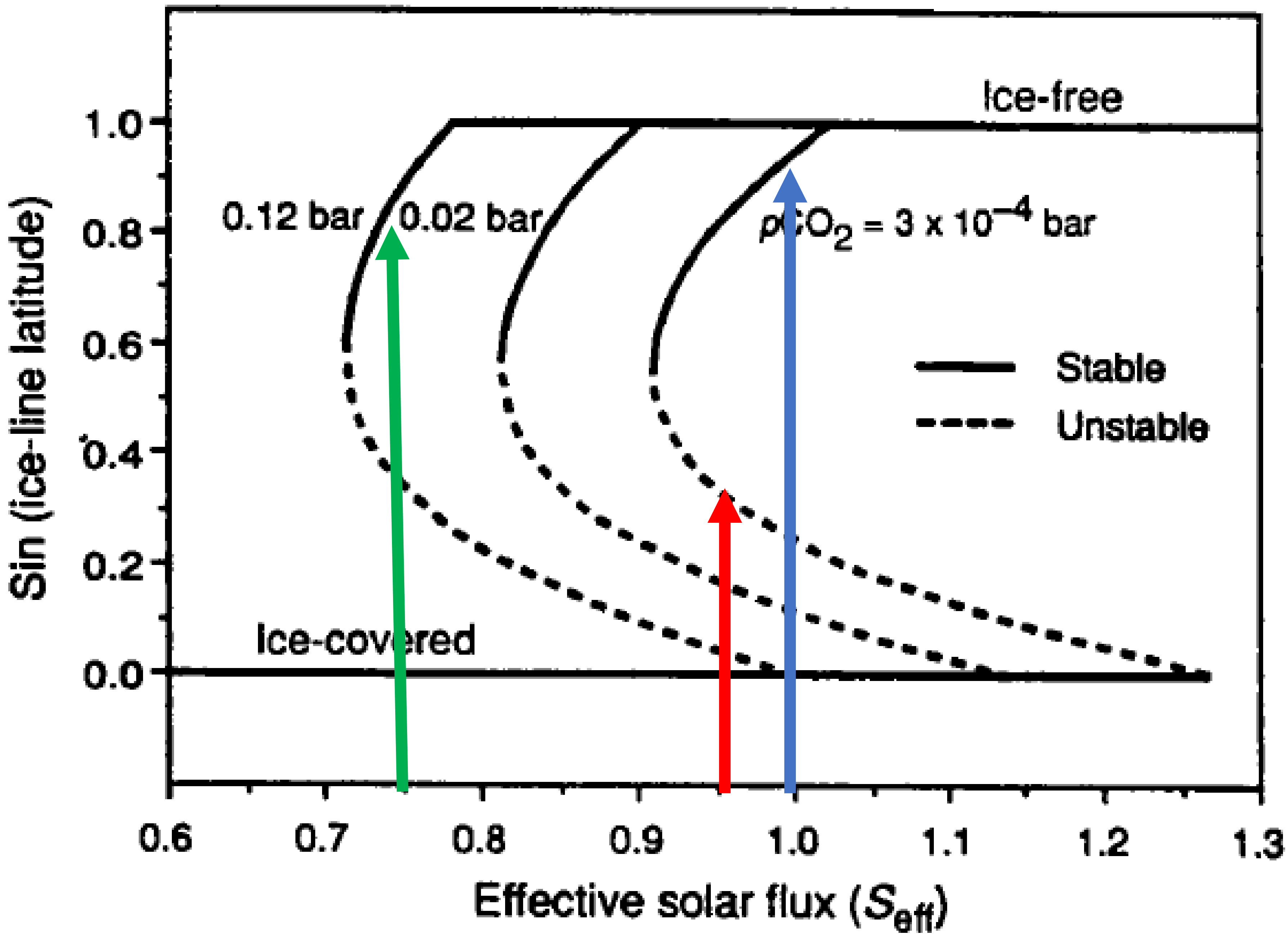
CO_2 and incoming solar radiation are primary drivers of the past climate change



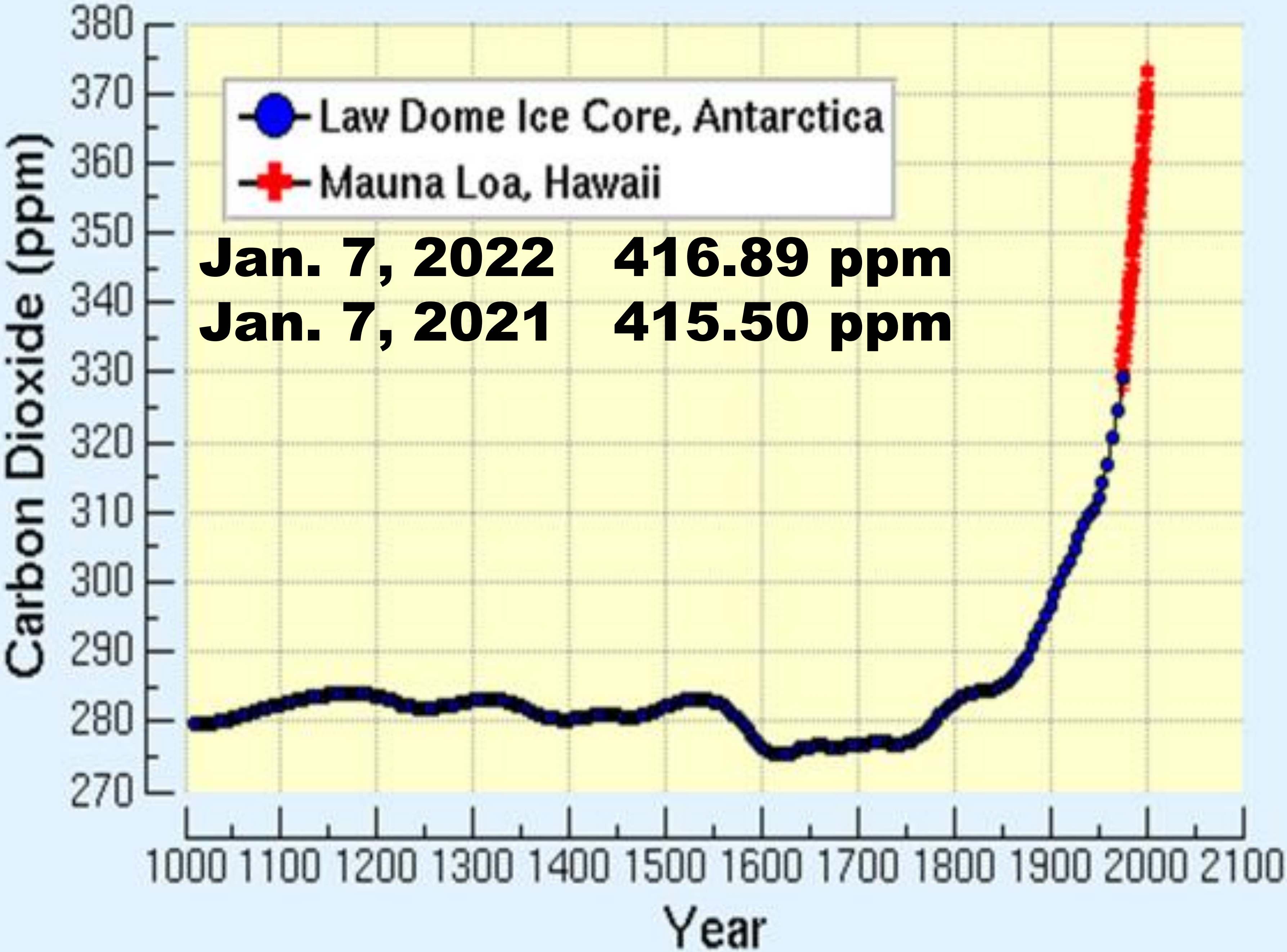


Heterogeneous Chemistry
STRATOSPHERE
Increased Planetary Albedo
N_2O_5 HNO_3
$ClONO_3$ ClO
HCl
hν + OH
SO_2
HCl
Ash
SO_2
H_2SO_4
Warming
Nucleation and Particle Growth
Removal Processes
TROPOSPHERE
Rainout
H_2O, HCl, Ash
Cirrus Modification
Infrared
Surface cooling
Impact on SST ocean circulation and marine biogeochemistry
Tephra deposit
Effect on vegetation

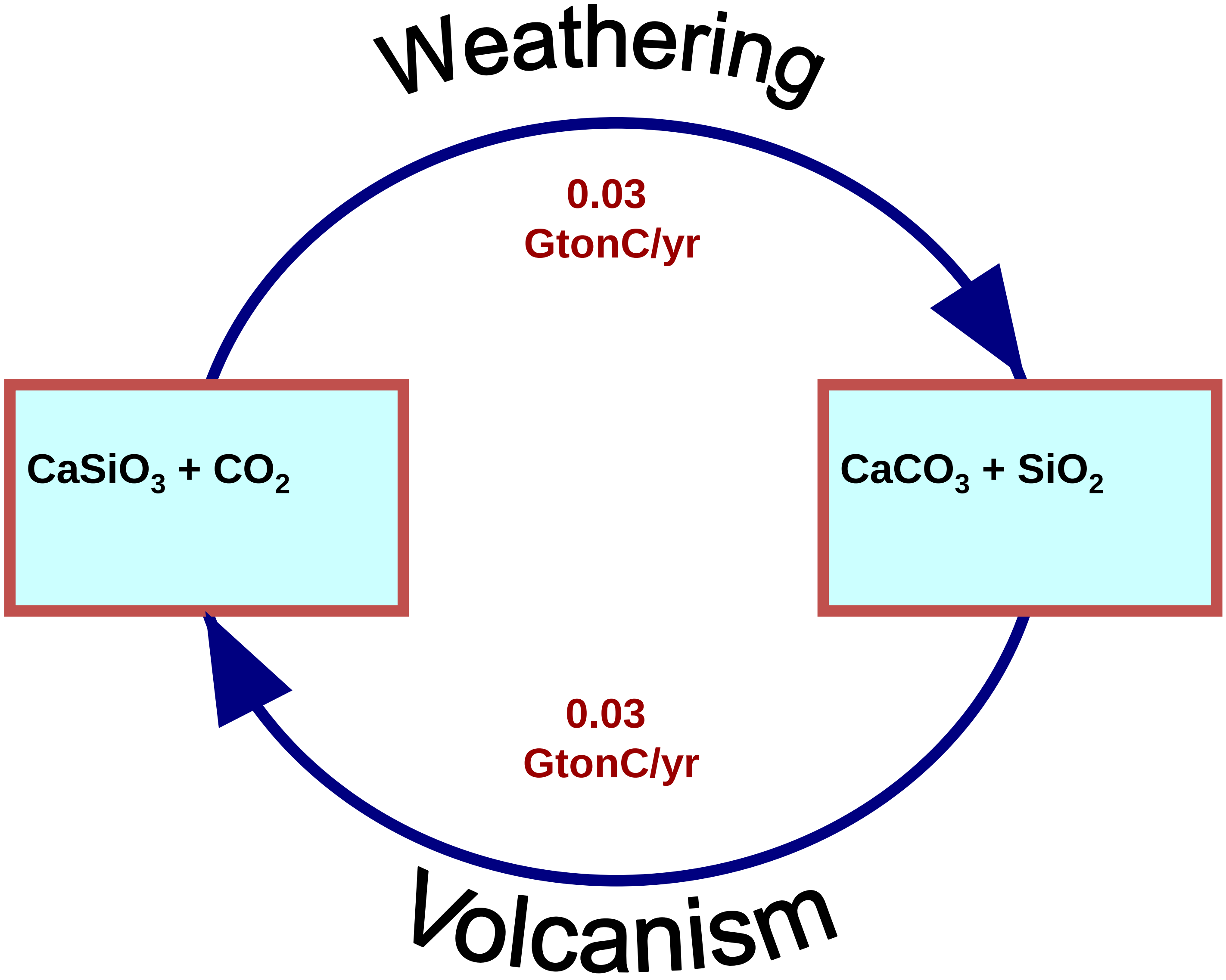

GCM data from 1991 to 1996
GCM
GCM (No Water Vapour feedback)
Temperature (k)
0.2
0.1
0
-0.1
-0.2
-0.3
-0.4
-0.5
-0.6
-0.7
-0.8
Eruption
1991
1992
1993
1994
1995
1996
1991 - 1996



Ice-free
Ice-covered
0.12 bar
0.02 bar
$pCO_2 = 3 \times 10^{-4}$ bar
Stable
Unstable
Sin (ice-line latitude)
Effective solar flux (S_{eff})
1.0
0.8
0.6
0.4
0.2
0.0
0.6
0.7
0.8
0.9
1.0
1.1
1.2
1.3


Law Dome Ice Core, Antarctica
Mauna Loa, Hawaii
Jan. 7, 2022 416.89 ppm
Jan. 7, 2021 415.50 ppm
Carbon Dioxide (ppm)
380
370
360
350
340
330
320
310
300
290
280
270
1000 1100 1200 1300 1400 1500 1600 1700 1800 1900 2000 2100
Year

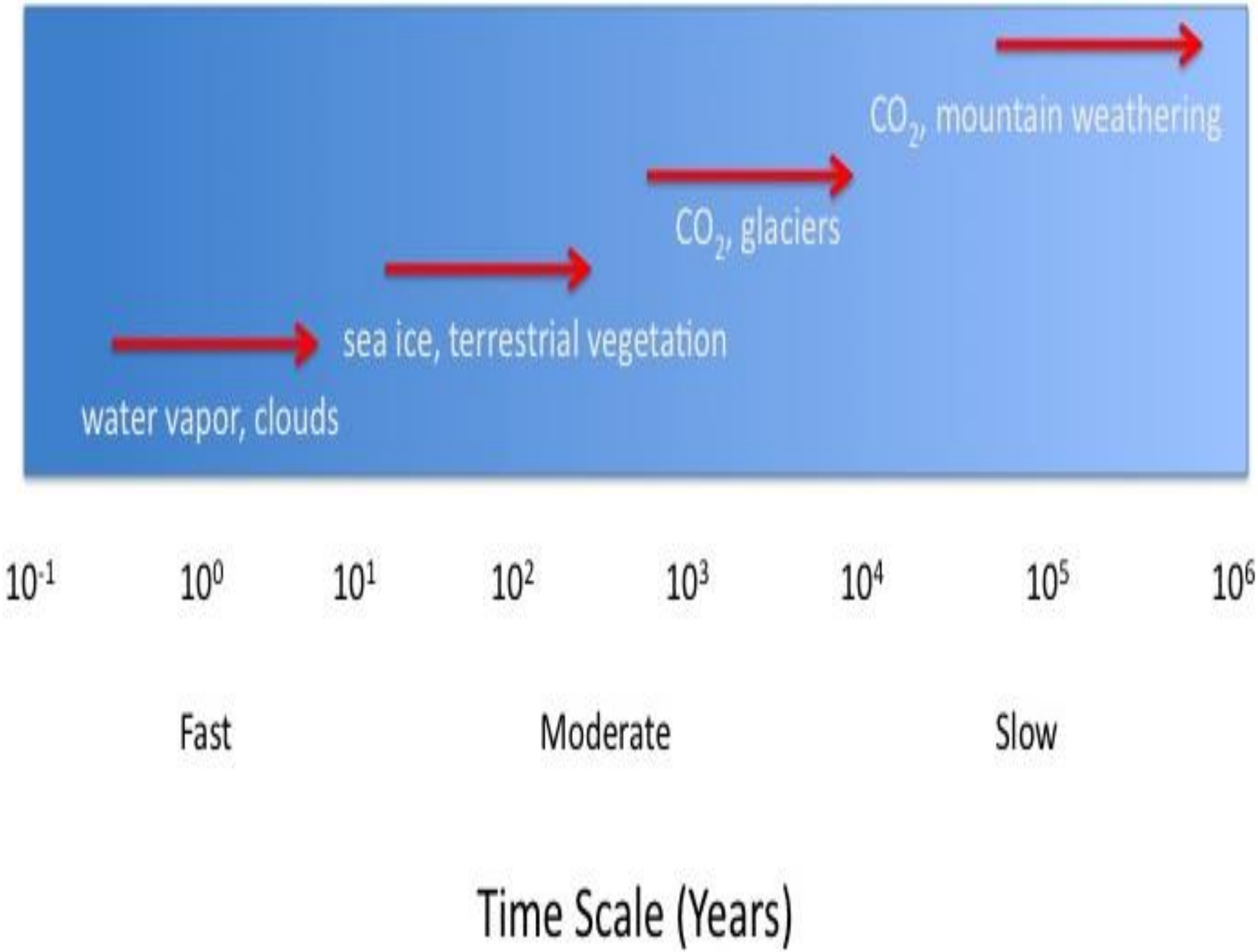
The Long-term Inorganic Carbon Cycle:



The global temperature is increasing ten times faster than in the past

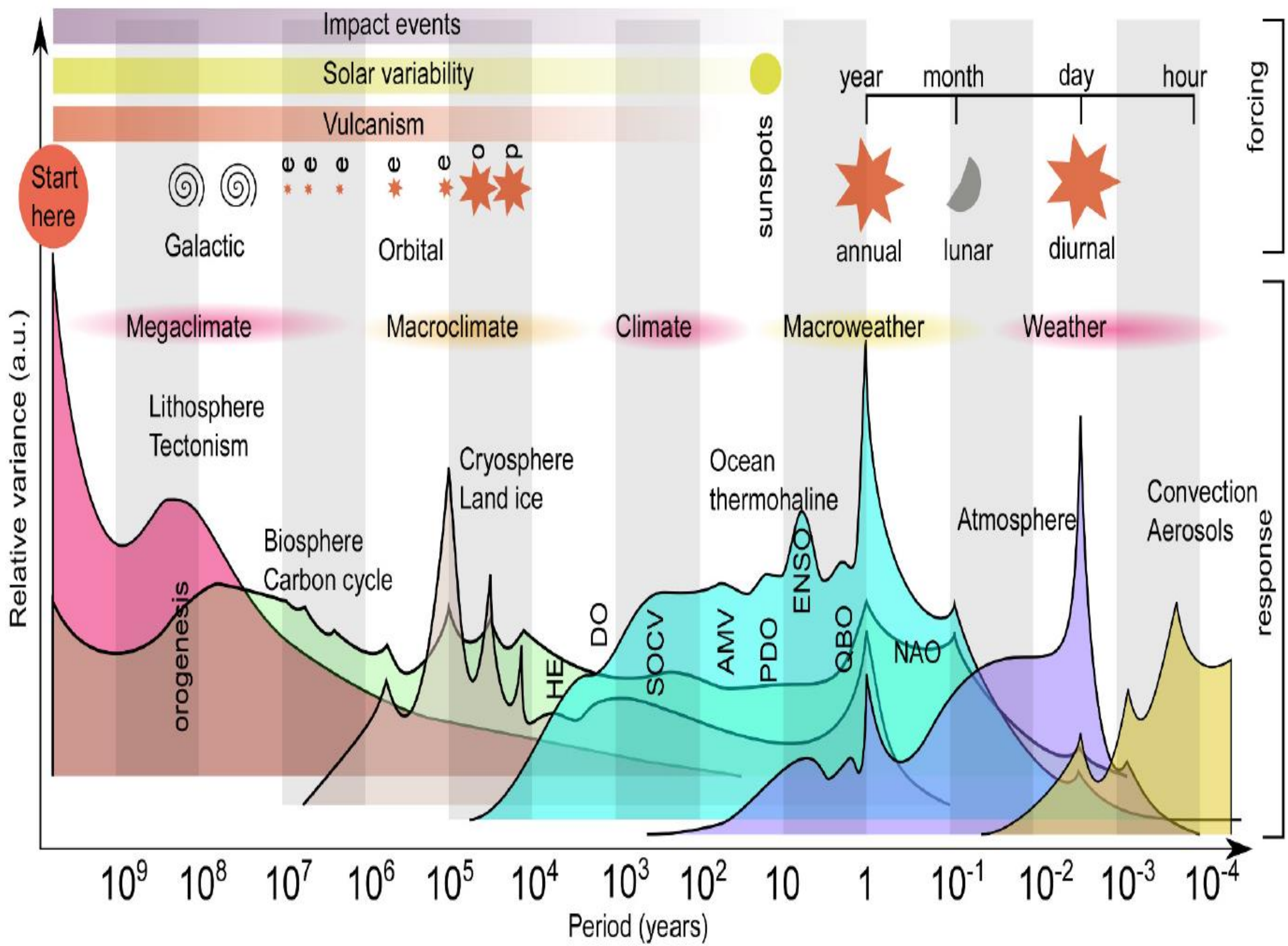
CO_2 increased by 20 ppm in 100 years during an abrupt climate change (15,000 years ago). In the 21st century CO_2 increased by 20 ppm in 10 years

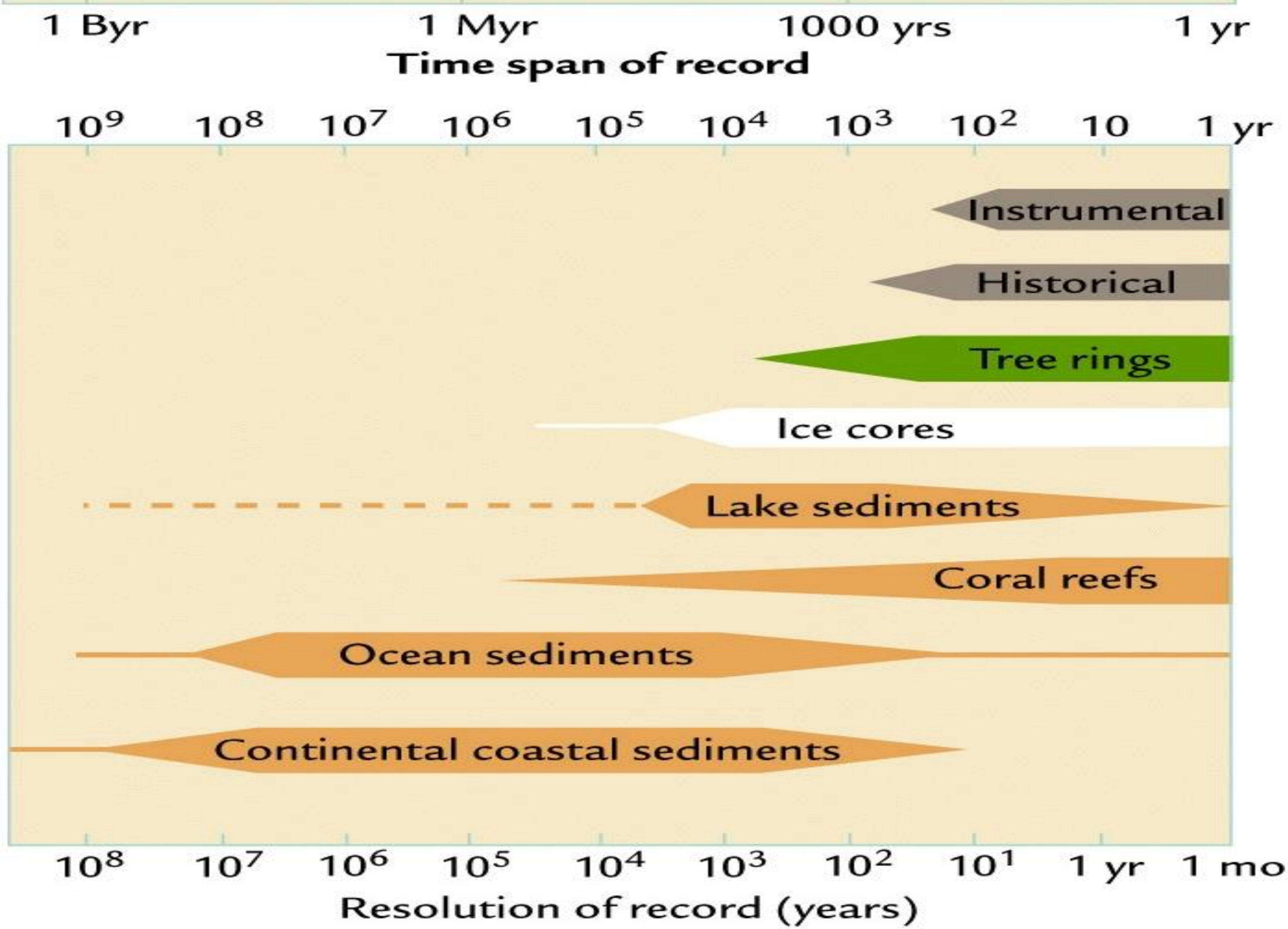
TO UNDERSTAND HOW EARTH'S CLIMATE WILL EVOLVE IN THE FUTURE, WE MUST UNDERSTAND HOW NATURAL CLIMATE VARIED BEFORE 1850



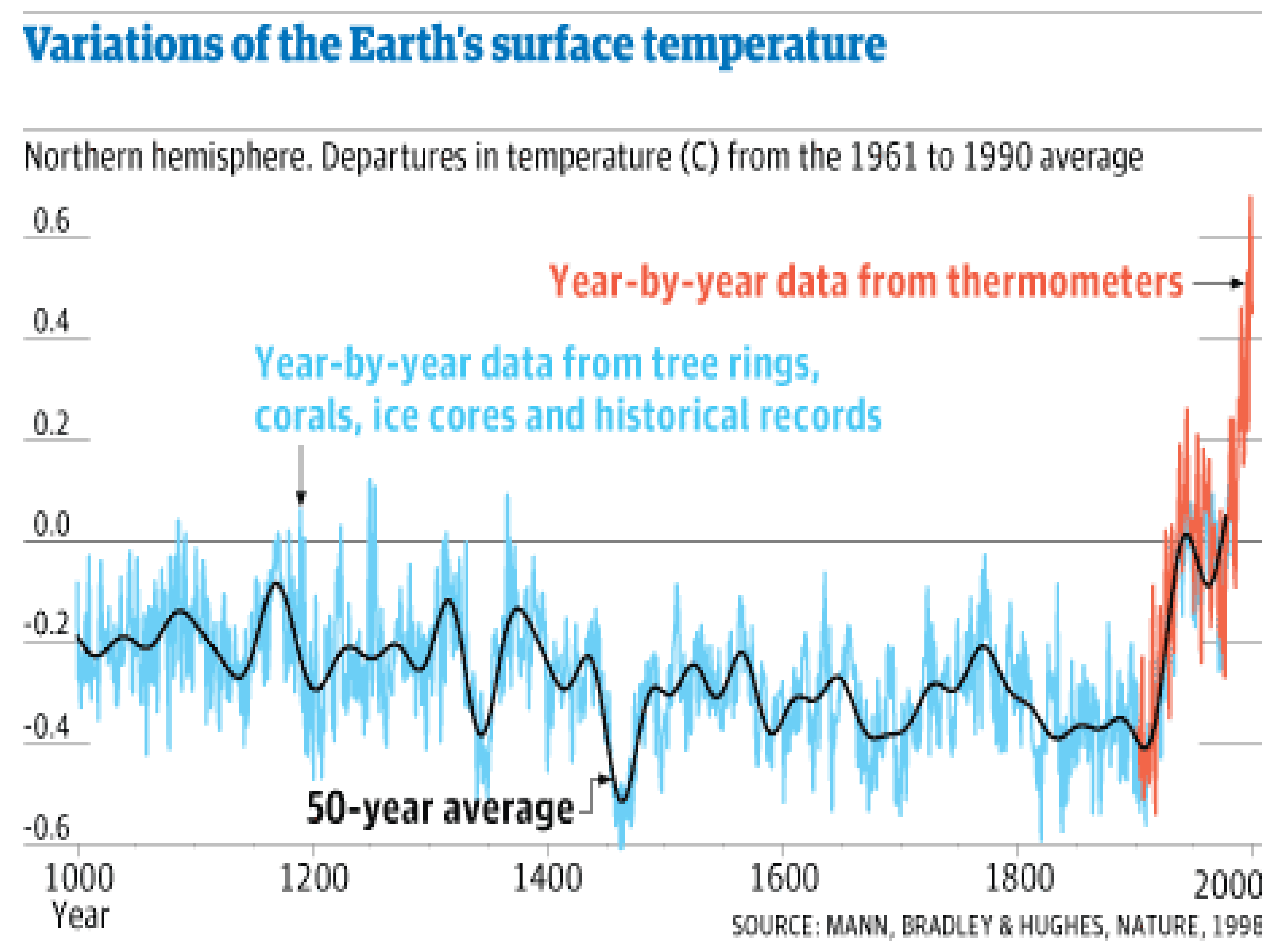
CO_2, mountain weathering
CO_2, glaciers
sea ice, terrestrial vegetation
water vapor, clouds
10^{-1}
10^{0}
10^{1}
10^{2}
10^{3}
10^{4}
10^{5}
10^{6}
Fast
Moderate
Slow
Time Scale (Years)

An overview of climatic variability and its causal mechanisms. J. Murray Mitchell Jr. QR, 1976

