H. Horvath   July 27, 2019

Radiative forcing by aerosols

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Weather:

Is the state of the atmosphere at a particular place and time as regards to heat, cloudiness, dryness, sunshine, wind, rain, visibility, particles etc. (Webster Merriam)

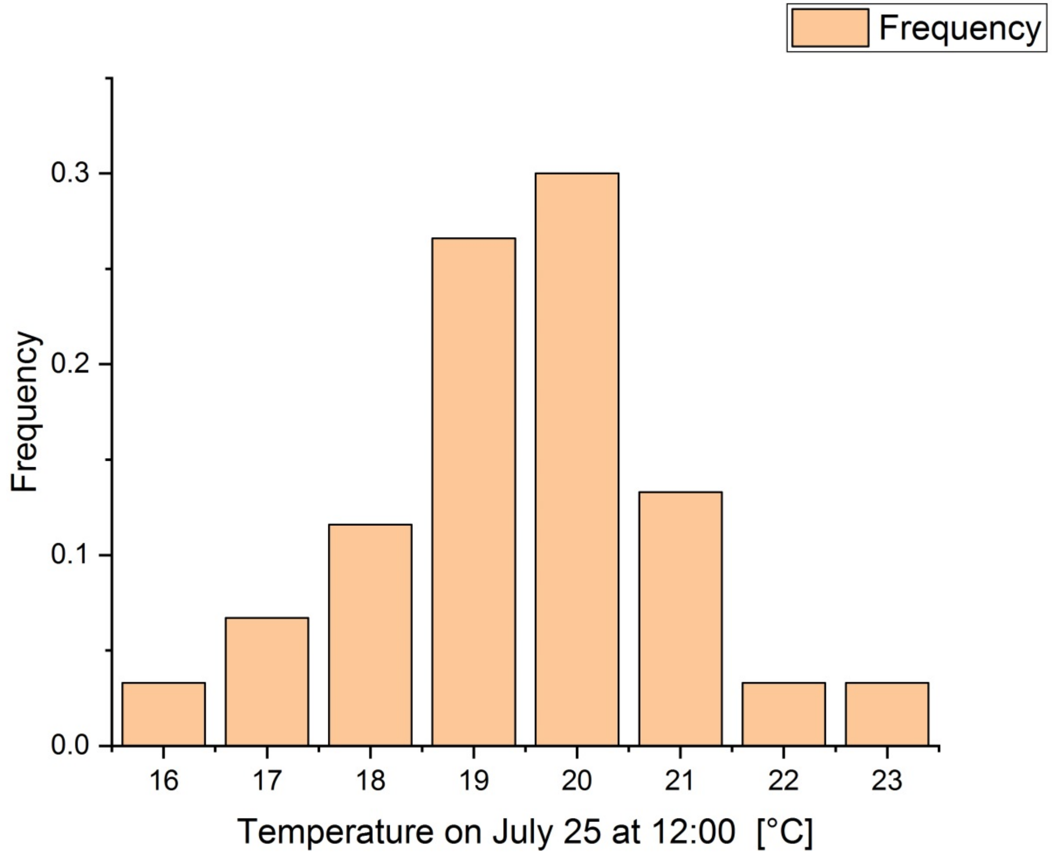
Weather is variable: Rain now, no rain two minutes later. Hot today, cold after tomorrow.

Variability in the range of minutes to days.

Predictability of weather at best for 5 days (in regions with variable weather).

For all quantities measured it is possible to make a statistical analysis:

Example:



Temperature statistics

Sometimes warmer / colder, but frequently 19 or 20 °C

Climate: in a narrow sense is usually defined as the "average weather," or more rigorously, as the statistical description in terms of the mean and variability of relevant quantities over a period ranging from months to thousands or millions of years.

The classical period is 30 years, as defined by the World Meteorological Organization (WMO). These quantities are most often surface variables such as temperature, precipitation, and wind. Climate in a wider sense is the state, including a statistical description, of the climate system

Climate differs from weather, in that weather only describes the short-term conditions of these variables in a given region.

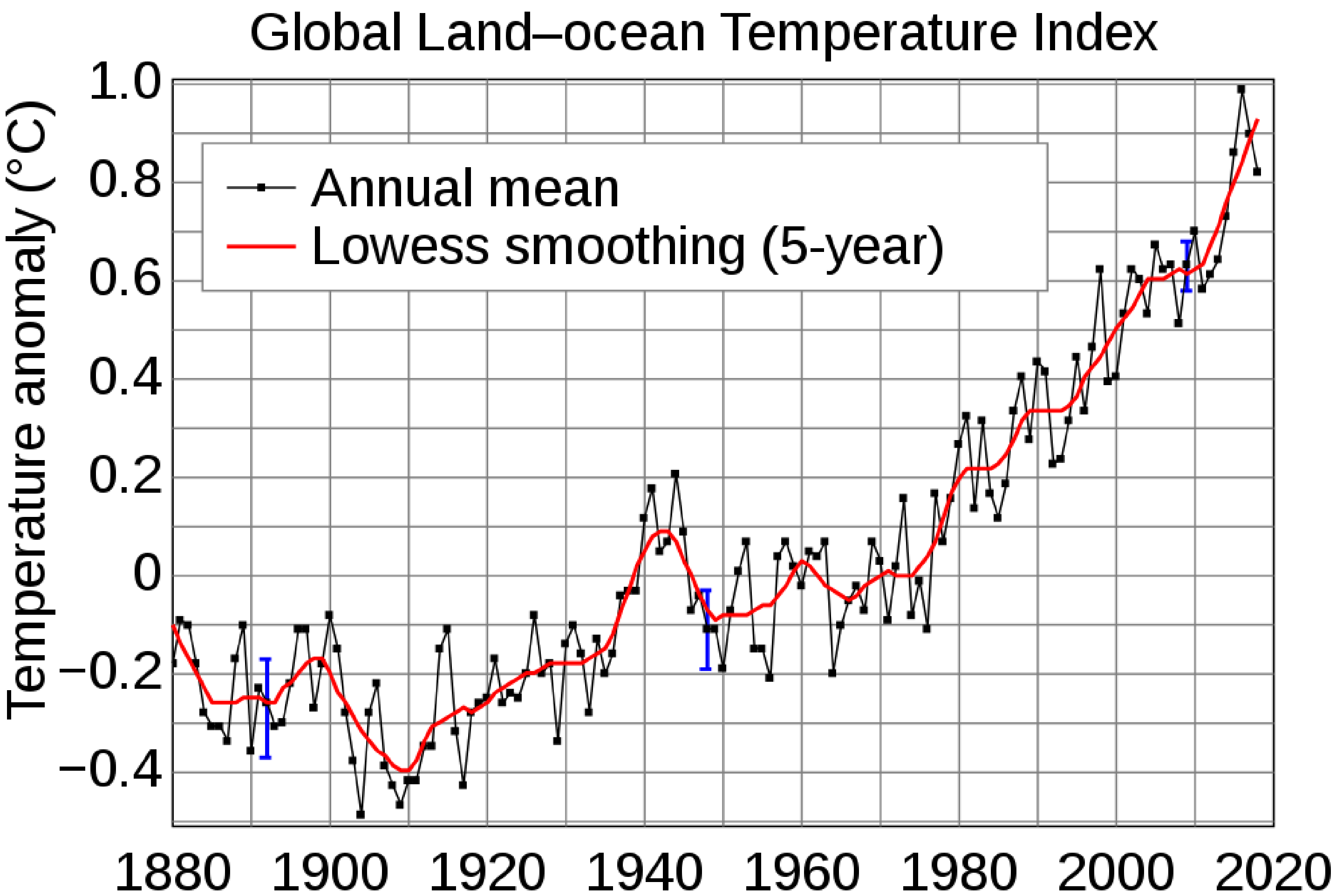
"Climate is what you expect, weather is what you get."[

Reference years are 1901-1930, 1931-1960, 1961-1990.
Also other reference years are used.

