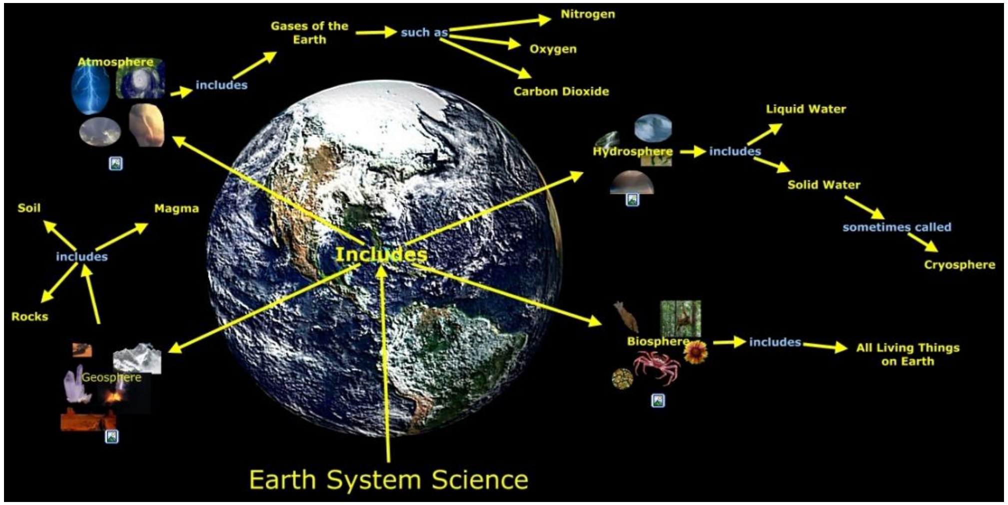


Lecture # 4

Surface/atmospheric energy budget

Earth system science

Lecturer: **Dr Eleni ATHANASOPOULOU**
Research Fellow IERSD/NOA

Lecture outline and structure

- Sun and solar energy (1)
- The transmittance of solar energy towards the earth (2)
- The radiative balance at the top of the atmosphere (3)
- Climate and earth's annual energy budget (4)
- The effect of the atmosphere on radiation (4)
- Surface energy balance (4)
- How do we observe these phenomena? (5)
- Influences on these phenomena (6)
- Radiative forcing of aerosols (7)

Important messages

Earth systems – Climate

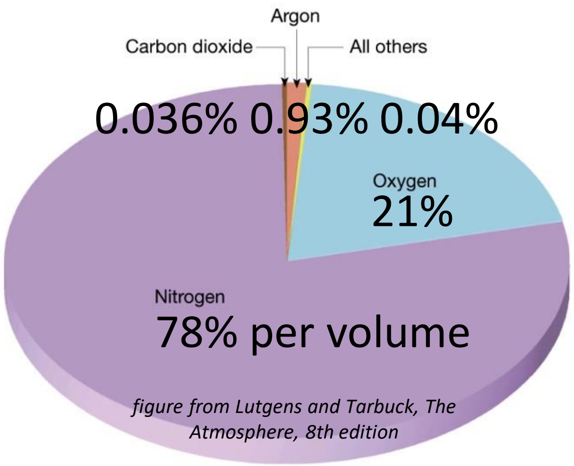
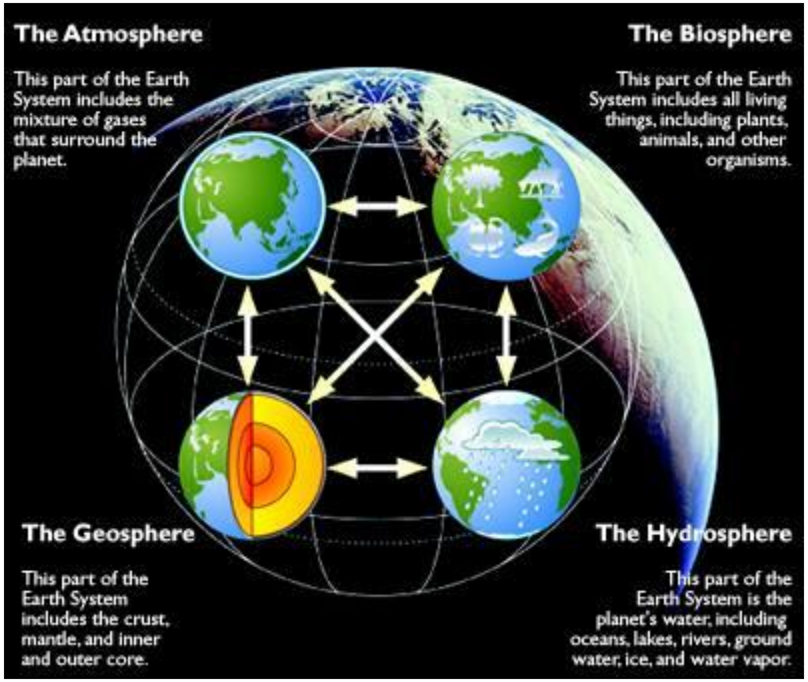


