The Quantum Mechanics of Global Warming

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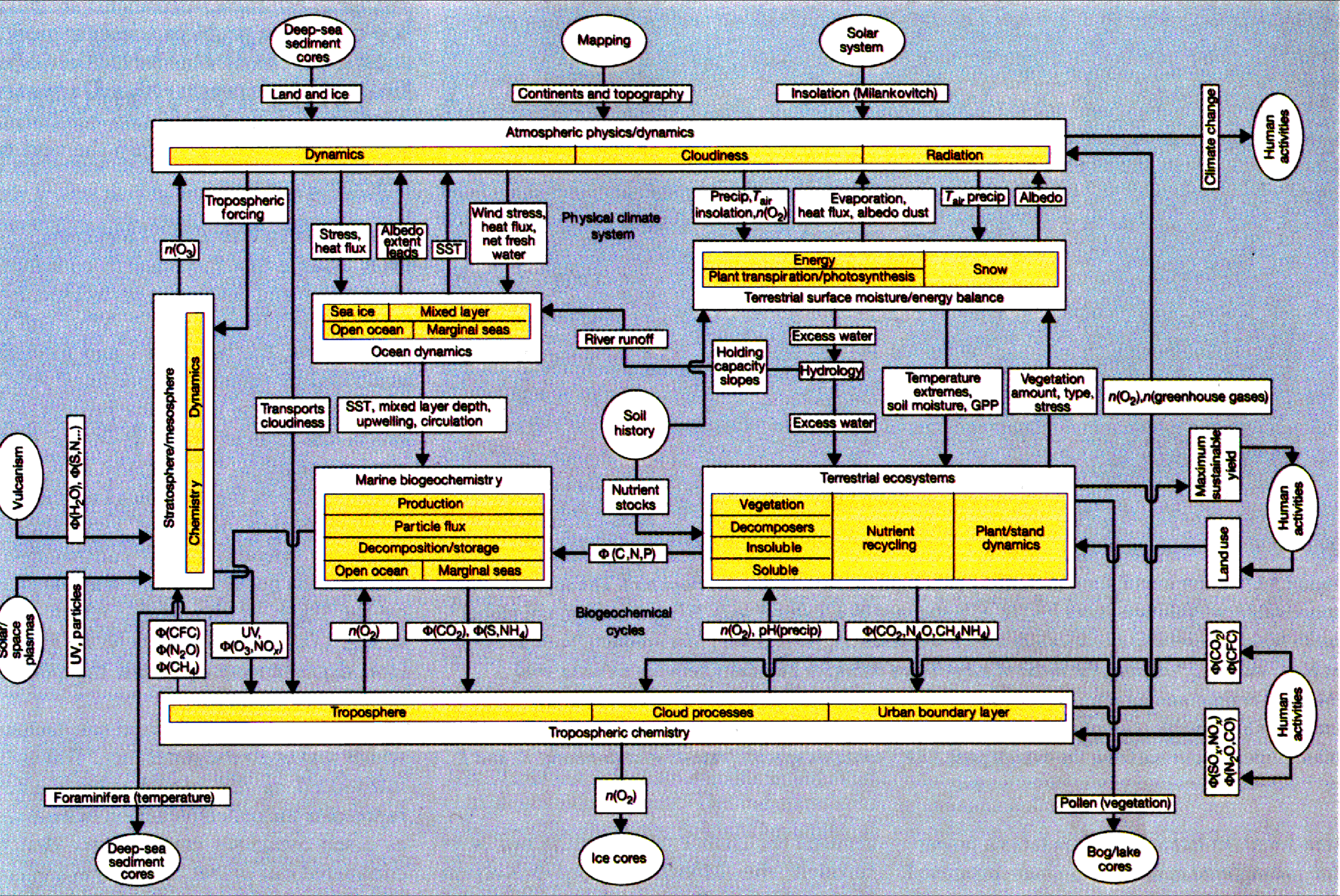
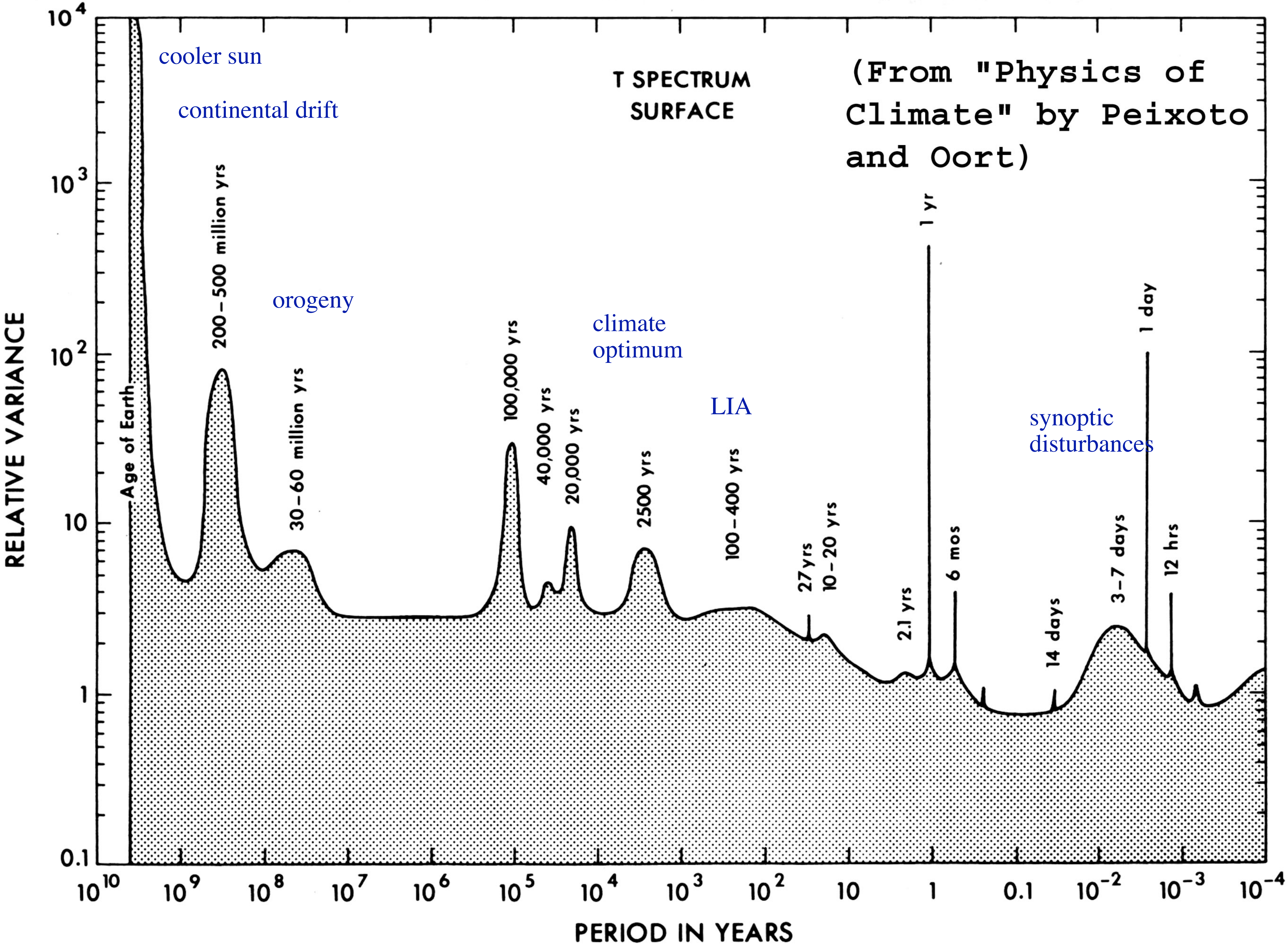
Richardson's Human Weather Computer (1917 --1922)

"Lewis Fry Richardson's imaginary `forecast factor' would have employed some 64,000 human computers to keep up with the pace of the weather, The workers sit in tiers inside a great spherical theater; the director, atop a pedestal in the middle, shines a beam of light on those places where the calculation is getting ahead or falling behind." [Brian Hayes, *American Scientist* **80**, 10 -- 14 (2001).]


Deep-sea sediment cores
Mapping
Solar system
Land and ice
Continents and topography
Insolation (Milankovitch)
Atmospheric physics/dynamics
Dynamics
Cloudiness
Radiation
Climate change
Human activities
Tropospheric forcing
$n(O_3)$
Stress, heat flux
Albedo extent leads
SST
Wind stress, heat flux, net fresh water
Physical climate system
Precip, T_{air} insolation, $n(O_2)$
Evaporation, heat flux, albedo dust
T_{air} precip
Albedo
Energy
Plant transpiration/photosynthesis
Snow
Terrestrial surface moisture/energy balance
Sea ice
Mixed layer
Open ocean
Marginal seas
Ocean dynamics
River runoff
Holding capacity slopes
Excess water
Hydrology
Excess water
Temperature extremes, soil moisture, GPP
Vegetation amount, type, stress
$n(O_2)$, n(greenhouse gases)
Stratosphere/mesosphere
Dynamics
Chemistry
Transports cloudiness
SST, mixed layer depth, upwelling, circulation
Soil history
Vulcanism
$\Phi(H_2O)$, $\Phi(S,N,..)$
Marine biogeochemistry
Production
Particle flux
Decomposition/storage
Open ocean
Marginal seas
Nutrient stocks
Terrestrial ecosystems
Vegetation
Decomposers
Insoluble
Soluble
Nutrient recycling
Plant/stand dynamics
Maximum sustainable yield
Human activities
Land use
$\Phi(C,N,P)$
Solar/space plasmas
UV, particles
$\Phi(CFC)$
$\Phi(N_2O)$
$\Phi(CH_4)$
UV, $\Phi(O_3,NO_x)$
$n(O_2)$
$\Phi(CO_2)$, $\Phi(S,NH_4)$
Biogeochemical cycles
$n(O_2)$, pH(precip)
$\Phi(CO_2,N_2O,CH_4NH_4)$
$\Phi(CO_2)$ $\Phi(CFC)$
Human activities
Troposphere
Cloud processes
Urban boundary layer
Tropospheric chemistry
$\Phi(SO_x,NO_x)$ $\Phi(N_2O,CO)$
Foraminifera (temperature)
$n(O_2)$
Pollen (vegetation)
Deep-sea sediment cores
Ice cores
Bog/lake cores



T SPECTRUM
SURFACE
(From "Physics of Climate" by Peixoto and Oort)
cooler sun
continental drift
orogeny
climate optimum
LIA
synoptic disturbances
Age of Earth
200–500 million yrs
30–60 million yrs
100,000 yrs
40,000 yrs
20,000 yrs
2500 yrs
100–400 yrs
27 yrs
10–20 yrs
2.1 yrs
1 yr
6 mos
14 days
3–7 days
1 day
12 hrs
RELATIVE VARIANCE
PERIOD IN YEARS

Outline

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- Quantum Mechanics #1: blackbody radiation

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- QM #2: Why we aren’t freezing

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  - Coriolis Force
  - Stratification & Differential Heating
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- Ecosystems and feedbacks

Crisis in 19th Century Classical Physics

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UV Catastrophe!

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New constant of nature makes it possible to write the correct intensity.

$$\begin{aligned} \Delta I(T,\nu) &= \frac{2\pi h\nu^3}{c^2}\,\frac{1}{e^{h\nu/k_BT}-1}\,\Delta\nu \\ &\rightarrow \frac{2\pi k_BT\nu^2}{c^2}\,\Delta\nu \text{ for } k_BT \gg h\nu \\ &\rightarrow 0 \text{ for } \nu \rightarrow \infty \end{aligned}$$

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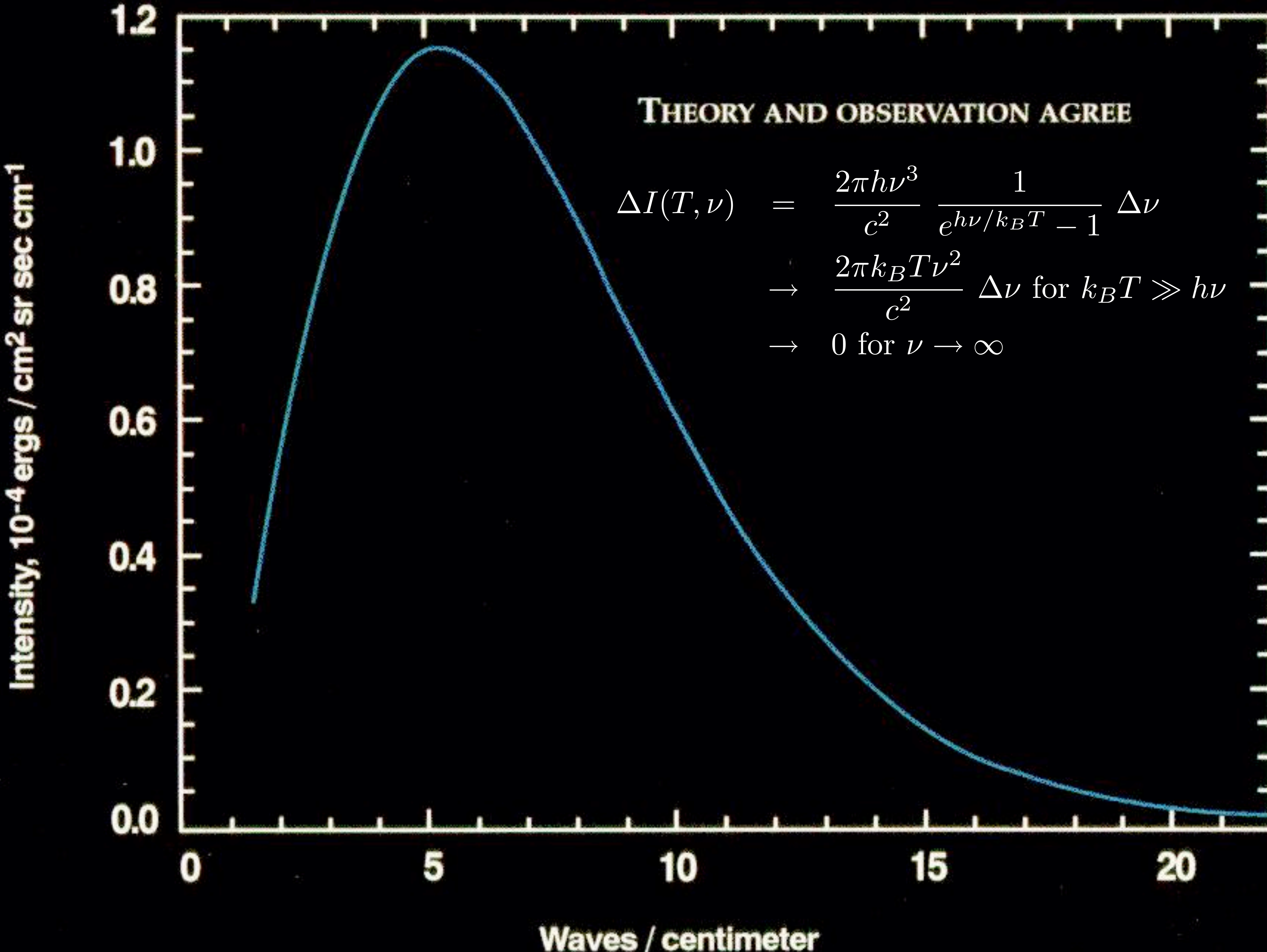
Now we can do that sum over frequency!

$$I = \sigma T^4$$
$$\sigma \equiv \frac{2\pi^5 k_B^4}{15h^3c^2} = 5.67 \times 10^{-8}\frac{W}{m^2K^4}$$

Cosmic Microwave Background Spectrum from COBE



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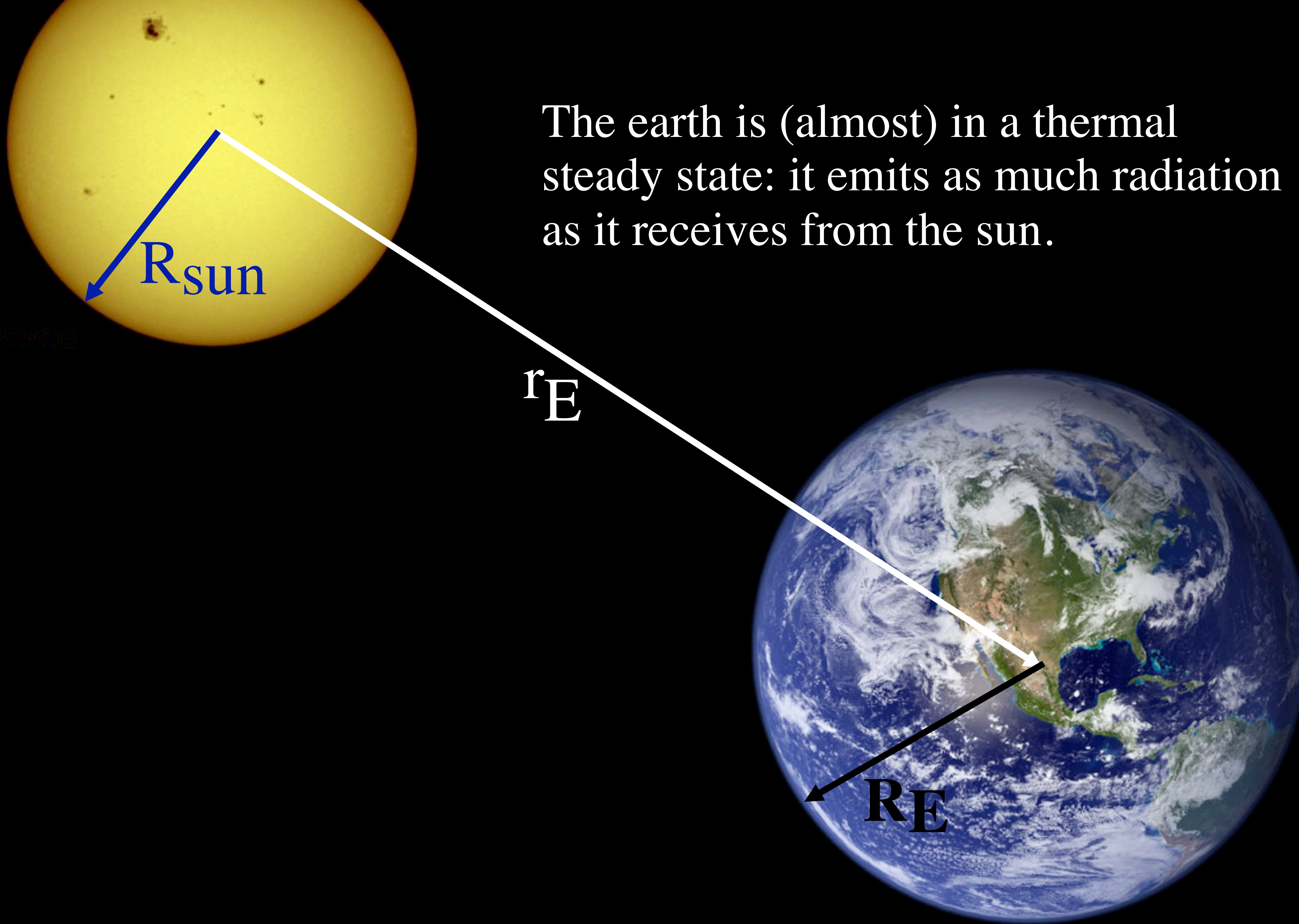
Temperature of the Earth

The earth is (almost) in a thermal steady state: it emits as much radiation as it receives from the sun.



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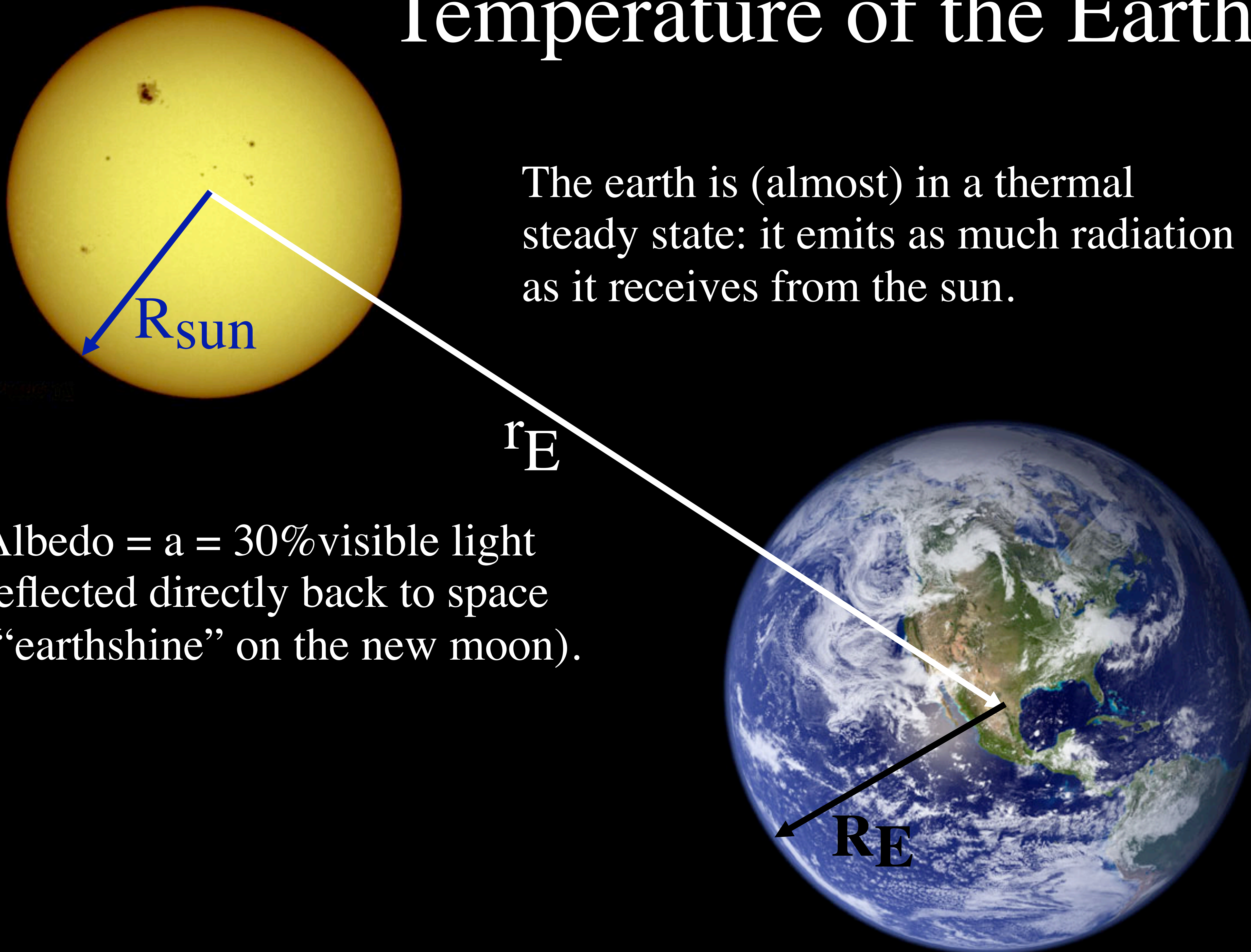

Albedo = a = 30%visible light reflected directly back to space ("earthshine" on the new moon).

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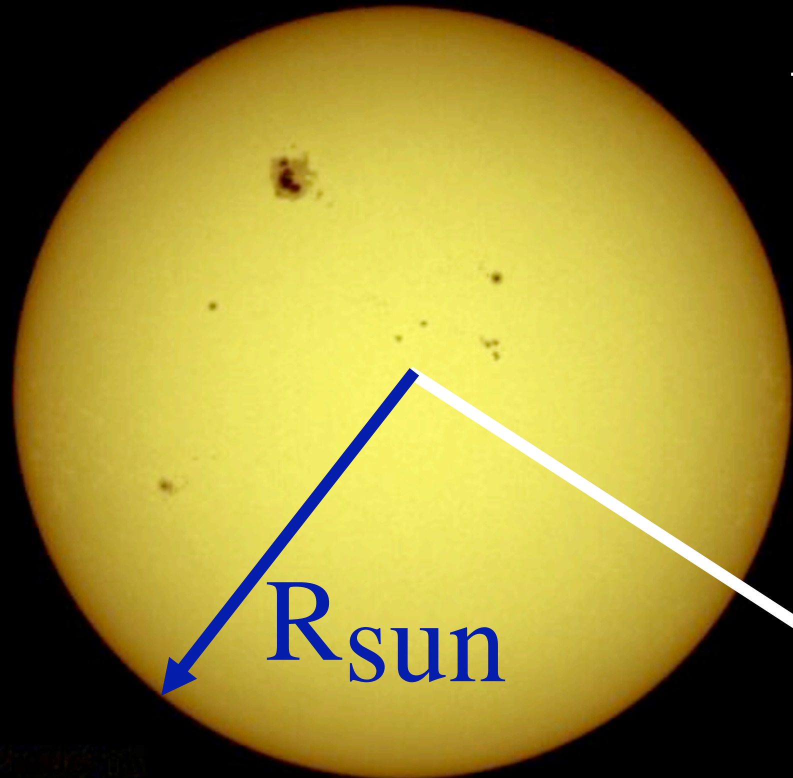

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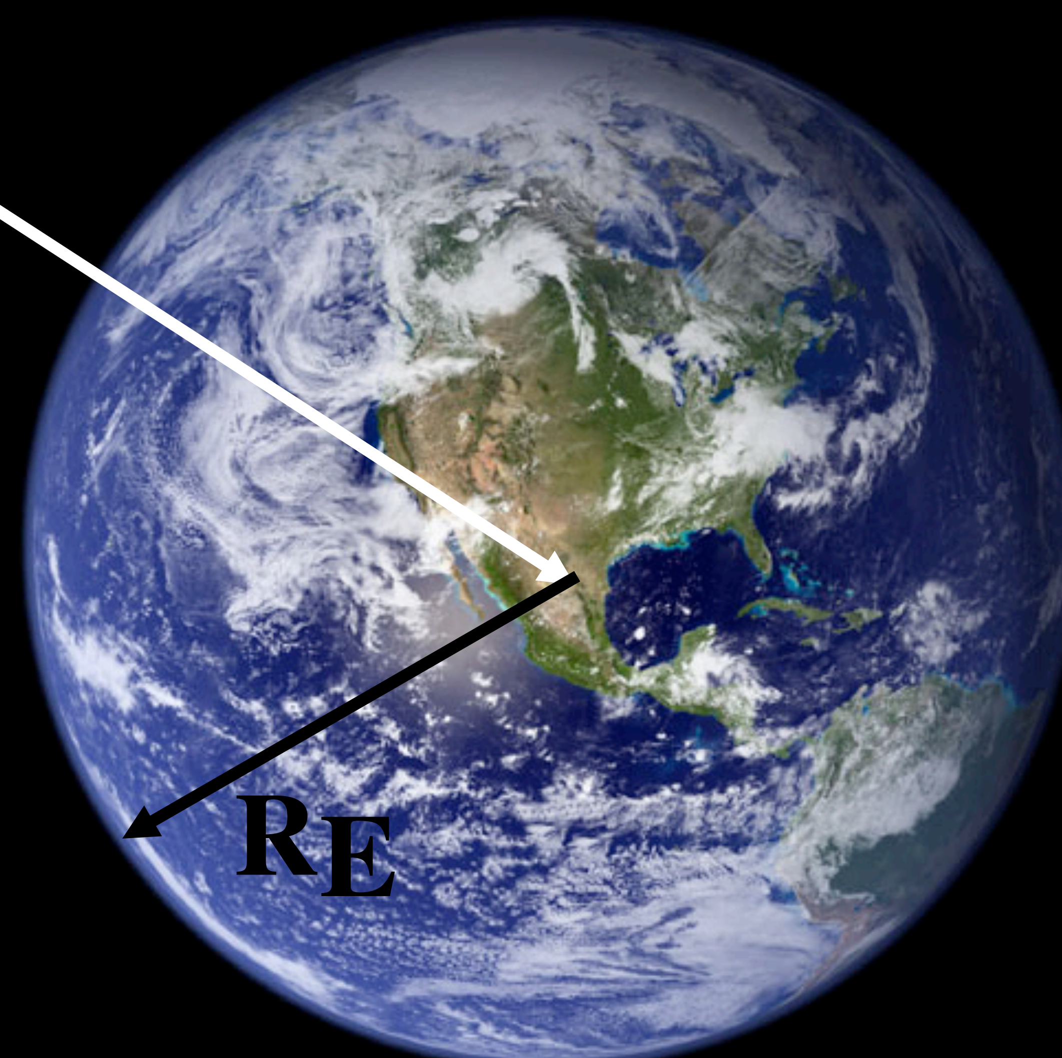

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$$fraction = \frac{\pi R_E^2}{4\pi r_E^2} \times (1 - a)$$

Energy Balance

$$\begin{aligned} Luminosity &= Area \times Intensity \\ &= 4\pi R_{sun}^2 \times \sigma T_{sun}^4 \end{aligned}$$

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Space

incoming
energy flux

outgoing
energy flux (IR)

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\begin{aligned}
r_E &= 150 \times 10^9 m \\
R_{sun} &= 6.96 \times 10^8 m \\
T_{sun} &= 5,800 K
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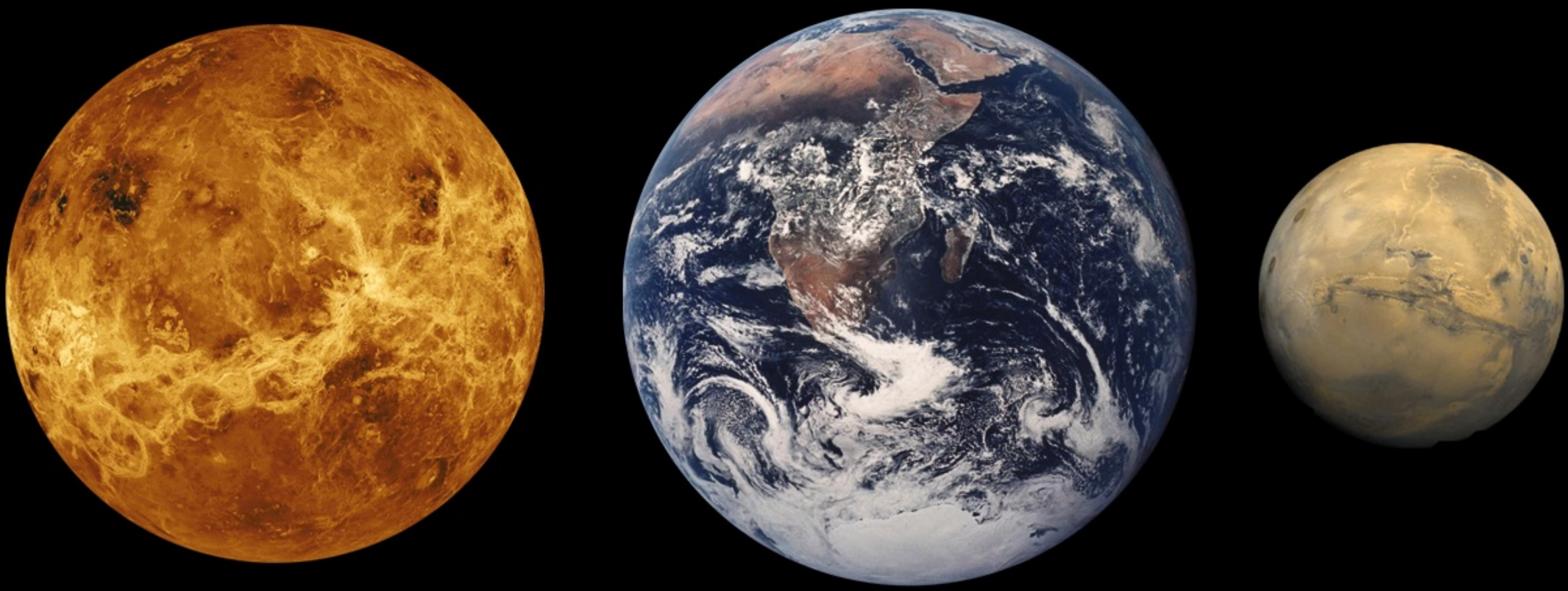
FREEZING

Terrestrial Planets



Planet	Earth
calculated temperature	-18 ^{0}C
actual temperature	15 ^{0}C
greenhouse warming	33 ^{0}C

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calculated temperature	-18 ^{0}C	-56 ^{0}C
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calculated temperature	-18 ^{0}C	-56 ^{0}C	-39 ^{0}C
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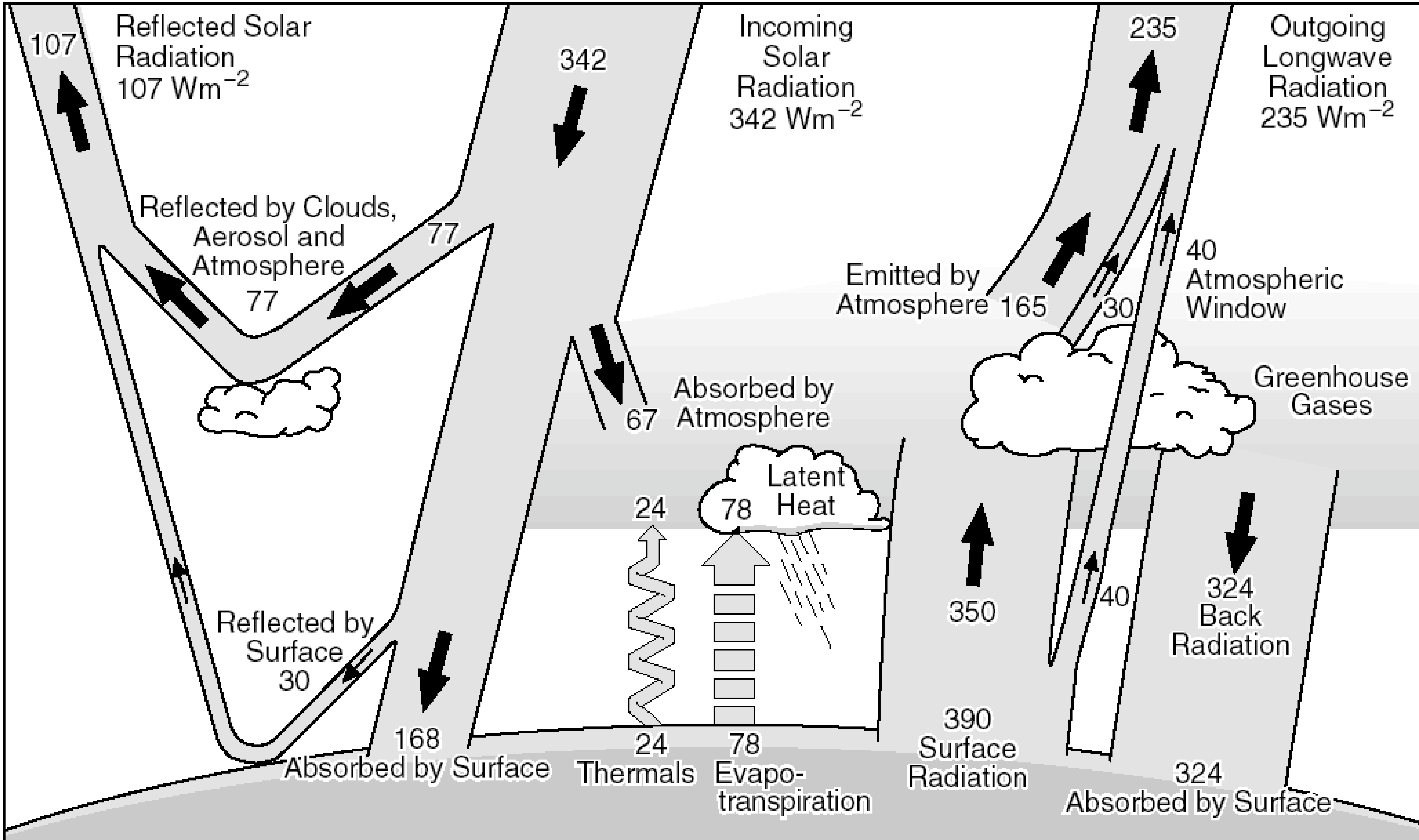
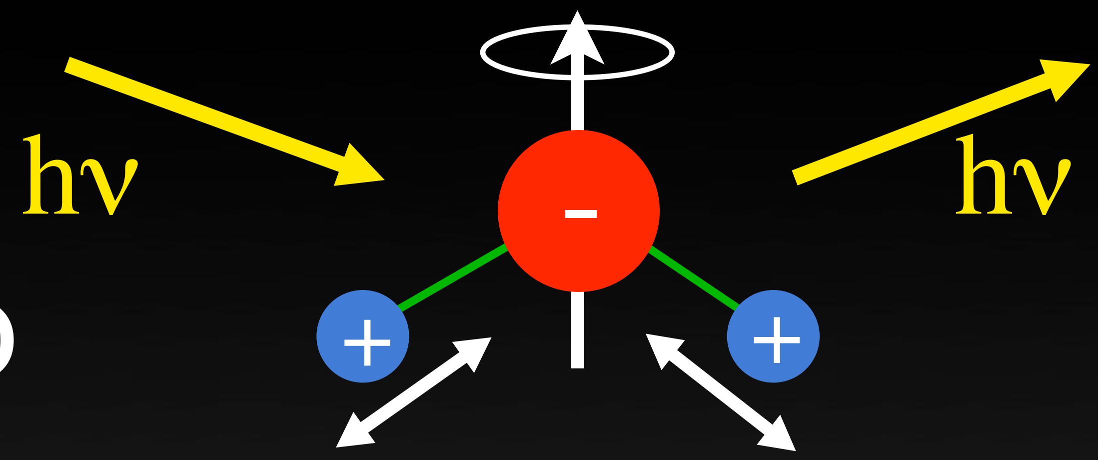
Water Vapour: 65%   Carbon Dioxide: 21%

Why We Aren't Freezing



from *Climate Change 1995: The Science of Climate Change*



H_2O

$$h\nu = E_f - E_i$$

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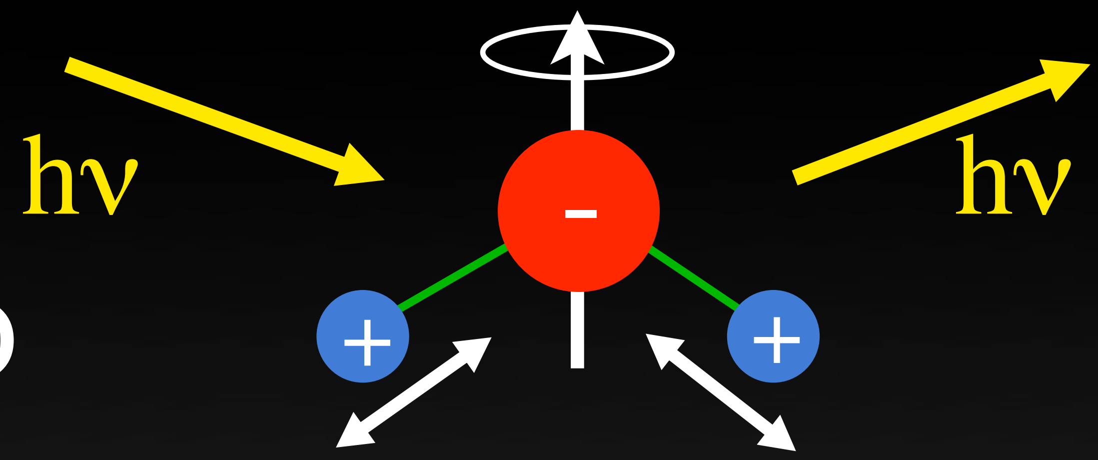