Climate determined

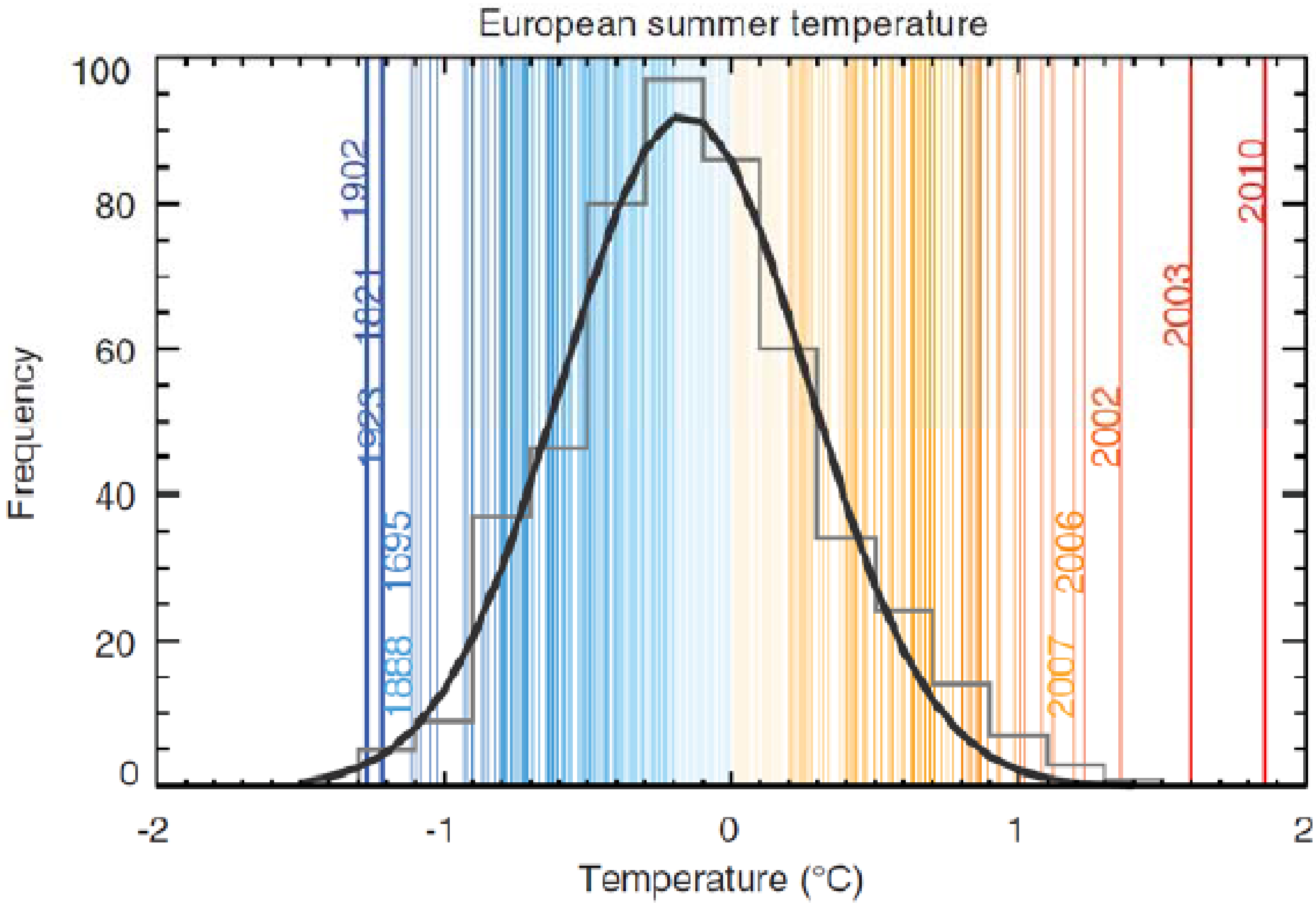
- on the one hand by factors which are constant at least in the time scale of hundred or thousand years such as latitude, altitude, proportion of land to water, proximity to oceans and mountains. Plate tectoncis may change these, but timescale is million of years.
- Large scale ocean fluxes, which redistribute heat between land and water (global and regional scale) Time scale ??
- Alteration of /or emission of greenhouse gases Time scale: ~ 100 yr (maybe)
- Density and type of vegetation (affecting solar flux absorption, water retention, rainfall, mainly regional ??)
- Aerosol by reducing solar flux to ground and absorption in atmosphere (time scale??).
- Input of solar flux

Global average temperature has increased in the last 100 years: „Global warming“



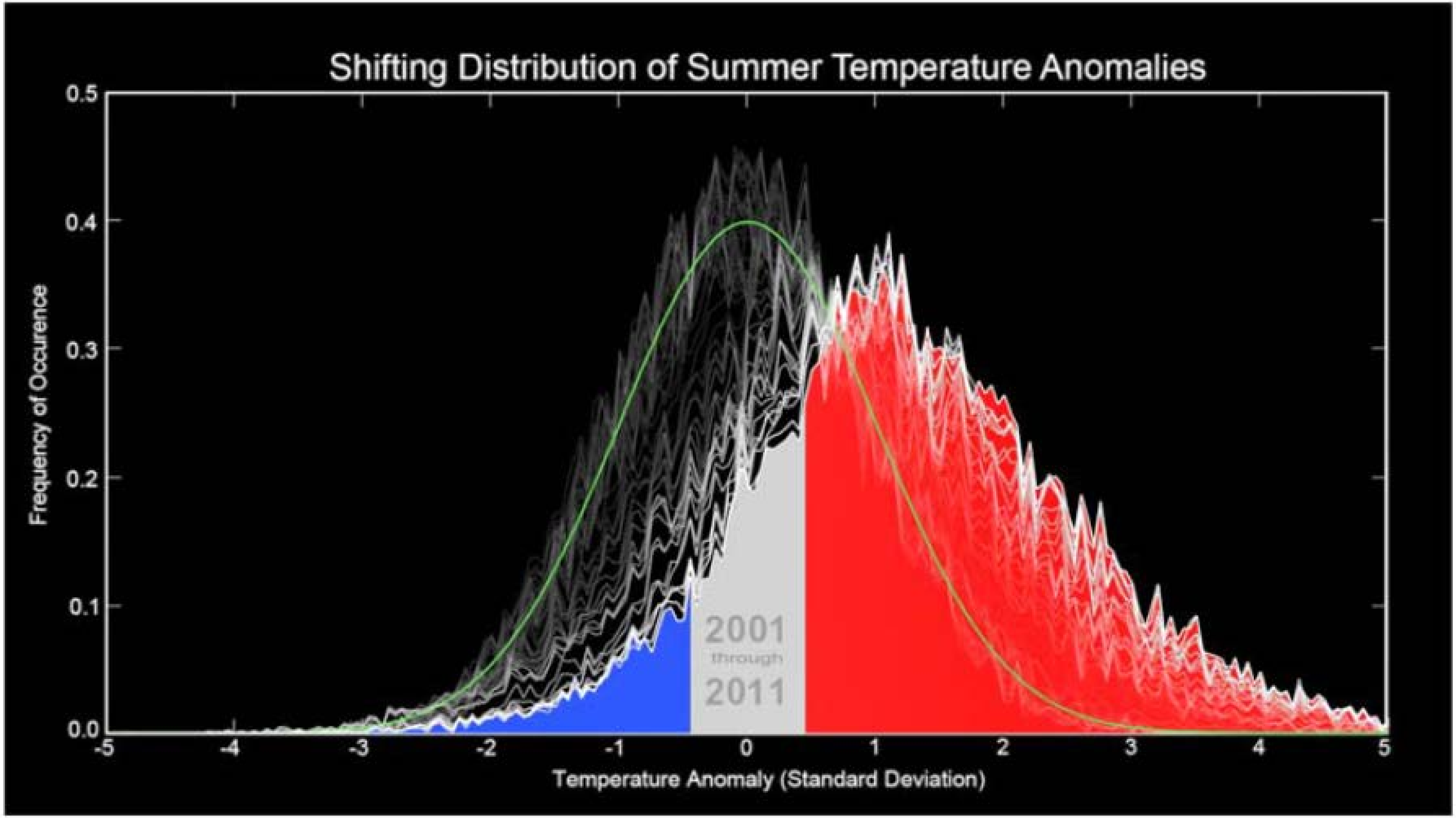
Land-ocean temperature index, 1880 to present, with base period 1951-1980. The solid black line is the global annual mean and the solid red line is the five-year lowess smooth, i.e. a nonparametric regression analysis that relies on a k-nearest-neighbor model. The function is evaluated using a fraction of data corresponding to a ten year window of data, giving an effective smoothing of approximately five years. The blue uncertainty bars (95% confidence limit) account only for incomplete spatial sampling. This is based upon Fig. 1A in Hansen *et al*. (2006) and Fig. 9a in Hansen *et al*. (2010). The graph shows an overall long-term warming trend. (from: https://en.wikipedia.org/wiki/Global_warming

European summer temperatures for 1500–2010
relative to the 1970-1999 period



Barriopedro et al. (2011, Science)

Summer temperature anomales on the Northern Hemisphere 1951 -2011
Relative to 1951 to 1980 (https://svs.gfsc.nasa.gov/3975



Radiation in the atmosphere and the aerosol:

On the average the radiation budget is balanced.

Solar radiation reaching the earth must be reflected / re-emitted in exactly the same quantity, otherwise temperature would increase/decrease continuously

Incoming on earth with radius R:

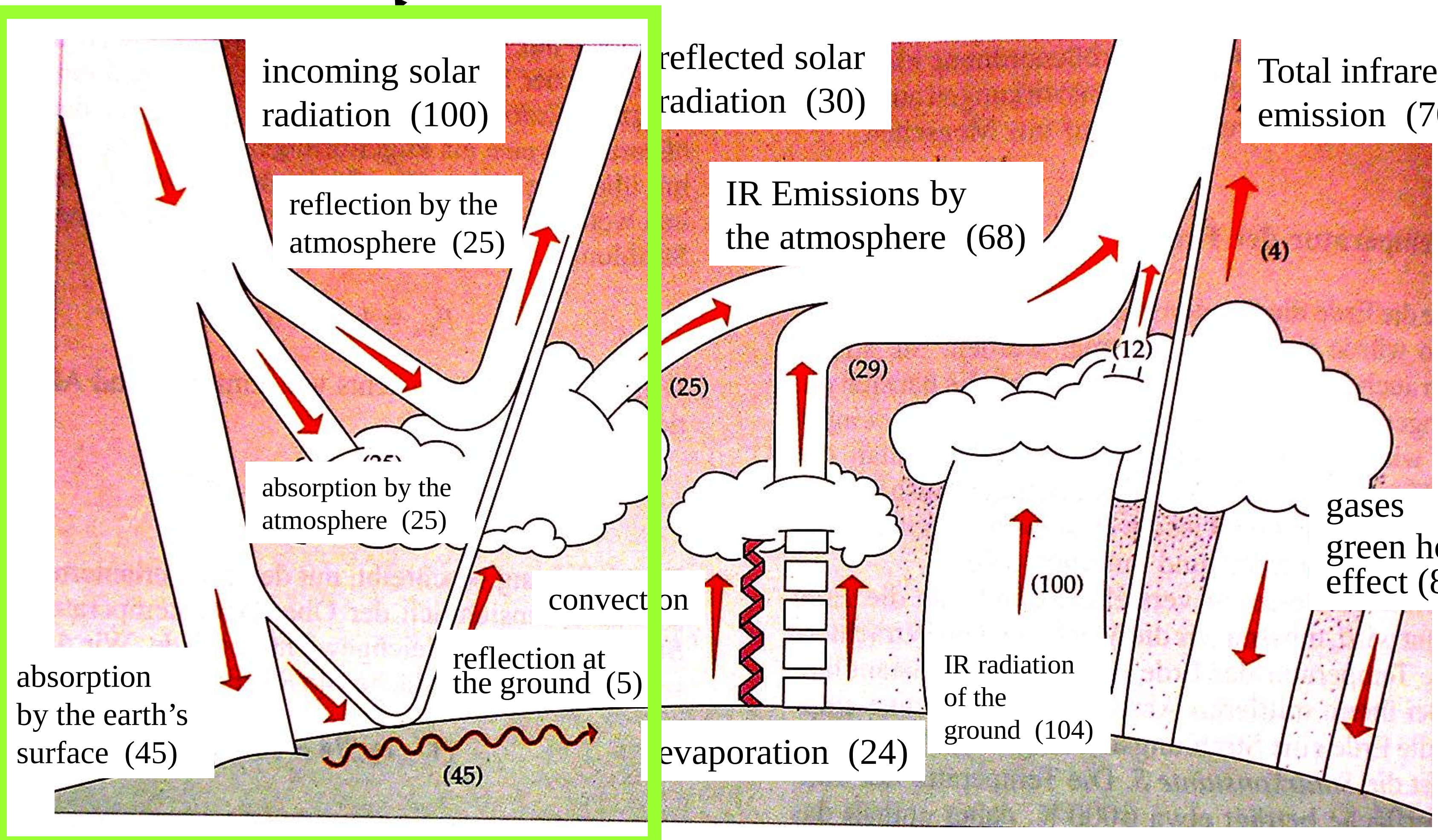
$$S.R^2\pi = 1.7 \, . \, 10^{17} W$$ (S .. Extraterrstric solar flux density)

~35% reflected, ~20% in absorbed in atmosphere,

~45% reach the ground, are absorbed.

