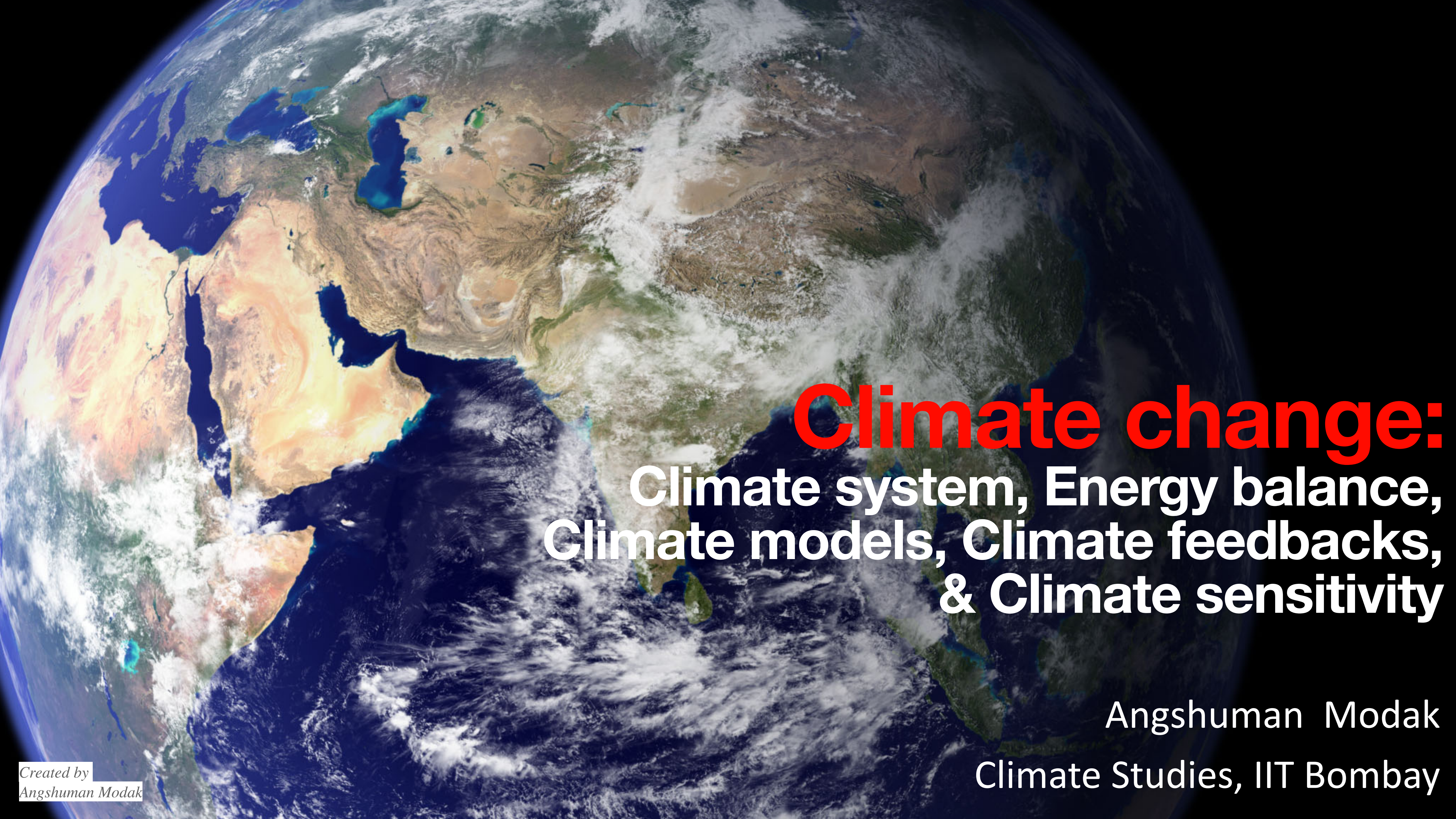

Climate change:

Climate system, Energy balance, Climate models, Climate feedbacks, & Climate sensitivity

Angshuman Modak

Climate Studies, IIT Bombay

Weather & Climate

"Weather describes the conditions of the atmosphere at a certain place and time with reference to temperature, pressure, humidity, wind, and other key parameters (meteorological elements) "

"The presence of clouds, precipitation, occurrence of special phenomena e.g. thunderstorms, dust storms, tornados and others" defines weather

Cubasch *et al.*, 2013

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Angshuman Modak

Climate & Weather

- Climate is usually defined as the average of weather. Typically, the period for averaging is 30 years (WMO- World Meteorological Organization)

- Temperature
- Precipitation
- Wind

Climate is what you expect. Weather is what actually happens

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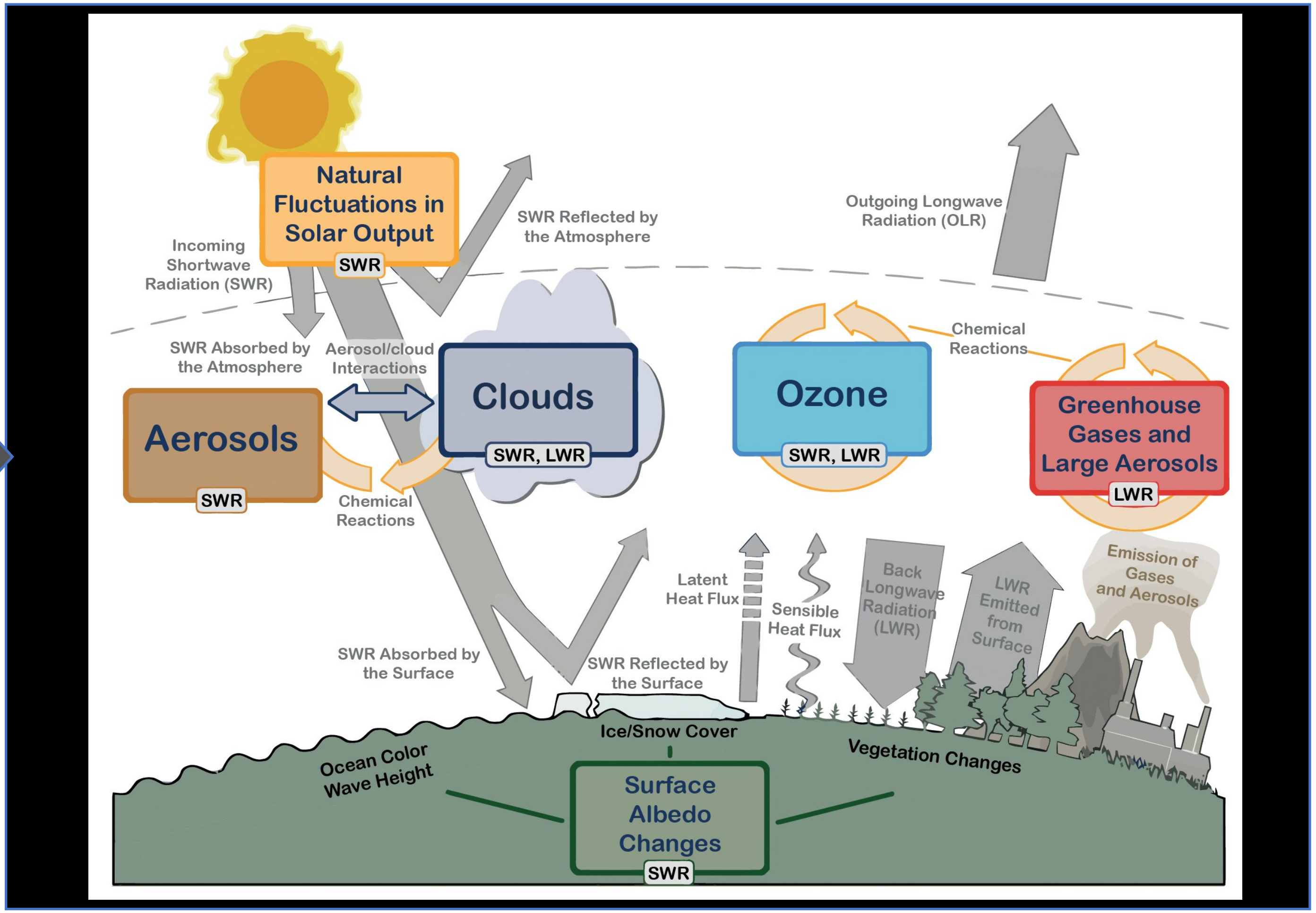
Climate system

In 1992, the United Nations' Framework Convention on Climate Change (UNFCCC) defined the climate system as 'the totality of the atmosphere, hydrosphere, biosphere and geosphere and their interactions'.

Climate system

Perturb the system

NASA



Response of the system

★ ***The key point is that when we perturb any of the components of the climate system we ultimately affect the planetary energy budget***

Cubasch *et al.*, 2013

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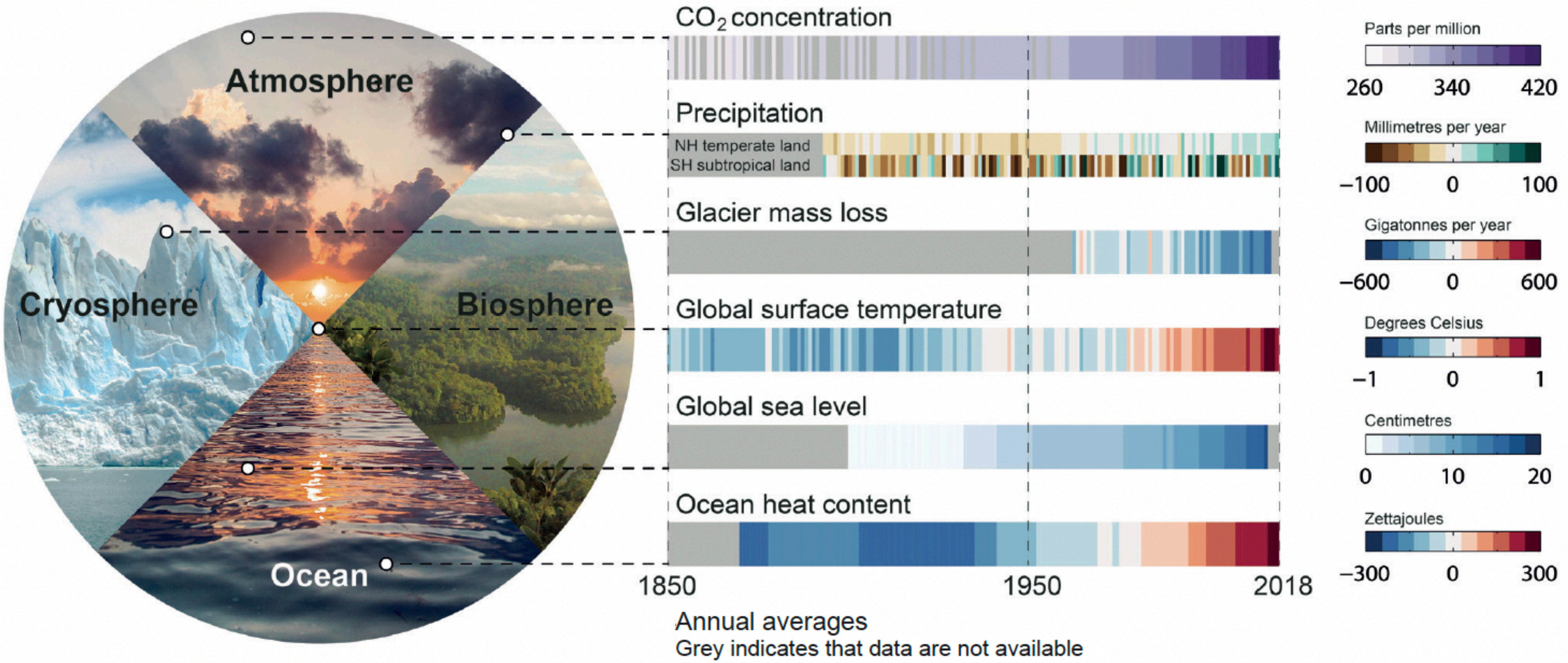
Climate change (since 1850…)



Datasets and baselines used are: (i) CO2: Antarctic ice cores (Lüthi et al., 2008; Bereiter et al., 2015) and direct air measurements (Tans and Keeling, 2020) (see Figure 1.5 for details); (ii) precipitation: Global Precipitation Climatology Centre (GPCC) V8 (updated from Becker et al., 2013), baseline 1961–1990 using land areas only with latitude bands 33N–66N and 15S–30S; (iii) glacier mass loss: Zemp et al. (2019); (iv) global surface air temperature (GMST): HadCRUT5 (Morice et al., 2021), baseline 1961–1990; (v) sea level change: (Dangendorf et al., 2019), baseline 1900–1929; (vi) ocean heat content (model–observation hybrid): Zanna et al. (2019), baseline 1961–1990.

IPCC AR6, Chen et al. 2021

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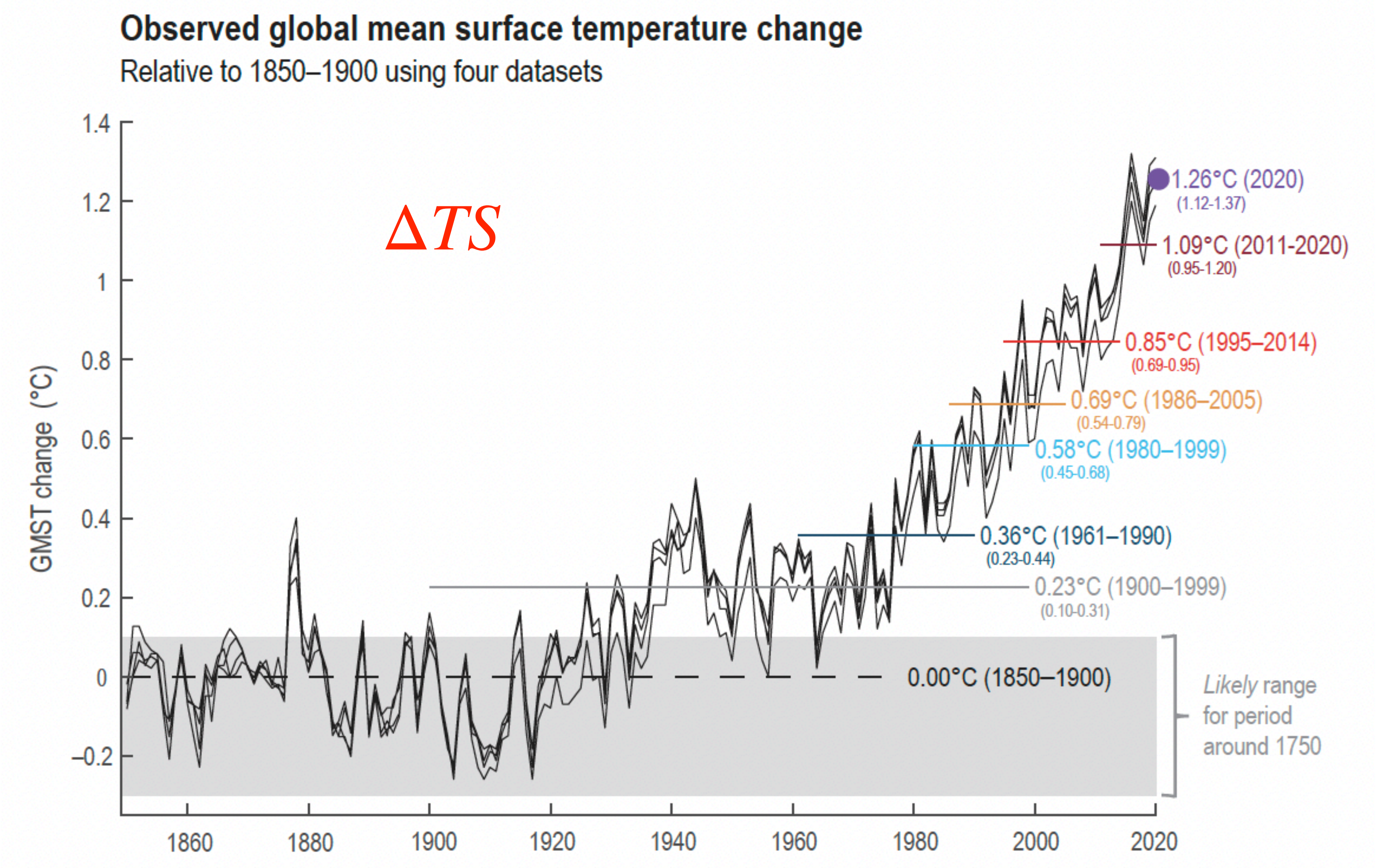

ΔTS

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IPCC AR6, Chen et al. 2021

History

In 1827, Fourier formulated the question of what determines Earth’s temperature and developed the idea of the planetary energy balance

Fourier, J.-B. (1827) Mémoires de l’Académie des sciences de l’Institut de France.

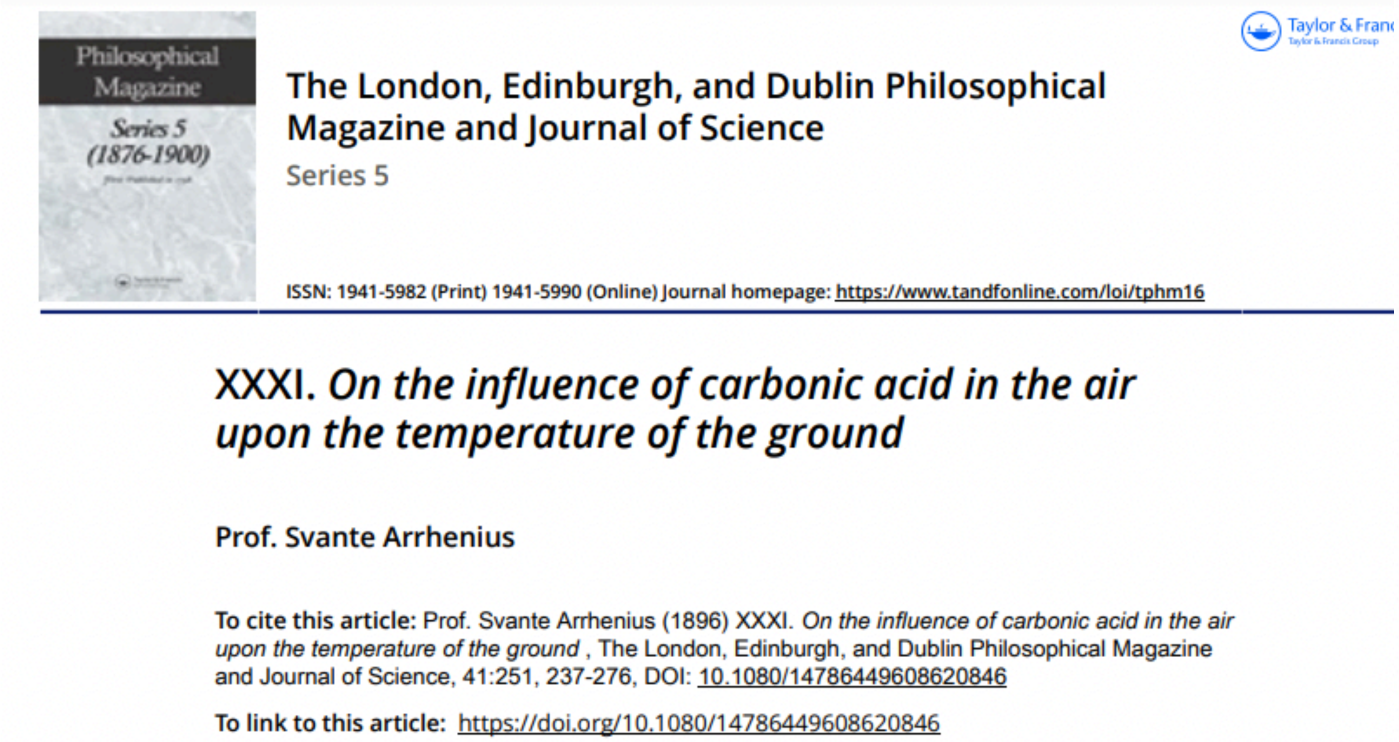
Jean-Baptiste Joseph Fourier

Svante August Arrhenius

Arrhenius 1896 calculations suggesting that changes in carbon dioxide would induce changes in the surface temperature

Further read: Pierrehumbert 2004

Arrhenius 1896



The London, Edinburgh, and Dublin Philosophical Magazine and Journal of Science

Series 5

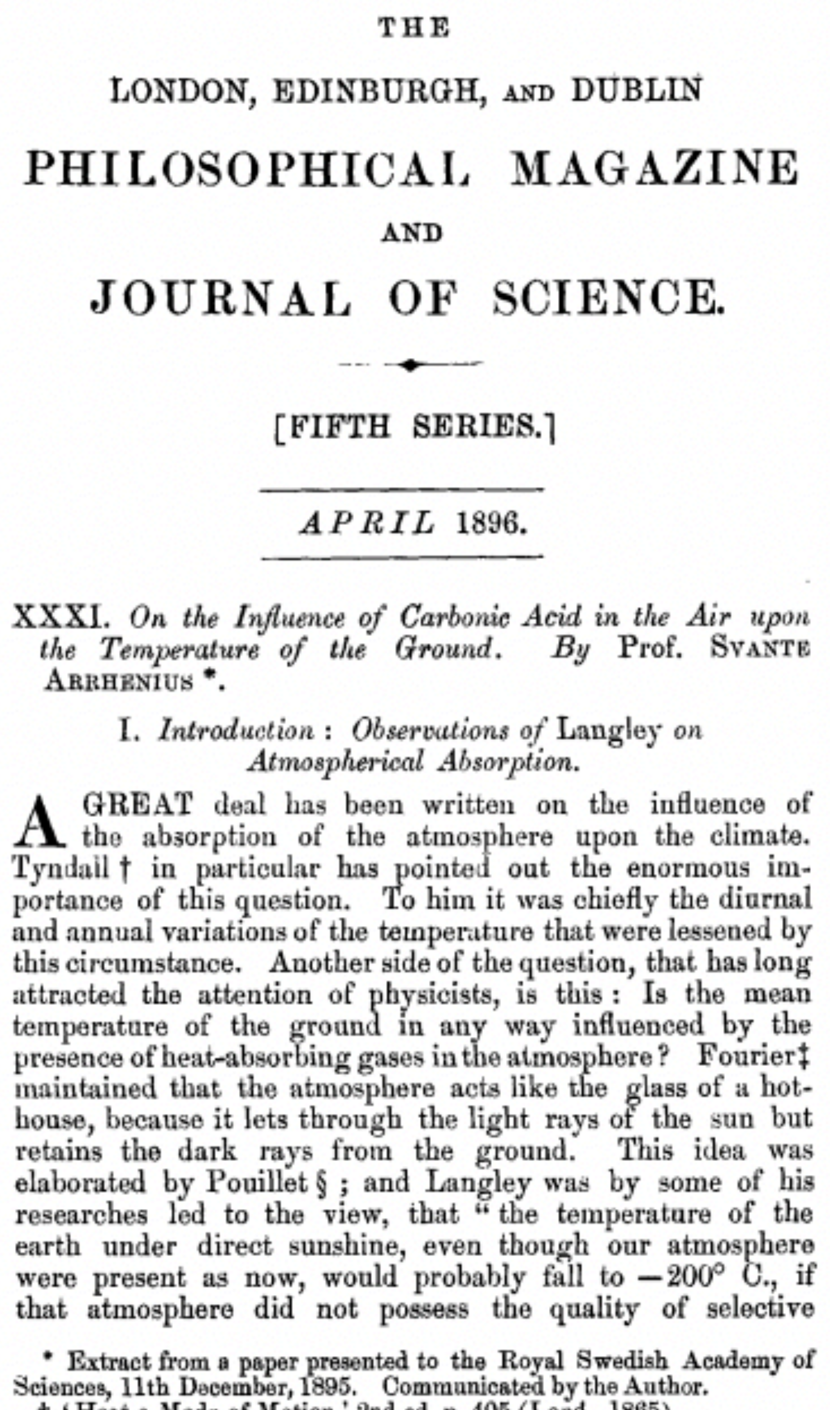
ISSN: 1941-5982 (Print) 1941-5990 (Online) Journal homepage: https://www.tandfonline.com/loi/tphm16

XXXI. *On the influence of carbonic acid in the air upon the temperature of the ground*

Prof. Svante Arrhenius

To cite this article: Prof. Svante Arrhenius (1896) XXXI. *On the influence of carbonic acid in the air upon the temperature of the ground* , The London, Edinburgh, and Dublin Philosophical Magazine and Journal of Science, 41:251, 237-276, DOI: 10.1080/14786449608620846

To link to this article: https://doi.org/10.1080/14786449608620846



THE
LONDON, EDINBURGH, AND DUBLIN
PHILOSOPHICAL MAGAZINE
AND
JOURNAL OF SCIENCE.