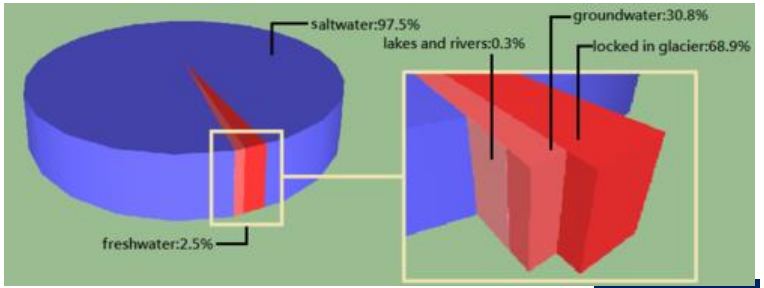
figure from Lutgens and Tarbuck, The Atmosphere, 8th edition



The **biosphere** is the biological component of earth systems = all living organisms on earth, together with the dead organic matter produced by them

The earth systems continuously exchange energy

- Geosphere = Earth's interior = many types of rocks and hundreds of minerals. But, a small number of elements. A total of 98.7% of the crust (by weight) consists of just 8 elements, including **oxygen (46.6%), silicon (27.72%), aluminum (8.13%), iron (5.00%), calcium (3.63%), sodium (2.83%), potassium (2.70%) and magnesium (2.09%)**.