Absorption causes heating of the ground

Visible radiation, (infrared will be treated below)



Tipler: Physik, Spektrum 1994, p 576

Taken from Stephen H. Schneider The greenhouse effect: Science and policy, *Science* **243**, 771 - 781

Temperature of the earth strongly depends on the reflective properties (albedo a) for sunlight and IR absorption and emission.

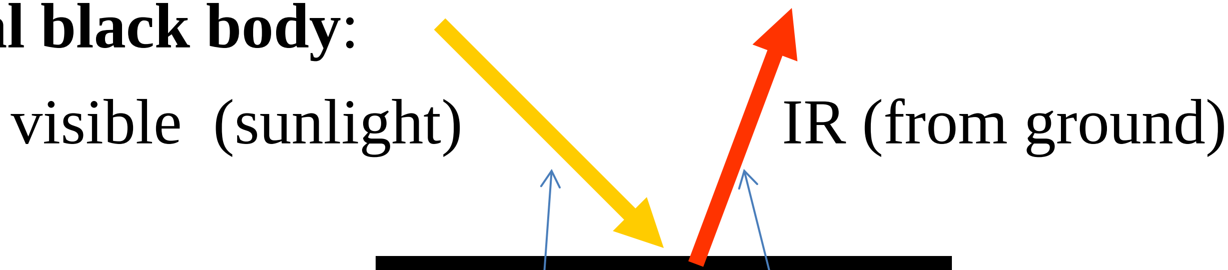
We will see step by step

Total radiation from sun: $S.R^2\pi$ (solar constant • cross section)

Since earth rotates, it is distributed on the whole surface: $4R^2\pi$

Thus average flux densiy: $S_0 = S/4 = \frac{1}{4} .1360\ W/m^2 = 340\ W/m^2$

(1) Assume earth as **ideal black body**:

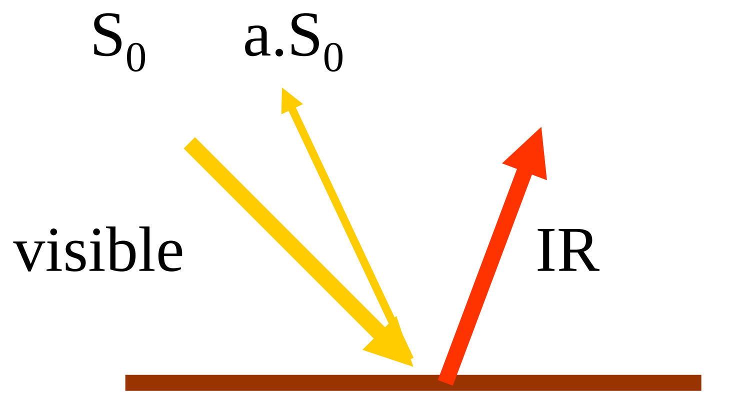


Incoming visible radiation is completely absorbed and causes a rise of temperature T_e of the surface such that IR emission equals the incoming solar radiation.

$\rightarrow 340\ W/m^2 = \sigma.T_e^4$

$\rightarrow T_e = 278.3K = 5.2°C$

(2) **Surface of earth has albedo a for visible light, black in IR,**



Albedo is $a = \dfrac{\text{reflected flux (in all directions)}}{\text{incident flux}}$

i.e. $a.S_0$ is reflected,
thus only $(1\text{–}a).S_0$ is absorbed.

Average albedo for earth is 0.3

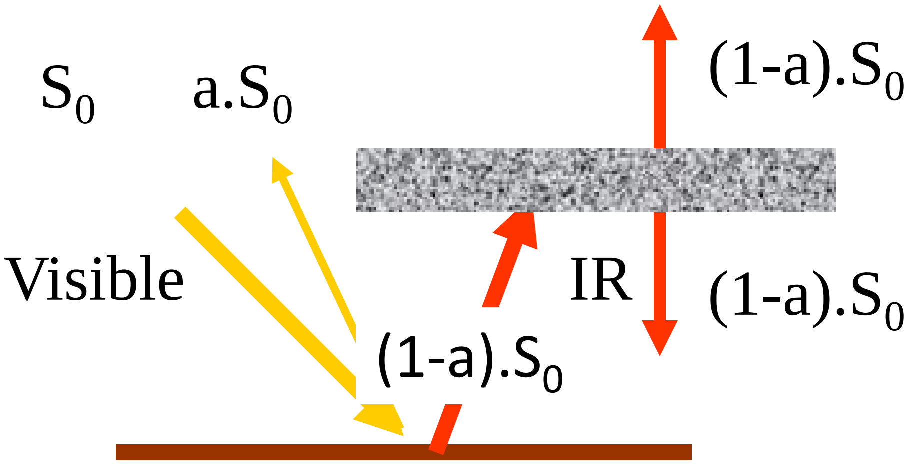
With a = 0.3 -----> $\sigma.T_e^4 = 0.7 \,.\, 340\ W/m^2$
------> $T_e = 254.5K$ oder -18,6°C (average temperature on earth !!!!)

Lower temperature since partly the sunlight is reflected,
→ Less sunlight absorbed →thus less IR is emitted,
→ lower surface temp. Very cold !!!!! ????

Example Moon: a = 0.12 → average temp -13.6°C

But our globe has IR absorbing atmosphere

(3) **Pure green house**: All IR is absorbed by the atmosphere. I.e. Atmospheric transmission T=0, absorption A=1. Causes heating of the atmosphere. It emits IR both to the ground and in the space



IR to space only originates from the atmosphere (since T = 0). It must equal the absorbed sunlight $(1-a).S_0$

----> Ground receives $2.(1-a).S_0$, thus must emit $2. (1-a).S_0$.

Therfore $\sigma.T_e^4 = \mathbf{2} \,.\, 0.7 \,.\, 340\ W/m^2$

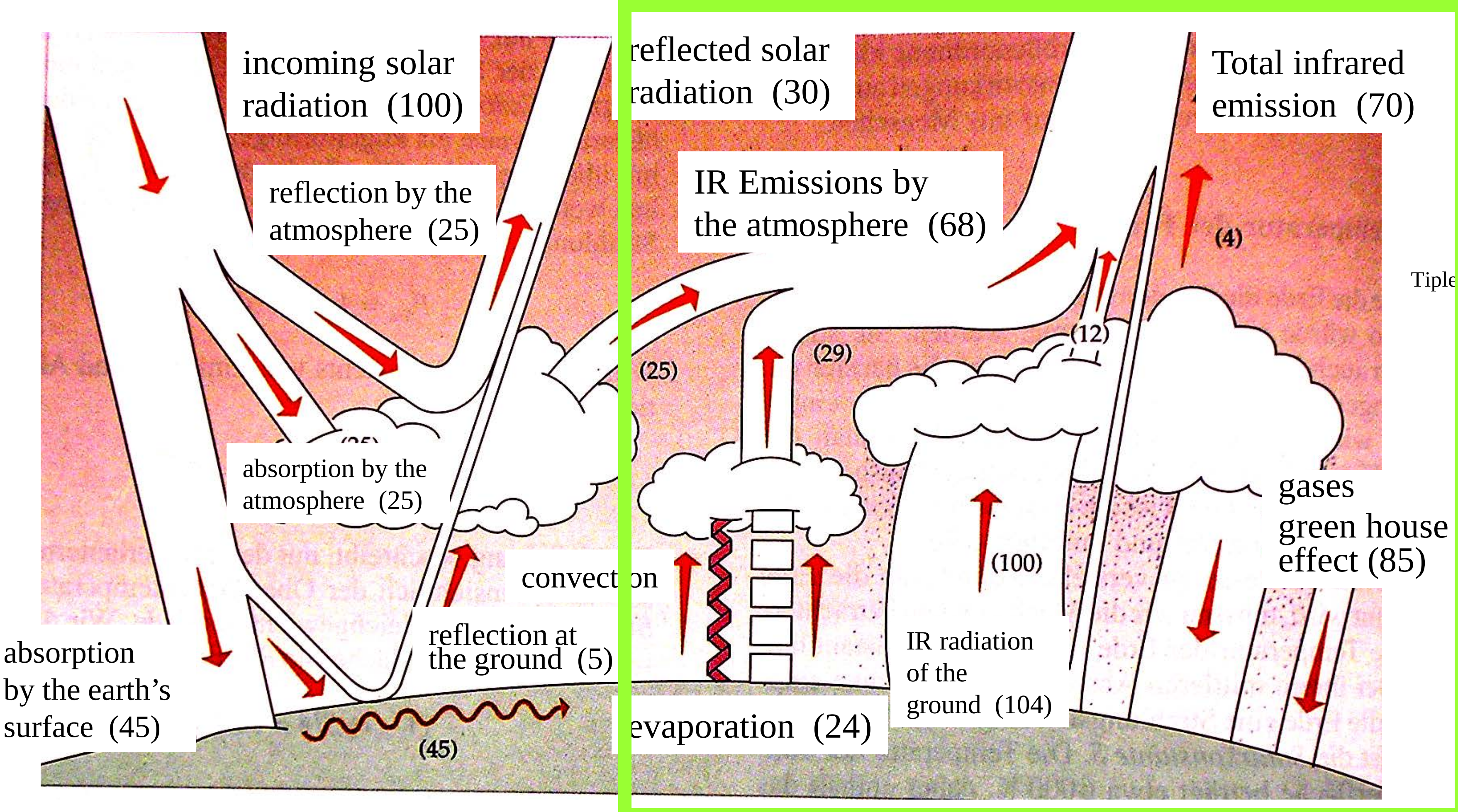
yields T = 302.7 K = 29.5 °C

Realistic atmosphere (still much simplified)

Atmosphere is not completely black in the IR: Some IR goes through, therefore less IR radiation back to the ground.