[FIFTH SERIES.]

APRIL 1896.

XXXI. *On the Influence of Carbonic Acid in the Air upon the Temperature of the Ground. By* Prof. SVANTE ARRHENIUS *.

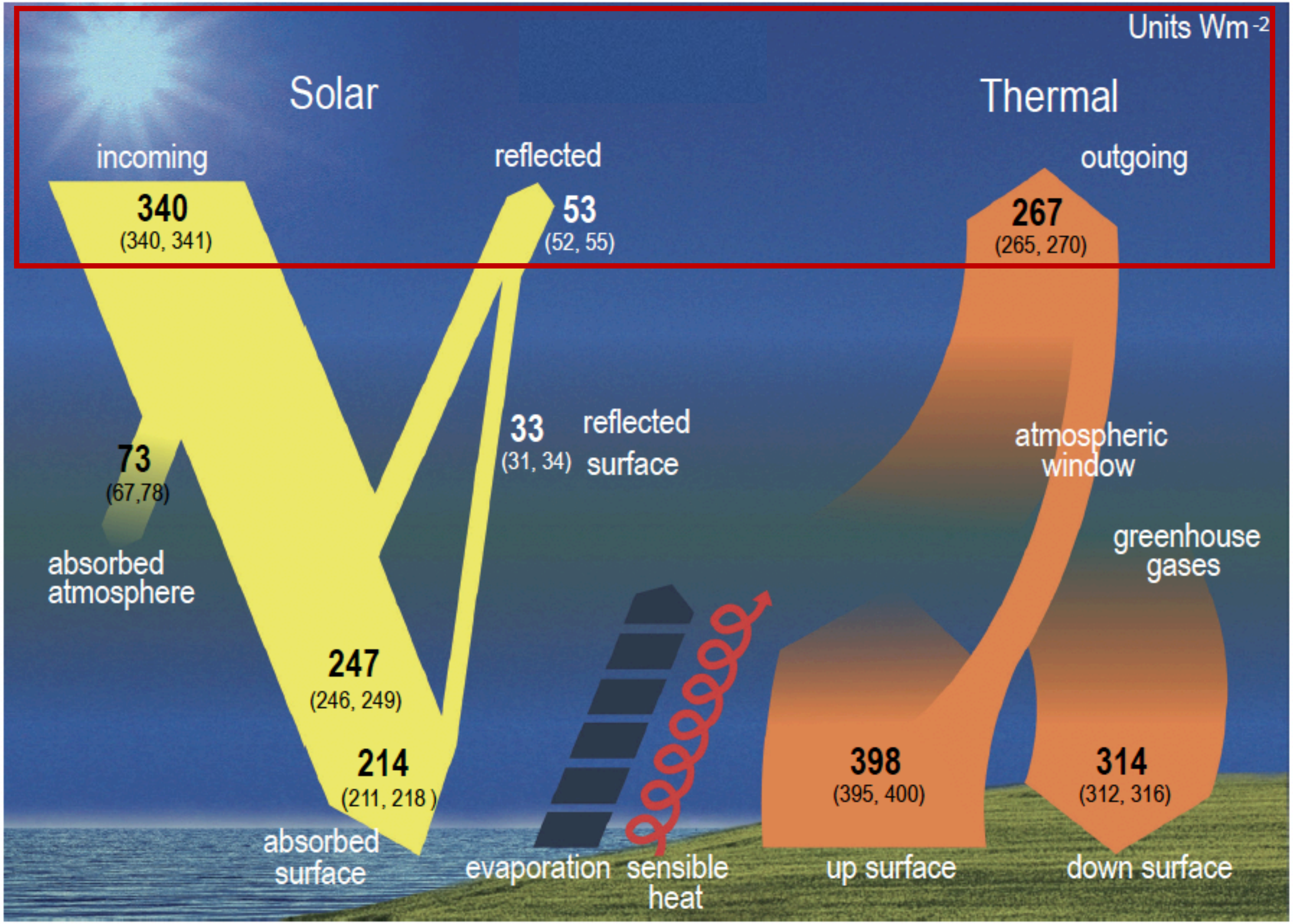
I. *Introduction : Observations of* Langley *on Atmospherical Absorption.*

A GREAT deal has been written on the influence of the absorption of the atmosphere upon the climate. Tyndall † in particular has pointed out the enormous importance of this question. To him it was chiefly the diurnal and annual variations of the temperature that were lessened by this circumstance. Another side of the question, that has long attracted the attention of physicists, is this : Is the mean temperature of the ground in any way influenced by the presence of heat-absorbing gases in the atmosphere? Fourier‡ maintained that the atmosphere acts like the glass of a hothouse, because it lets through the light rays of the sun but retains the dark rays from the ground. This idea was elaborated by Pouillet § ; and Langley was by some of his researches led to the view, that "the temperature of the earth under direct sunshine, even though our atmosphere were present as now, would probably fall to −200° C., if that atmosphere did not possess the quality of selective

* Extract from a paper presented to the Royal Swedish Academy of Sciences, 11th December, 1895. Communicated by the Author.

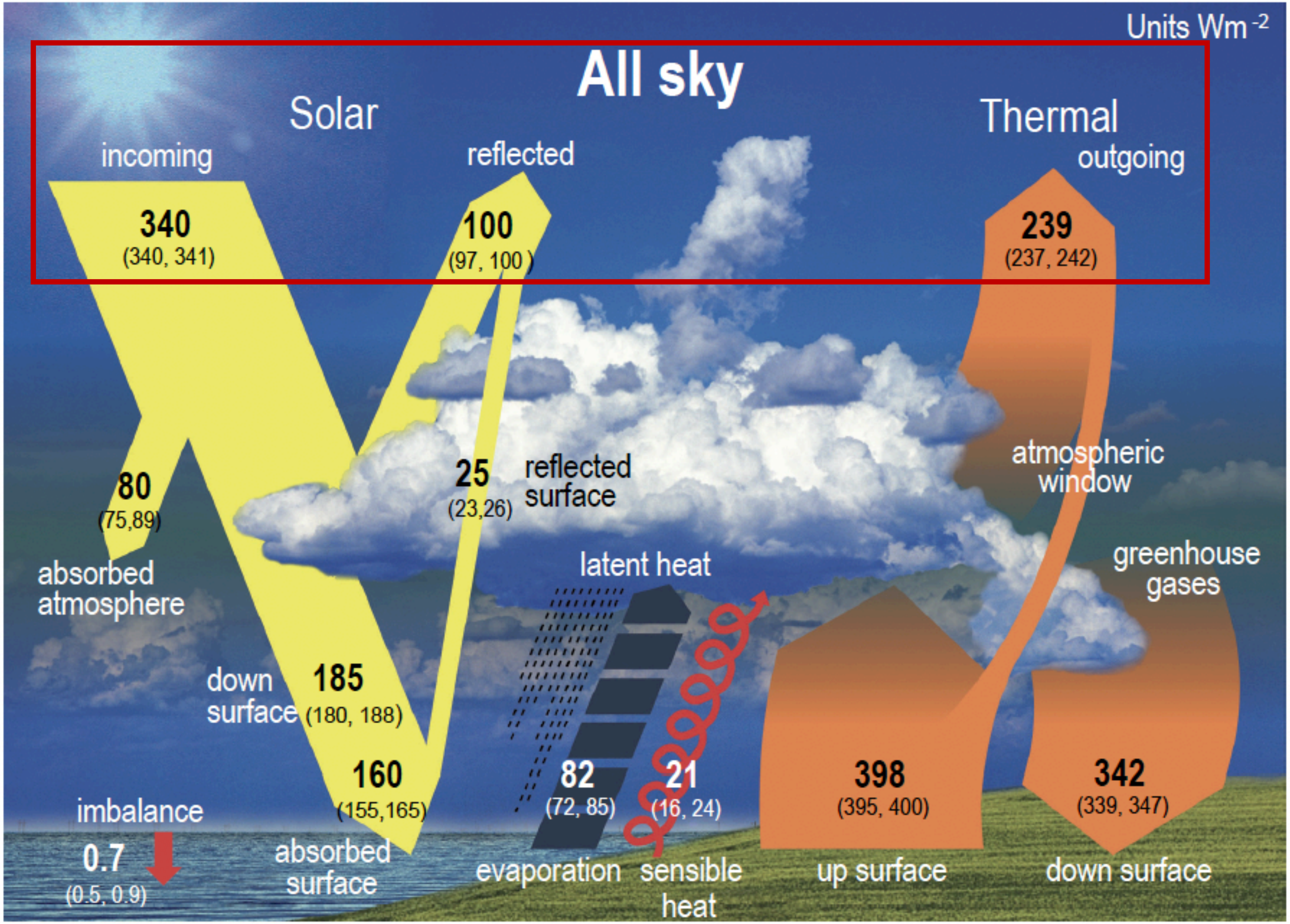
IPCC AR6

Energy flows in the climate system



IPCC AR6

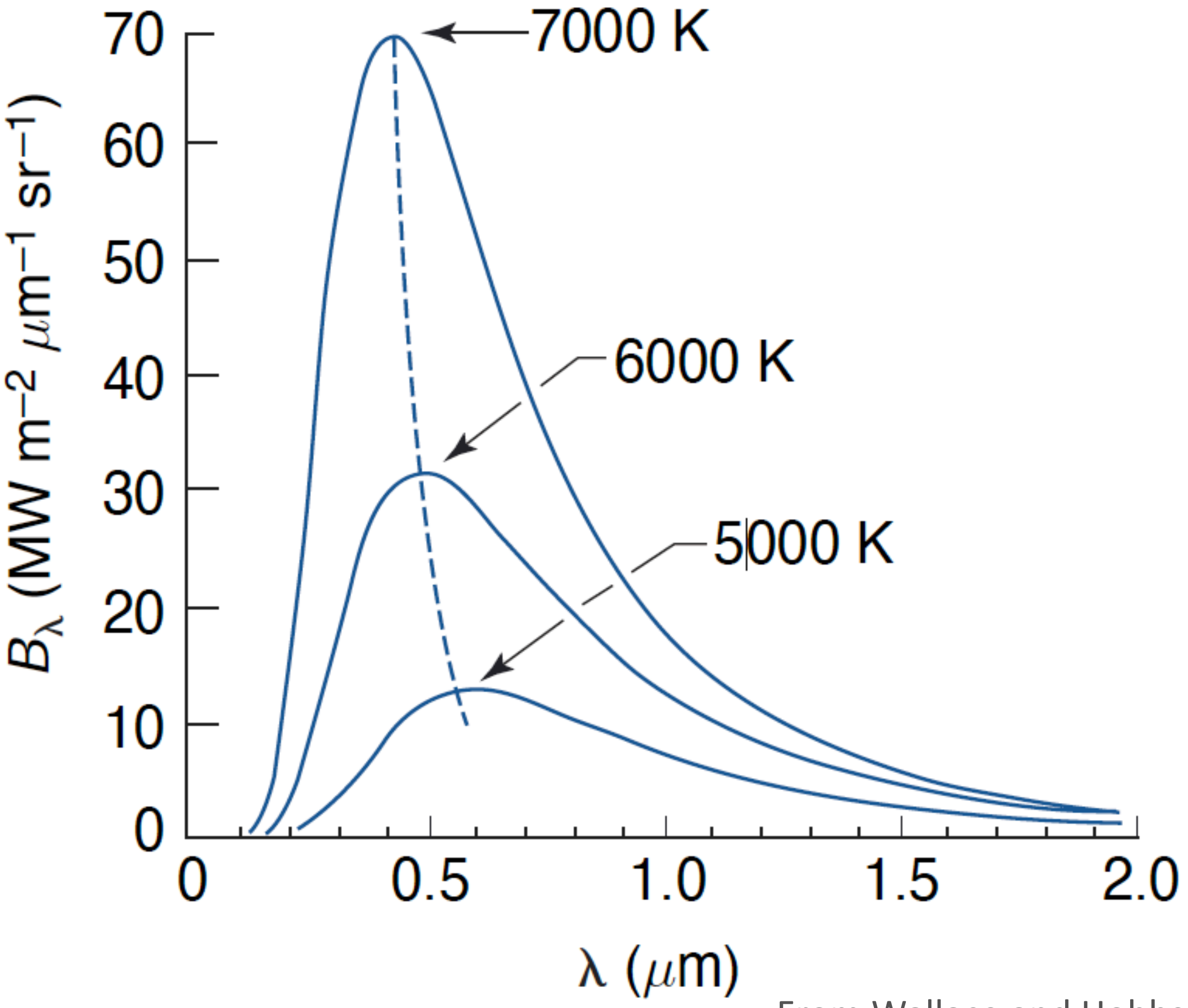
Energy flows in the climate system



Stefan-Boltzmann Law

The blackbody flux density/irradiance obtained by integrating the Planck's function over all wavelengths is given by the Stefan–Boltzmann law, $e_b = \sigma T^4$

How much is Earth's surface temperature?

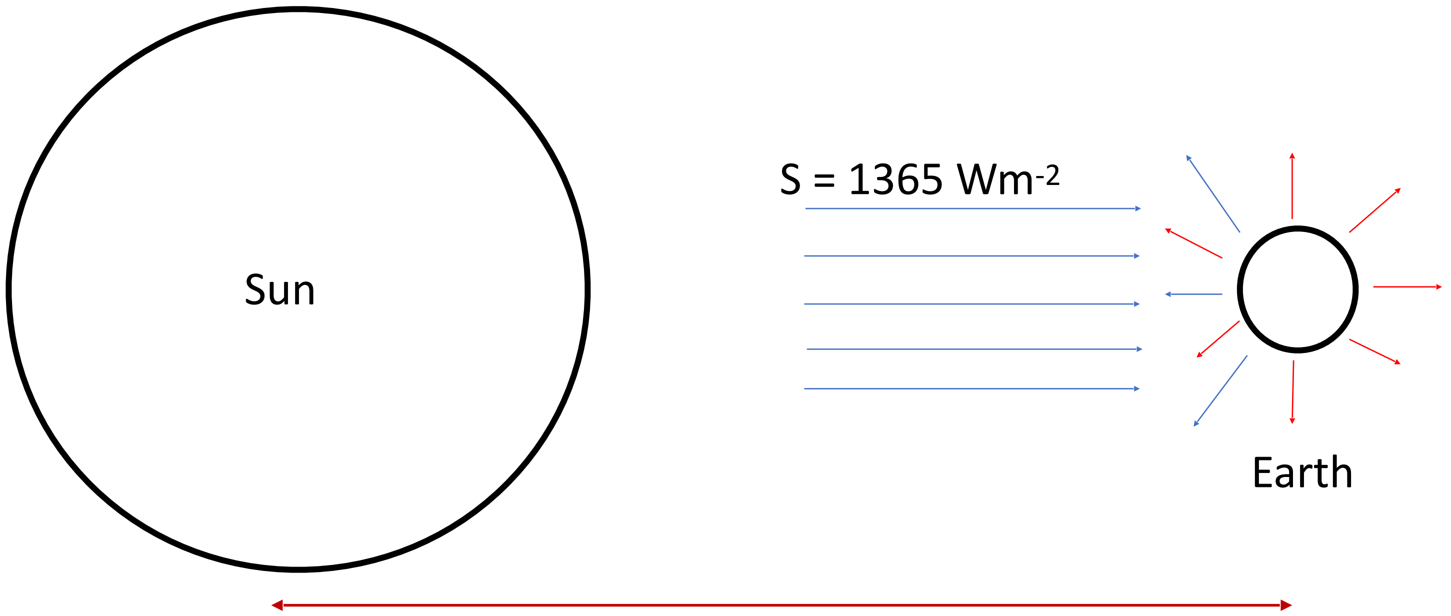


From Wallace and Hobbs

Created by
Angshuman Modak

Energy balance (N)

Radiation incident – reflected back radiation = radiation emitted by Earth because of its temperature



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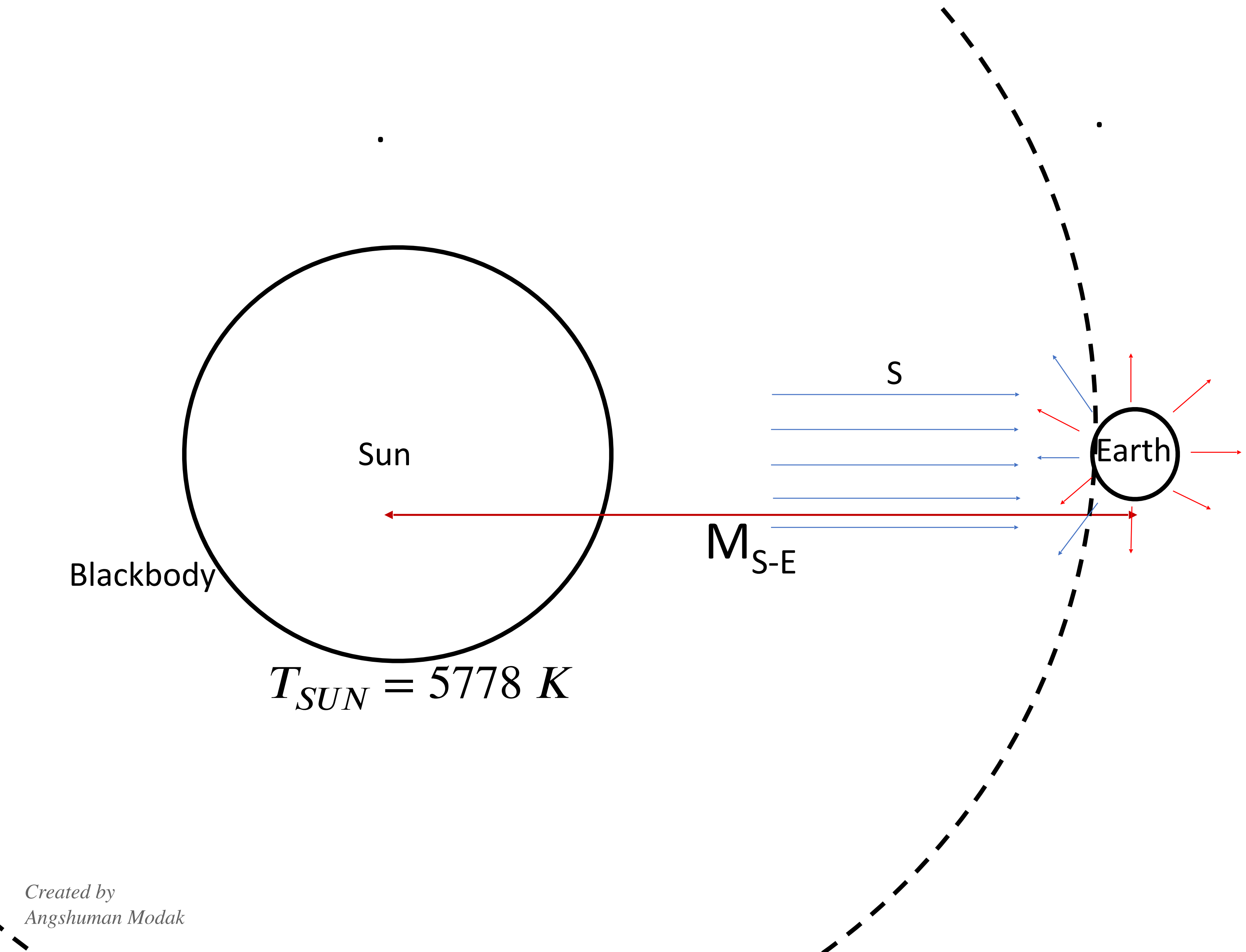
Solar constant



$$T_{SUN} = 5778\ K$$

$$\frac{4\pi R_{SUN}^{2}\,.\,\sigma T_{SUN}^{4}}{\cdot}$$

$$= 1365\ Wm^{-2}$$

$$R_S = 6.96\ \times\ 10^{8}\ m$$

$$M_{S-E} = 1.496\ \times\ 10^{11}\ m$$

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Angshuman Modak

Energy balance (N)