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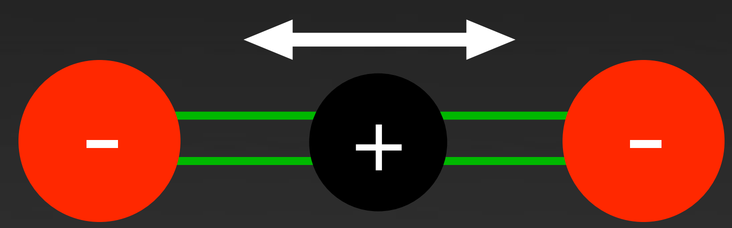
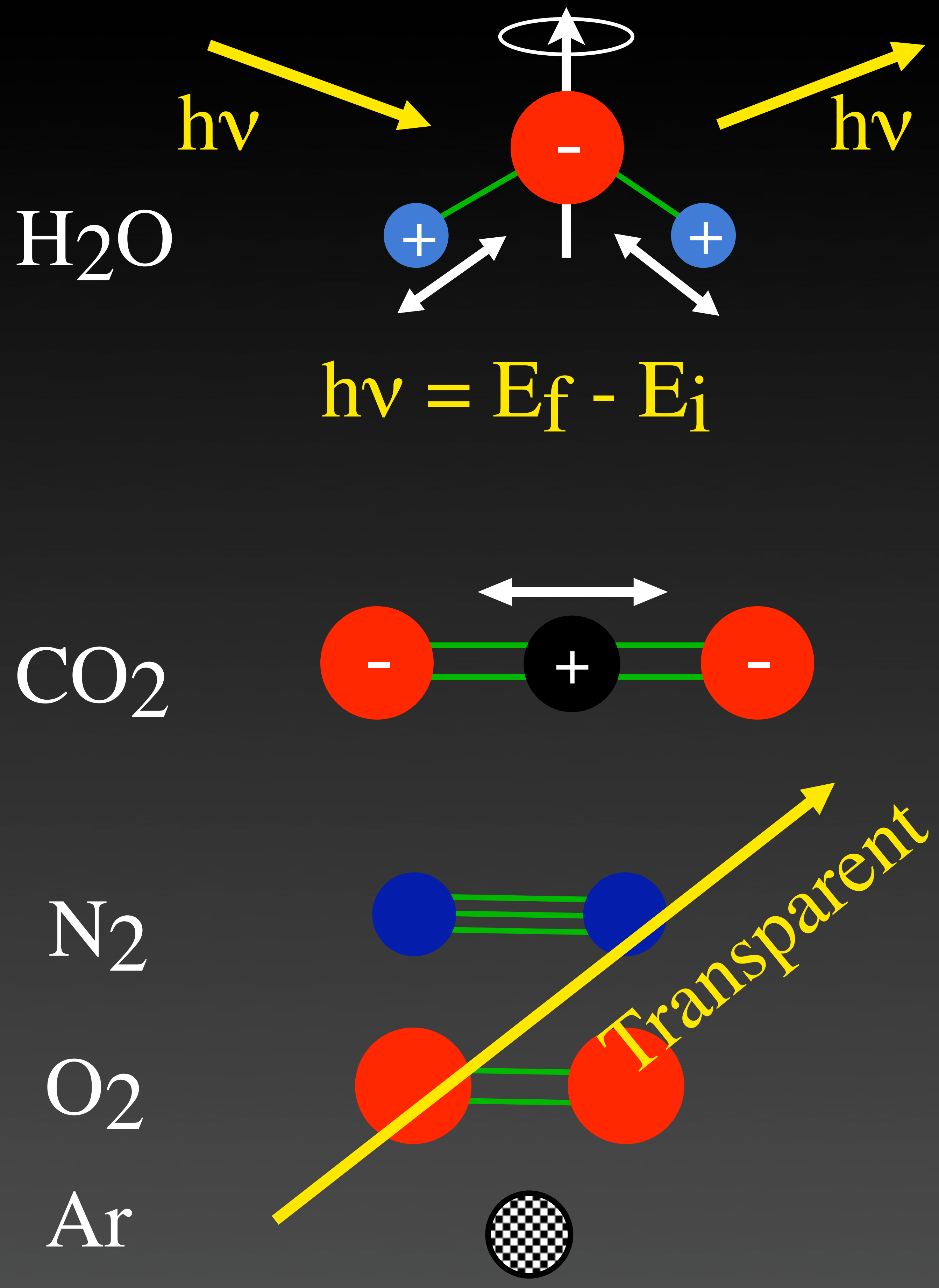
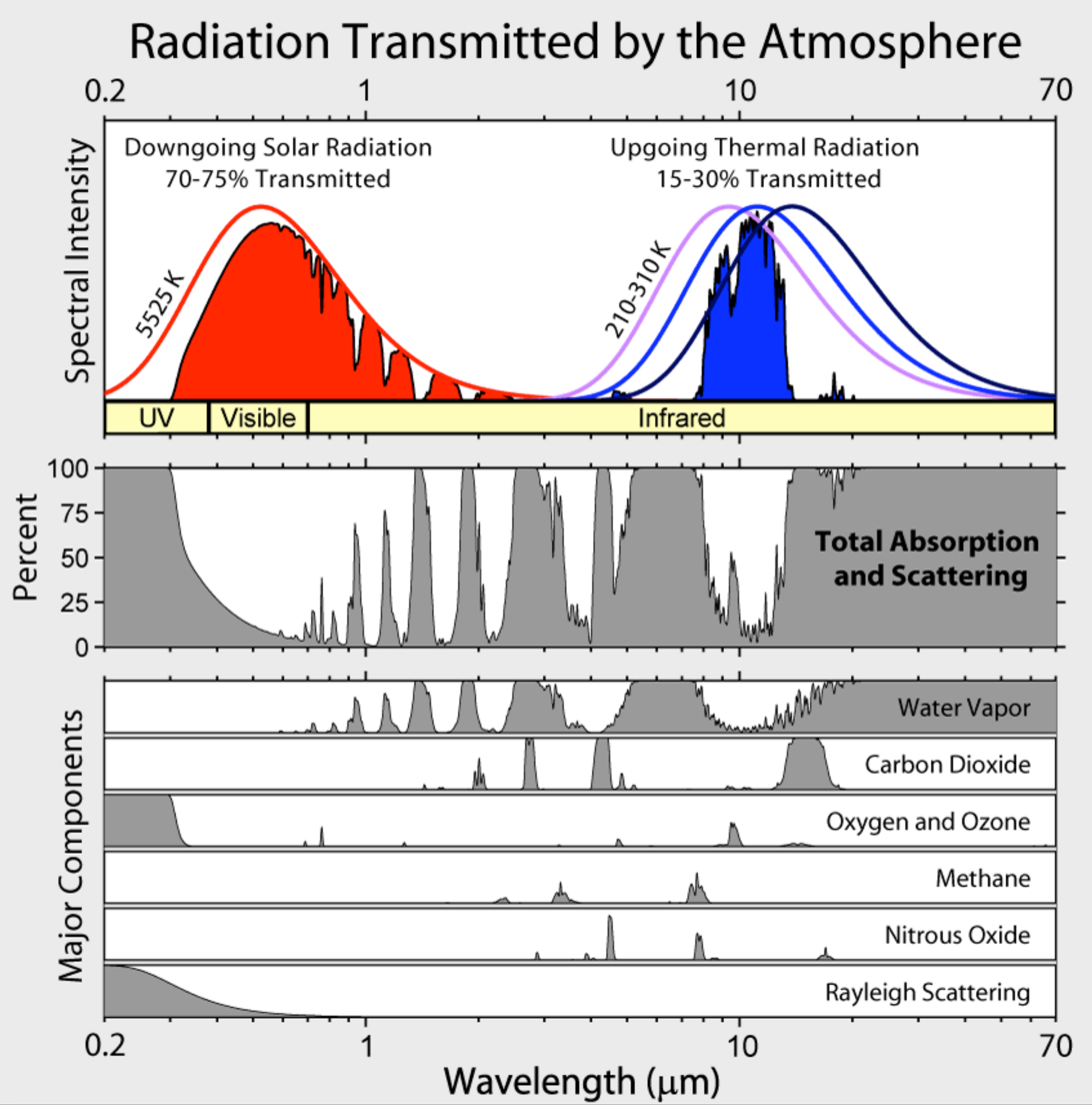
CO_2





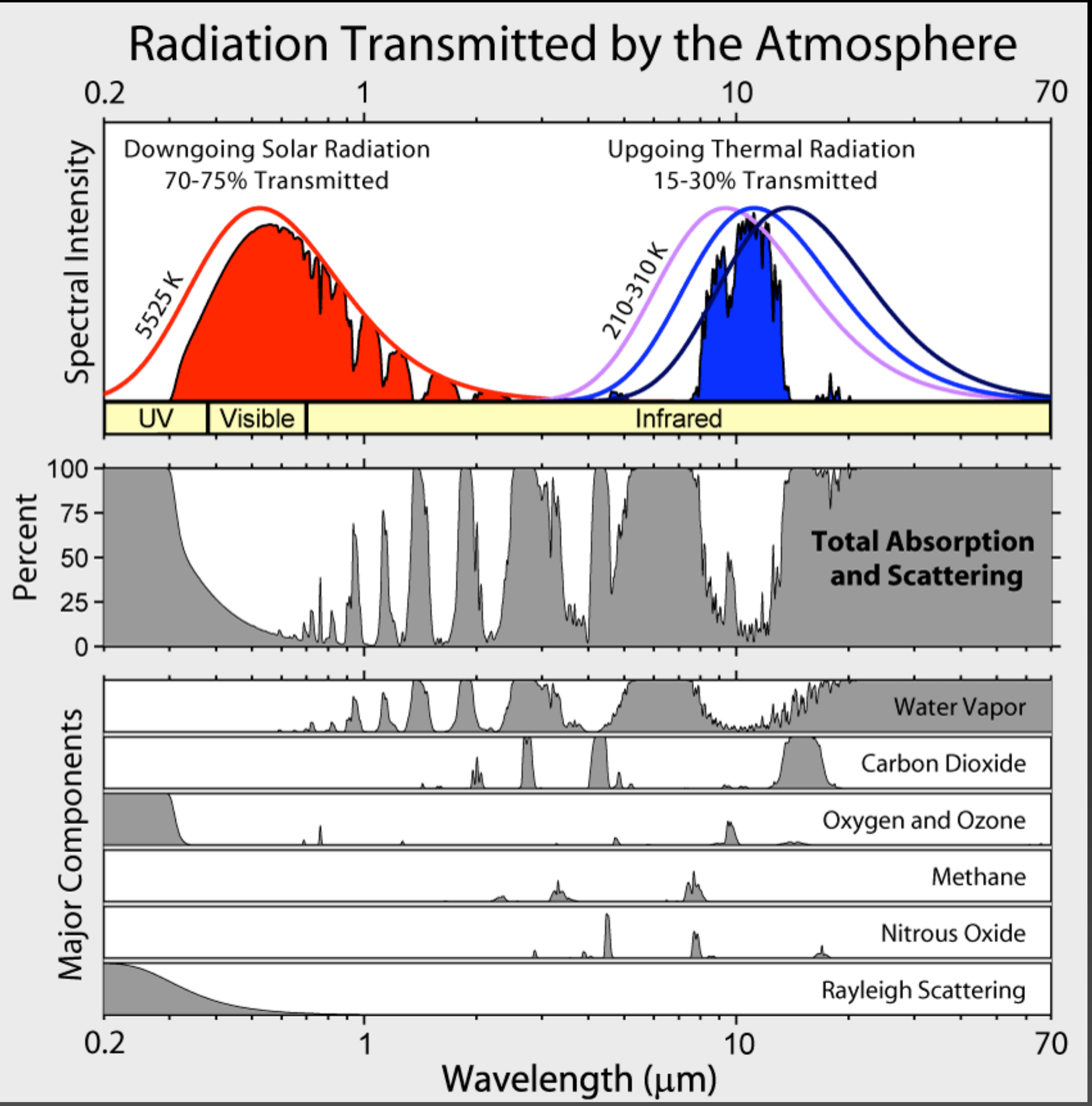
hν
hν
H_2O
-
+
+
hν = E_f - E_i
CO_2
-
+
-
N_2
O_2
Ar
Transparent



Principal greenhouse gas: water vapor

Secondary: carbon dioxide, methane, CFC's, …

Robert A. Rohde for the Global Warming Art project



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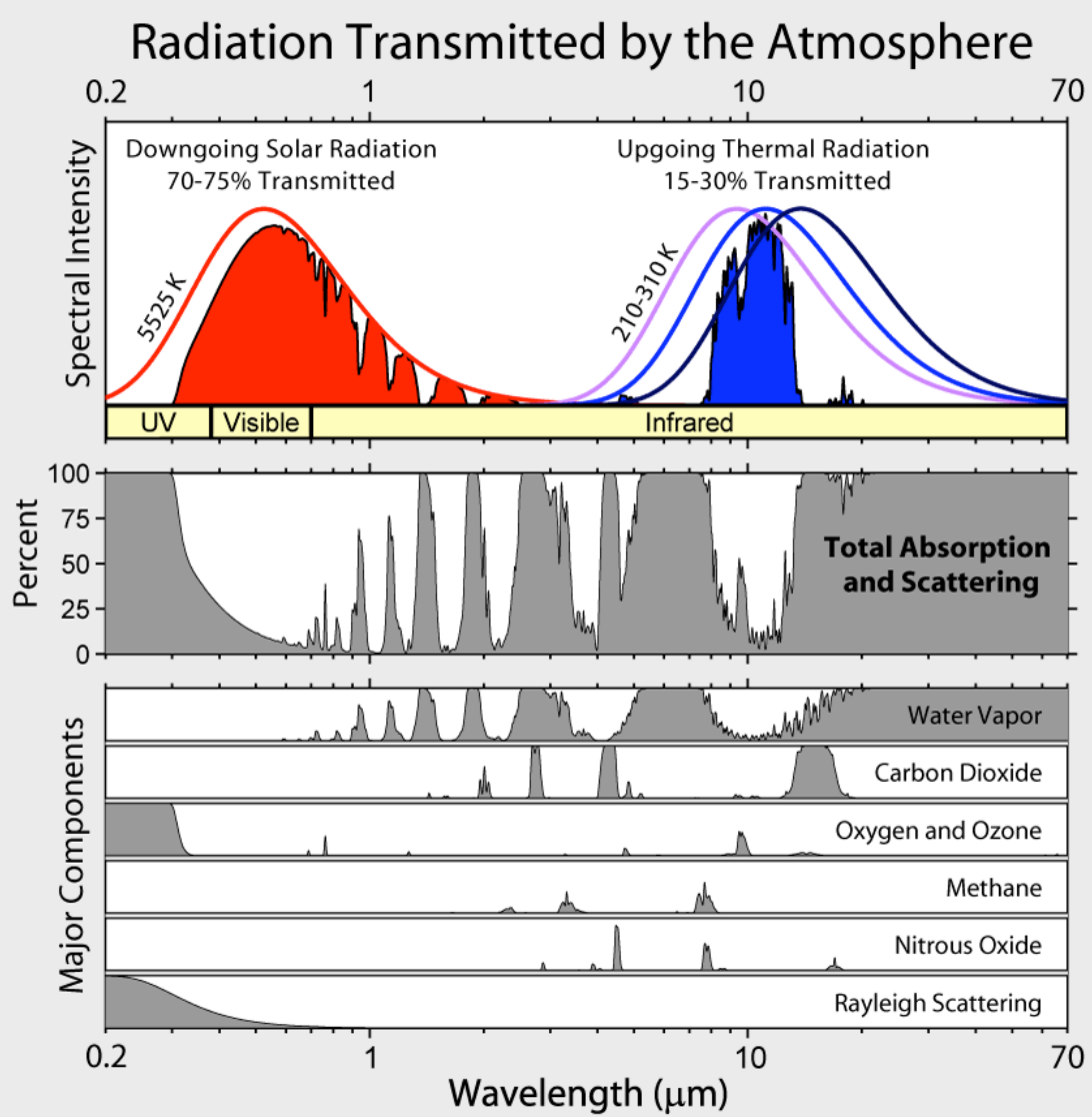

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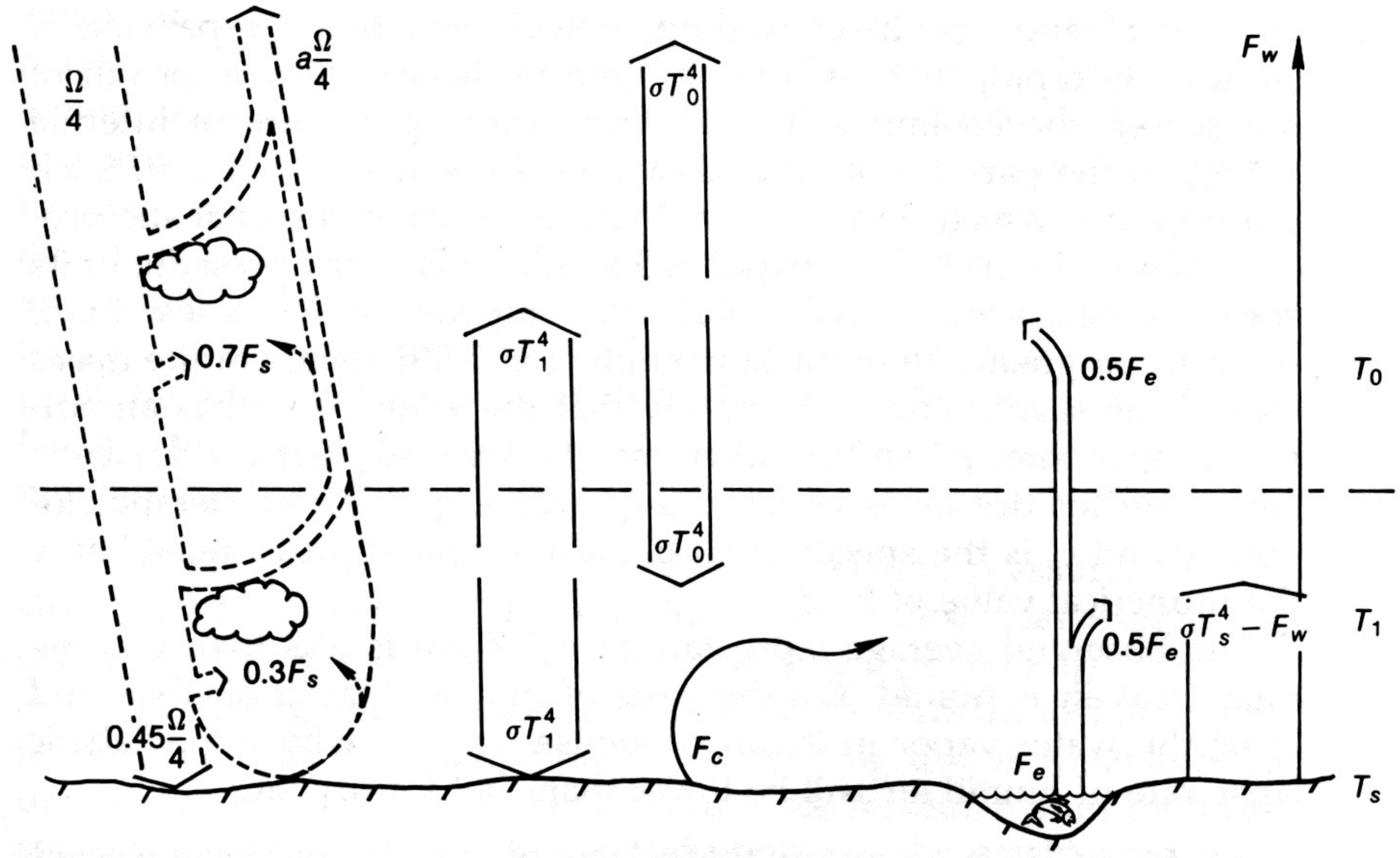
IR photons are on average absorbed and emitted about 2x on way out to space

John Harte, *Consider a Spherical Cow*



$\Omega = 1372\ W/m^2$

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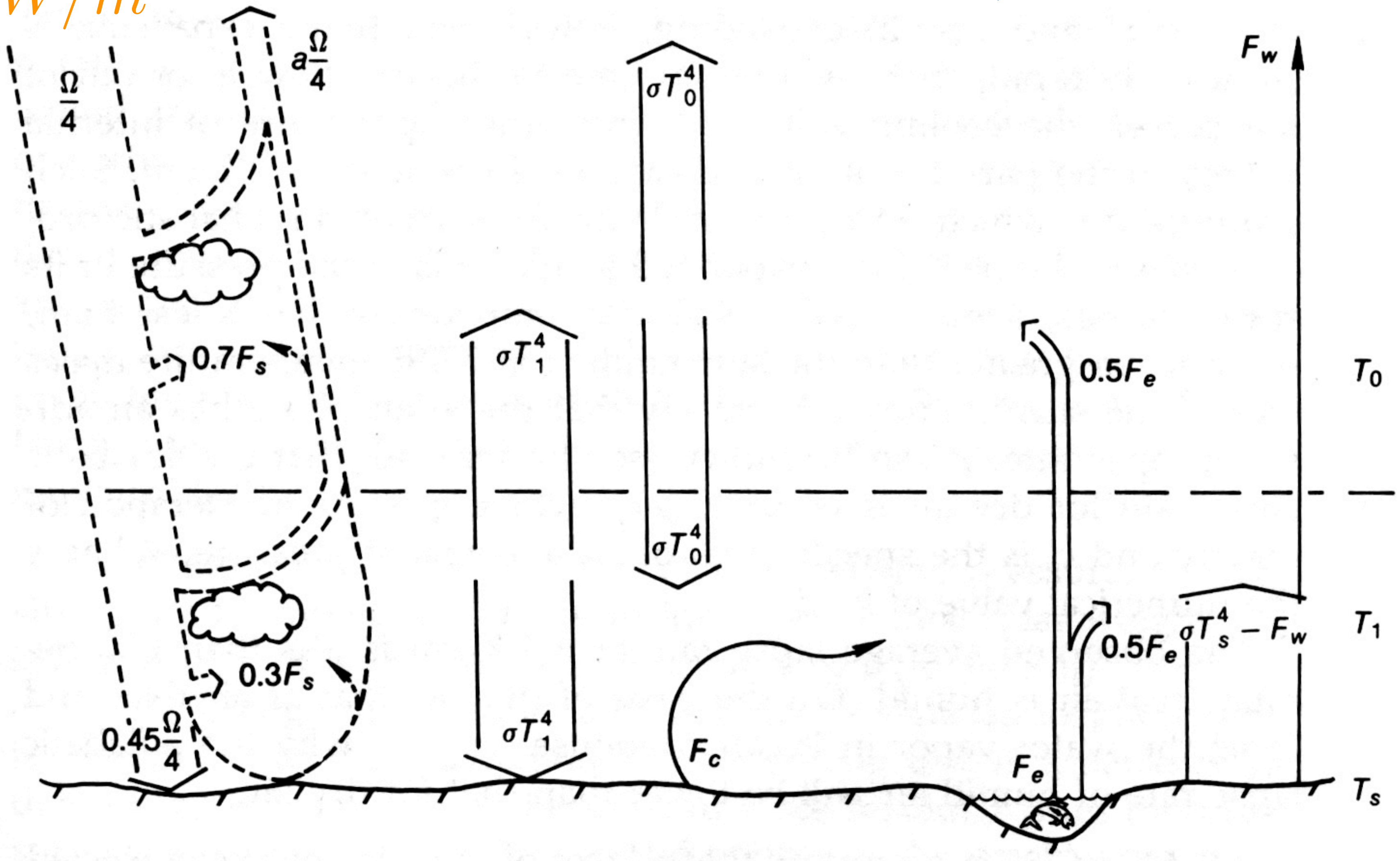

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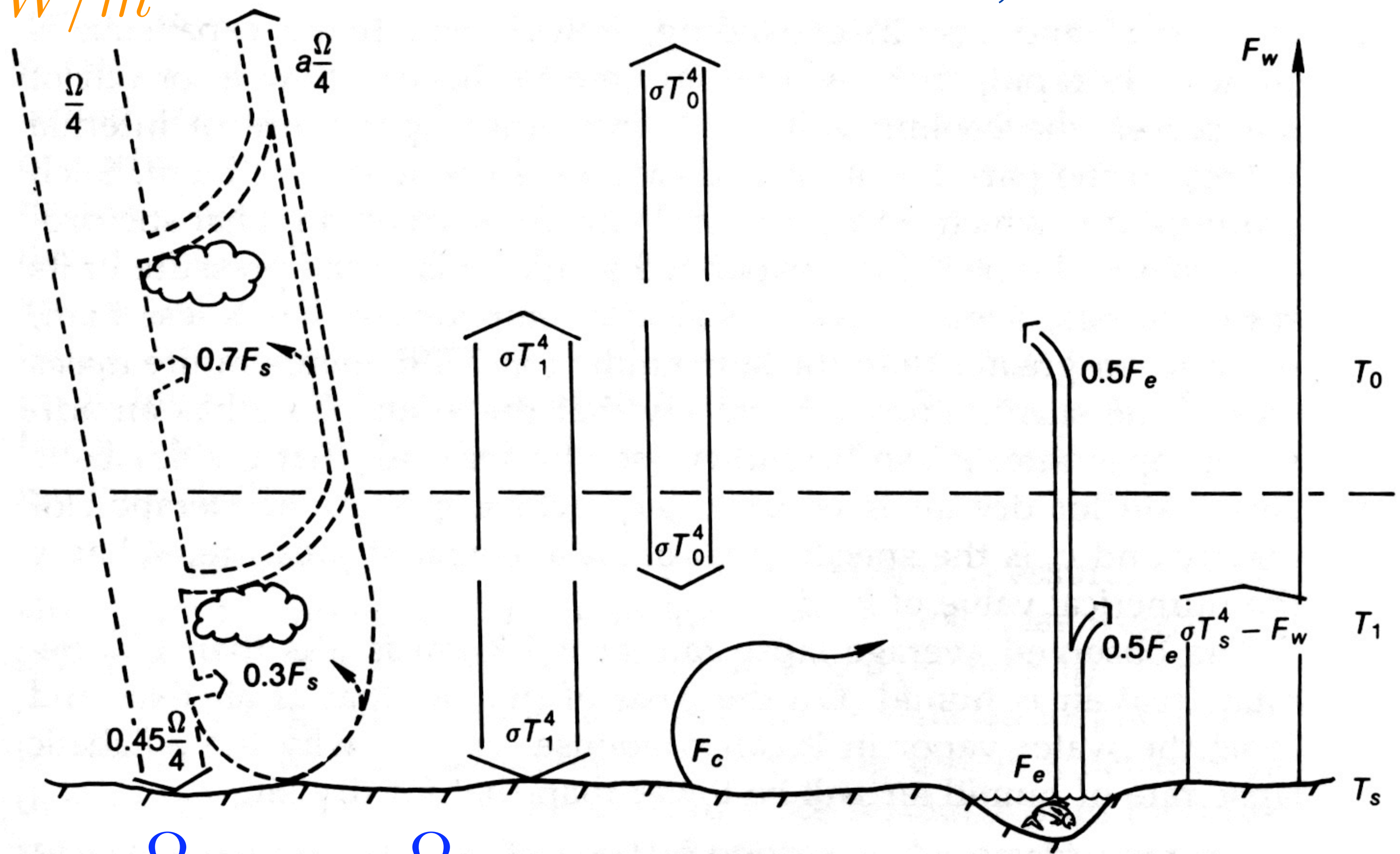

$$\begin{aligned}
\frac{\Omega}{4} &= a\frac{\Omega}{4} + \sigma T_0^4 + F_w \\
2\sigma T_0^4 &= \sigma T_1^4 + 0.5F_e + 0.7F_s \\
2\sigma T_1^4 &= \sigma T_0^4 + \sigma T_s^4 - F_w + F_c + 0.5F_e + 0.3F_s
\end{aligned}$$

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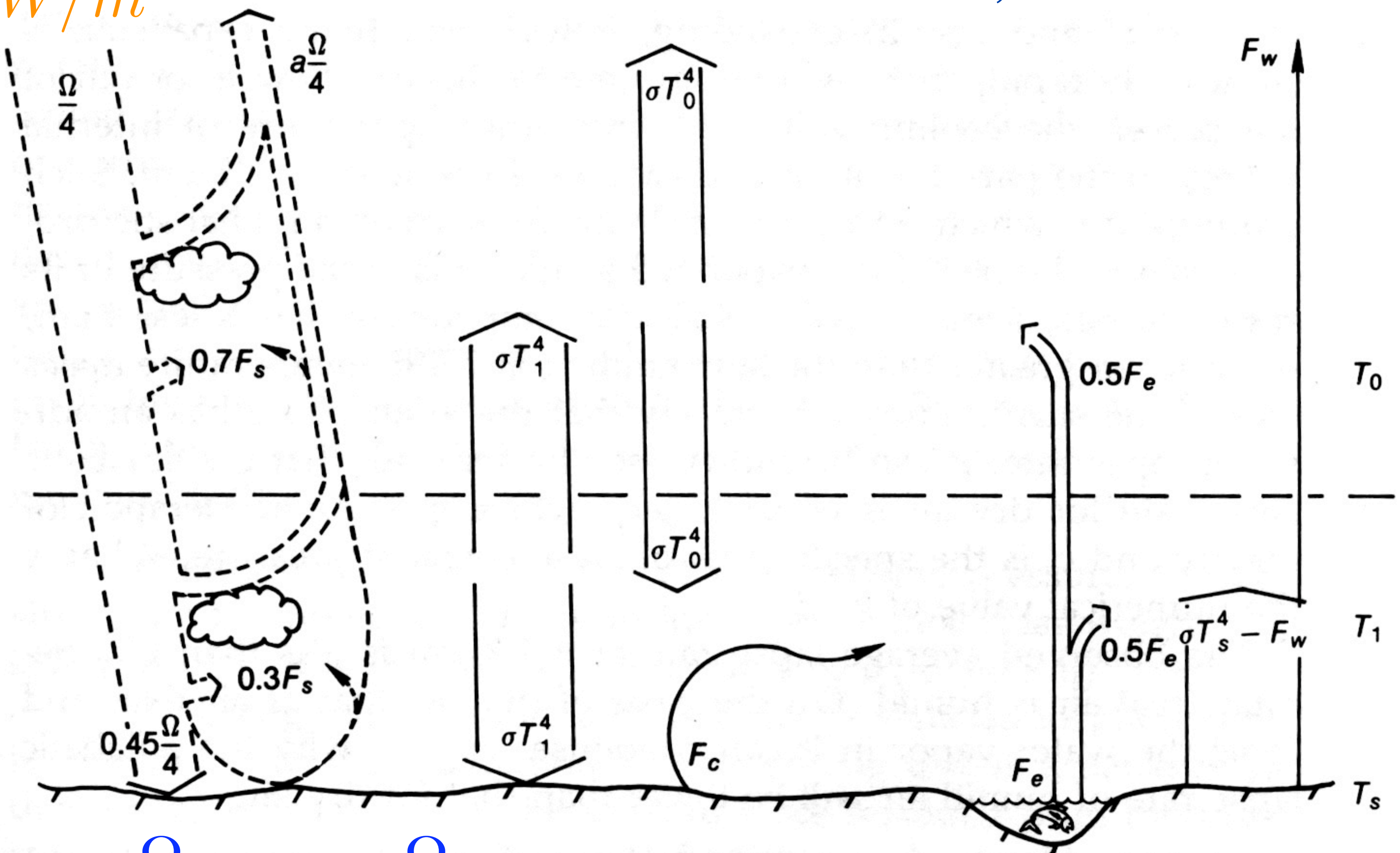

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F_s	$\approx$	$86\ W/m^2$	Solar flux absorbed by atmosphere
F_e	$\approx$	$80\ W/m^2$	Latent heat from evaporating water
F_w	$\approx$	$20\ W/m^2$	IR flux directly to space
F_c	$\approx$	$17\ W/m^2$	Convective heat transfer

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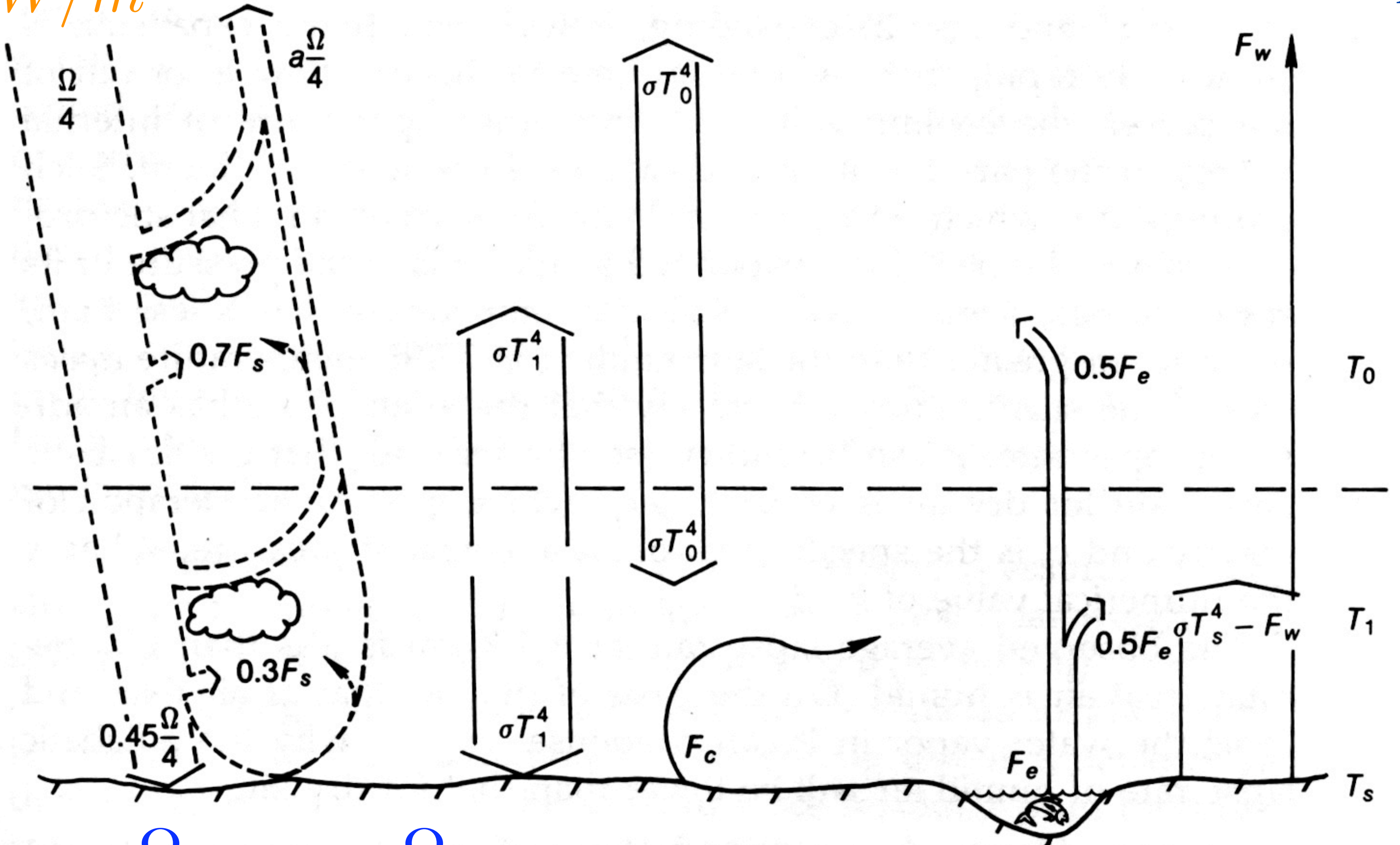

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$F_s \approx 86\ W/m^2$ Solar flux absorbed by atmosphere

$F_e \approx 80\ W/m^2$ Latent heat from evaporating water

$F_w \approx 20\ W/m^2$ IR flux directly to space

$F_c \approx 17\ W/m^2$ Convective heat transfer

$$T_0 = 250K$$
$$T_1 = 278K$$
$$T_s = 289K = 16C$$

Excellent agreement for such a simple model

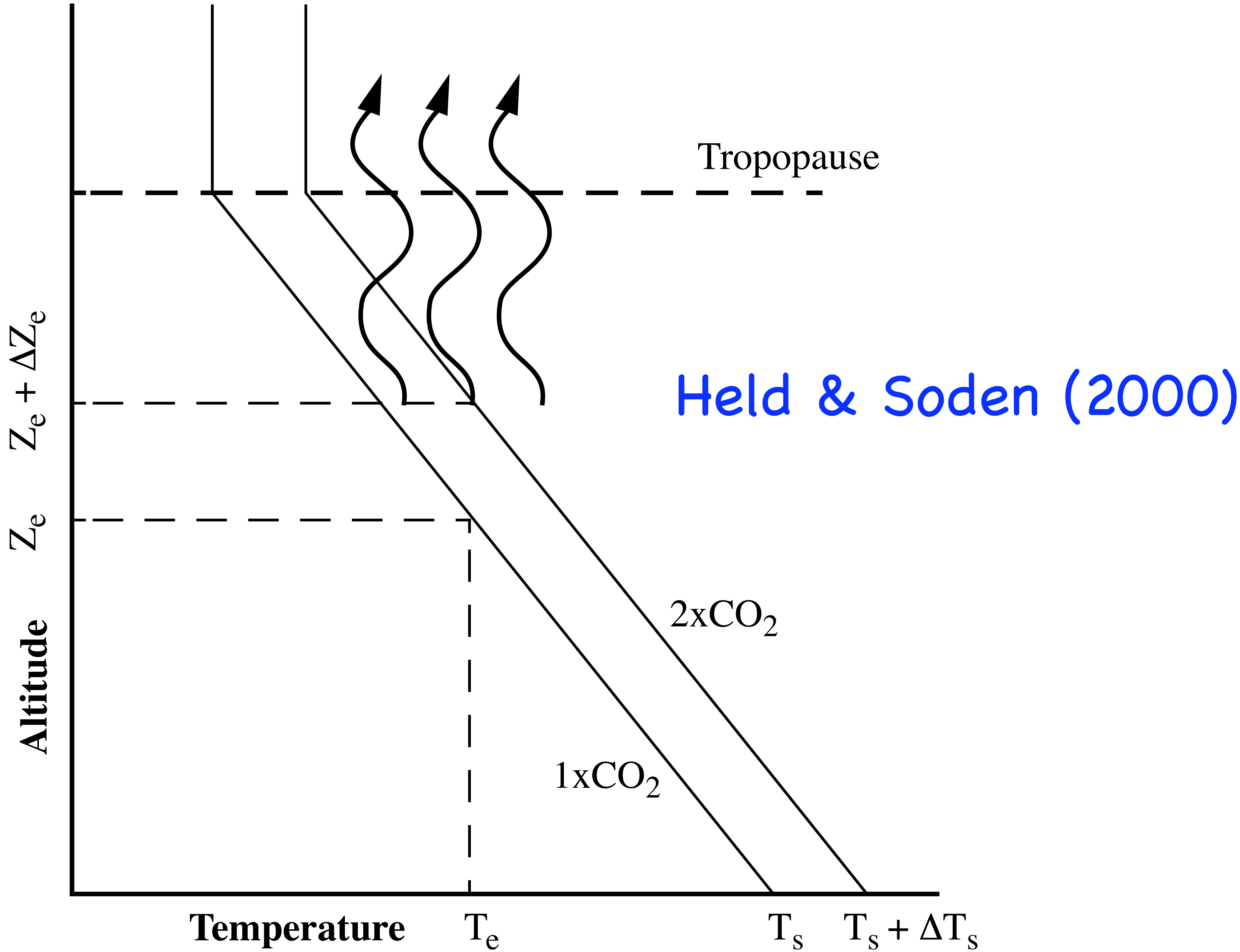
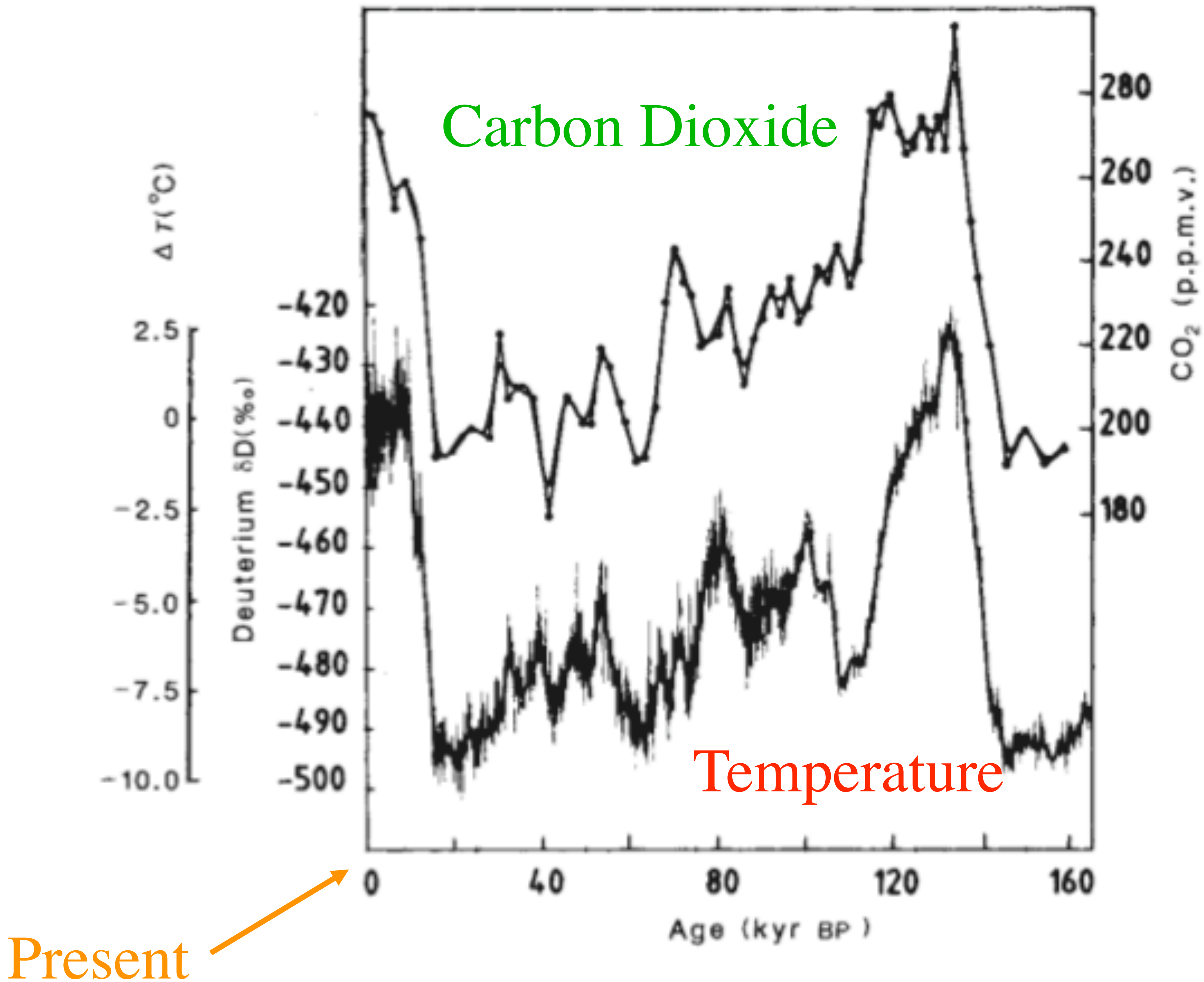


Figure 1 Schematic illustration of the change in emission level (Z_e) associated with an increase in surface temperature (T_s) due to a doubling of CO_2 assuming a fixed atmospheric lapse rate. Note that the effective emission temperature (T_e) remains unchanged.