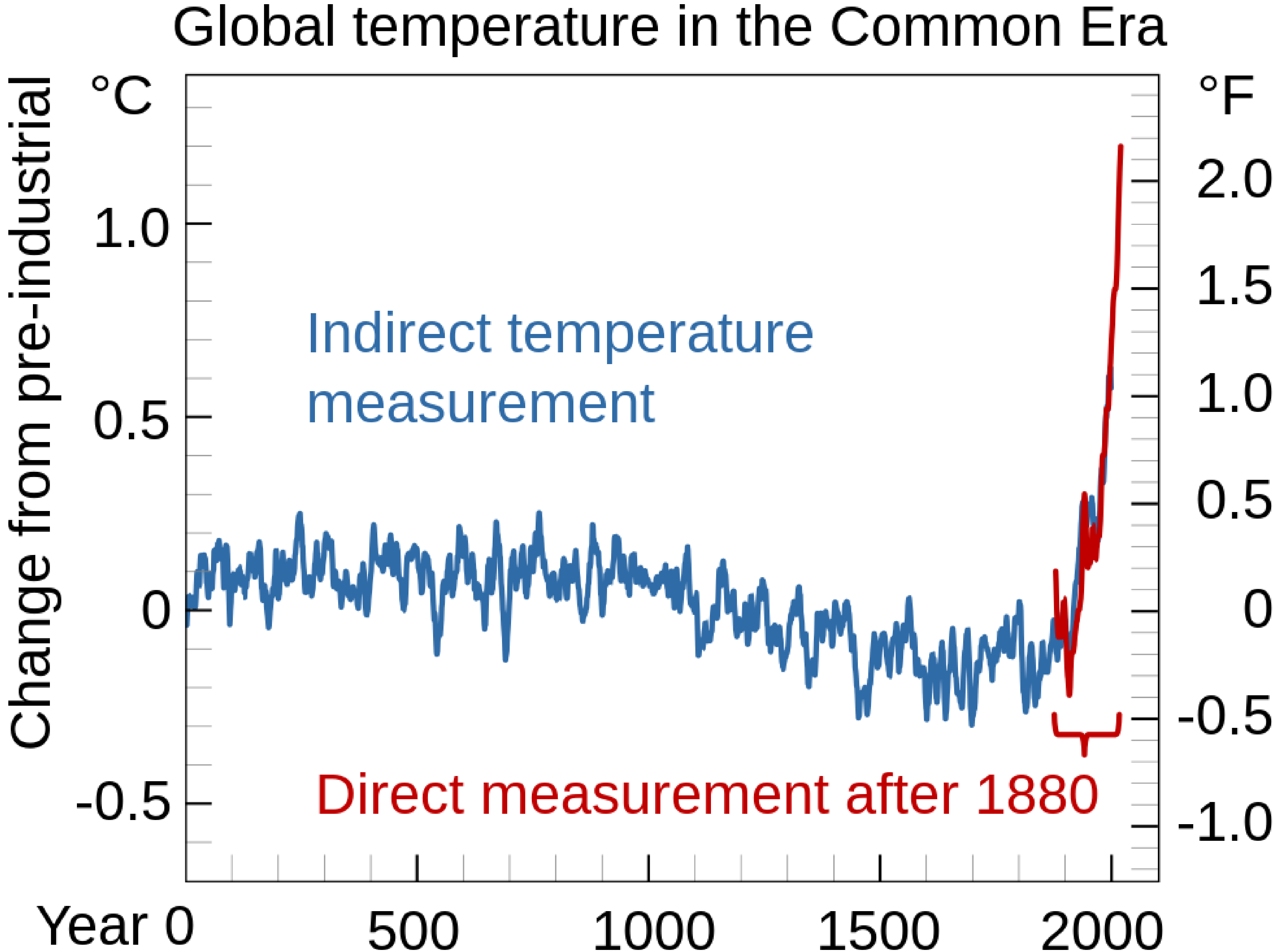




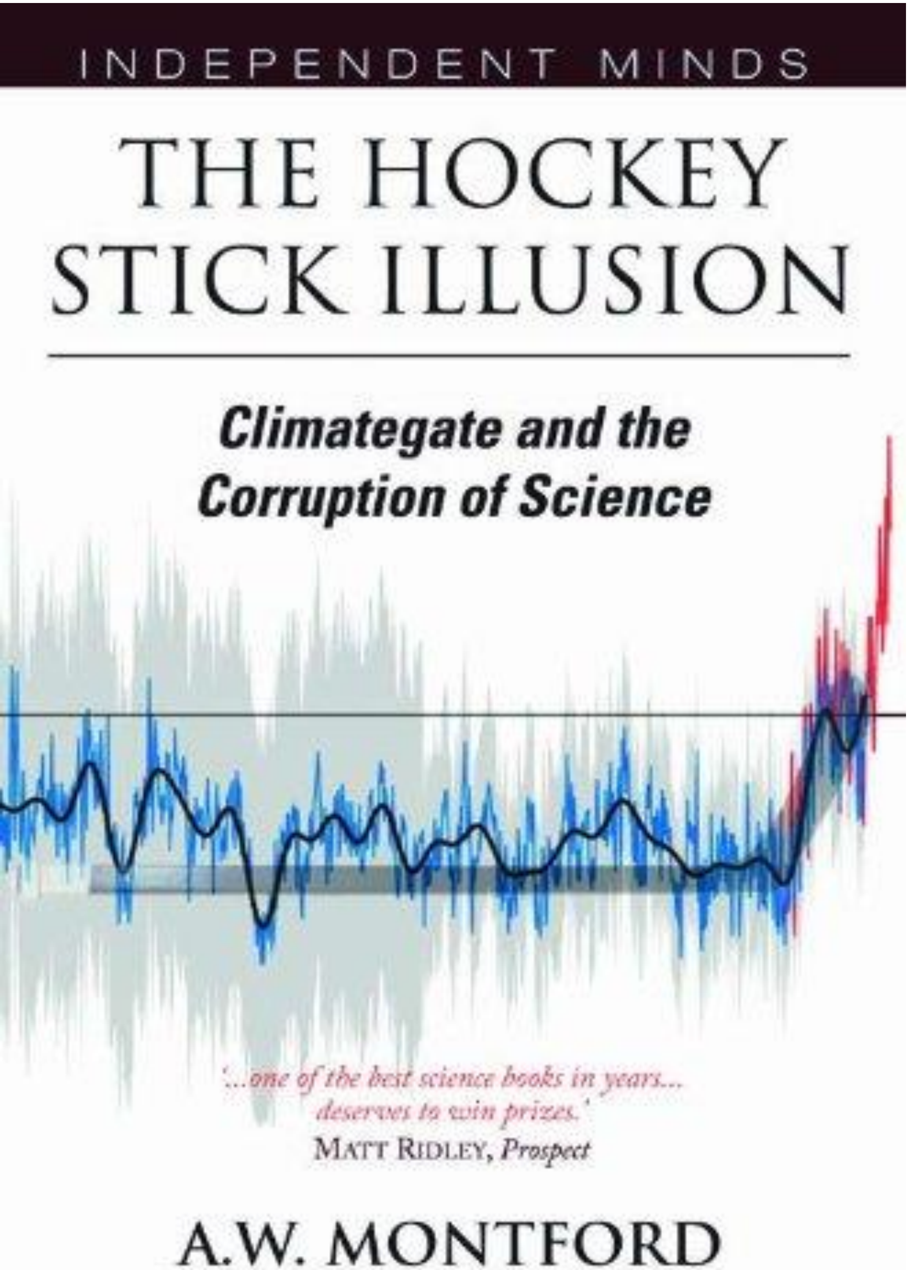
PROXY EVIDENCE FOR CLIMATE CHANGE



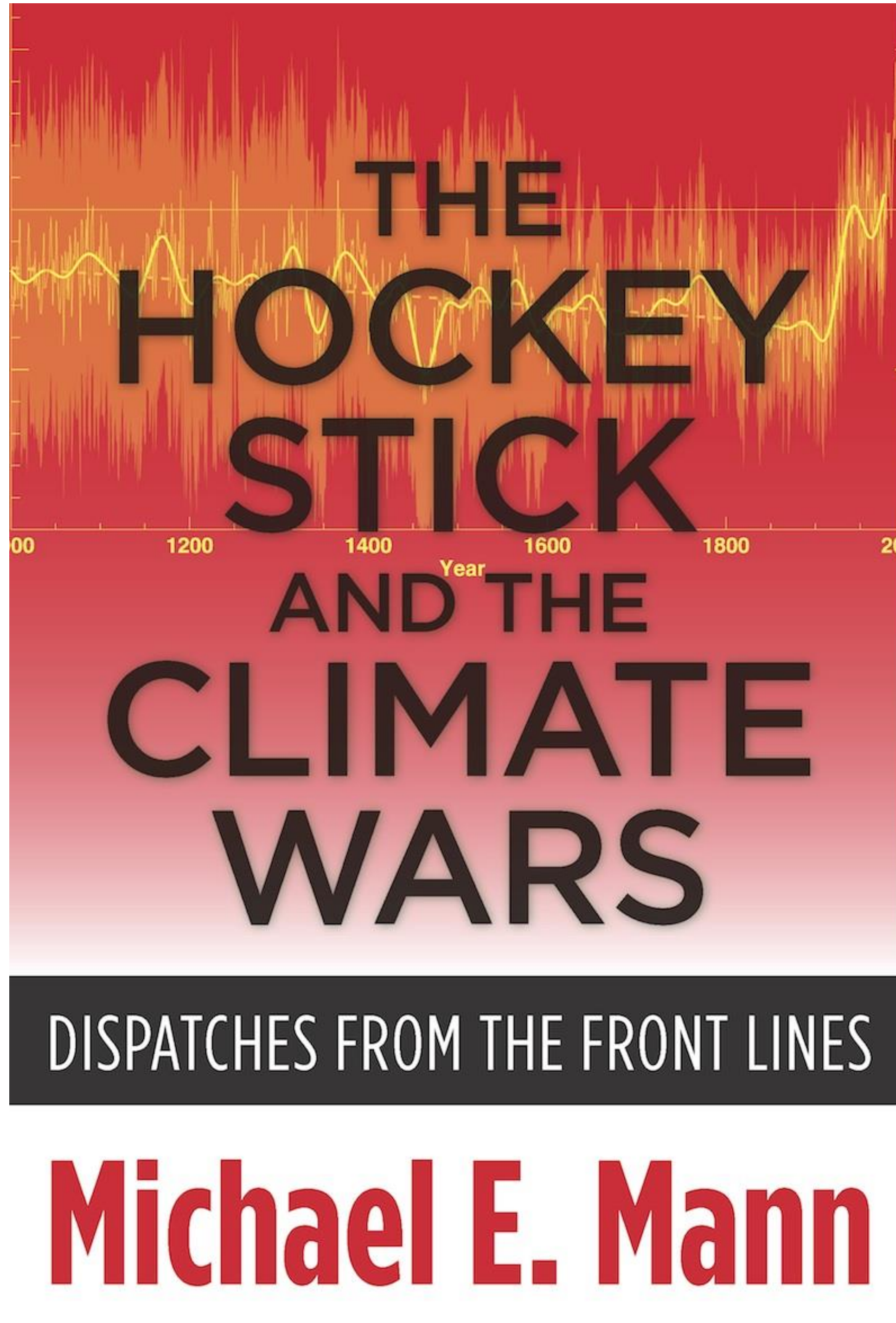
Variations of the Earth's surface temperature
Northern hemisphere. Departures in temperature (C) from the 1961 to 1990 average
0.6
0.4
0.2
0.0
-0.2
-0.4
-0.6
Year-by-year data from thermometers
Year-by-year data from tree rings, corals, ice cores and historical records
50-year average
1000
1200
1400
1600
1800
2000
Year
SOURCE: MANN, BRADLEY & HUGHES, NATURE, 1998

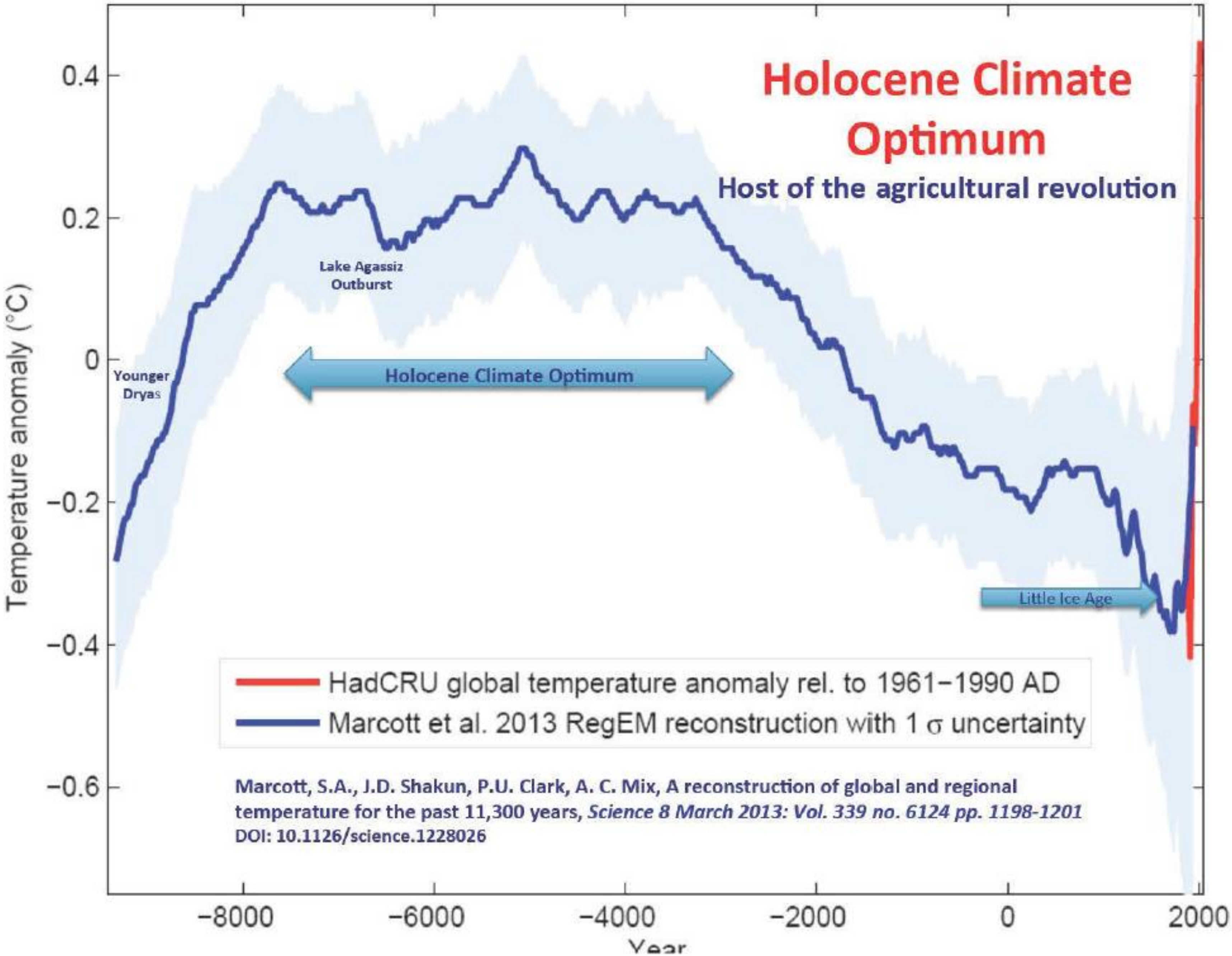


Global temperature in the Common Era
Change from pre-industrial
°C
°F
1.0
0.5
0
-0.5
2.0
1.5
1.0
0.5
0
-0.5
-1.0
Indirect temperature measurement
Direct measurement after 1880
Year 0
500
1000
1500
2000



The book uses the full range of smear tactics to peddle climate change denial



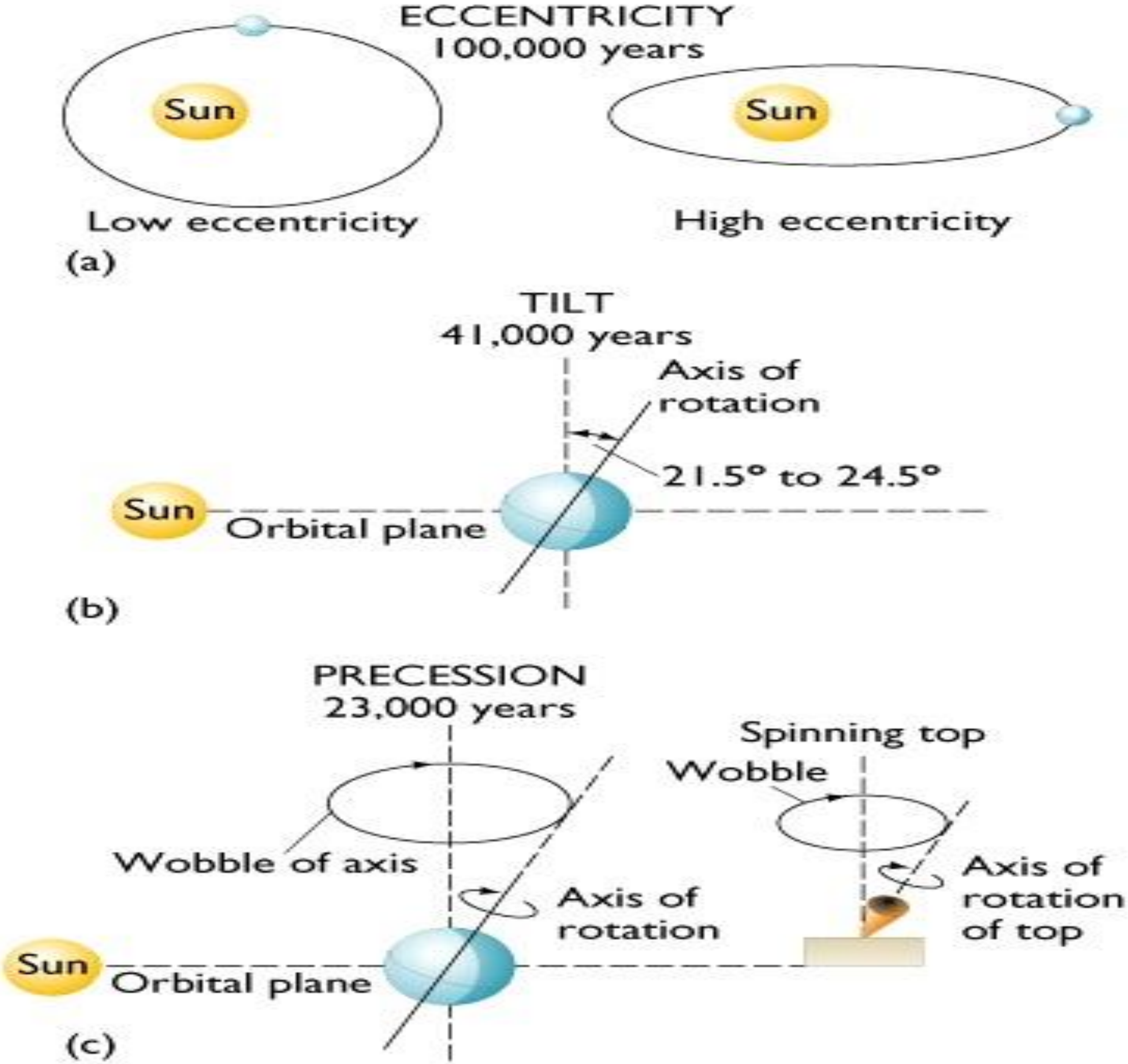

Holocene Climate Optimum
Host of the agricultural revolution
Lake Agassiz Outburst
Younger Dryas
Holocene Climate Optimum
Little Ice Age
HadCRU global temperature anomaly rel. to 1961−1990 AD
Marcott et al. 2013 RegEM reconstruction with 1 σ uncertainty
Marcott, S.A., J.D. Shakun, P.U. Clark, A. C. Mix, A reconstruction of global and regional temperature for the past 11,300 years, Science 8 March 2013: Vol. 339 no. 6124 pp. 1198-1201
DOI: 10.1126/science.1228026
Temperature anomaly (°C)
0.4
0.2
0
−0.2
−0.4
−0.6
−8000
−6000
−4000
−2000
0
2000
Year

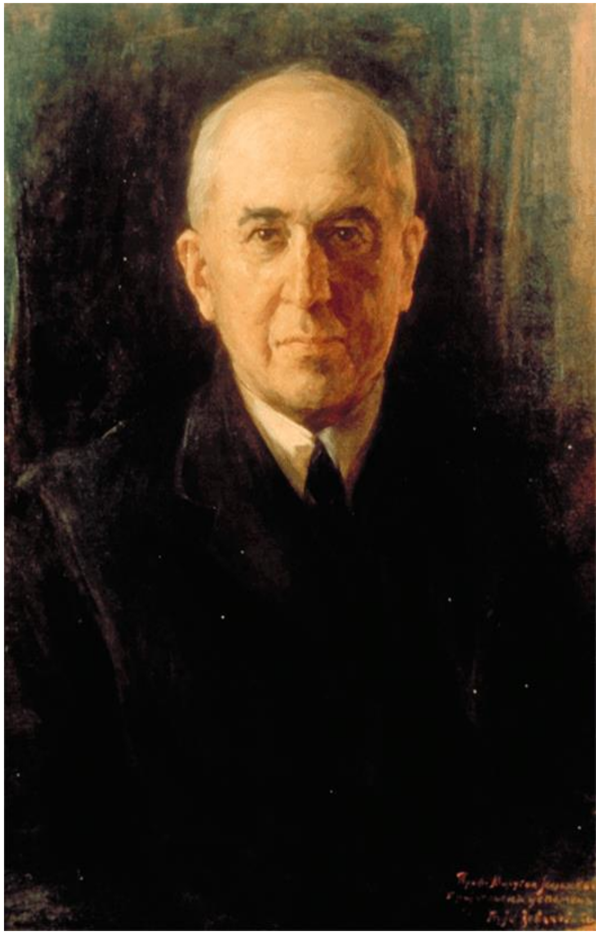
ICE AGES

Stirations &Erratics

Louis Agassiz

Milankovitch Hypothesis



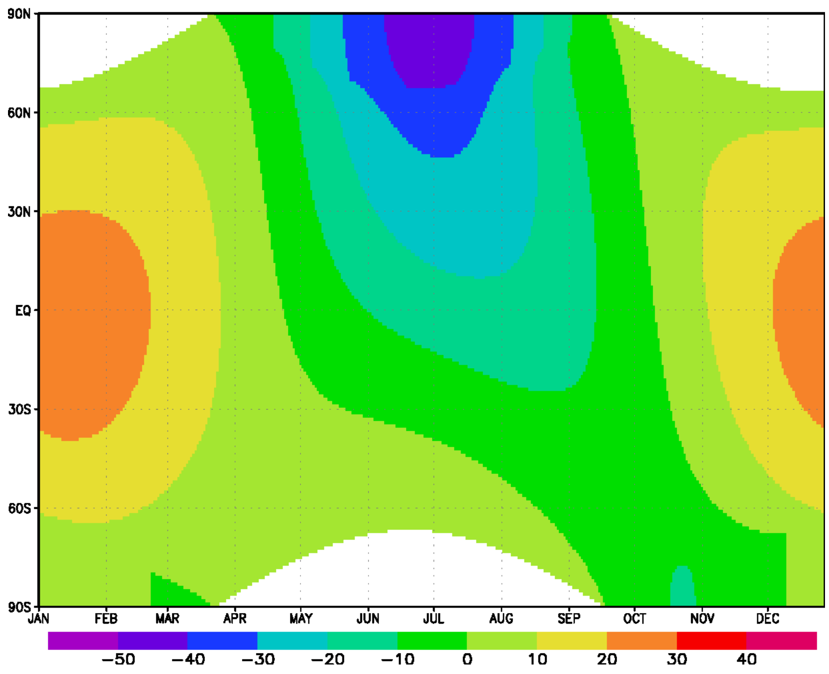


Milankovitch Hypothesis: Polar summers with lower solar radiation lead to the accumulation of the ice in polar regions

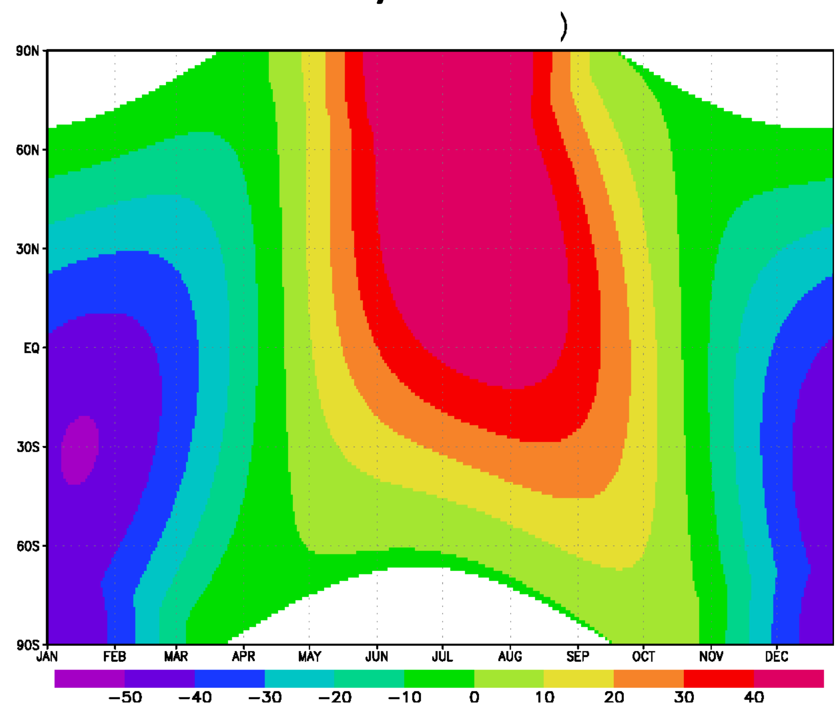
Incident solar radiation (Wm^{-2})

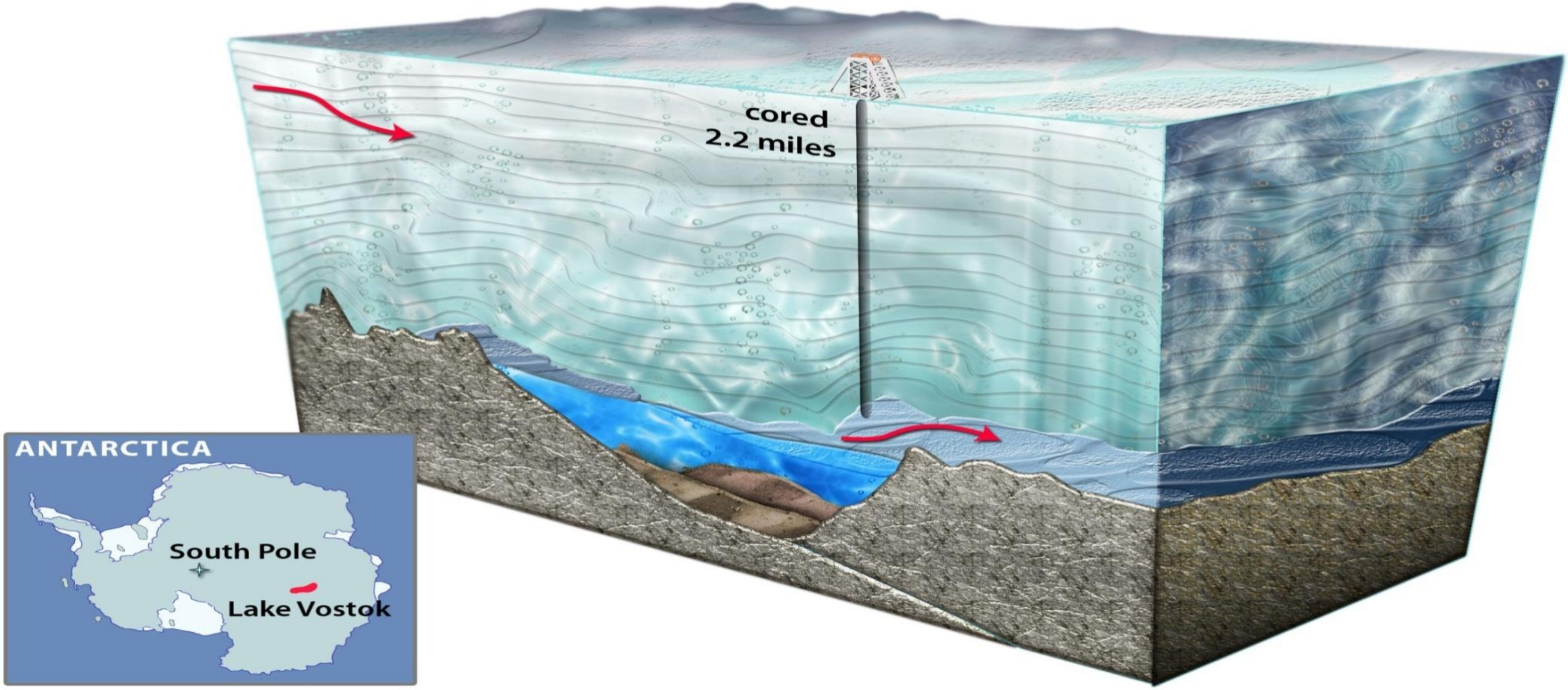
Deviation from present day value

115 kyr BP

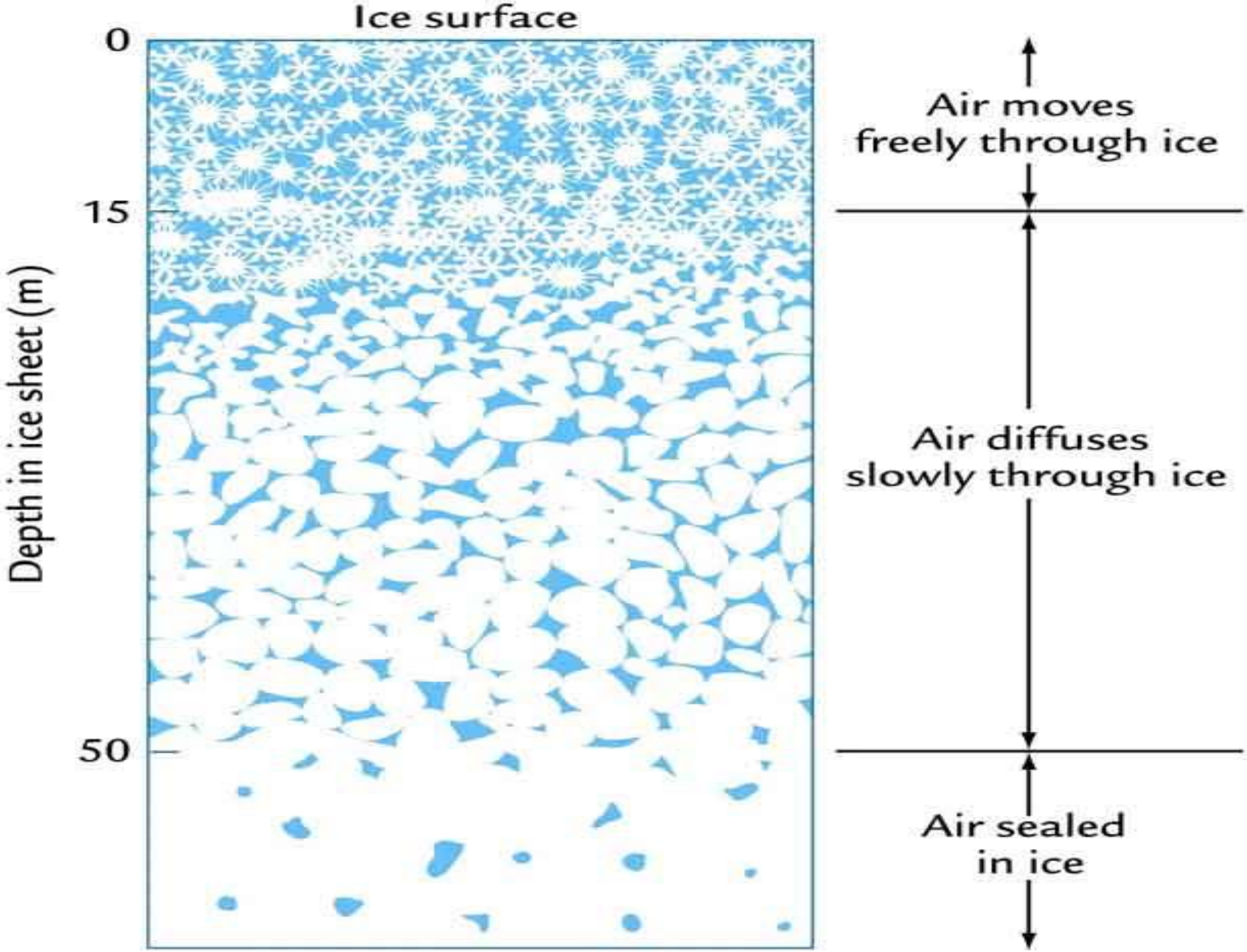


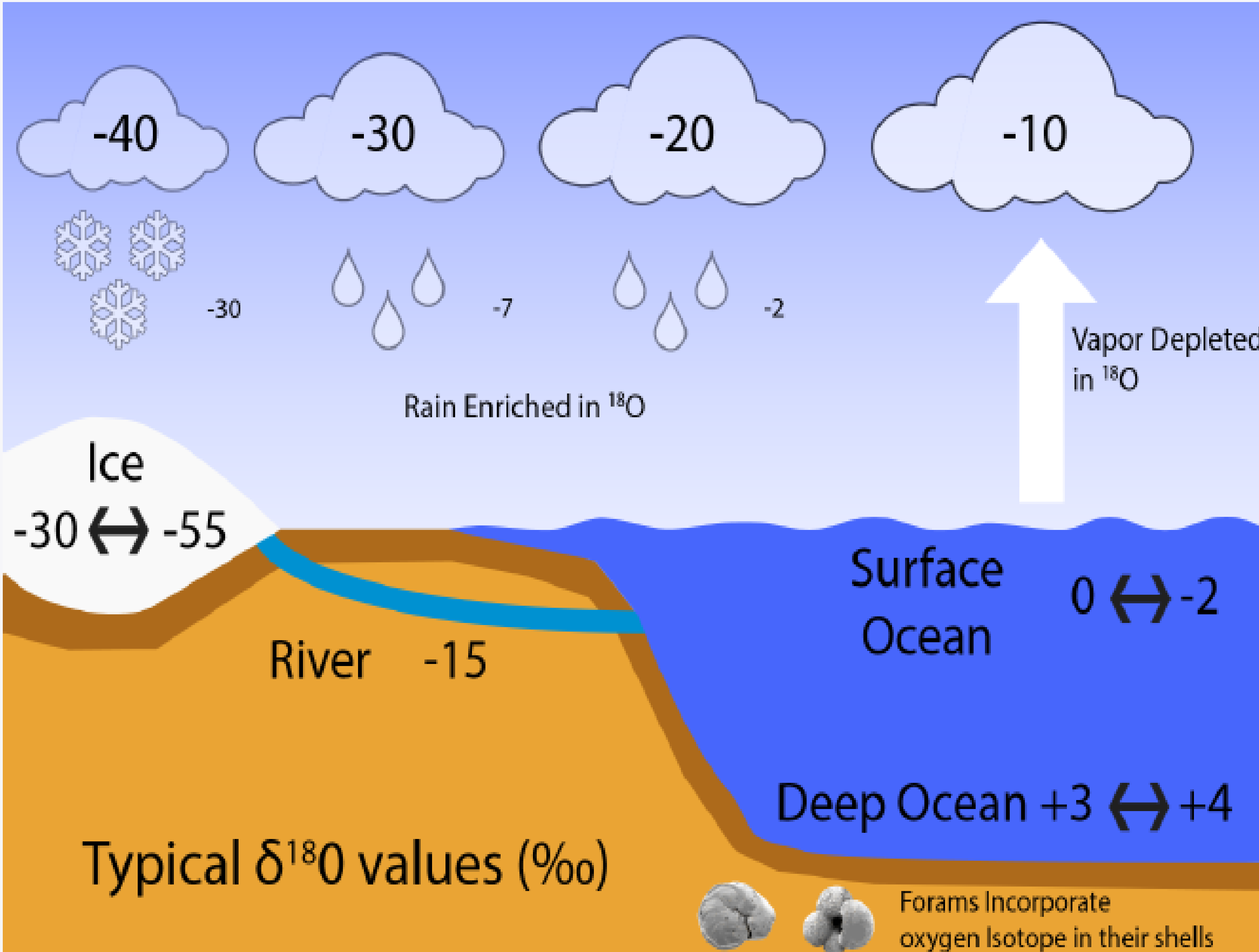
125 kyr BP





- Scientists searched for the oldest ice in an ice sheet, drill from the top of the highest ice domes.
- Drilling is done over the summer in which it takes a few summers to drill completely through an ice sheet.
- Some ice cores can be dated by counting annually deposited layers.