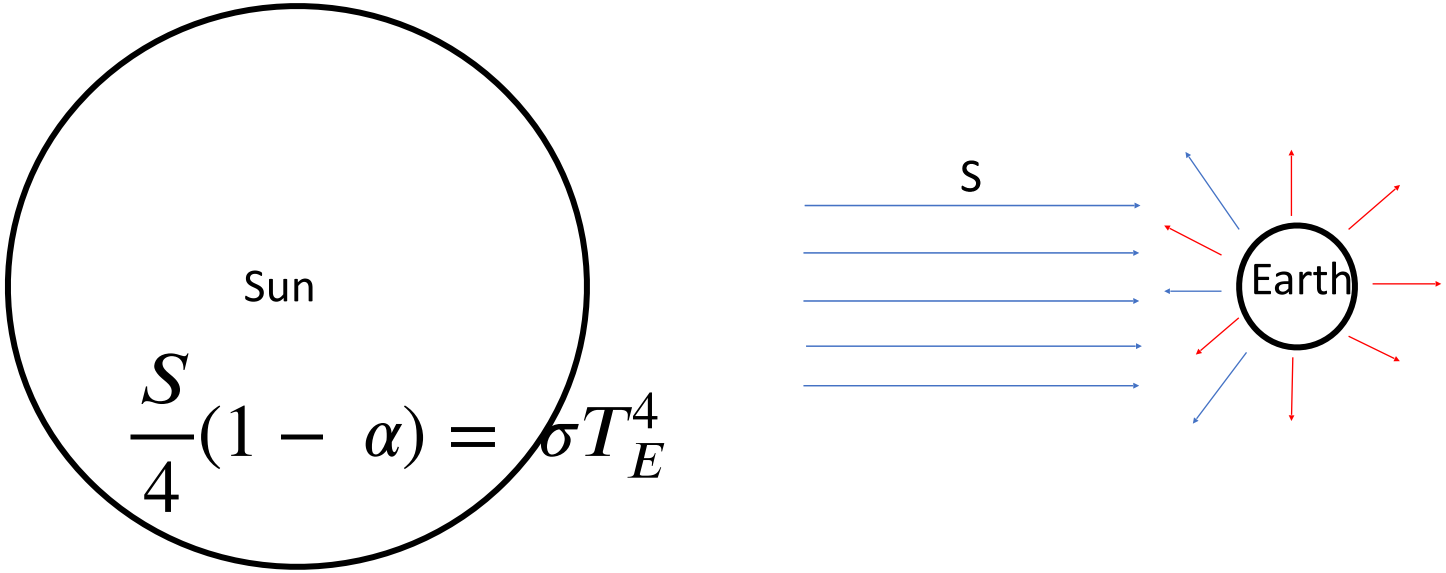
Radiation incident – reflected back radiation – radiation emitted by Earth = N

Setting N = 0 we can solve,

$$S\,\pi R_E^2 \;-\; \alpha\, S\,\pi R_E^2 \;-\; \sigma T_E^4\, 4\pi R_E^2 = 0$$

Here, T_E is the effective radiating temperature of Earth or emission temperature.

Assuming a single uniform temperature.



$$\frac{S}{4}(1-\ \alpha) = \ \sigma T_E^4$$

$$S\ = 1365\ Wm^{-2}$$

$$\alpha\ = 0.29$$

$$T_E = 255\ K$$

Currently, the global mean temperature of earth is around

$$T_s = 289K$$

$$T_s - T_E = 34K$$

Greenhouse effect

Created by
Angshuman Modak

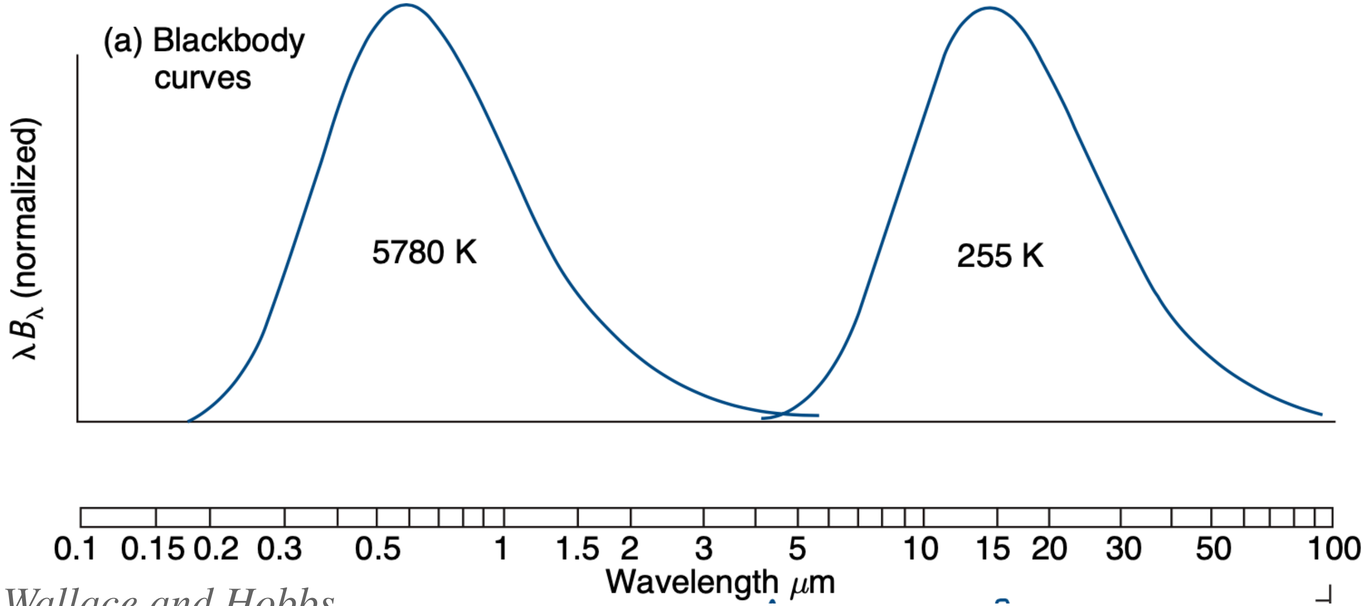
Greenhouse effect and greenhouse gases

Currently, the global mean surface temperature of earth is around

$$T_s = 289K, T_E = 255K$$

Greenhouse effect

$$\sigma T_S^4 - \sigma T_E^4 = 150 W m^{-2}$$



Wallace and Hobbs

The major gases like the Nitrogen, Oxygen, Argon 99.9% but the minor gases H2O, CO2, CH4, N2O,… As these gases have strong absorptions.

How do we get to T_s ?

So, we need to develop our simple model. Perhaps we can start with a model with single layer atmosphere.

But let's see at the maps of the quantities we just derived at the top of the atmosphere.

Created by Angshuman Modak

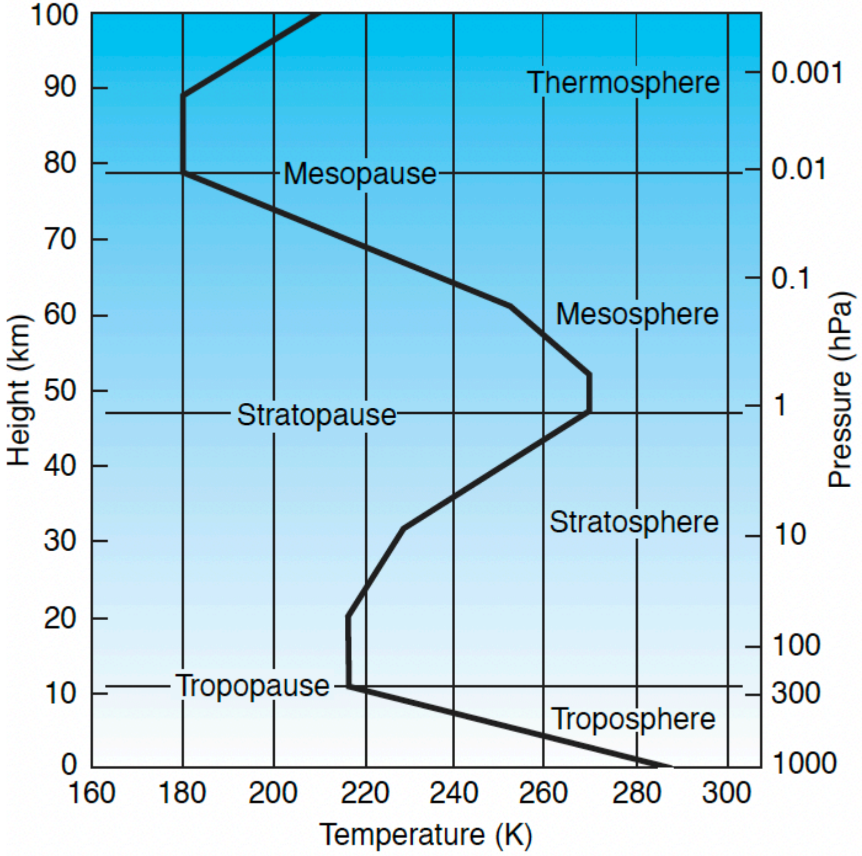
Before going ahead solve this

A small blackbody satellite is orbiting the Earth at a distance far enough away so that the flux density of Earth radiation is negligible, compared to that of solar radiation. Suppose that the satellite suddenly passes into the Earth’s shadow. At what rate will it initially cool?

The satellite weighs 1000 kg and a specific heat 1000 J/kg/K. It is spherical with a radius r = 1 m, and temperature is uniform over its surface.

Answer: 15.5 K/hour

Let’s take peek at “the Atmosphere”



From Wallace and Hobbs
Atmospheric Science: An introductory survey
2005

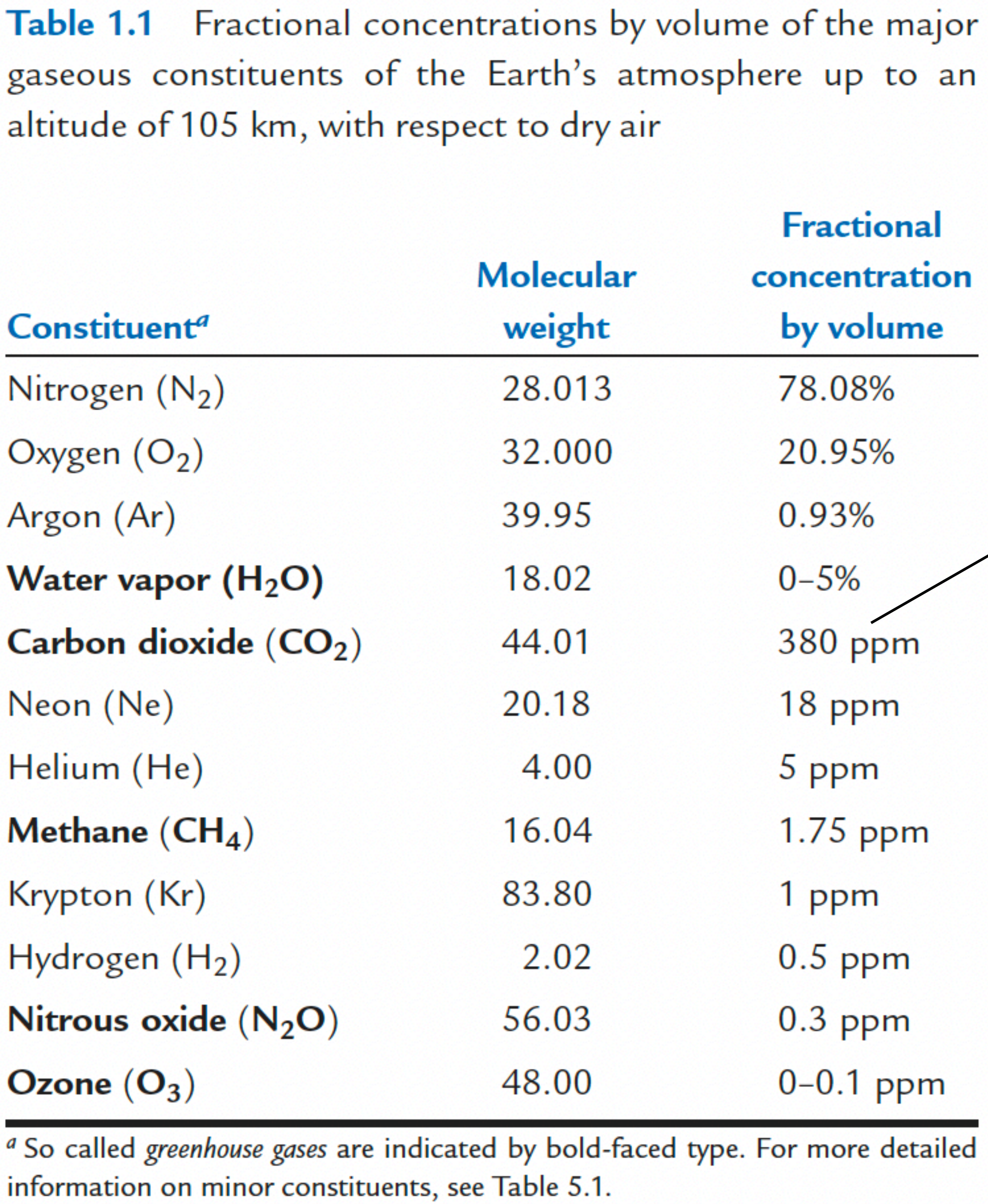


Table 1.1 Fractional concentrations by volume of the major gaseous constituents of the Earth’s atmosphere up to an altitude of 105 km, with respect to dry air

Constituent[a]	**Molecular weight**	**Fractional concentration by volume**
Nitrogen (N_2)	28.013	78.08%
Oxygen (O_2)	32.000	20.95%
Argon (Ar)	39.95	0.93%
Water vapor (H_2O)	18.02	0–5%
Carbon dioxide (CO_2)	44.01	380 ppm
Neon (Ne)	20.18	18 ppm
Helium (He)	4.00	5 ppm
Methane (CH_4)	16.04	1.75 ppm
Krypton (Kr)	83.80	1 ppm
Hydrogen (H_2)	2.02	0.5 ppm
Nitrous oxide (N_2O)	56.03	0.3 ppm
Ozone (O_3)	48.00	0–0.1 ppm

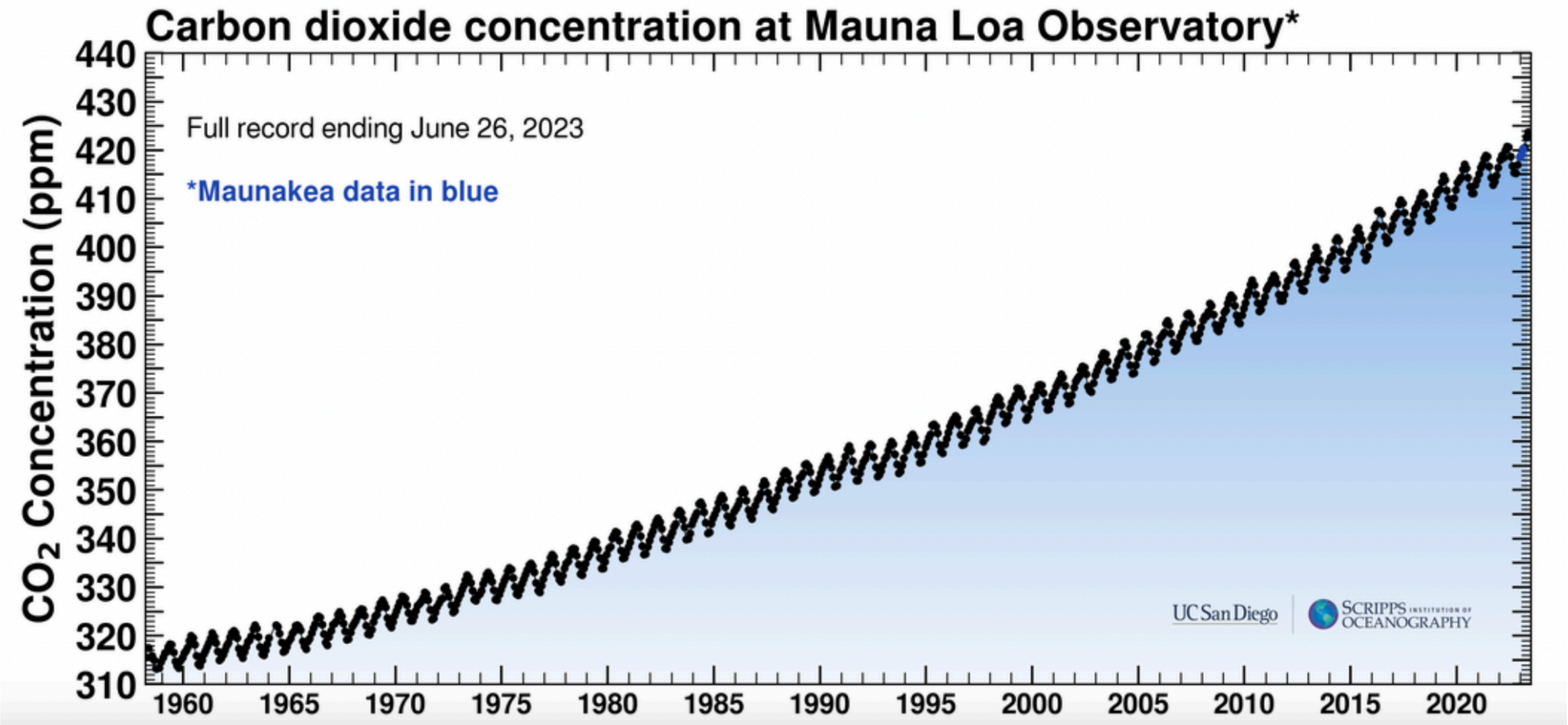
[a] So called *greenhouse gases* are indicated by bold-faced type. For more detailed information on minor constituents, see Table 5.1.

How many Gigatonnes of carbon ?

Does COVID-19 pandemic has an influence on the rise in CO2 concentration?

*Latest CO_2 reading: 422.93 ppm

The Keeling curve



https://keelingcurve.ucsd.edu/

http://doi.org/10.6075/J08W3BHW

Energy balance (N)

$$\frac{S}{4}(1-\alpha)-\sigma T_E^4 = N = 0$$

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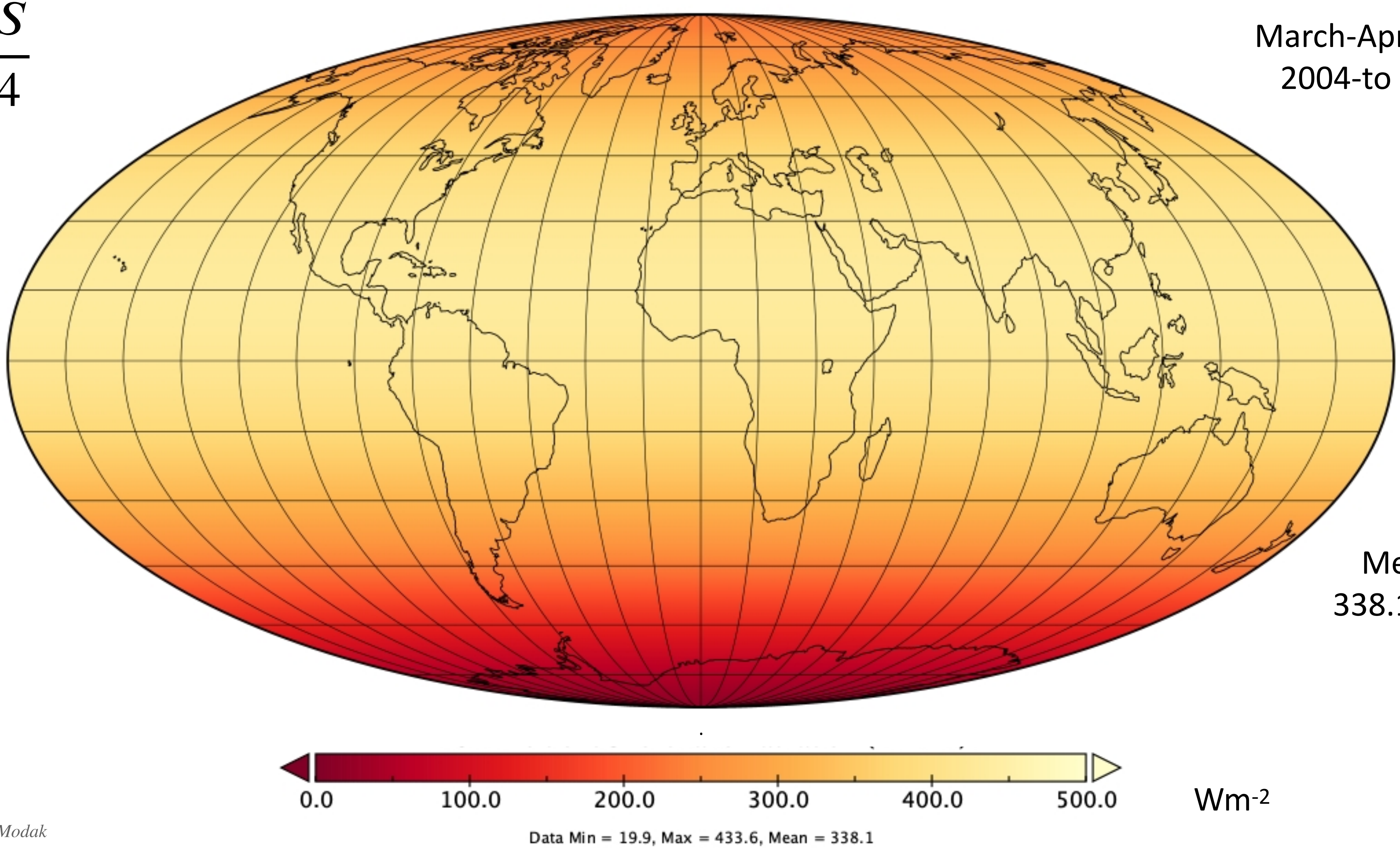
Model (MPI-ESM) simulated TOA incoming solar radiation