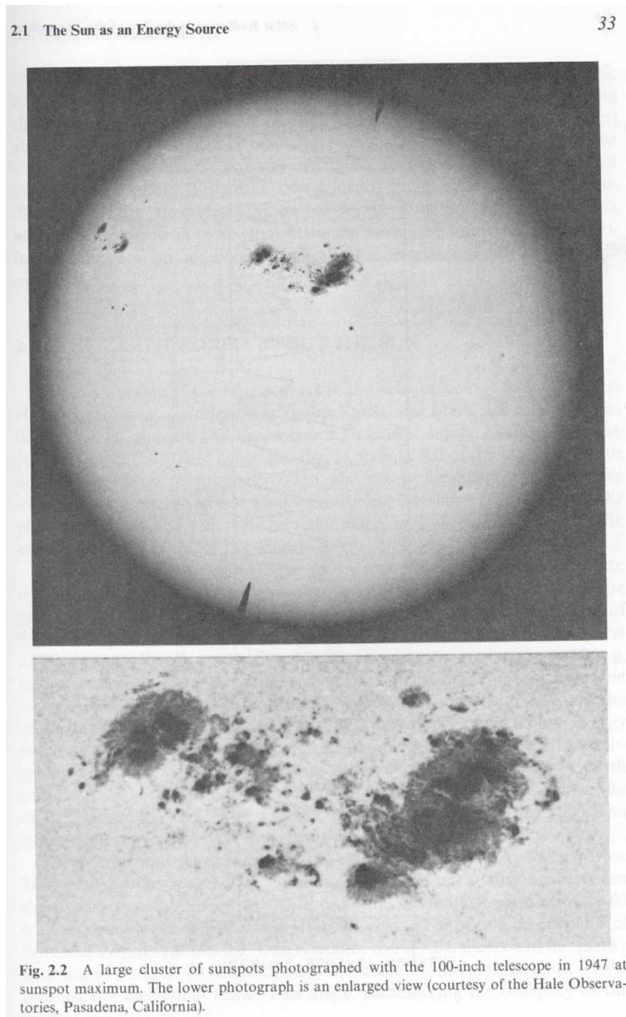


Climate – Energy

- ➢ *Internal sources: Geothermal, Rotational*
- ➢ **<u>External sources:</u>**

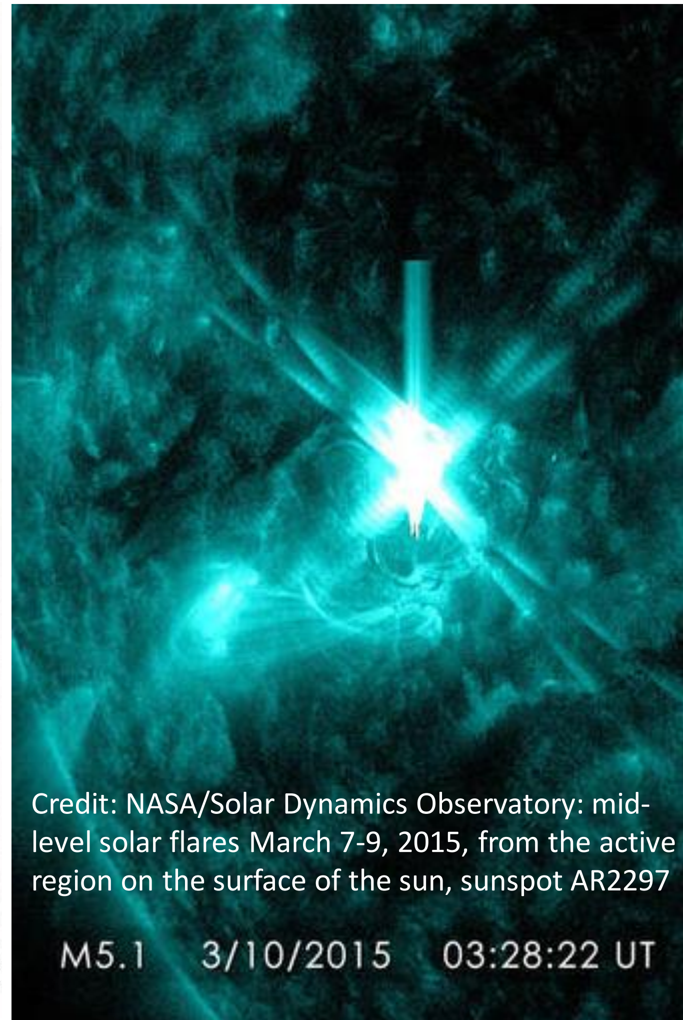
The energy that drives the climate system <u>comes mainly from the Sun*</u>

**A star or planet often is modeled as a ‘black body’ = ideal, of radiative energy: absorbs radiation at all wavelengths incident on it; necessarily emits radiation at all wavelengths*

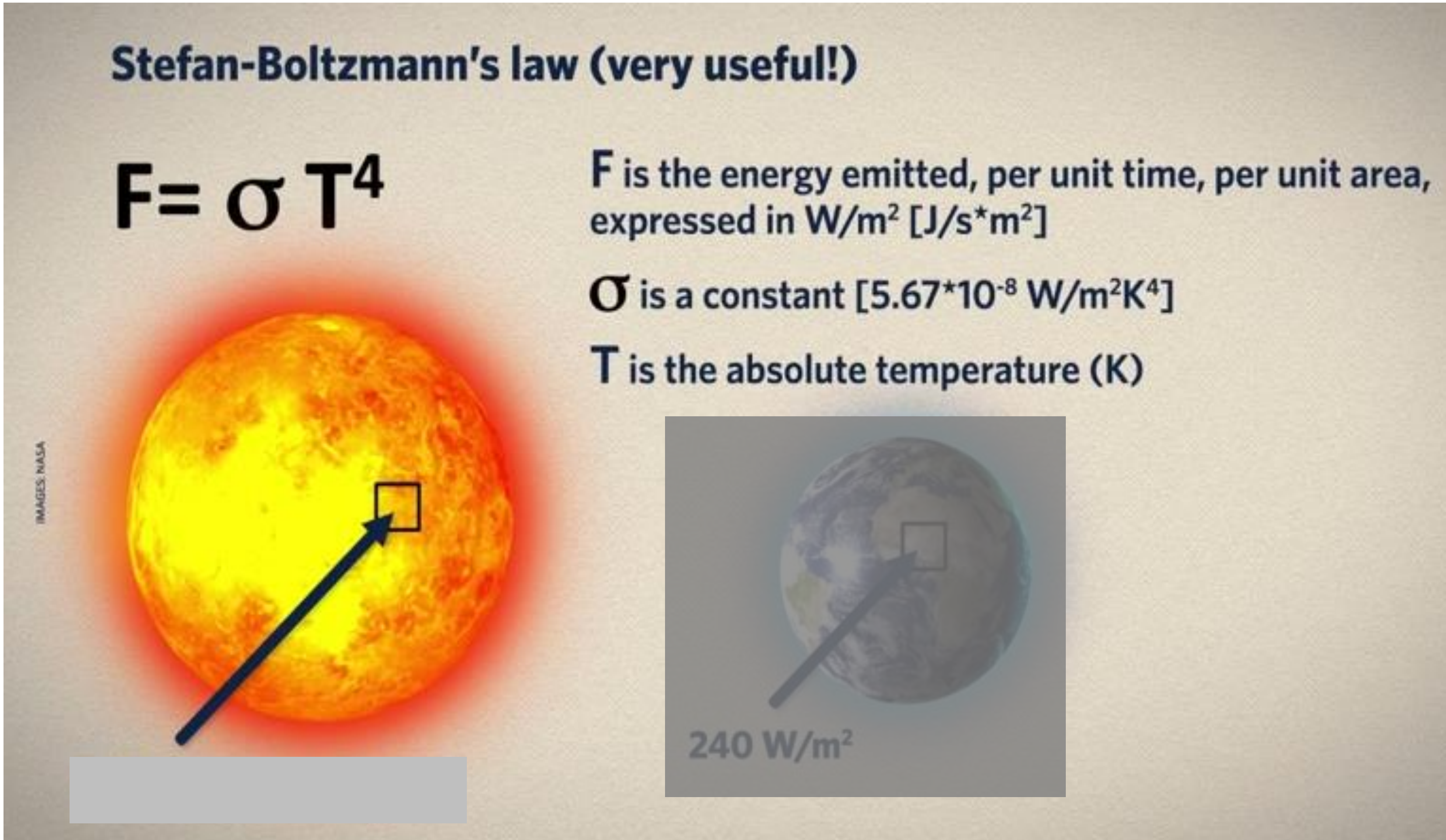


2.1 The Sun as an Energy Source 33

Fig. 2.2 A large cluster of sunspots photographed with the 100-inch telescope in 1947 at sunspot maximum. The lower photograph is an enlarged view (courtesy of the Hale Observatories, Pasadena, California).