Furthermore: heat is transferred to the atmosphere by non radiative processes:
such as evaporation and condensation of water vapor, convective heat transfer

infrared and non radiative transfer



Tiple : Physik

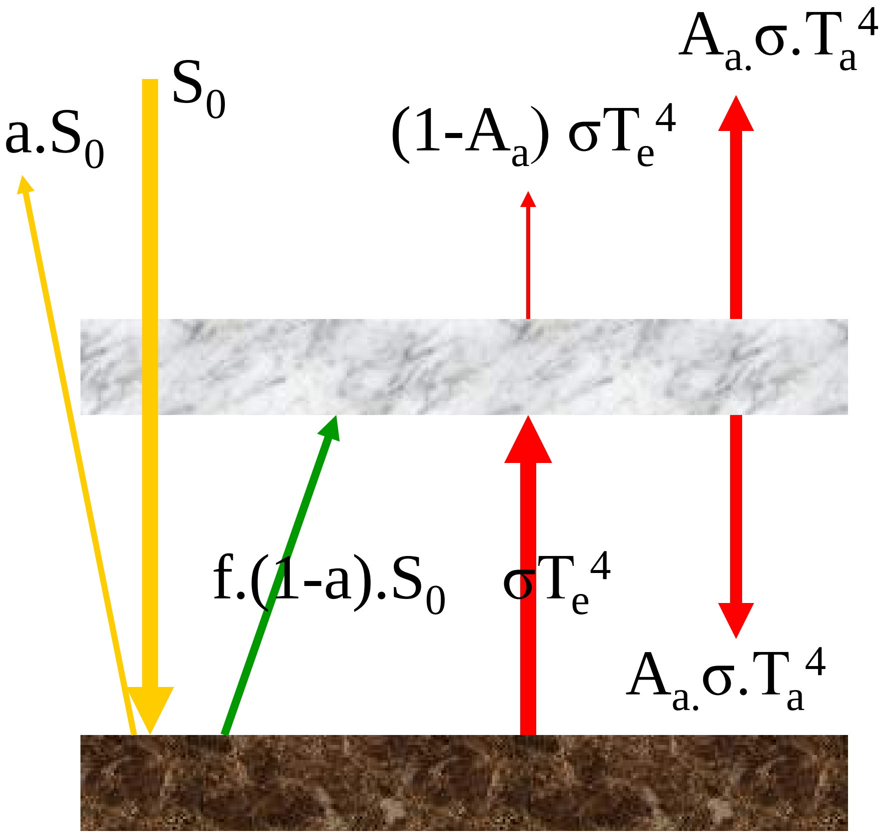
Characteristics of the realistic, but still simple atmosphere – earth system:

a …….. Average albedo of the earth in the visible and near infrared
(average of clouds, ground, sea, aerosol, snow …)
it is ratio of refleced (diffuse) solar flux density to incident solar flux density.

A_a ….. Absorbtivity of the atmosphere in the thermal Infrared:
$A_a=1$ means all IR is absorbed by the atmosphere, nothing is transmitted
if $A_a<1$ of a flux density F reaching the atmosphere,
the amount $F.A_a$ is absorbed and the amount $F.(1-A_a)$ is transmitted .

f ……. Fraction of solar flux density absorbed by the ground which is transferred to the atmosphere by non radiatve processes

Simplified real atmosphere



Sunlight: incident S_0

"reflected (diffuse)" $a.\ S_0$

Non radiative transfer:

$f.(1\text{-}a).S_0$ to the atmosphere

Thermal infrared

σT_e^4 from ground

$(1\text{-}A_a)\ \sigma T_e^4$ goes through the atmosphere.

$A_{a.}\sigma.T_a^4$ emitted by the atmosphere both to the ground and to the space

Balance at the top of the atmosphere: $(1\text{-}a)\ S_0 = (1\text{-}A_a)\ \sigma T_e^4 + A_{a.}\sigma.T_a^4$

Balance at the ground: $(1\text{-}a)\ S_0 + A_{a.}\sigma.T_a^4 = f.(1\text{-}a).S_0 + \sigma T_e^4$

Both balance equations contain the unknown T_e und T_a: solving is simple and yields:

$$T_e^4 = \frac{(2-f)(1-a).\, S_0}{(2-A_a).\, \sigma} \quad \text{or} \quad T = \sqrt[4]{\frac{(2-f)(1-a).S_0}{\sigma.(2-A_a)}}$$

For IR transmission of the Atmosphere $(1-A_a)$ of 0.03 to 0.08 and 30% evaporation + convection the average temperature (f=0.3) is 15.3 to 11.9°C

Easily can be seen:

If albedo a of earth increases, Temperature decreases.

(Albedo includes reflection by ground, clouds, ice, snow, scattering by aerosol)

If IR absorption of the atmosphere A_a increases, temperature increases. Greenhouse effect

If non radiative transfer f increases, temperature decreases

Changes of f, a, A can cause climate change:

$$T = \sqrt[4]{\frac{(2-f)(1-a).S_0}{\sigma.(2-A_a)}}$$

Green house effect: Combustion of coal, oil and gas increases CO_2 concentration. Atmosphere better absorbs IR, A_a ↑ --> T rises

If for unexpected reasons suddenly CO2 emissions would stop, the CO2 would remain in the atmosphere for considerable time (>100y), so we have to live with the greenhouse effect even long after the end of the "Carbon Age"

White house effect: Combustion of coal also produces Sulfur dioxide, converted to sulfate aerosol. increases albedo, a ↑, temperature decreases (solar radiation to gound decreases, reflected sunlight increases).

Journal of Aerosol Science Volume 27, Issue 3, April 1996, Pages 359-382

Stephen E.Schwartz: The whitehouse effect—Shortwave radiative forcing of climate by anthropogenic aerosols: an overview

$$T = \sqrt[4]{\frac{(2-f)(1-a).S_0}{\sigma.(2-A_a)}}$$

Source: Alan bron (talk) - Own work (Original text: self-made), Public Domain, https://commons.wikimedia.org/w/index.php?curid=31397657

If for unexpected reasons suddenly the particle and particle precursor emissions would stop, the particles would remain in the atmosphere for a few weeks (stratosphere longer). No more counter action to green house effect!

But other important consequences:

Xu Qun (Atmospheric Environment 35 (2001) 5029–5040) 263 citations

Southward move of the summer monsoon rainy belt:

Sulfates by coal combustion decrease solar radiation in China

Land does not heat so much, less difference in barometric pressure between China and sea.

Monsoon less strong, does not go so far north as previously

More rain (floods) in the not so far north, droughts in the north "monsoon gets stuck"

Recommendation by the author: reduce emissions by coal fired power plants

More speculations:

$$T = \sqrt[4]{\frac{(2-f)(1-a).S_0}{\sigma.(2-A_a)}}$$

Massive use of solar energy: Solar collectors are black.
Albedo **a** decreases, temperature increases

Growing population: more urbanization, need for more food,

Snow fresh	0.8 .... 0.9
Snow old	0.4 .... 0.8
Clouds	0.6 .... 0.9
New concrete	0.55
Average albedo earth	0.3
Field unworked	0.3
Desert	0.26
Lawn	0.18 .... 0.23
Forest	0.05 .... 0.18
Water	0.08 .... 0.22

https://commons.wikimedia.org/wiki/File:Albedo

Growing population: more urbanization, albedo increases, temperature decreases
Growing population needs more food, irrigated land has low albedo, temperature increases.

What will dominate: There is much space for speculations

Generally agreed opinion:

1. Present temperature increase caused by CO_2 increase, due to combustion of fossile fuel (A$_a$ of the atmosphere increases)
2. Increased load of aerosol causes a decrease of temperature

No experimental proof for (1) CO_2↑ → T↑

But proof for (2) aerosol ↑ → T↓ : Vulcanic eruptions.

Historic example : 15 March 44 B.C. Julius Caesar murdered:
simultaneously Mt. Etna in Sicily, Italy, erupted .
Plutarch (50-120) reports: sky very hazy, daylight weak, sun, moon, and stars were bloody red, later othe colors. Interpreted as Caesar being divinized. Das neue Universum, Neur und Umwelt. Vulkane ändern das Klima, Süpdwestverlag, Munich, Germany pp 72 – 77, 1983.
Cold summer with weak sunshine followed, snow in summer, bad or no harvest, famine.
The same was also reported in Chines historic records, 8500 km away. So at least a phenomenon for the northern hemisphere

But bluddy red sun, other color effects are an aerosol phenomenon of micrometer and submicrometer sized particles , and not divinzation of G.J. Caesar.
This part of science was known44 B.C.

1815 Tambora eruption (5 to 10 April) : very large eruption: volcanic explosivity index (VEI) of 7 (range 1 to 8)
>100 km^3 of material ejected , substantial particle load in troposhere and stratsosphere .

Observation in Eastern United States (16000 km away): In the spring and summer of 1816, a persistent "dry fog" was observed in parts of the East USA. The fog reddened and dimmed the sunlight, such that sunspots were visible to the naked eye. Neither wind nor rainfall dispersed the "fog".
(It has later been characterized as a "stratospheric sulfate aerosol veil“).
Ground frozen in June, bad or no harvest etc.