Ice surface
0
15
50
Depth in ice sheet (m)
Air moves freely through ice
Air diffuses slowly through ice
Air sealed in ice


-40
-30
-20
-10
-30
-7
-2
Vapor Depleted in ^{18}O
Rain Enriched in ^{18}O
Ice
-30 ⟷ -55
Surface Ocean
0 ⟷ -2
River -15
Deep Ocean +3 ⟷ +4
Typical $\delta^{18}O$ values (‰)
Forams Incorporate oxygen Isotope in their shells

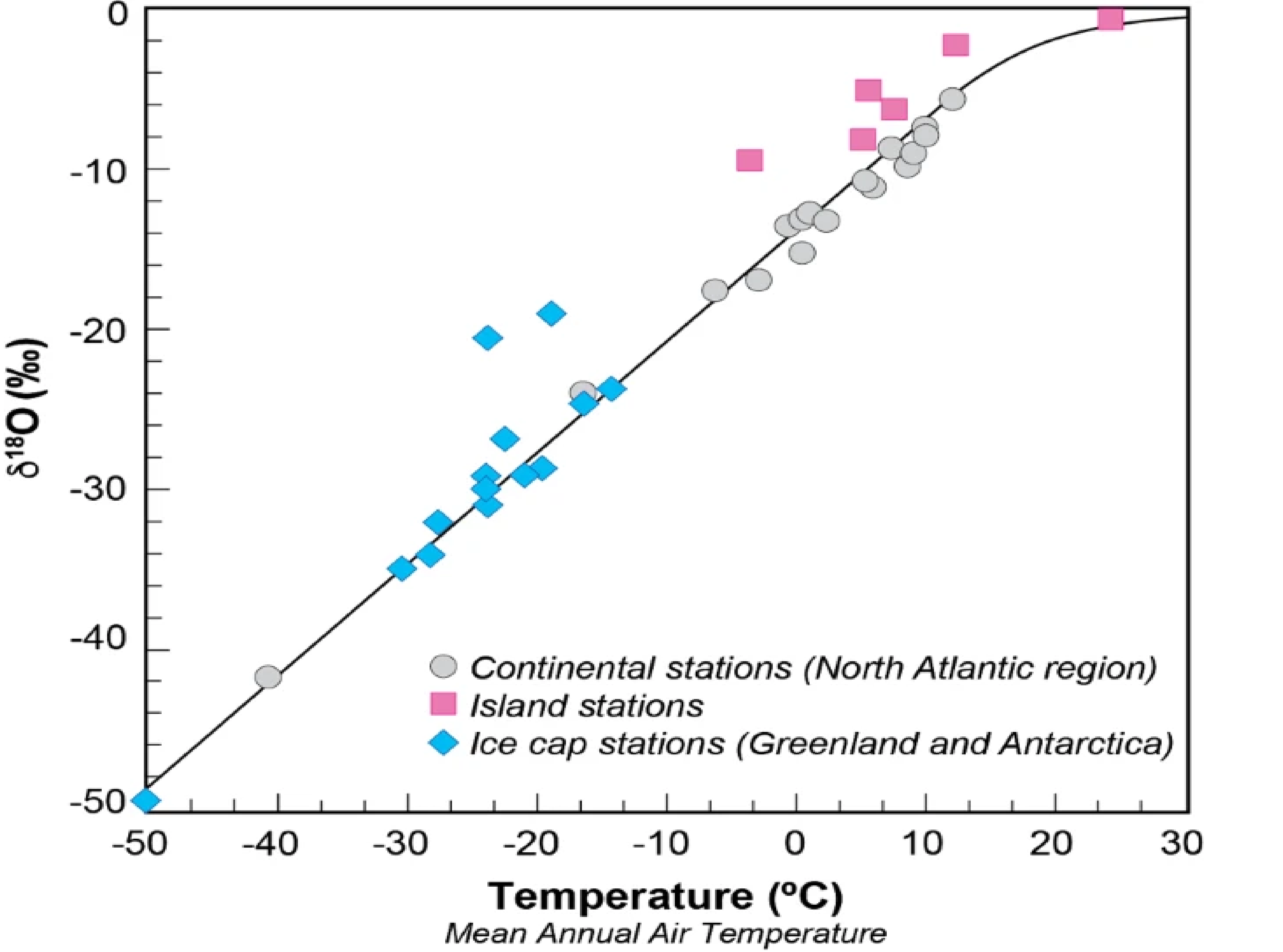
$\delta^{18}O$

- As water vapor is transported poleward in the hydrologic cycle, each cycle of evaporation and condensation lowers the ratio of $H_2{}^{18}O$ to $H_2{}^{16}O$, in a process called fractionation.
- This ratio is expressed as $\delta^{18}O$.

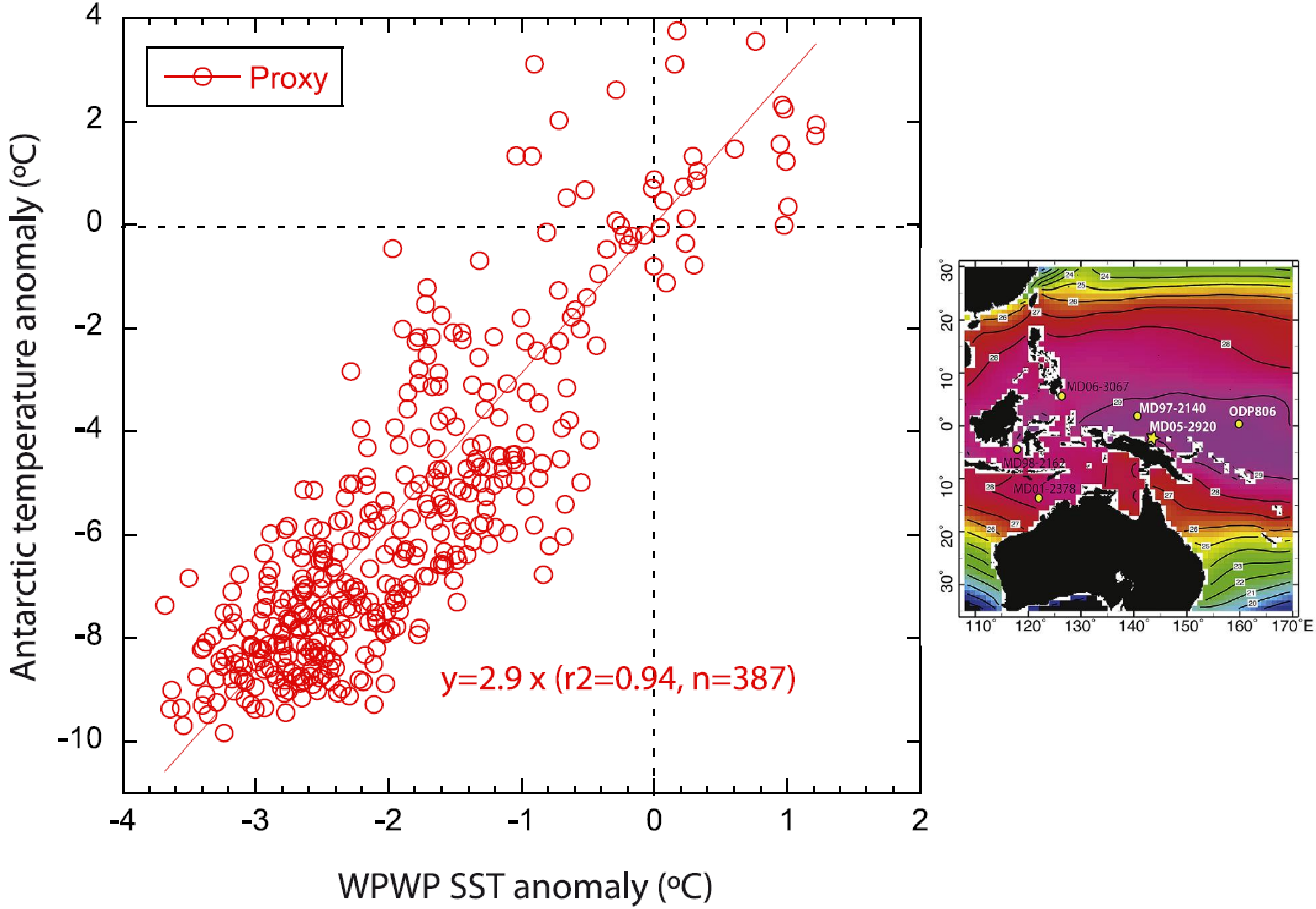
$$\delta^{18}O = \frac{{}^{18}O/{}^{16}O_{sample} - {}^{18}O/{}^{16}O_{std}}{{}^{18}O/{}^{16}O_{std}} \times 1000$$

$\delta^{18}O$ and Global Ice Volume

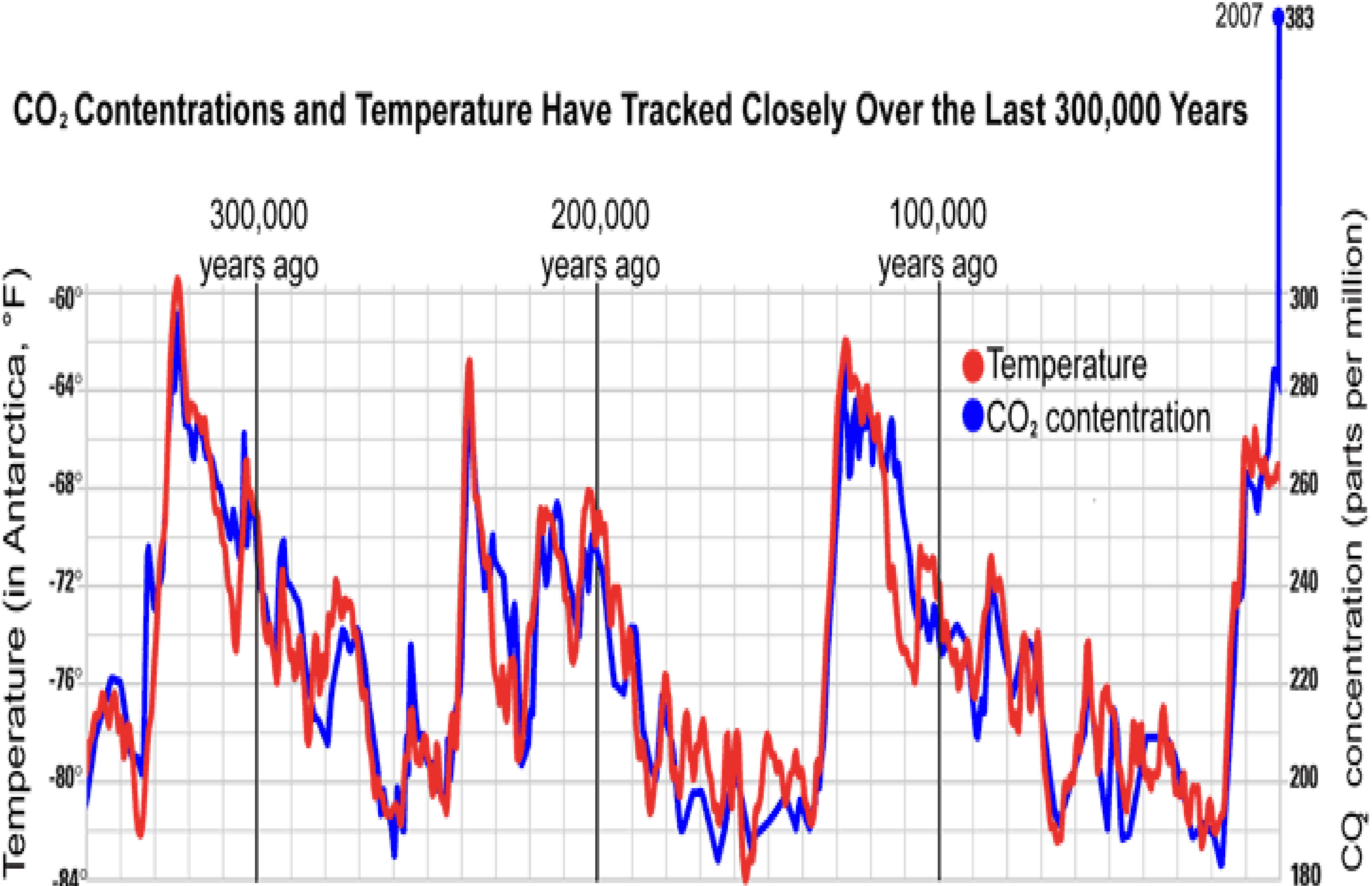
- As ice sheets grow, the water removed from the ocean has lower $\delta^{18}O$ than the water that remains.
- Thus the $\delta^{18}O$ value of sea water in the global ocean is linearly correlated with ice volume (larger $\delta^{18}O \rightarrow$ larger ice sheets).
- A time series of global ocean $\delta^{18}O$ is equivalent to a time series of ice volume.



Continental stations (North Atlantic region)
Island stations
Ice cap stations (Greenland and Antarctica)
δ18O (‰)
0
-10
-20
-30
-40
-50
-50
-40
-30
-20
-10
0
10
20
30
Temperature (ºC)
Mean Annual Air Temperature

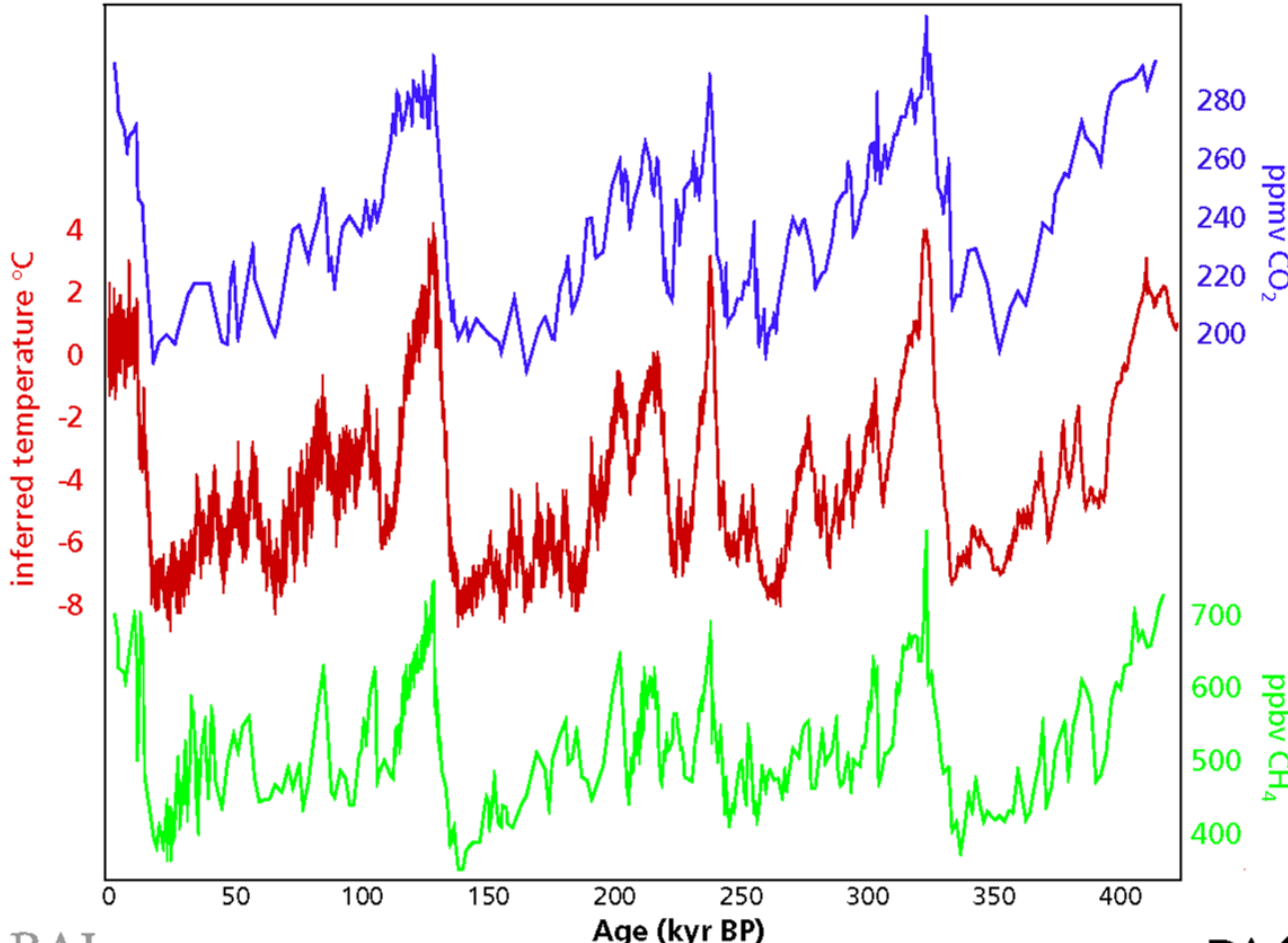


Proxy
y=2.9 x (r2=0.94, n=387)
Antarctic temperature anomaly (oC)
WPWP SST anomaly (oC)
4
2
0
-2
-4
-6
-8
-10
-4
-3
-2
-1
0
1
2
MD06-3067
MD97-2140
ODP806
MD05-2920
MD98-2162
MD01-2378
30˚
20˚
10˚
0˚
10˚
20˚
30˚
110˚
120˚
130˚
140˚
150˚
160˚
170˚E



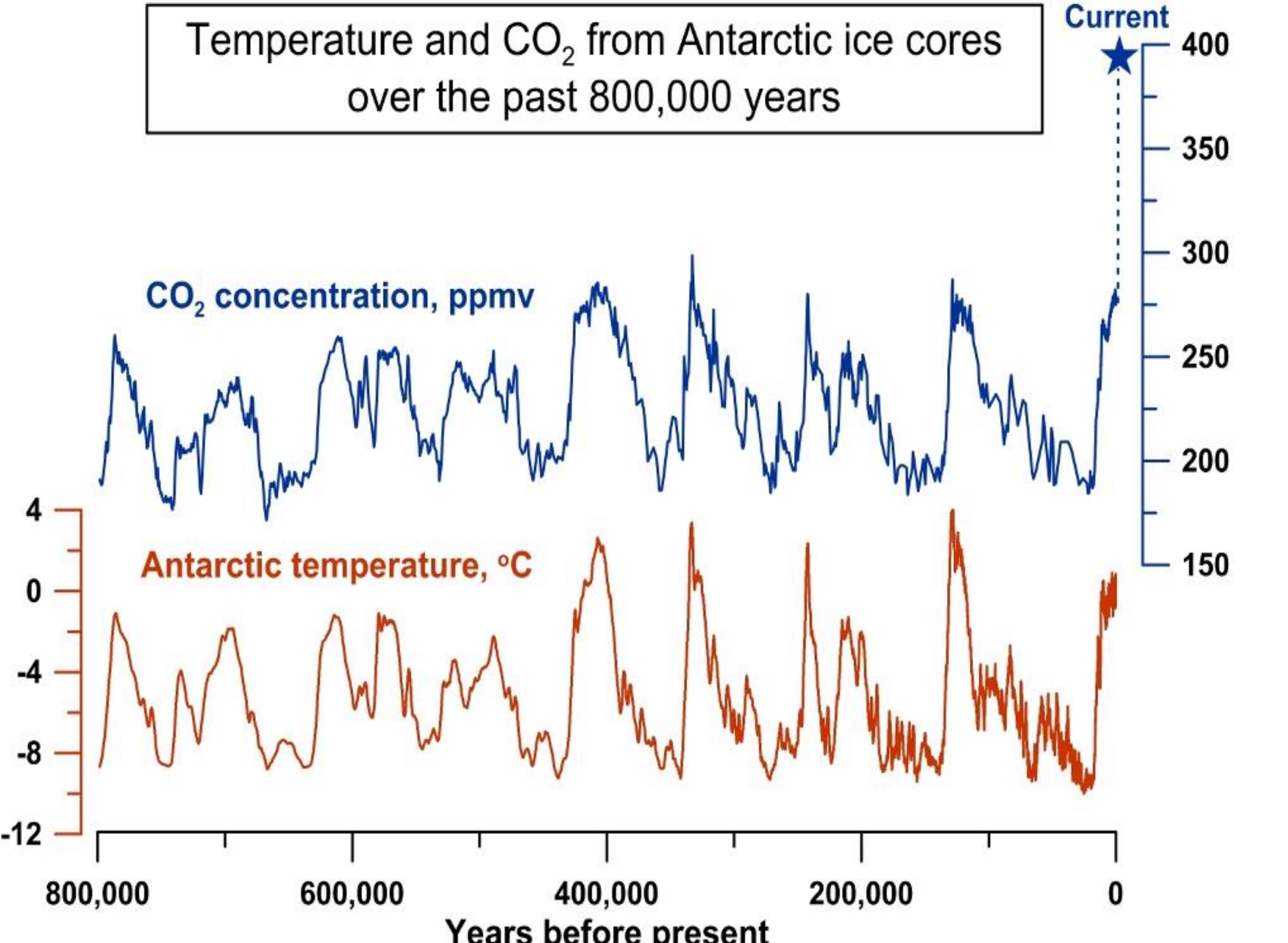
CO_2 Contentrations and Temperature Have Tracked Closely Over the Last 300,000 Years
2007
383
300,000 years ago
200,000 years ago
100,000 years ago
Temperature (in Antarctica, °F)
-60°
-64°
-68°
-72°
-76°
-80°
-84°
Temperature
CO_2 contentration
CQ concentration (parts per million)
300
280
260
240
220
200
180

4 glacial cycles recorded in the Vostok ice core



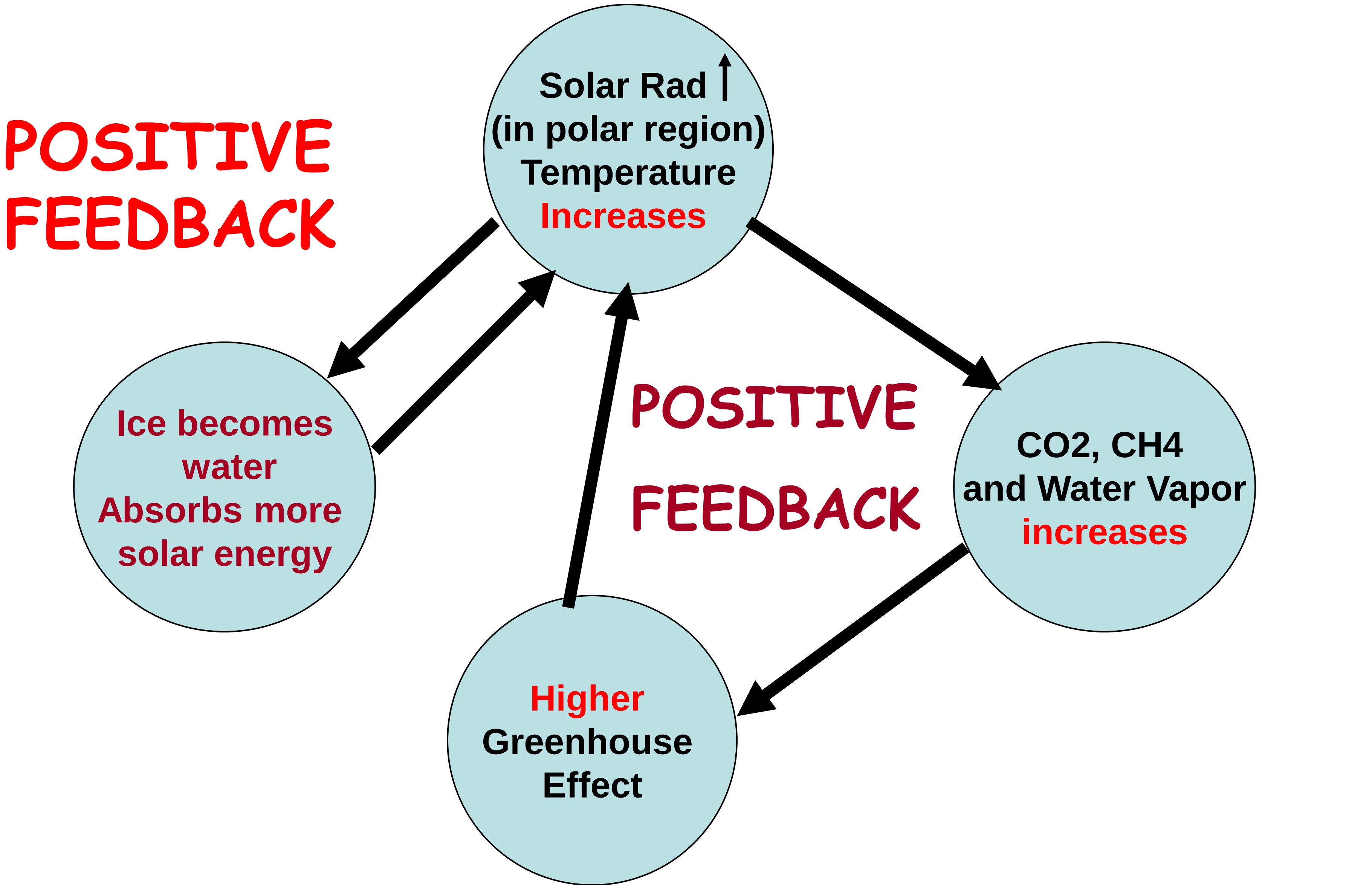
J.R. Petit et al., *Nature,* **399**, 429–36, 1999.