Emitted Solar Energy - F



The total energy flux from an object at all wavelengths depends only <u>on temperature</u>.

Solar Temperature - T

Wien's law

(as temperature increases, the wavelength (λ) of radiation decreases)

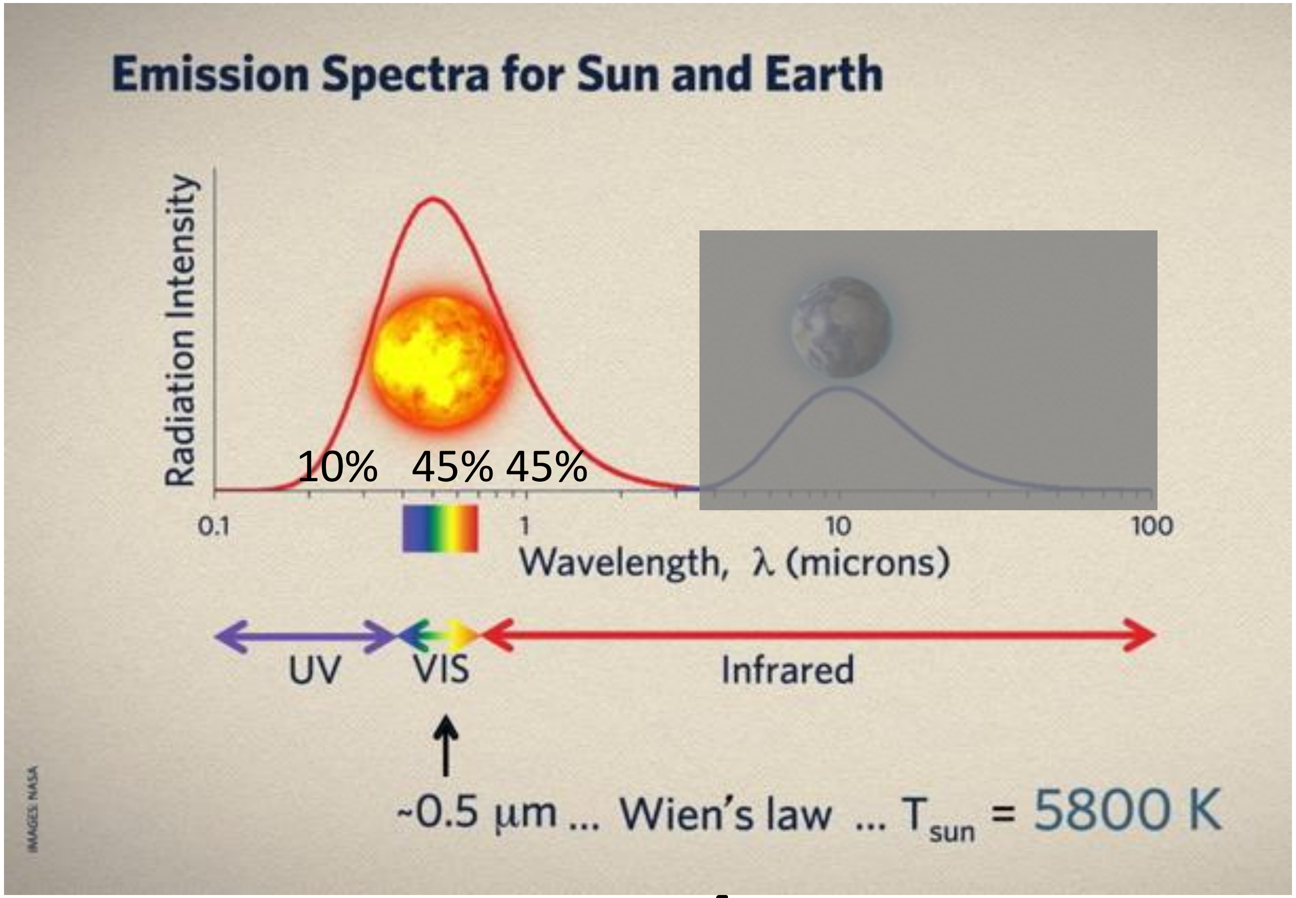
$$\lambda_m = w / T$$

λ_m = wavelength of maximum intensity (μm)
w = Wien's constant (2897 μm K)
T = absolute temperature (K)

$$T = w / \lambda_m$$

The temperature of an object is determined by the <u>wavelength</u> at which it emits radiation at <u>maximum intensity</u>