Average global temperatures decreased by 0.4–0.7 °C.[2] This resulted in major food shortages across the Northern Hemisphere.

Could this be true or was this exaggeration??

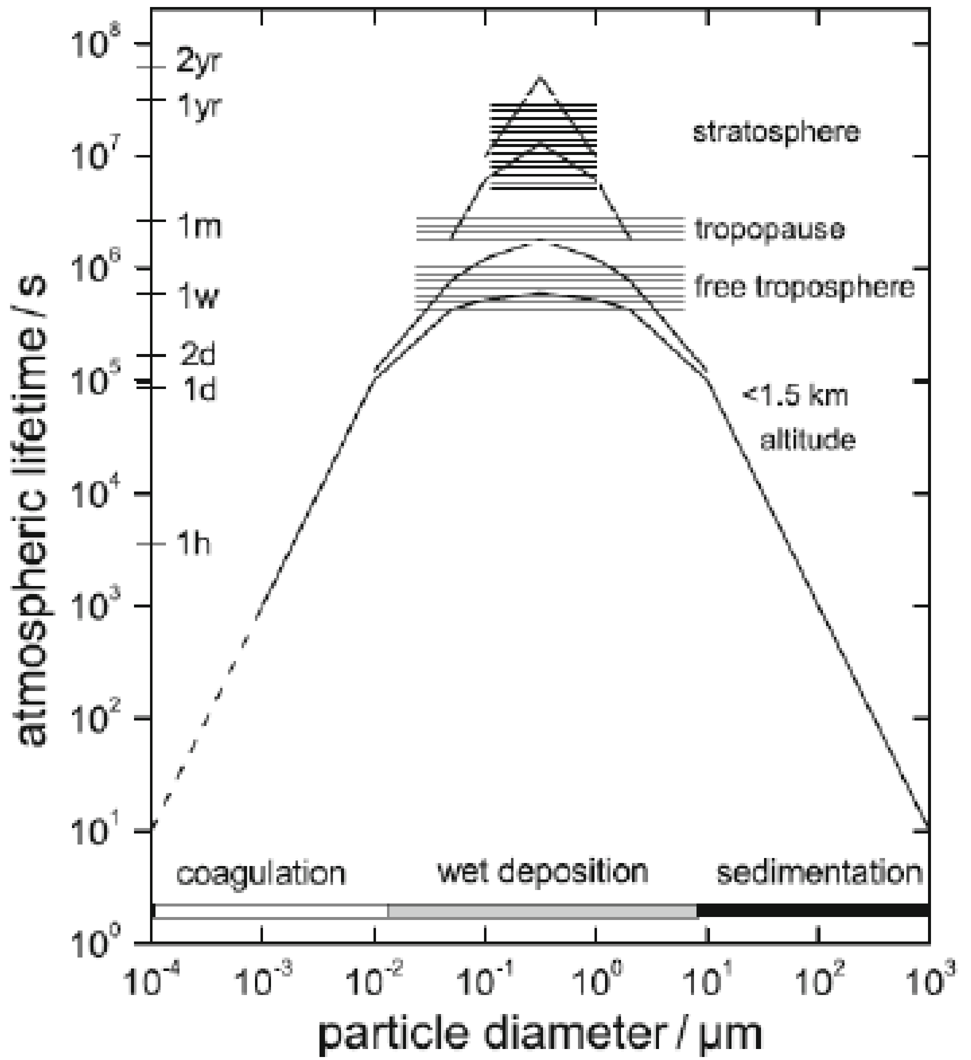
A simple model:
Assumption: 100 km^3 of material ejected, a small fraction makes it to the stratosphere
Also SO_2 emitted by volcanos : transformed to sulfuric acid droplets in the stratosphere.

100 km3 having density of water are 10^{14}kg Fraction between 10^{-4} and 10^{-6} reaches the stratosphere (in our model).

Mt. Redoubt (altitude 3120m), Eruption 1989, Alaska, USA, Plume rises to 14000 m

R. Clucas - https://web.archive.org/web/20051111095409/http://wrgis.wr.usgs.gov/dds/dds-39/album.html

Particles with diameter of 0.6 µm have half life time in stratosphere of ~ 1 year

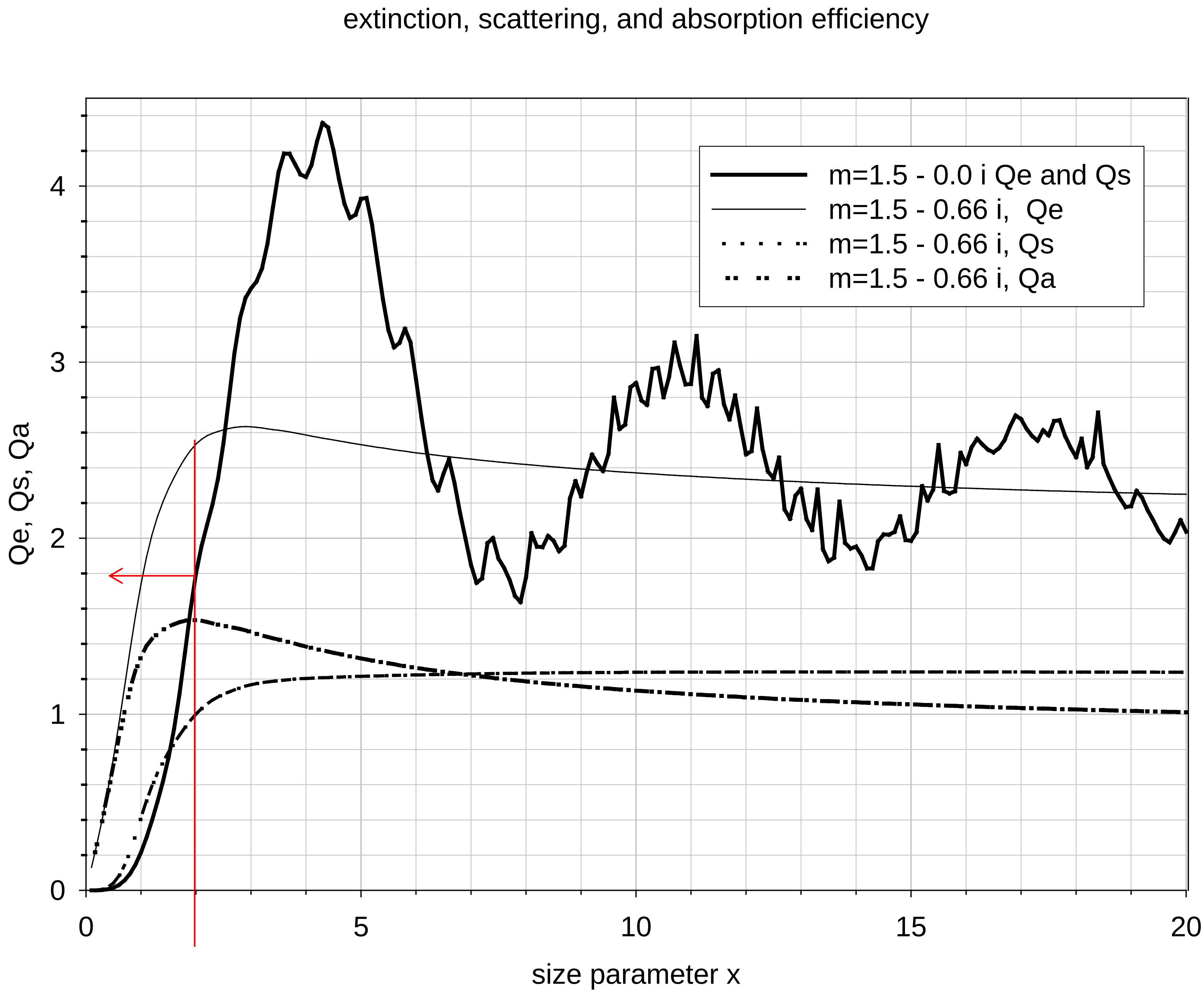


Jaenicke R. (1080) Atmospheric Aerosols and Global Climate *J. Aerosol Science* **11**, 577 - 580

Further assumption: particles in the stratosphere have a diameter of 0.6µm (half life time in stratosphere is ~ 1 year) , mainly scatter light , have density of water

For wavelenght of λ=0.55 µm the size parameter is $x = \frac{0.6 \cdot \pi}{0.55}$=1.97

Using the graph for Q_e factors one obtains Q=1.8 (slide 30 of aerosol radiation interaction)


extinction, scattering, and absorption efficiency
m=1.5 - 0.0 i Qe and Qs
m=1.5 - 0.66 i, Qe
m=1.5 - 0.66 i, Qs
m=1.5 - 0.66 i, Qa
Qe, Qs, Qa
0
1
2
3
4
0
5
10
15
20
size parameter x

Specific cross section of particles = $\dfrac{\text{extinction coefficient}}{\text{mass of particles per volume of air}}$

$$= \frac{N.Q_e.r^2.\pi}{N.\frac{4\pi}{3}r^3.\rho_{particle}} = \frac{4.Q_e}{3.r.\rho_{particle}} = 8000\ m^2.kg^{-1}$$

For the moment we consider a fraction of 10^{-5} (i.e. 0.001 %) of the ejected 10^{14}kg particles which are 10^9 kg to be in the stratosphere.