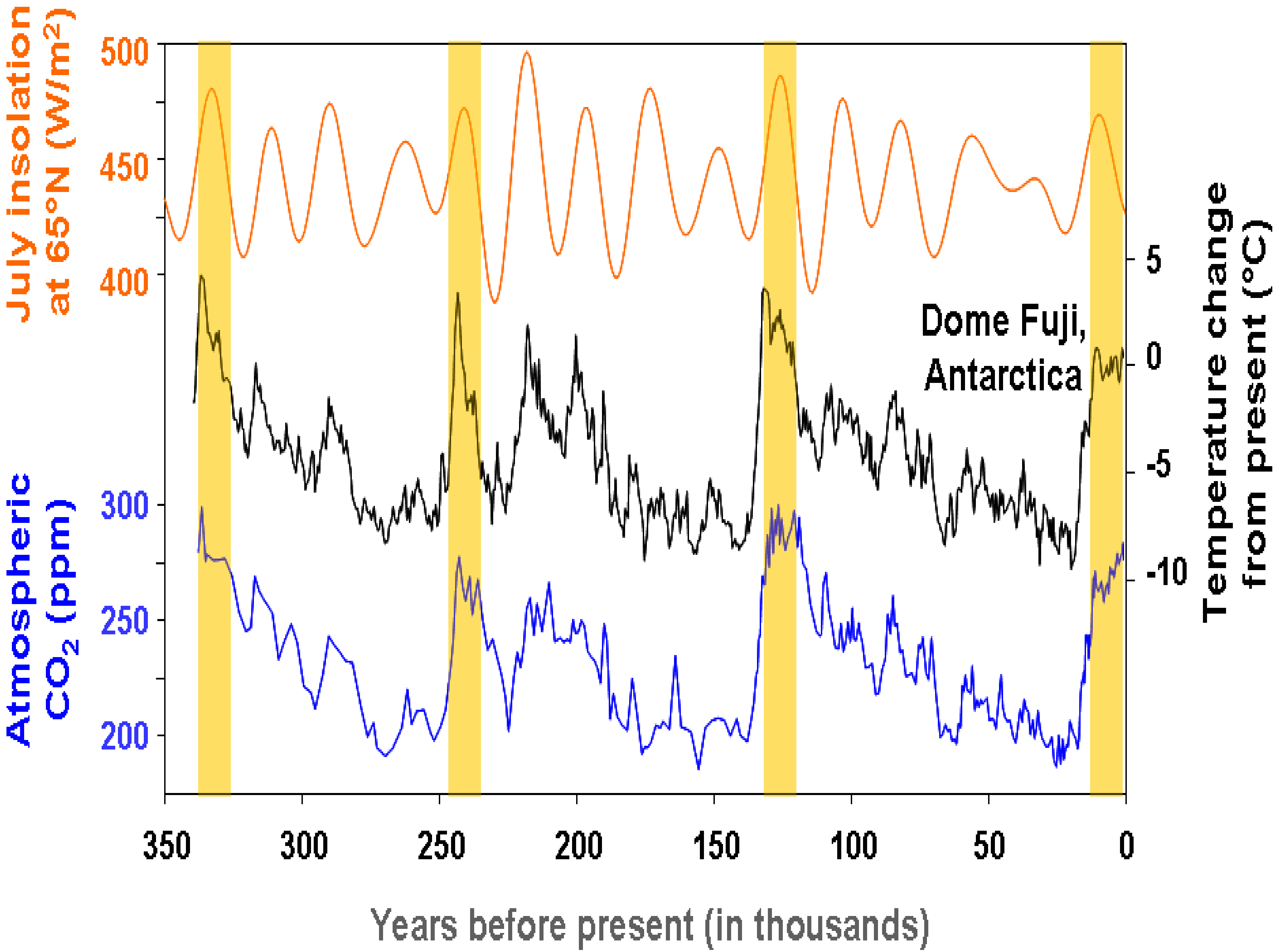
6.1



Temperature and CO2 from Antarctic ice cores over the past 800,000 years
Current
400
350
300
250
200
150
CO2 concentration, ppmv
Antarctic temperature, °C
4
0
-4
-8
-12
800,000
600,000
400,000
200,000
0
Years before present

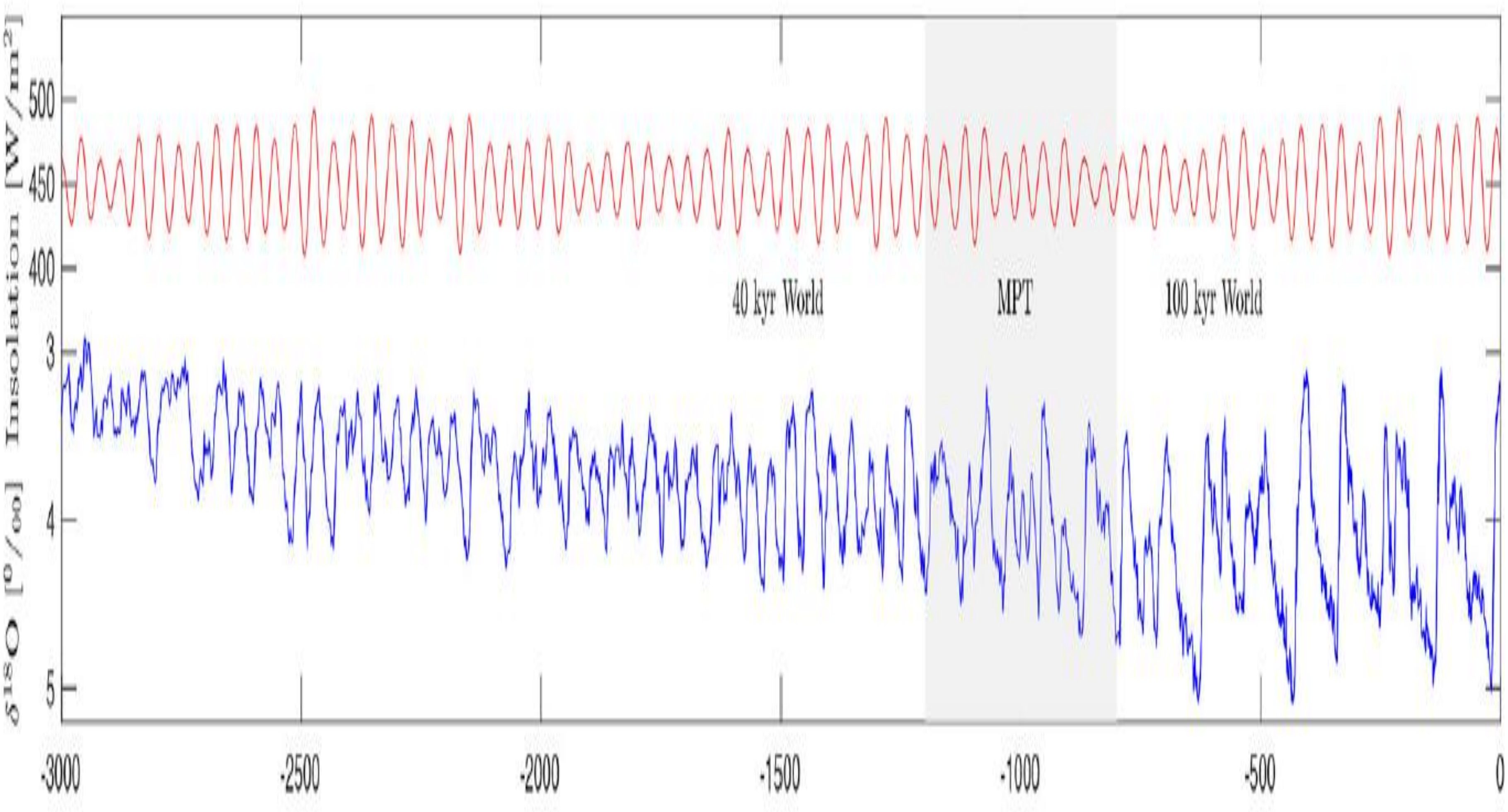
The change in Solar radiation was amplified many times by postive feedbacks

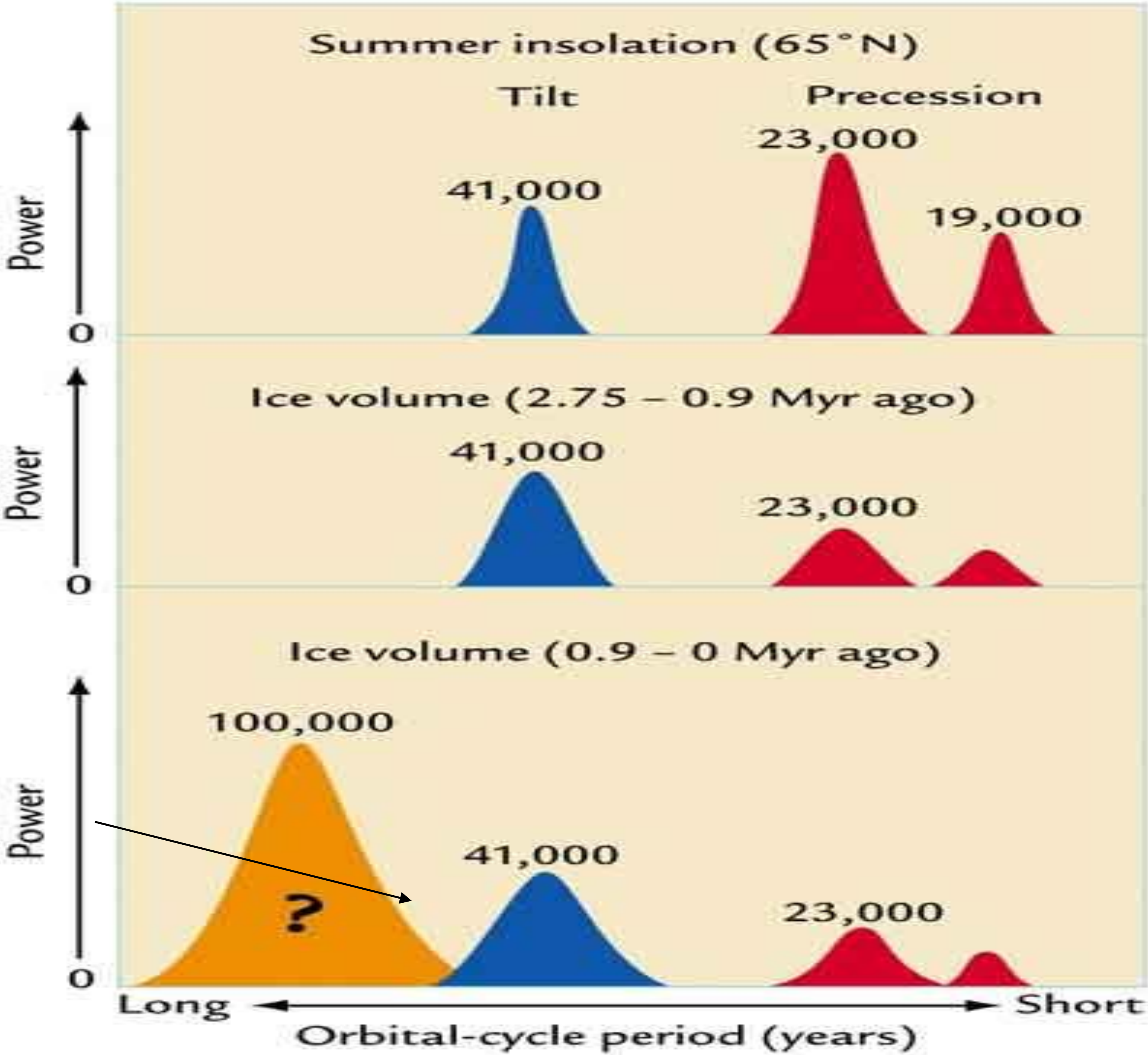




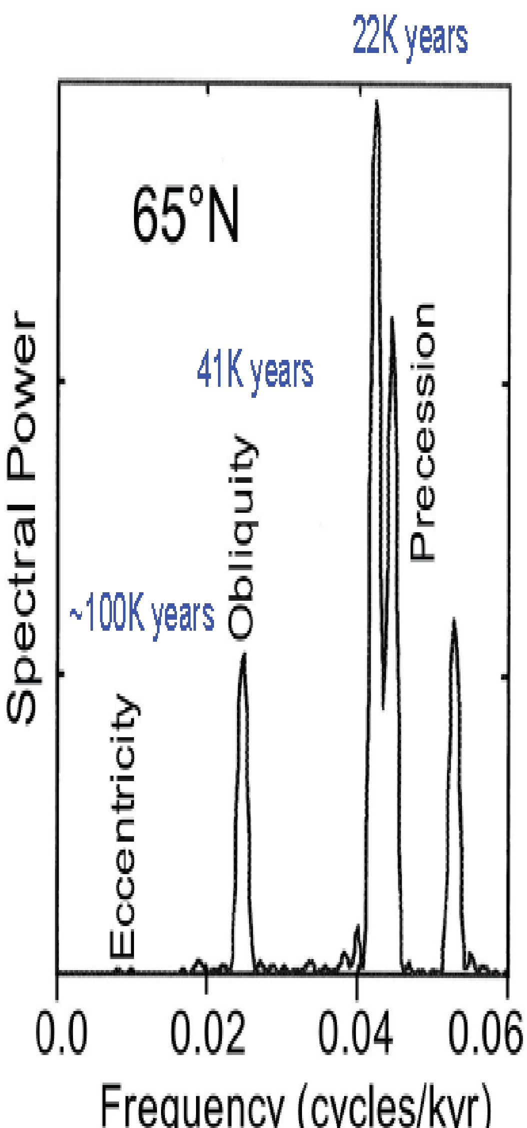
July insolation at 65°N (W/m²)
500
450
400
Atmospheric CO₂ (ppm)
300
250
200
Dome Fuji, Antarctica
Temperature change from present (°C)
5
0
-5
-10
350
300
250
200
150
100
50
0
Years before present (in thousands)

The stacked benthic foraminifera isotope record of the Pleistocene (blue). The record is a proxy for global ice volume. The red curve is the annually averaged insolation at 65N latitude
Quantification and interpretation of the climate variability record
By Anna Von der Hydet et al., Global and Planetary Change, 2021




Summer insolation (65°N)
Tilt
Precession
23,000
41,000
19,000
Power
0
Ice volume (2.75 – 0.9 Myr ago)
41,000
23,000
Power
0
Ice volume (0.9 – 0 Myr ago)
100,000
41,000
?
23,000
Power
0
Long
Short
Orbital-cycle period (years)

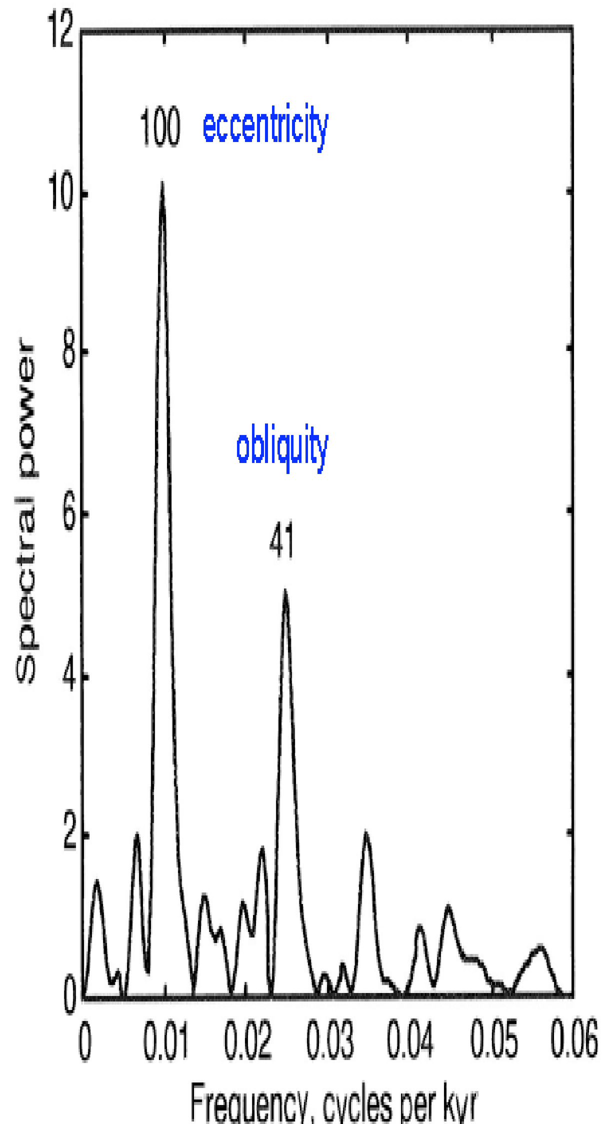
Spectral Analysis of Solar Input



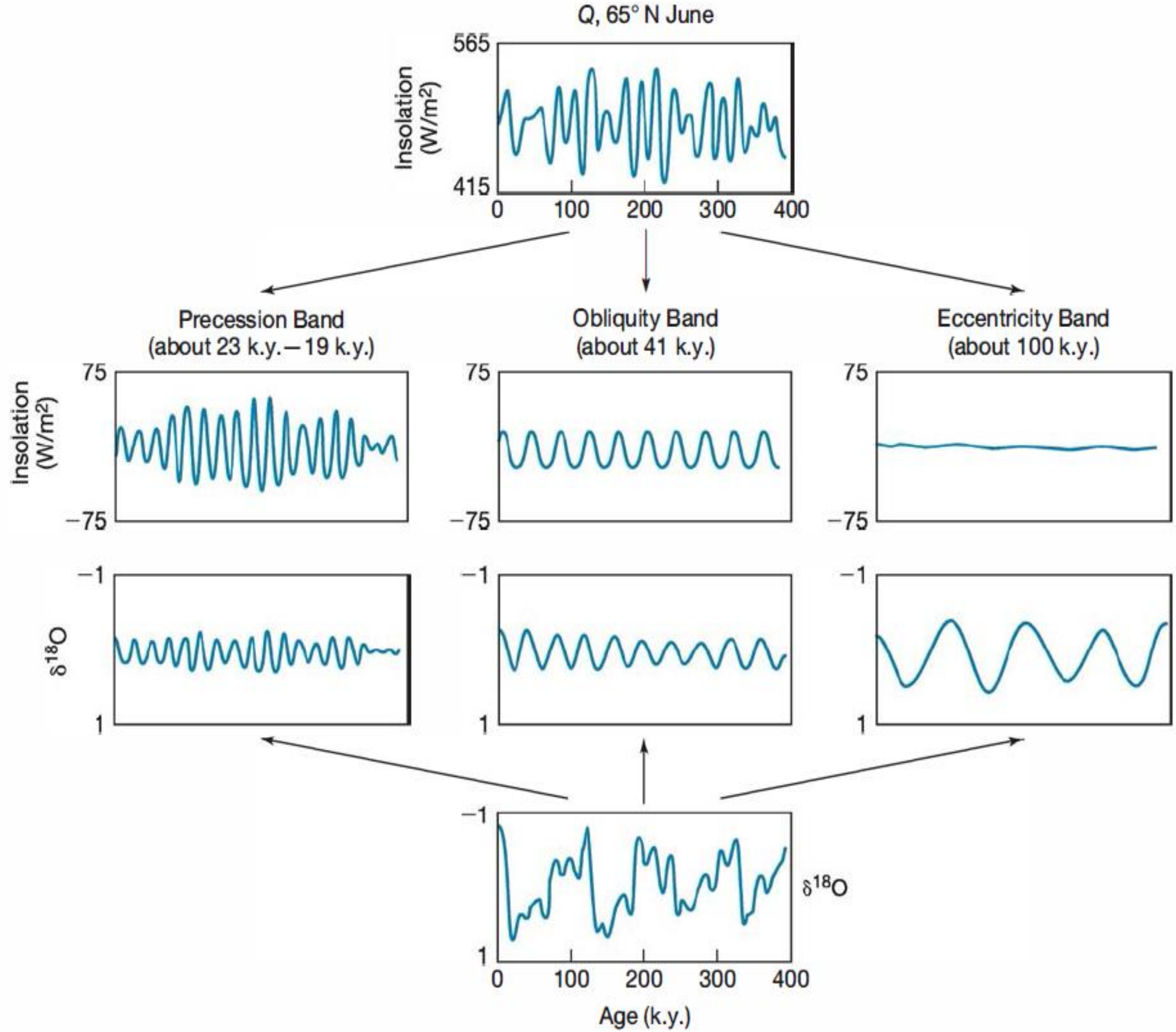
Not immediately obvious why eccentricity has such a low peak

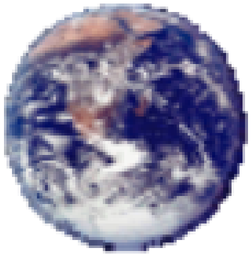
This suggests that spectral analysis may not properly identify low frequencies on the background of a rapidly oscillating time series

Spectral analysis of Vostok ice core



If the rapidly varying precession of the equinoxes acts merely as a "carrier wave" for changes in obliquity and eccentricity, precession would not affect climate, and the non-appearance of a spectral peak corresponding to precession might be understandable.


Q, 65° N June
565
Insolation (W/m2)
415
0
100
200
300
400
Precession Band
(about 23 k.y. – 19 k.y.)
Obliquity Band
(about 41 k.y.)
Eccentricity Band
(about 100 k.y.)
75
Insolation (W/m2)
–75
–1
δ18O
1
Age (k.y.)



Glacial Cycles

Salzman-Maasch Model

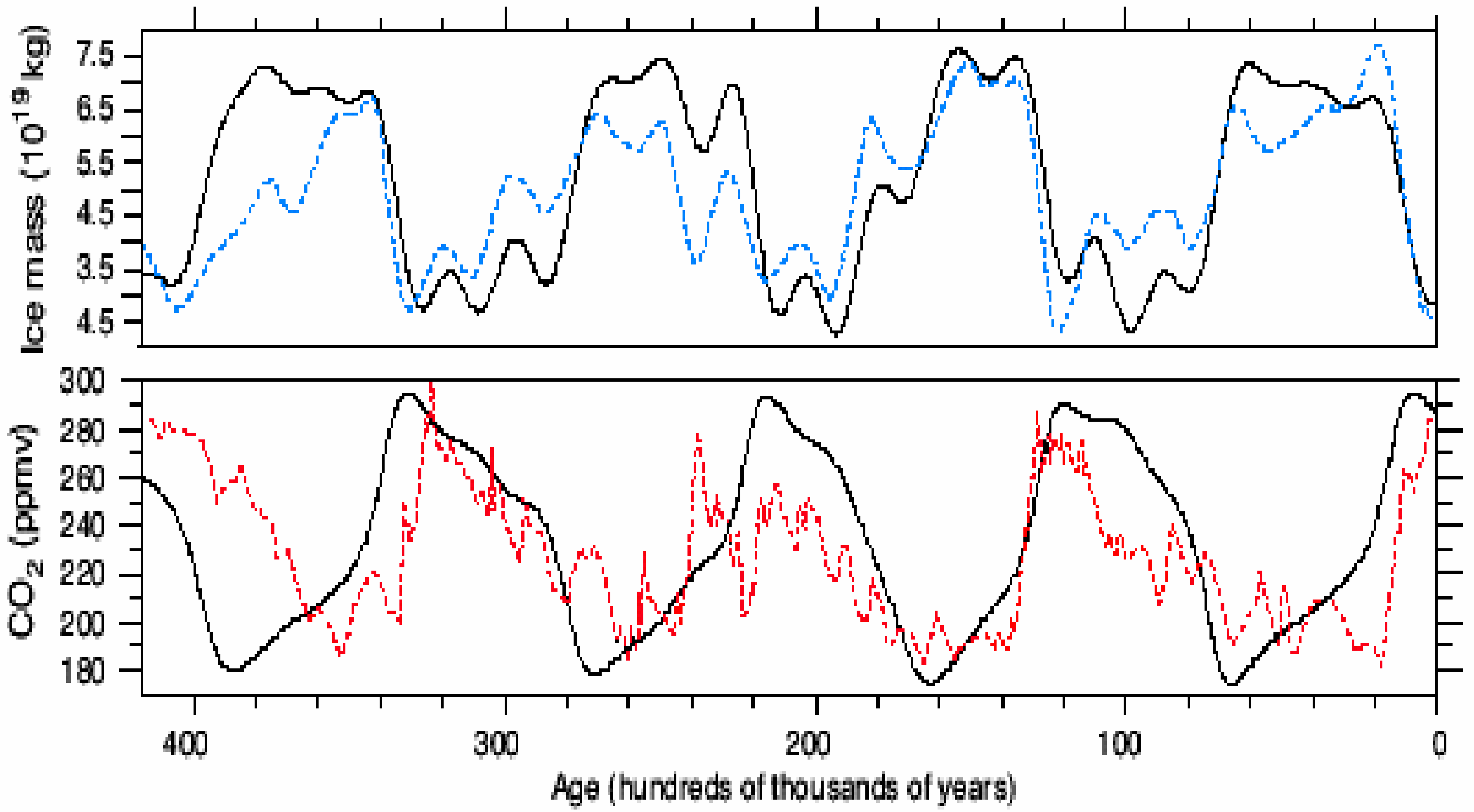
Milankovitch forcing

global ice mass $\longrightarrow$ $\dot{X} = -X - Y - uM(t)$

atmospheric CO_2 $\longrightarrow$ $\dot{Y} = -pZ + rY + sZ^2 - Z^2 Y$

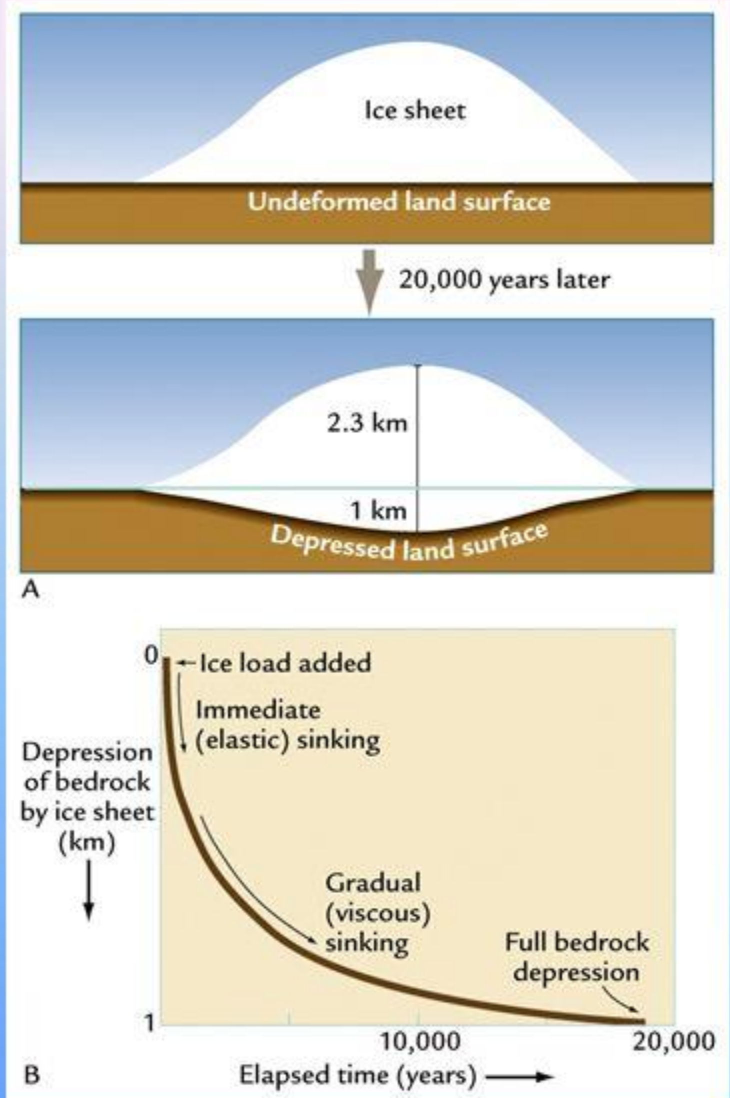
deep ocean temperature $\longrightarrow$ $\dot{Z} = -q(X + Z)$

Barry Salzman and Kirk A. Maasch, "A Low-Order Dynamical Model of Global Climatic Variability Over the Full Pleistocene," *Journal of Geophysical Research* **95** (D2), 1955-1963 (1990)



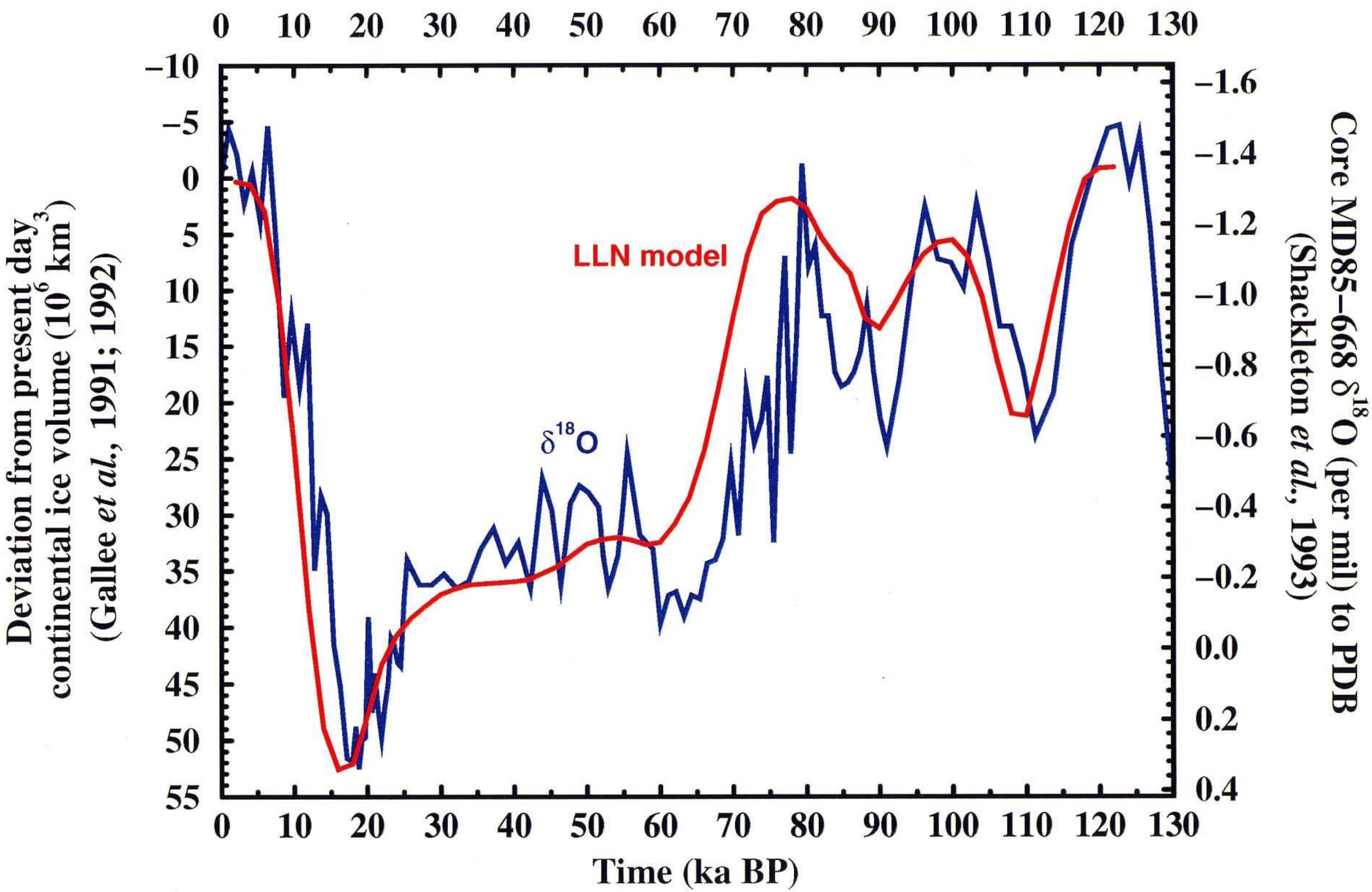
Solution of the dynamical system climate model of Saltzman and Maasch (1988) for the past 400 thousand years subject to the earth orbital radiative forcing. The model prediction for ice (top panel) and carbon dioxide (bottom panel) are shown. For comparison, the dashed blue curve in the top panel is the SPECMAP ∂18O estimate of ice variations and the dashed red curve in the bottom panel is the Vostok core estimate of CO_2 variation.

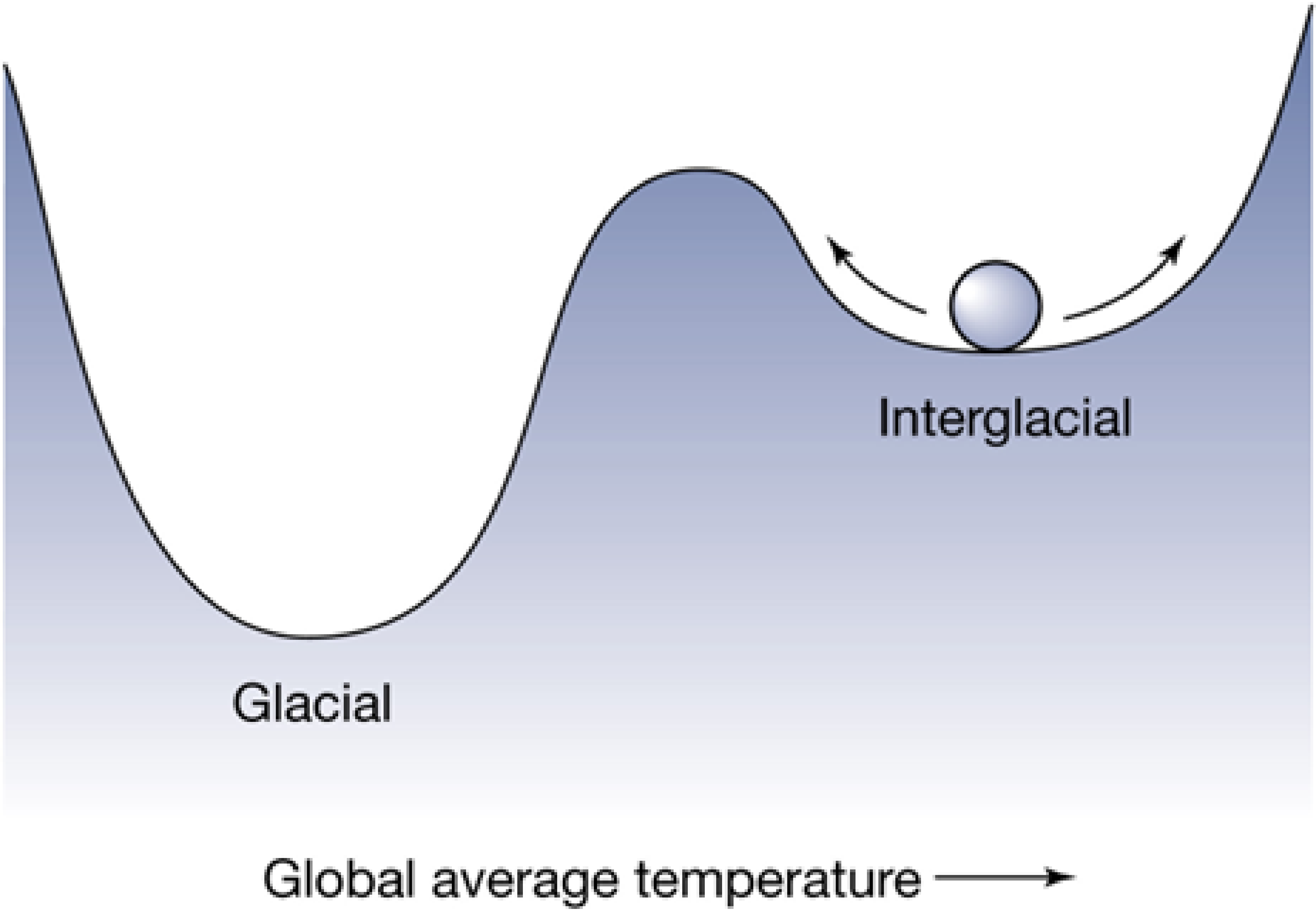
Bedrock Sinking



- A 3.3 km thick ice sheet
  - Eventually would reach equilibrium by depressing the bedrock 1.0 km.
  - This would lower the ice sheet's surface elevation 1.0 km
    - Resulting 6.5° C change in temperature
    - Large effects on mass balance of the ice sheet.