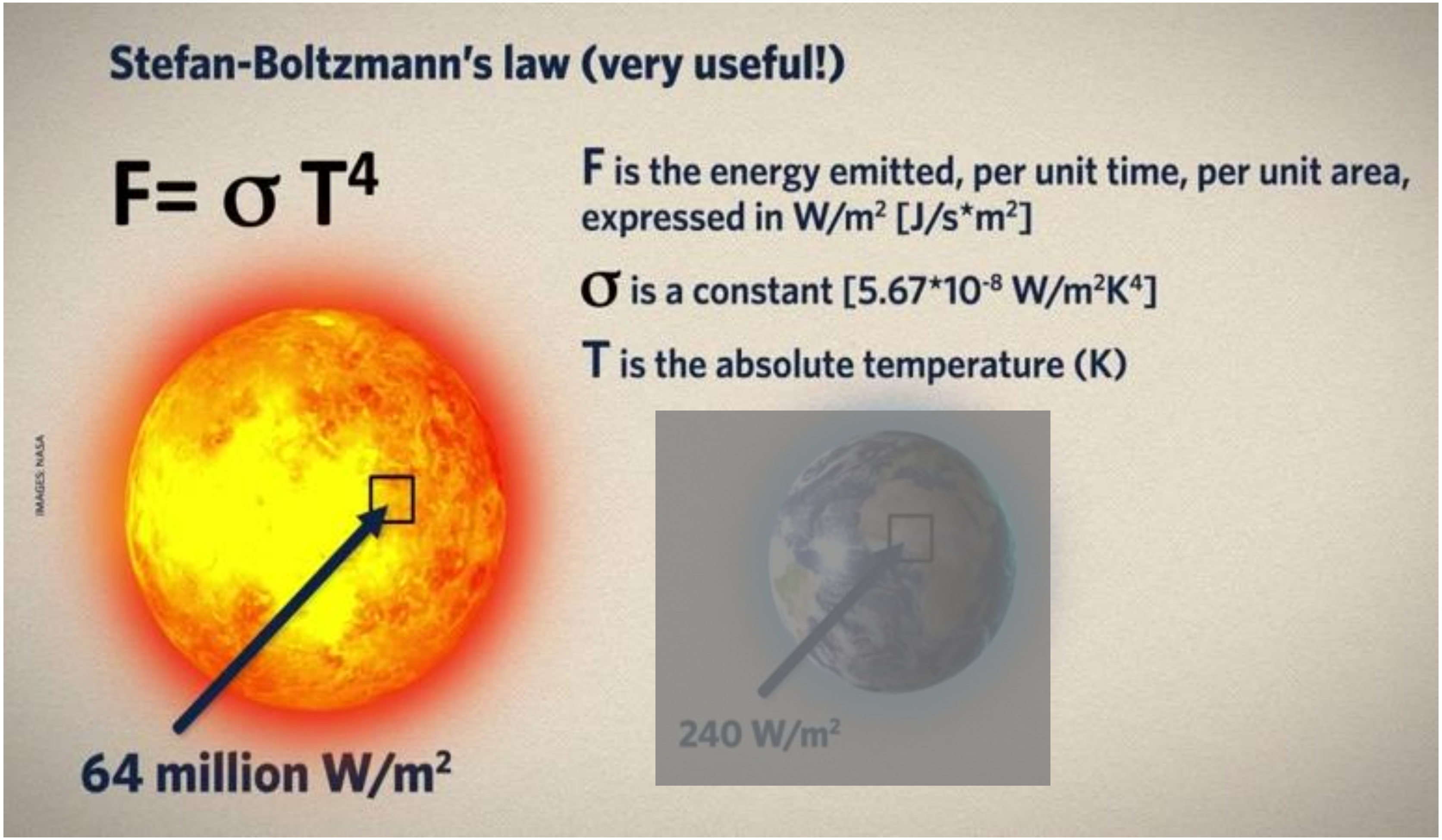
Solar Temperature - T



$$T = w / \lambda_m$$

The radiation emitted from the sun maximizes at the wavelength of about 0.5 μm, thus its absolute temperature is calculated around 5800 K.