Their total optical cross section is $8000\ m^2.kg^{-1}$ 10^9 kg = 8. 10^{12} m^2

These particles are distributed on one hemisphere

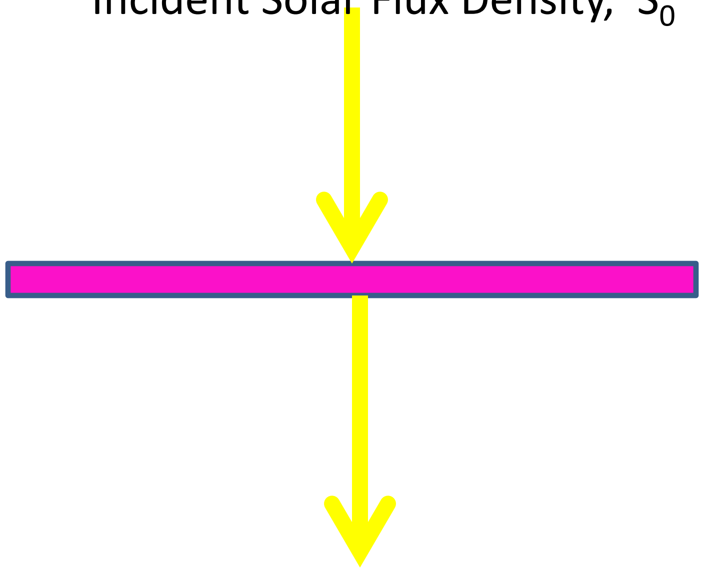
Surface is $2.\pi.R^2 = 2.\pi.(6370\ km)^2 = 2.56.10^{14}m^2$

Therfore the optical cross section per m^2 is $\frac{8.10^{12}m^2}{2.56.10^{12}m^2} = 0.0314 = \delta$

This is the optical depth of the vulcanic aerosol layer in the stratosphere.

Next simplification: perpendicular incidence of the solar radiation on this layer.

Incident Solar Flux Density, S_0



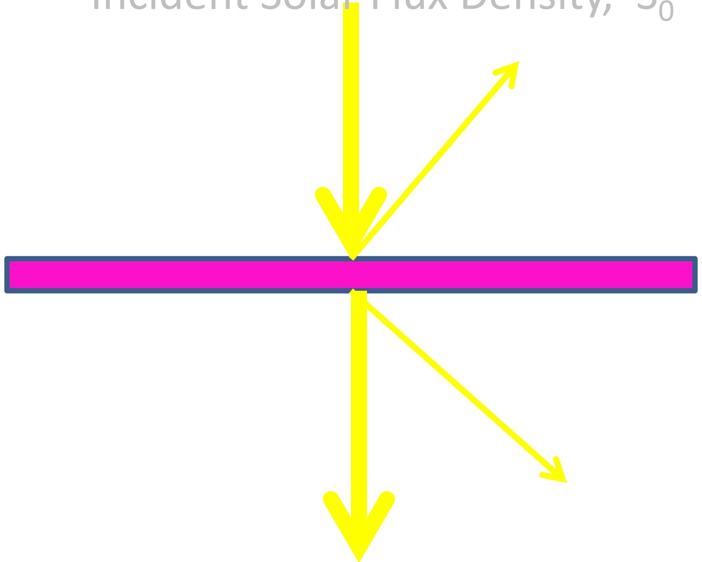
Stratospheric aerosol layer

Transmitted Solar Flux density $S_0.e^{-\delta} = S_0.0.9691$, almost no attenuation

Incident Solar Flux Density, S_0

Attenuation in layer is by scattering,

Upwards



Stratospheric aerosol layer

And downwards

Transmitted Solar Flux density $S_0.e^{-\delta} = S_0.0.9691$, almost no attenuation

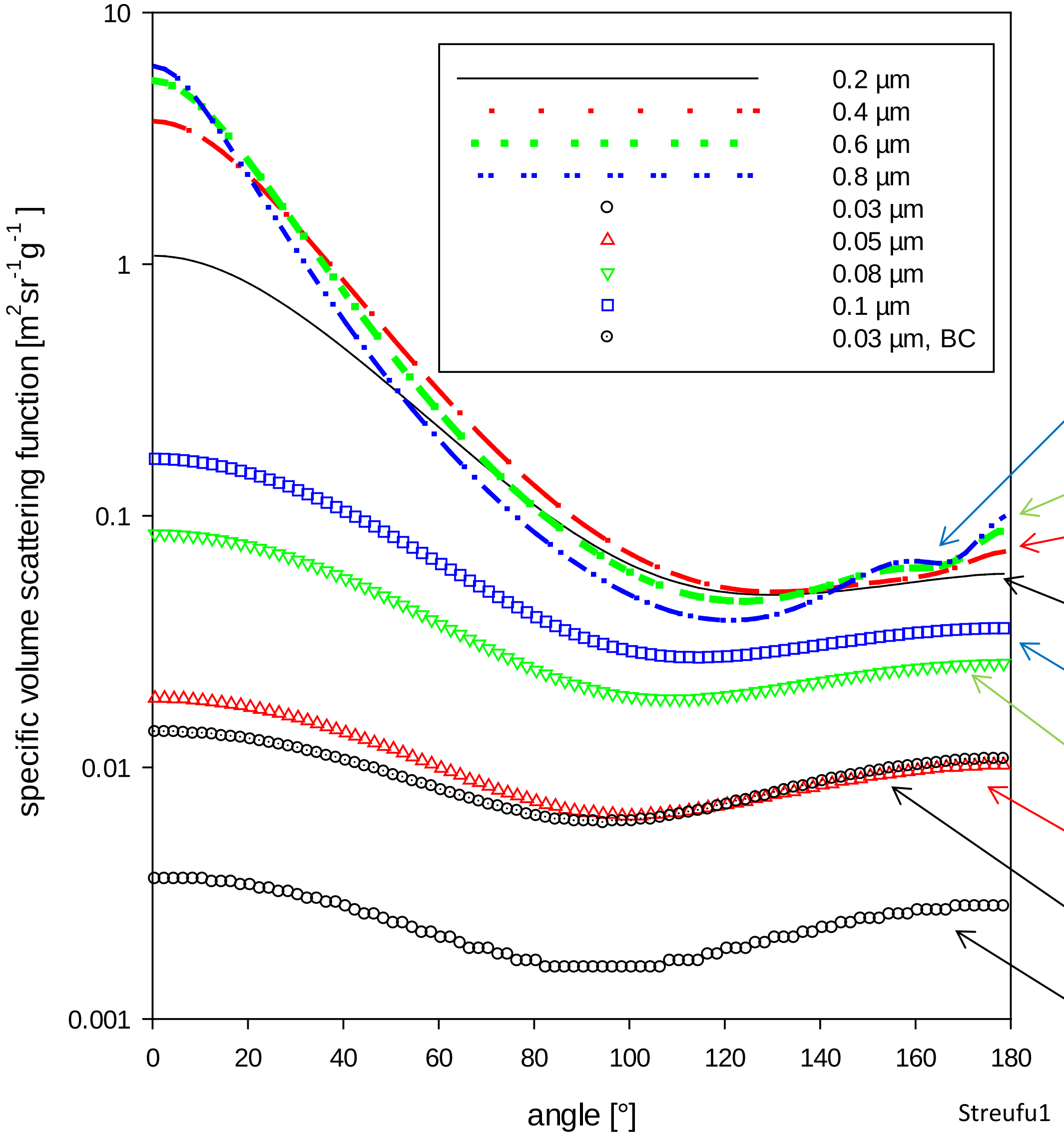
Scattering upwards is „lost“ for energy budget. It amounts to

$(S_0 - S_0.e^{-\delta}).\,b \approx S_0.\,\delta.\,b$ b ……. Backscatterd fraction

Backscattered fraction for d=0.6 µm is b=0.077 (Slide 51 of aerosol radiation interaction)

Therefore the downward flux desity is reduced by 340 Wm^{-2} . 0.0314 . 0.077 = 0.82 $W.m^{-2}$

m = 1.5 - 0.01 i



Spherical particles with lognormal size distribution, volumem modal diameter as parameter

refr. In.	D	b	g
1.5 - 0.01i	0.8	0.078	0.715
1.5 - 0.01i	0.6	0.077	0.705
1.5 - 0.01i	0.4	0.085	0.669
1.5 - 0.01i	0.2	0.148	0.530
1.5 - 0.01i	0.1	0.281	0.314
1.5 - 0.01i	0.08	0.327	0.245
1.5 - 0.01i	0.05	0.408	0.129
2-i	0.03	0.462	0.053
1.5 - 0.01i	0.03	0.461	0.055

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Using the smaller input of solar flux density in the formula for the average temperature

$$T = \sqrt[4]{\frac{(2-f)(1-a).S_0}{\sigma.(2-A_a)}}$$

We obtain a lower temperature , since less input.

In this case it is 0.695°C lower.

Summary: Volcanic eruption, 100 km^3 ejected, a small fraction reaches the stratosphere

Fraction of ejected particles In stratosphere	Temperature change
10^{-6}	-0.07 °C
10^{-5}	-0.69 °C
10^{-4}	-6.87 °C

Important remark

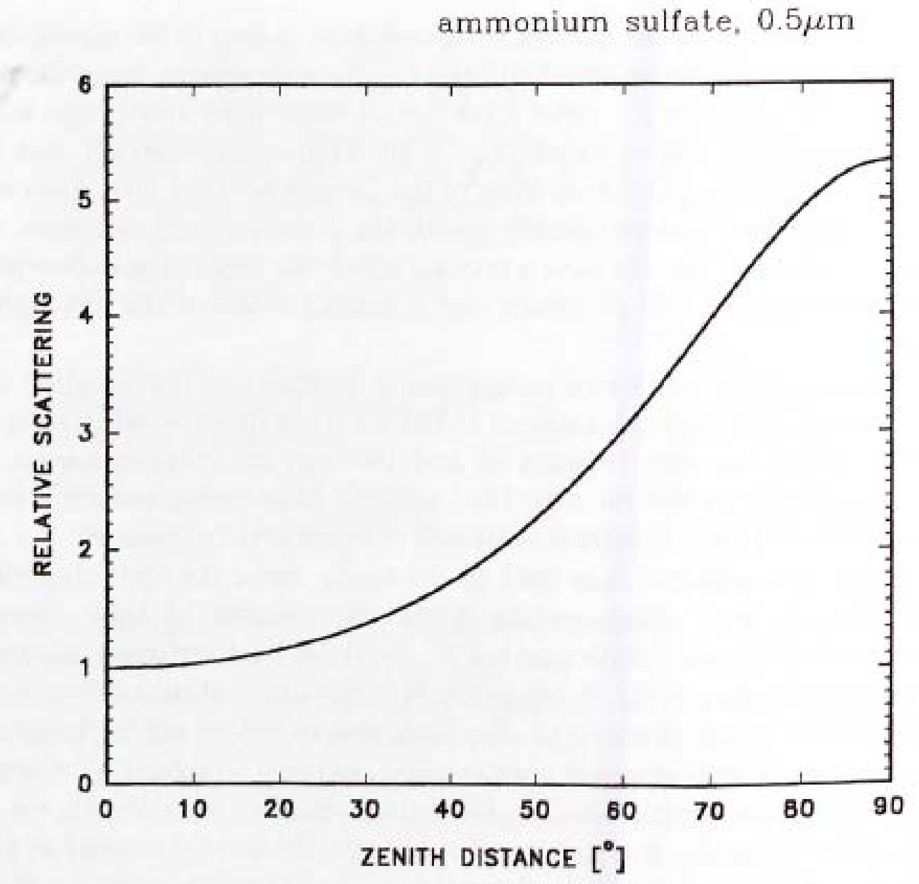
Many simplifications:

- Spherical particles (no problem with sulphuric acid particles)
- Perpendicular incidence on dust layer. (oblique incidence woud have larger depth (δ) and in addition more backscatering)
- Aerosol in troposphere not considered
- Multiple scattering neglected

→ Same temperature decrease possible with less mass of particles

Figure 4. Variation of upwards scattered light by a volume element of aerosol as a function of the zenith distance. All values are relative to the backscattered light at perpendicular incidence. The aerosol particles consist of ammonium sulfate with $d_g = 0.5\,\mu m$ and $\sigma_g = 1.8$

H. Horvath (1998) Influence of atmospheric aerosols upon the global radiation balance. Chapter 13 of "Environmental particles" R.M. Harrison and R.E. van Grieken, eds. pp 543-596, John Wiley & Sons, London, revised second edition 1999 Page 572



So far: considered only average temperature on earth,
gives some insight.

Will this temperature be reached??
Most likely not, since many feedbacks (both positive and negative):

e.g. Gaia hypothesis (Charlson R.J., Lovelock J.E., Andreae M.O. & Warren S.G. Oceanic phytoplacton, atmospheric sulfur, cloud albedo and climate. Nature **326** 655 – 661 (1987))

Assume temperature increases because of more CO_2.
→ Temperature of ocean increases
→ Phytoplankton has better living conditions
→ More Dimethylsulfite (DMS, CH_3-S-CH_3) produced by metabolism.
CH_3-S-CH_3 is gaseous. Oxidized in the atmosphere, eventually
H_2SO_4 droplets: Act es cloud condensation nuclei
→ more but smaller cloud droplets → albedo increases (see next slide)
→ temperature decreases (negative feedback, stabilizes temperature??)

Insert: Cloud albedo and number of cloud droplets.

Assume a certain quantity of water vapor availble for cloud droplets
V is volume of liquid water available per m^3
N Number of Cloud Concensation Nuclei per m^3

Radius of cloud droplets thus is obtained by $N.r^3 \cdot \frac{4\pi}{3} = V$

or $r = \sqrt[3]{\frac{3V}{4\pi N}}$ or $r \propto N^{-\frac{1}{3}}$

Cloud droplets are >5µm → geometric optics is good approximation

→ Scattering coefficient of N droplets with radius r is $\sigma_s = N.r^2\pi$

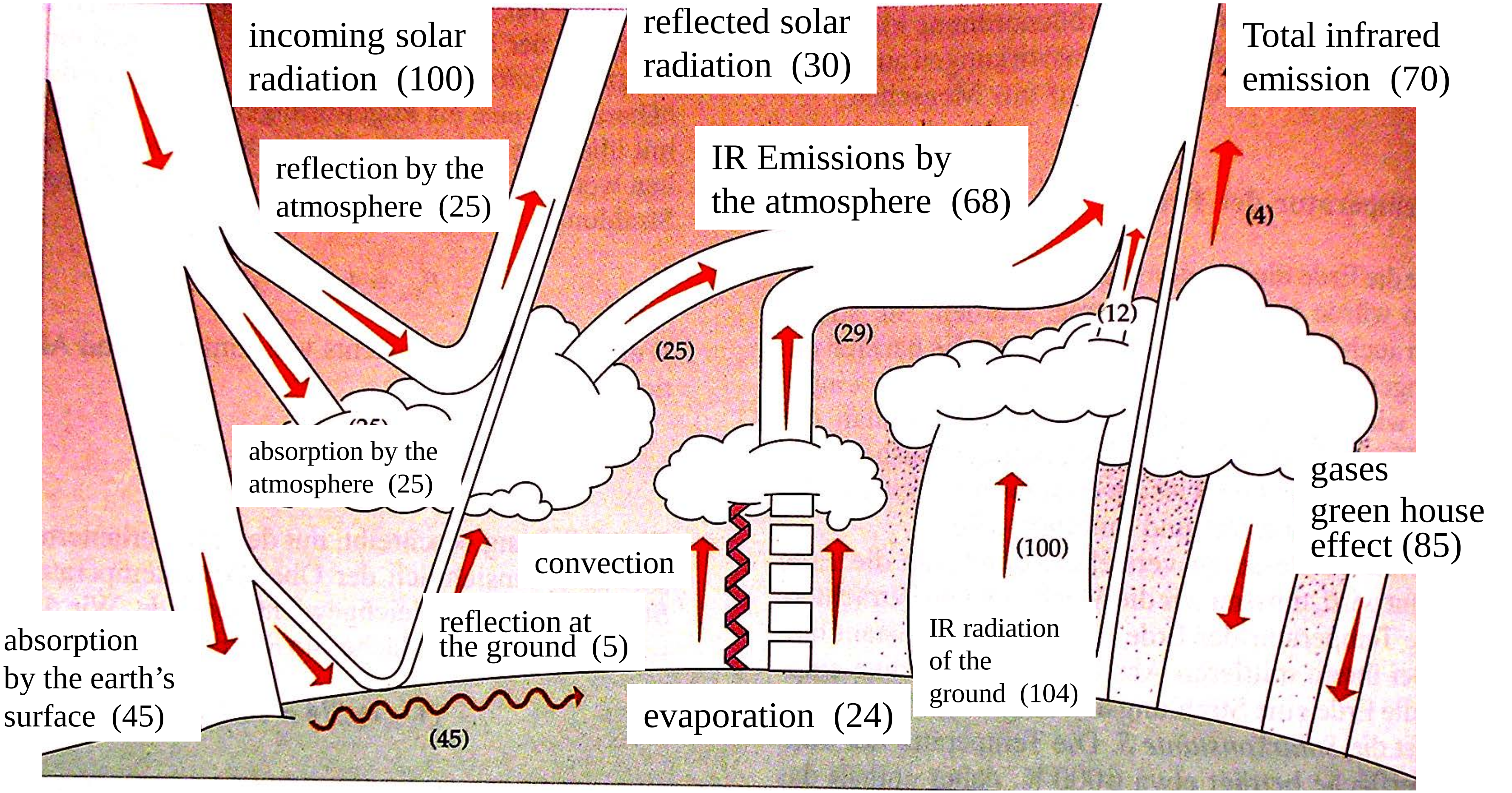
Since $r \propto N^{-\frac{1}{3}}$ → $\sigma_s \propto N^{\frac{1}{3}}$ therefore cloud albedo increases

when the number of Cloud Condensation Nuclei increases
(N. B. with same amount of water!!)

Radiative forcing characterizes influence of a component of the Climate system on radiative balance.

Radiative forcing is a hypothetical value of the change in net radiation (top of the atmosphere) if one parameter in the climate system is altered and no feedbacks are considered.
E.g. an assumed removal of sulfate particles, which scatter sunlight in the atmosphere and back to space. With no sulfate particles we would receive more radiation from the sun, thus the radiative forcing of sulfate particles would be negative, since we receive less solar radiation if sulfate particles are present.

Usually the reference for radiative forcing is the time before the industrial revolution (1750).



Tipler: Physik, Spektrum 1994, p 576

Taken from Stephen H. Schneider The greenhouse effect: Science and policy, *Science* **243**, 771 - 781