$$\frac{S}{4}$$

March-April-May
2004-to 2015



Mean =
338.1 Wm^{-2}

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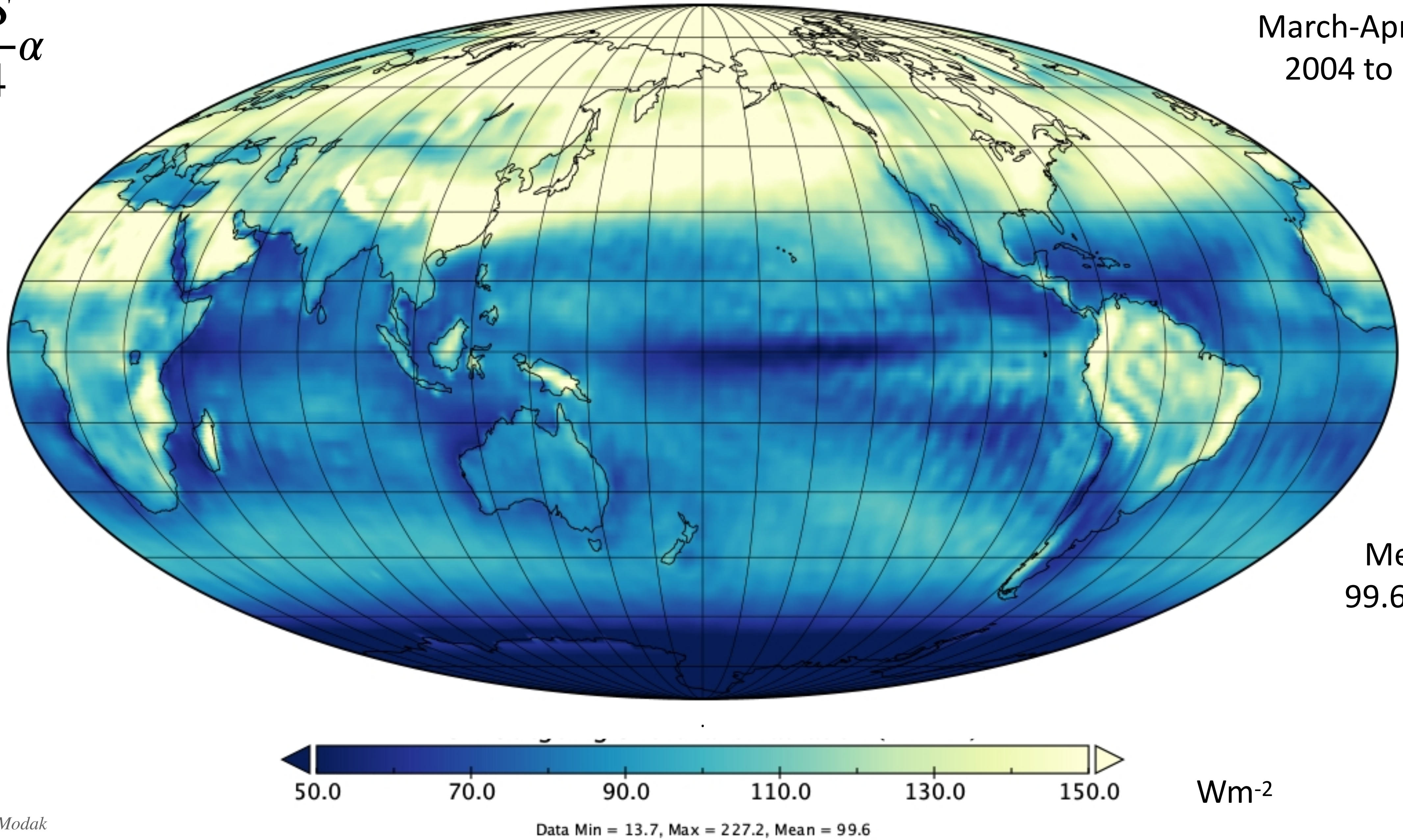
Model (MPI-ESM) simulated TOA albedo

$$\frac{S}{4}\alpha$$

March-April-May
2004 to 2015



Wm^{-2}

Mean =
99.6 Wm^{-2}

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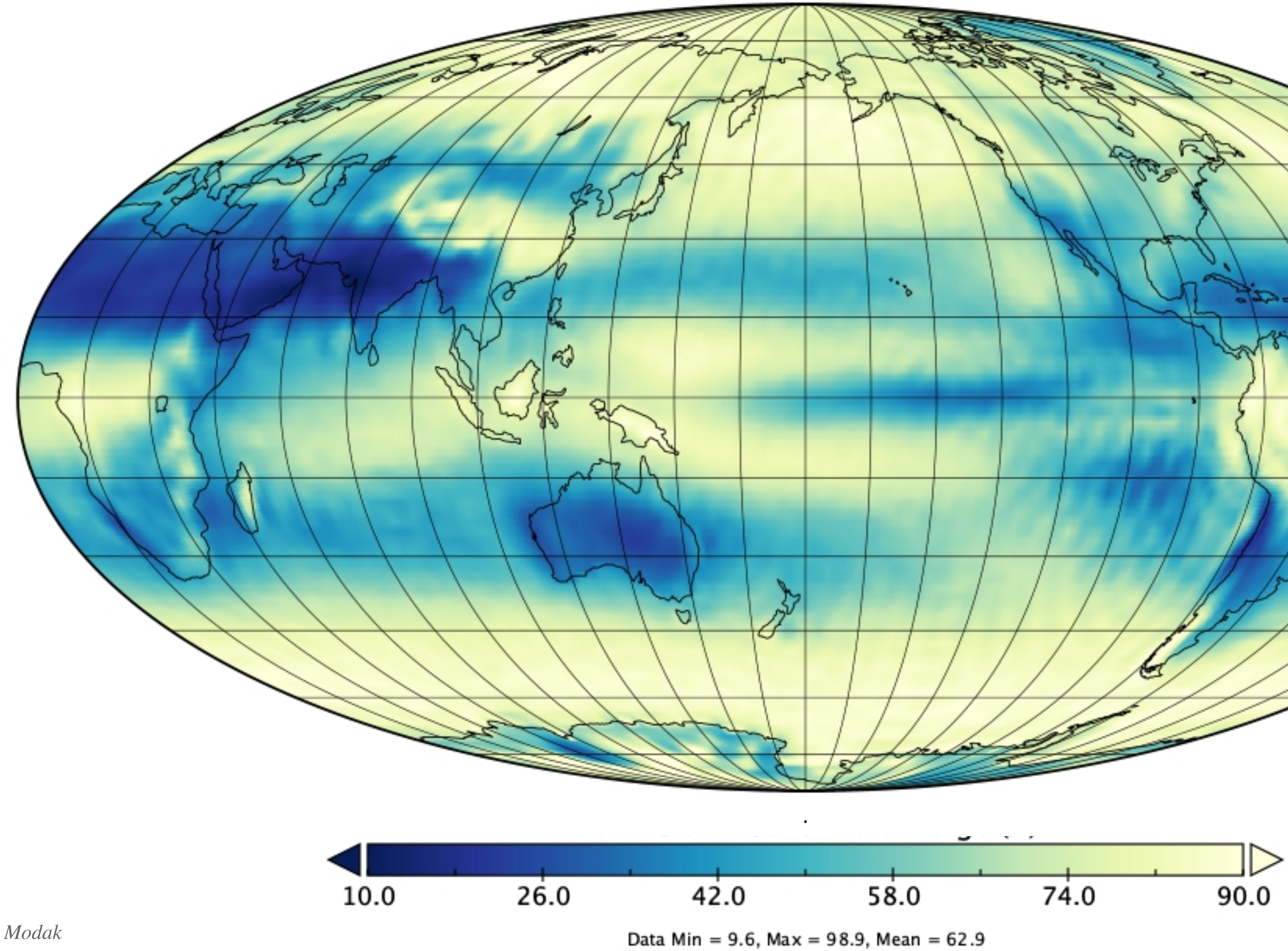
Model (MPI-ESM) simulated Total Cloud cover

March-April-May
2004 to 2015



%

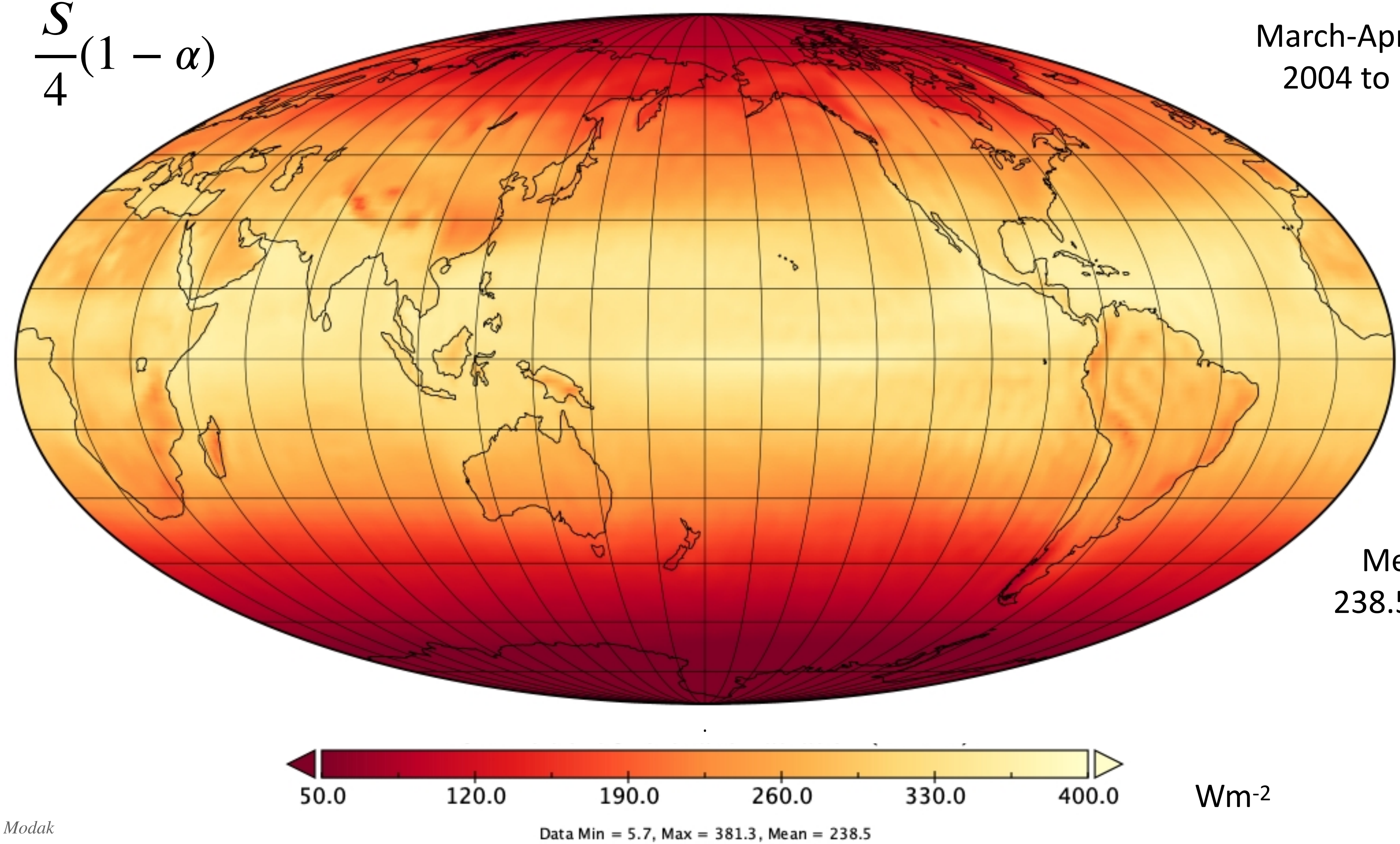
Mean =
62.9 %

*Created by
Angshuman Modak*

Model (MPI-ESM) simulated TOA net shortwave radiation

$$\frac{S}{4}(1-\alpha)$$

March-April-May
2004 to 2015



Mean =
238.5 Wm^{-2}

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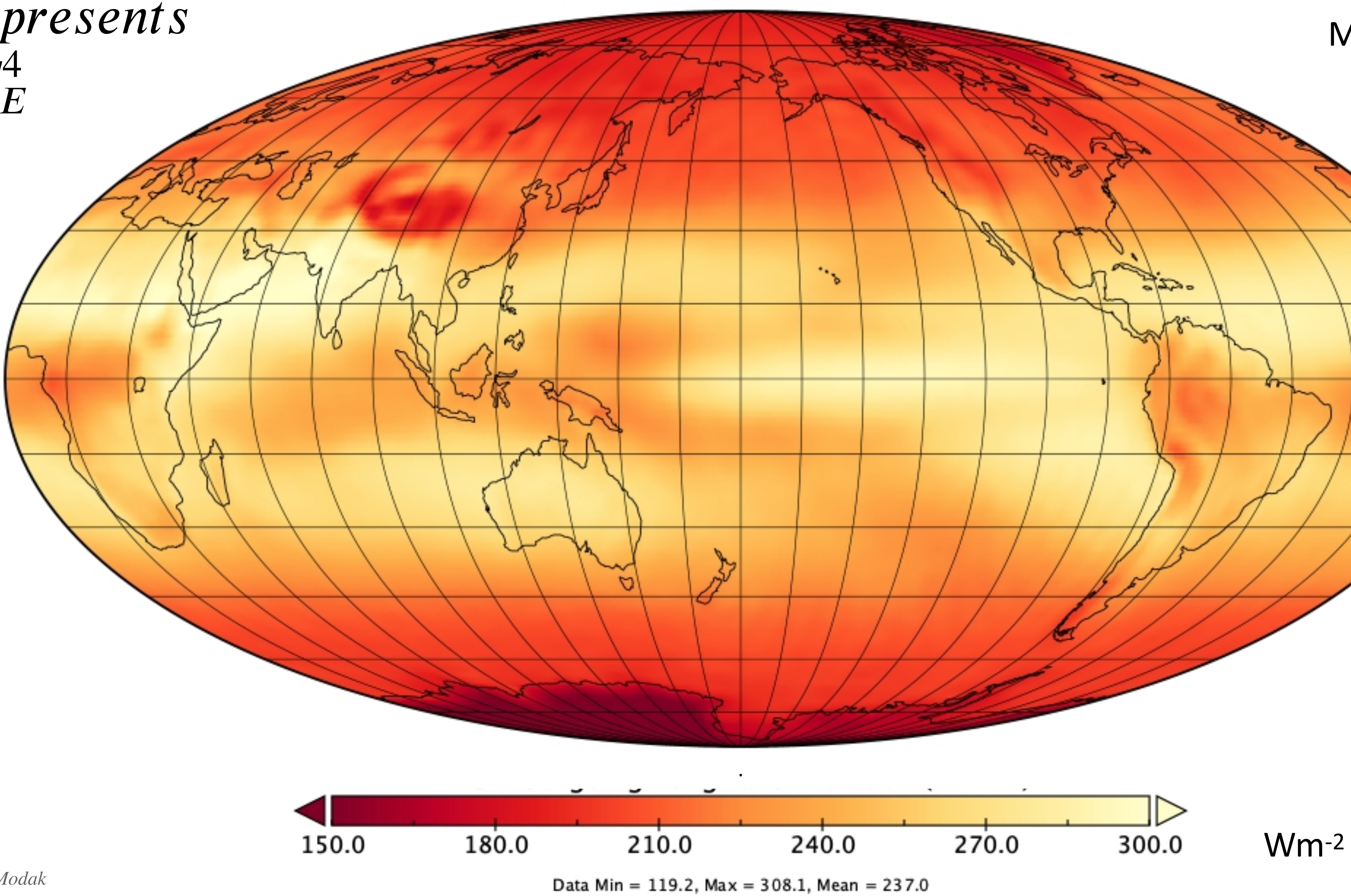
Model (MPI-ESM) simulated TOA outgoing longwave radiation

Represents σT_E^4

March-April-May
2004 to 2015



Mean =
237.0 Wm^{-2}

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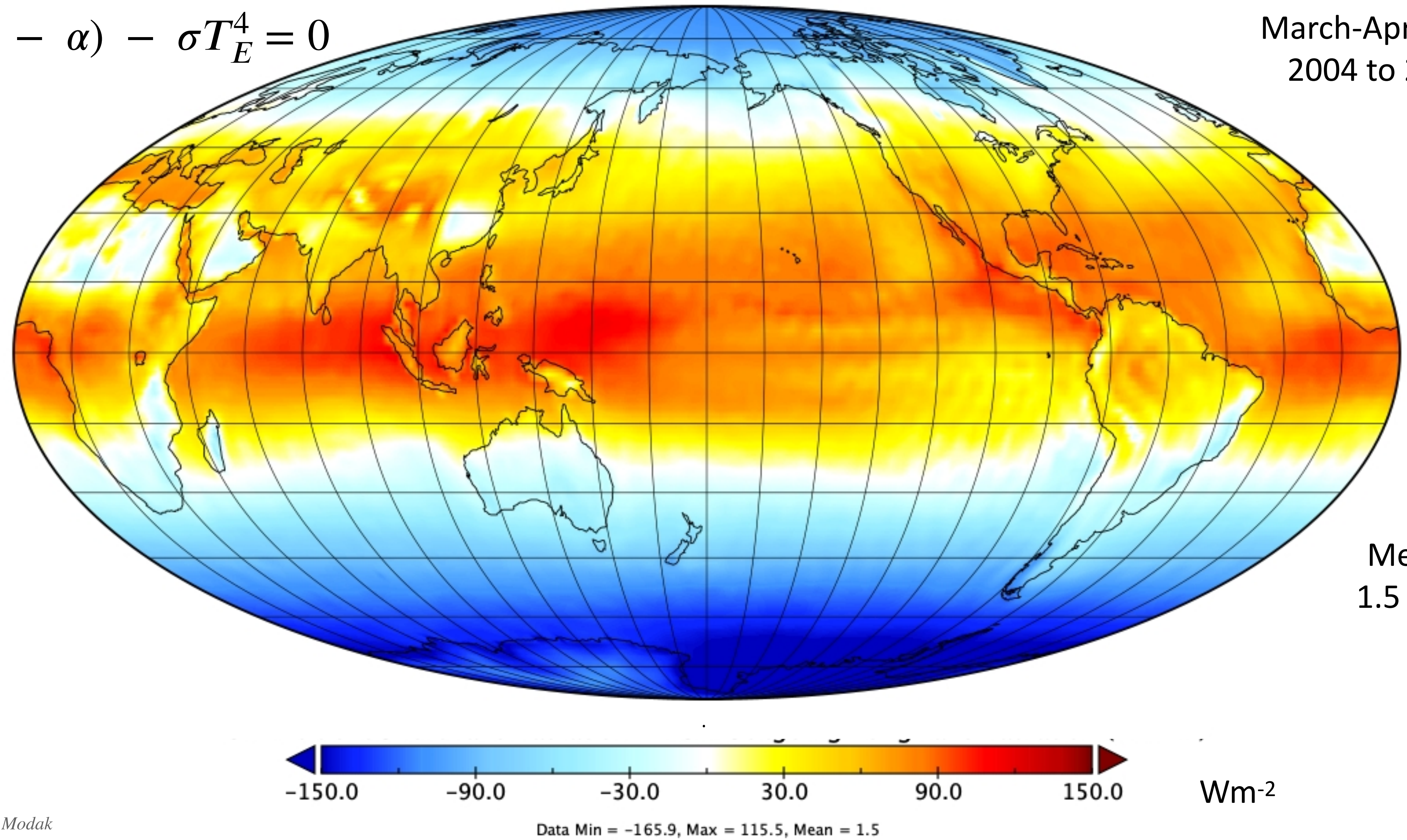
Angshuman Modak