The Past 160,000 Years

J. M. Barnola *et al.*, Nature **329**, 408 (1987)



Quantum Zero-Point Motion

(Harold Urey, “The thermodynamic properties of isotopic substances,” 1946)

Quantum Zero-Point Motion

Classically: All motion ceases at absolute zero temperature.
Everything freezes into a solid.

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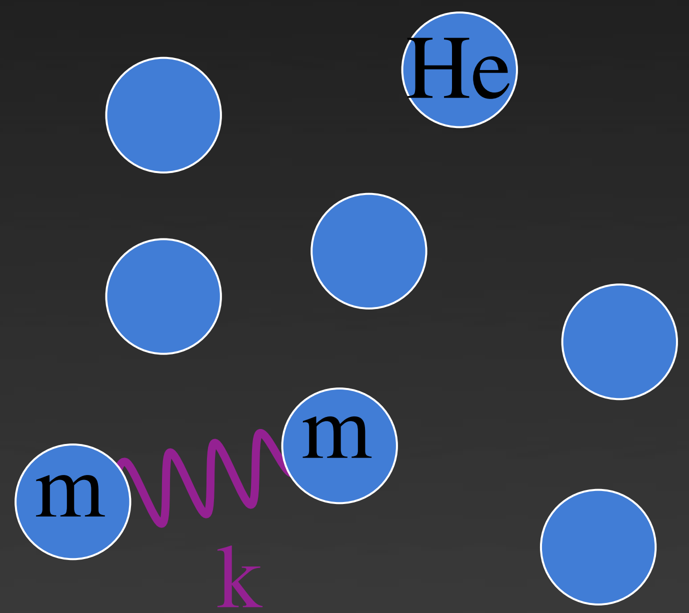
Small mass --> large quantum zero-point motion and energy.

$$\nu = \frac{1}{2\pi}\sqrt{\frac{2k}{m}}$$

$$E_0 = \frac{1}{2}\,h\nu$$



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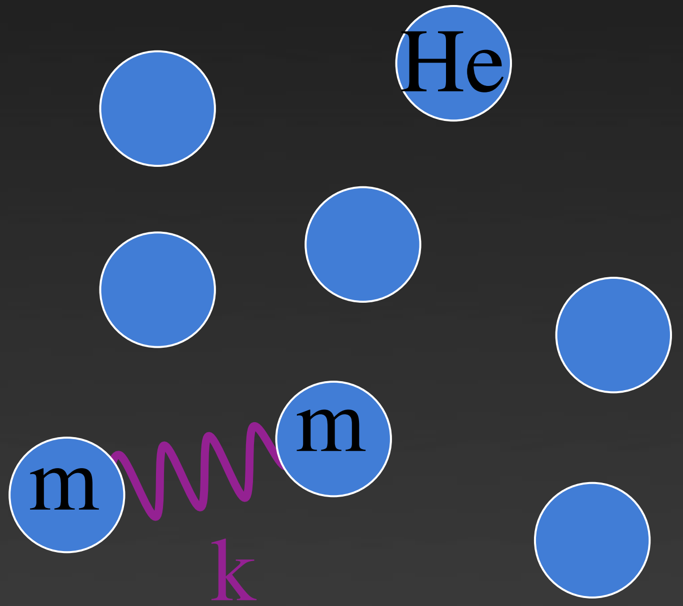


^{18}O versus ^{16}O in H_2O: Classically both molecules have same energy.

Quantum zero-point energy means that ^{18}O water is slightly less likely to evaporate during cold spells.

(Harold Urey, "The thermodynamic properties of isotopic substances," 1946)

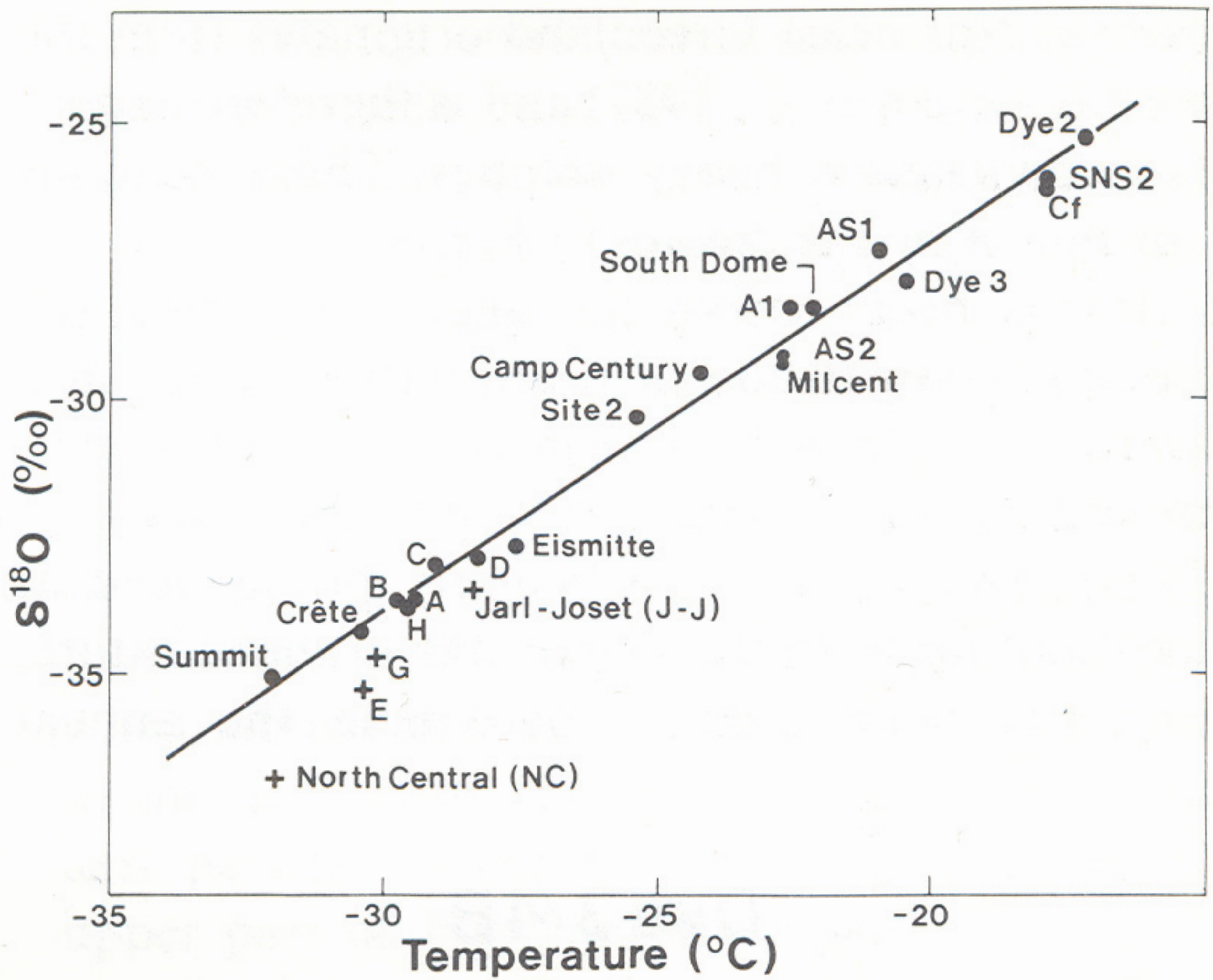
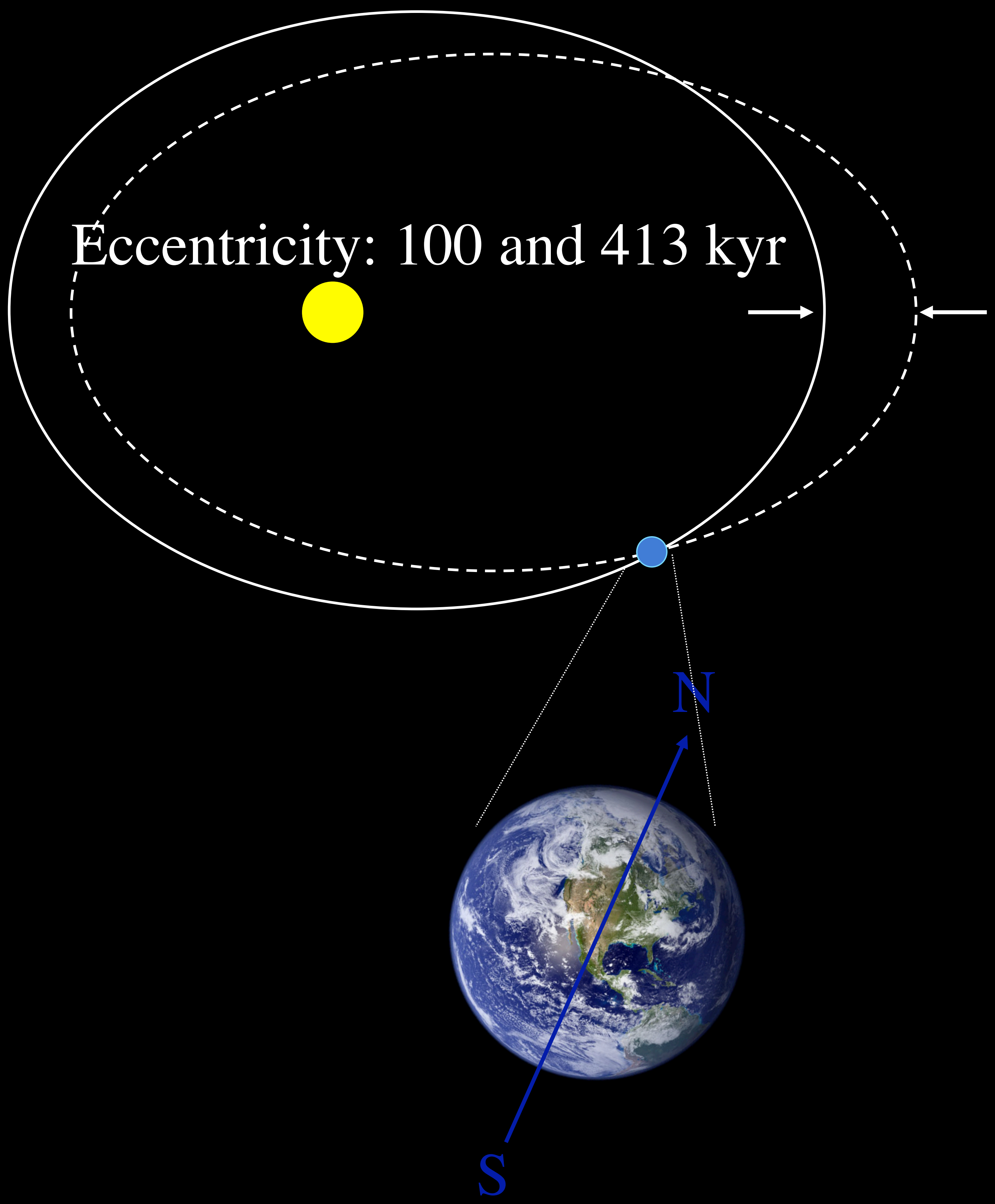
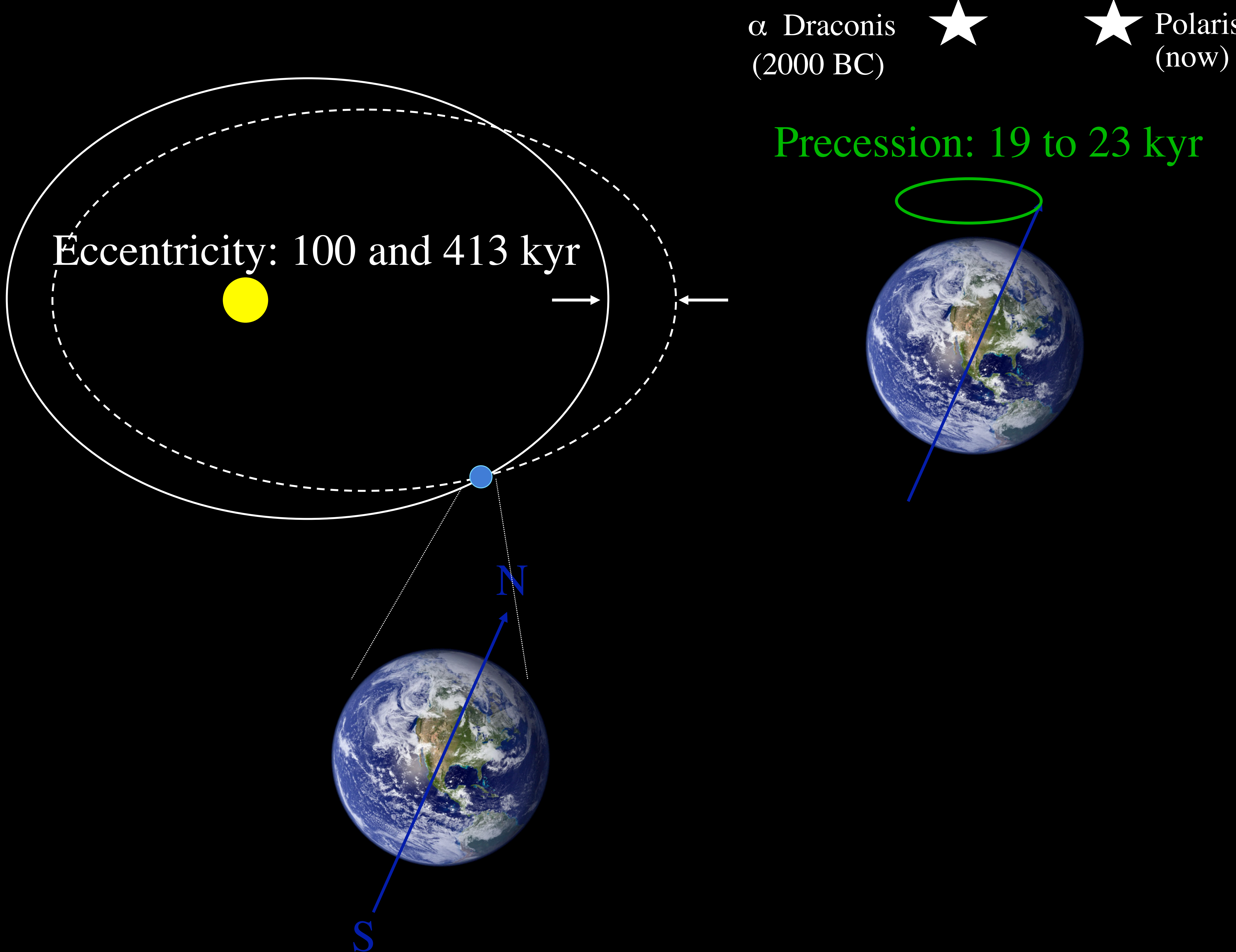
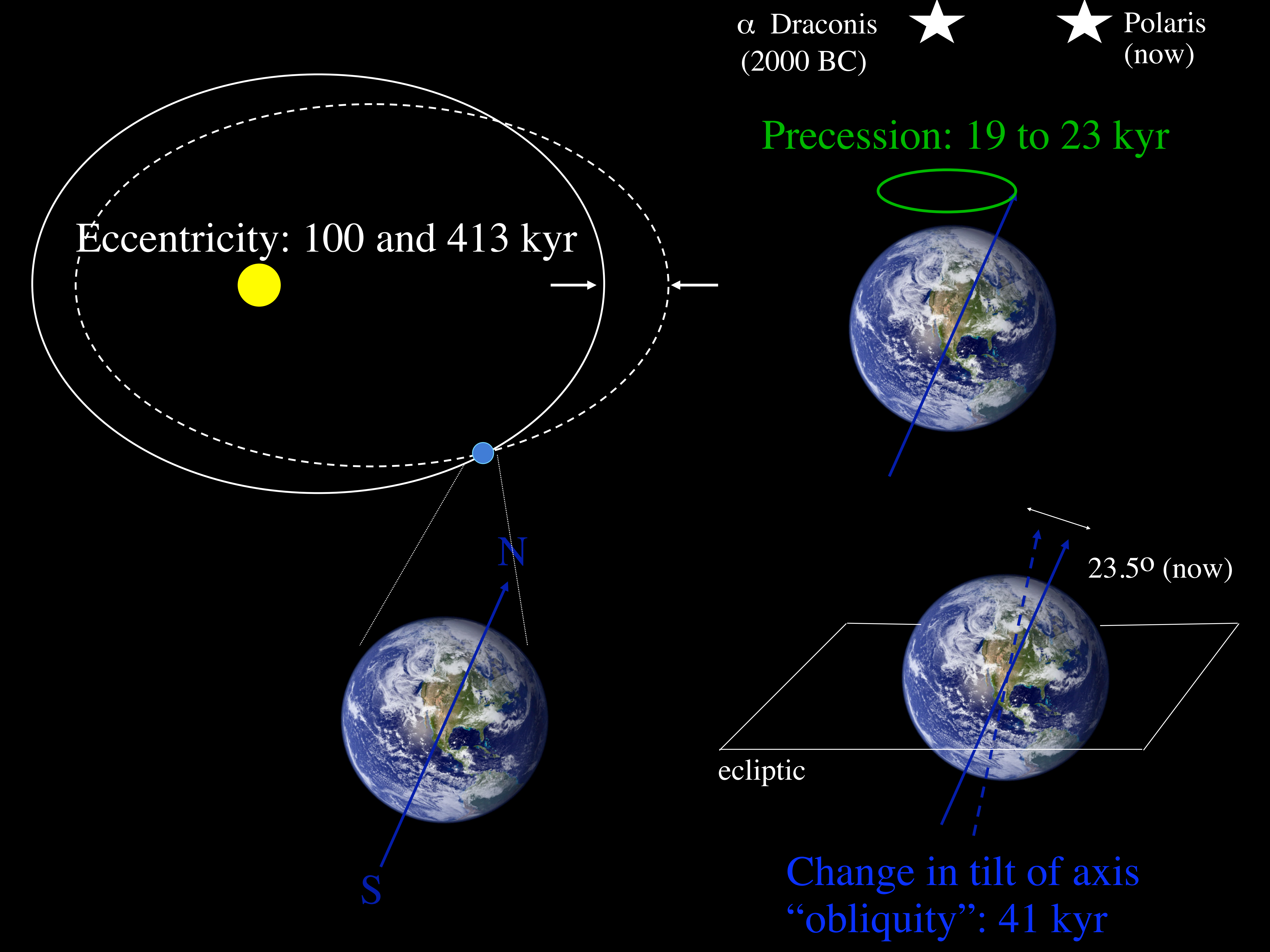


Fig. 3. Mean $\delta^{18}O$ of snow deposited on the Greenland ice sheet plotted against the annual mean surface temperature as represented by the temperature at 10 or 20 m depths.

S. J. Johnsen *et al*. Tellus **41B**, 452 (1989)


Eccentricity: 100 and 413 kyr
N
S


α Draconis
(2000 BC)
Polaris
(now)
Precession: 19 to 23 kyr
Eccentricity: 100 and 413 kyr
N
S


α Draconis
(2000 BC)
Polaris
(now)
Precession: 19 to 23 kyr
Eccentricity: 100 and 413 kyr
N
S
23.5º (now)
ecliptic
Change in tilt of axis
"obliquity": 41 kyr

Spectral Analysis of Isotope Records

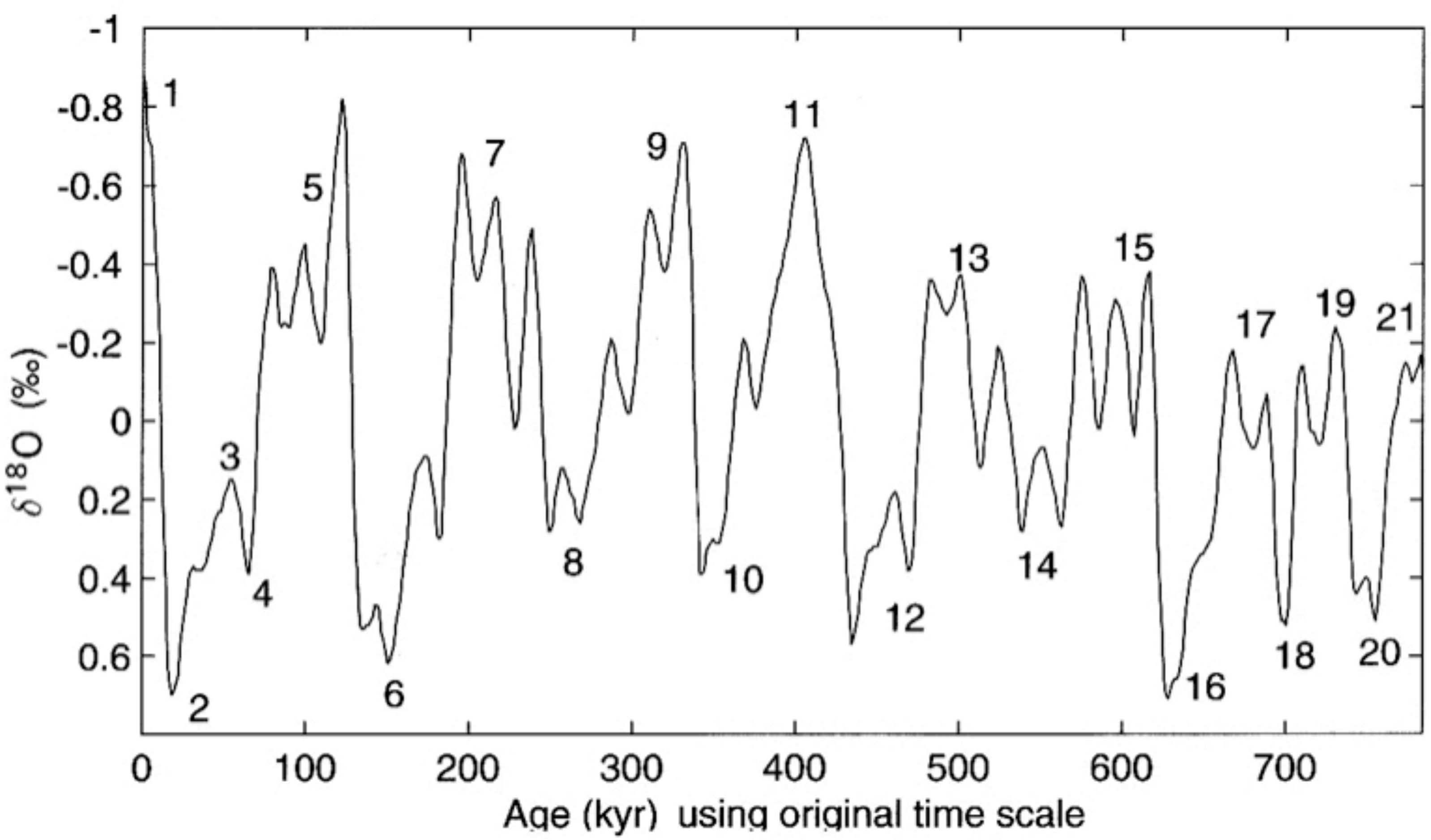


Fig. 4.4. SPECMAP δ^{18}O stack with marine isotope stage numbers.

Figures from *Ice Ages and Astronomical Causes: Data, Spectral Analysis, and Mechanisms* by R. Muller and G. MacDonald

Spectral Analysis of Isotope Records

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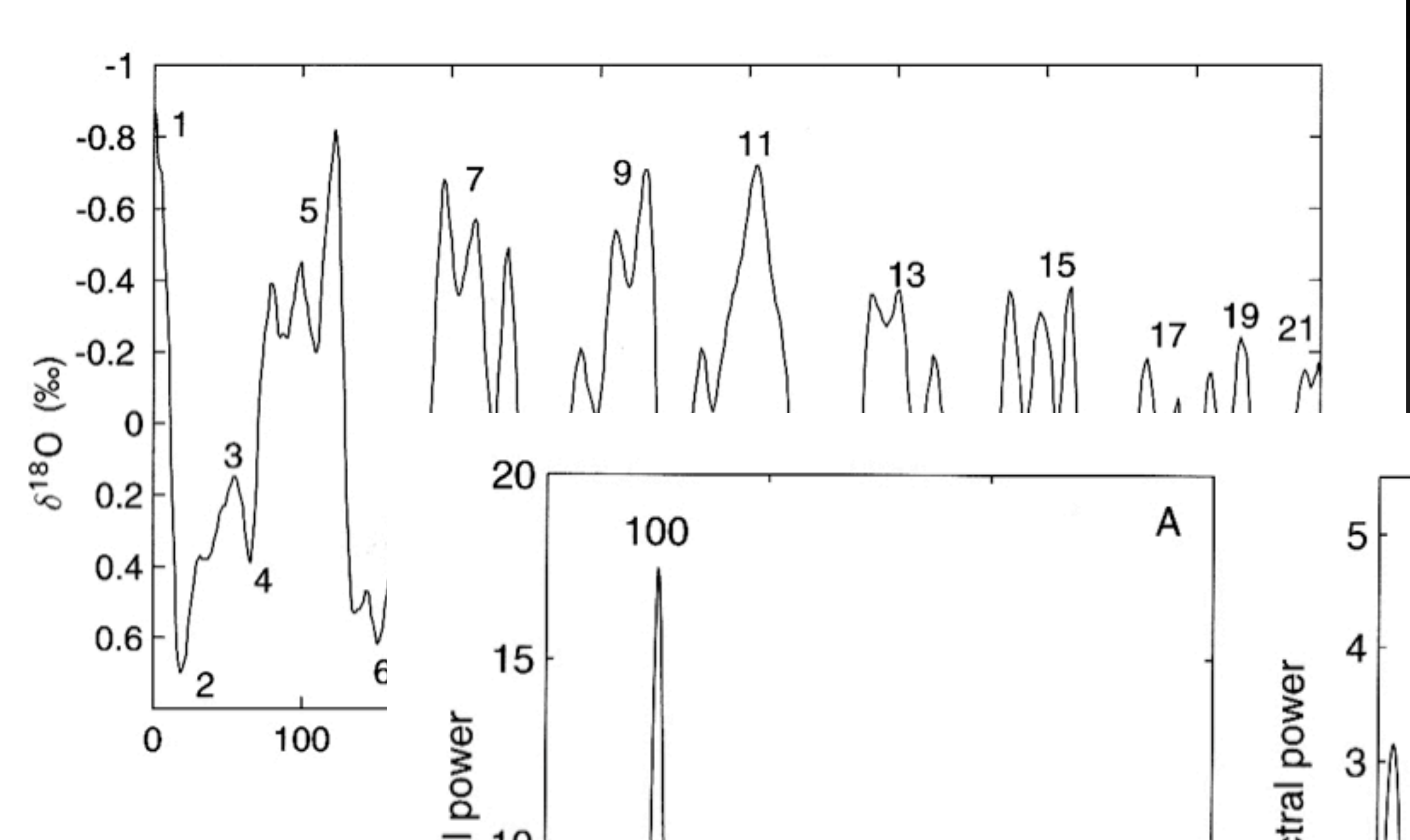


Fig. 4.4. SPECM

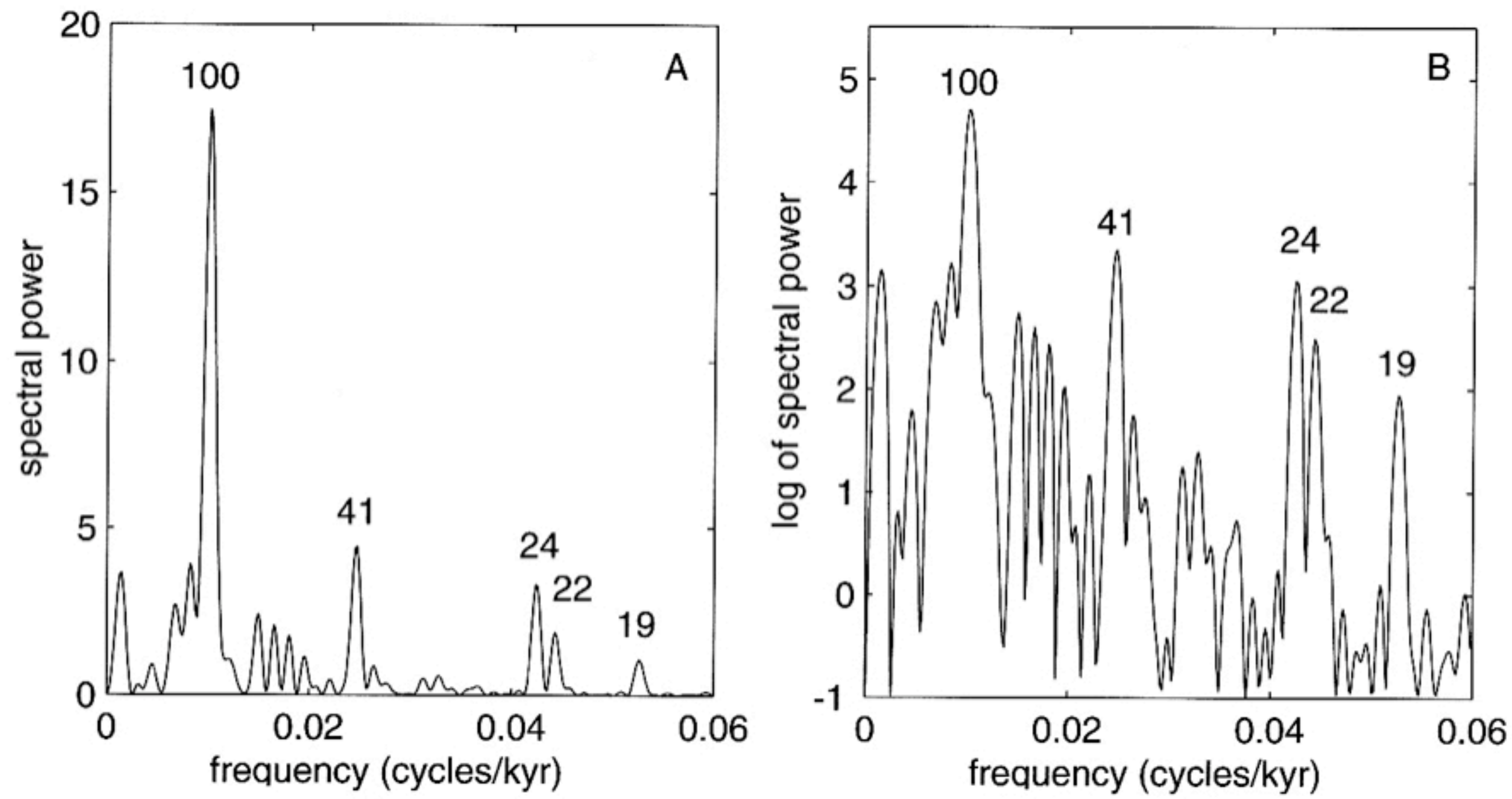


Fig. 4.5. Spectrum of original SPECMAP stack.

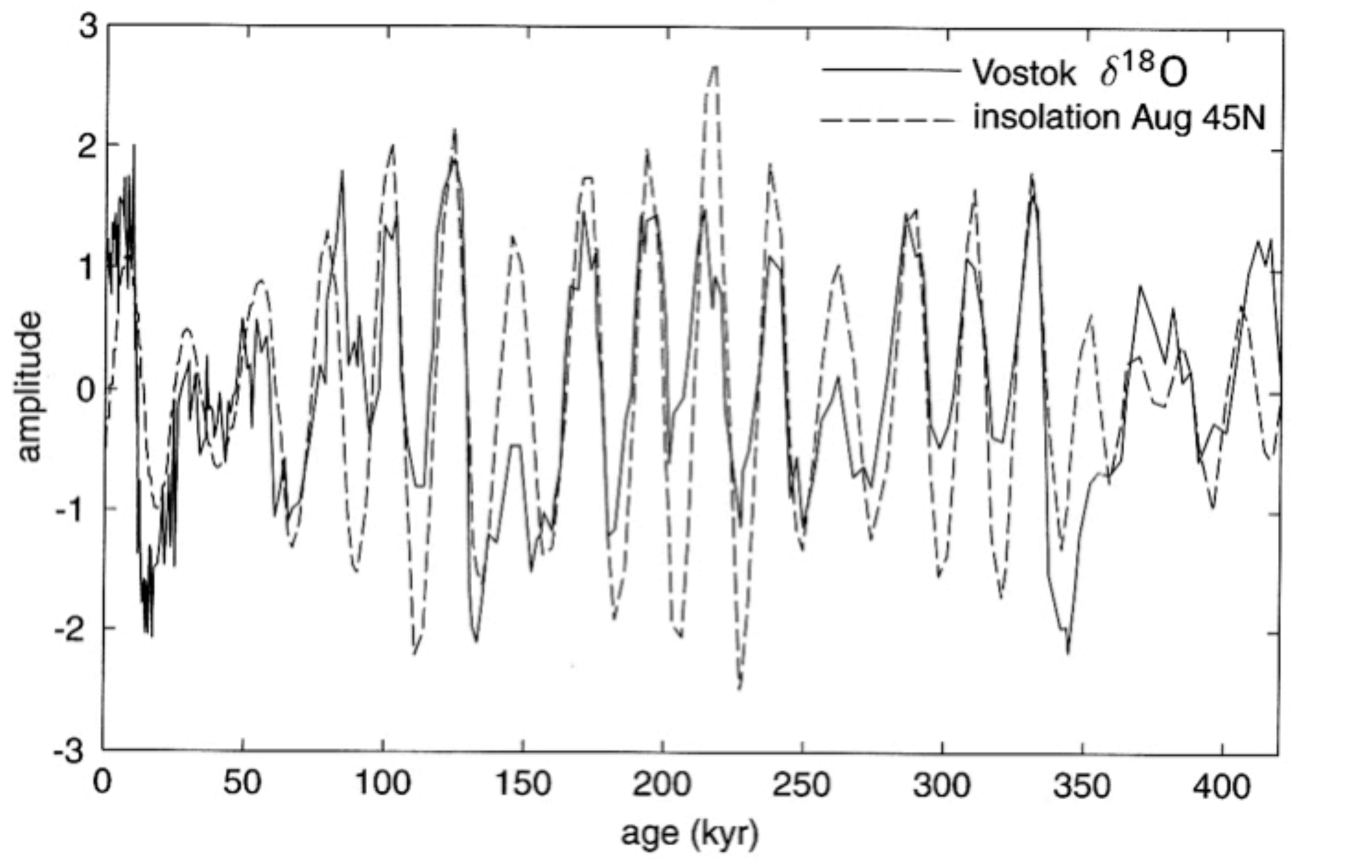
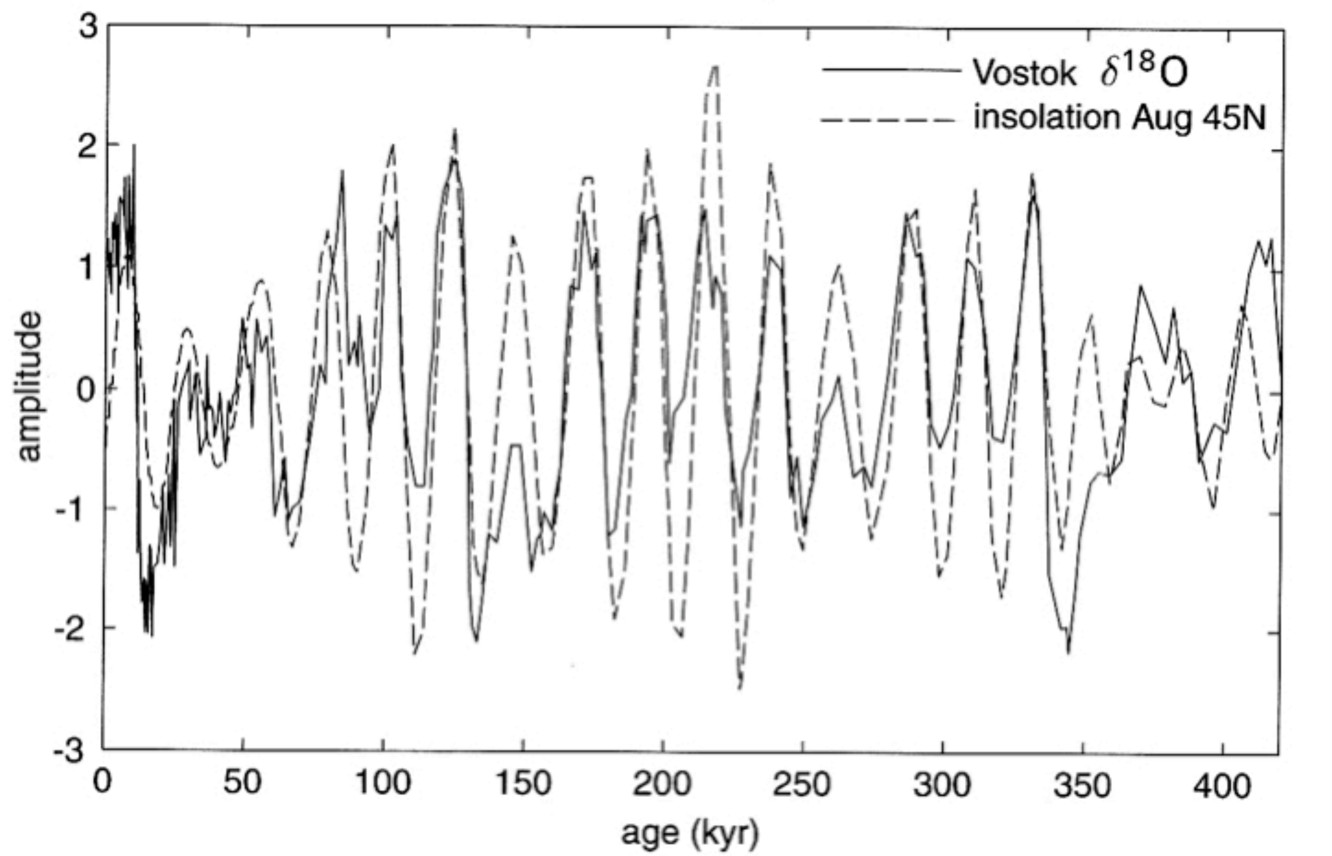


Fig. 4.40. Vostok oxygen and August 45N insolation. No phase lag used.