Simulation of the last glacial cycle by a coupled sectorally averaged climate ice-sheet model, Gallee et al., Journal of Geophysical Research, 97,1992




Interglacial
Glacial
Global average temperature

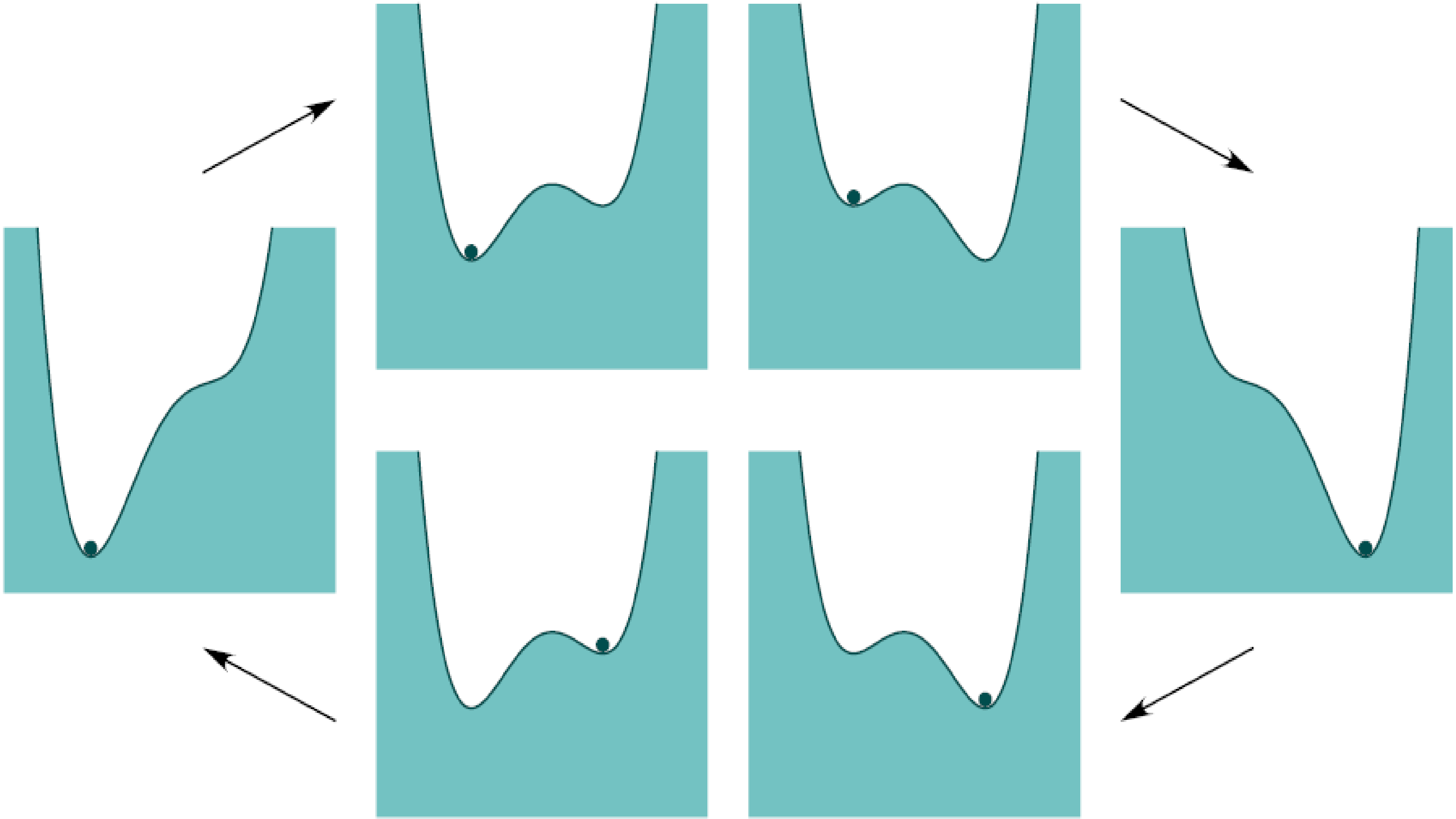
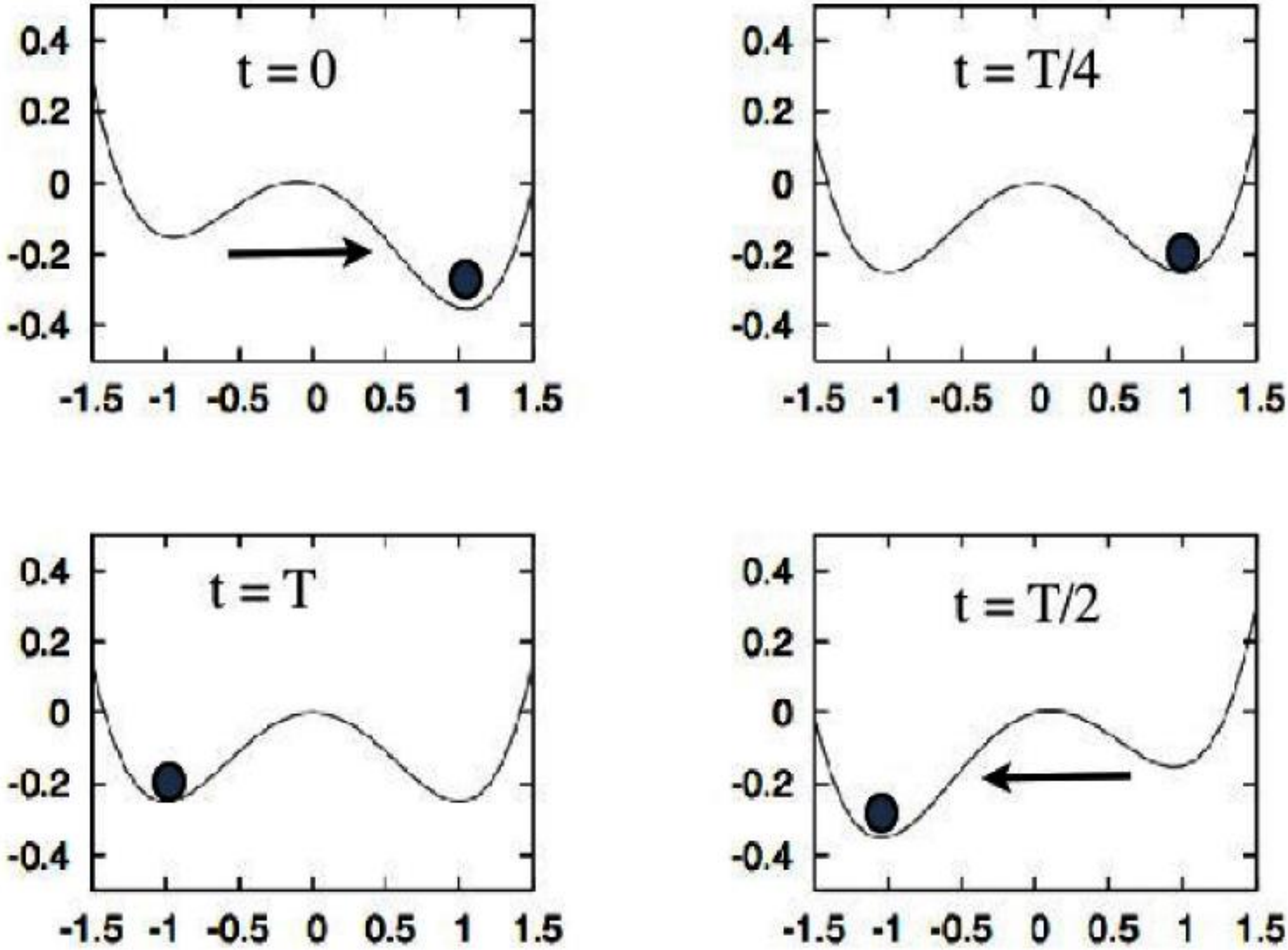
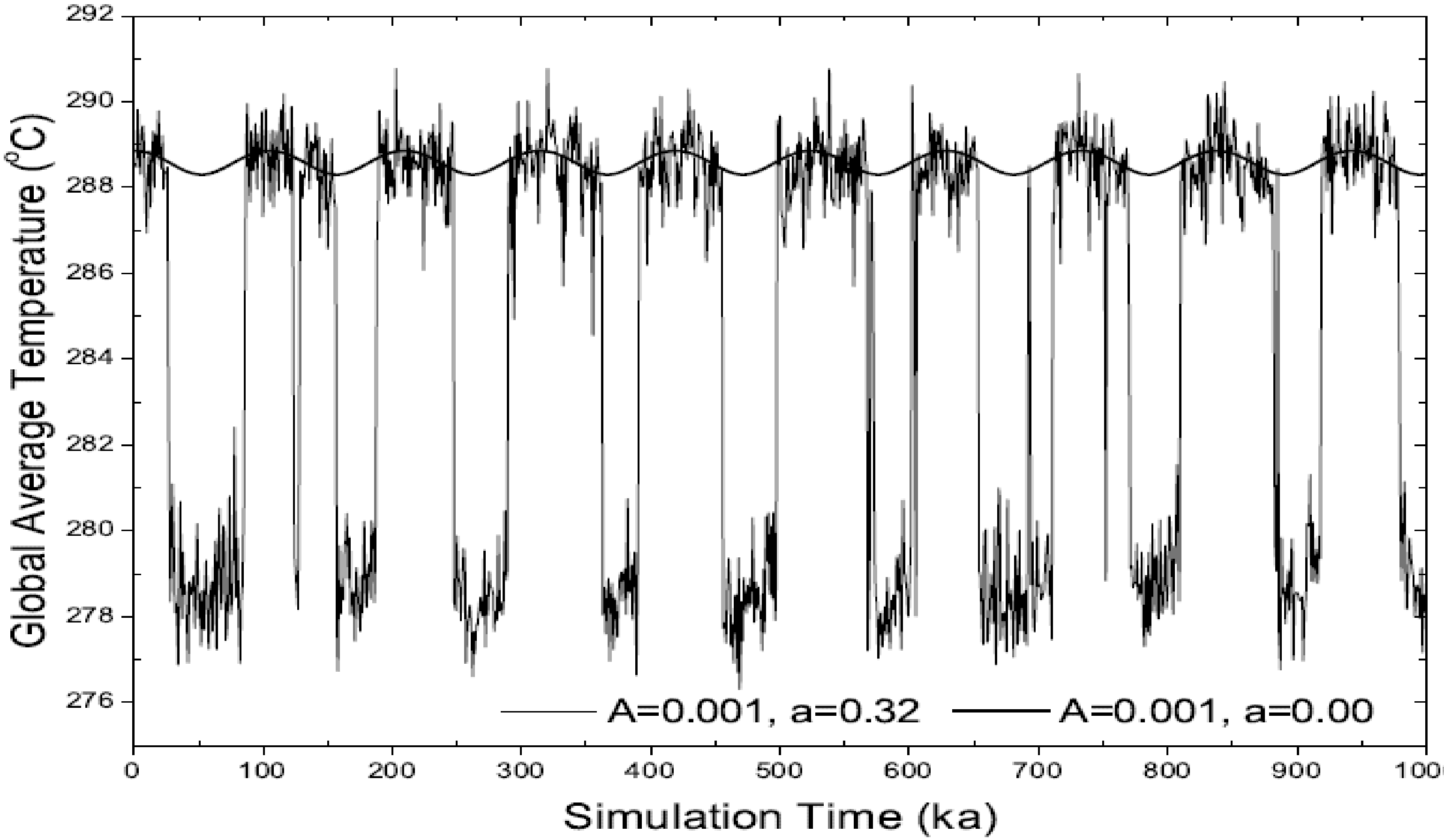


FIGURE 4. The potential $V(x,t) = \frac{1}{4}x^4 - \frac{1}{2}x^2 - \lambda(t)x$, with $\lambda(t) = K\cos(2\pi t)$, when K exceeds the threshold λ_c. In the deterministic case, with $\varepsilon \ll 1$, the overdamped particle jumps to a new well whenever $|\lambda(t)|$ becomes larger than λ_c, leading to hysteresis. Larger values of ε increase the size of hysteresis cycles, but additive noise of sufficient intensity decreases the size of typical cycles, because it advances transitions to the deeper well.


t = 0
0.4
0.2
0
-0.2
-0.4
-1.5 -1 -0.5 0 0.5 1 1.5
t = T/4
0.4
0.2
0
-0.2
-0.4
-1.5 -1 -0.5 0 0.5 1 1.5
t = T
0.4
0.2
0
-0.2
-0.4
-1.5 -1 -0.5 0 0.5 1 1.5
t = T/2
0.4
0.2
0
-0.2
-0.4
-1.5 -1 -0.5 0 0.5 1 1.5

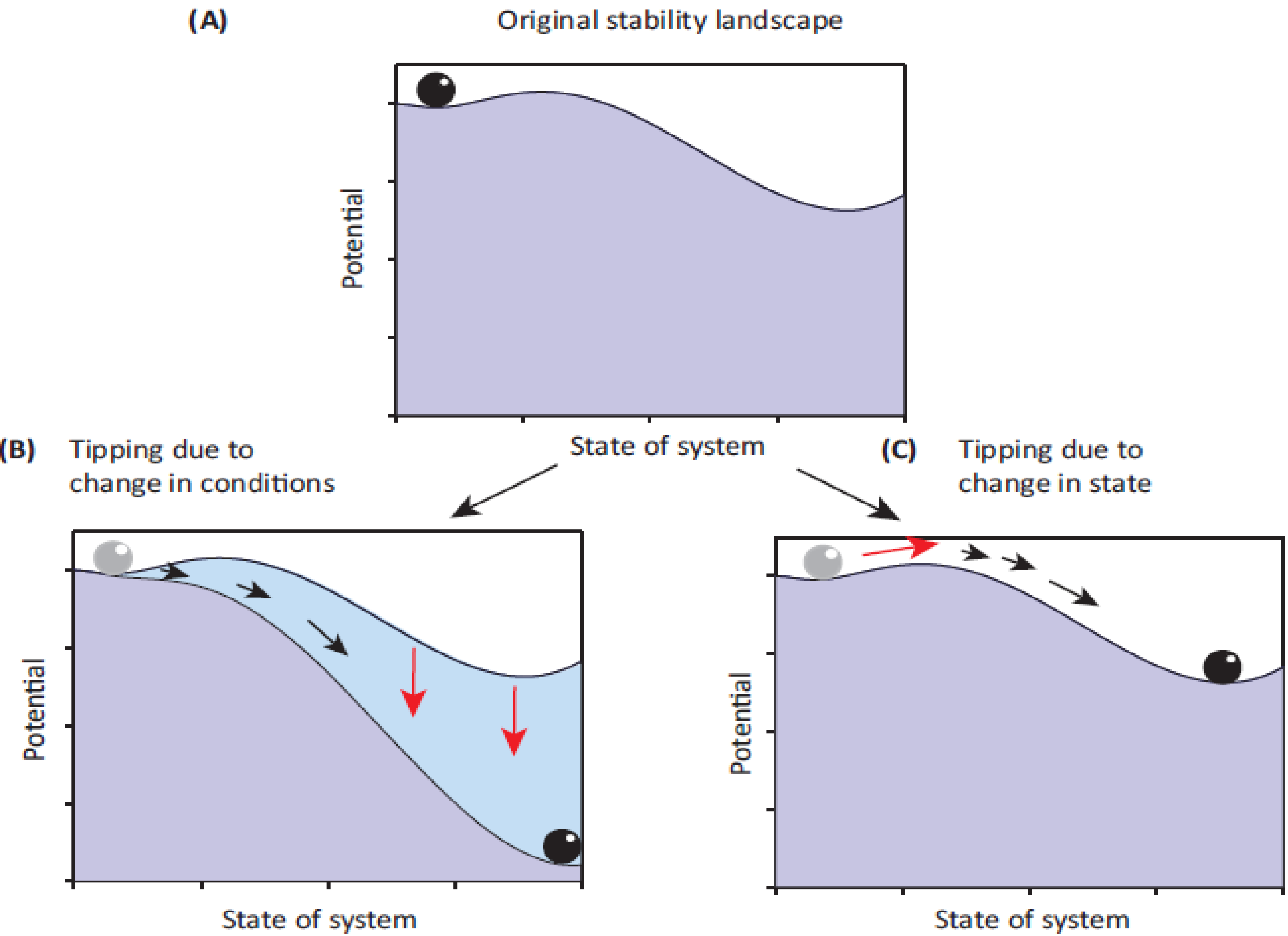
$$C\frac{dT}{dt} = \frac{S[1 + A\cos\omega(t)]}{4}[1 - \alpha_m(T)] - \varepsilon\sigma_0(T + 273.15)^4 + a\overline{\Gamma}(t)$$



o

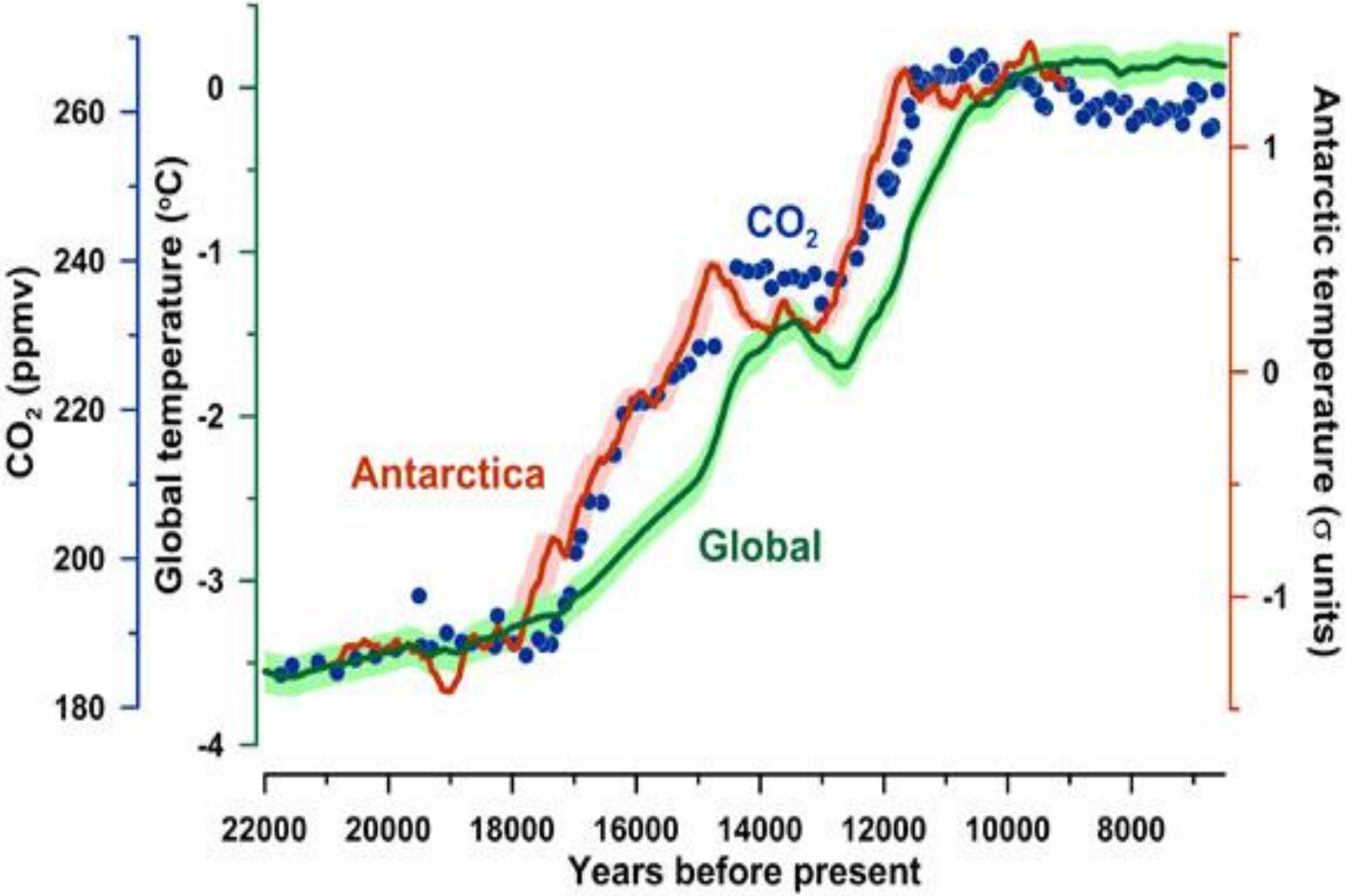
Fig. 6. The solution trajectory of Equation (5) when $A = 0.001$ and $a = 0.32$ (thin line) or 0.00 (strong line).

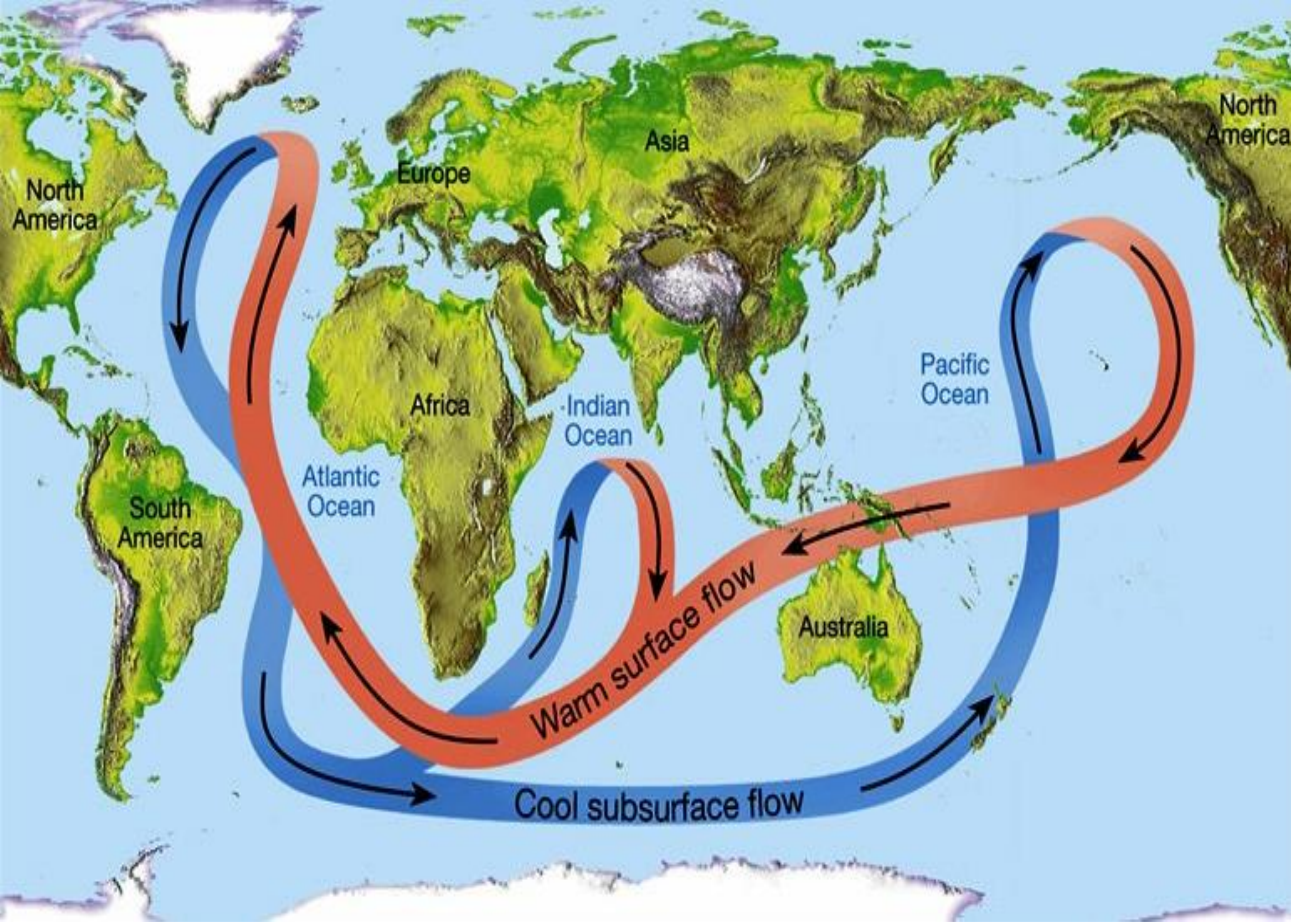
Case	a	A	Stochastic Resonance Happened?
1	0	0.001	No
2	0.22	0.001	No
3	0.26	0.001	Yes
4	0.28	0.001	Yes
5	0.32	0.001	Yes
6	0.39	0.001	No
7	0.32	0	No

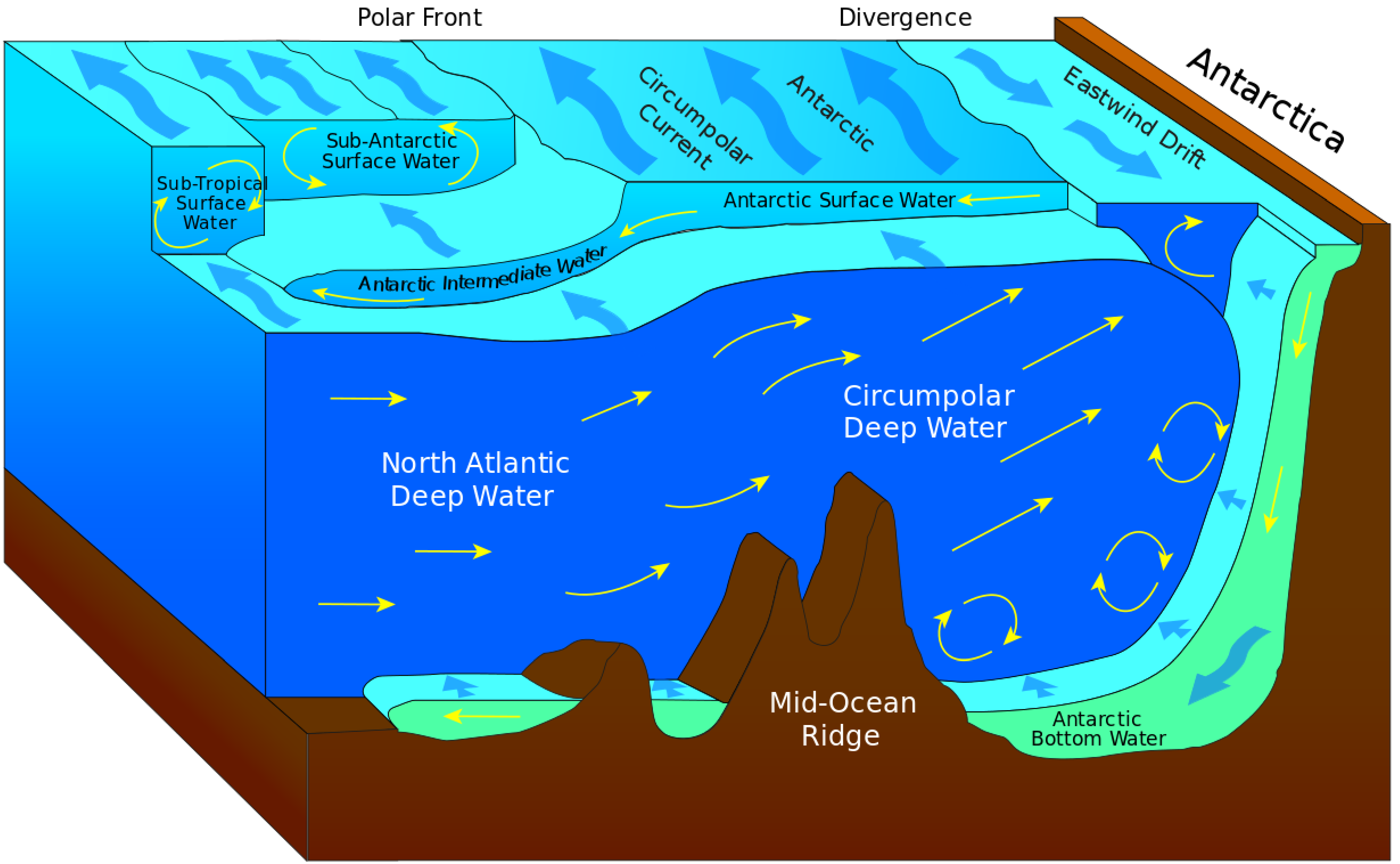

(A)
Original stability landscape
Potential
State of system
(B)
Tipping due to
change in conditions
Potential
State of system
(C)
Tipping due to
change in state
Potential
State of system