Emitted Solar Energy - F



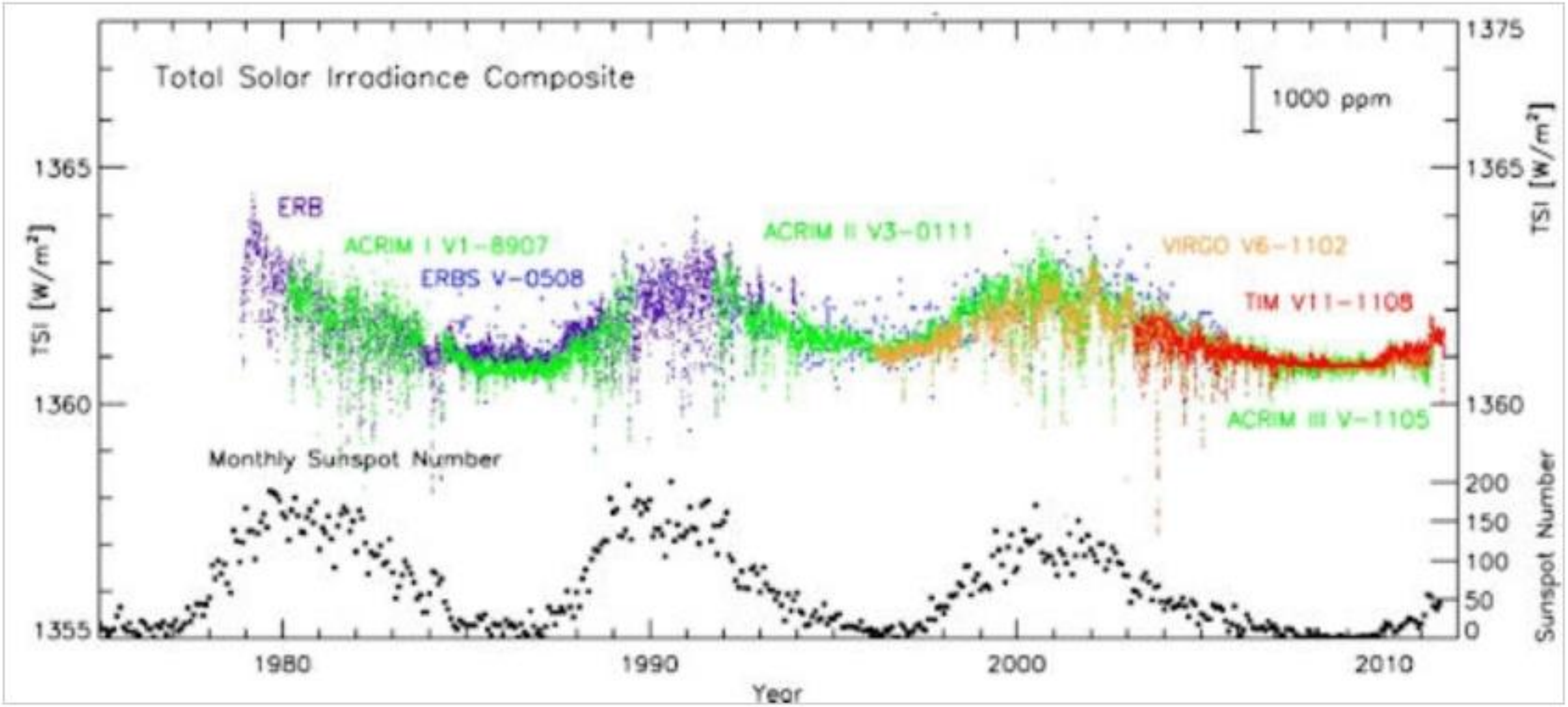
The radiative energy emitted from the surface of the sun is ~ 64×10^6 Watts per second per square meter

Key points (1)

- The Sun is the major source of the energy of the Earth
- The absolute temperature of a planet is dependent on the wavelength at which it emits the maximum amount of radiative energy (the Wien's Law)
- The radiative energy emitted by a planet is determined by its absolute temperature (Stefan-Boltzmann's Law)
- The flux of the radiative energy from the Sun per second at its surface is 64×10^6 W m^{-2}
- The radiation of sun occurs in the ultra-violet, visible and infrared wavelengths of light, i.e. it radiates energy across the range of 0.1 – 4 μm in the electromagnetic spectrum. Its peak radiation is in the visible wavelength of 0.5 μm (cyan)
- The flux of radiative energy at the surface of a circle with its center at the Sun and its radius at the top of the atmosphere (ToA) of the Earth, i.e. the radiative energy of the Sun that reaches the ToA of the earth is:

Solar Energy at the Top of the Atmosphere (ToA)

The quantity that arrives at the Earth (perpendicular to the solar rays) is about 1360 W/m², and this is known as the solar constant (S_0) or total solar irradiance (TSI).



Space-borne measurements of the total solar irradiance (TSI) show ~0.1 percent variations with solar activity on 11-year and shorter timescales. These data have been corrected for calibration offsets between the various instruments used to measure TSI. SOURCE: Courtesy of Greg Kopp, University of Colorado.