What amplifies orbital forcing to produce ice ages?



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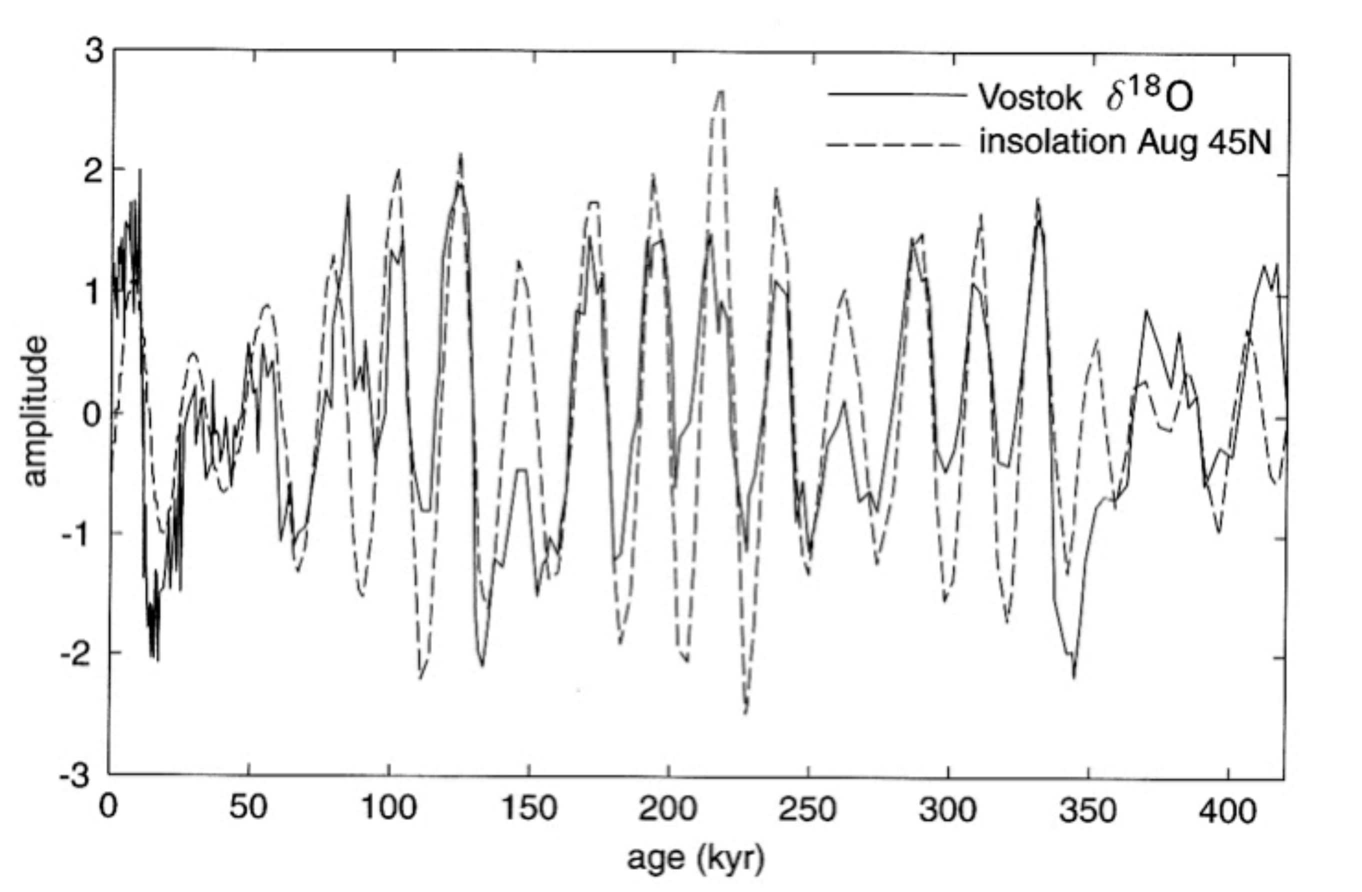
What amplifies orbital forcing to produce ice ages?

Why does 100 kyr eccentricity period dominate climate signal?



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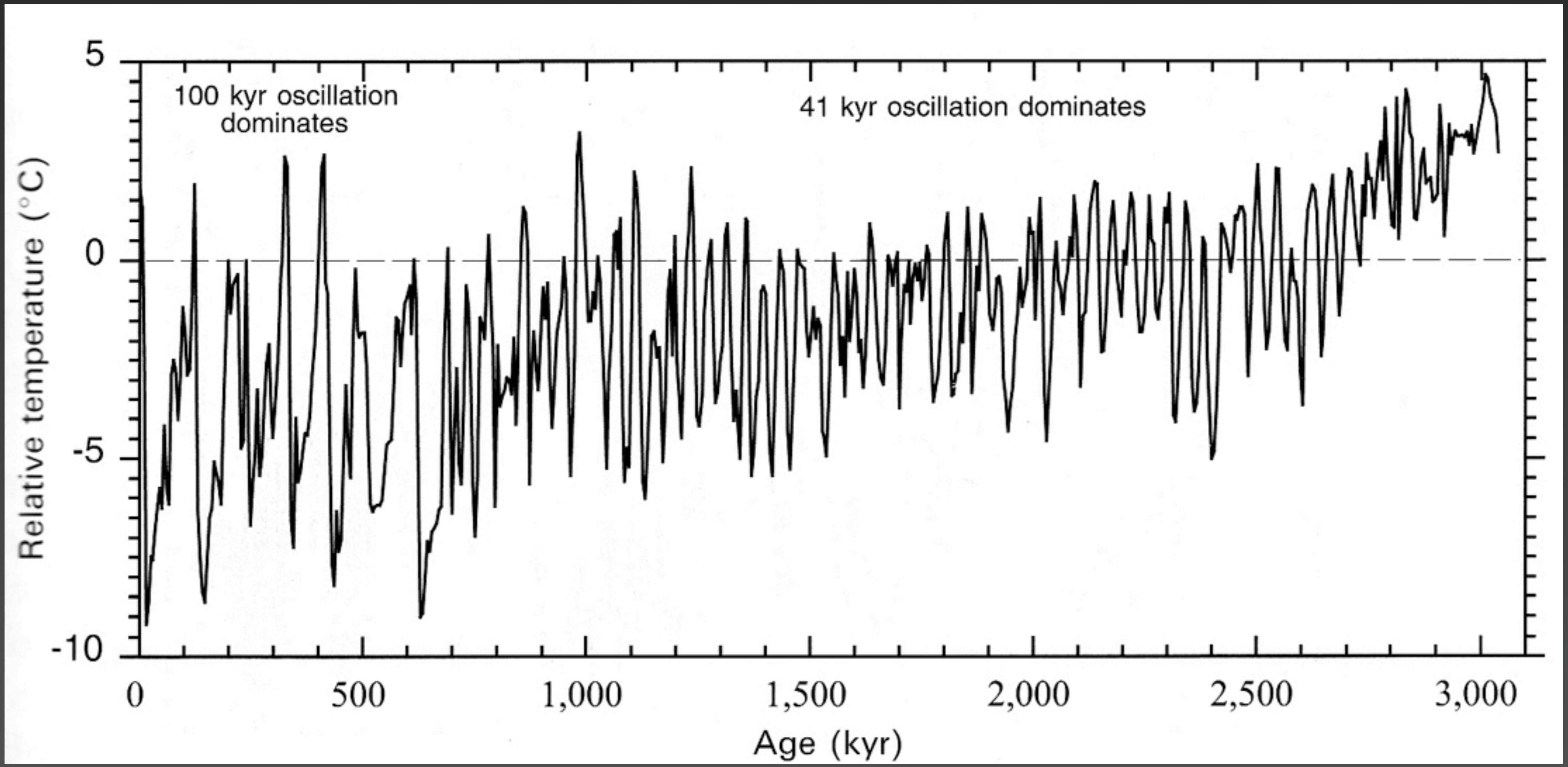
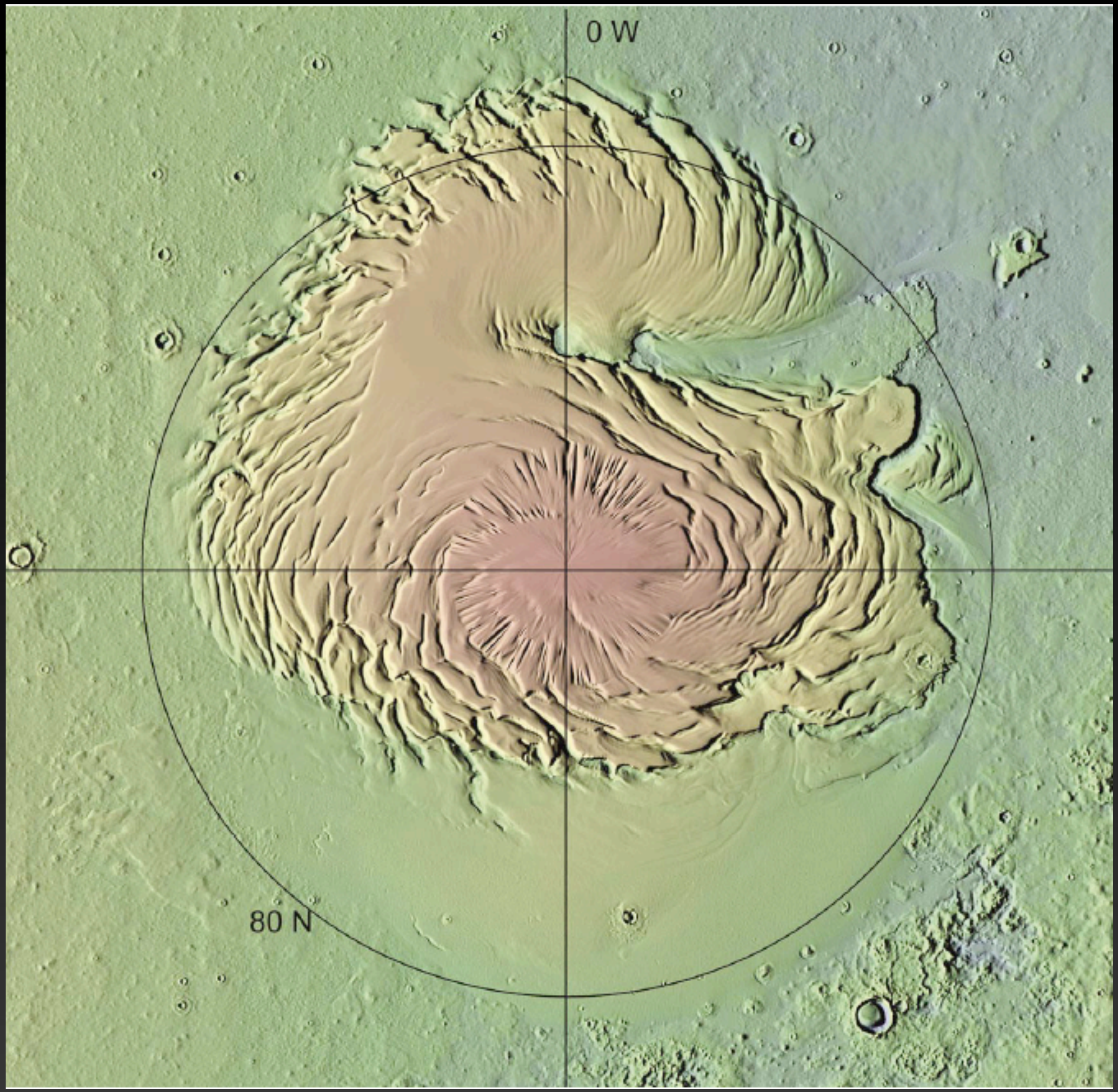
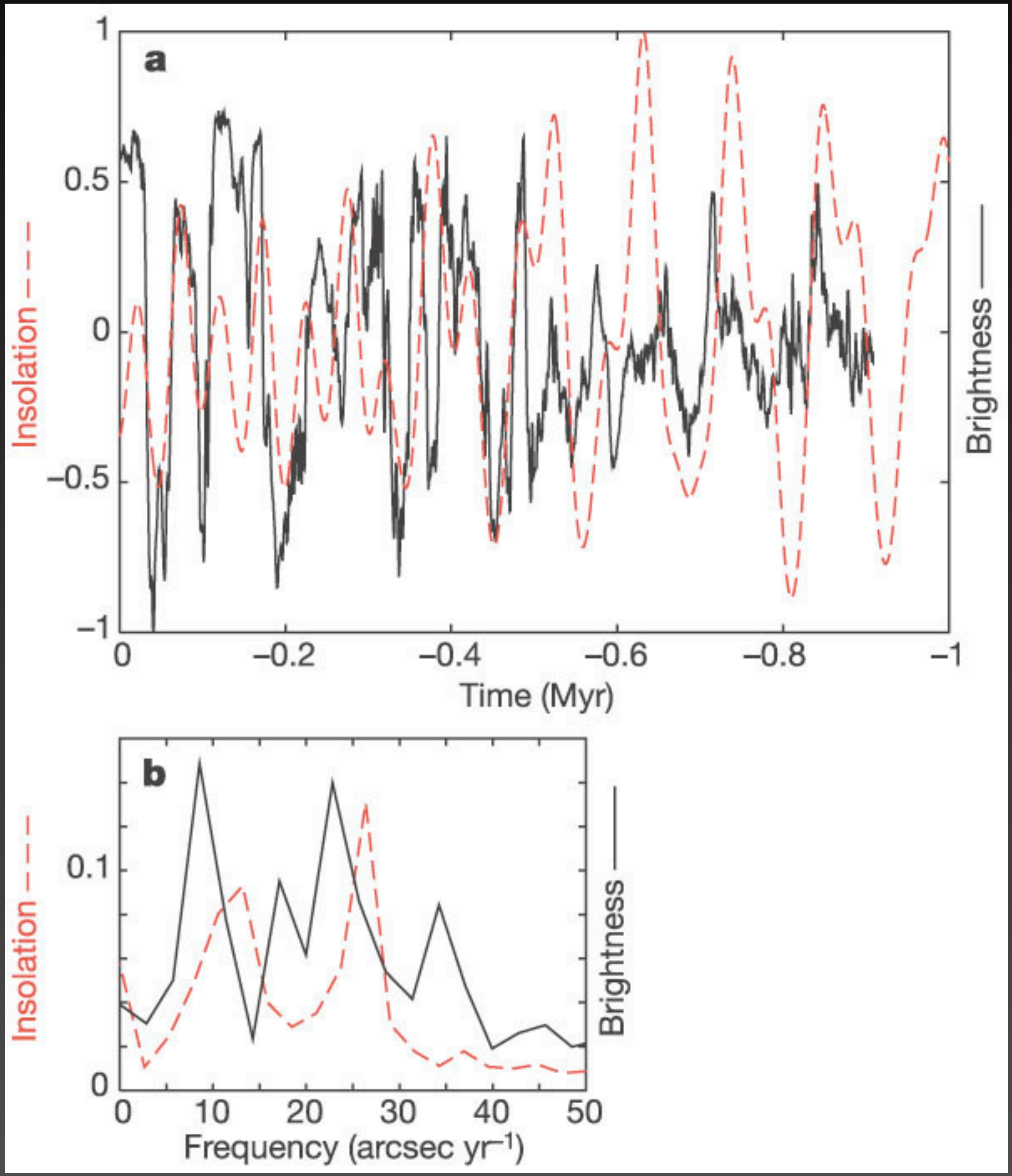


Why did the 41 kyr period dominate 1.5 million years ago?

Martian Climate May Also Show Orbital Forcing

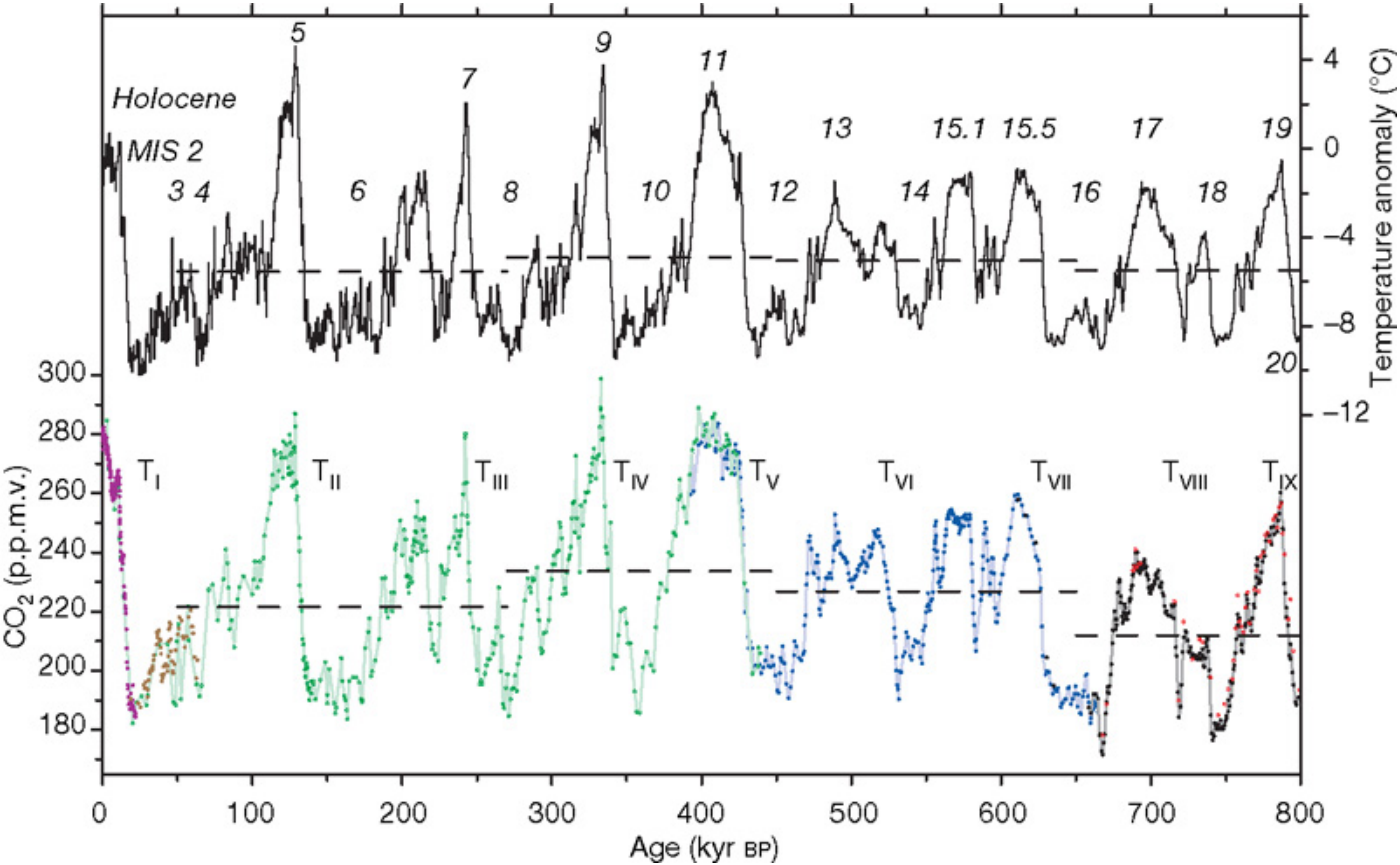


North Polar Cap of Mars



Laskar, Levrard, and Mustard, Nature **419**, 375 (2002); Head *et al*. Nature **426**, 797 (2003).

D. Lüthi *et al.* Nature **453,** 379 (2008)



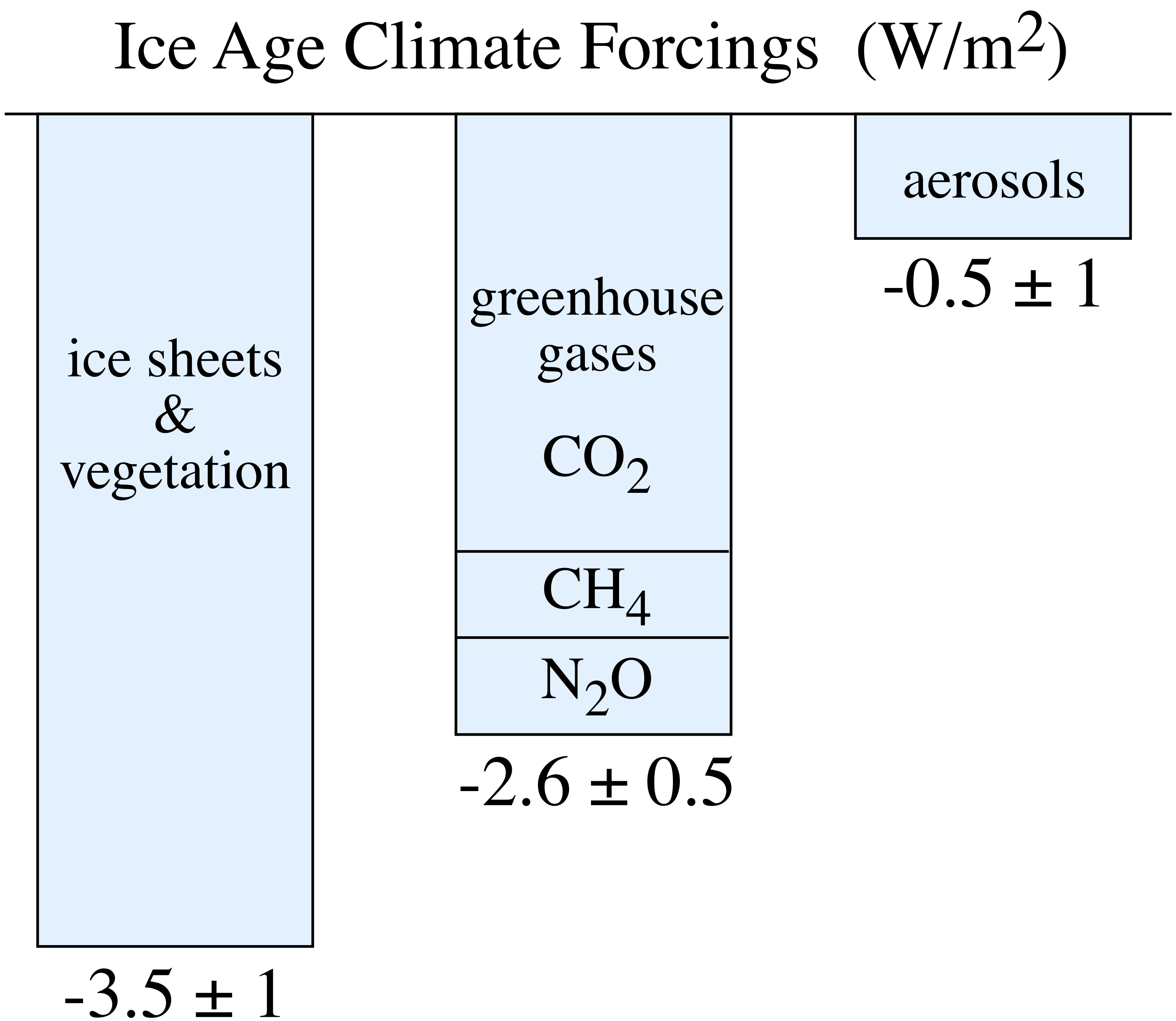
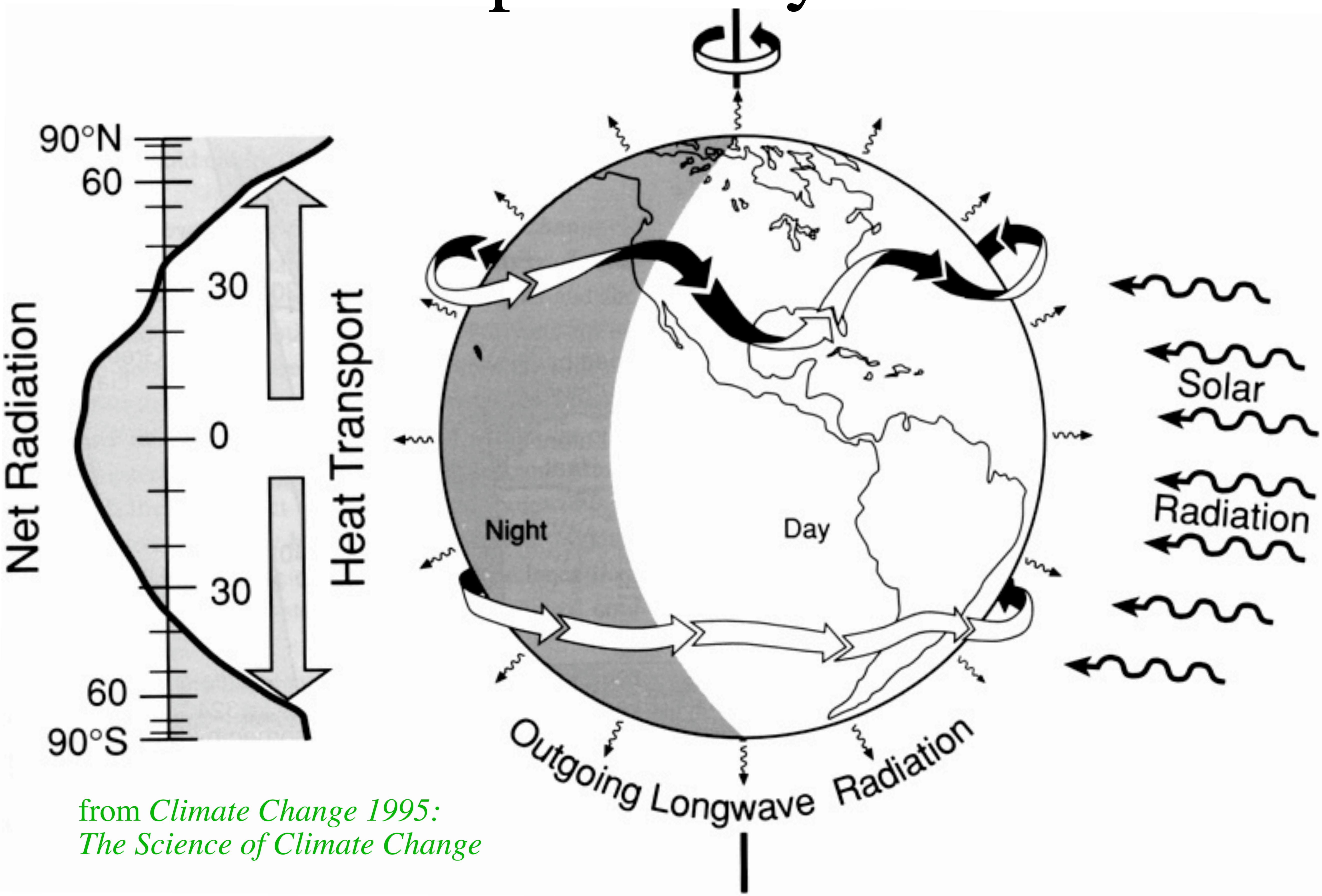


Fig 2. Global radiative forcings during the last ice age relative to the current interglacial period. The total forcing is -6.6 ± 1.5 W/m^2. Thus, the 5°C cooling of the ice age implies a climate sensitivity of 0.75°C per 1 W/m^2 forcing.

Hansen, J. et al., The missing climate forcing, Phil. Trans. R. Soc. London. B, 352, 231-240, 1997.

Atmospheric Dynamics



from *Climate Change 1995: The Science of Climate Change*

Single Layer Models

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$$\frac{D\omega}{Dt} = 0$$

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Vorticity

$$\omega = \hat{r} \cdot (\vec{\nabla} \times \vec{v})$$

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$$\frac{\partial \omega}{\partial t} + \vec{v} \cdot \vec{\nabla} \omega = 0$$

$$\begin{aligned} \vec{v} &= \hat{r} \times \vec{\nabla} \psi \\ \vec{\nabla} \cdot \vec{v} &= 0 \\ \omega &= \nabla^2 \psi \end{aligned}$$

Single Layer Models

$$\frac{D\omega}{Dt} = 0$$

Vorticity

$$\omega \quad = \quad \hat{r} \cdot (\vec{\nabla} \times \vec{v})$$

$$\frac{\partial \omega}{\partial t} + \vec{v} \cdot \vec{\nabla} \omega = 0 \qquad \frac{\partial \omega}{\partial t} + J(\psi, \omega) = 0$$

$$\begin{aligned} \vec{v} &= \hat{r} \times \vec{\nabla}\psi \\ \vec{\nabla} \cdot \vec{v} &= 0 \\ \omega &= \nabla^2 \psi \end{aligned}$$

$$J(\psi, \omega) \equiv \frac{\partial \psi}{\partial x}\frac{\partial \omega}{\partial y} - \frac{\partial \psi}{\partial y}\frac{\partial \omega}{\partial x}$$

Freely Decaying Turbulence on Sphere

Coriolis Force

Coriolis Force

$$\frac{\partial q}{\partial t} + J(\psi, q) = 0$$

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Relative vorticity

$$\begin{aligned} q &= \omega + f \\ &= \nabla^2 \psi + f \end{aligned}$$

Coriolis term

Absolute vorticity

Coriolis Force

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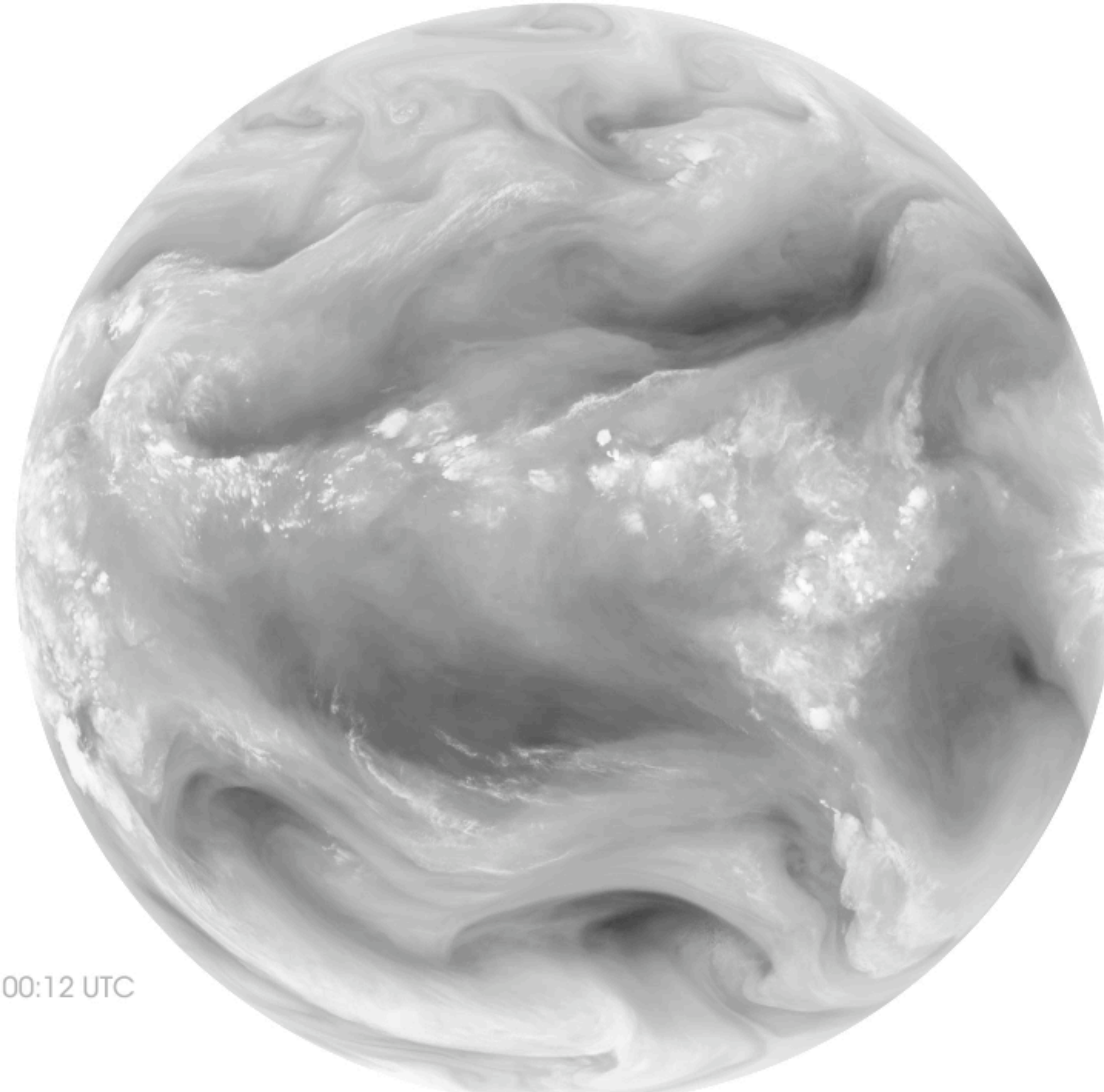
Coriolis term

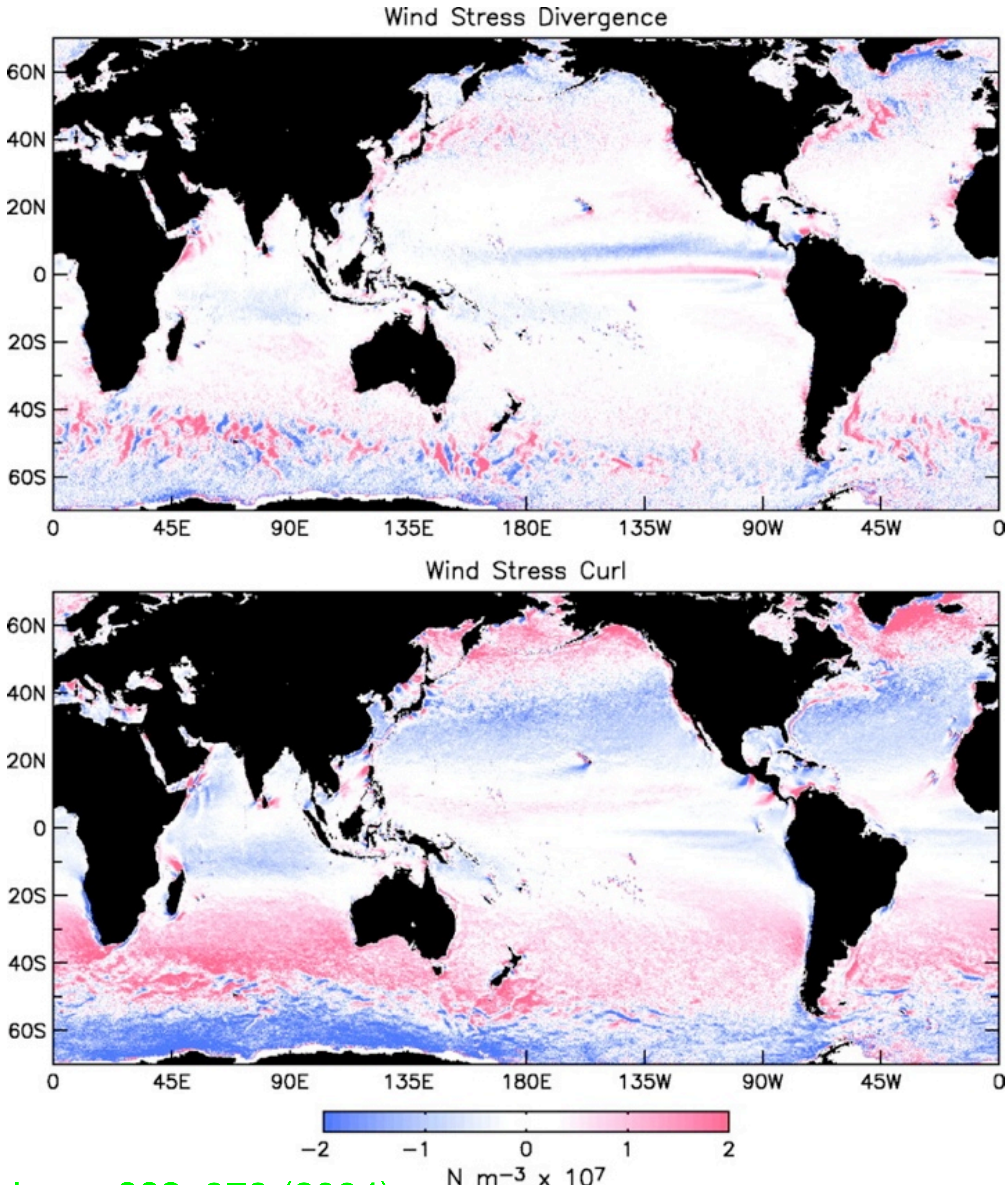
Absolute vorticity

$$f = 2\Omega \sin(\phi)$$



October 7, 2007 00:12 UTC

Coriolis Force



Chelton *et al.*, Science **303**, 978 (2004)

Stratification

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$$q = \nabla^2 \psi + f - \frac{\psi}{\ell_R^2}$$