Model (MPI-ESM) simulated TOA net radiation

Represents

$$\frac{S}{4}(1-\alpha)-\sigma T_E^4=0$$

March-April-May
2004 to 2015



Wm^{-2}

Mean =
$1.5\ Wm^{-2}$

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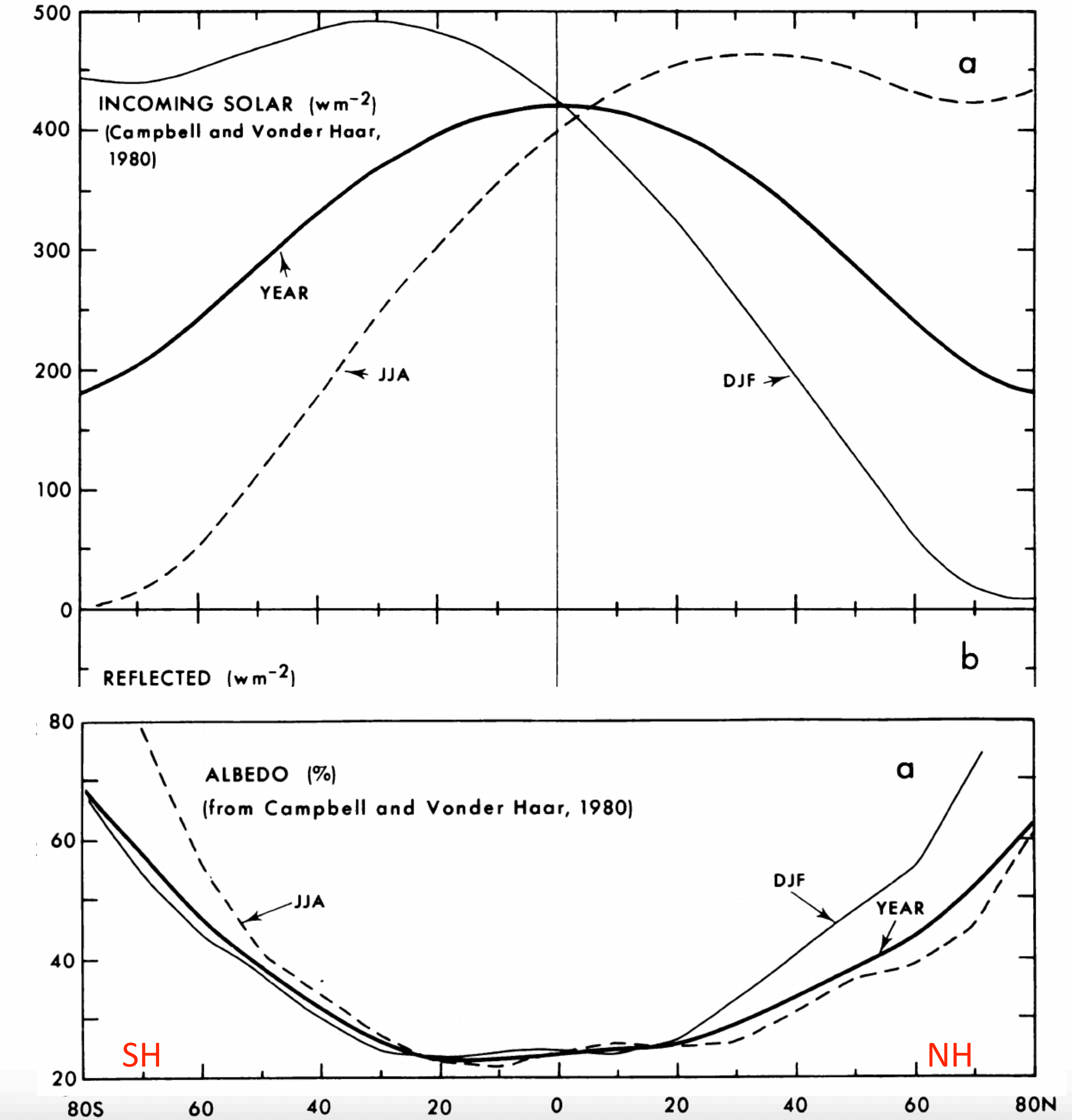

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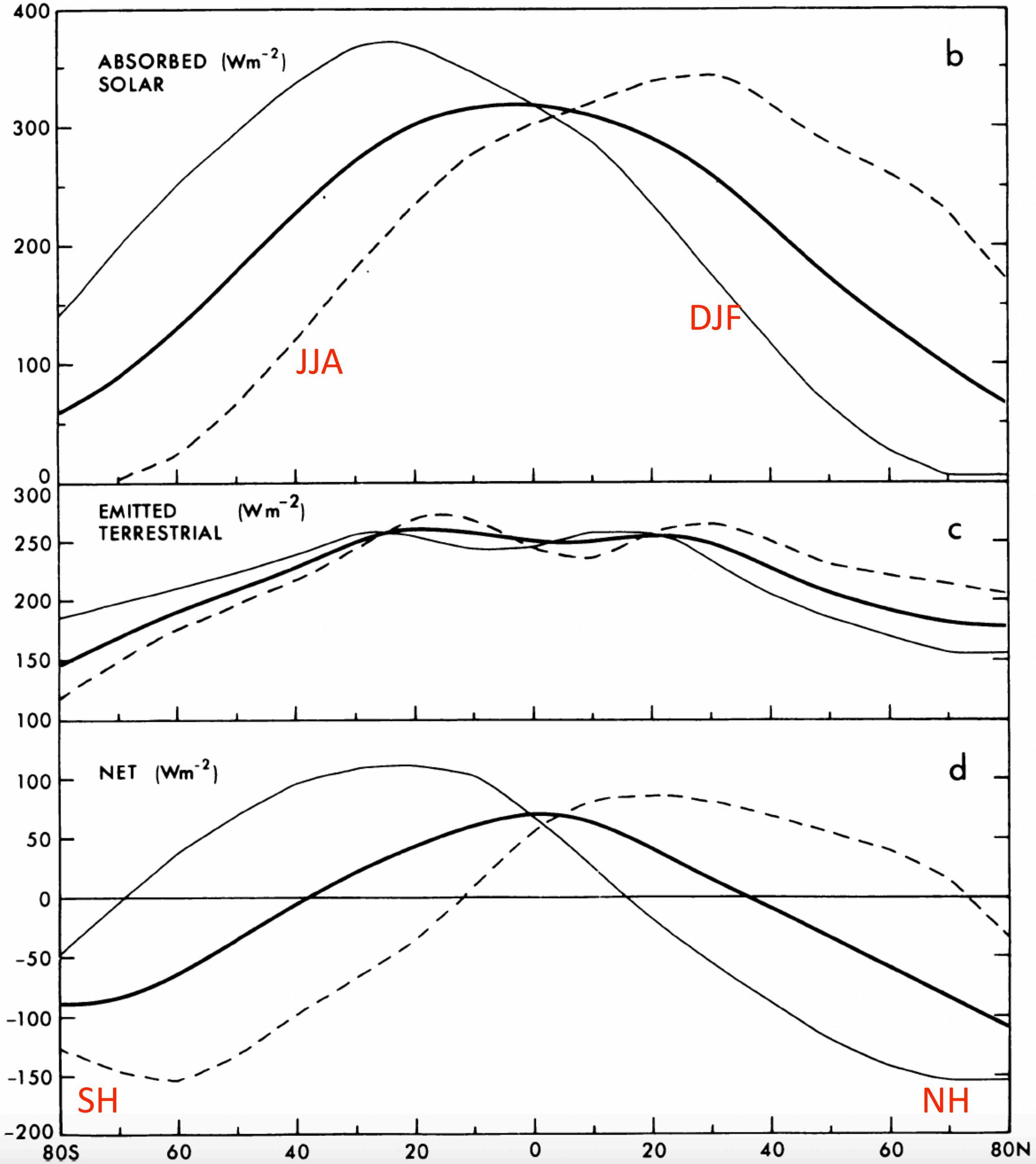
Piexoto and Oort 1991



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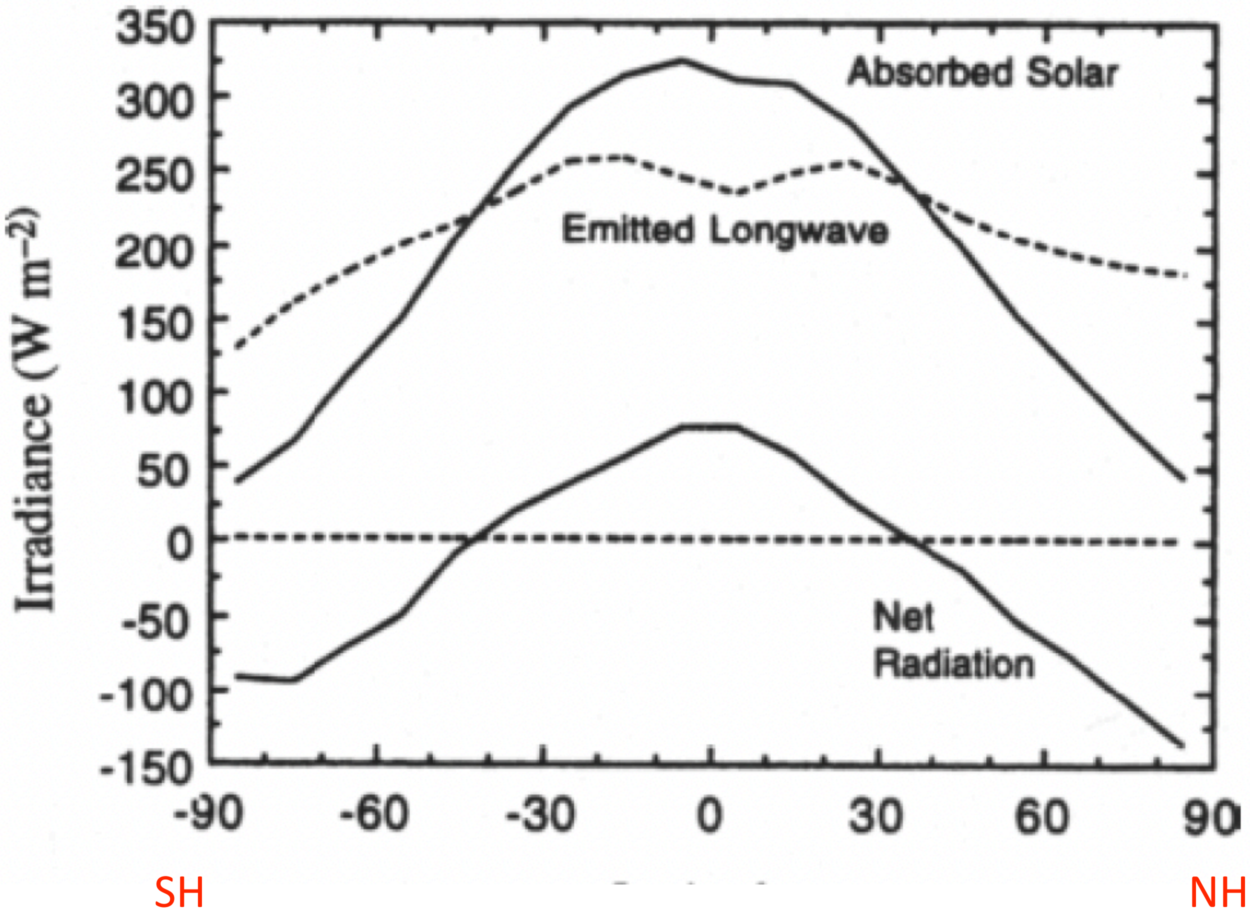
Piexoto and Oort 1991



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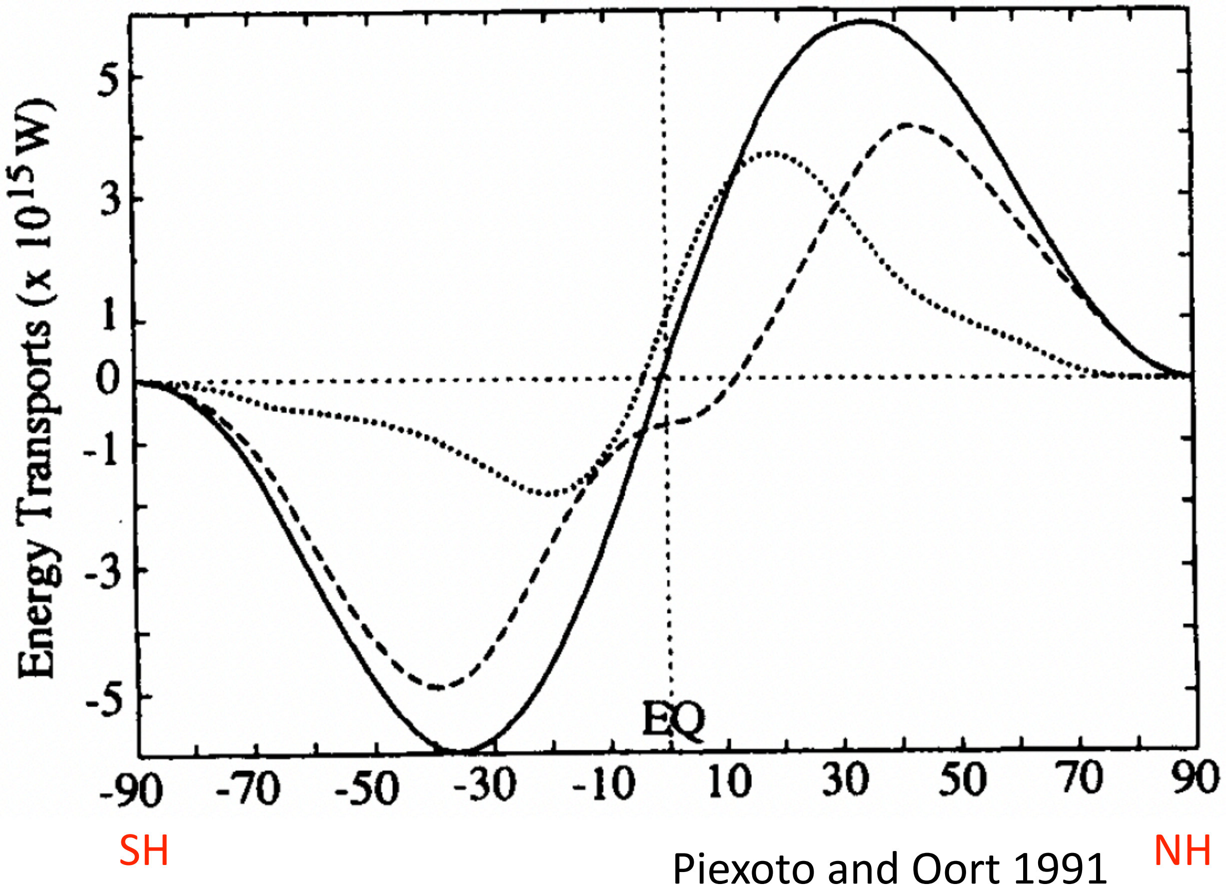
Curry and Webster



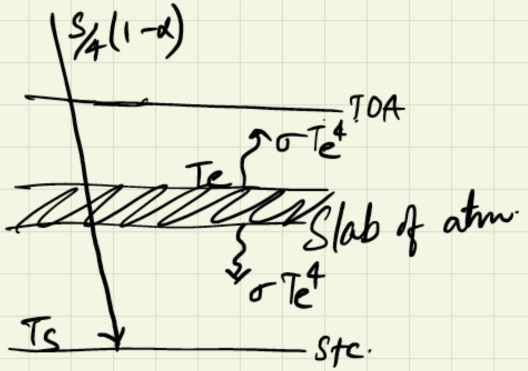
Piexoto and Oort 1991

The perfectly absorbing slab atmosphere

1- layer atmosphere

$$N = \frac{S}{4}(1-\alpha) - \sigma T_e^4$$

Earth is considered a black body.



$$N_{TOA} = \frac{S}{4}(1-\alpha) - \sigma T_e^4$$

$$N_{Sfc} = \frac{S}{4}(1-\alpha) + \sigma T_e^4 - \sigma T_s^4$$

$$\sigma T_s^4 = \frac{S}{4}(1-\alpha) + \sigma T_e^4$$

$$= \frac{S}{4}(1-\alpha) + \frac{S}{4}(1-\alpha)$$

$$\alpha = 0.3$$

$$T_s = \left[\frac{1}{\sigma}\cdot\frac{S}{2}(1-\alpha)\right]^{1/4}$$

- A slab of perfect greenhouse gas
- Atmosphere is perfectly transmissive to sunlight but a blackbody absorber in the infrared
- $T_s = \left(\frac{S(1-\alpha)}{2\sigma}\right)^{\frac{1}{4}}$

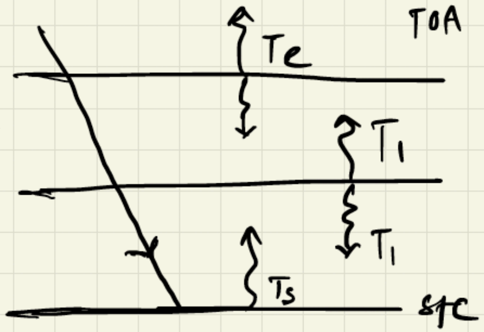
Created by Angshuman Modak

The perfectly absorbing slab atmosphere

2-layer atmosphere

$$N_{TOA} = \frac{S}{4}(1-\alpha) - \sigma T_e^4$$

$$N_{sfc} = \frac{S}{4}(1-\alpha) + \sigma T_1^4 - \sigma T_s^4$$



$$\sigma T_s^4 = \frac{S}{4}(1-\alpha) + \sigma T_1^4 \quad — 1$$

$$= \frac{S}{4}(1-\alpha) + \sigma T_1^4$$

$$2\sigma T_1^4 = \sigma T_e^4 + \sigma T_s^4 \quad — 2$$

$$\Rightarrow \sigma T_1^4 = \frac{1}{2}(\sigma T_e^4 + \sigma T_s^4)$$

$$2\sigma T_s^4 = \frac{S}{2}(1-\alpha) + \sigma T_e^4 + \sigma T_s^4$$

$$\Rightarrow \sigma T_s^4 = \frac{S}{2}(1-\alpha) + \frac{S}{4}(1-\alpha) = \frac{3S}{4}(1-\alpha)$$

$$\Rightarrow T_s = \left[3\,S/4\sigma\,(1-\alpha)\right]^{1/4}$$

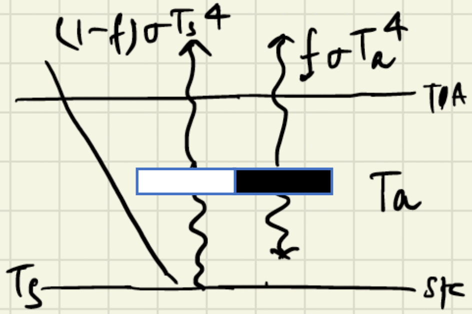
- 2-layers
- A slab of perfect greenhouse gas
- Atmosphere is perfectly transmissive to sunlight but a blackbody absorber in the infrared
- $$T_s = \left(\frac{3S(1-\alpha)}{4\sigma}\right)^{\frac{1}{4}}$$
- For n-layers what would be Ts ?

Created by Angshuman Modak

The partially absorbing slab atmosphere

f → fraction of energy

Atm. emits and absorbs



$$N_{TOA} = \frac{S}{4}(1-\alpha) - f\sigma T_a^4 - (1-f)\sigma T_s^4$$

$$N_{sfc} = \frac{S}{4}(1-\alpha) + f\sigma T_a^4 - \sigma T_s^4$$

$$T_s^4 = \frac{S(1-\alpha)}{2\sigma(2-f)}, \quad T_a^4 = \frac{S(1-\alpha)}{4\sigma(2-f)}$$

$T_s > T_e$ under all conditions.

if $f\uparrow$ $T_s\uparrow$, $T_a\uparrow$

if $f = 1$, $T_a \rightarrow T_e$

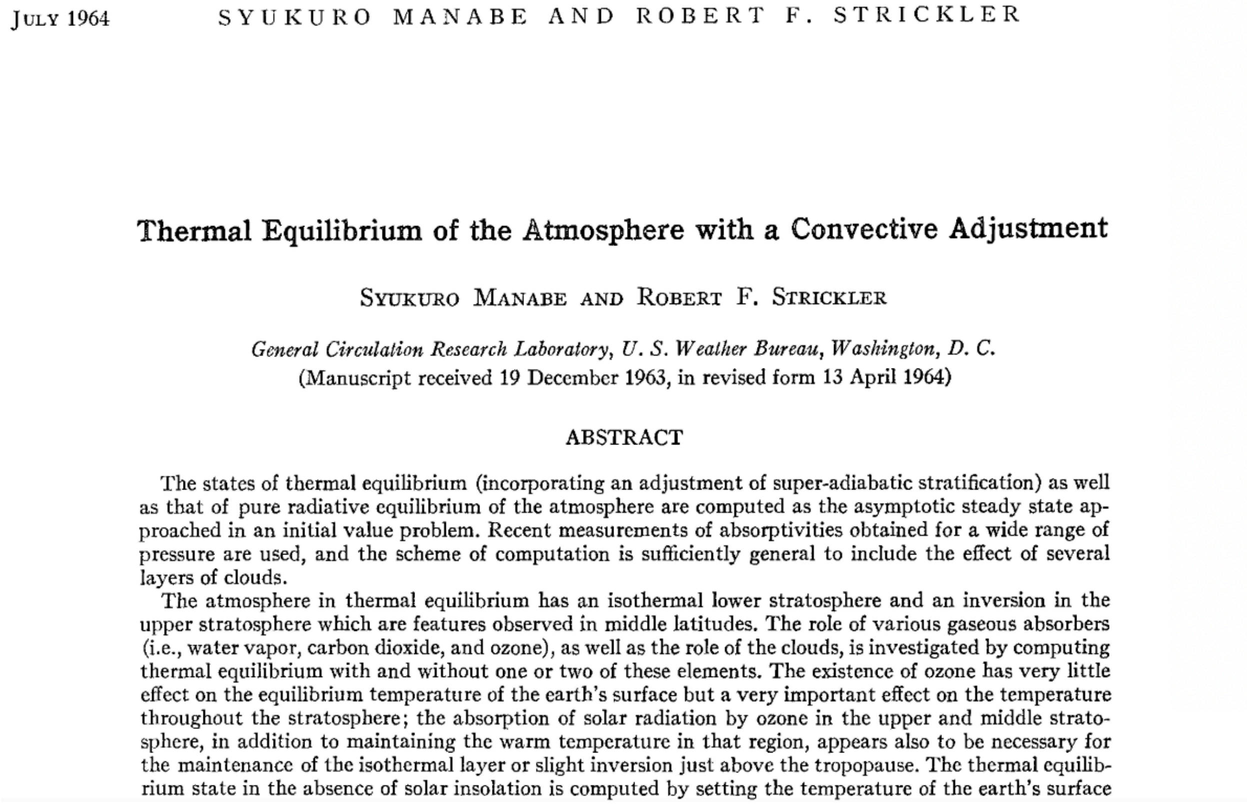
$f = 0$, $T_s \Rightarrow T_e$

- Atmosphere is transparent to SW
- f - fraction of energy that is absorbed
- How Ts and Ta are related?
- For Ts = 288K, $\alpha = 0.3$
- what is the value of f ?