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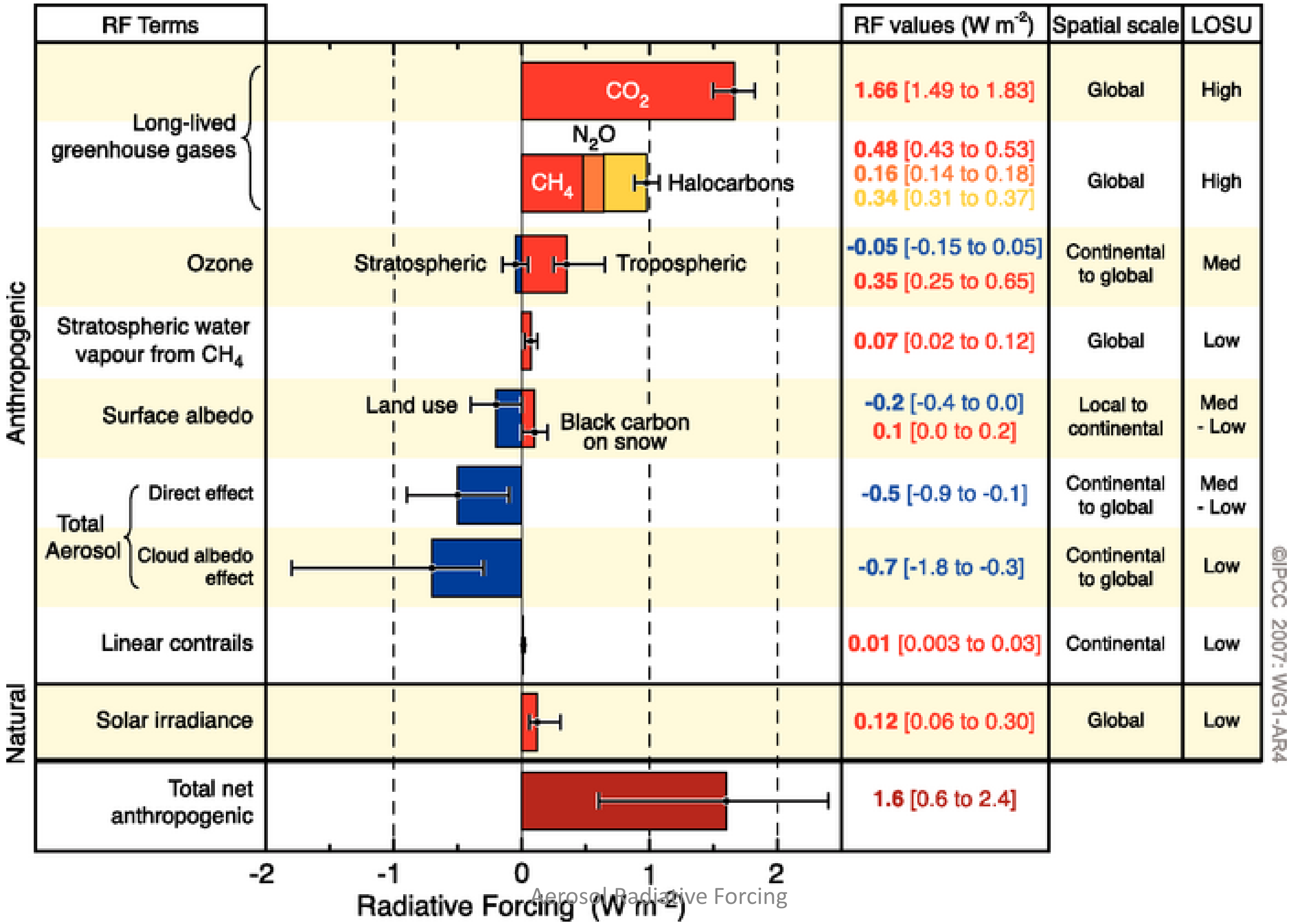
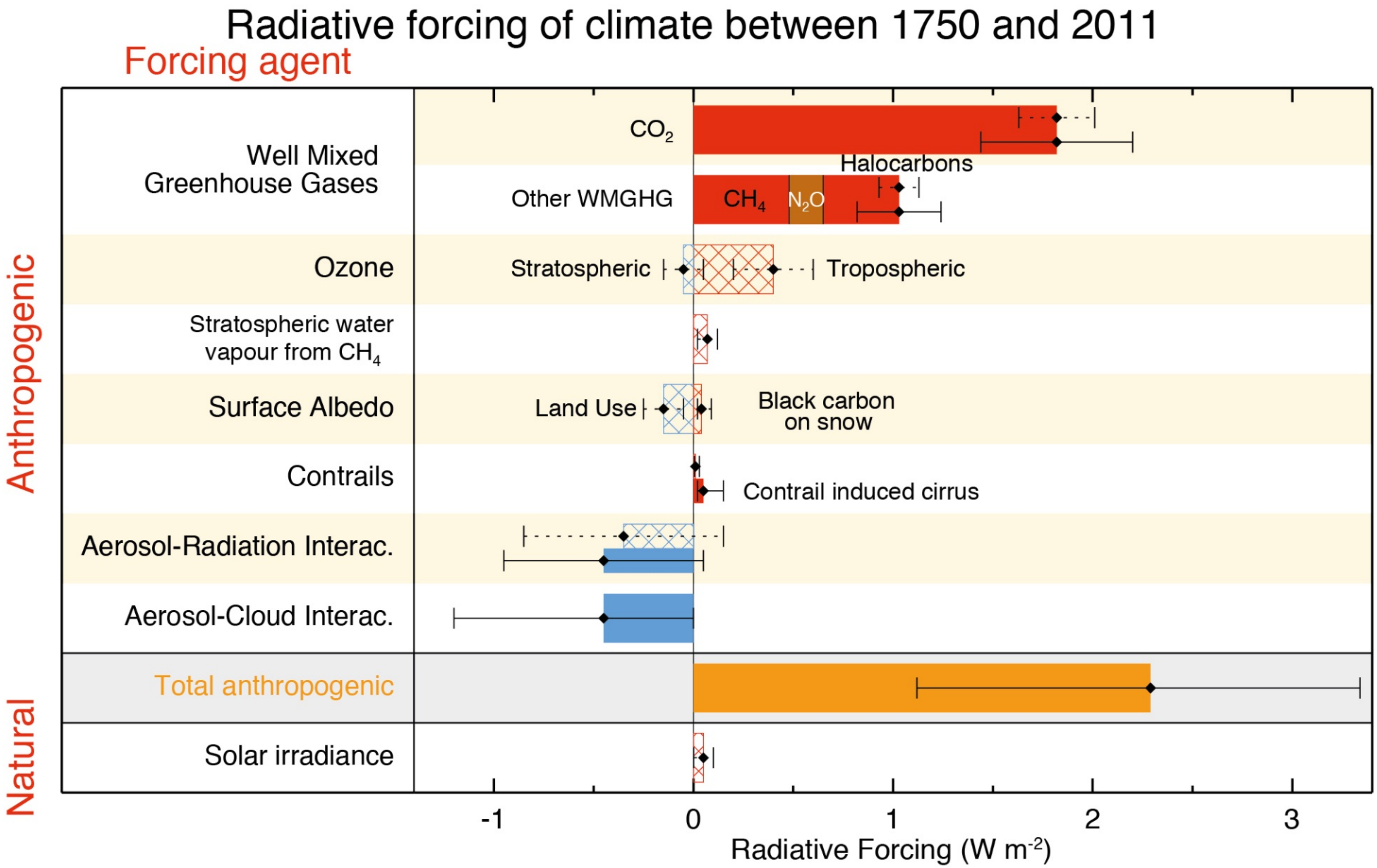
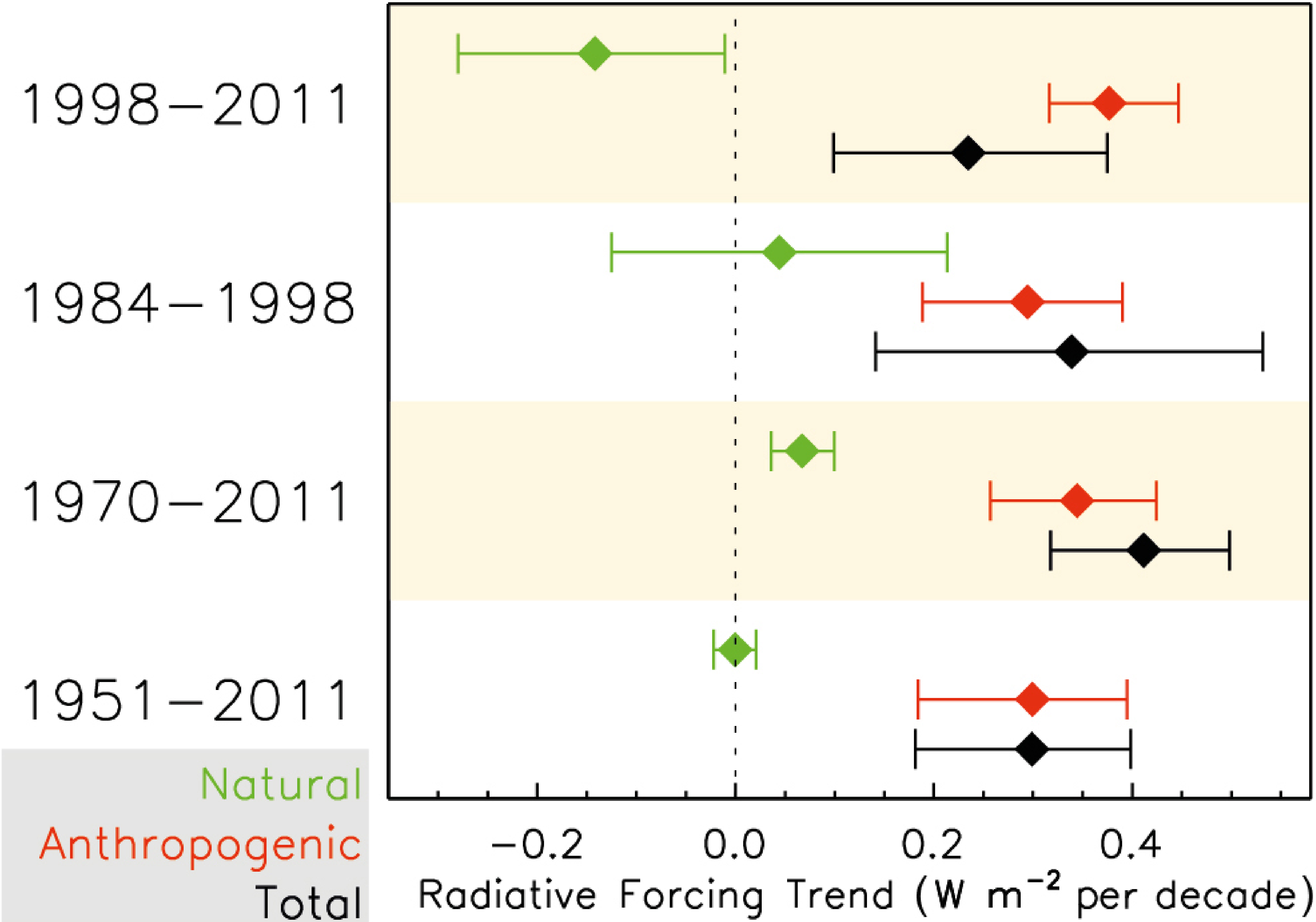
Climate Change 2007: Working Group I: The Physical Science Basis
http://www.ipcc.ch/publications_and_data/ar4/wg1/en/figure-spm-2.html





Fifth assessment report –climate change 2013 **Chapter 8 - Anthropogenic and Natural Radiative Forcing**
http://www.ipcc.ch/report/graphics/index.php?t=Assessment%20Reports&r=AR5%20-%20WG1&f=Chapter%2008


1998–2011
1984–1998
1970–2011
1951–2011
Natural
Anthropogenic
Total
−0.2
0.0
0.2
0.4
Radiative Forcing Trend (W m^{-2} per decade)

Thank you for your attention!!