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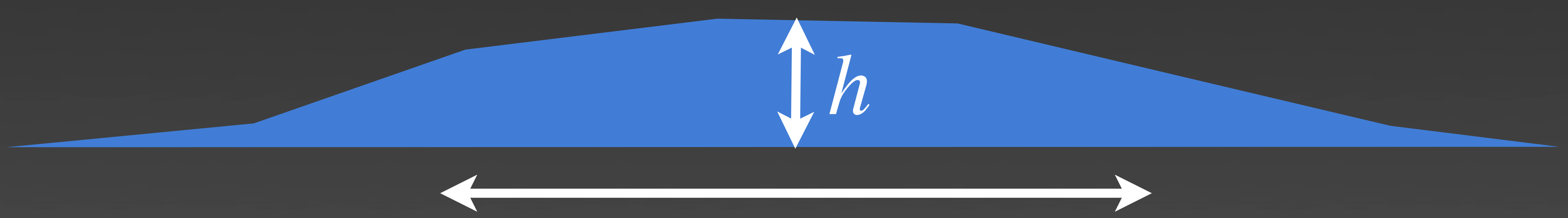
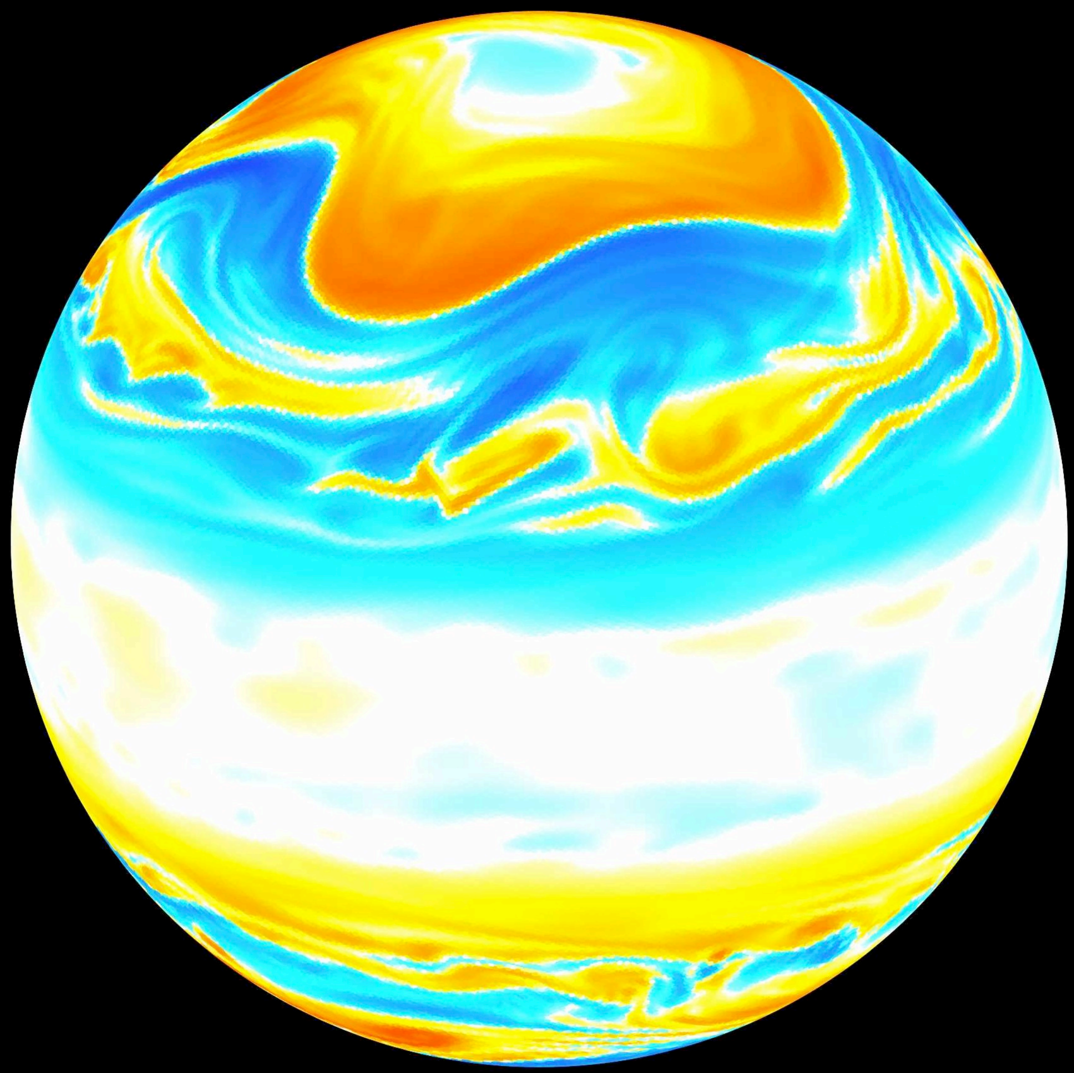


$$\ell_R = \mathcal{O}(1,000 \text{ km})$$

Stratification Sets Synoptic Length Scale



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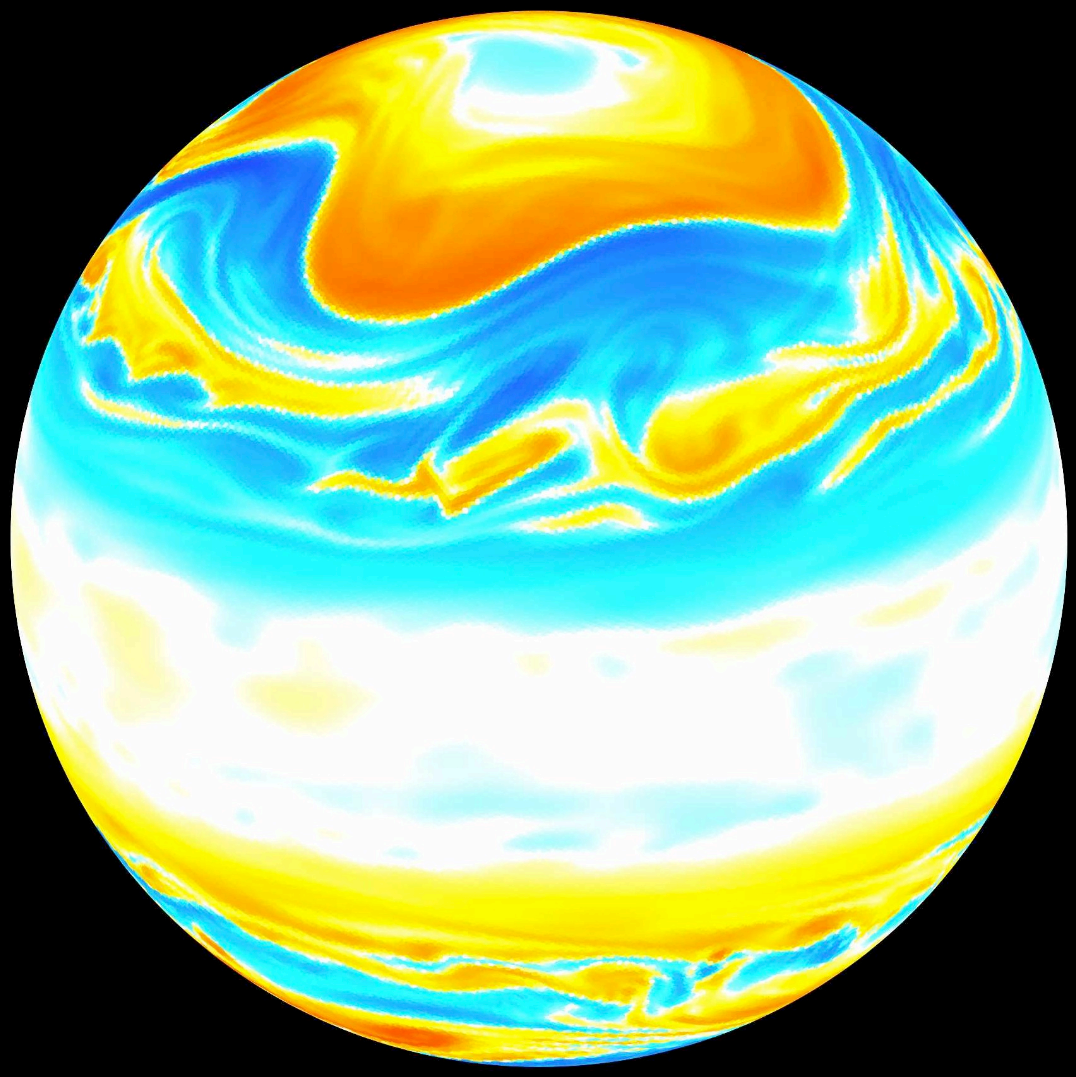
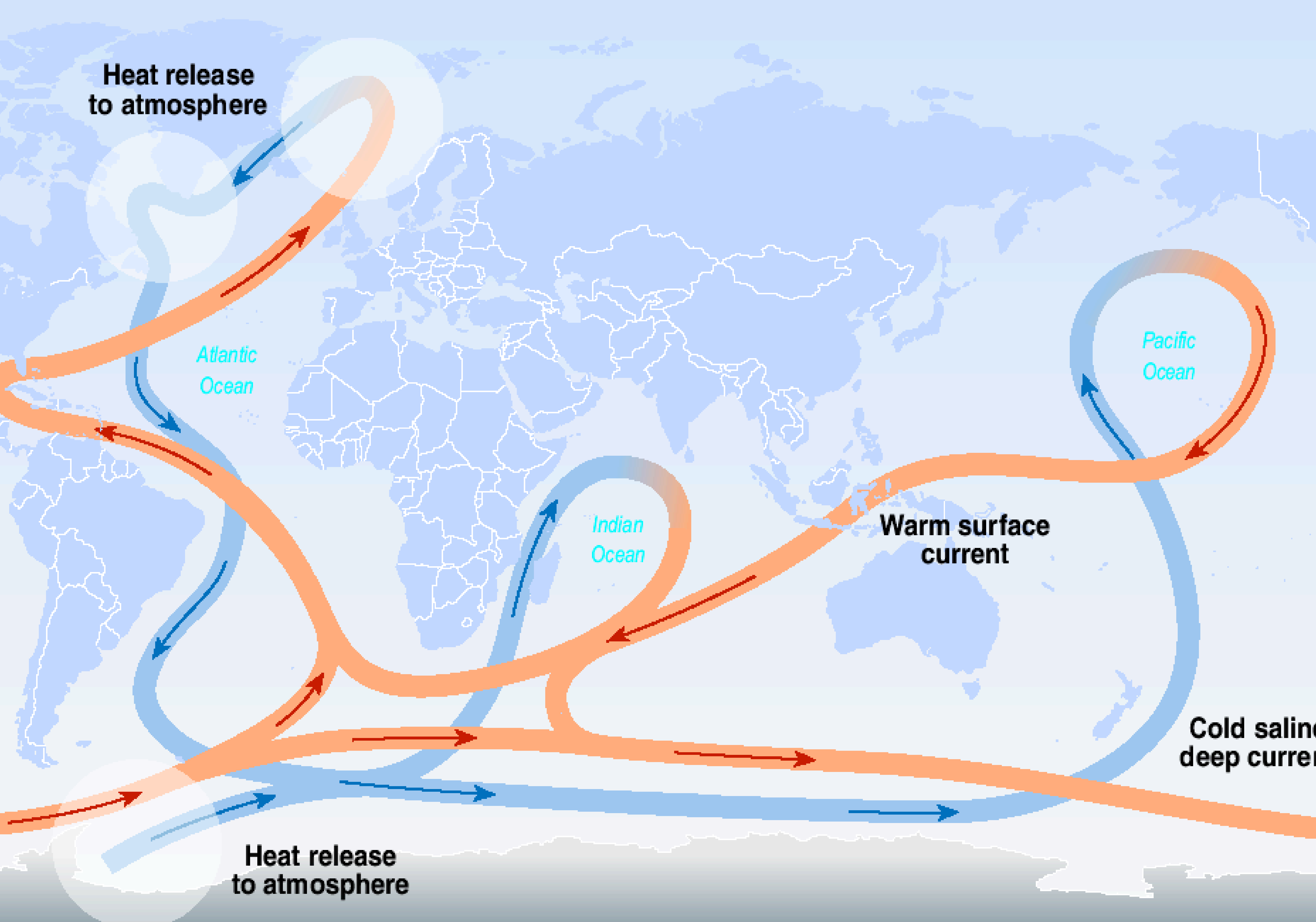


Great ocean conveyor belt



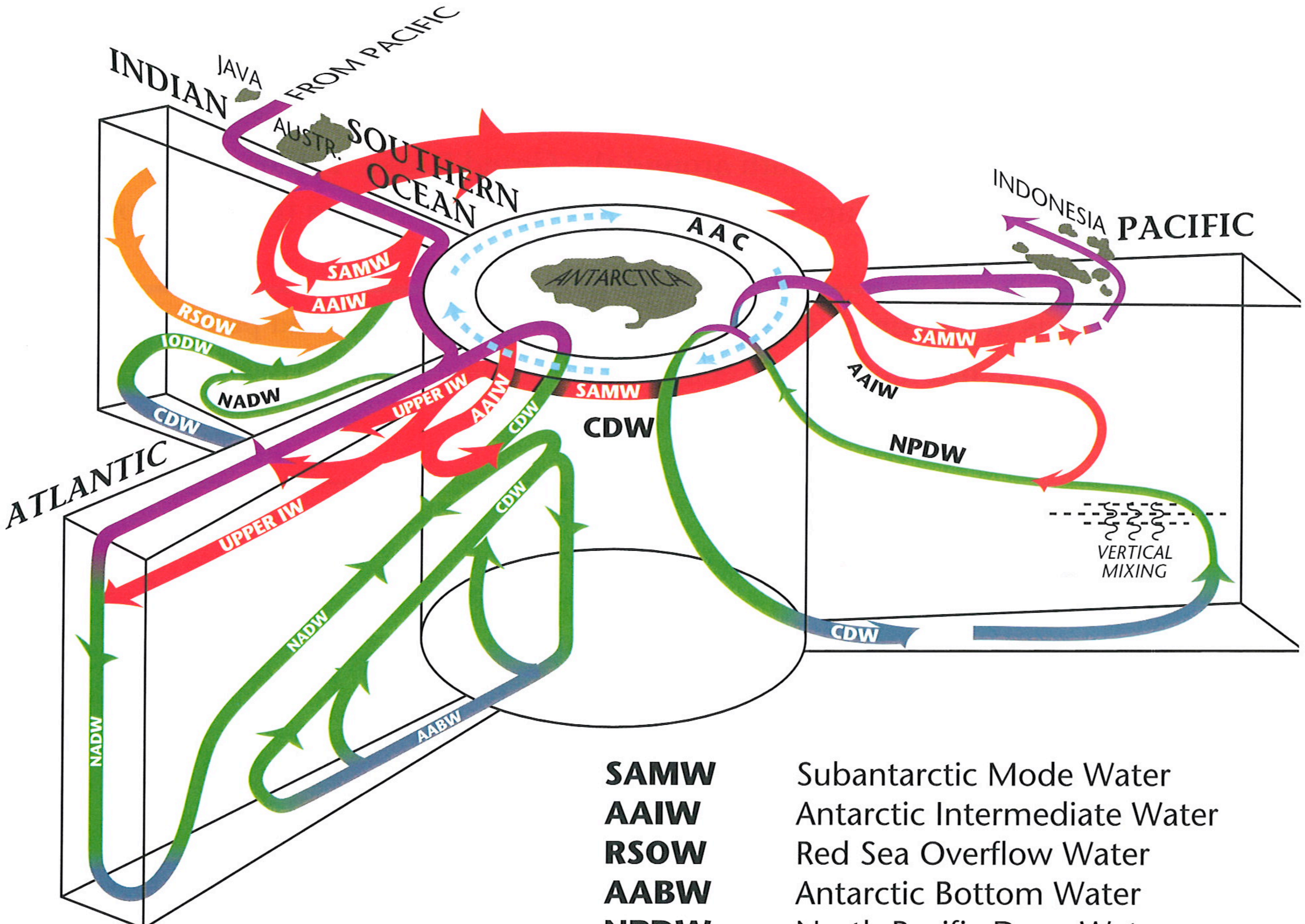
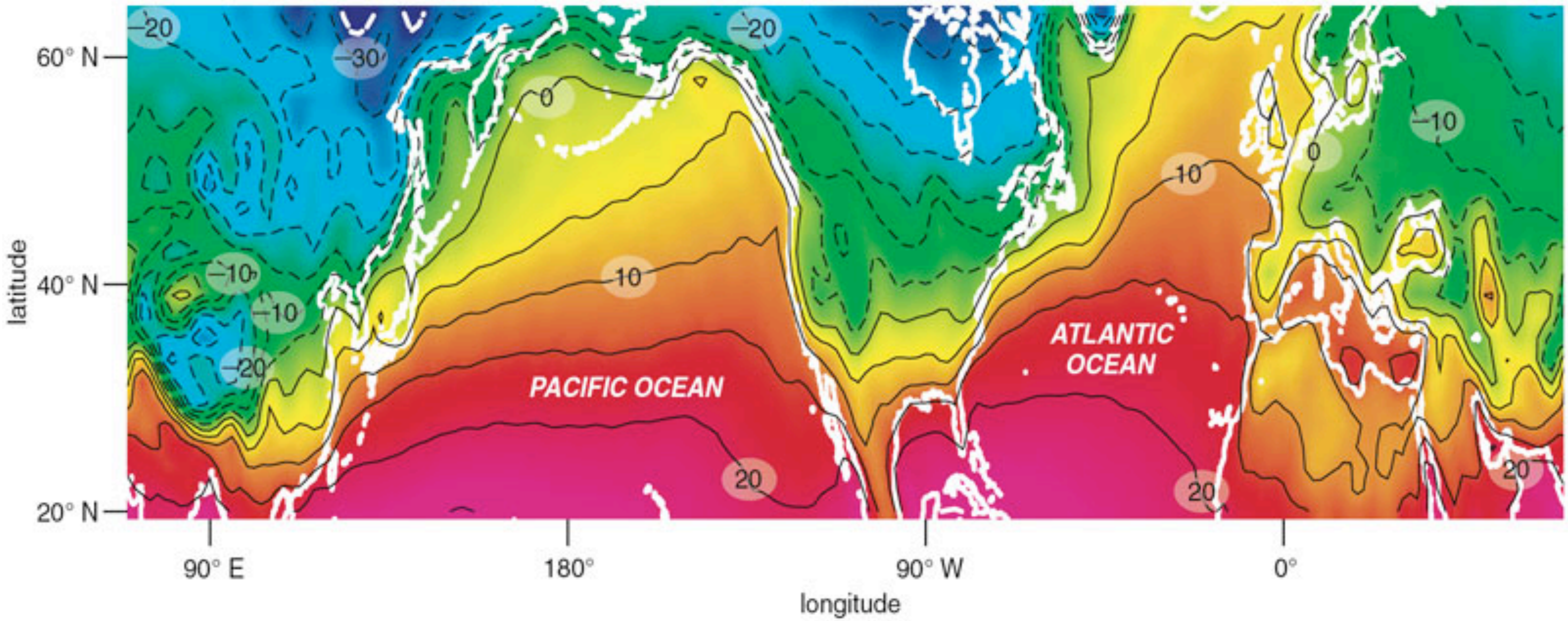


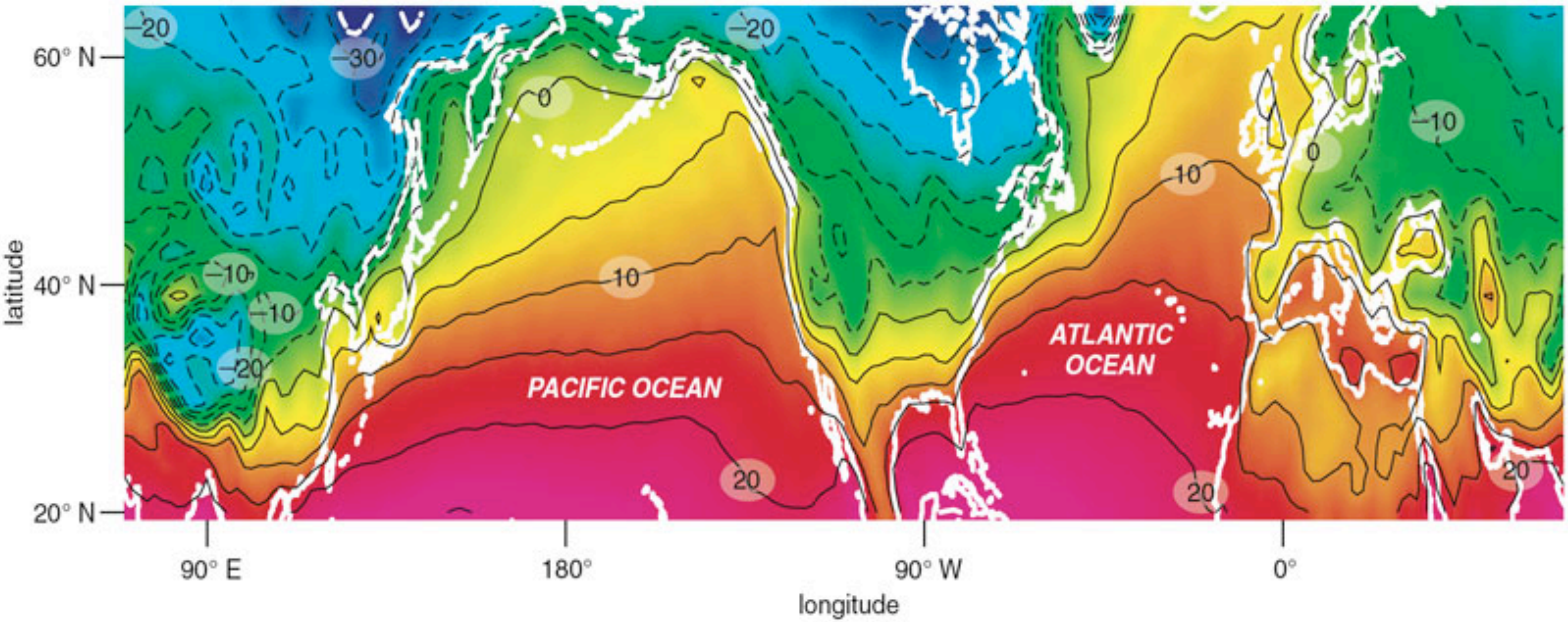
Figure I-91: A new version of Figure I-90 with schematic meridional sections of interbasin flow for each ocean with their global linkages.

SAMW	Subantarctic Mode Water
AAIW	Antarctic Intermediate Water
RSOW	Red Sea Overflow Water
AABW	Antarctic Bottom Water
NPDW	North Pacific Deep Water
AAC	Antarctic Circumpolar Current
CDW	Circumpolar Deep Water
NADW	North Atlantic Deep Water
UPPER IW	$26.8 \leq \sigma_\theta \leq 27.25$
IODW	Indian Ocean Deep Water

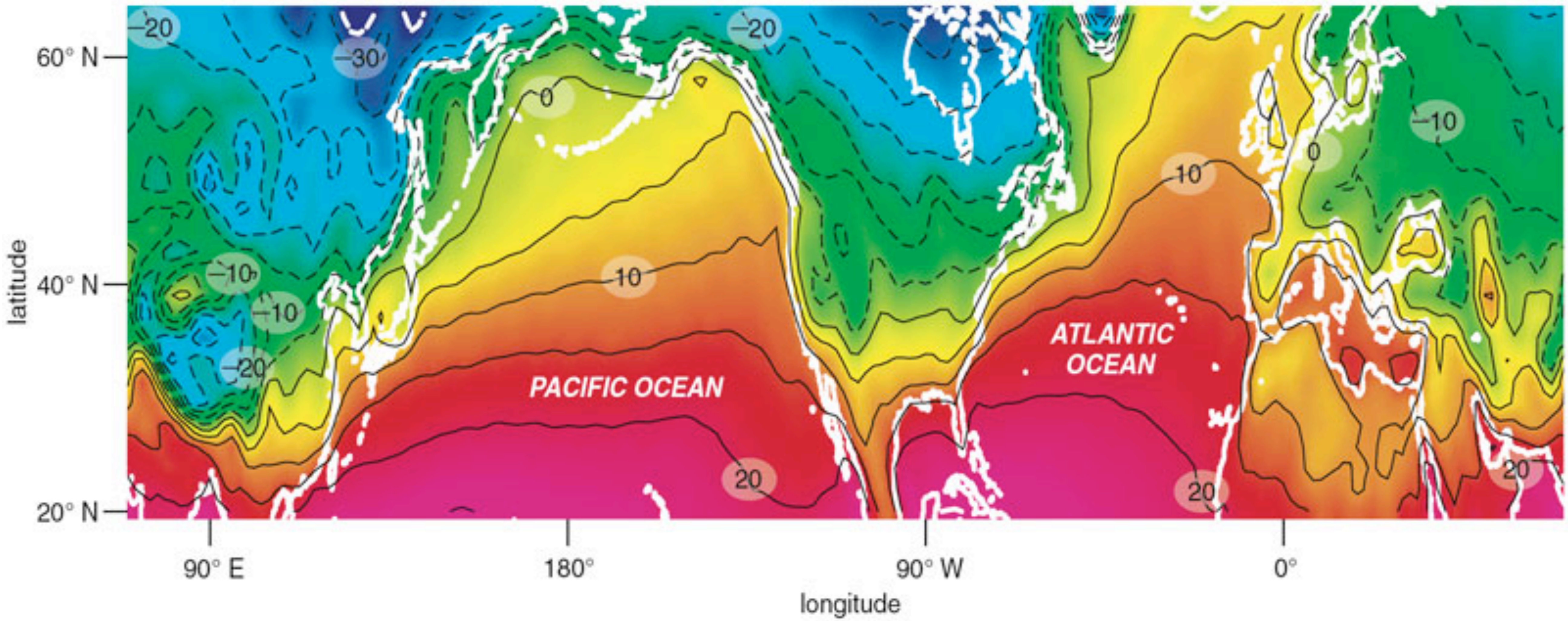
W. J. Schmitz, WHOI technical report 96-03



City	Latitude	January (°F)	August (°F)

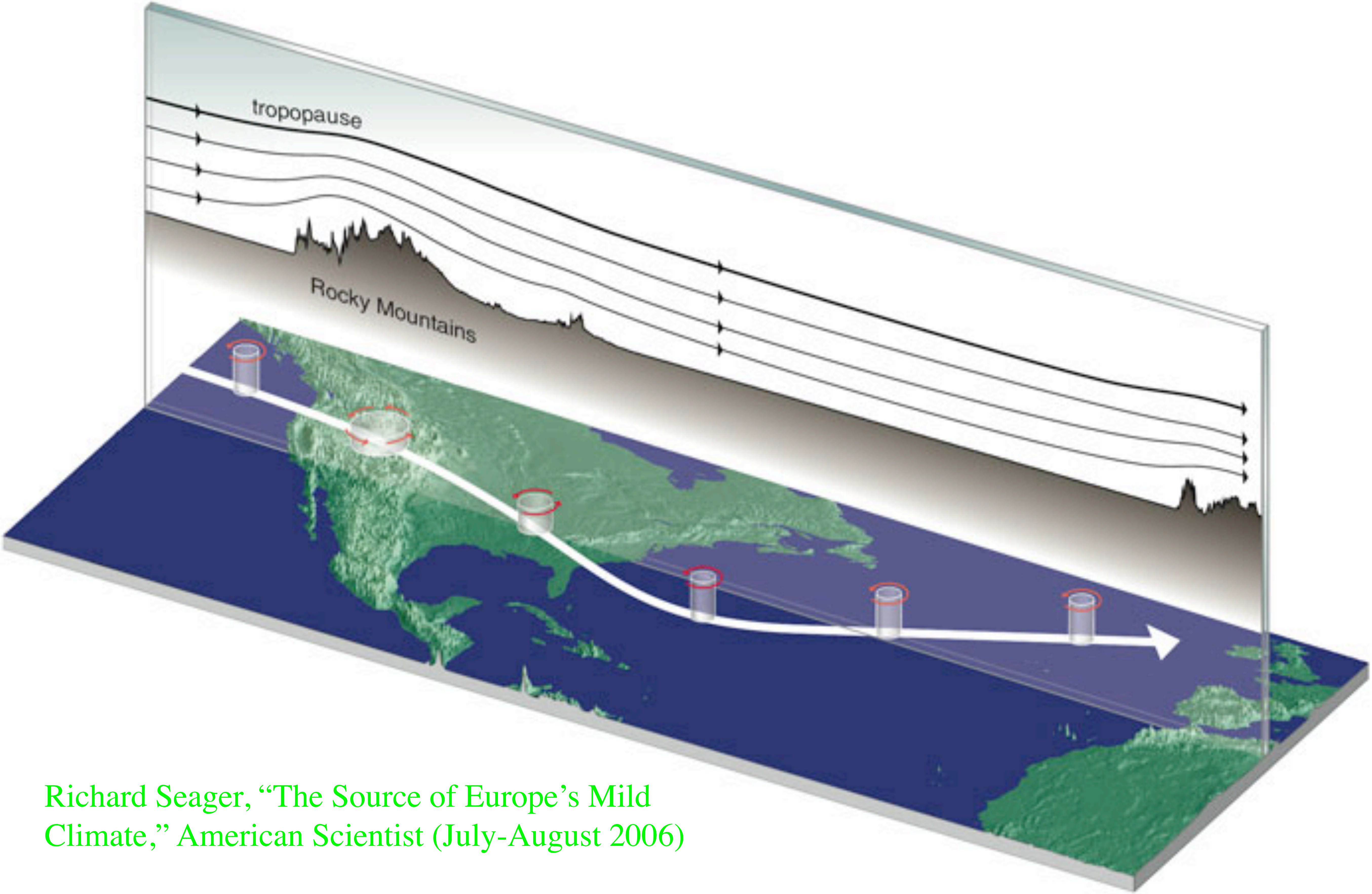


City	Latitude	January (°F)	August (°F)
Glasgow	56°	34 to 45	52 to 64



City	Latitude	January (°F)	August (°F)
Glasgow	56°	34 to 45	52 to 64
Sitka	57°	30 to 38	52 to 62

Topography & Angular Momentum

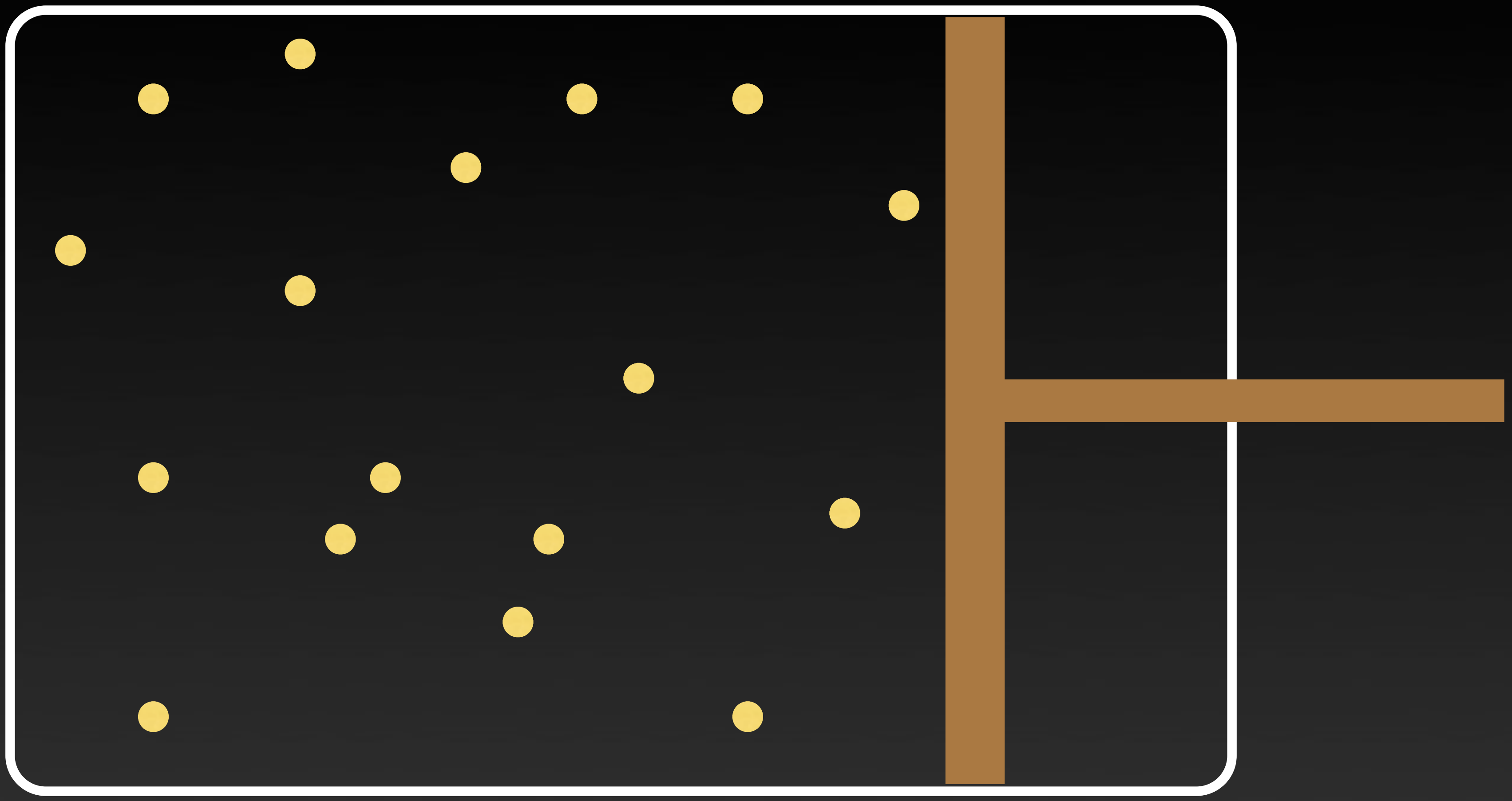


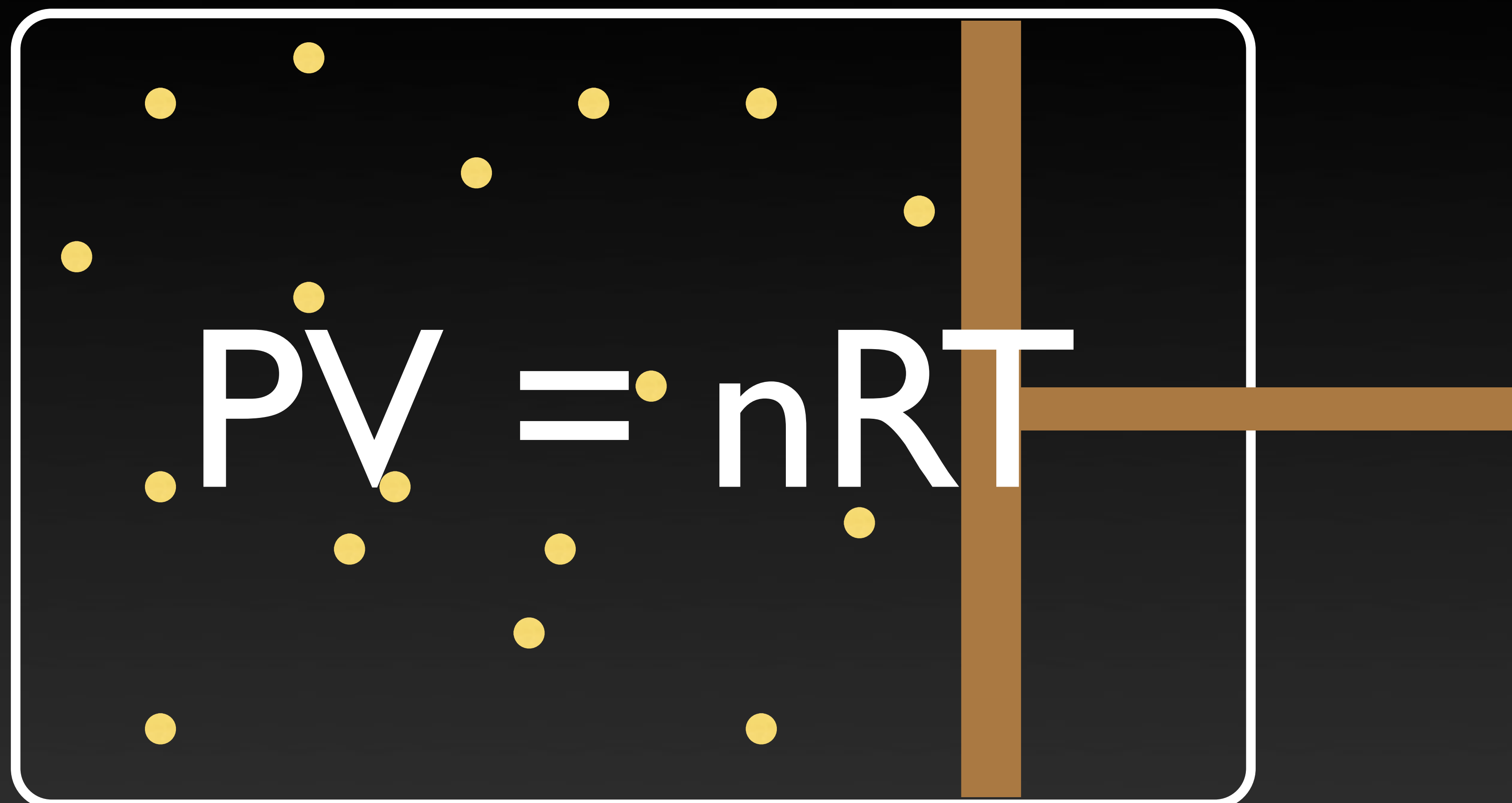
Richard Seager, "The Source of Europe's Mild Climate," American Scientist (July-August 2006)

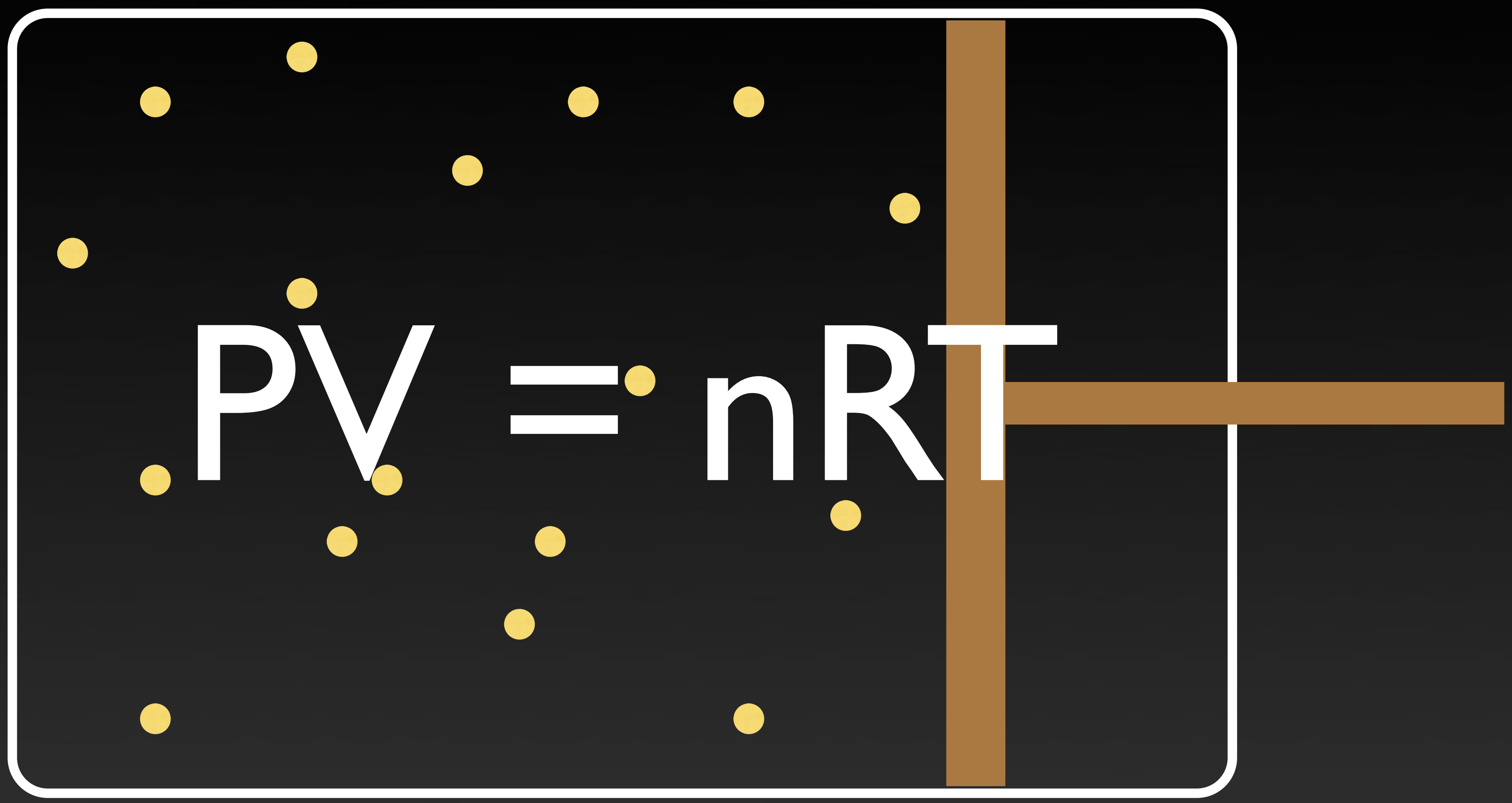
Quantum Field Theory of Global Warming?

"More than any other theoretical procedure, numerical integration is also subject to the criticism that it yields little insight into the problem. The computed numbers are not only processed like data but they look like data, and a study of them may be no more enlightening than a study of real meteorological observations. An alternative procedure which does not suffer this disadvantage consists of deriving a new system of equations whose unknowns are the statistics themselves."