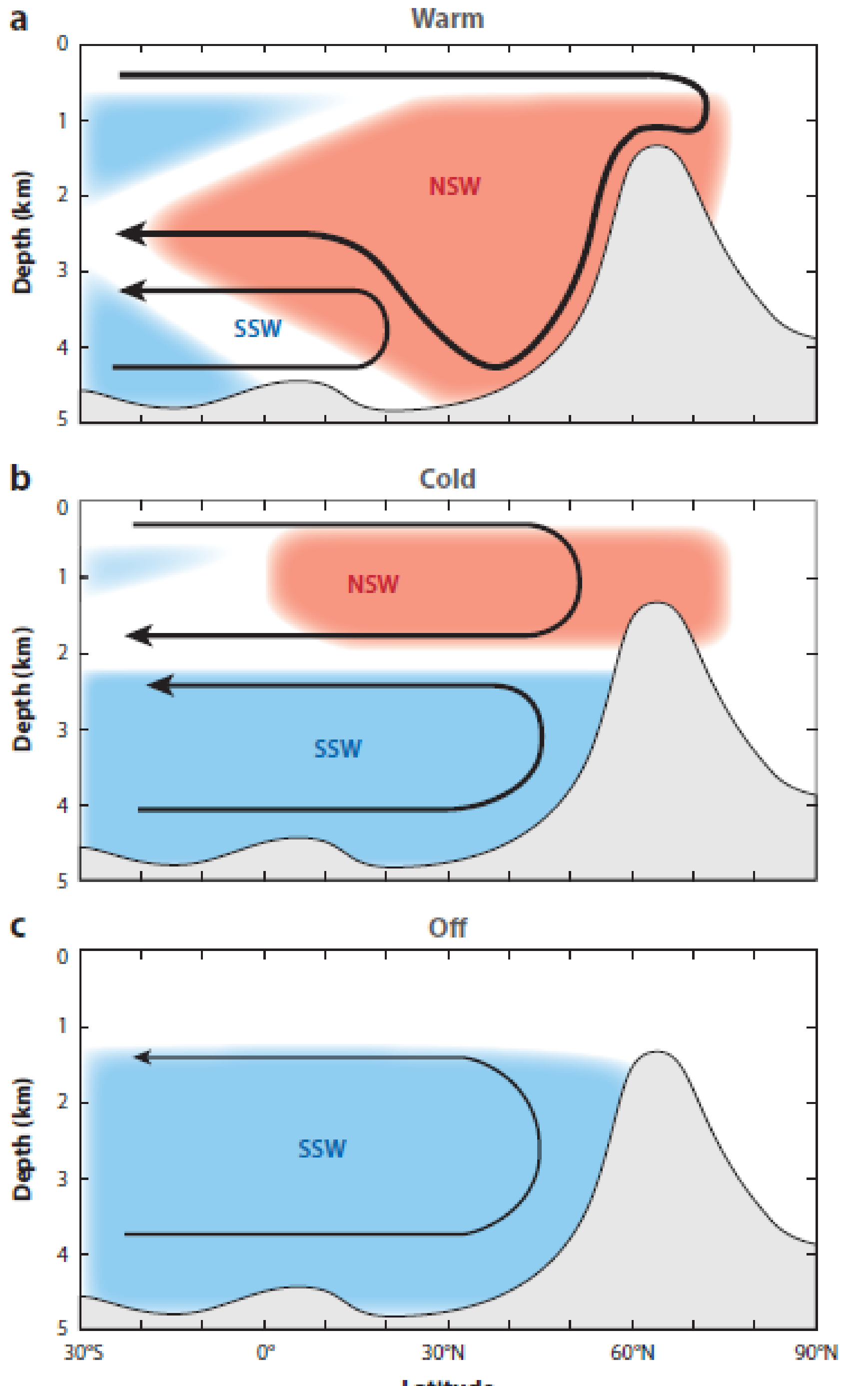
Abrupt Change
in
Atlantic Meridional Ocean Circulation(AMOC)

Temperature and CO_2 over the last deglaciation



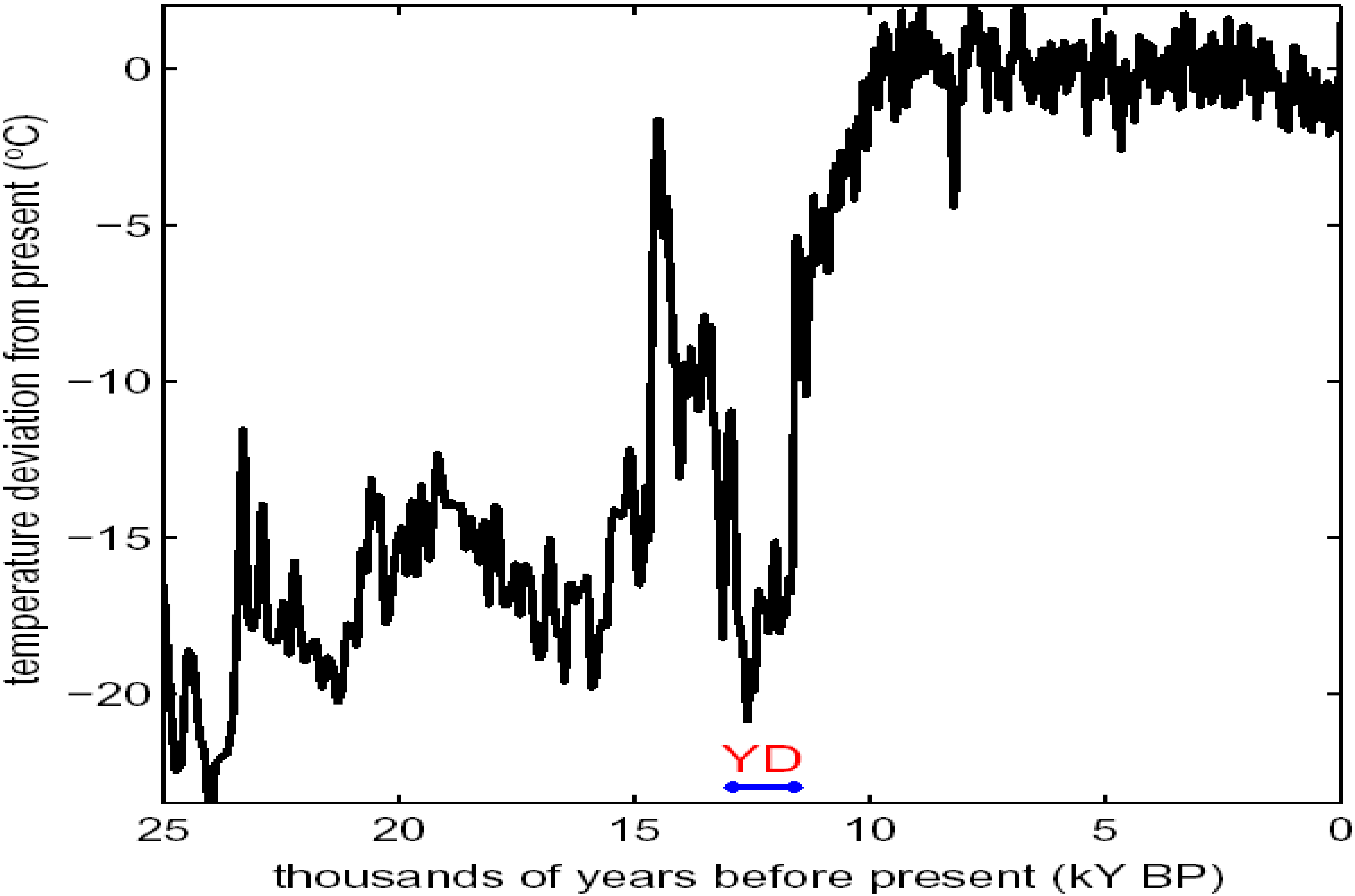

North America
Europe
Asia
North America
Pacific Ocean
Africa
Indian Ocean
Atlantic Ocean
South America
Australia
Warm surface flow
Cool subsurface flow


Polar Front
Divergence
Antarctica
Circumpolar Current
Antarctic
Eastwind Drift
Sub-Antarctic Surface Water
Sub-Tropical Surface Water
Antarctic Surface Water
Antarctic Intermediate Water
North Atlantic Deep Water
Circumpolar Deep Water
Mid-Ocean Ridge
Antarctic Bottom Water

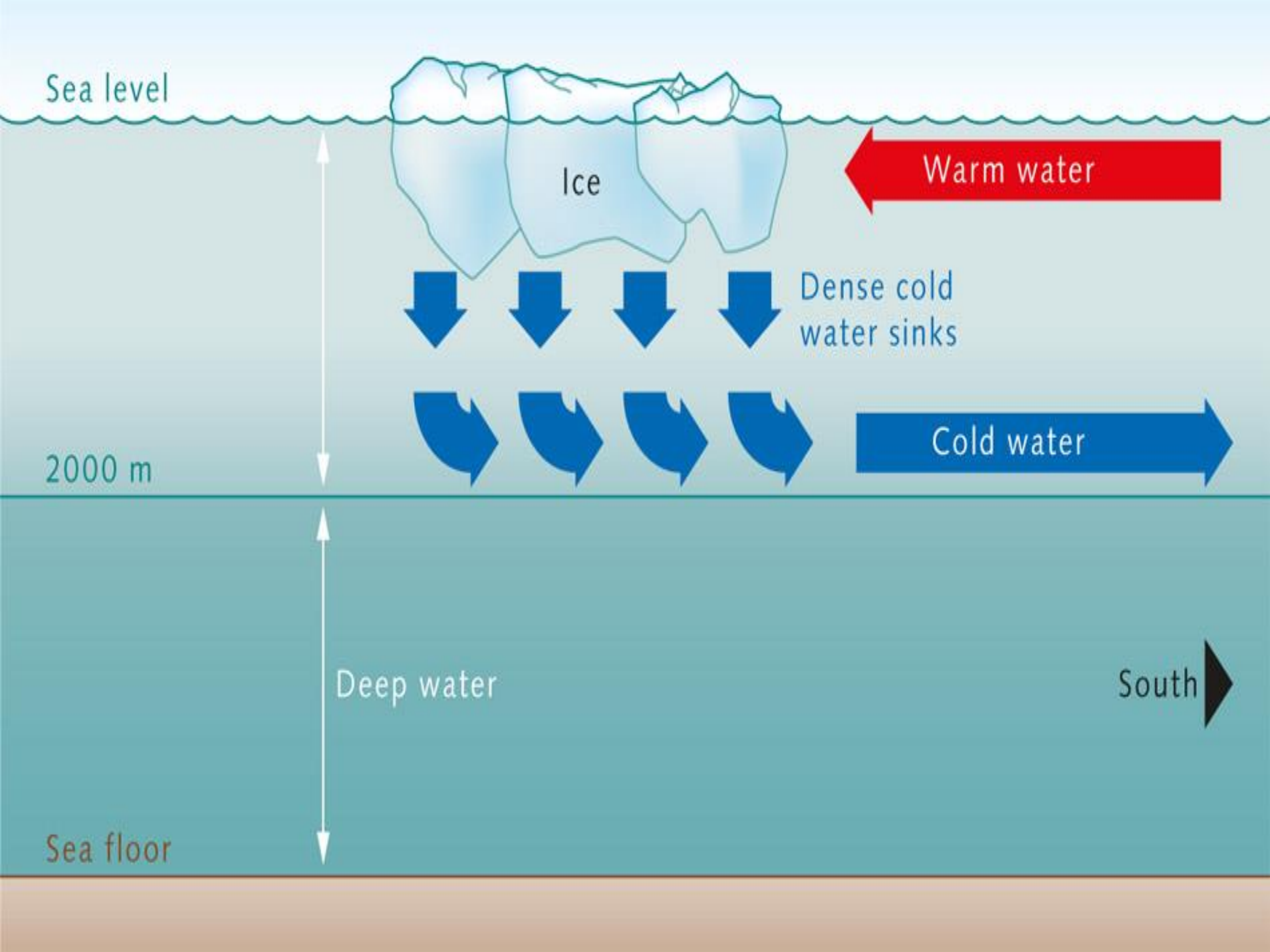


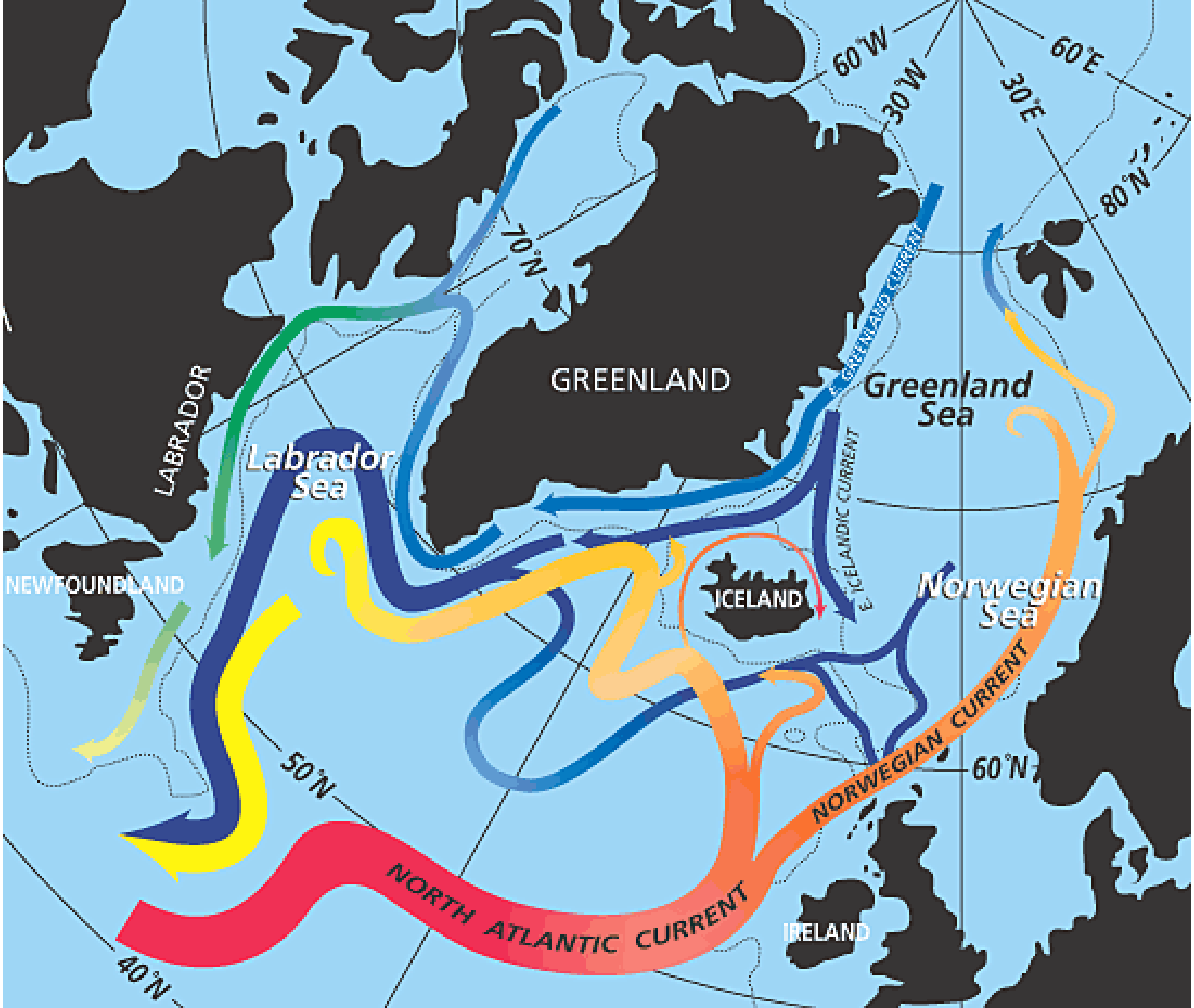
a
Warm
NSW
SSW
b
Cold
NSW
SSW
c
Off
SSW
Depth (km)
0
1
2
3
4
5
30°S
0°
30°N
60°N
90°N
Latitude

Central Greenland Temperature Deviations

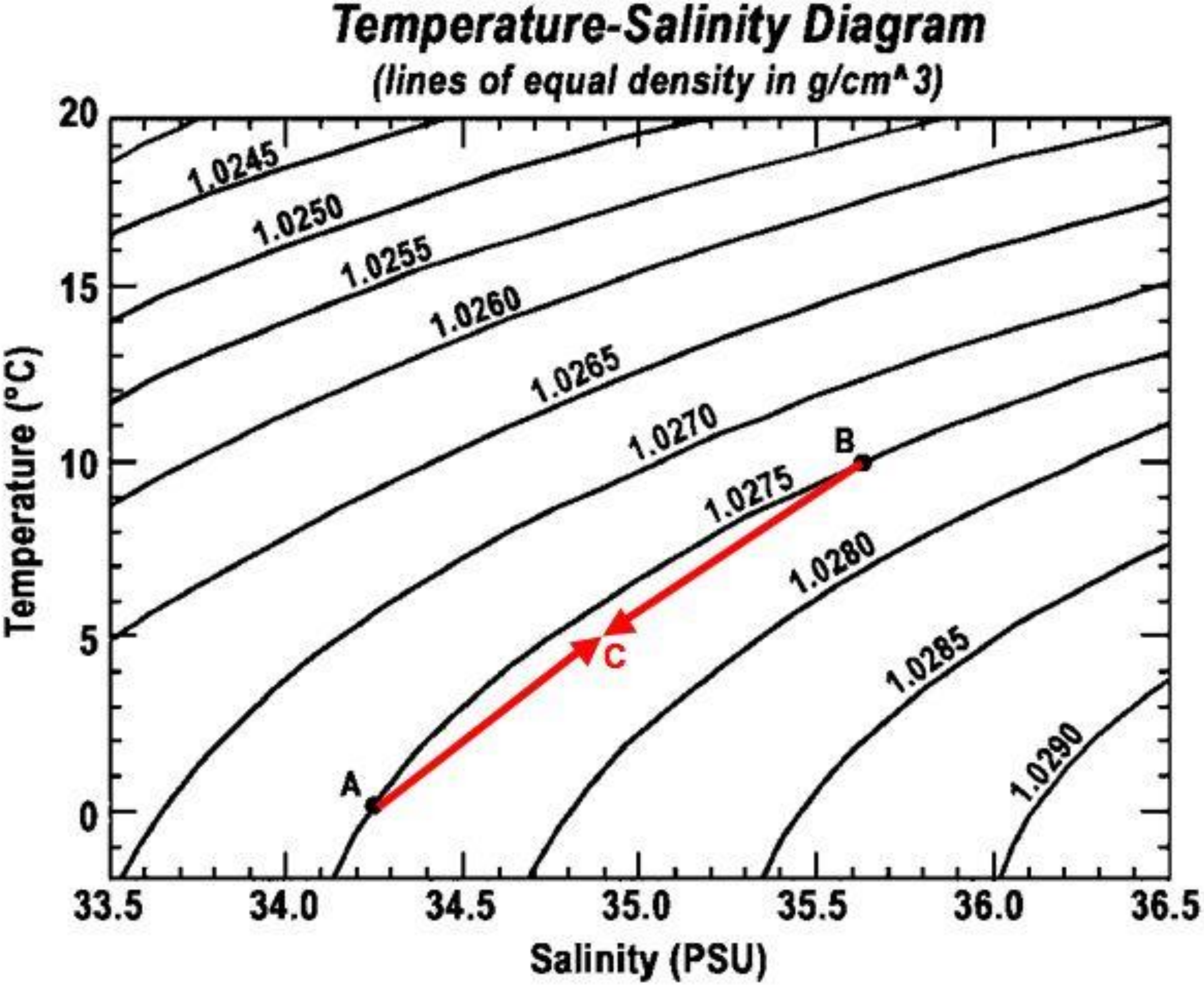


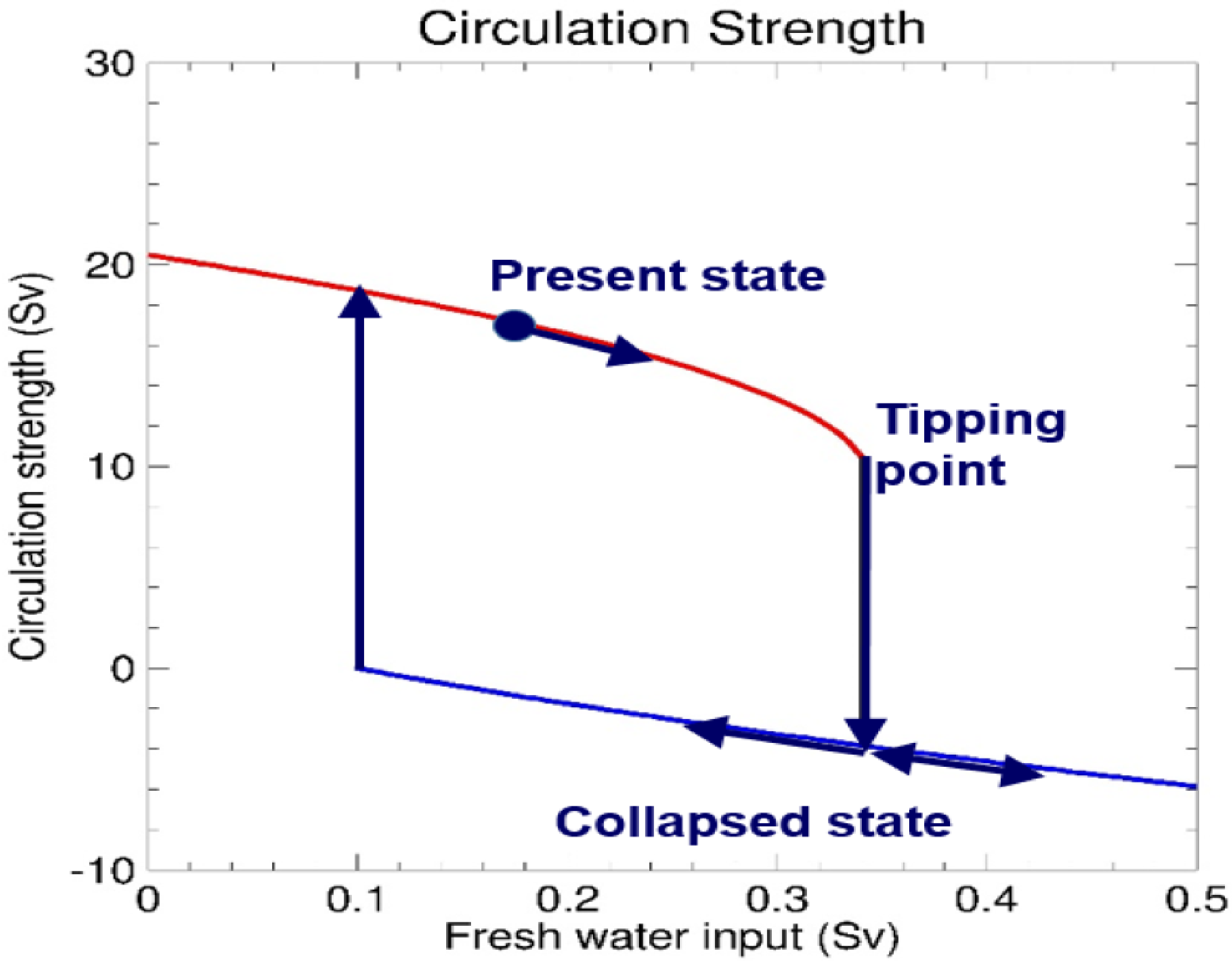
Data from Meese et al. (1994) and Stuiver et al. (1995).
20 year running mean, $\delta^{18}O$-temp conversion based on Cuffey et al, 1995

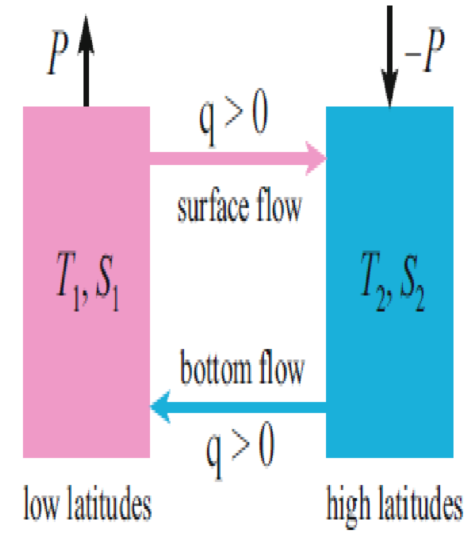

Sea level
Ice
Warm water
Dense cold water sinks
Cold water
2000 m
Deep water
South
Sea floor



60°W
60°E
30°W
30°E
80°N
70°N
GREENLAND
E. GREENLAND CURRENT
Greenland Sea
LABRADOR
Labrador Sea
NEWFOUNDLAND
ICELAND
E. ICELANDIC CURRENT
Norwegian Sea
NORWEGIAN CURRENT
60°N
50°N
40°N
NORTH ATLANTIC CURRENT
IRELAND

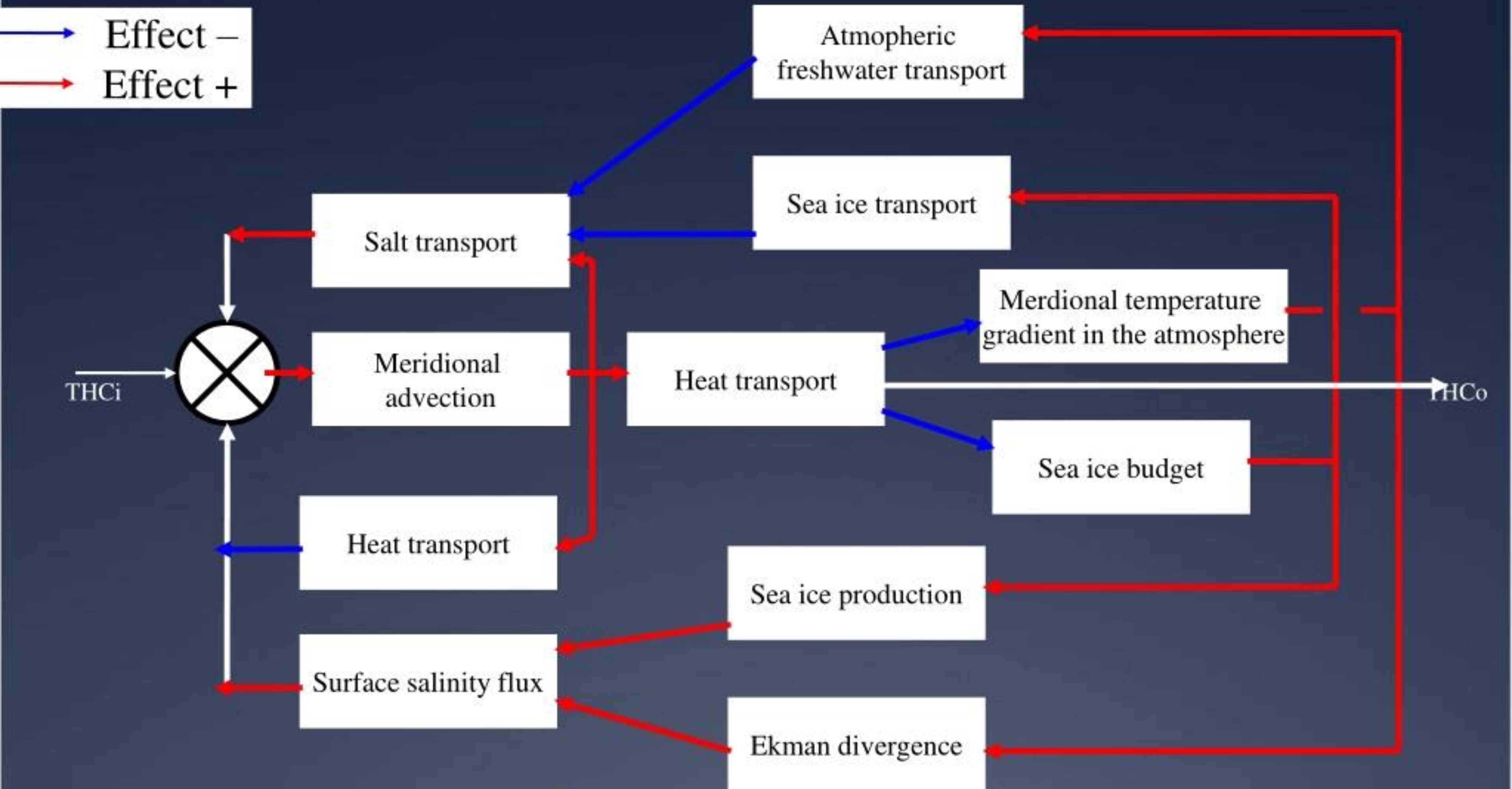

Temperature-Salinity Diagram
(lines of equal density in g/cm^3)
Temperature (°C)
Salinity (PSU)
20
15
10
5
0
33.5
34.0
34.5
35.0
35.5
36.0
36.5
1.0245
1.0250
1.0255
1.0260
1.0265
1.0270
1.0275
1.0280
1.0285
1.0290
A
B
C





The AMOC tipping point in many models is around 750 ppm of CO2 in many model simulations

THC internal feedbacks



Stocker et al., 2001

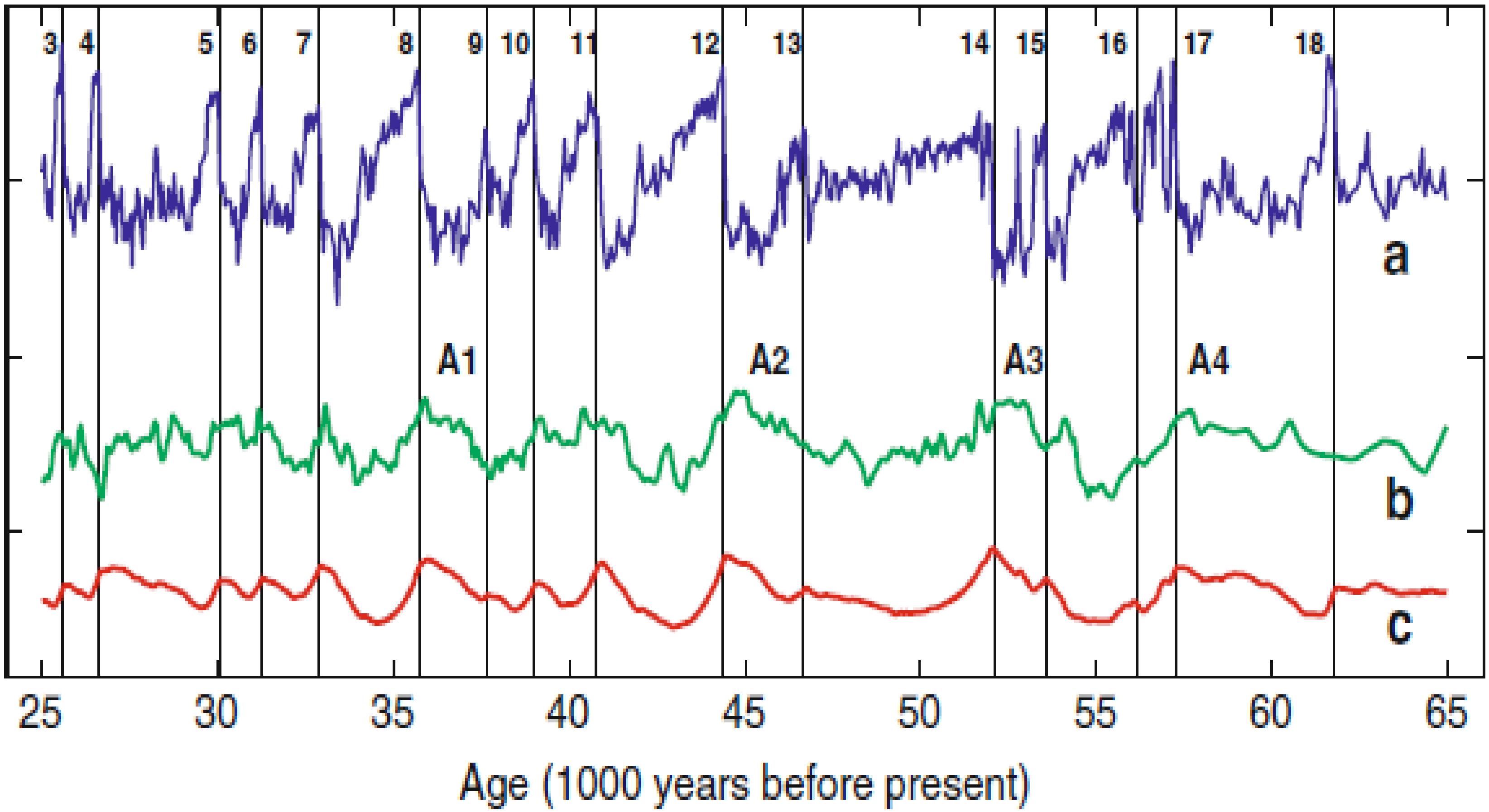
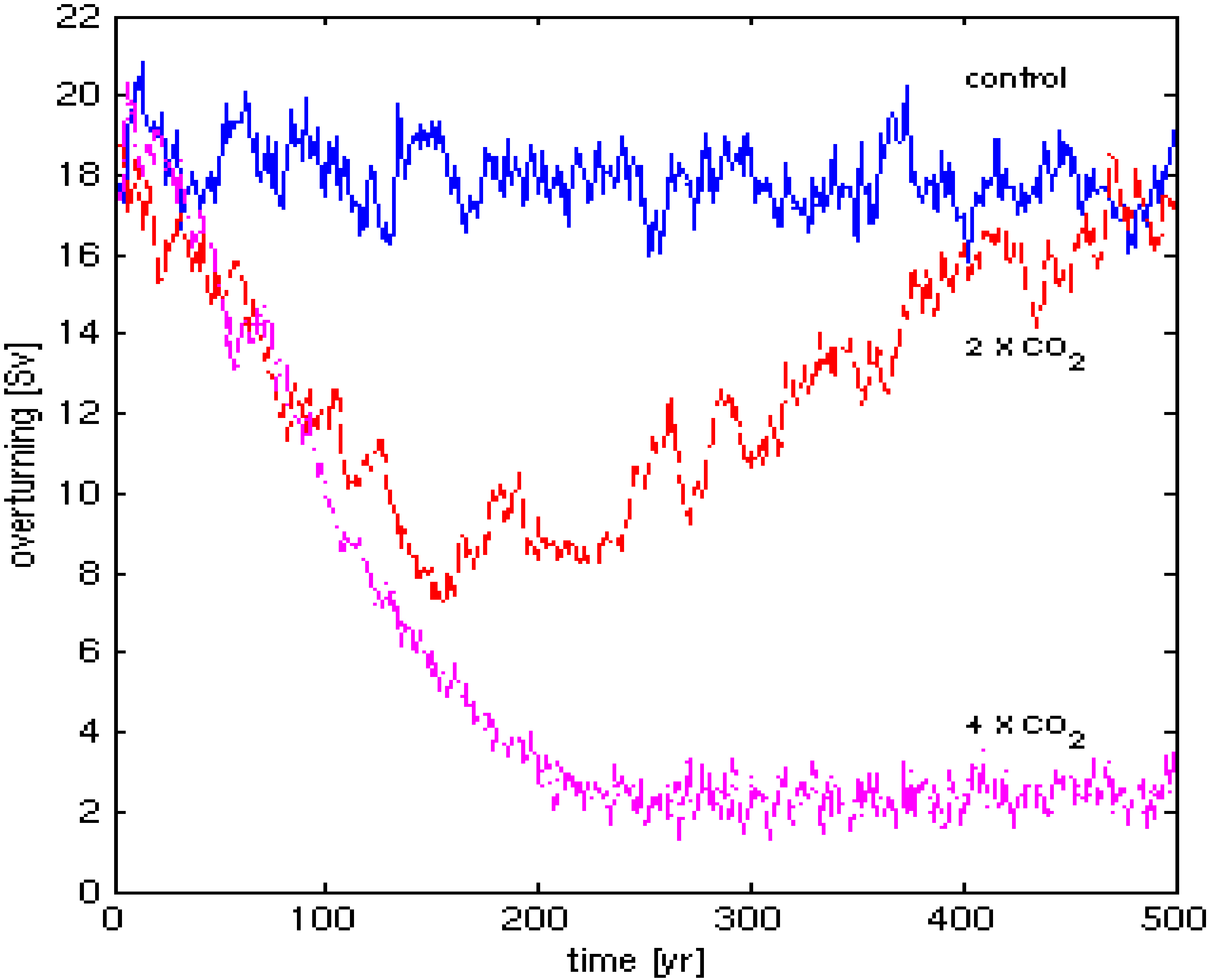


Fig. 9.3 High-pass filtered time series of the temperatures in Greenland (a) and Antarctica (b) derived from ice cores. (c) is the simulated temperature according to (9.2) with input (a). The abrupt Dansgaard–Oeschger events of the north hence become manifest in the local isotope maxima in Antarctica (A1, A2, . . .). Figure from Stocker and Johnsen (2003).