Created by
Angshuman Modak

Radiative equilibrium

Radiative convective equilibrium (RCE)



JULY 1964 SYUKURO MANABE AND ROBERT F. STRICKLER

Thermal Equilibrium of the Atmosphere with a Convective Adjustment

SYUKURO MANABE AND ROBERT F. STRICKLER

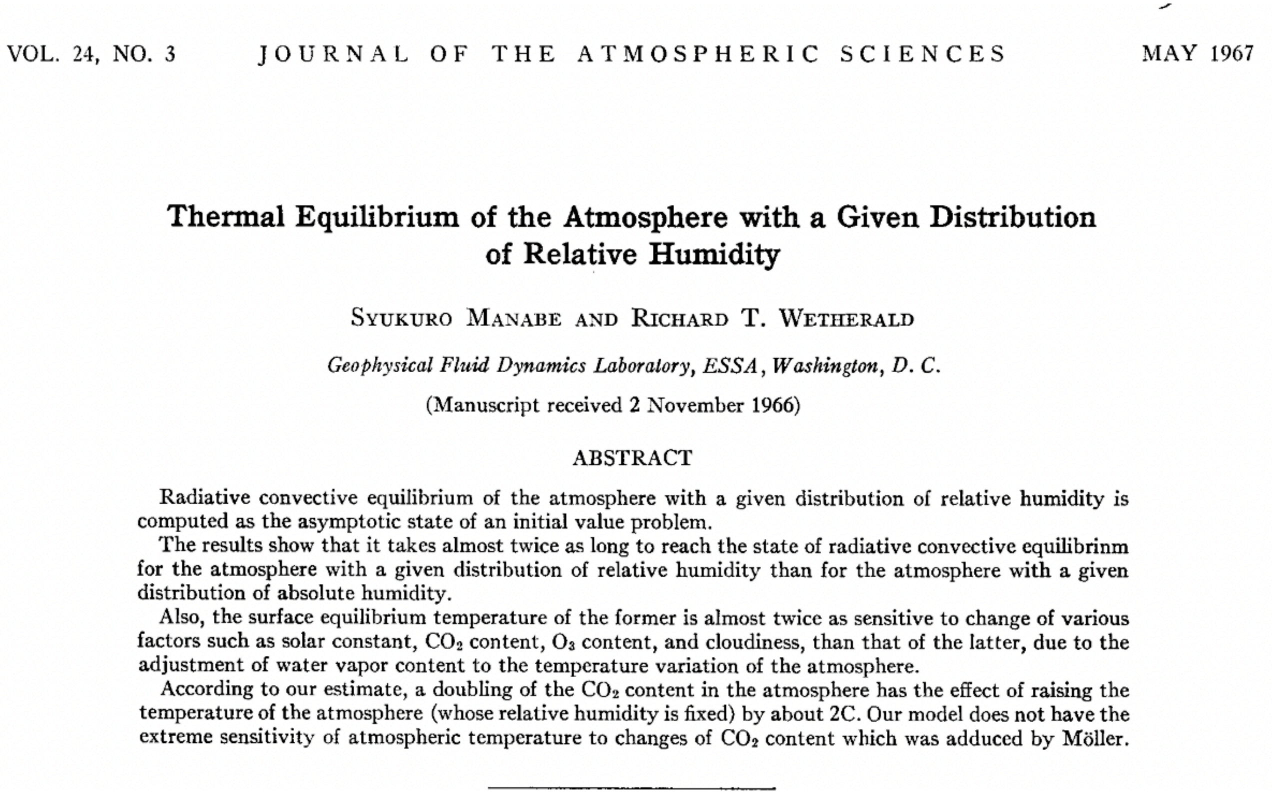
General Circulation Research Laboratory, U. S. Weather Bureau, Washington, D. C.

(Manuscript received 19 December 1963, in revised form 13 April 1964)

ABSTRACT

The states of thermal equilibrium (incorporating an adjustment of super-adiabatic stratification) as well as that of pure radiative equilibrium of the atmosphere are computed as the asymptotic steady state approached in an initial value problem. Recent measurements of absorptivities obtained for a wide range of pressure are used, and the scheme of computation is sufficiently general to include the effect of several layers of clouds.

The atmosphere in thermal equilibrium has an isothermal lower stratosphere and an inversion in the upper stratosphere which are features observed in middle latitudes. The role of various gaseous absorbers (i.e., water vapor, carbon dioxide, and ozone), as well as the role of the clouds, is investigated by computing thermal equilibrium with and without one or two of these elements. The existence of ozone has very little effect on the equilibrium temperature of the earth's surface but a very important effect on the temperature throughout the stratosphere; the absorption of solar radiation by ozone in the upper and middle stratosphere, in addition to maintaining the warm temperature in that region, appears also to be necessary for the maintenance of the isothermal layer or slight inversion just above the tropopause. The thermal equilibrium state in the absence of solar insolation is computed by setting the temperature of the earth's surface



VOL. 24, NO. 3 JOURNAL OF THE ATMOSPHERIC SCIENCES MAY 1967

Thermal Equilibrium of the Atmosphere with a Given Distribution of Relative Humidity

SYUKURO MANABE AND RICHARD T. WETHERALD

Geophysical Fluid Dynamics Laboratory, ESSA, Washington, D. C.

(Manuscript received 2 November 1966)

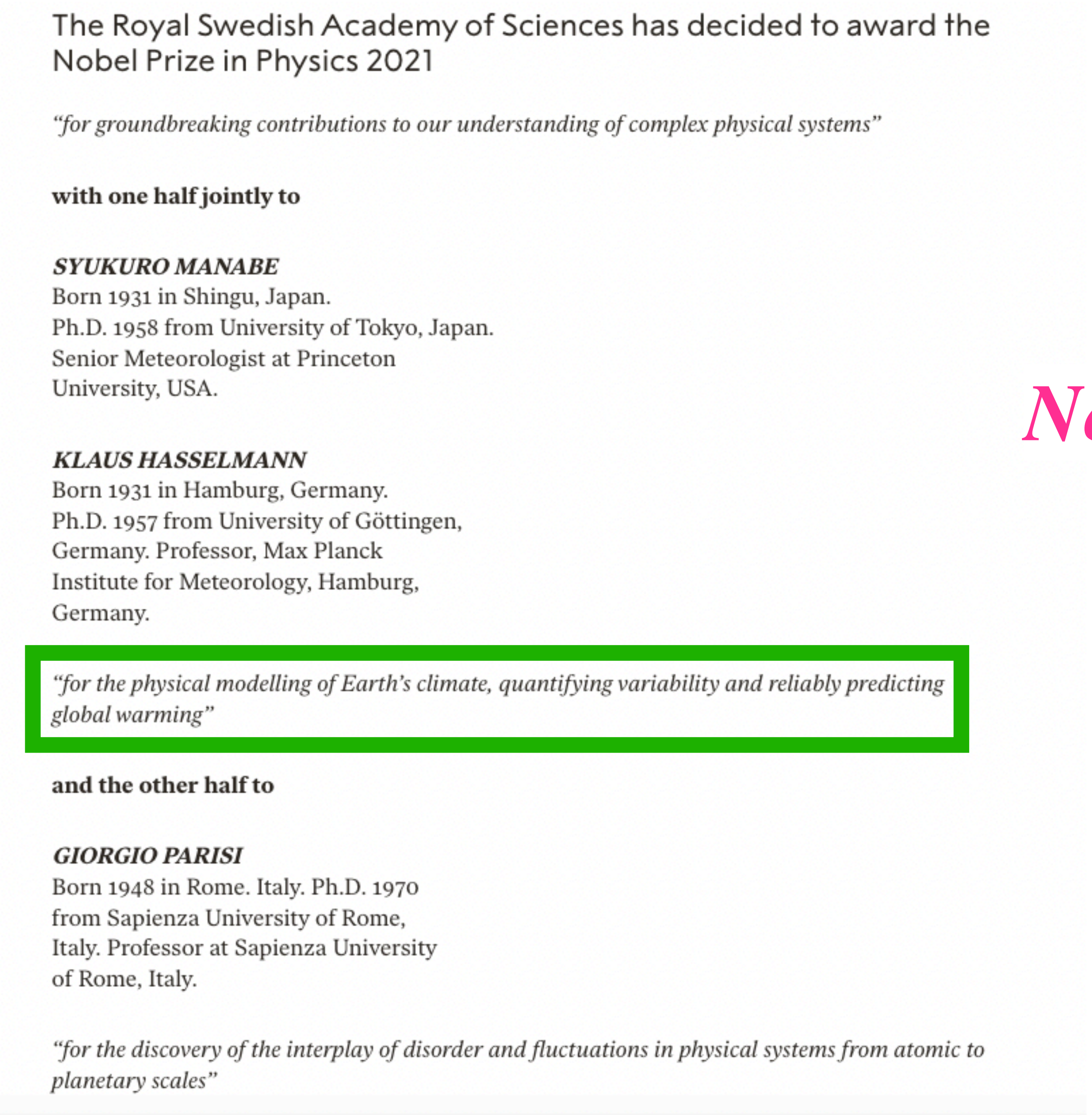
ABSTRACT

Radiative convective equilibrium of the atmosphere with a given distribution of relative humidity is computed as the asymptotic state of an initial value problem.

The results show that it takes almost twice as long to reach the state of radiative convective equilibrium for the atmosphere with a given distribution of relative humidity than for the atmosphere with a given distribution of absolute humidity.

Also, the surface equilibrium temperature of the former is almost twice as sensitive to change of various factors such as solar constant, CO_2 content, O_3 content, and cloudiness, than that of the latter, due to the adjustment of water vapor content to the temperature variation of the atmosphere.

According to our estimate, a doubling of the CO_2 content in the atmosphere has the effect of raising the temperature of the atmosphere (whose relative humidity is fixed) by about 2C. Our model does not have the extreme sensitivity of atmospheric temperature to changes of CO_2 content which was adduced by Möller.



The Royal Swedish Academy of Sciences has decided to award the Nobel Prize in Physics 2021

"for groundbreaking contributions to our understanding of complex physical systems"

with one half jointly to

SYUKURO MANABE
Born 1931 in Shingu, Japan.
Ph.D. 1958 from University of Tokyo, Japan.
Senior Meteorologist at Princeton
University, USA.

KLAUS HASSELMANN
Born 1931 in Hamburg, Germany.
Ph.D. 1957 from University of Göttingen,
Germany. Professor, Max Planck
Institute for Meteorology, Hamburg,
Germany.

"for the physical modelling of Earth's climate, quantifying variability and reliably predicting global warming"

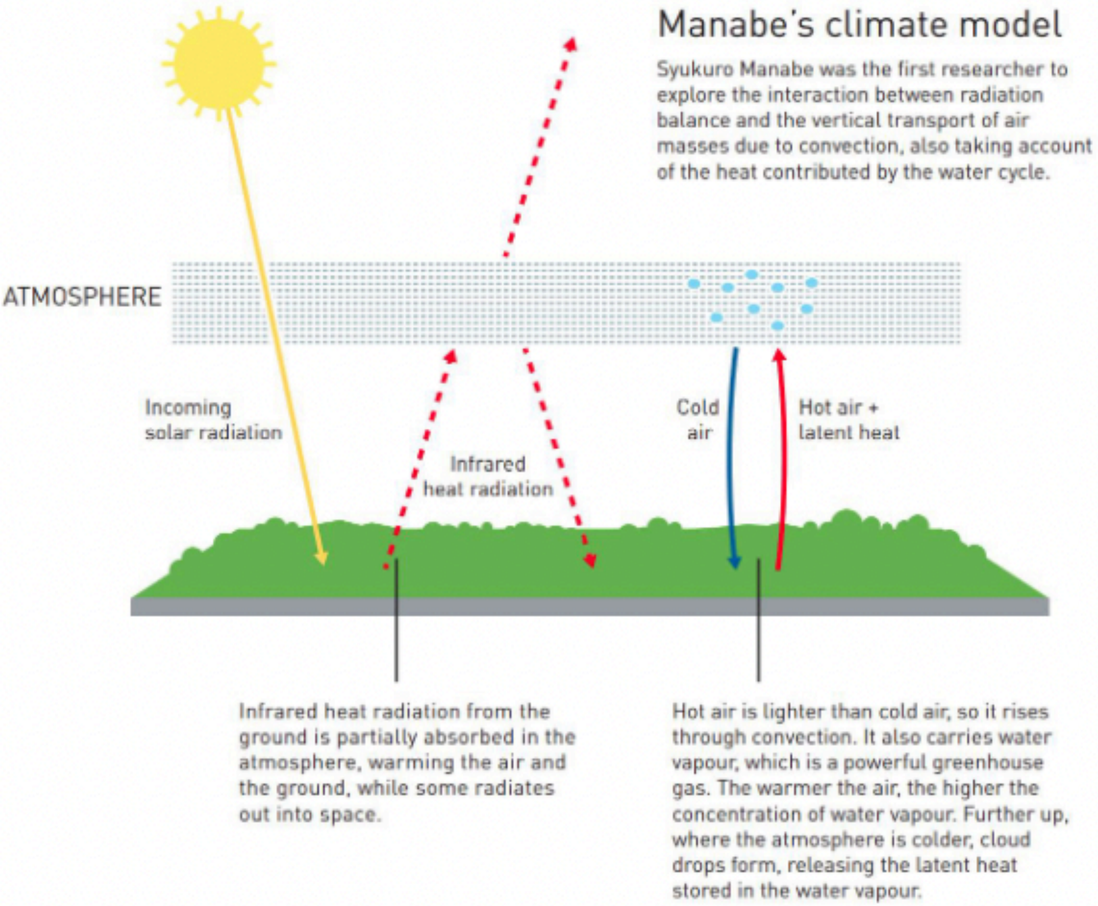
and the other half to

GIORGIO PARISI
Born 1948 in Rome. Italy. Ph.D. 1970
from Sapienza University of Rome,
Italy. Professor at Sapienza University
of Rome, Italy.

"for the discovery of the interplay of disorder and fluctuations in physical systems from atomic to planetary scales"

https://www.nobelprize.org/prizes/physics/2021/popular-information/

Nobel Prize in Physics 2021

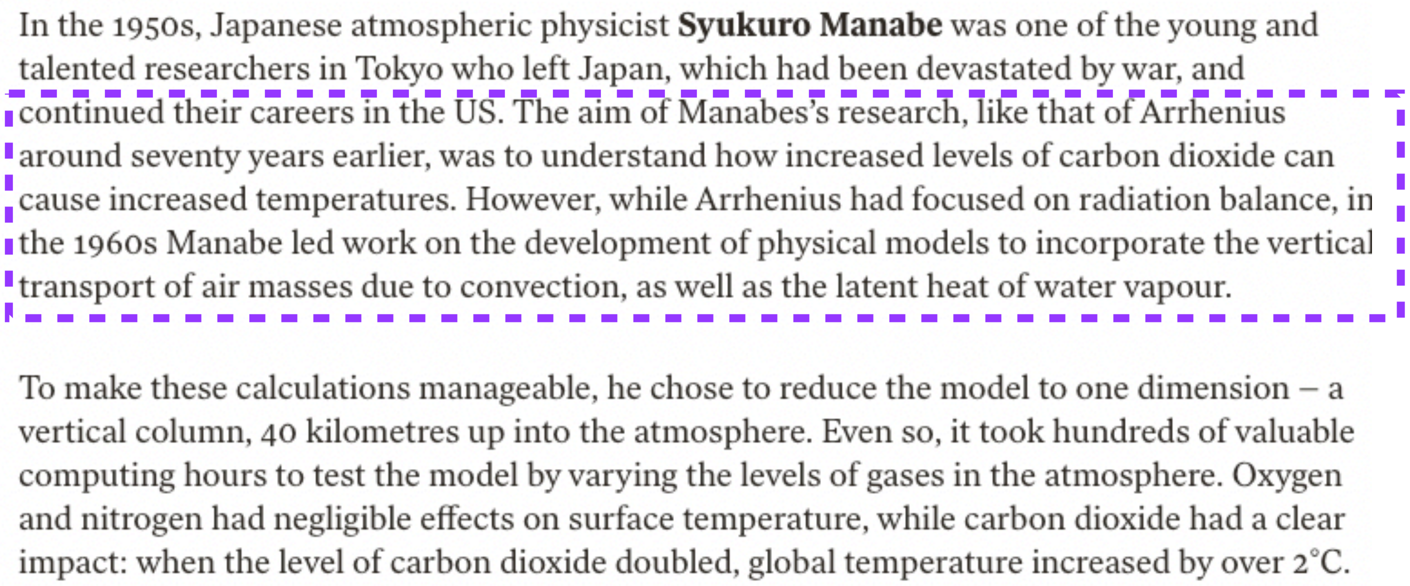


Manabe's climate model

Syukuro Manabe was the first researcher to explore the interaction between radiation balance and the vertical transport of air masses due to convection, also taking account of the heat contributed by the water cycle.

Infrared heat radiation from the ground is partially absorbed in the atmosphere, warming the air and the ground, while some radiates out into space.

Hot air is lighter than cold air, so it rises through convection. It also carries water vapour, which is a powerful greenhouse gas. The warmer the air, the higher the concentration of water vapour. Further up, where the atmosphere is colder, cloud drops form, releasing the latent heat stored in the water vapour.



In the 1950s, Japanese atmospheric physicist **Syukuro Manabe** was one of the young and talented researchers in Tokyo who left Japan, which had been devastated by war, and continued their careers in the US. The aim of Manabes's research, like that of Arrhenius around seventy years earlier, was to understand how increased levels of carbon dioxide can cause increased temperatures. However, while Arrhenius had focused on radiation balance, in the 1960s Manabe led work on the development of physical models to incorporate the vertical transport of air masses due to convection, as well as the latent heat of water vapour.

To make these calculations manageable, he chose to reduce the model to one dimension – a vertical column, 40 kilometres up into the atmosphere. Even so, it took hundreds of valuable computing hours to test the model by varying the levels of gases in the atmosphere. Oxygen and nitrogen had negligible effects on surface temperature, while carbon dioxide had a clear impact: when the level of carbon dioxide doubled, global temperature increased by over 2°C.

Source: https://www.nobelprize.org/prizes/physics/2021/popular-information/

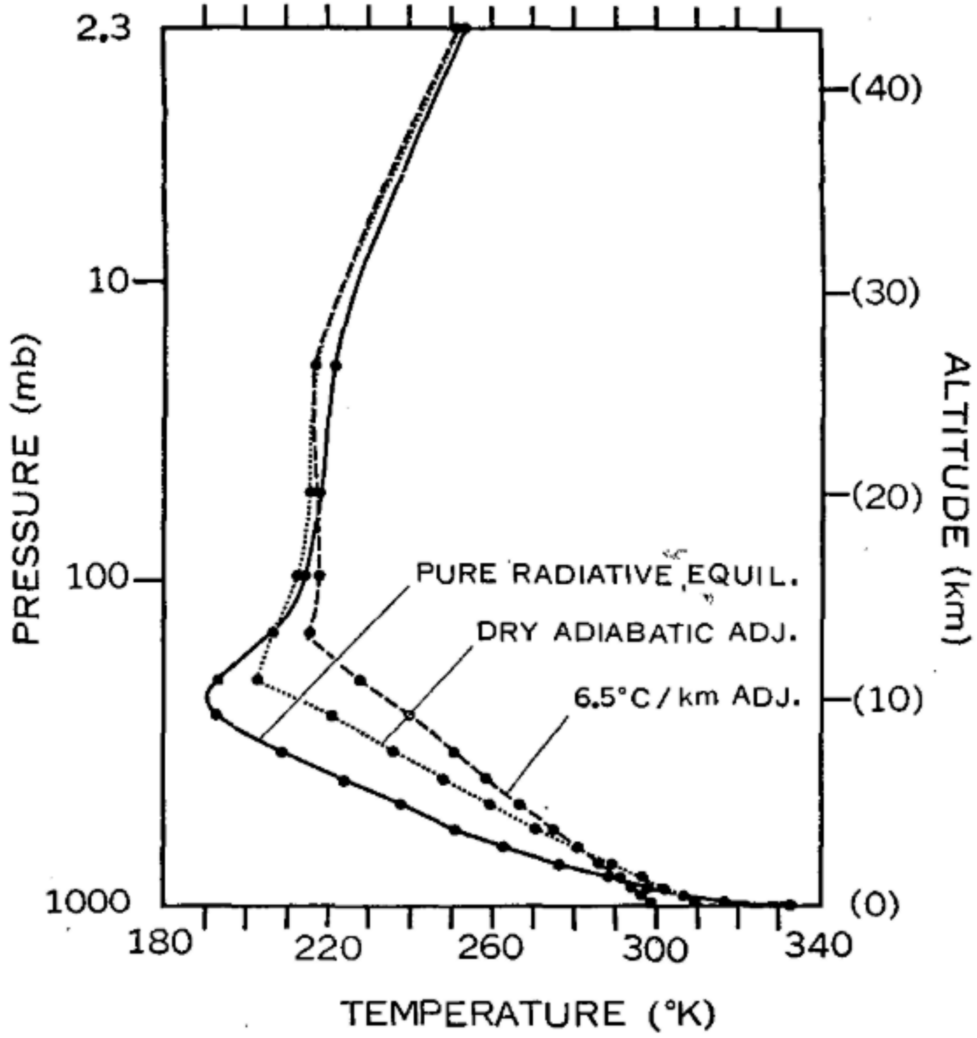
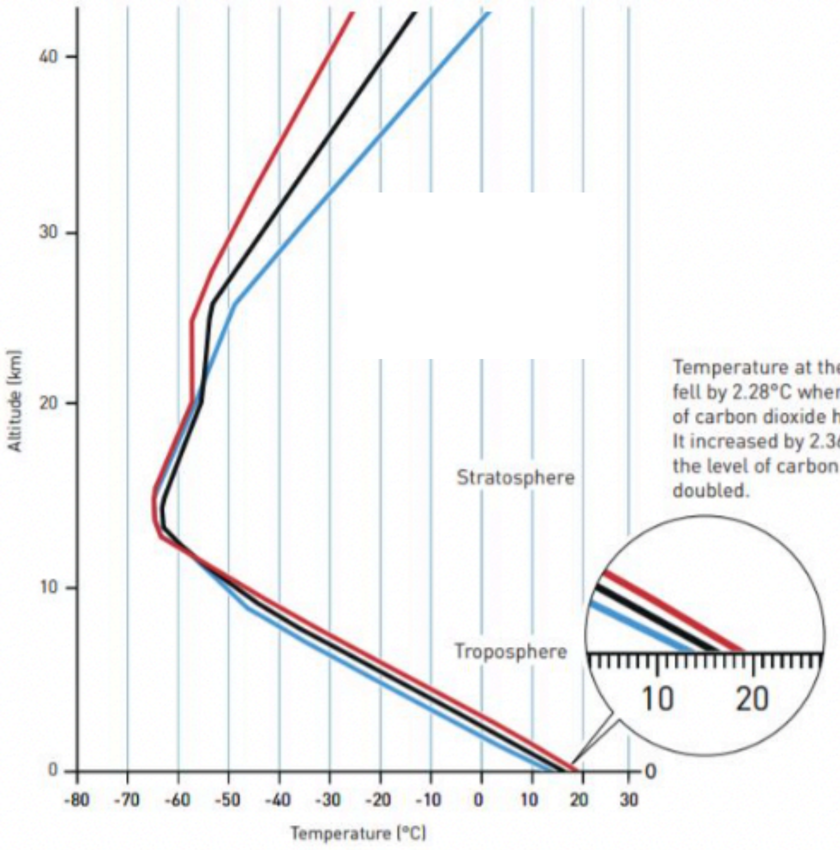


FIG. 4. The dashed, dotted, and solid lines show the thermal equilibrium with a critical lapse rate of 6.5 deg km^{-1}, a dry-adiabatic critical lapse rate (10 deg km^{-1}), and pure radiative equilibrium.