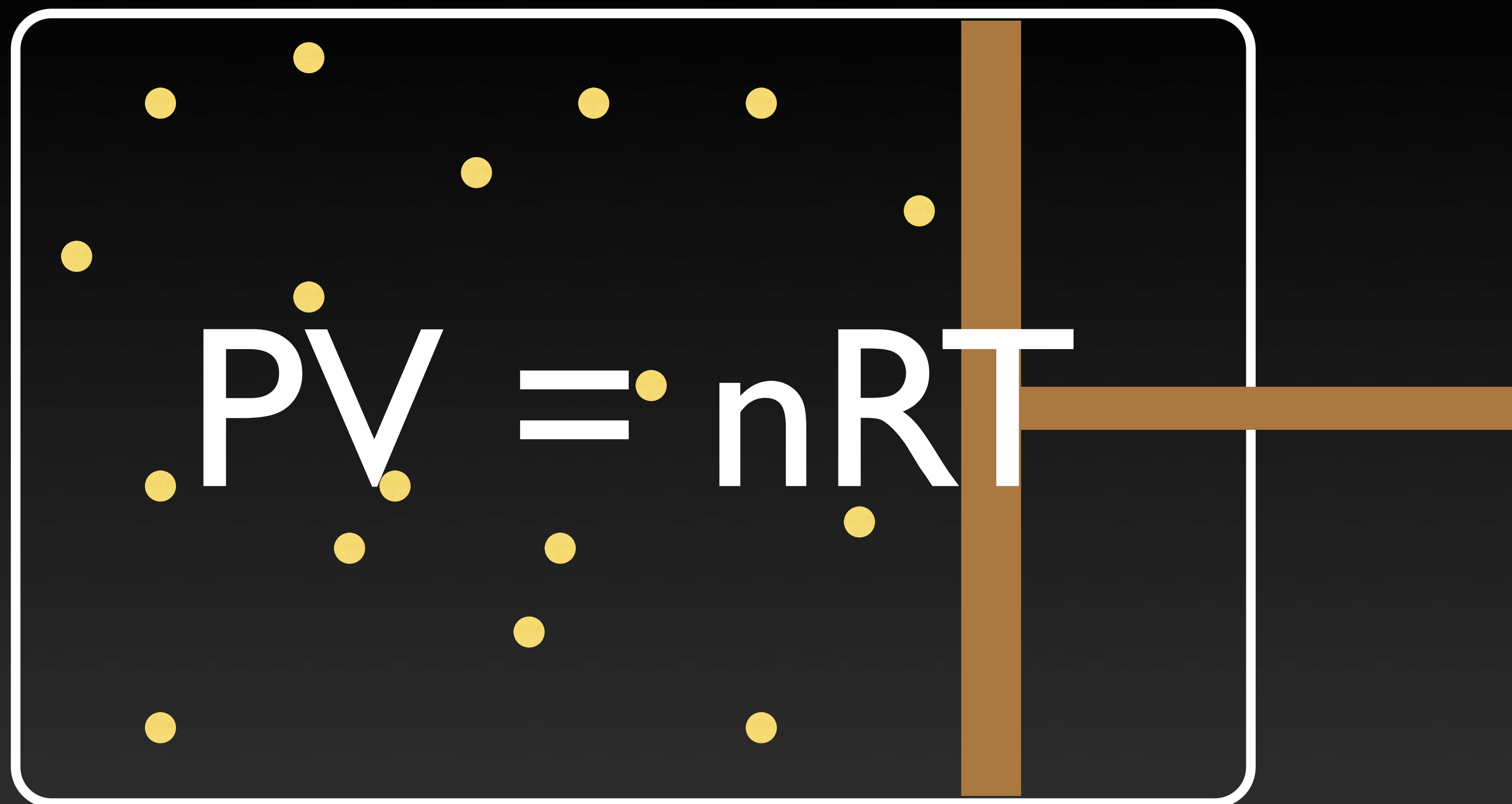
Edward Lorenz, The Nature and Theory of the General Circulation (1967)




PV = nRT



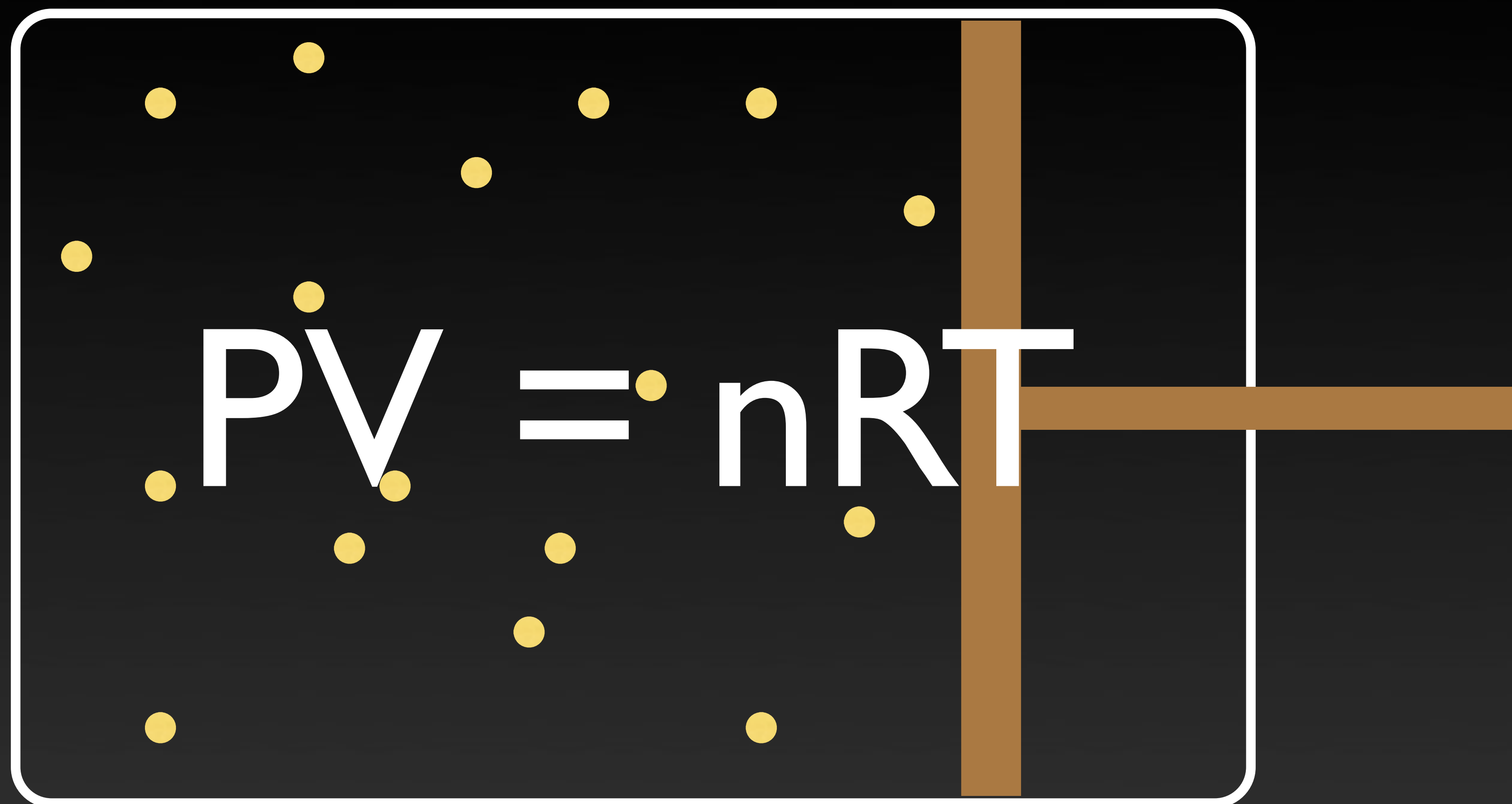
Thermodynamics vs. Statistical Mechanics



$$PV = nRT$$

Thermodynamics vs. Statistical Mechanics

Equilibrium vs. Out-of-Equilibrium



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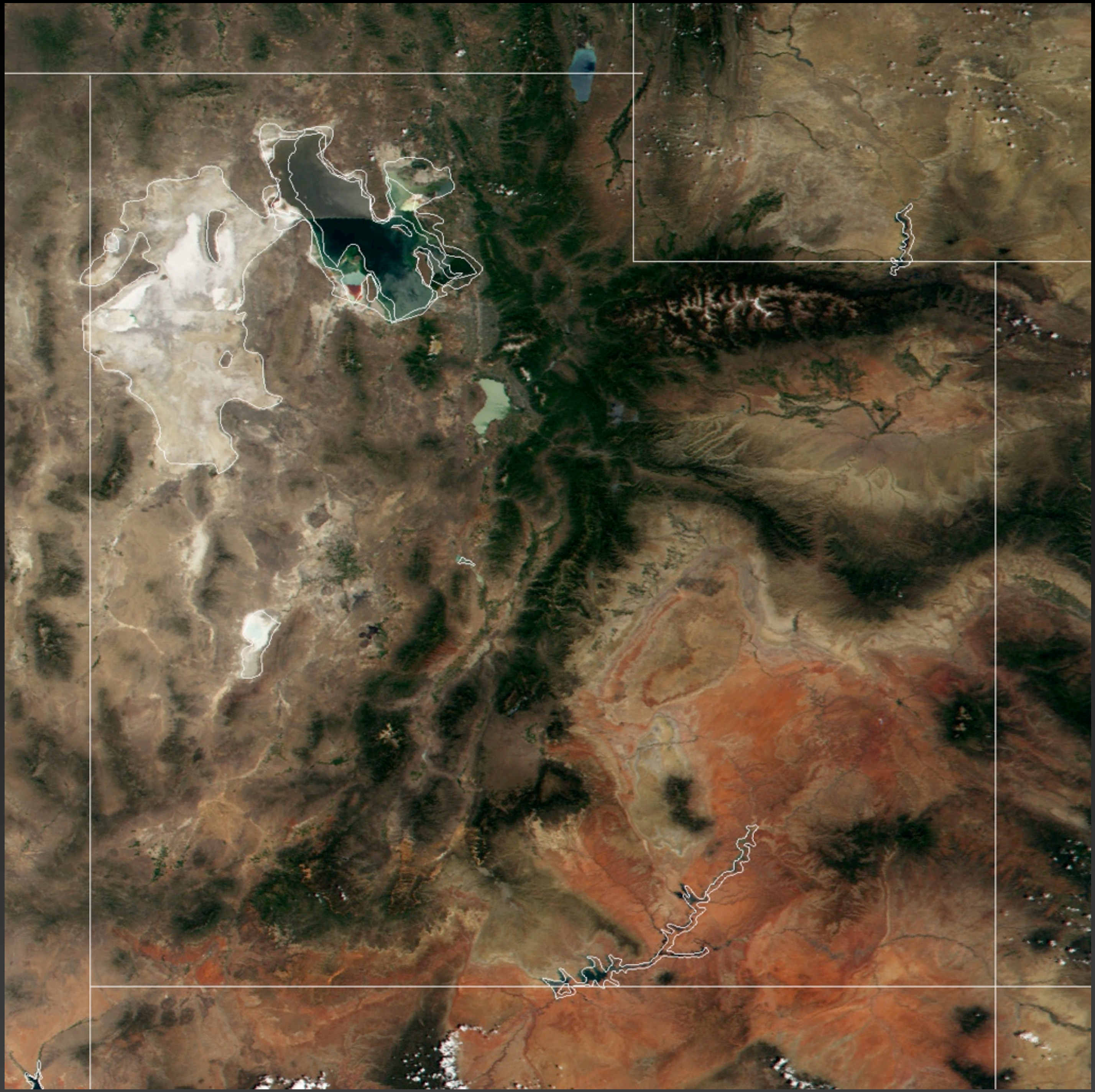
Thermodynamics vs. Statistical Mechanics

Equilibrium vs. Out-of-Equilibrium




Hopf Functional Approach

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$$\frac{dx}{dt} = x^2$$

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$$i\frac{\partial}{\partial t}\Psi = u\frac{\partial^2}{\partial u^2}\Psi$$

Hopf Functional Approach

$$\frac{dx}{dt} = x^2 \qquad\qquad \Psi(t,u) \equiv e^{iux(t)}$$

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Hopf Functional Approach

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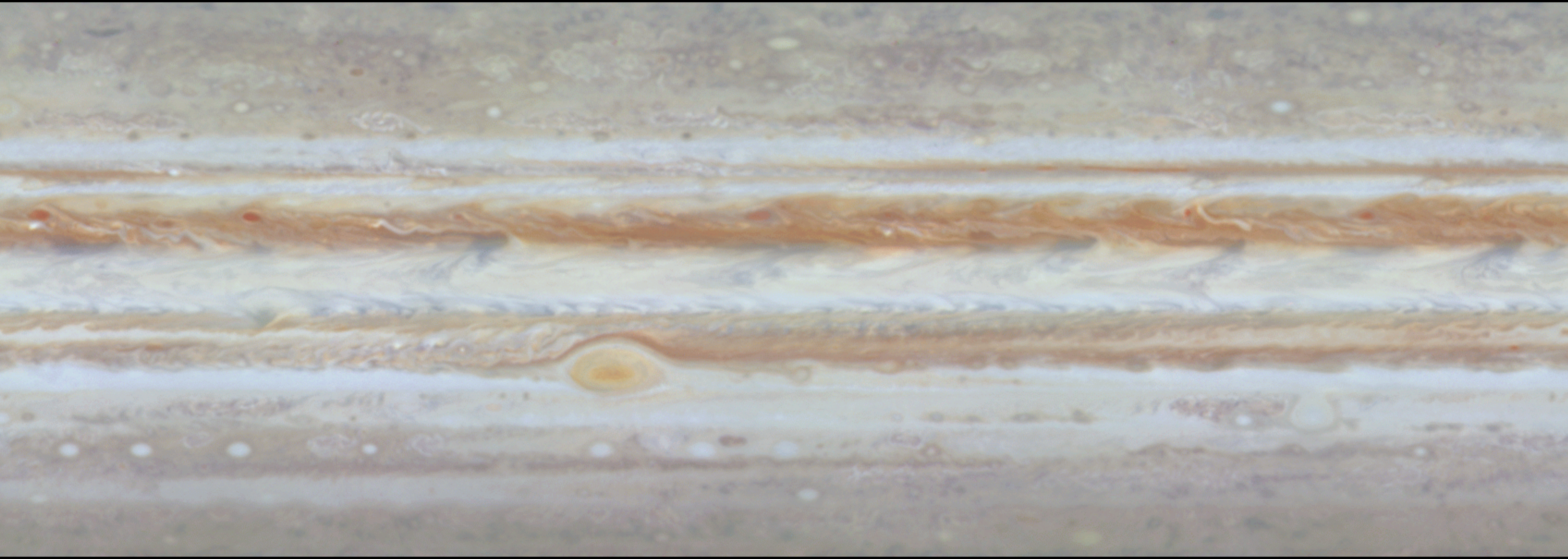
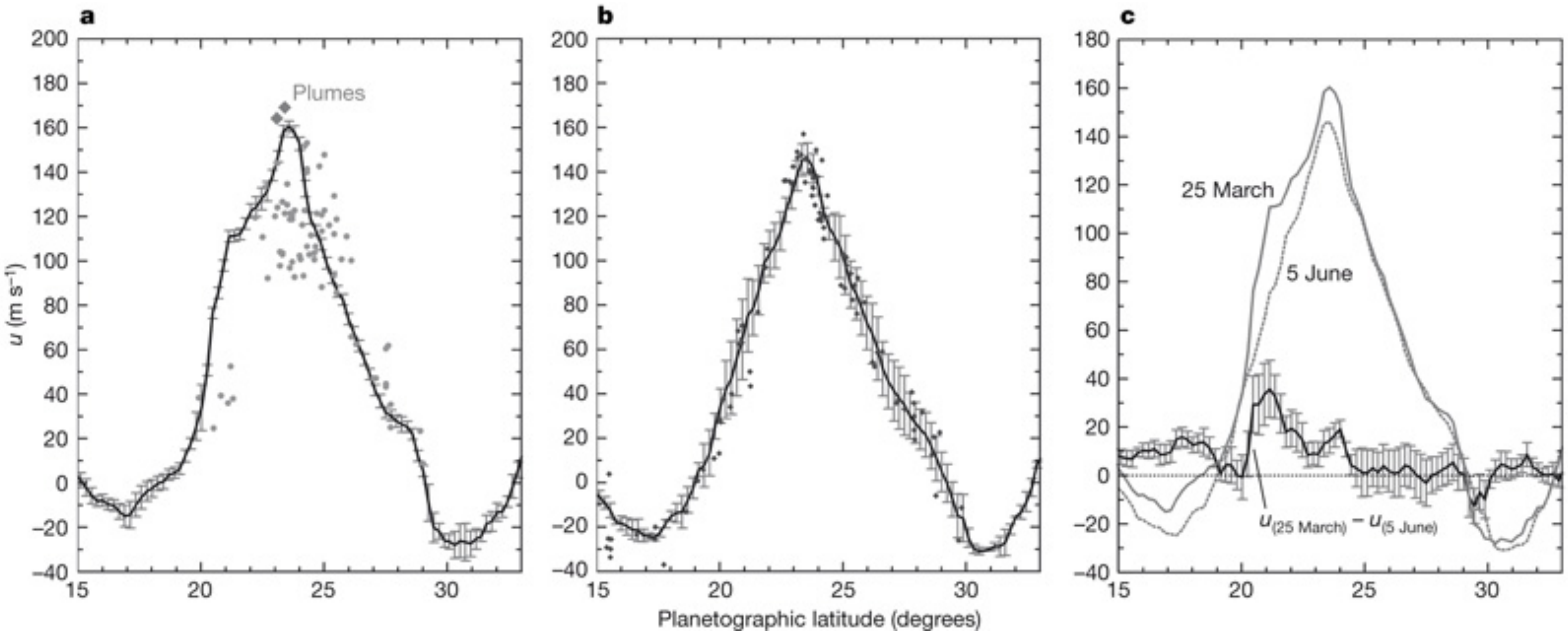
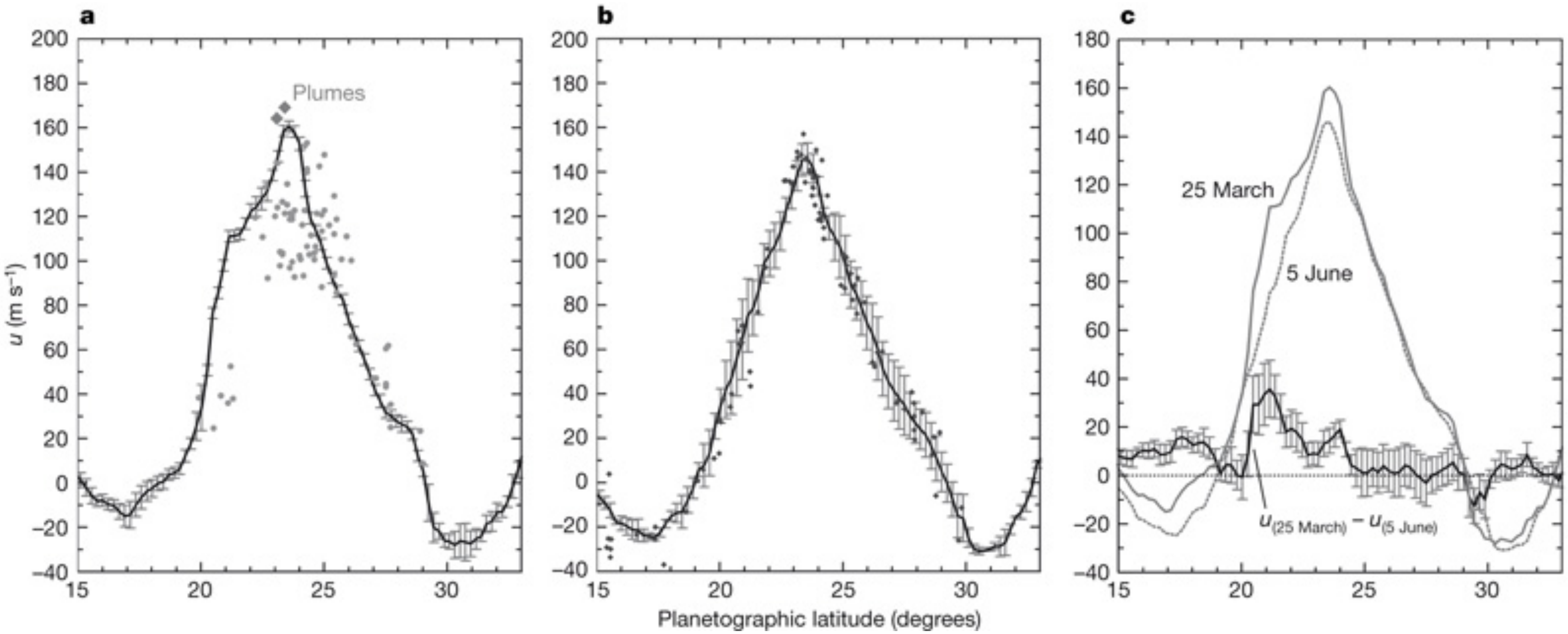
$$i\frac{\partial}{\partial t}\Psi = u\frac{\partial^2}{\partial u^2}\Psi \qquad\qquad i\frac{\partial}{\partial t}\overline{\Psi} = u\frac{\partial^2}{\partial u^2}\overline{\Psi}$$

$$\begin{aligned}
\hat{H}\overline{\Psi}_0 &= 0 \\
\overline{\Psi}_0(u) &= \exp\{iu\langle x\rangle - \frac{1}{2!}u^2(\langle x^2\rangle - \langle x\rangle^2) + \ldots\} \\
\langle x\rangle &= -i\frac{\partial\overline{\Psi}_0(u)}{\partial u}\bigg|_{u=0}
\end{aligned}$$

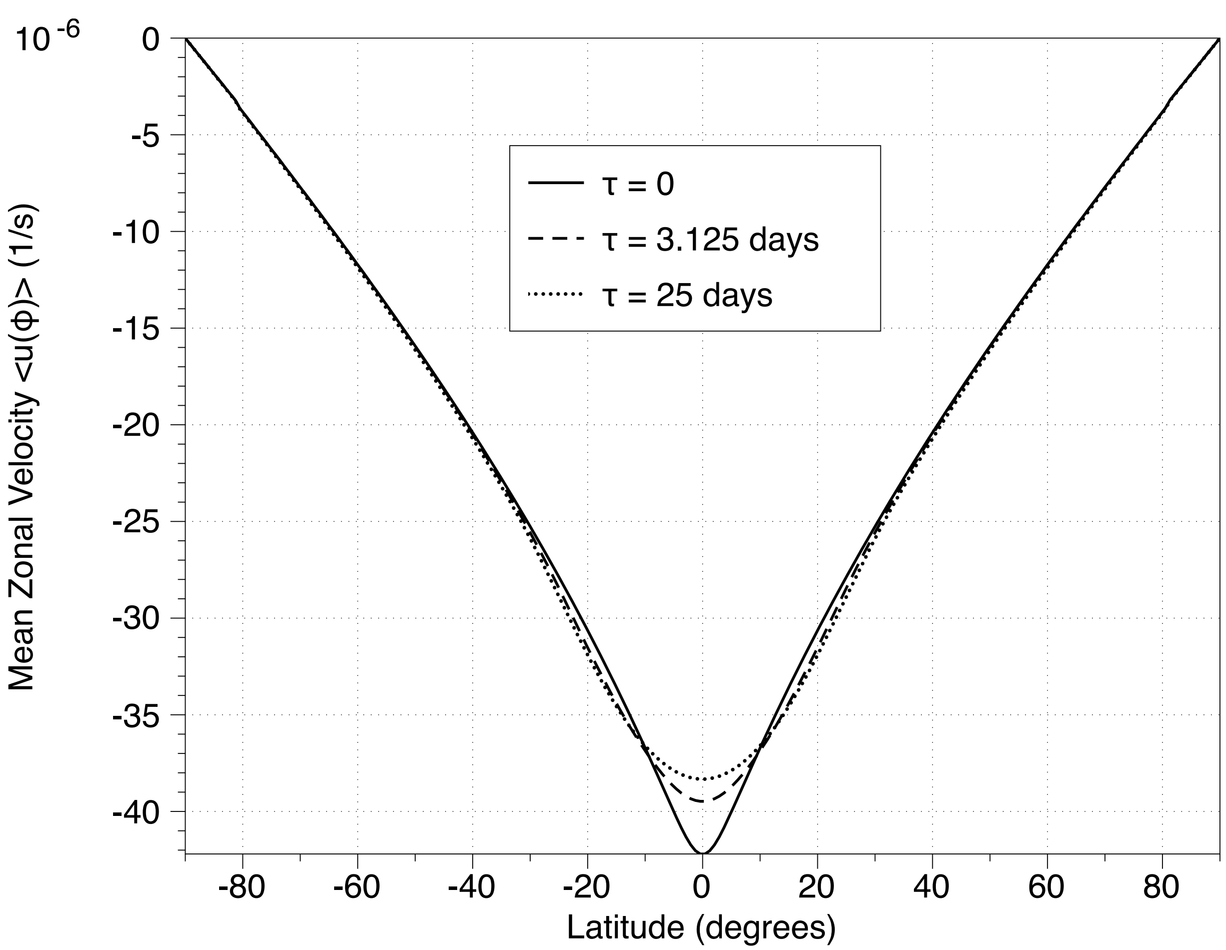


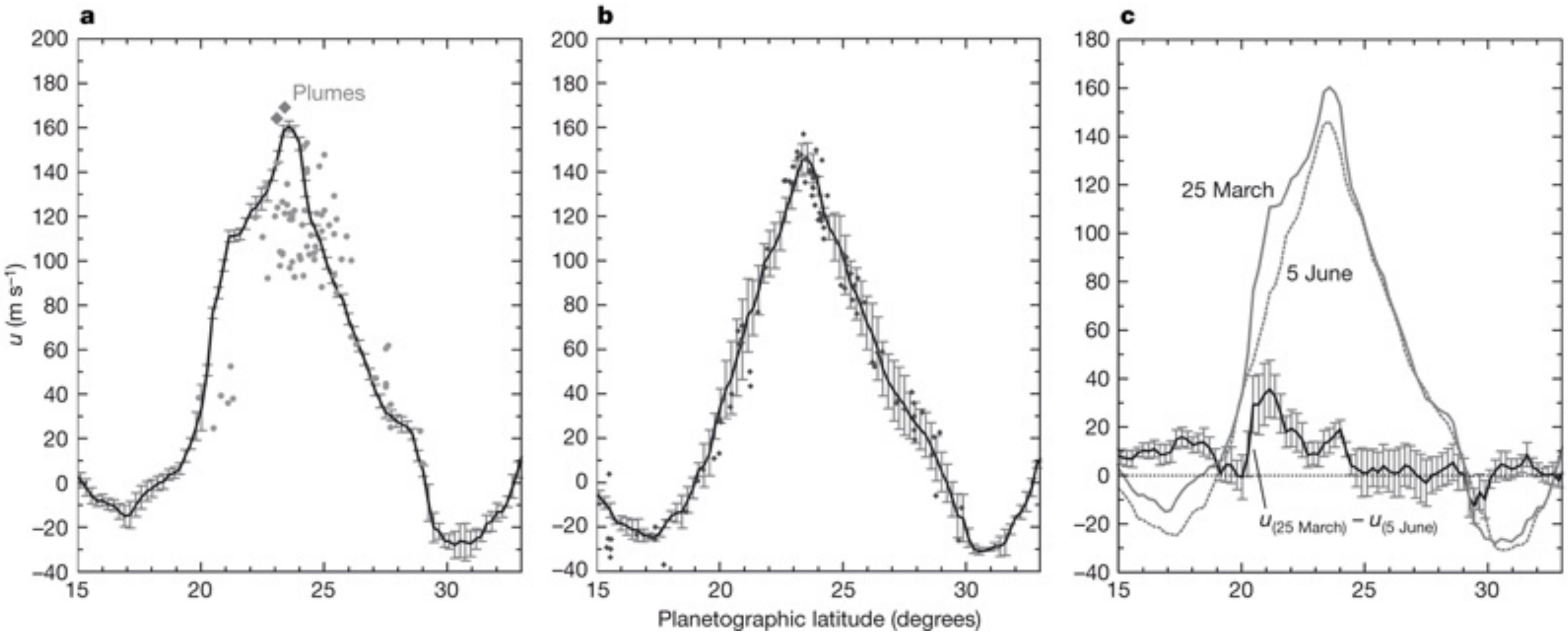


A. Sanchez-Lavega *et al.* Nature **451**, 437 (2008)

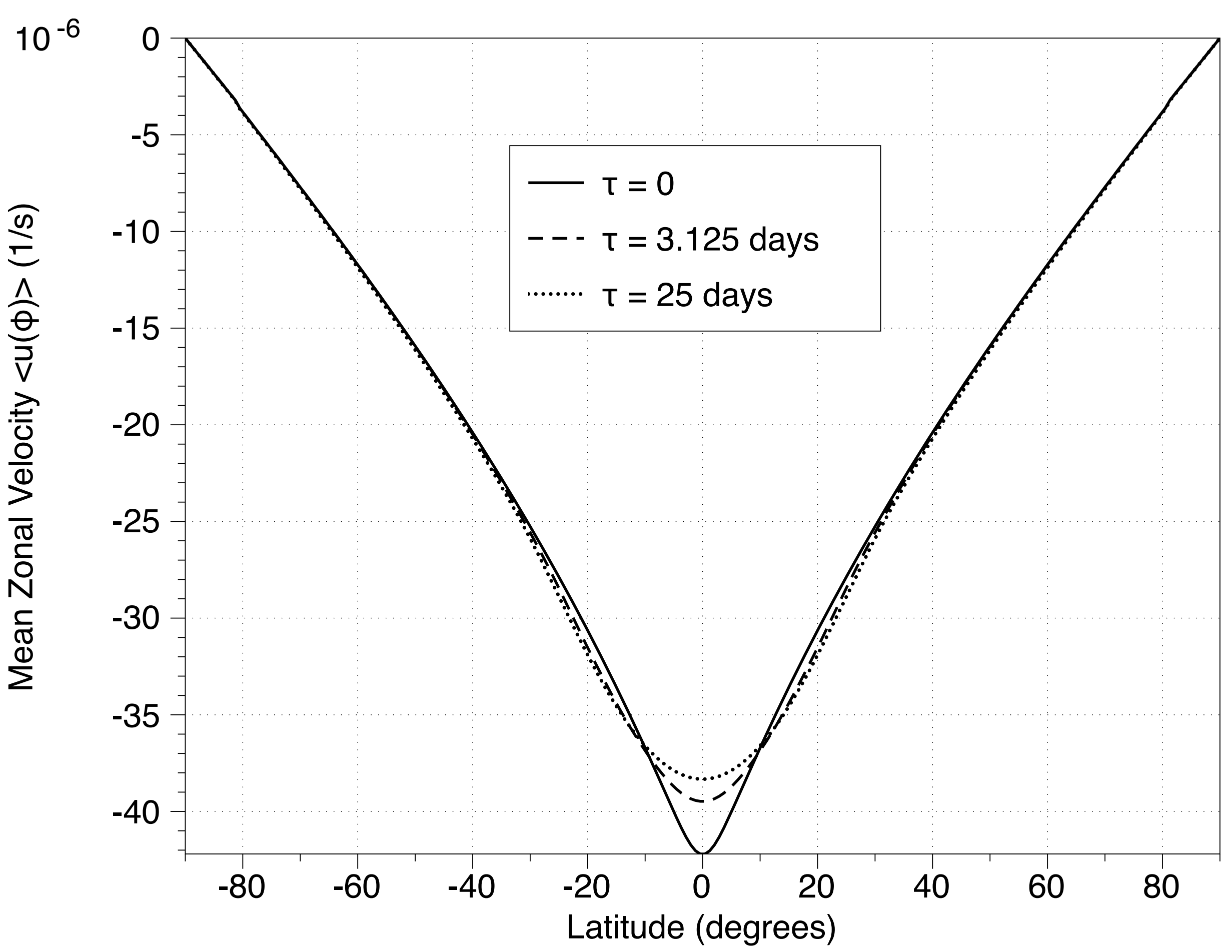


A. Sanchez-Lavega *et al.* Nature **451**, 437 (2008)





A. Sanchez-Lavega *et al.* Nature **451**, 437 (2008)



$$\frac{\partial q}{\partial t} + J[\psi, q] = \frac{q_{\rm jet} - q}{\tau}$$

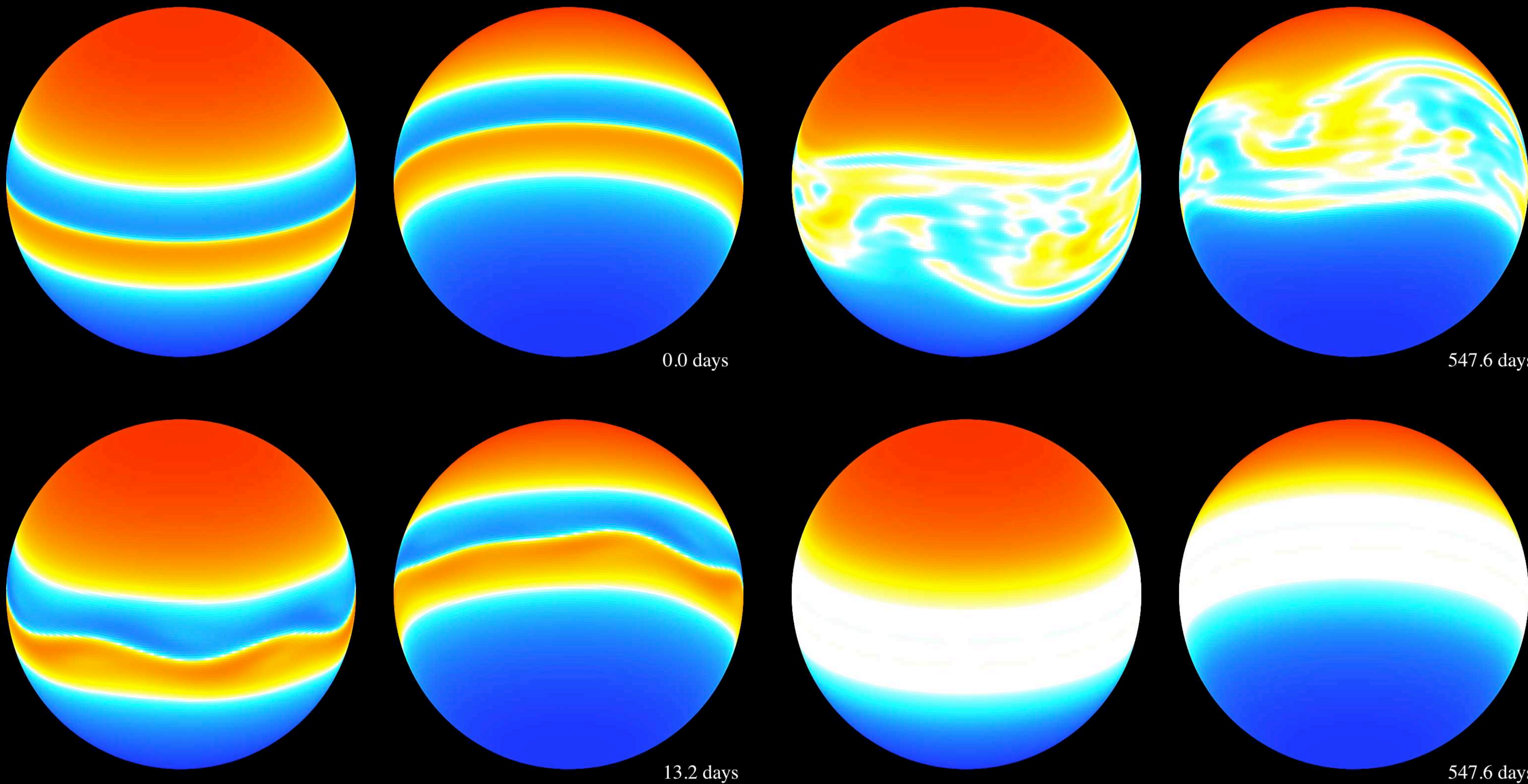
Direct Numerical Simulation of Jet

jet relaxation time = 25 days

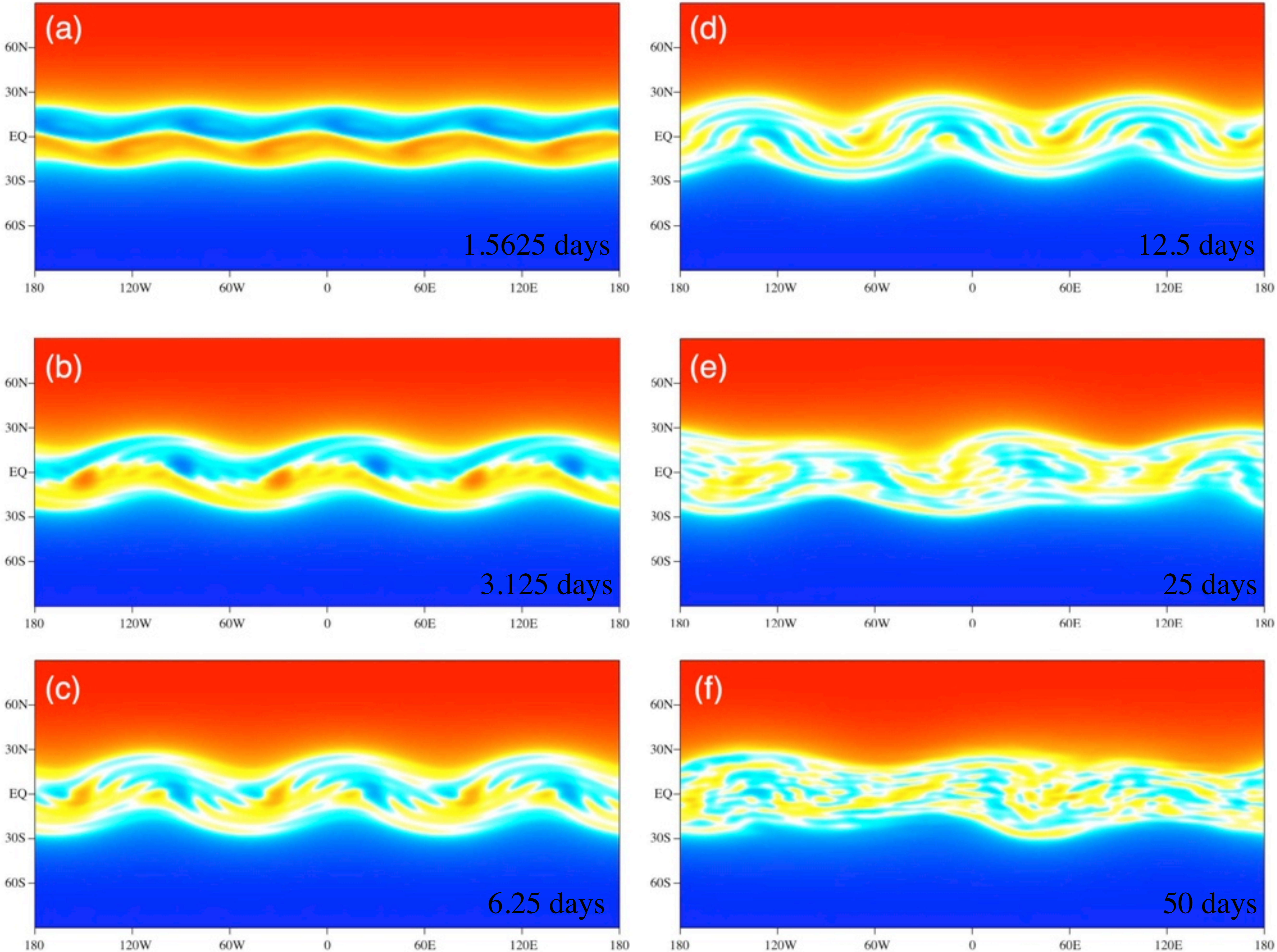
J. B. M, E. Conover, and T. Schneider, J. Atmos. Sci. **65**, 1955 (2008)