Introduction to Climate Modelling by Thomas Stocker, Springer, 2011

Manabe and Stouffer (1994)



Risk of tipping the overturning circulation due to increasing rates of ice melt

Lohmann and Ditlevsena

Proceedings of the National Academy of Sciences March 2021

Using a global ocean model subject to freshwater forcing, we show that a collapse of the Atlantic Meridional Overturning Circulation can indeed be induced even by small-amplitude changes in the forcing, if the rate of change is fast enough

Abrupt climate change as a rate-dependent cascading tipping point

Lohmann et al., Earth System Dynamics,2021

An abrupt resurgence of the overturning circulation is induced before a bifurcation point is reached due to the fast rate of change of the sea ice. Because of the multi-scale nature of the climate system, this type of tipping cascade may also be a risk concerning future global warming. The relatively short timescales involved make it challenging to detect these tipping points from observations

Vellinga and Wood (2008)

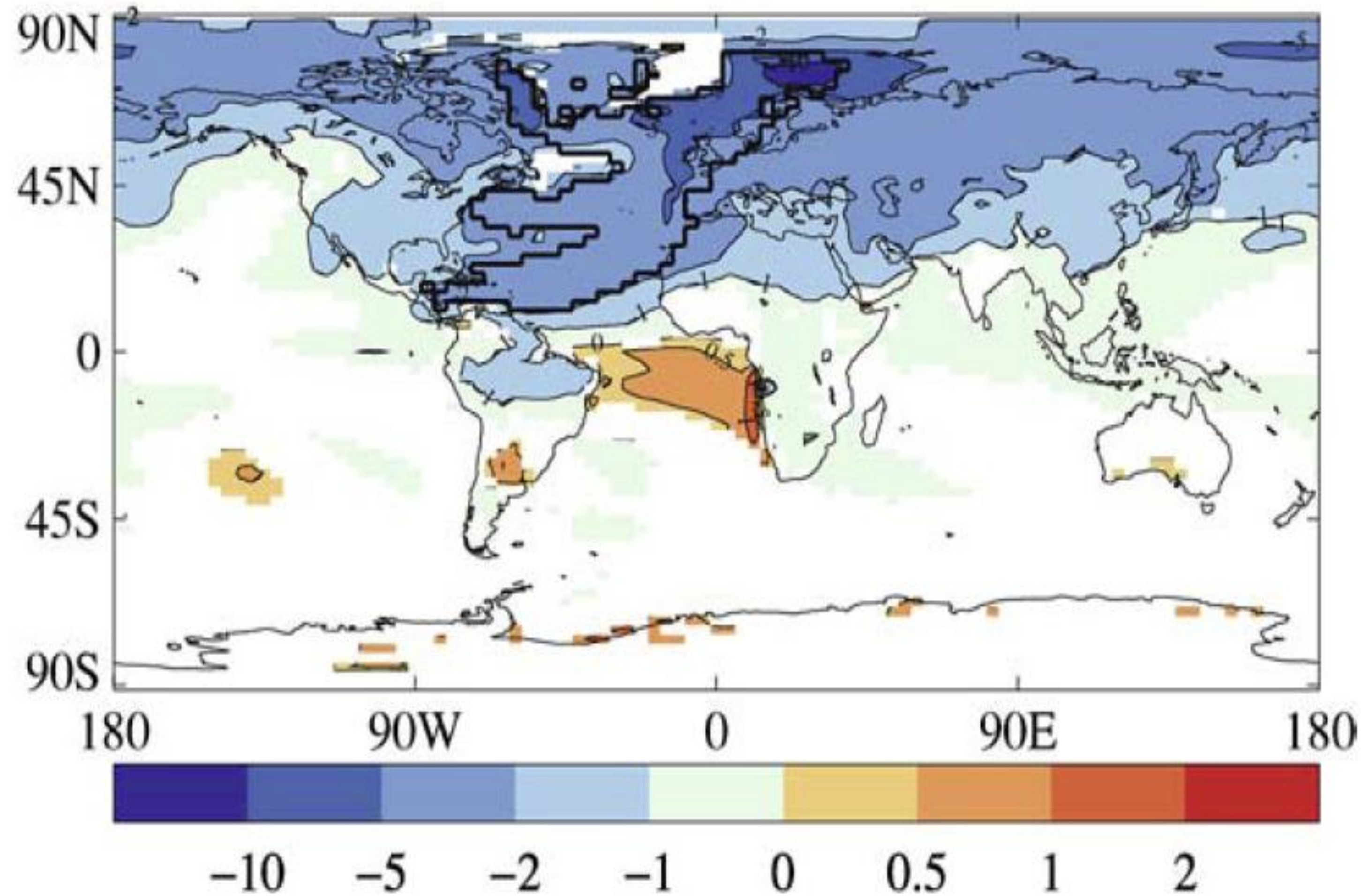
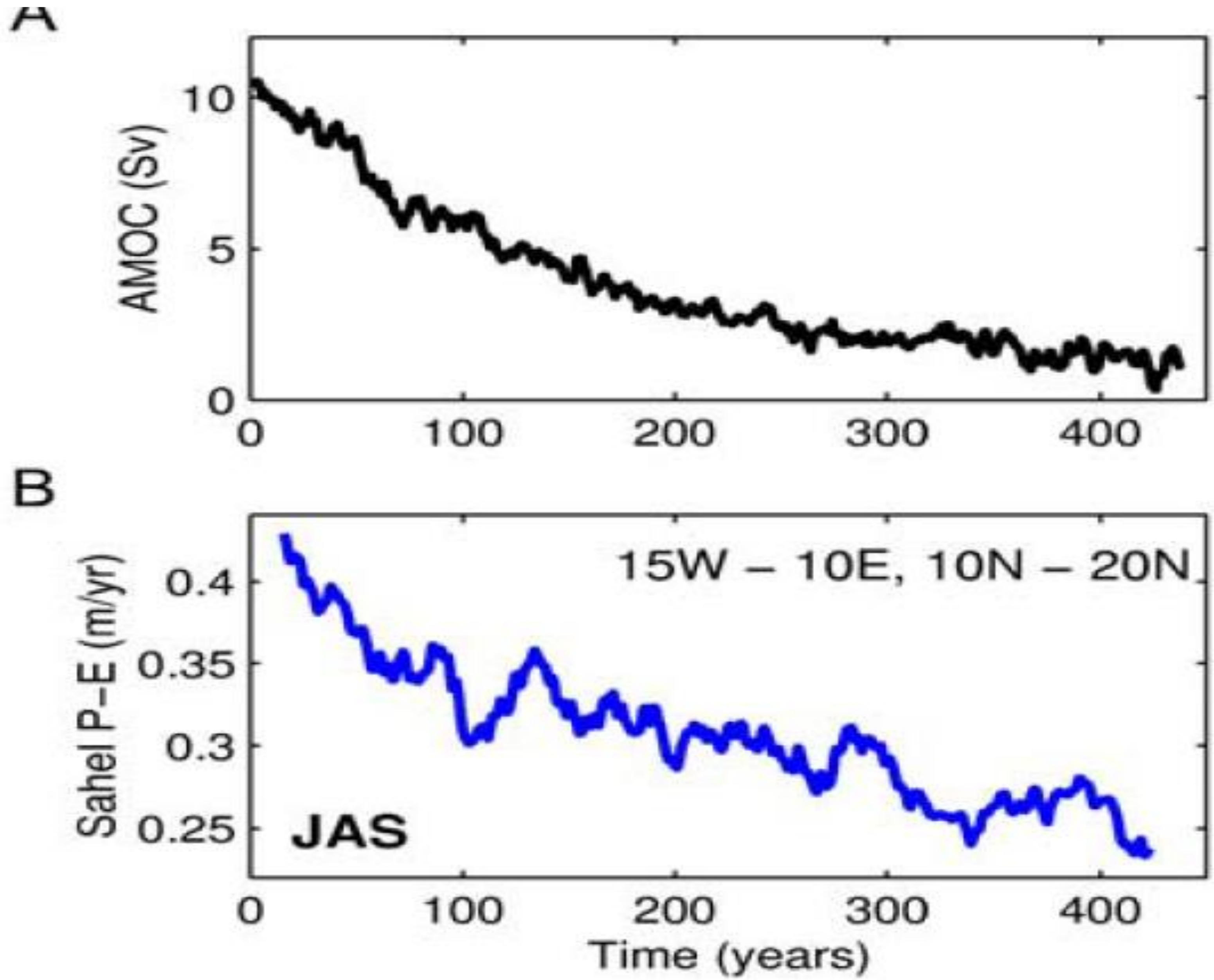


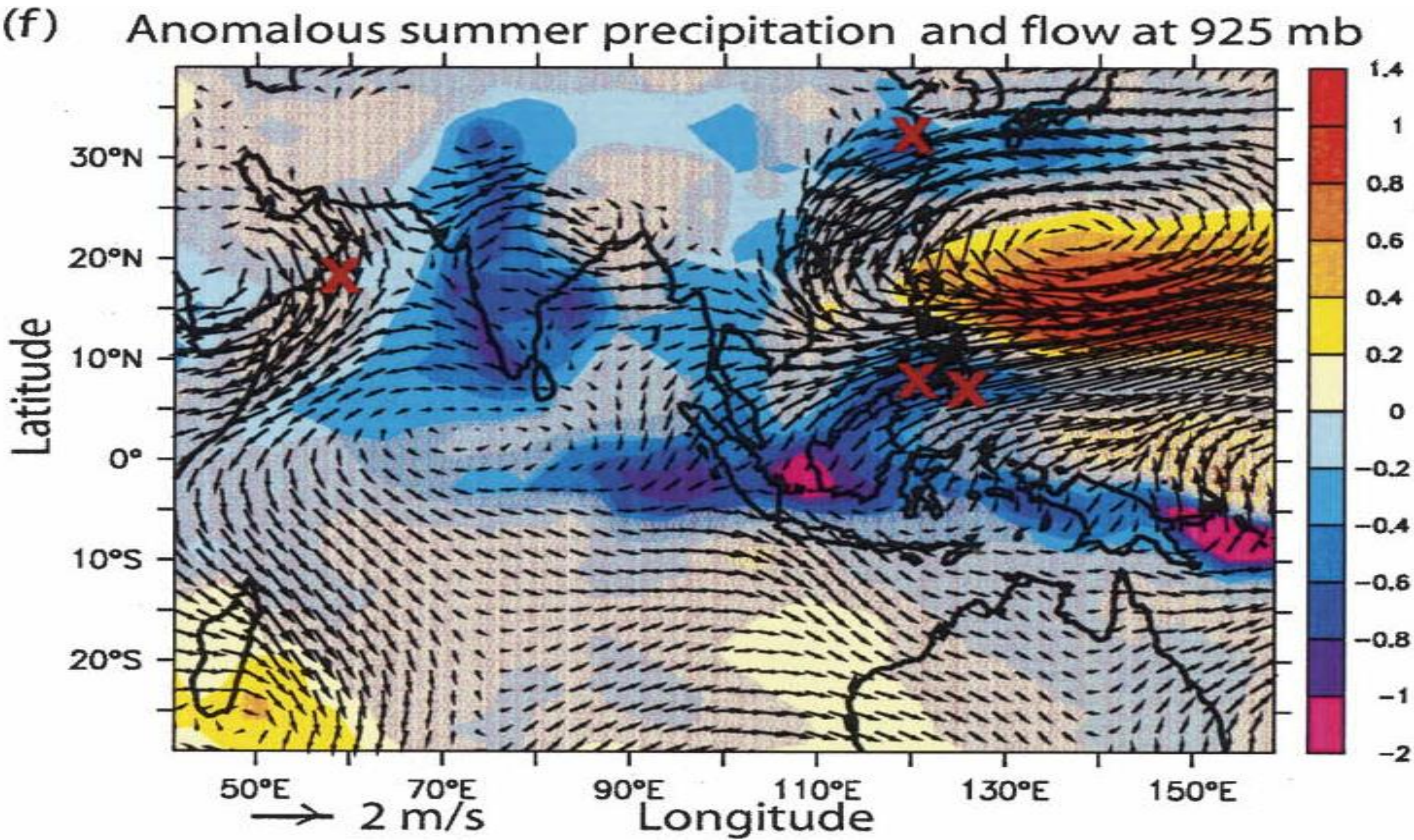
Fig. 4 Difference in surface air temperature between experiments PG and G in the years 2049–2059. This difference is therefore the temperature change that a sudden THC shutdown would cause relative to an IS92a global warming scenario in 2049–2059. The area where cooling causes temperature to fall below pre-industrial conditions is outlined by the heavy solid line, areas where the difference is not significant have been masked.

Sahel megadroughts triggered by glacial slowdowns of Atlantic meridional overturning

Mulitza et al.,Paleoceanography , 2008



To explore the response of the global climate to a weakening of the Atlantic thermohaline circulation, a perturbation experiment is conducted in which an extra freshwater forcing of 0.6 Sv is uniformly distributed over the northern North Atlantic (55°–75°N, 63°W–4°E) for the entire 60-yr duration of the experiment.



ARTICLES
https://doi.org/10.1038/s41558-021-01097-4
nature climate change

Check for updates

Observation-based early-warning signals for a collapse of the Atlantic Meridional Overturning Circulation

Niklas Boers[1,2,3]

BRIEF COMMUNICATION
https://doi.org/10.1038/s41561-021-00699-z
nature geoscience

Check for updates

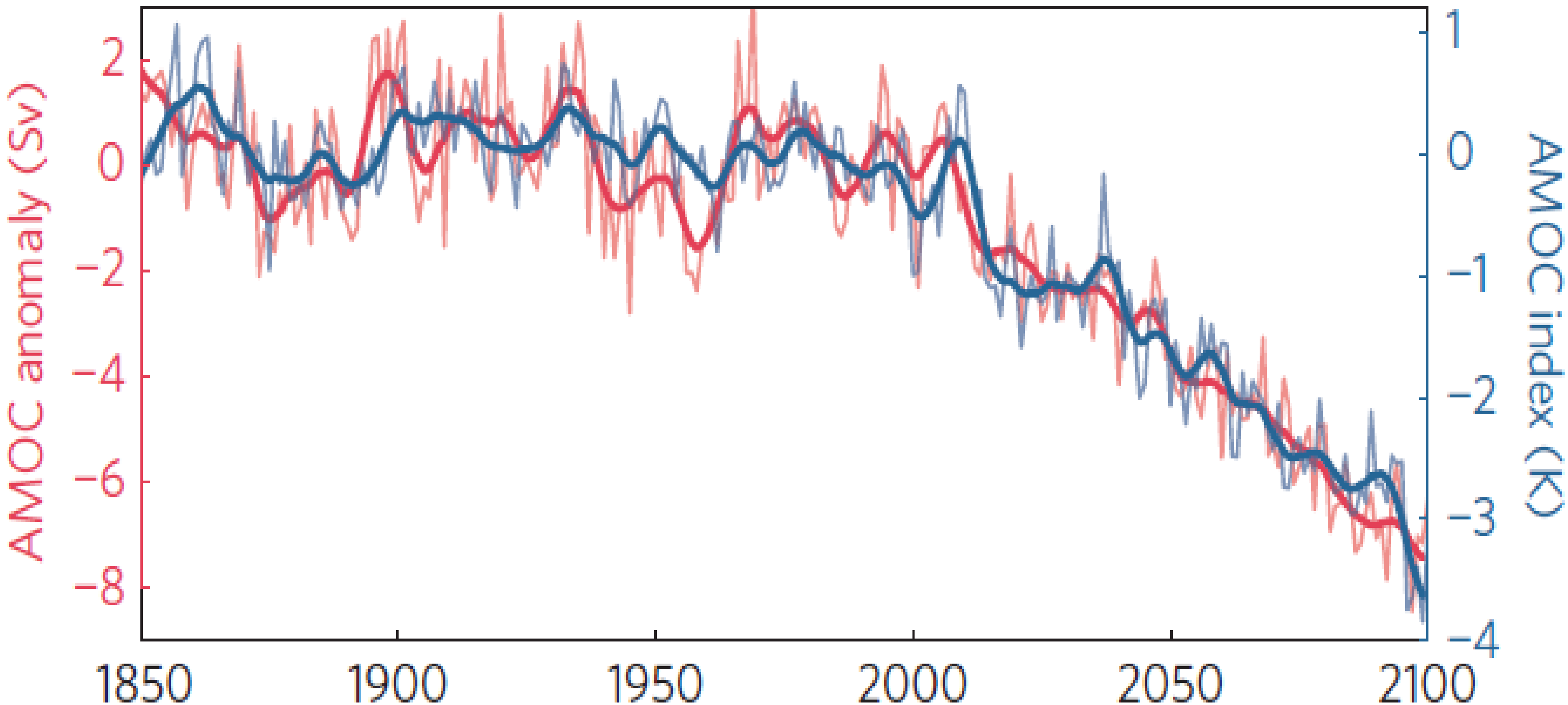
Current Atlantic Meridional Overturning Circulation weakest in last millennium

Current Atlantic Meridional Overturning Circulation weakest in last millennium

L. Caesar

After a long and relatively stable period, there was an initial weakening starting in the 19th century, followed by a second, more rapid, decline in the 20th century, leading to the weakest state of the AMOC occurring in recent decades.

Simulated with the MPI-ESM-MR global climate model of the Max Planck Institute in Hamburg[11]. **a**, Time series of the maximum overturning stream function (red) and the AMOC index (blue). Thin lines show annual values,



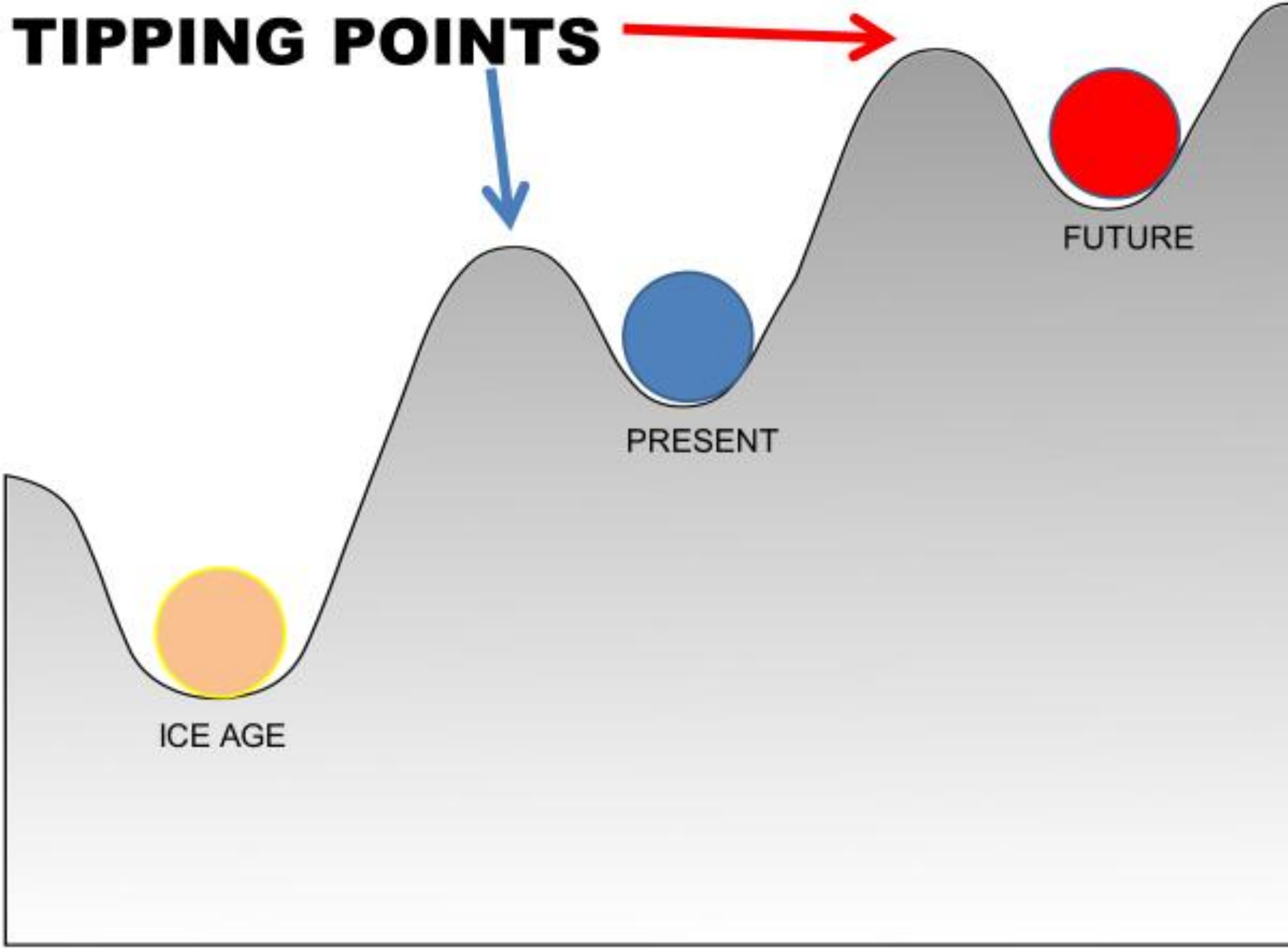
Rahmstorf, S., Box, J., Feulner, G. et al. Exceptional twentieth-century slowdown in Atlantic Ocean overturning circulation. Nature Clim Change 5, 475–480, 2015

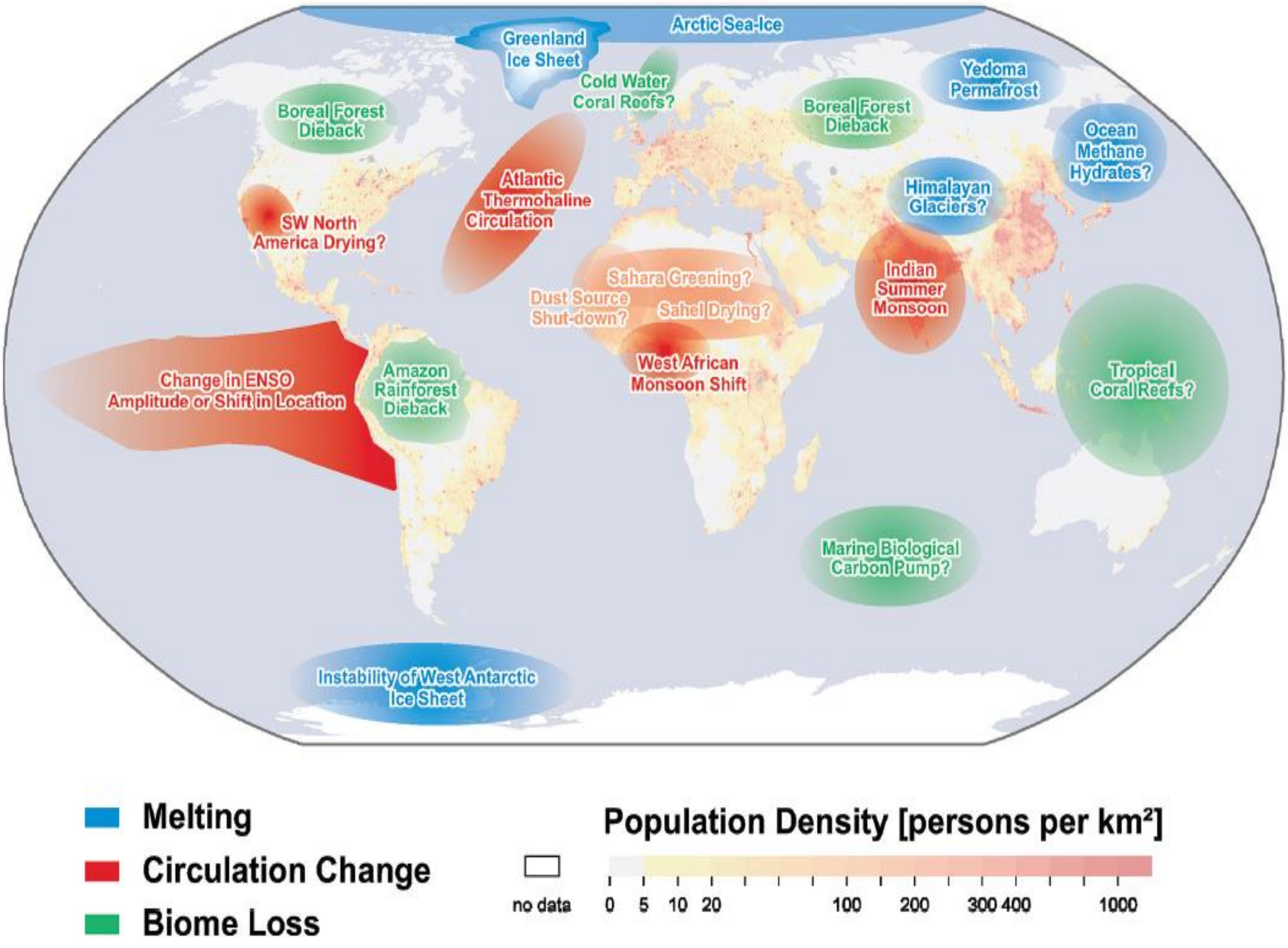
AMOC index = Sub-polar Gyre SST - NH SST

COMMENT | 27 November 2019 | Correction 09 April 2020

Climate tipping points — too risky to bet against

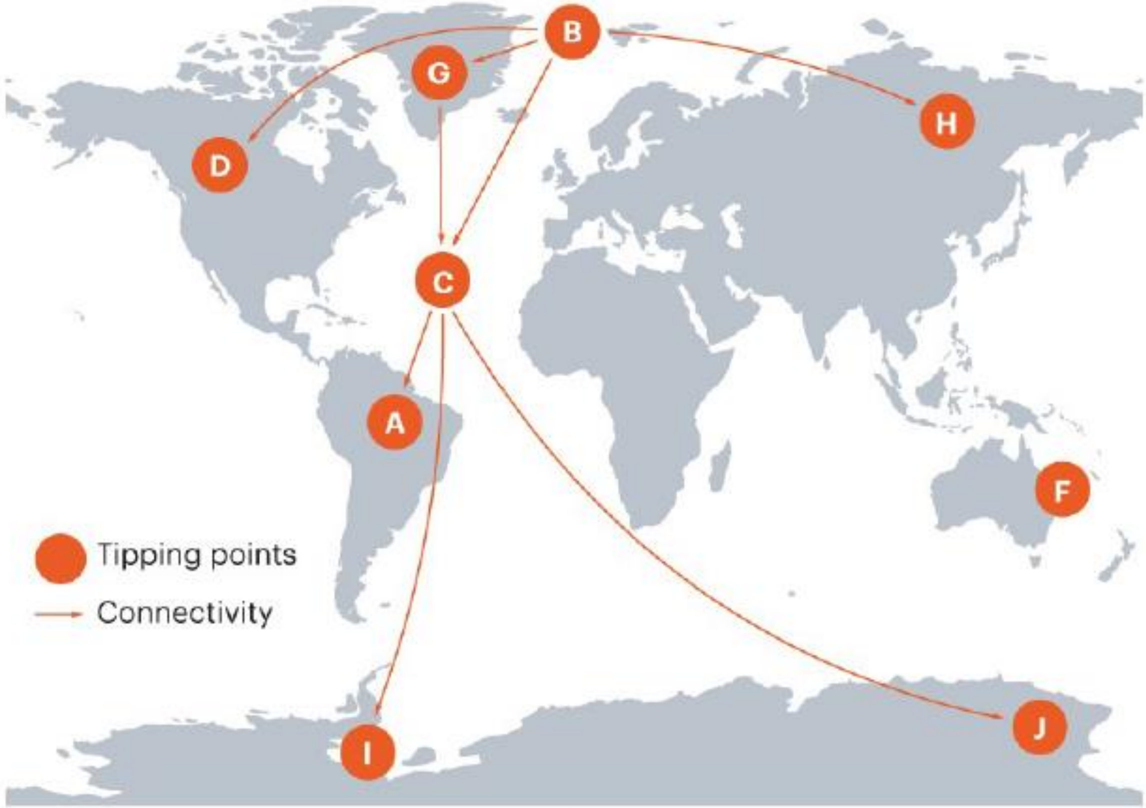
The growing threat of abrupt and irreversible climate changes must compel political and economic action on emissions.