Manabe & Strickler 1964

Carbon dioxide heats the atmosphere

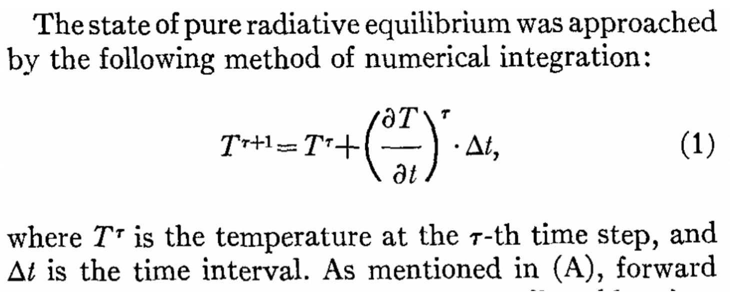
Increased levels of carbon dioxide lead to higher temperatures in the lower atmosphere, while the upper atmosphere gets colder. Manabe thus confirmed that the variation in temperature is due to increased levels of carbon dioxide; if it was caused by increased solar radiation, the entire atmosphere should have warmed up.



Temperature at the surface fell by 2.28°C when the level of carbon dioxide halved. It increased by 2.36°C when the level of carbon dioxide doubled.

Source: Manabe and Wetherald (1967) Thermal equilibrium of the atmosphere with a given distribution of relative humidity, Journal of the atmospheric sciences, Vol. 24, Nr 3, May.

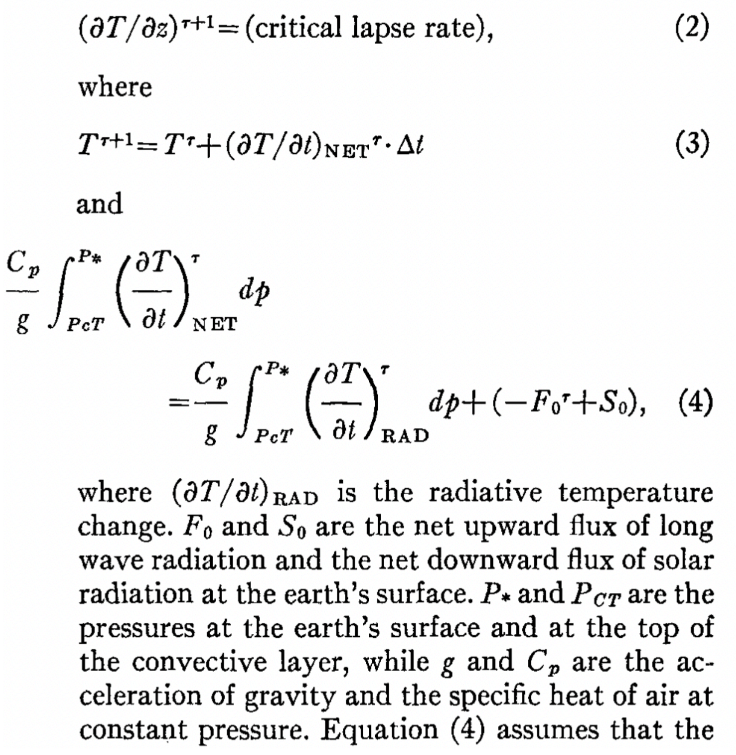
Coming back to Manabe & Strickler 1964



The state of pure radiative equilibrium was approached by the following method of numerical integration:

$$T^{\tau+1}=T^{\tau}+\left(\frac{\partial T}{\partial t}\right)^{\tau}\cdot\Delta t, \qquad (1)$$

where T^{τ} is the temperature at the τ-th time step, and Δt is the time interval. As mentioned in (A), forward



$$(\partial T/\partial z)^{\tau+1}=(\text{critical lapse rate}), \qquad (2)$$

where

$$T^{\tau+1}=T^{\tau}+(\partial T/\partial t)_{\mathrm{NET}}{}^{\tau}\cdot\Delta t \qquad (3)$$

and

$$\frac{C_p}{g}\int_{P_{cT}}^{P_*}\left(\frac{\partial T}{\partial t}\right)^{\tau}_{\mathrm{NET}}dp =\frac{C_p}{g}\int_{P_{cT}}^{P_*}\left(\frac{\partial T}{\partial t}\right)^{\tau}_{\mathrm{RAD}}dp+(-F_0{}^{\tau}+S_0), \qquad (4)$$

where $(\partial T/\partial t)_{\mathrm{RAD}}$ is the radiative temperature change. F_0 and S_0 are the net upward flux of long wave radiation and the net downward flux of solar radiation at the earth's surface. P_* and P_{CT} are the pressures at the earth's surface and at the top of the convective layer, while g and C_p are the acceleration of gravity and the specific heat of air at constant pressure. Equation (4) assumes that the

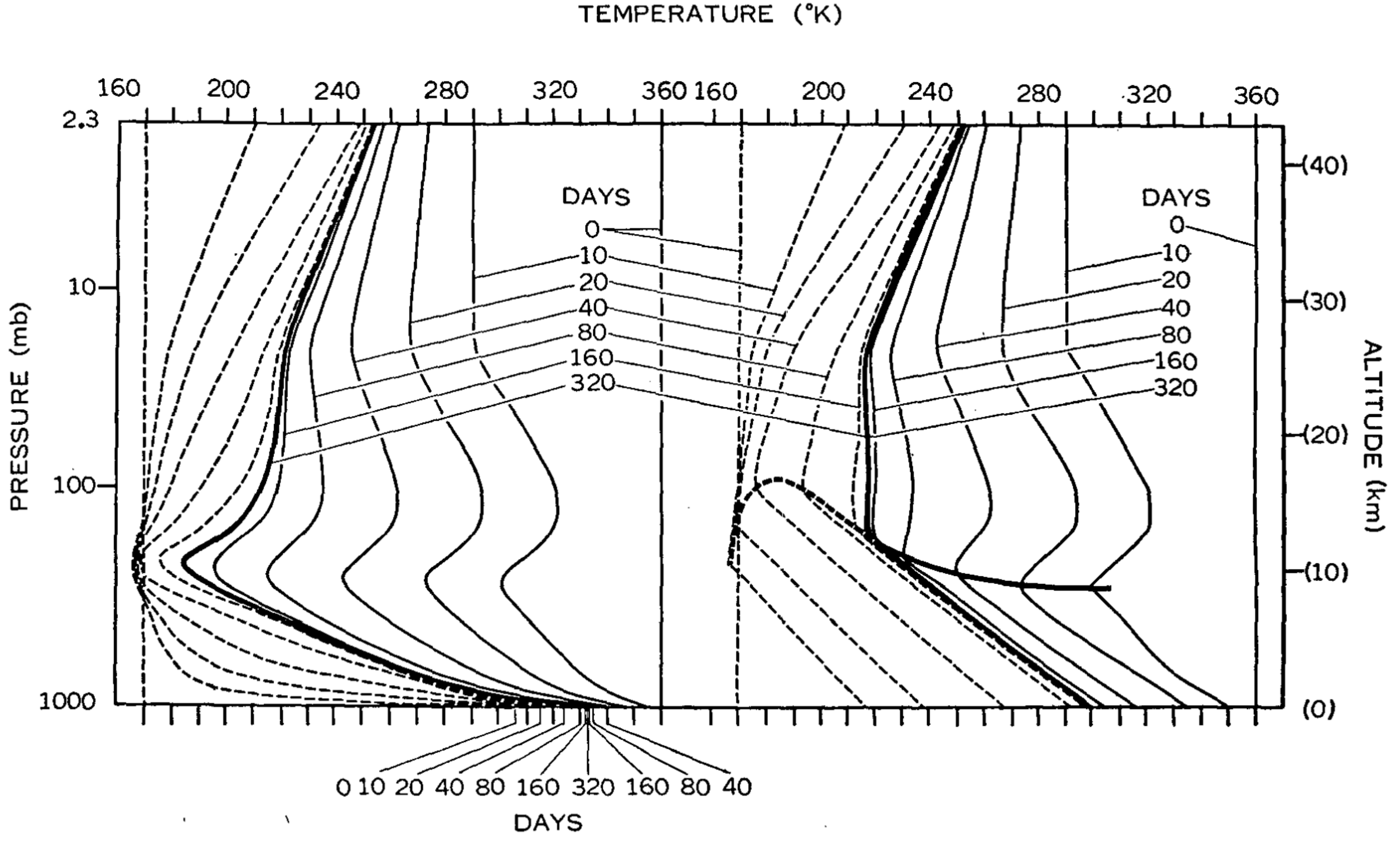
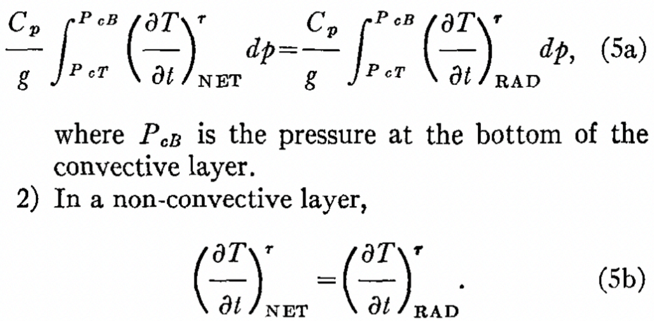


FIG. 1. The left and right hand sides of the figure, respectively, show the approach to states of pure radiative and thermal equilibrium. The solid and dashed lines show the approach from a warm and cold isothermal atmosphere.



$$\frac{C_p}{g}\int_{P_{cT}}^{P_{cB}}\left(\frac{\partial T}{\partial t}\right)^{\tau}_{\mathrm{NET}}dp=\frac{C_p}{g}\int_{P_{cT}}^{P_{cB}}\left(\frac{\partial T}{\partial t}\right)^{\tau}_{\mathrm{RAD}}dp, \qquad (5a)$$

where P_{cB} is the pressure at the bottom of the convective layer.

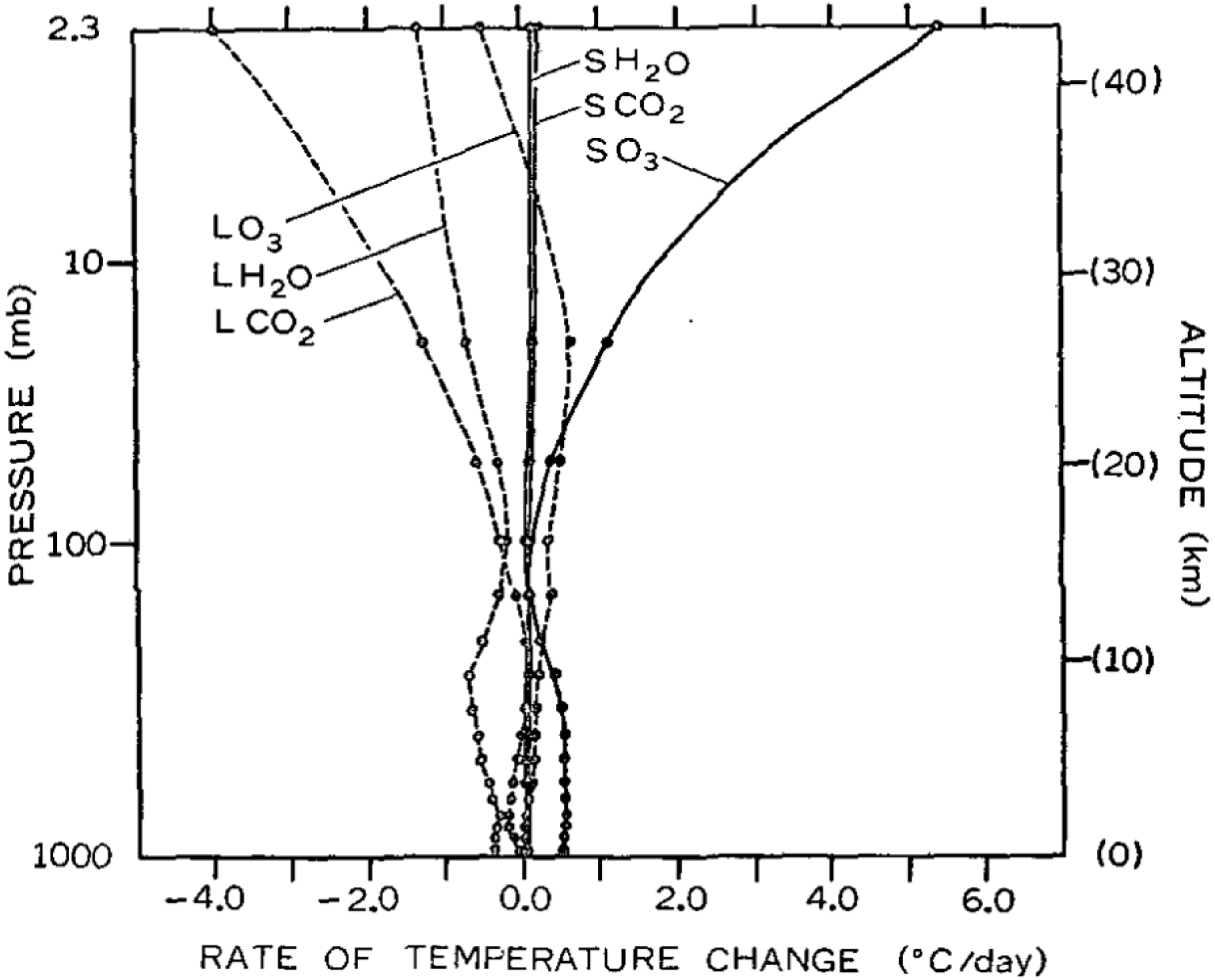
2) In a non-convective layer,

$$\left(\frac{\partial T}{\partial t}\right)^{\tau}_{\mathrm{NET}}=\left(\frac{\partial T}{\partial t}\right)^{\tau}_{\mathrm{RAD}}. \qquad (5b)$$

Coming back to Manabe & Strickler 1964

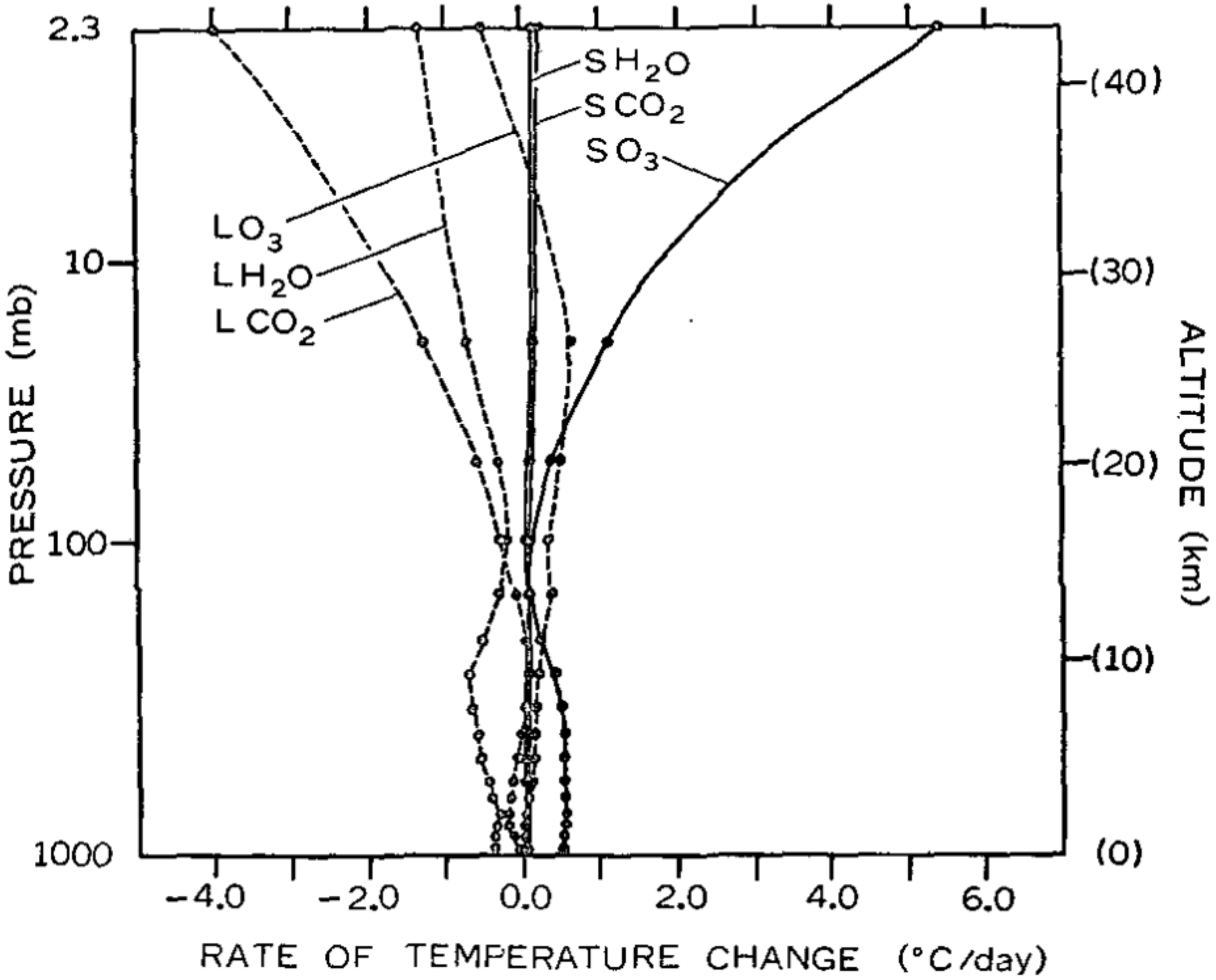
Good example to understand how models developed

1. Radiative equilibrium
2. Thermal equilibrium with convective adjustments
3. Atmospheric absorbers
4. Influence of clouds
5. Stratospheric water-vapor
6. Not just vertical but latitudinal variation of temperature