Direct Numerical Simulation of Jet

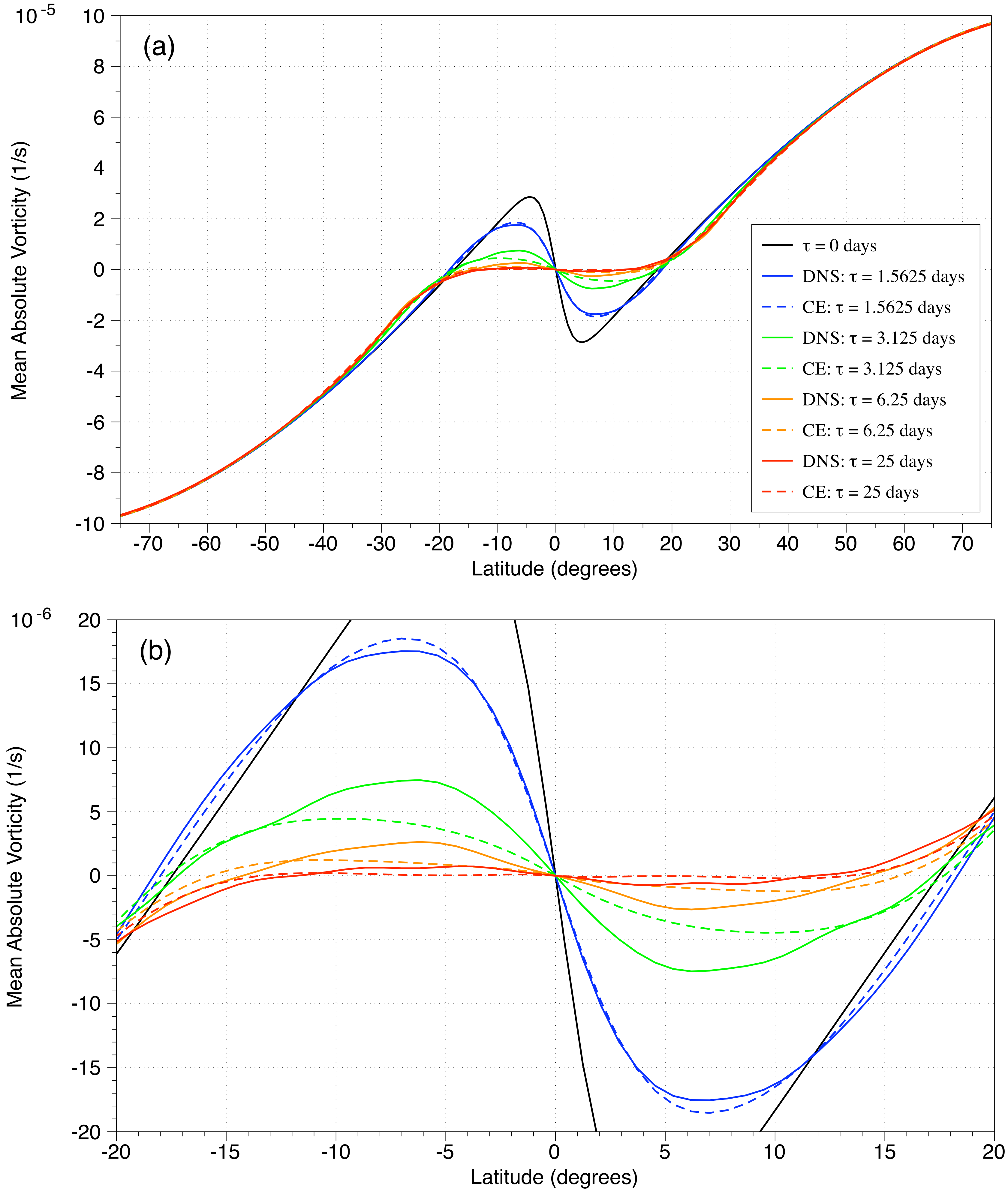
jet relaxation time = 25 days



J. B. M, E. Conover, and T. Schneider, J. Atmos. Sci. **65**, 1955 (2008)

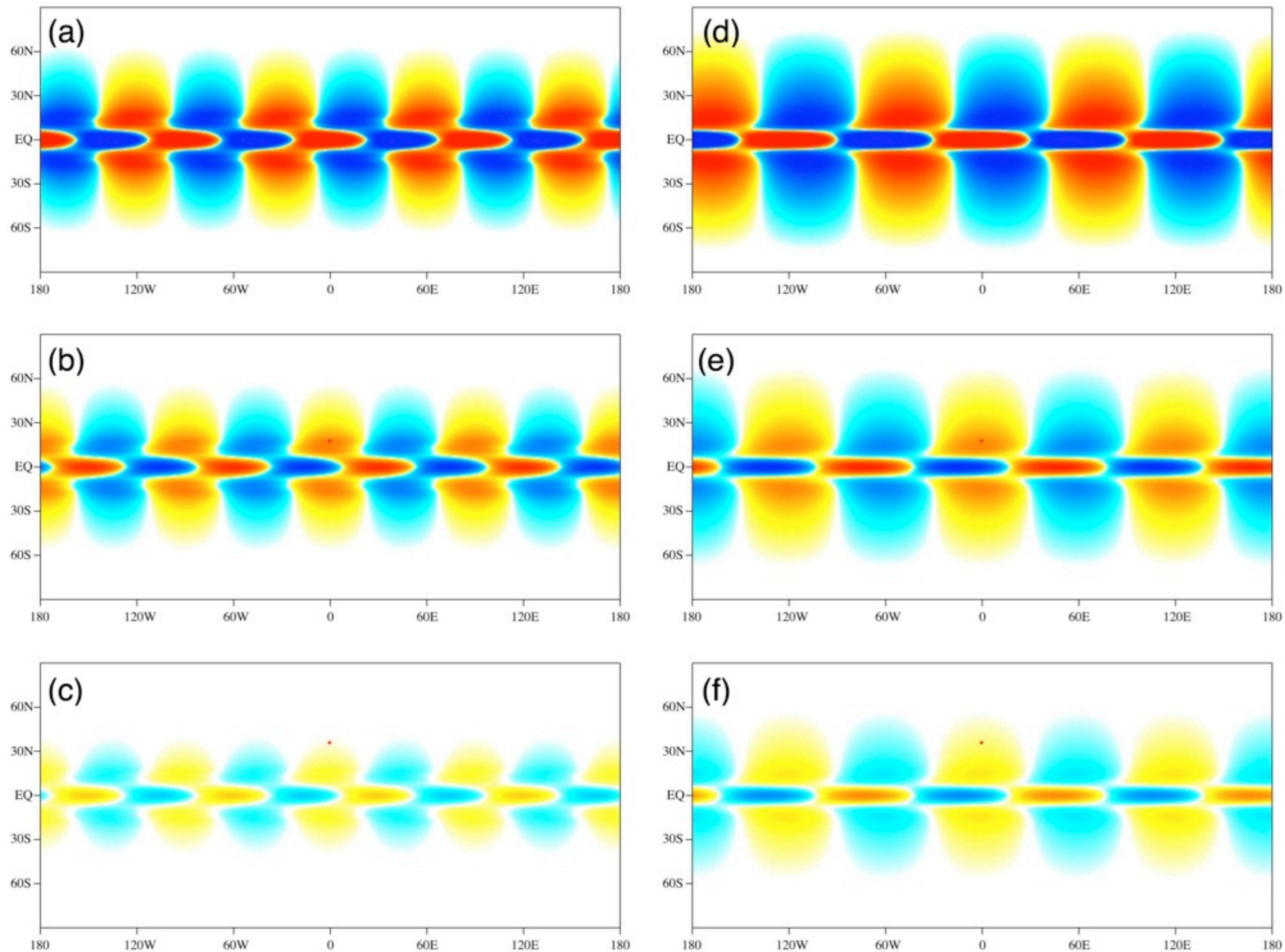


(a)
1.5625 days
(b)
3.125 days
(c)
6.25 days
(d)
12.5 days
(e)
25 days
(f)
50 days
60N
30N
EQ
30S
60S
50N
50S
180
120W
60W
0
60E
120E

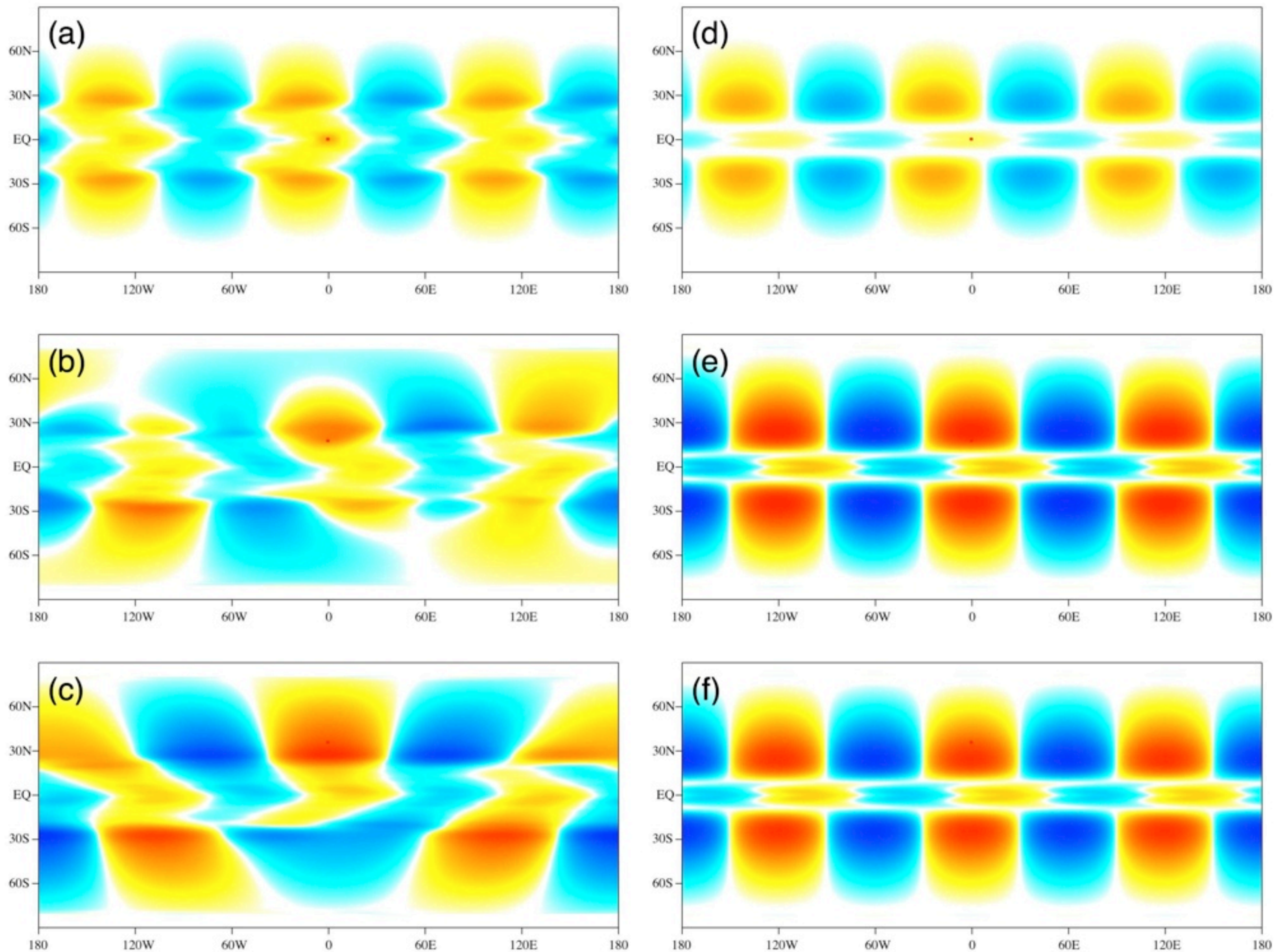


(a)
(b)
10 -5
10 -6
Mean Absolute Vorticity (1/s)
Latitude (degrees)
τ = 0 days
DNS: τ = 1.5625 days
CE: τ = 1.5625 days
DNS: τ = 3.125 days
CE: τ = 3.125 days
DNS: τ = 6.25 days
CE: τ = 6.25 days
DNS: τ = 25 days
CE: τ = 25 days

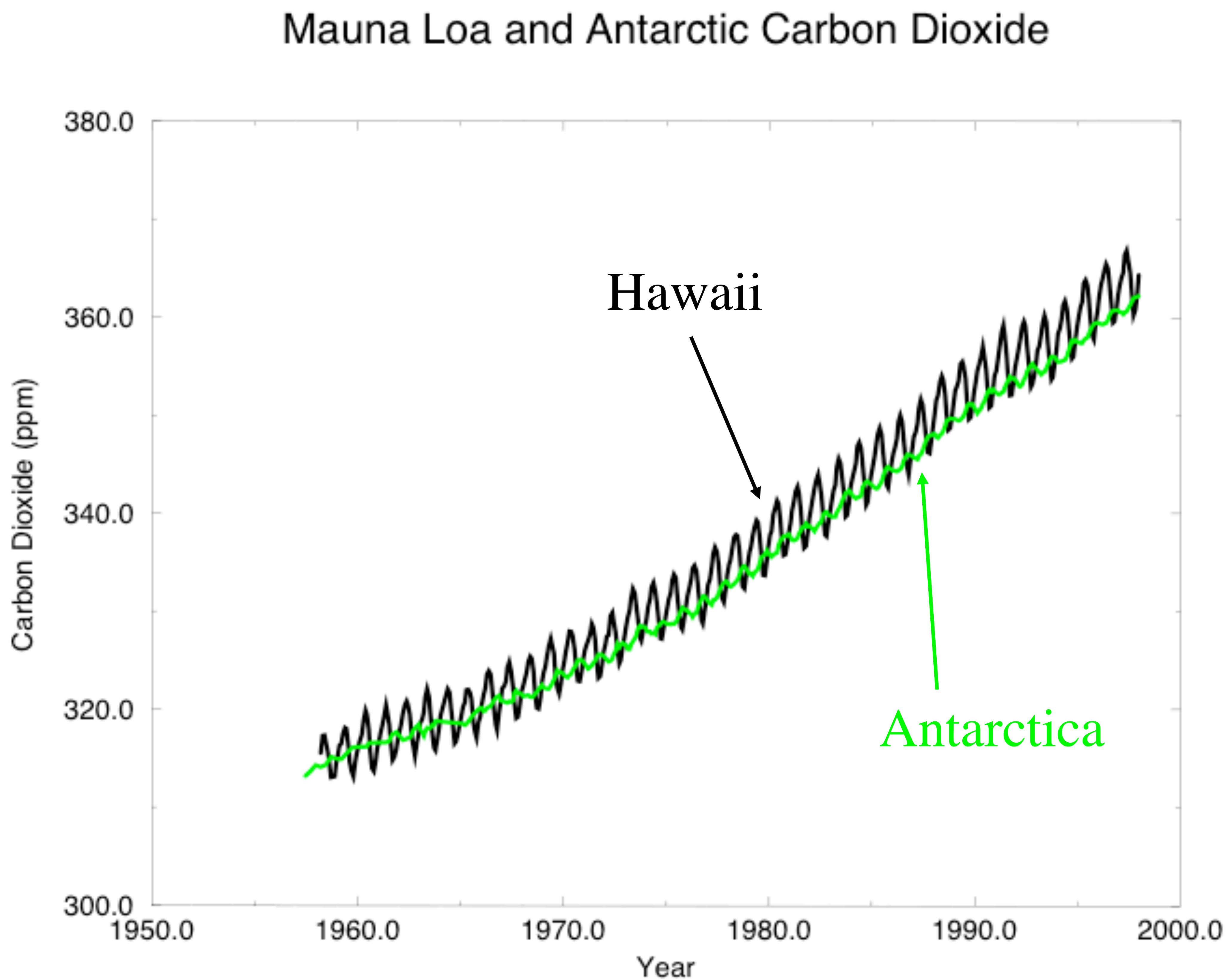
2nd Cumulant = 2-point Correlation Function



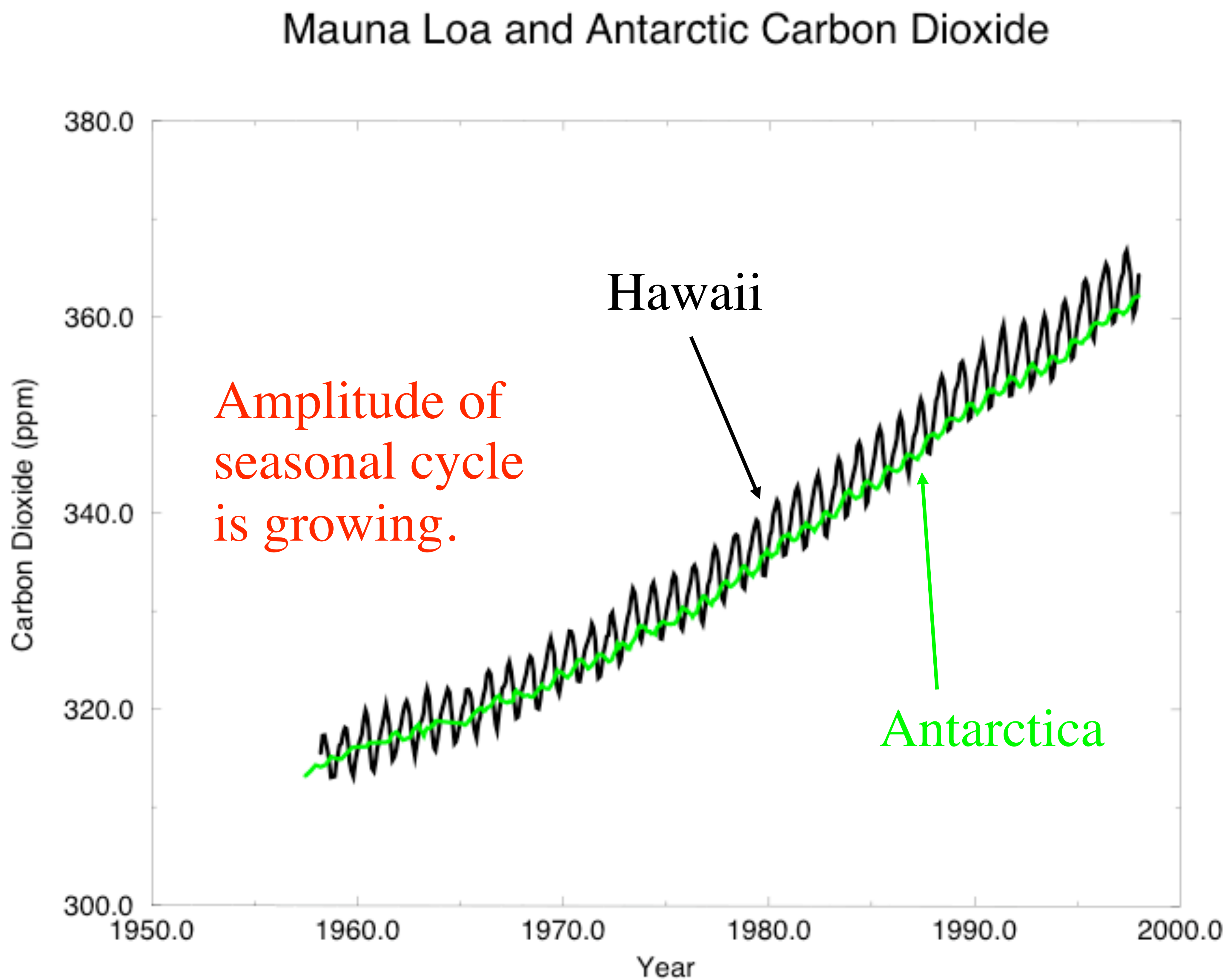
25 days



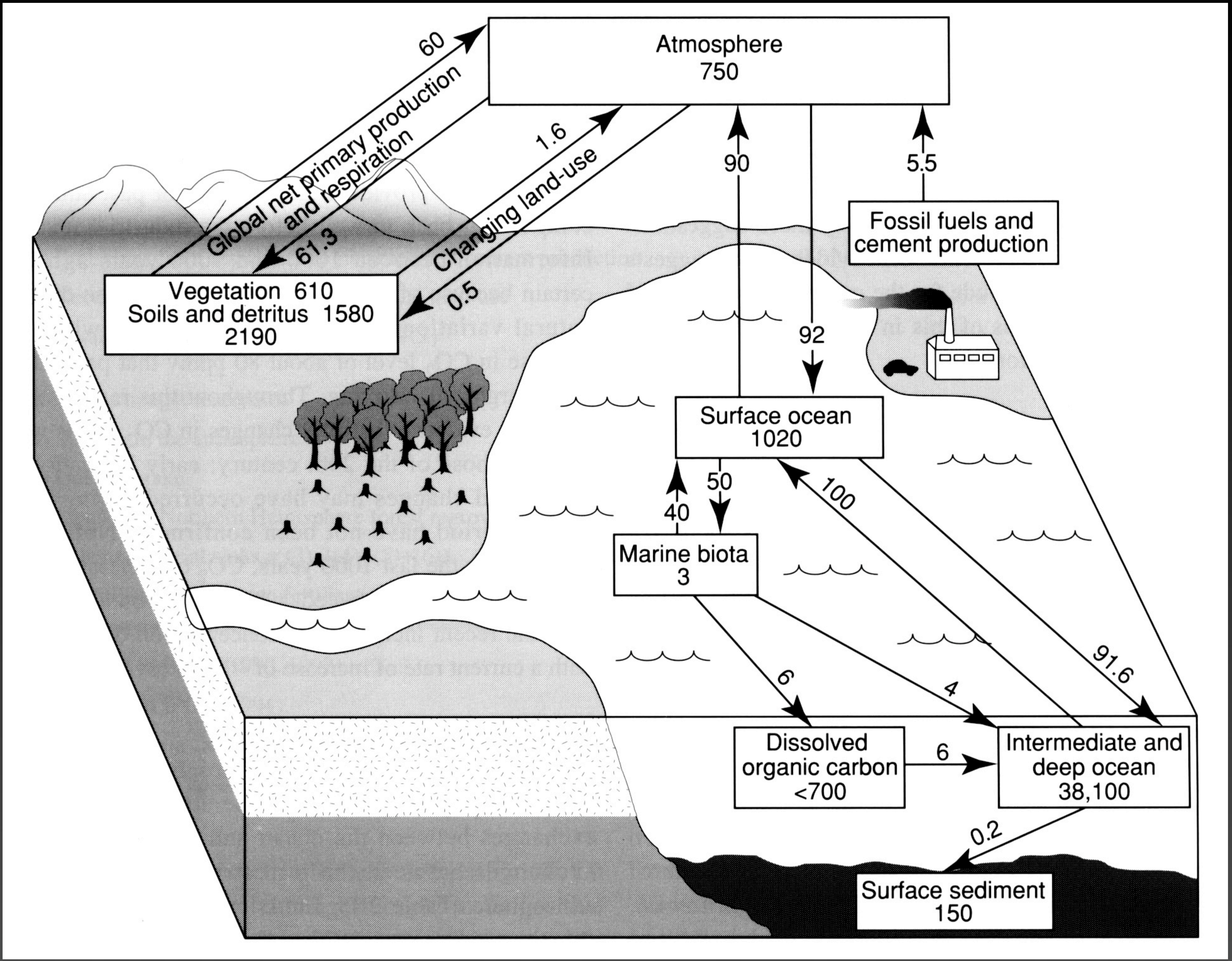
Ecosystems & Feedbacks



Ecosystems & Feedbacks



Vast Reservoirs of Carbon & Enormous Fluxes



Source: *Climate Change 1995*

THE NEW YORK TIMES **THE ENVIRONMENT** TUESDAY, FEBRUARY 19, 1991

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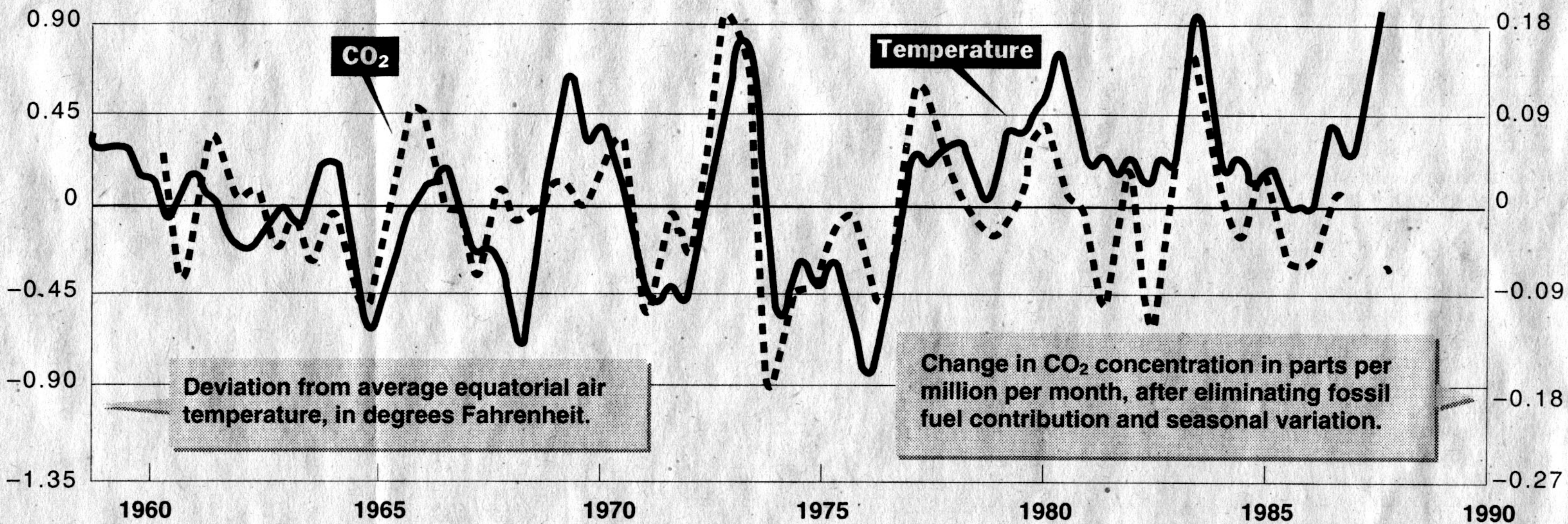
Temperature and CO_2, Moving in Tandem

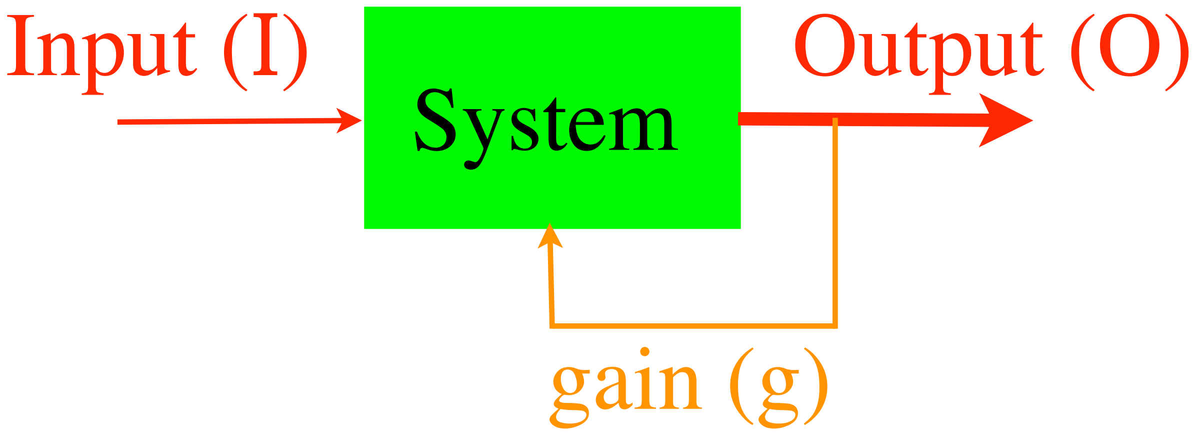
Research results indicate a strong correlation between variations in temperature and variations in atmospheric carbon dioxide concentration. Some scientists say that the temperature increases often precede the carbon dioxide rises, meaning that warming could build on itself to create further warming.



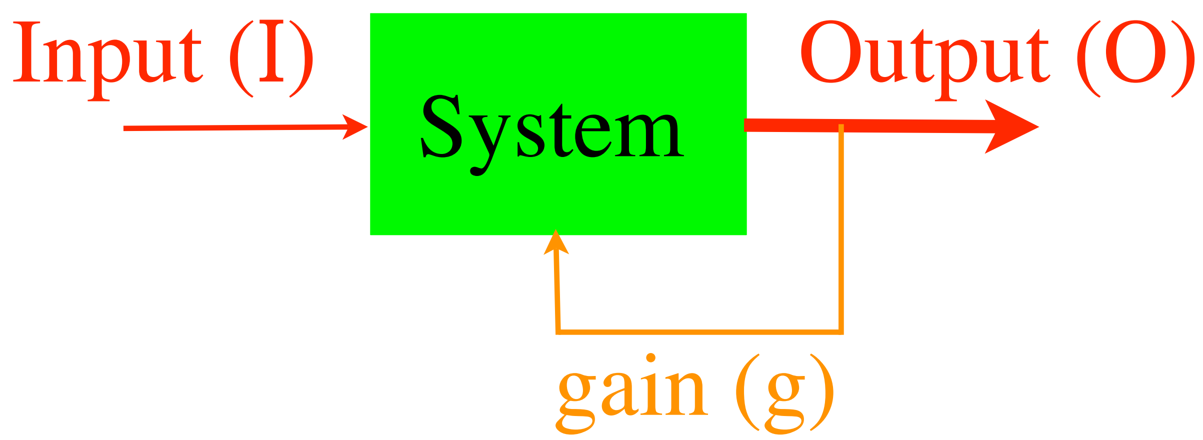
Sources: Dr. Michael Oppenheimer, and Dr. J.B. Marston

J. B. Marston, M. Oppenheimer, R. M. Fujita, and S. R. Gaffin, "CO_2 and temperature" Nature **349**, 573 (1991).

Physics of Feedbacks



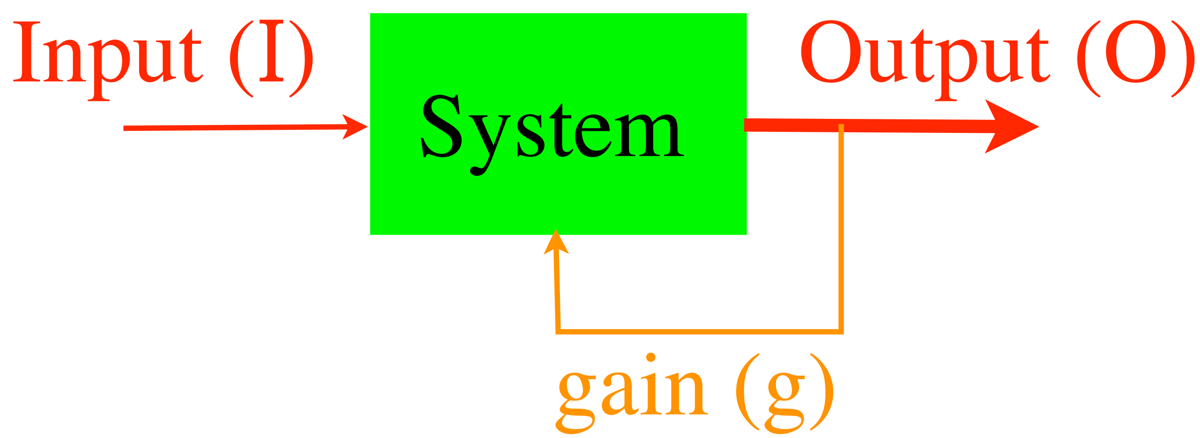
Physics of Feedbacks



$$\mathcal{O} = \mathcal{I} + g\mathcal{I} + gg\mathcal{I} + \cdots$$
$$= \frac{\mathcal{I}}{1-g} \quad \text{if } g < 1$$

$$g = \sum_i (\frac{\partial T}{\partial p_i})(\frac{\partial p_i}{\partial T})$$

Physics of Feedbacks



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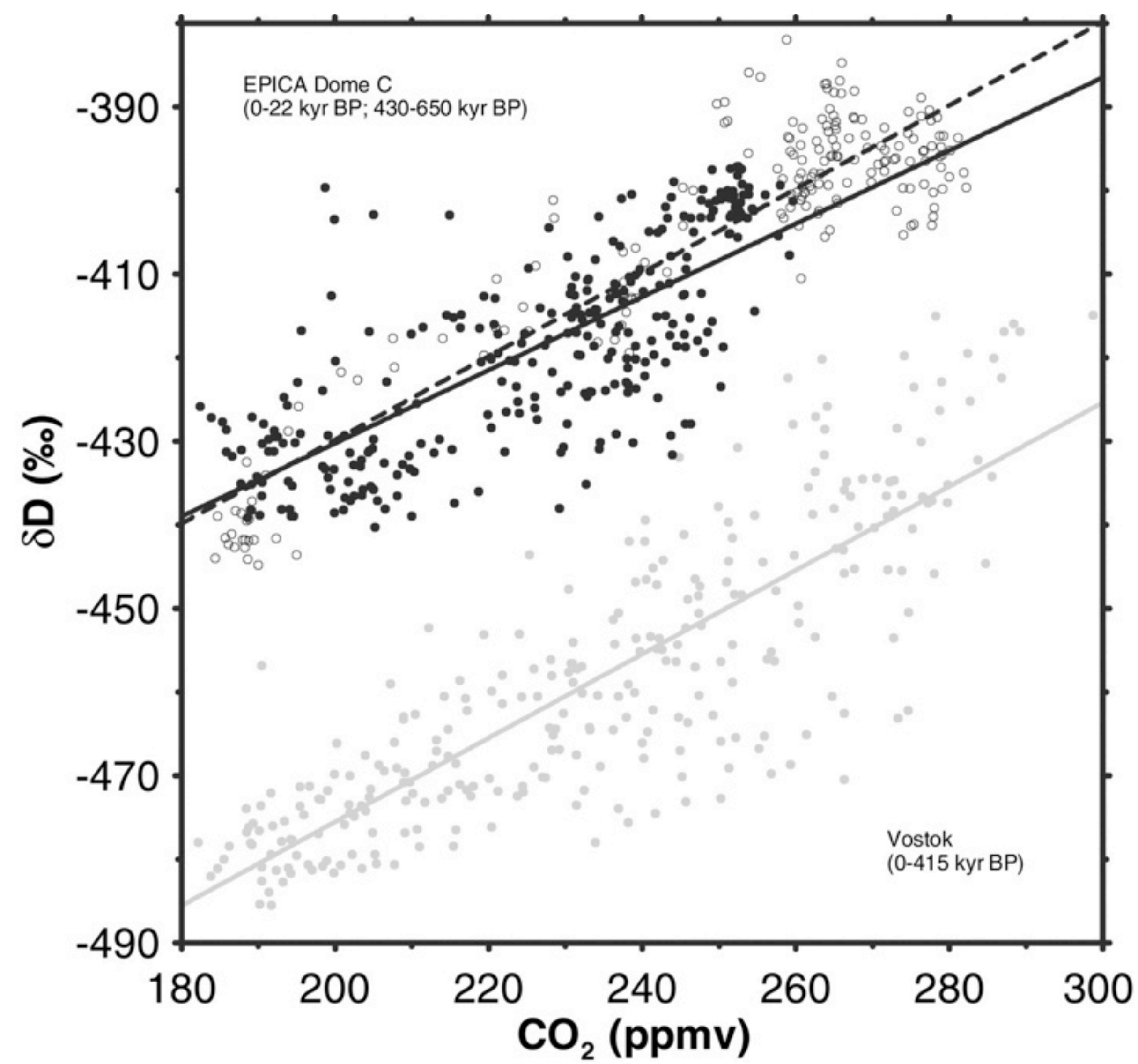

Some Feedbacks Already Included in Models

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Feedback Process	Gain g

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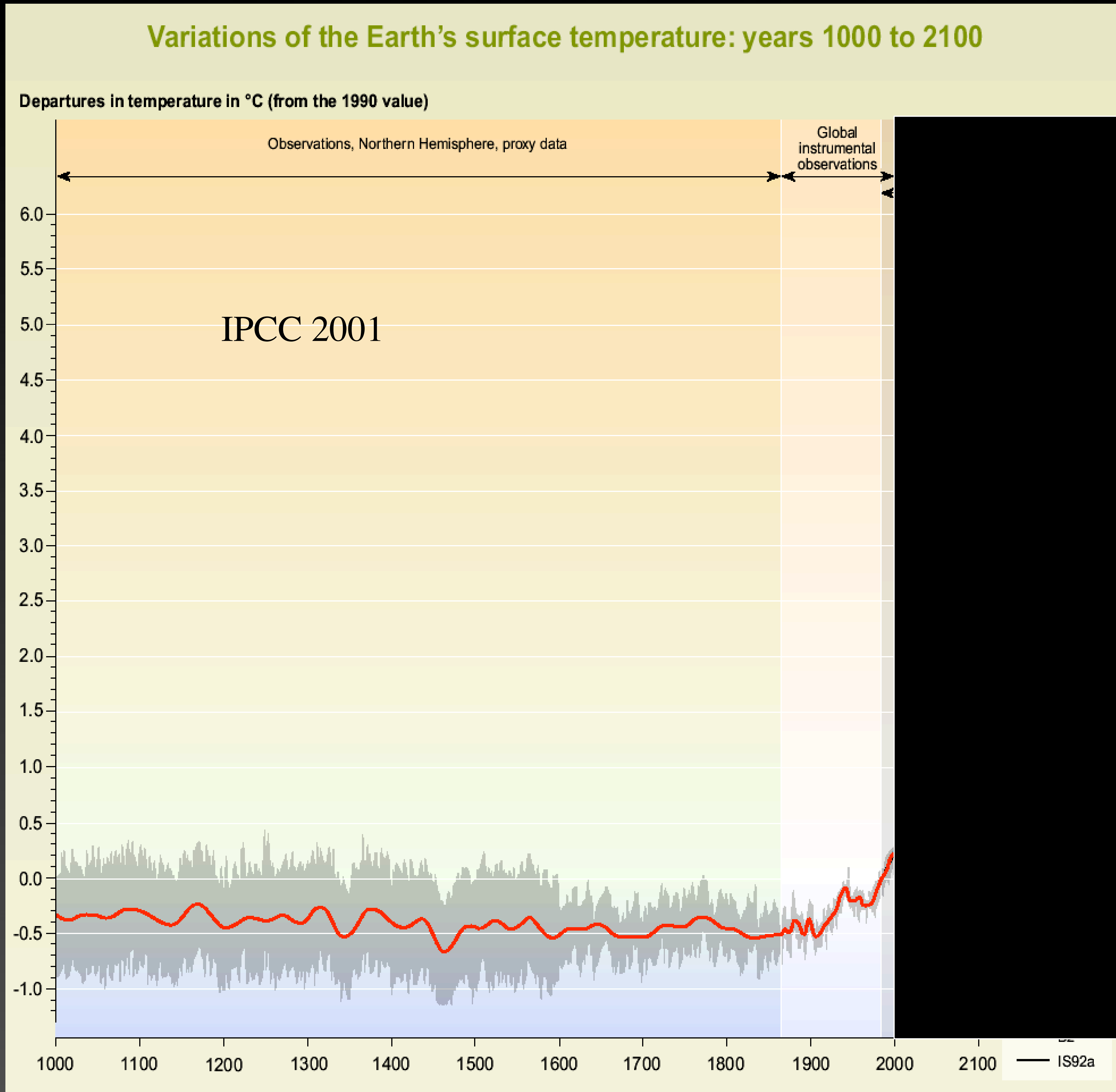
Total	0.71 (0.17 to 0.77)

$$\Delta T \approx 1°C/(1-0.71) \approx 3.4°C$$


Variations of the Earth's surface temperature: years 1000 to 2100
Departures in temperature in °C (from the 1990 value)
Observations, Northern Hemisphere, proxy data
Global instrumental observations
IPCC 2001
6.0
5.5
5.0
4.5
4.0
3.5
3.0
2.5
2.0
1.5
1.0
0.5
0.0
-0.5
-1.0
1000
1100
1200
1300
1400
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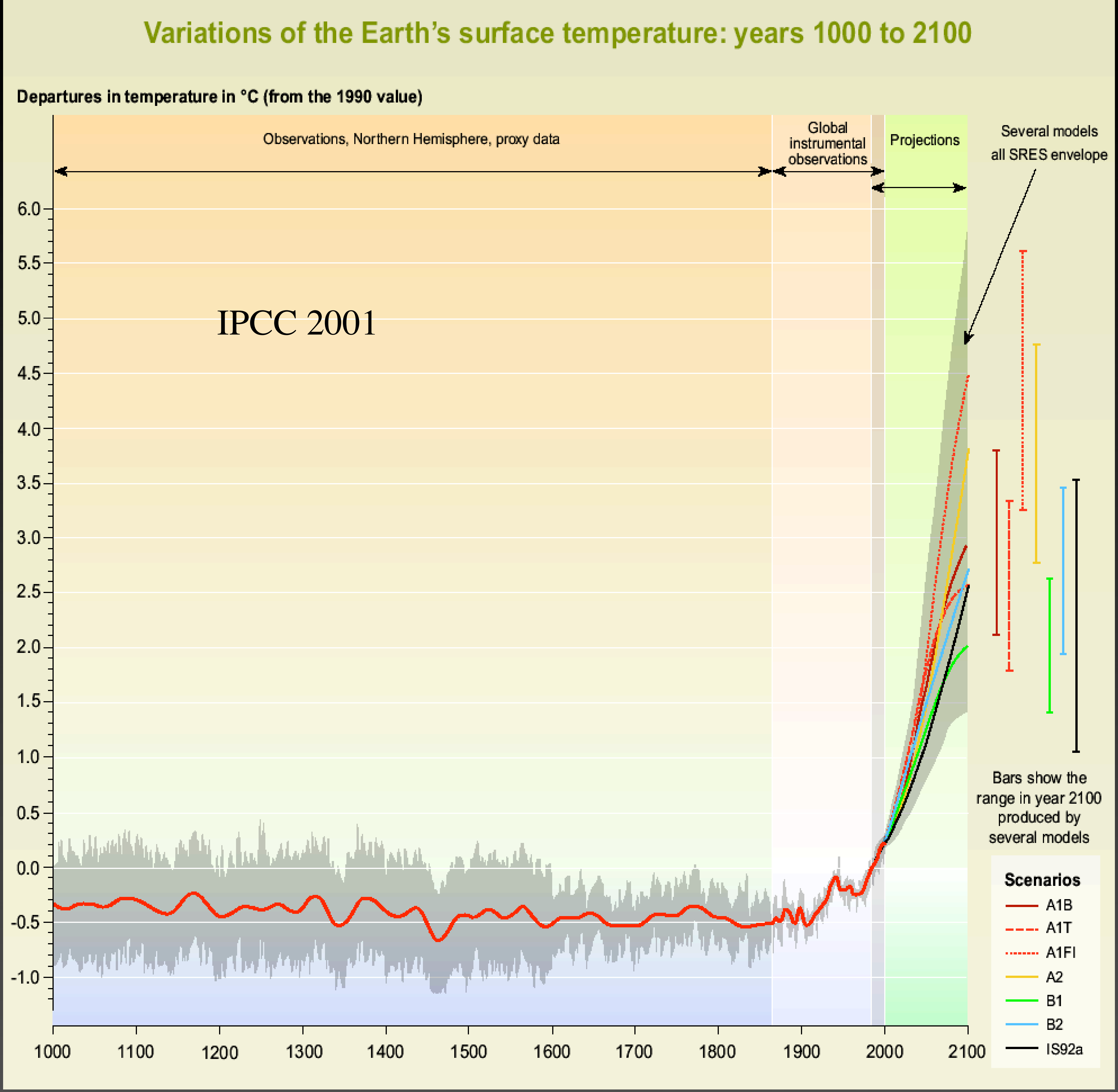
1600
1700
1800
1900
2000
2100
IS92a