Solar Energy at the Top of the Atmosphere (ToA)

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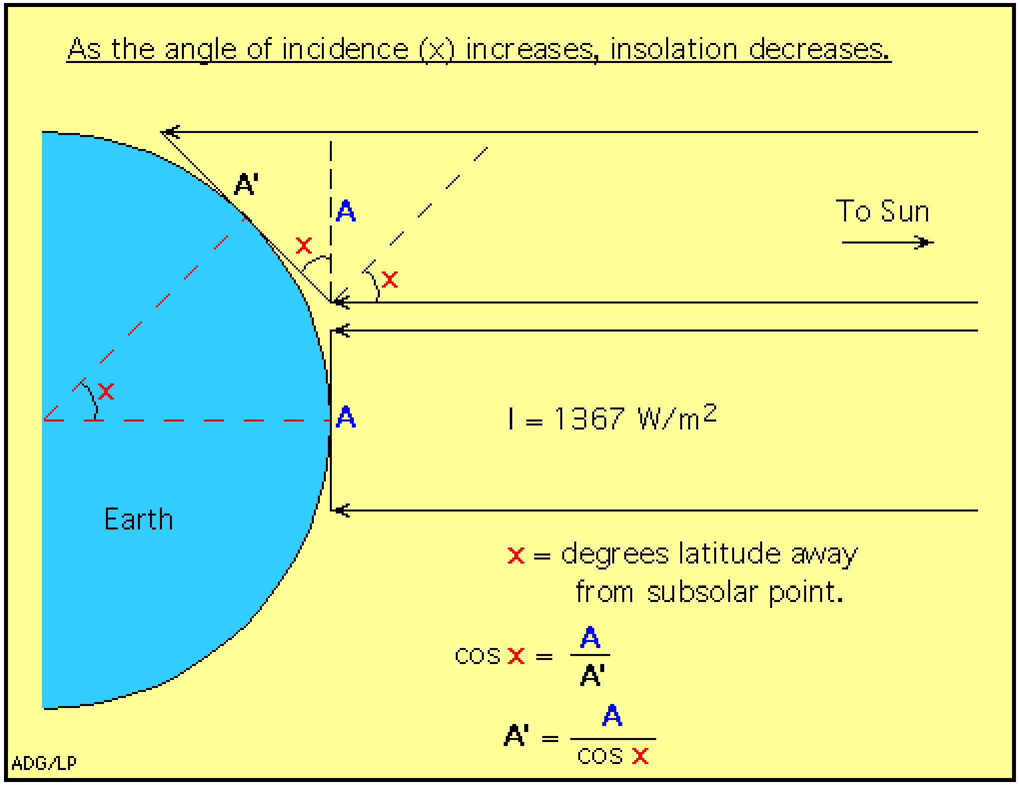
* *The* National Aeronautics and Space Administration (*NASA) value is 1353 ± 21 W m^{-2}. The World Metrological Organization (WMO) promotes a value of 1367 W m^{-2}.*

The actual insolation at the ToA depends on 4 geometrical and/or astronomical parameters:

1. Earth's rotation about its axis: on a daily basis one hemisphere is always dark, receiving no solar radiation at all: halves the total solar irradiance.

2. Earth's spherical shape: The progressive decrease in the angle of solar illumination with increasing latitude reduces the average solar irradiance by an additional one-half.

Incident solar energy ~ 340 W/m^2



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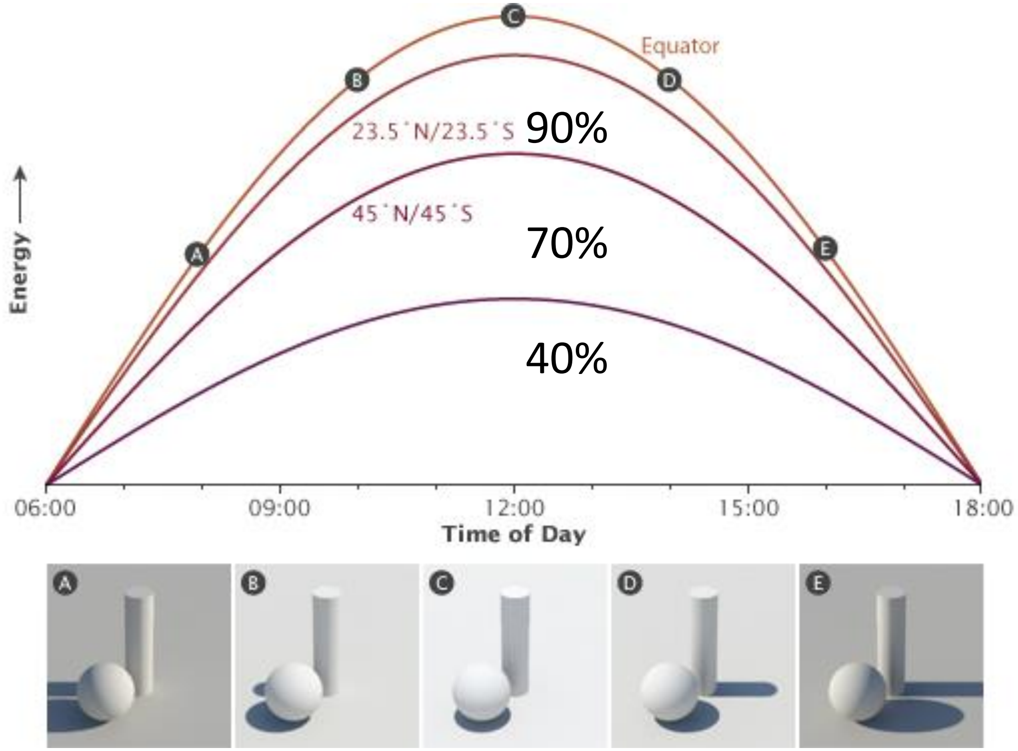