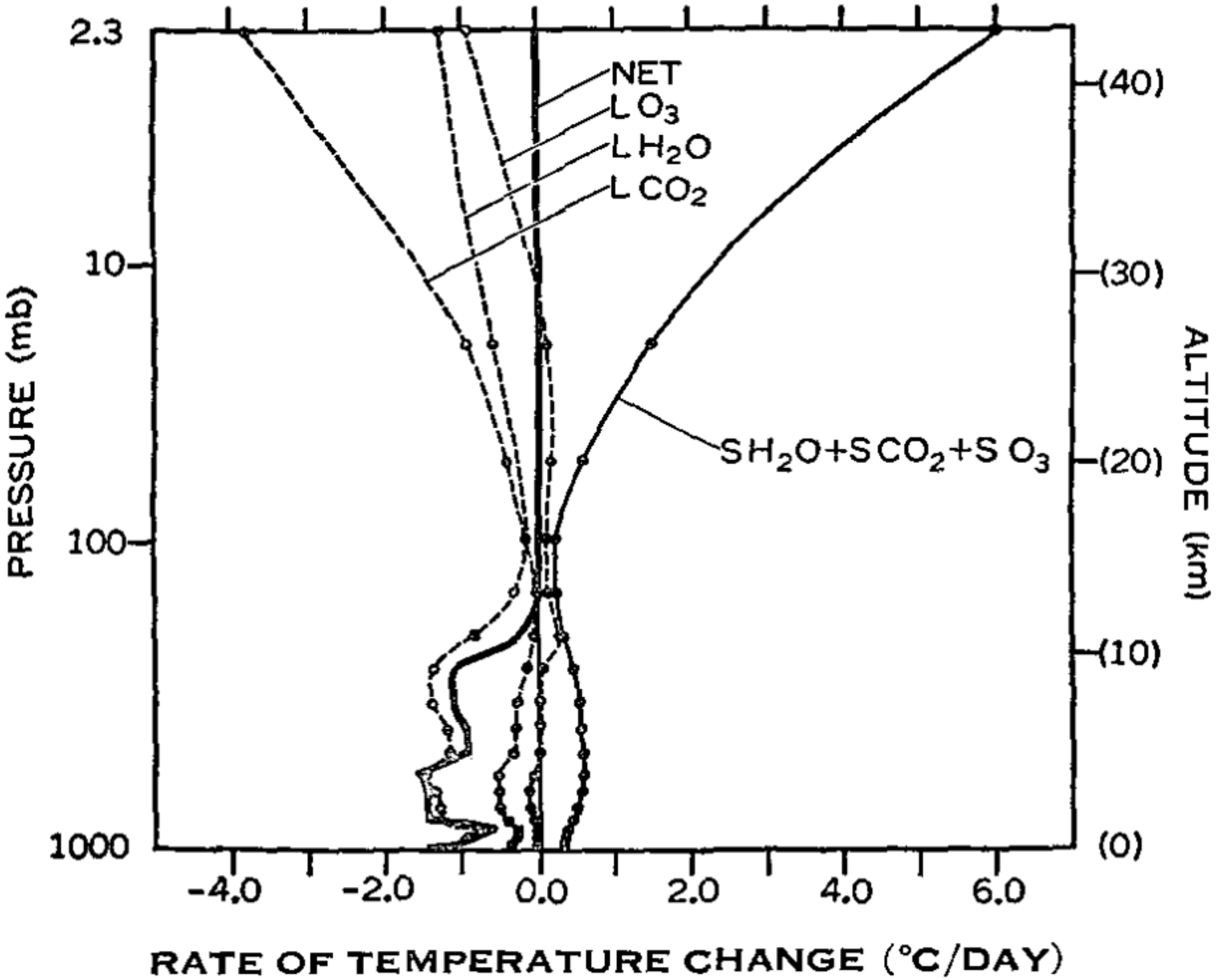


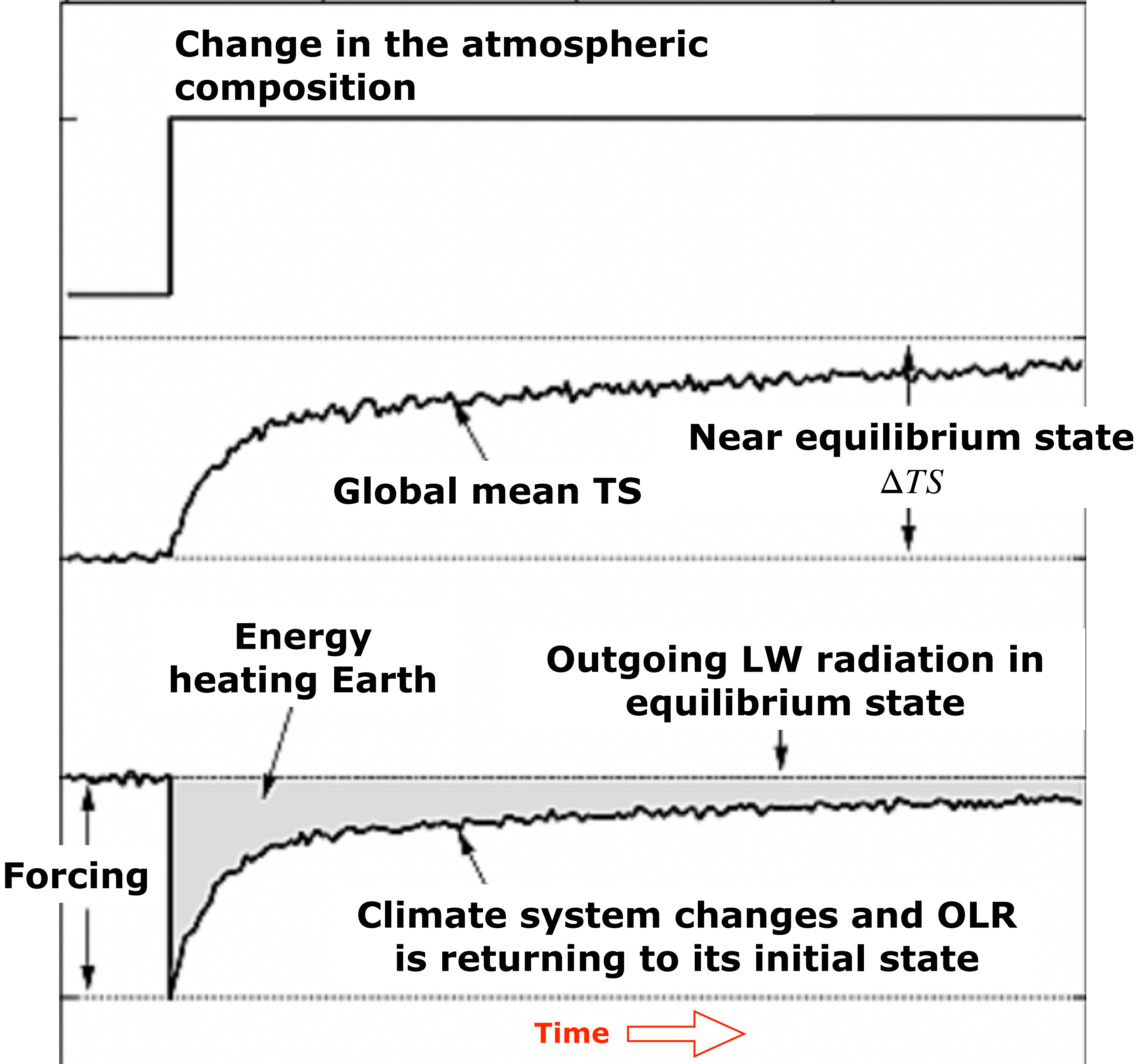
Coming back to Manabe & Strickler 1964

Radiative equilibrium



With clouds





Change in the atmospheric composition

Global mean TS

Near equilibrium state

ΔTS

Energy heating Earth

Outgoing LW radiation in equilibrium state

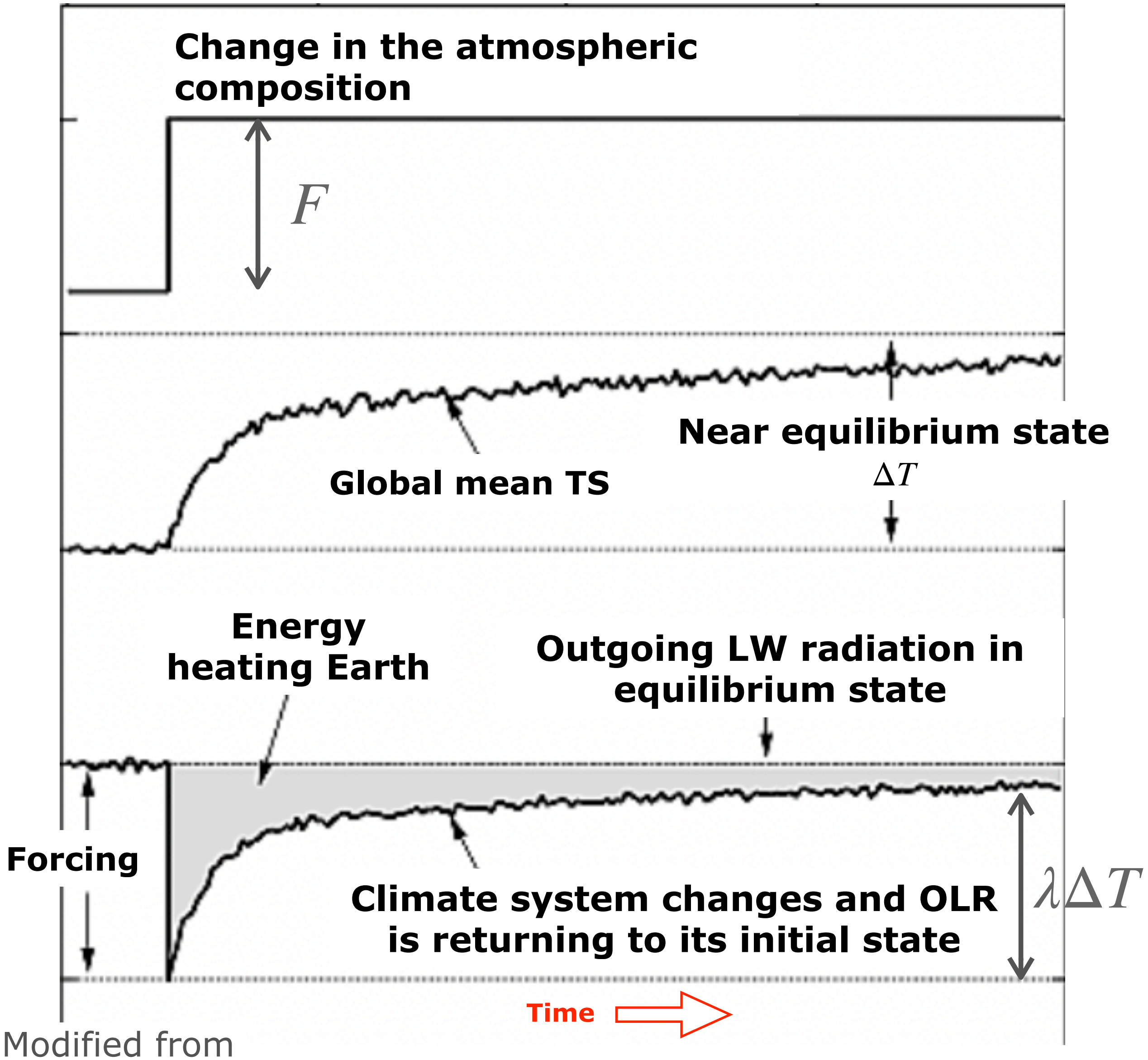
Forcing

Climate system changes and OLR is returning to its initial state

Time

Modified from Murphy et al. 2009

Climate feedback & sensitivity



Modified from Murphy et al. 2009

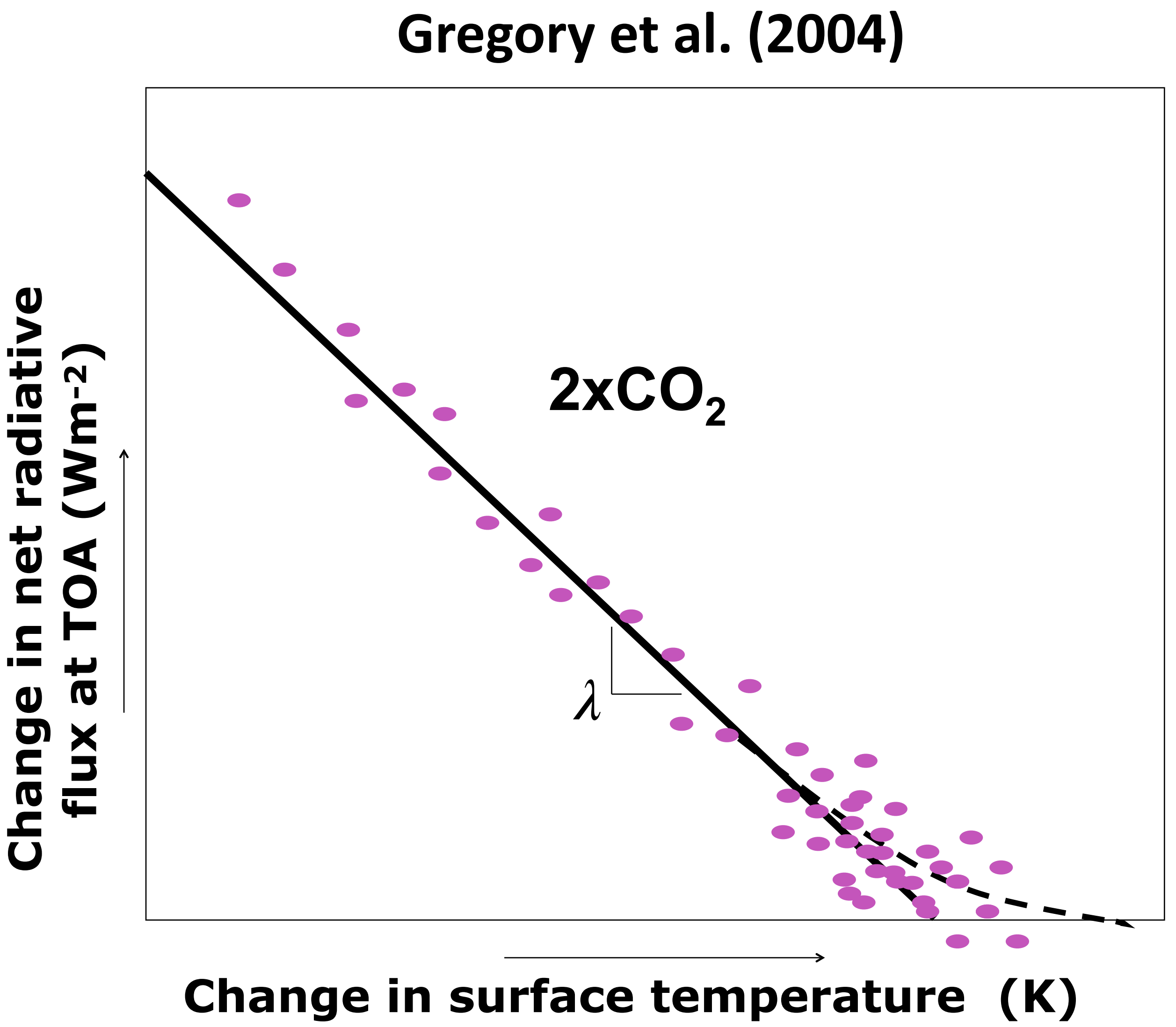
$$C \frac{dT}{dt} = F + \lambda \Delta T$$

C - Global heat capacity

F - external forcing

λ - climate feedback

Equilibrium Climate Sensitivity (ECS)



$$\Delta T = \frac{-F}{\lambda}$$

$$ECS = \frac{-F_{2xCO2}}{\lambda}$$

Central problem in climate science is to estimate the climate sensitivity

Created by Angshuman Modak

Climate feedback

$$\lambda = \lambda_{Planck} + \lambda_{Water\ vapor} + \lambda_{Lapse\ rate} + \lambda_{surface\ albedo} + \lambda_{Clouds}$$

$$\frac{S}{4}(1-\alpha) - \epsilon\sigma T_s^4 = N = 0$$

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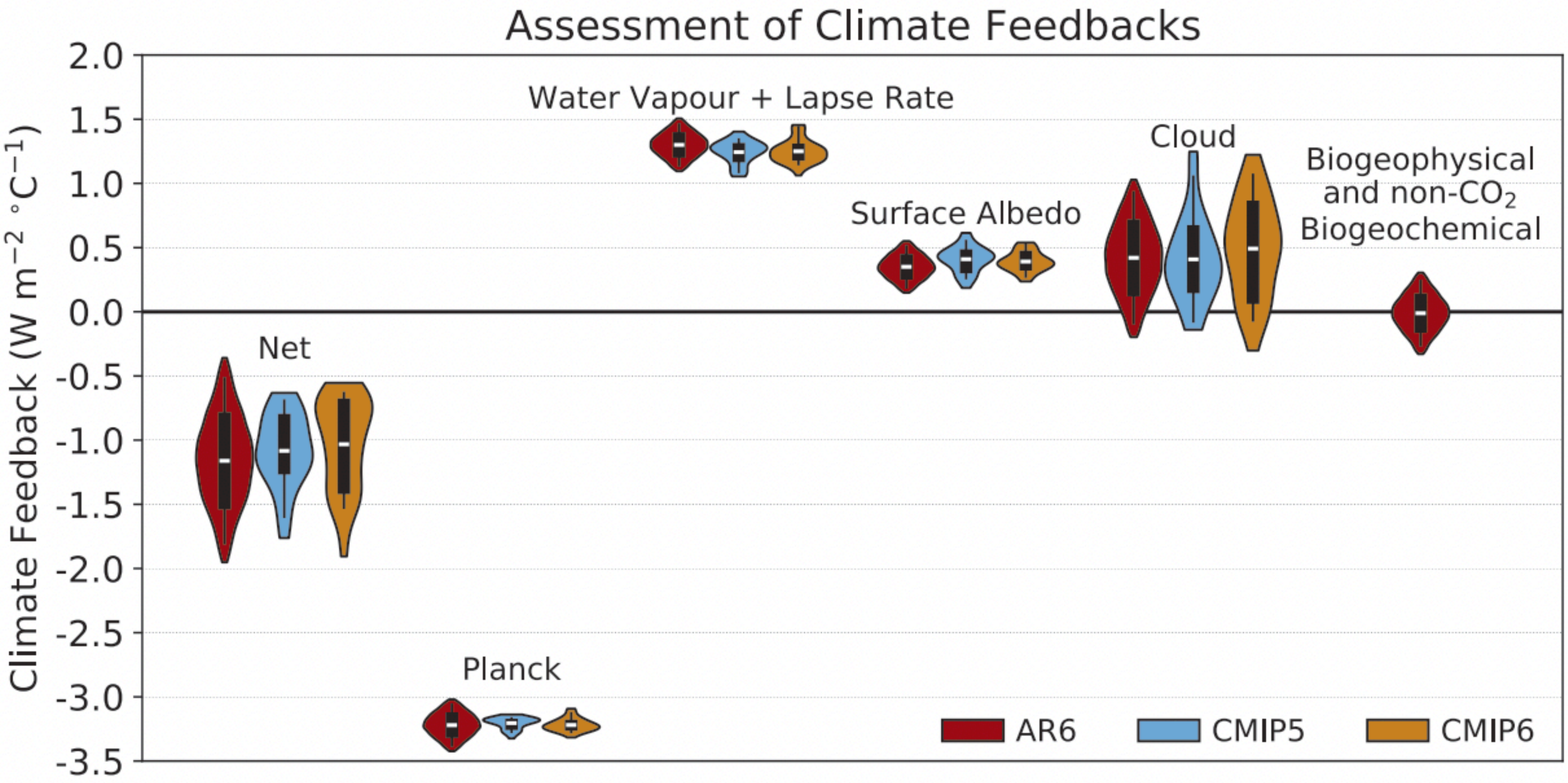
From IPCC AR6, Forster et al. 2021



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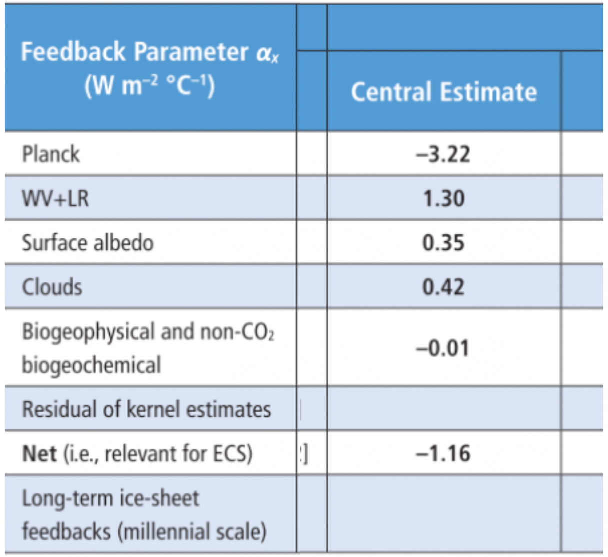
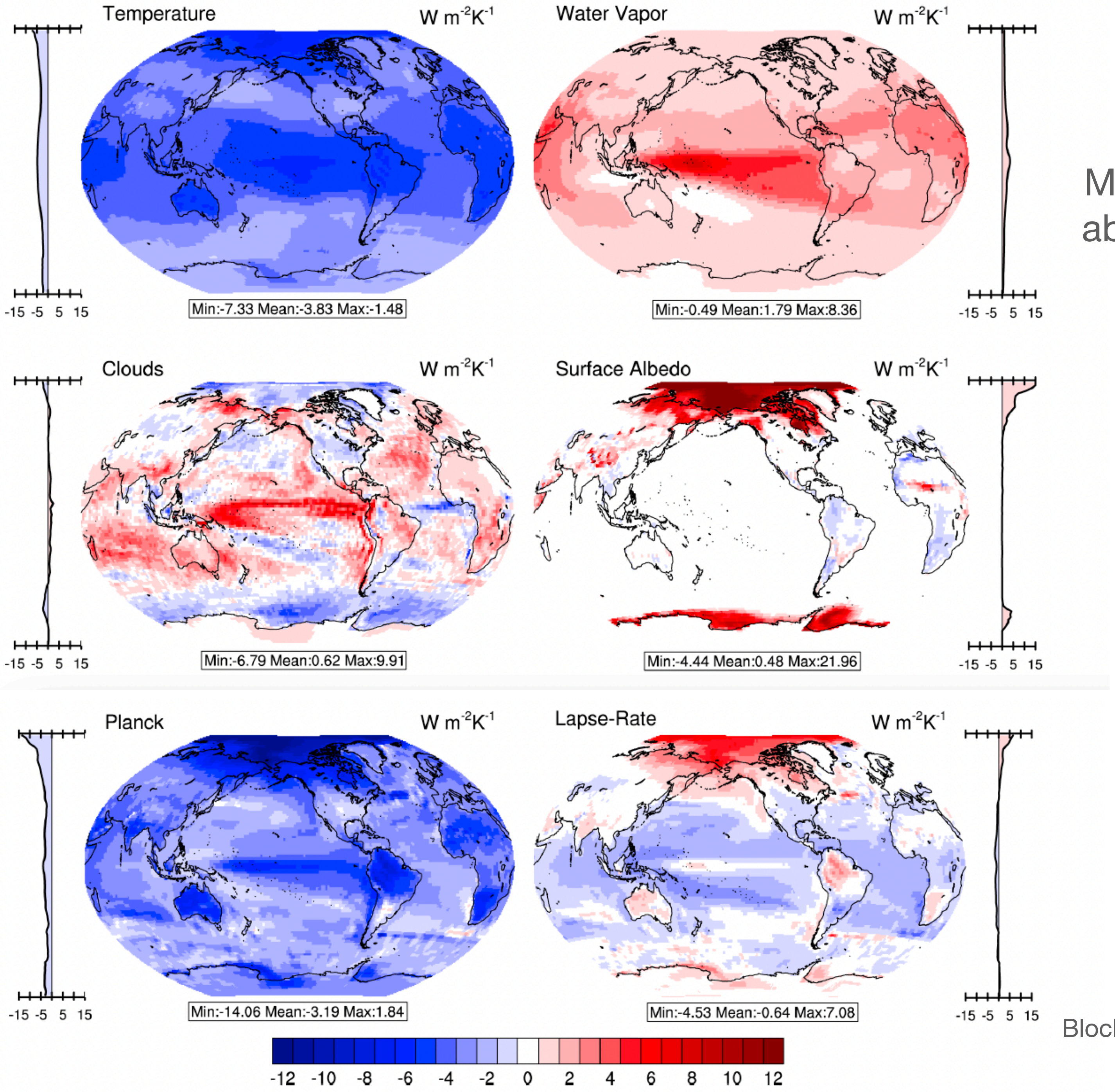


Feedback Parameter α_x (W m^{-2} °C^{-1})		Central Estimate
Planck		−3.22
WV+LR		1.30
Surface albedo		0.35
Clouds		0.42
Biogeophysical and non-CO$_2$ biogeochemical		−0.01
Residual of kernel estimates		
Net (i.e., relevant for ECS)	]	−1.16
Long-term ice-sheet feedbacks (millennial scale)		

IPCC AR6 chapter 7



MPI-ESM-LR
abrupt4xCO2

Block & Mauritsen 2013

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