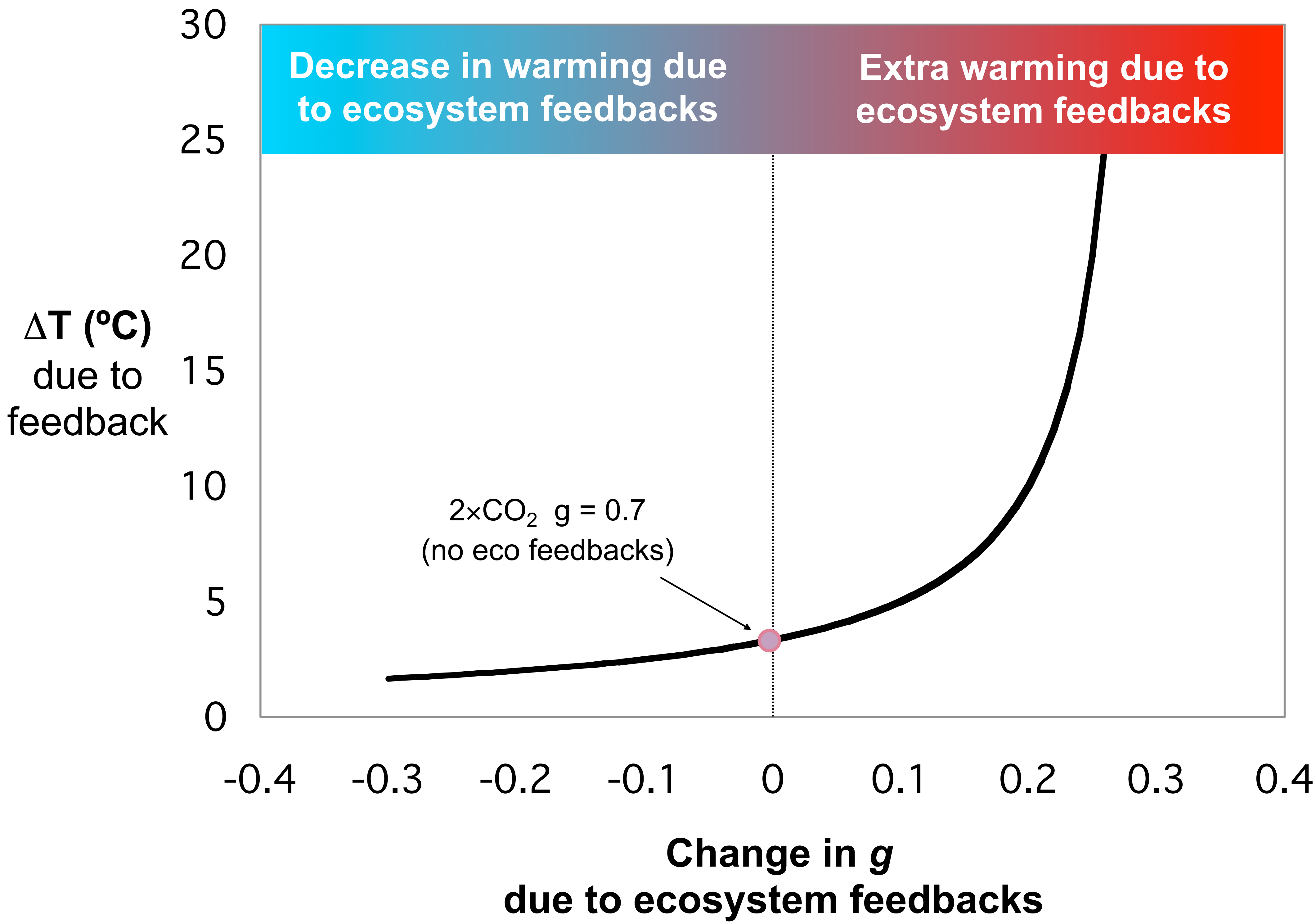


Variations of the Earth's surface temperature: years 1000 to 2100
Departures in temperature in °C (from the 1990 value)
Observations, Northern Hemisphere, proxy data
Global instrumental observations
Projections
Several models all SRES envelope
IPCC 2001
6.0
5.5
5.0
4.5
4.0
3.5
3.0
2.5
2.0
1.5
1.0
0.5
0.0
-0.5
-1.0
1000
1100
1200
1300
1400
1500
1600
1700
1800
1900
2000
2100
Bars show the range in year 2100 produced by several models
Scenarios
A1B
A1T
A1FI
A2
B1
B2
IS92a

Global Carbon Cycle

Small change in g causes large ΔT

Asymmetries

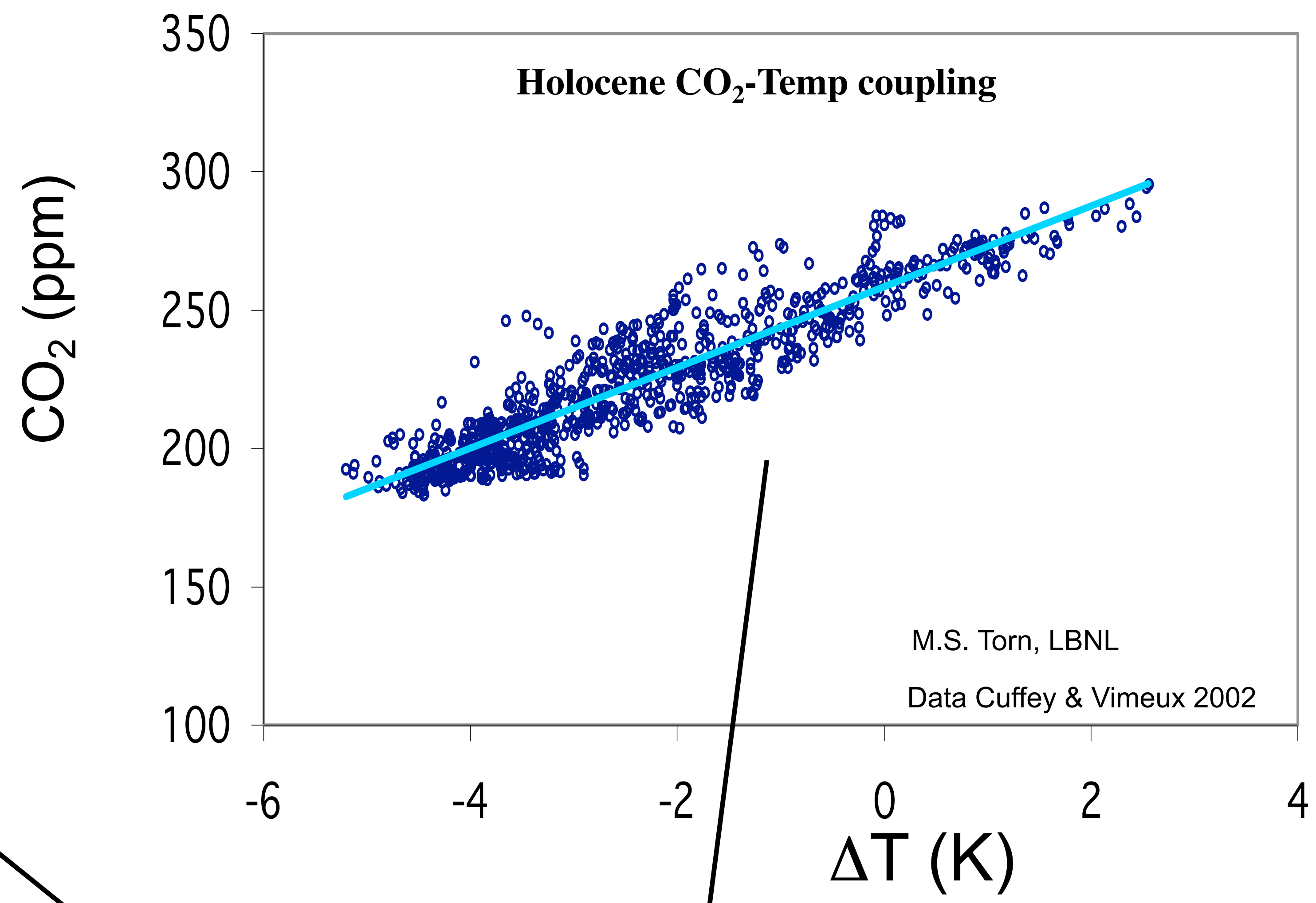


M.S. Torn, LBNL

An estimate of the contribution to g from Vostok core data:

Torn and Harte, GRL **33**, L10703 (2006)

General Circulation Models

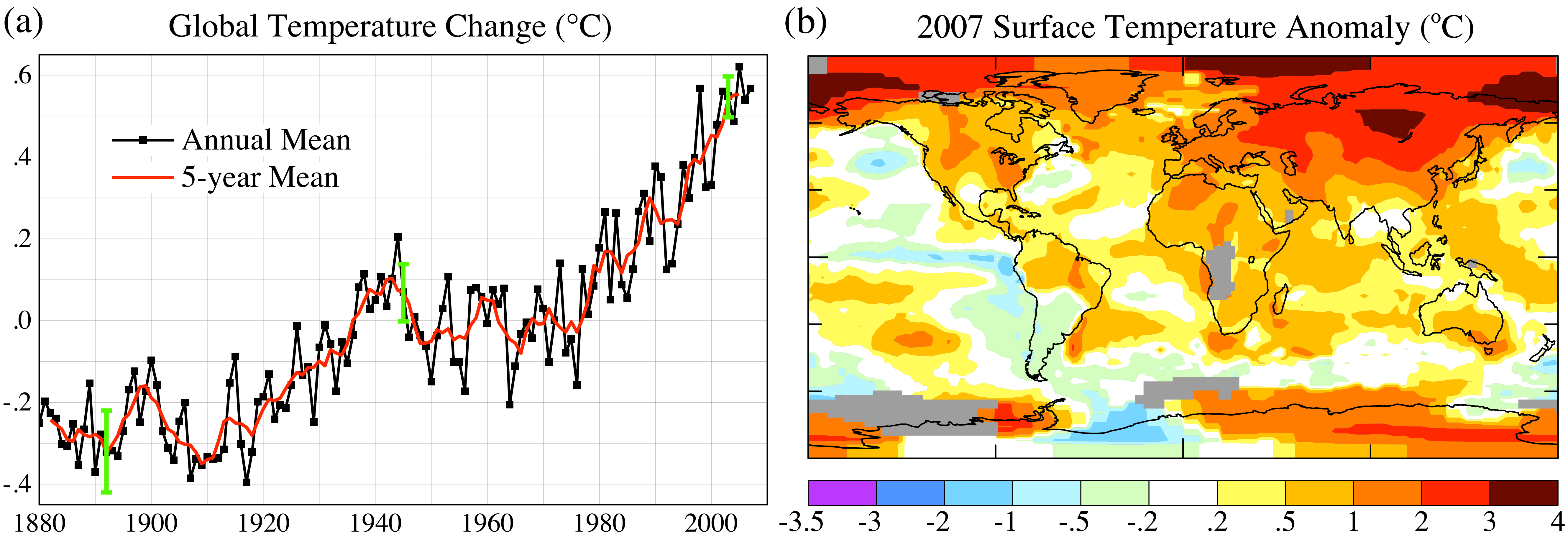


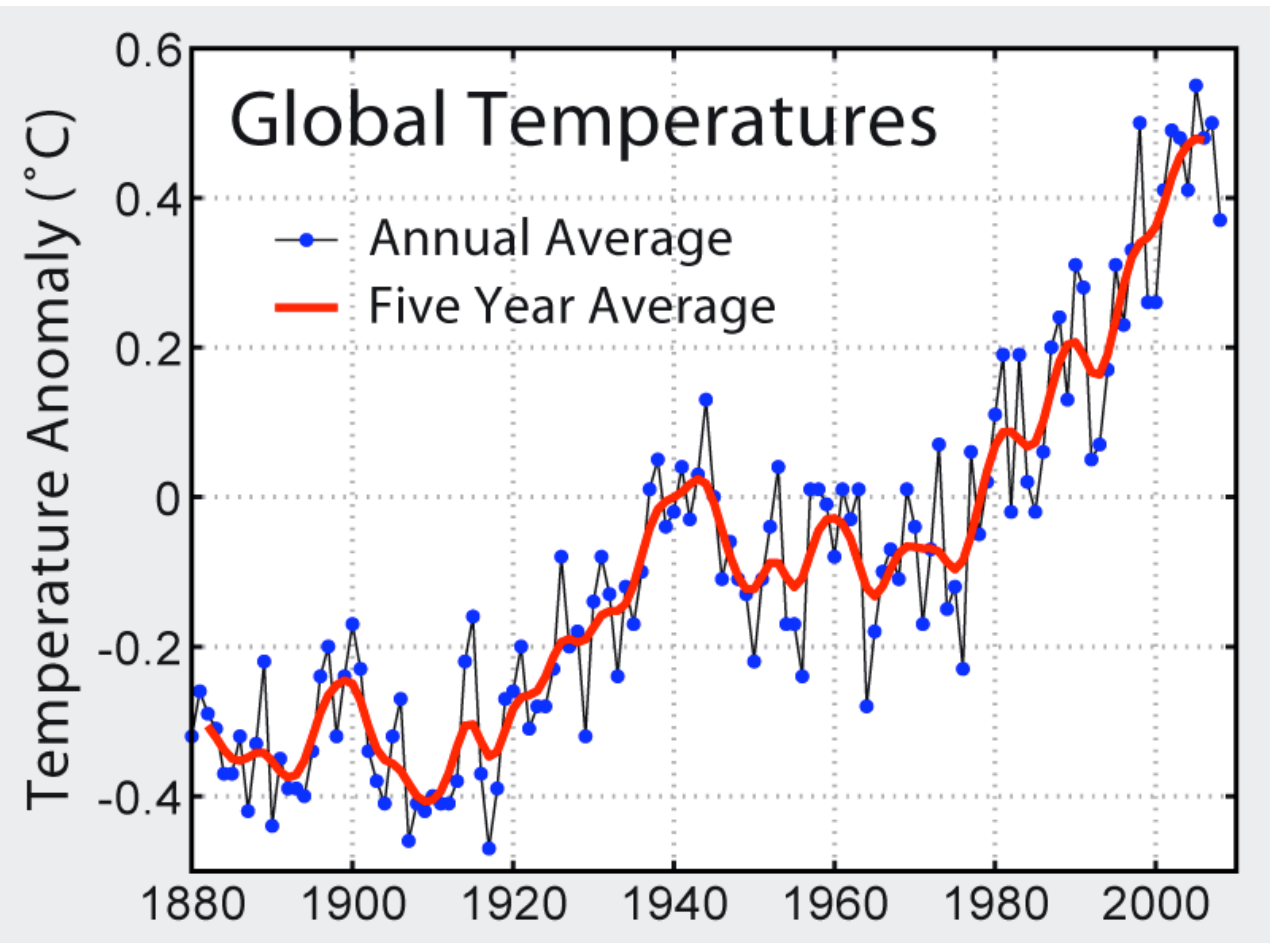
$$g_{\mathrm{CO_2}} = \frac{\partial T}{\partial [CO_2]} \cdot \frac{\partial [CO_2]}{\partial T} = \frac{1^\circ C}{275ppmv} \cdot \frac{14.6ppmv}{1^\circ C} = 0.053$$

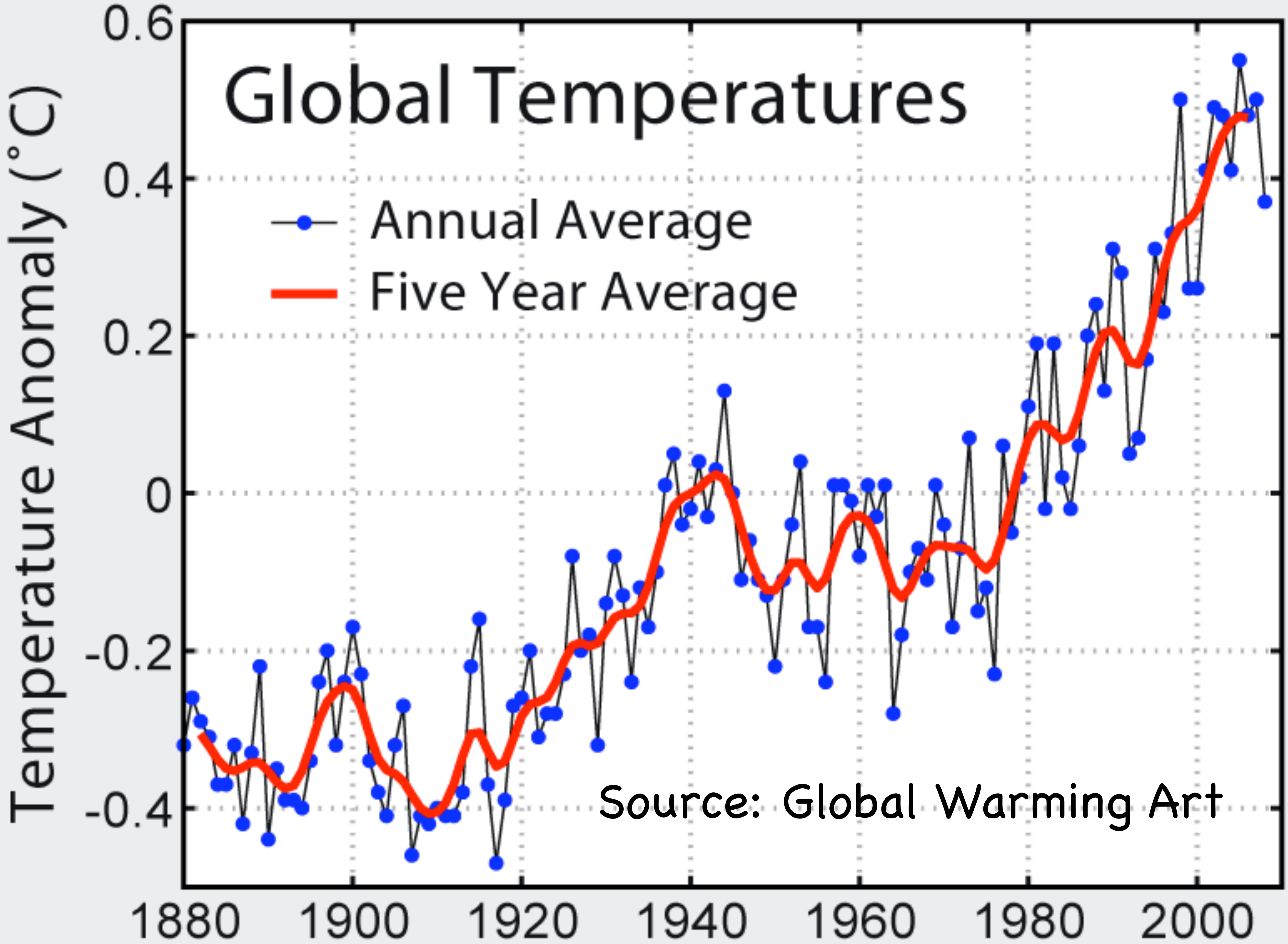
1°C/(1 - .71) = 3.4°C

1°C/(1 - .71 – .05) = 4.2°C

But where is the carbon coming from?


(a)
Global Temperature Change (°C)
Annual Mean
5-year Mean
.6
.4
.2
.0
-.2
-.4
1880
1900
1920
1940
1960
1980
2000
(b)
2007 Surface Temperature Anomaly (°C)
-3.5
-3
-2
-1
-.5
-.2
.2
.5
1
2
3
4


Global Temperatures
Annual Average
Five Year Average
Temperature Anomaly (°C)
0.6
0.4
0.2
0
-0.2
-0.4
1880
1900
1920
1940
1960
1980
2000


Global Temperatures
Annual Average
Five Year Average
Temperature Anomaly (°C)
0.6
0.4
0.2
0
-0.2
-0.4
1880
1900
1920
1940
1960
1980
2000
Source: Global Warming Art

What Can Modern Physics Contribute?

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Aspen Center for Physics

Summer 2005 Workshop

Novel Approaches To Climate

Funding: NSF, BP Research, & ICAM

John Harte's long-term ecosystem heating experiment at the Rocky Mountain Biological Laboratory near Aspen.

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Kavli Institute for Theoretical Physics

Physics of Climate Change
April 28 -- July 11, 2008
Frontiers of Climate Science
& Engineering the Earth
May 6 -- 10, 2008

Co-organizers:
J. Carlson, G. Falkovich, J. Harte,
J. B. Marston, and R. Pierrehumbert


SOCCER
ELWOOD

“Human beings are now carrying out a large scale geophysical experiment of a kind that could not have happened in the past nor be reproduced in the future. Within a few centuries we are returning to the atmosphere and oceans the concentrated organic carbon stored in sedimentary rocks over hundreds of millions of years. (Revelle and Suess, 1957)

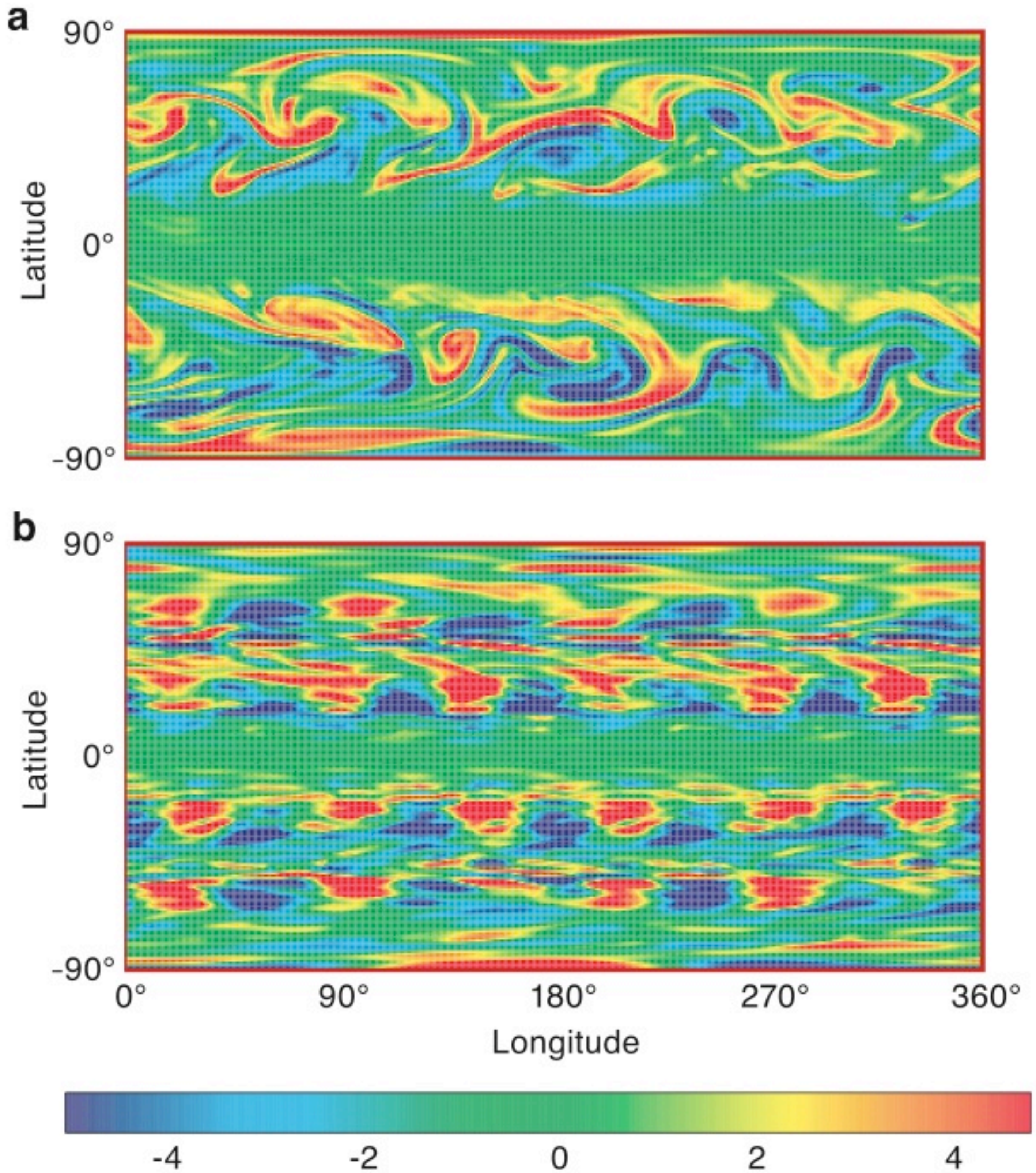


Figure 1. Typical instantaneous vorticity fields (10^{-5} s^{-1}) in (a) the full simulation and (b) the simulation without eddy-eddy interactions. The horizontal surface shown is in the mid-troposphere at $\sigma = 0.5$. The fields are shown at times after the simulations have reached statistically steady states.

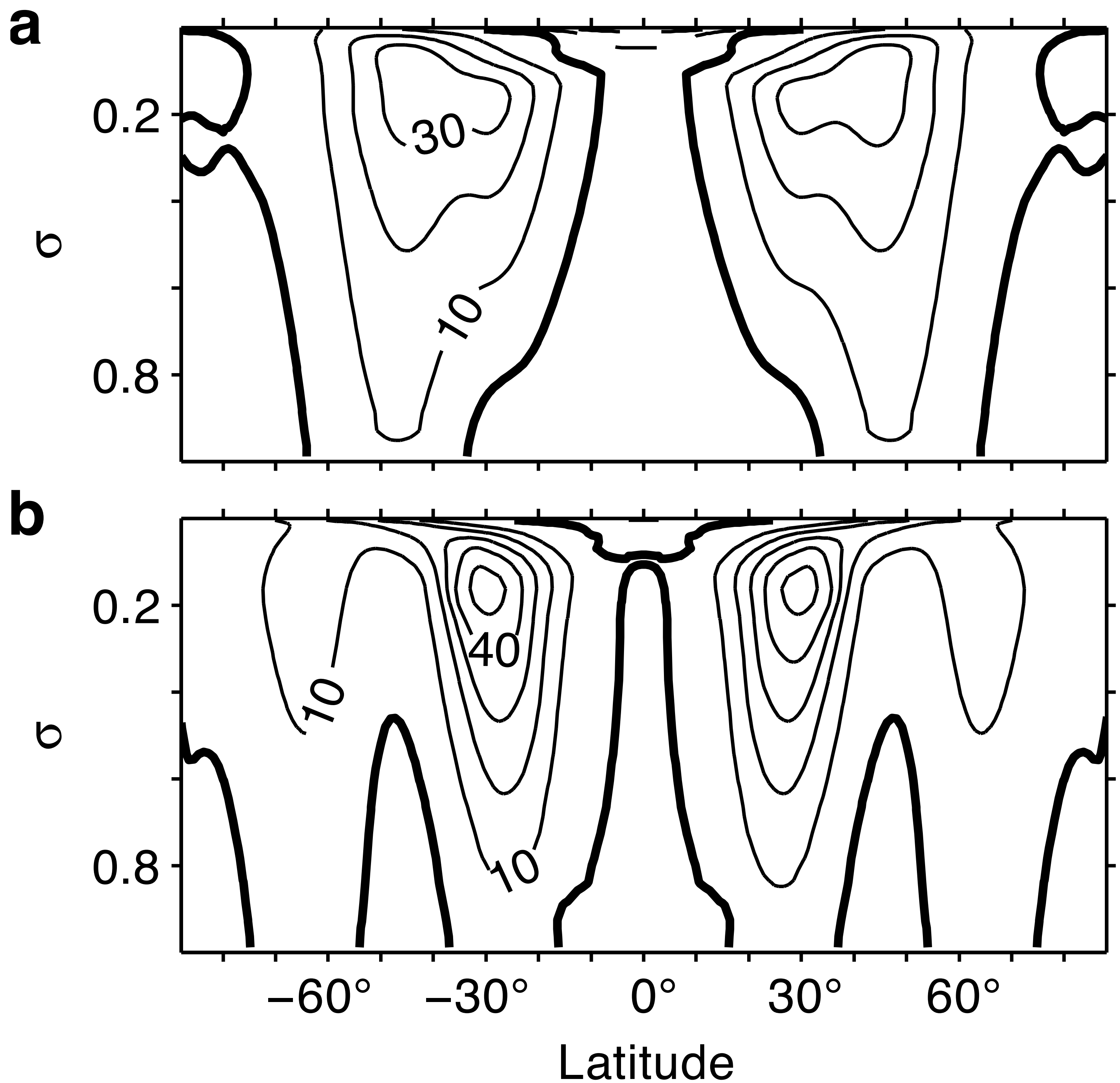
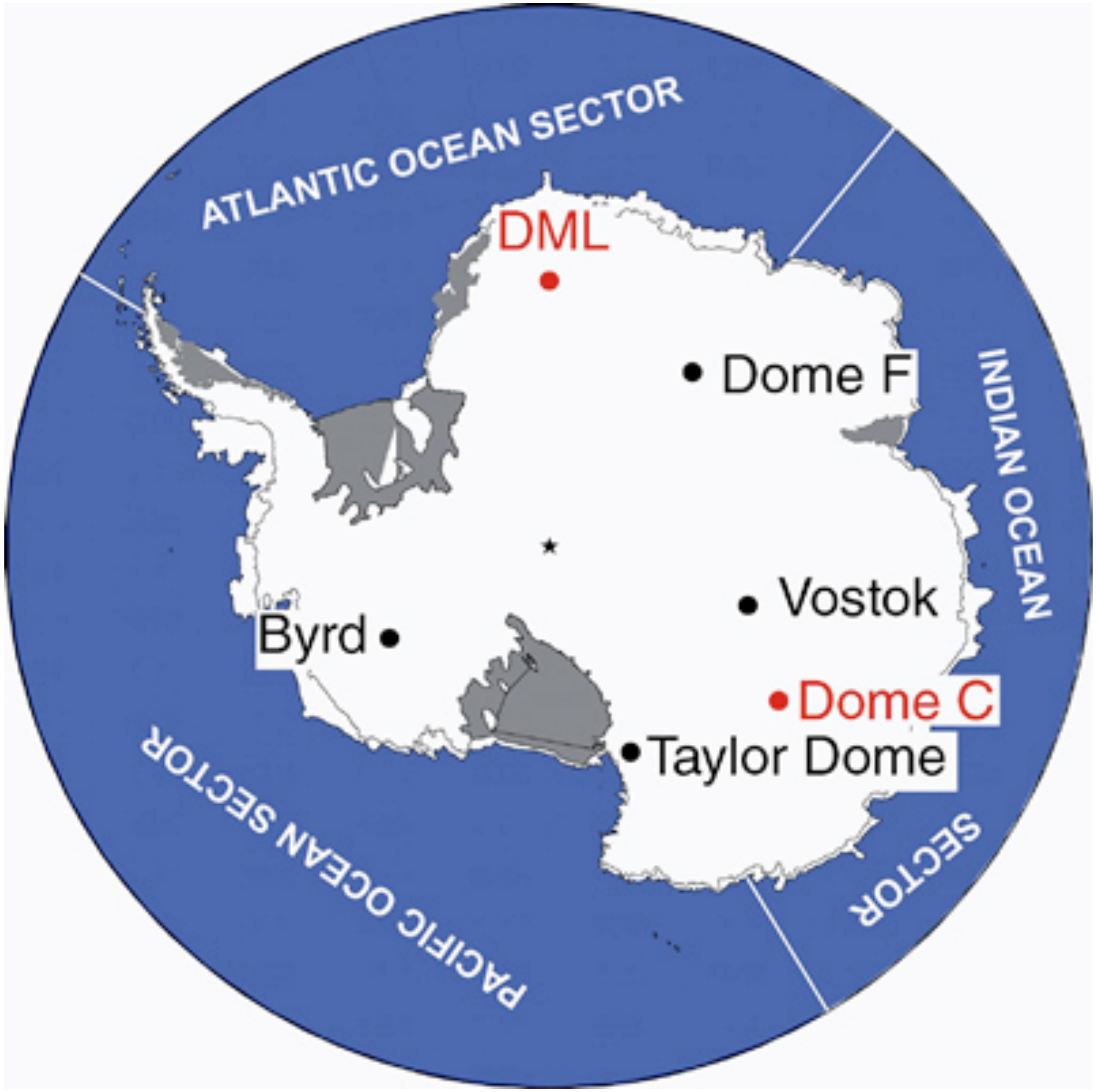


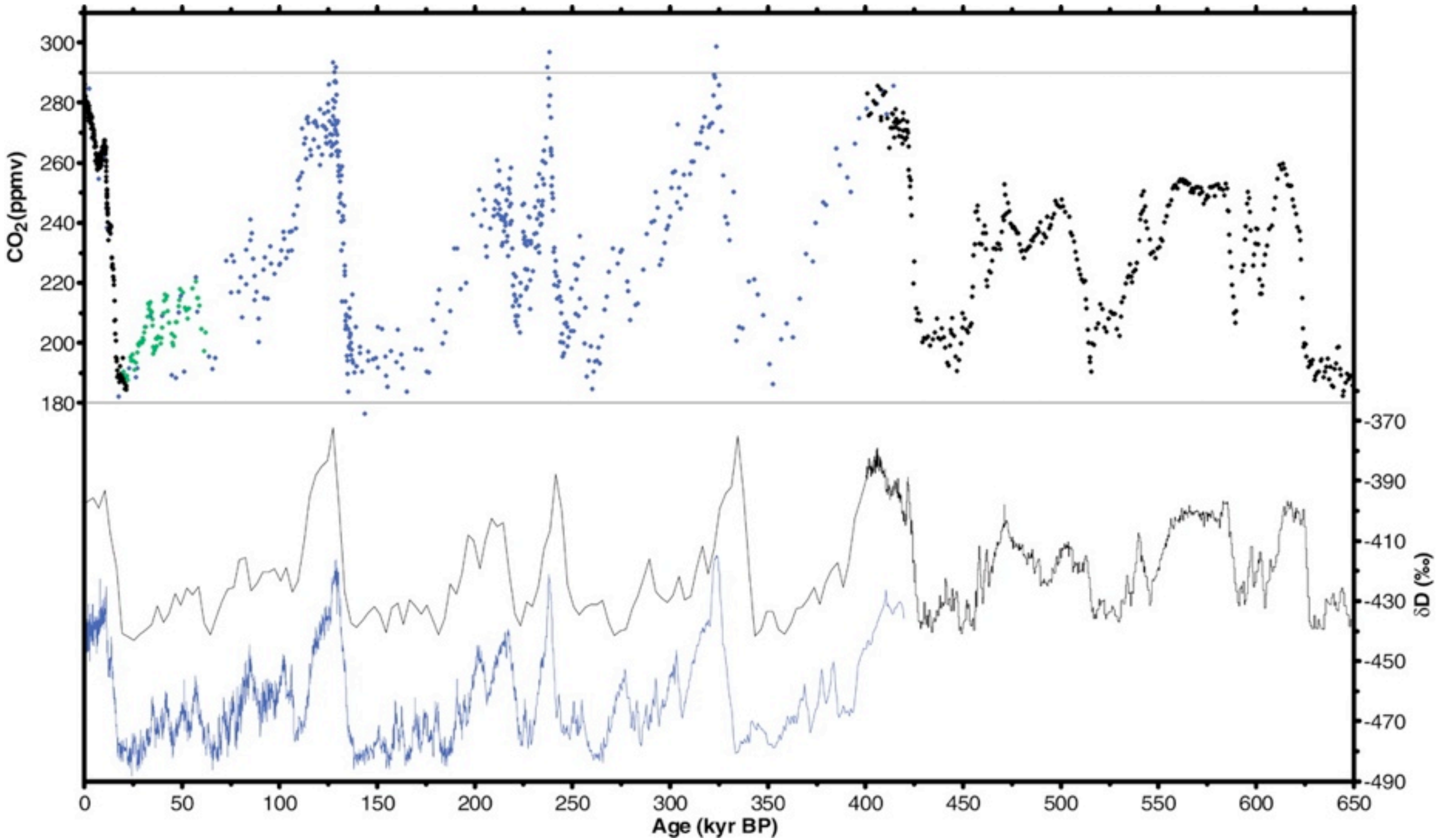
Figure 3. Mean eastward wind (m s^{-1}) in the meridional plane in (a) the full simulation and (b) the simulation without eddy-eddy interactions. The mean is a zonal, time, and interhemispheric average with mass weighting. The thick solid lines are the zero-wind lines.

Antarctic Dome C



Siegenthaler *et al*. Science **310**, 1313 (2005)

Antarctic Dome C



Siegenthaler *et al*. Science **310**, 1313 (2005)


Lake Mead