TIPPING POINTS
FUTURE
PRESENT
ICE AGE


Arctic Sea-Ice
Greenland Ice Sheet
Cold Water Coral Reefs?
Yedoma Permafrost
Boreal Forest Dieback
Boreal Forest Dieback
Ocean Methane Hydrates?
Himalayan Glaciers?
Atlantic Thermohaline Circulation
SW North America Drying?
Sahara Greening?
Dust Source Shut-down?
Sahel Drying?
Indian Summer Monsoon
West African Monsoon Shift
Change in ENSO Amplitude or Shift in Location
Amazon Rainforest Dieback
Tropical Coral Reefs?
Marine Biological Carbon Pump?
Instability of West Antarctic Ice Sheet
Melting
Circulation Change
Biome Loss
Population Density [persons per km²]
no data
0 5 10 20 100 200 300 400 1000

RAISING THE ALARM

Evidence that tipping points are under way has mounted in the past decade. Domino effects have also been proposed.



A. Amazon rainforest
Frequent droughts

B. Arctic sea ice
Reduction in area

C. Atlantic circulation
In slowdown since 1950s

D. Boreal forest
Fires and pests changing

F. Coral reefs
Large-scale die-offs

G. Greenland ice sheet
Ice loss accelerating

H. Permafrost
Thawing

I. West Antarctic ice sheet
Ice loss accelerating

J. Wilkes Basin, East Antarctica
Ice loss accelerating

Source: T. M. Lenton *et al.*

ANALYSIS

As Climate Change Worsens, A Cascade of Tipping Points Looms

BY FRED PEARCE · DECEMBER 5, 2019

Catalogue of abrupt shifts in Intergovernmental Panel on Climate Change climate models

PNAS,2015

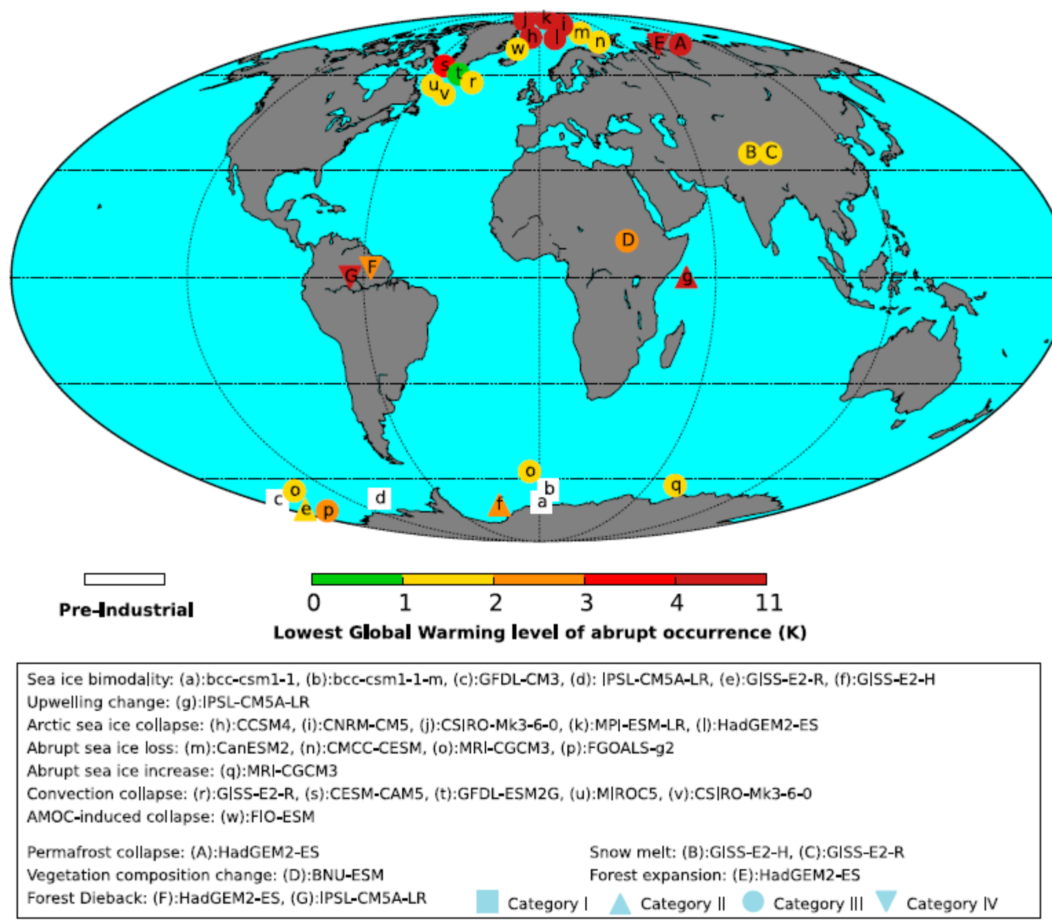


Fig. 1. Geographical location of the abrupt climate change occurrences. All 30 model cases listed in Table 1 are depicted. Of the 41 abrupt shifts, when regarding similar events for different simulations by the same climate model, this reduces to 30 distinct model cases. Marker color indicates the lowest global warming level, at which the abrupt change occurs, and the shape indicates category.

Future Climate Surprises
by Tim Lenton

Chapter 17 in

The future of World's Climate

Ann Henderson-Sellers and Kendal Mcguffie eds, Elsevier,2012

Risk = Probability of occurrence X Impact of event

A high impact event with low probability

is as important as

a low impact event with high probability

CONCLUSION

- **Earth's climate can change rapidly**
- **A cascade of tipping points can trigger rapid climate change**
- **Rapid climate change is a low-probability but high impact event**
- **The 1.5 C limit proposed in the Paris agreement is based on abundant caution**

NOBEL PRIZE IN CHEMISTRY 1995

Photo from the Nobel Foundation archive.

Paul J. Crutzen

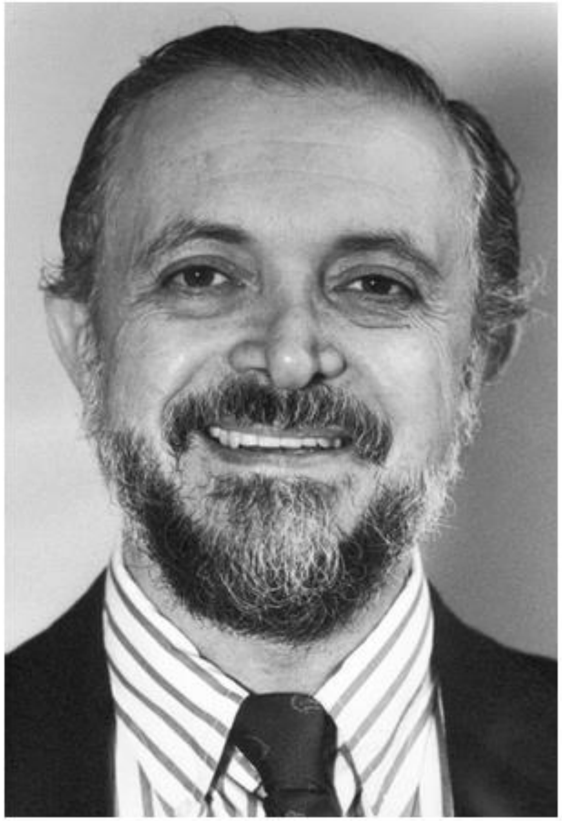
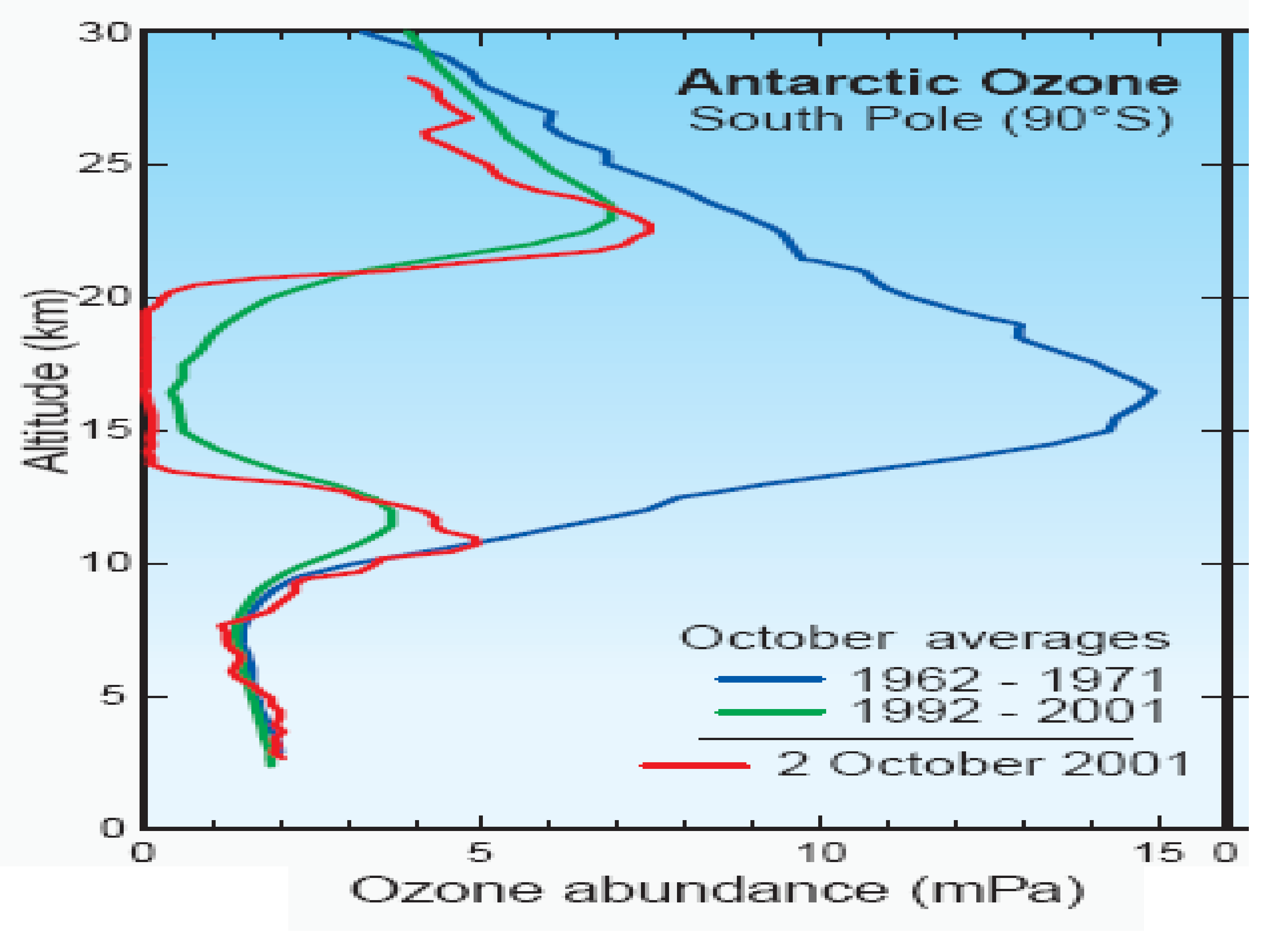


Photo from the Nobel Foundation archive.

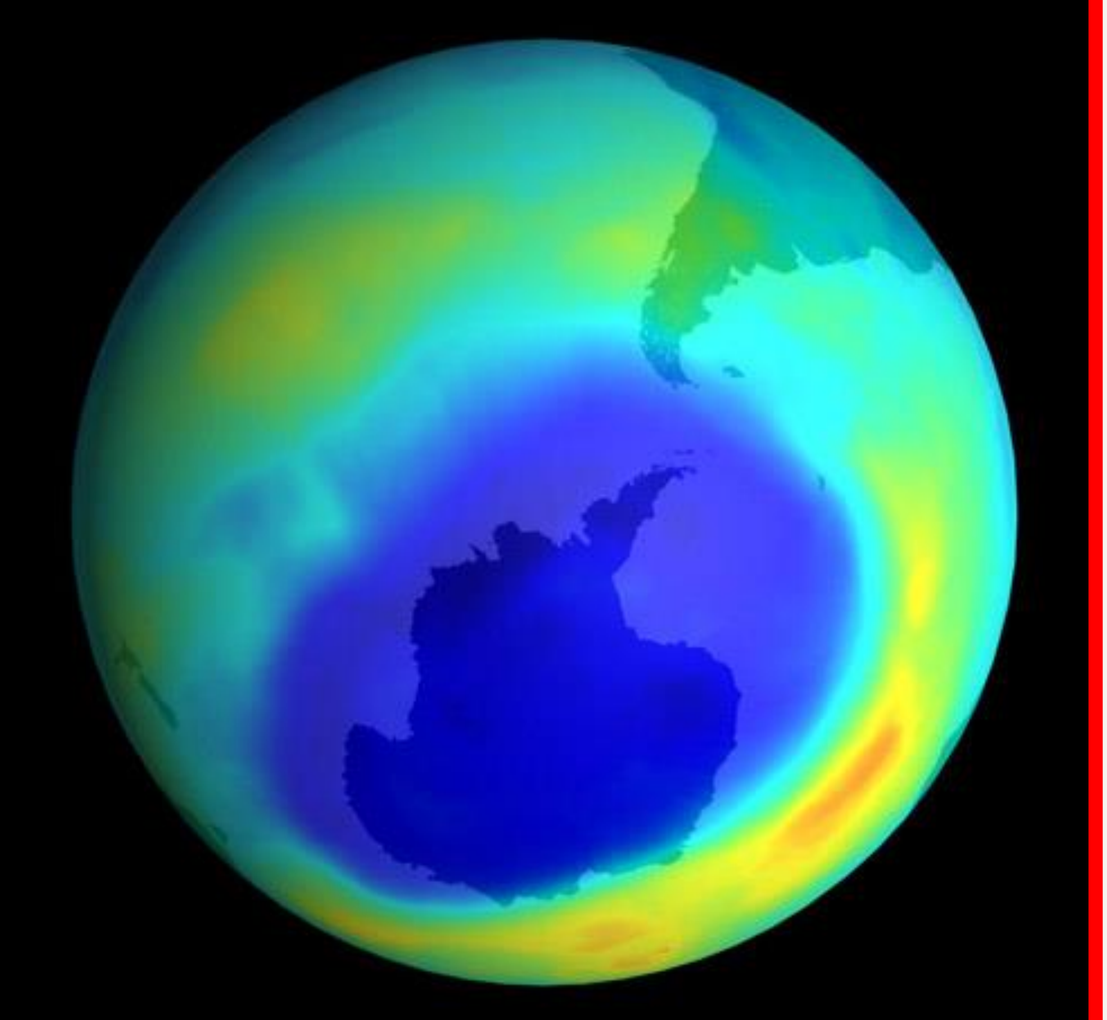
Mario J. Molina

Photo from the Nobel Foundation archive.

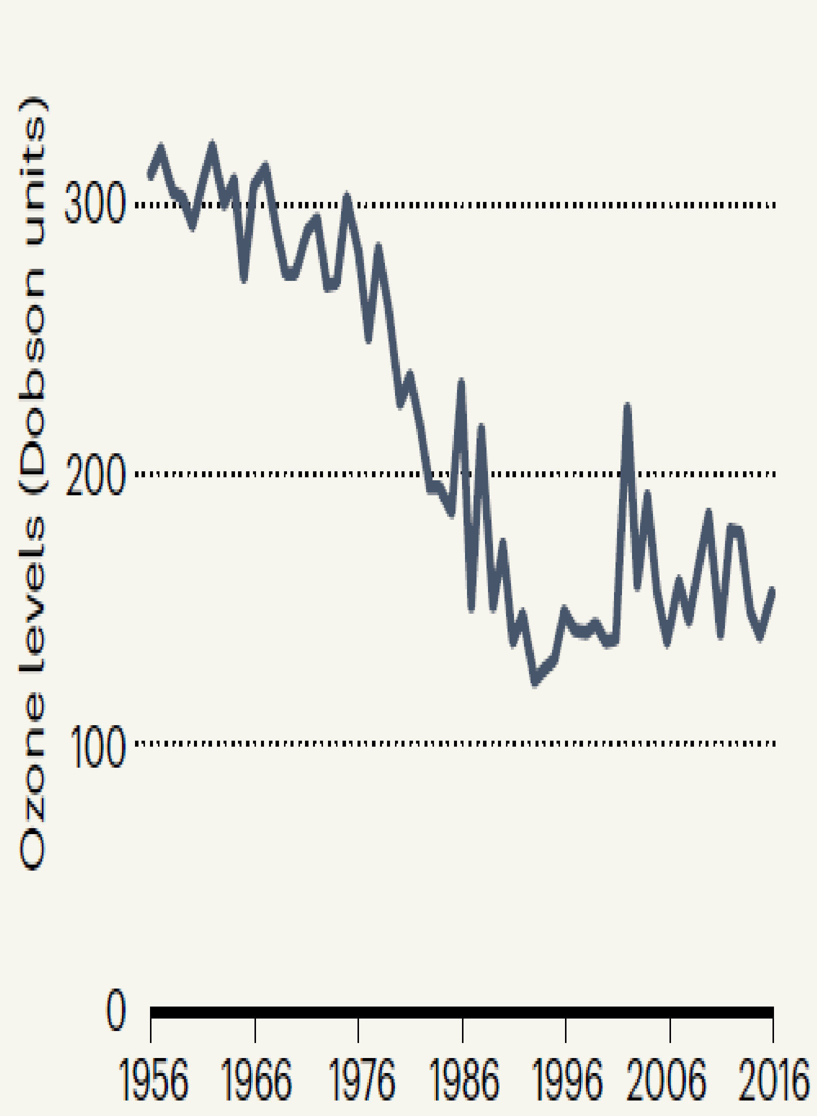
F. Sherwood Rowland



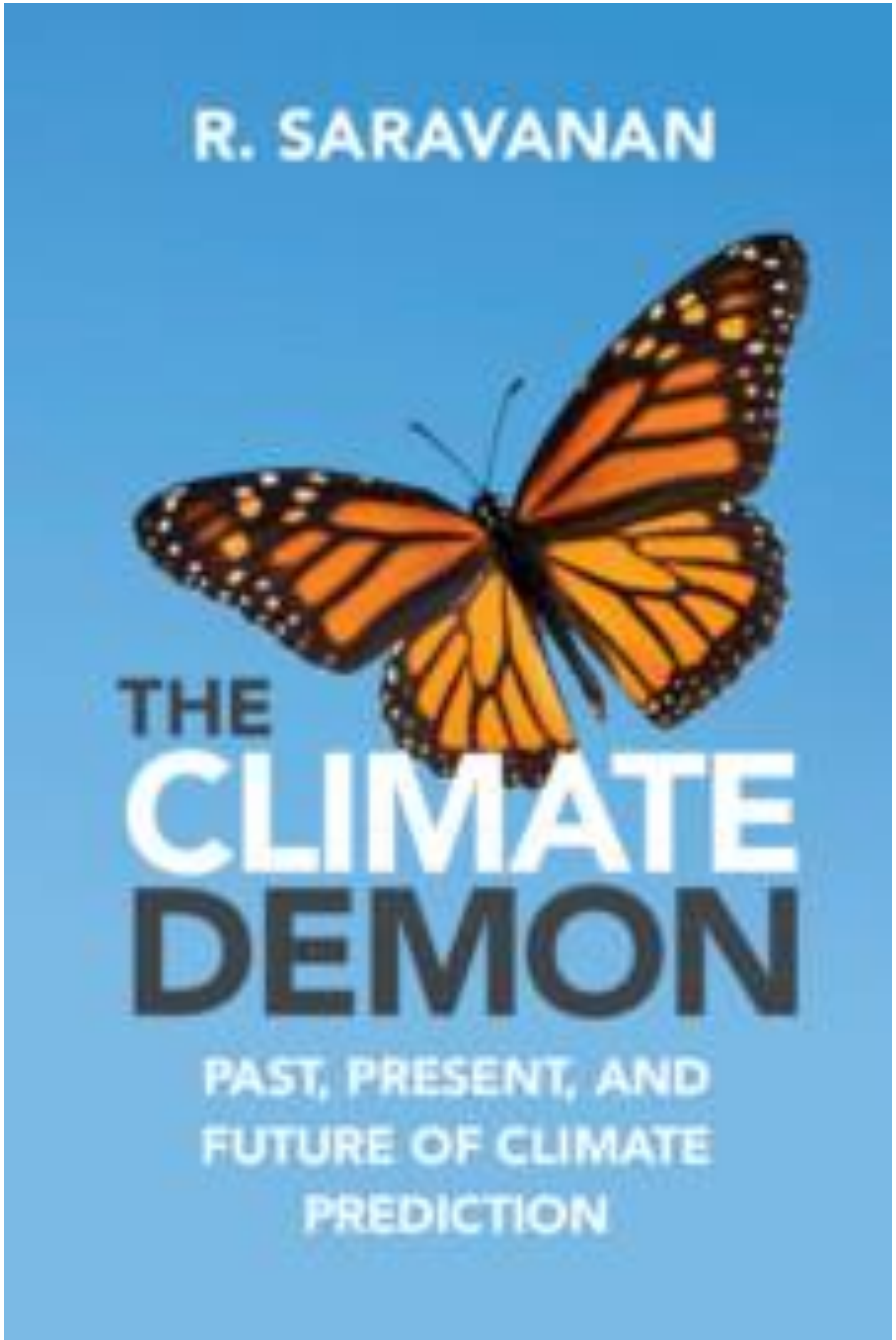
Antarctic Ozone
South Pole (90°S)
October averages
1962 - 1971
1992 - 2001
2 October 2001
Altitude (km)
0
5
10
15
20
25
30
0
5
10
15
0
Ozone abundance (mPa)

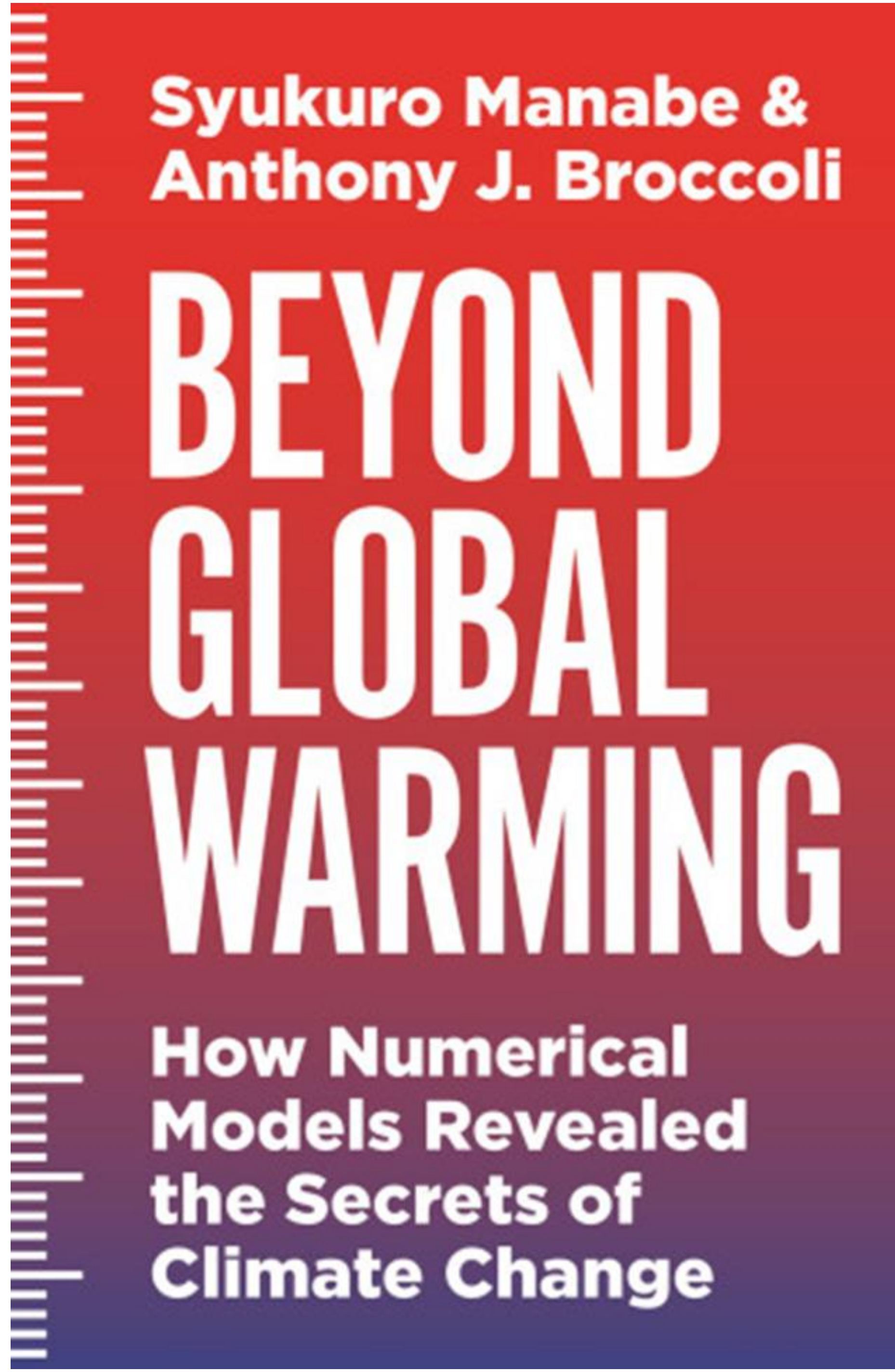


Antarctic ozone hole at its record size, September 10, 2000. Image credit: NASA



One Dobson Unit is the number of molecules of ozone that would be required to create a layer of pure ozone 0.01 millimeters thick at a temperature of 0 degrees Celsius and a pressure of 1 atmosphere


R. SARAVANAN
THE CLIMATE DEMON
PAST, PRESENT, AND FUTURE OF CLIMATE PREDICTION


Syukuro Manabe & Anthony J. Broccoli
BEYOND GLOBAL WARMING
How Numerical Models Revealed the Secrets of Climate Change

PERIODS ASSOCIATED TO THE MAIN TERMS

IN THE ANALYTICAL EXPANSIONS OF

PRECESSION

N	Ampl.	Period (years)
1.	0.0186080	23716
2.	0.0162752	22428
3.	−0.0130066	18976
4.	0.0098883	19155

OBLIQUITY

N	Ampl. (")	Period (years)
1.	−2462.22	41000
2.	−857.32	39730
3.	−629.32	53615
4.	−414.28	40521
5.	−311.76	28910

ECCENTRICITY

N	Ampl.	Period (years)
1.	0.011029	412885
2.	−0.008733	94945
3.	−0.007493	123297
4.	0.006724	99590
5.	0.005812	131248
6.	−0.004701	2305441

Scale and Scaling in the Climate System

Shaun Lovejoy[1], M. Crucifix[2] and A. de Vernal[3]

Montreal, Canada, 5-7 October 2015

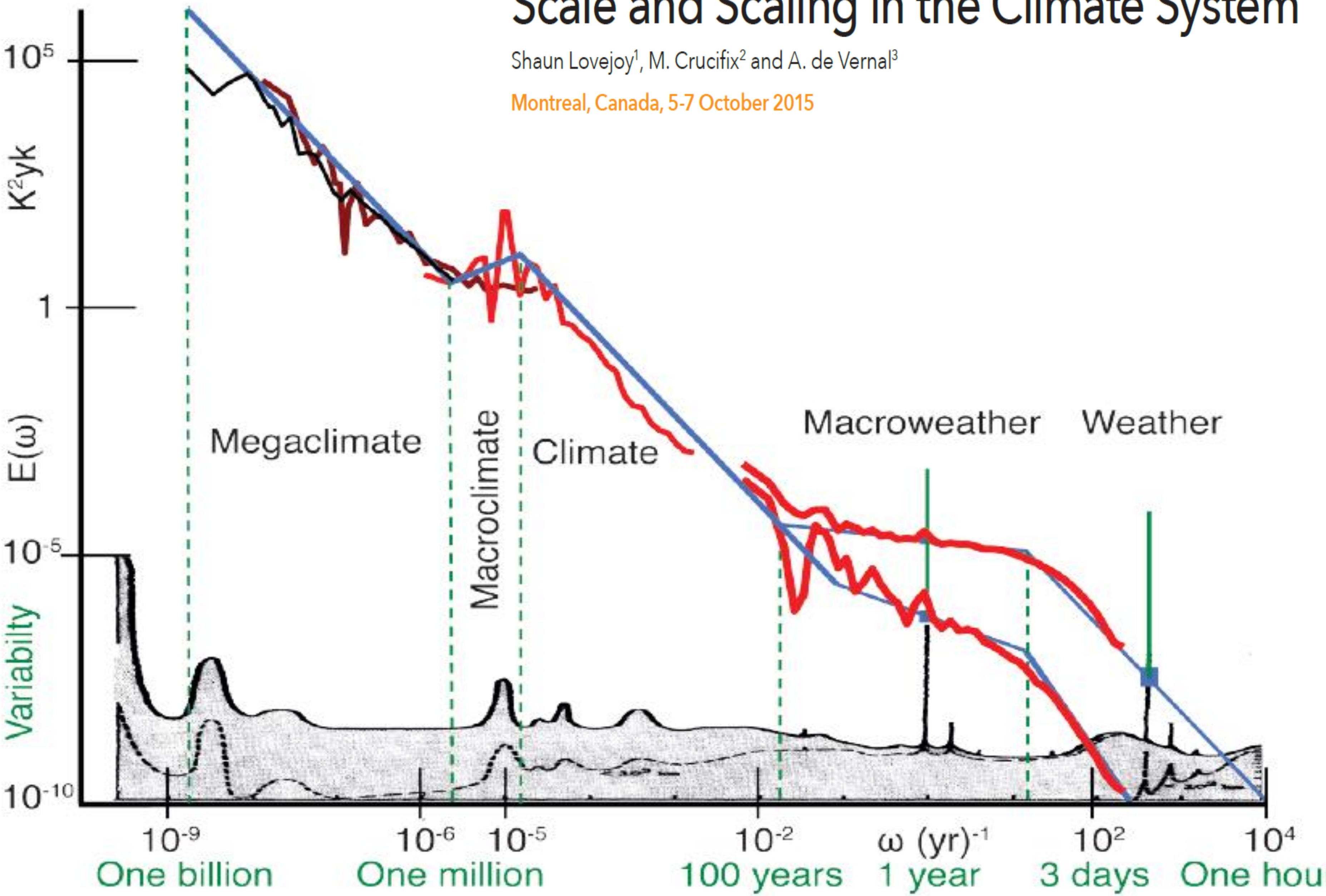


Figure 1: The temperature spectrum (E(ω)) giving the variance per interval of frequency (ω). The bottom (grey) is M. Mitchell's "educated guess" showing the still dominant view of a fairly flat (white noise) "background"