Source: http://earthobservatory.nasa.gov/

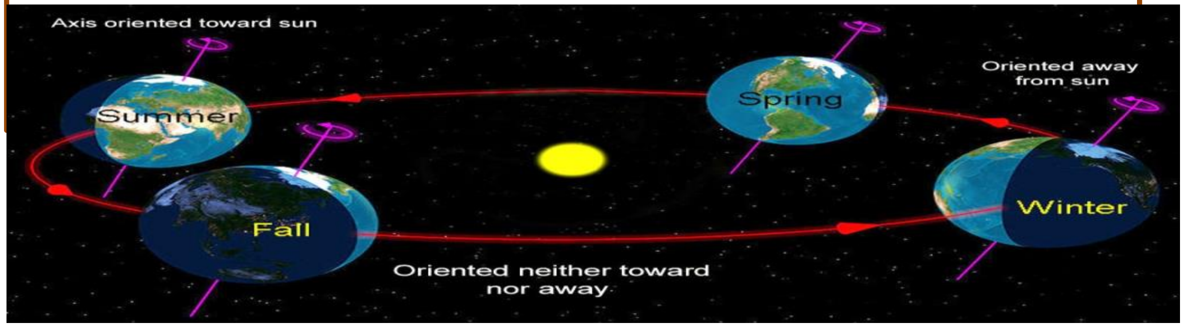
Solar Energy at the Top of the Atmosphere (ToA)

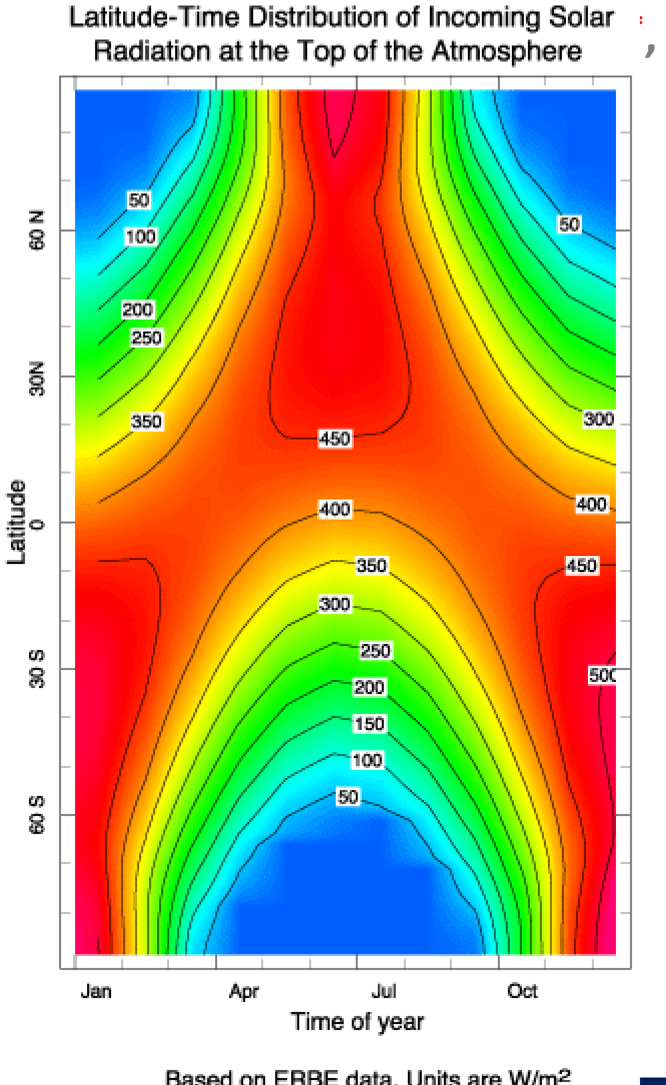
The quantity that arrives at the Earth (perpendicular to the and this is known as the solar constant (S_0) or tot

* *The* National Aeronautics and Space Administration (*NASA) value World Metrological Organization (WMO) promotes a value of 1367*

The actual insolation at the ToA depends on 4 geometrical and/or astronomical parameters:

3. Eccentricity of Earth's orbit: The radiation at the ToA varies ~3.5% over the year, as the Earth spins around the Sun. This is because the Earth's orbit is elliptical, with the Sun located in one of the foci of the ellipse. The Earth is closer to the sun at the perihelion (than at the aphelion).

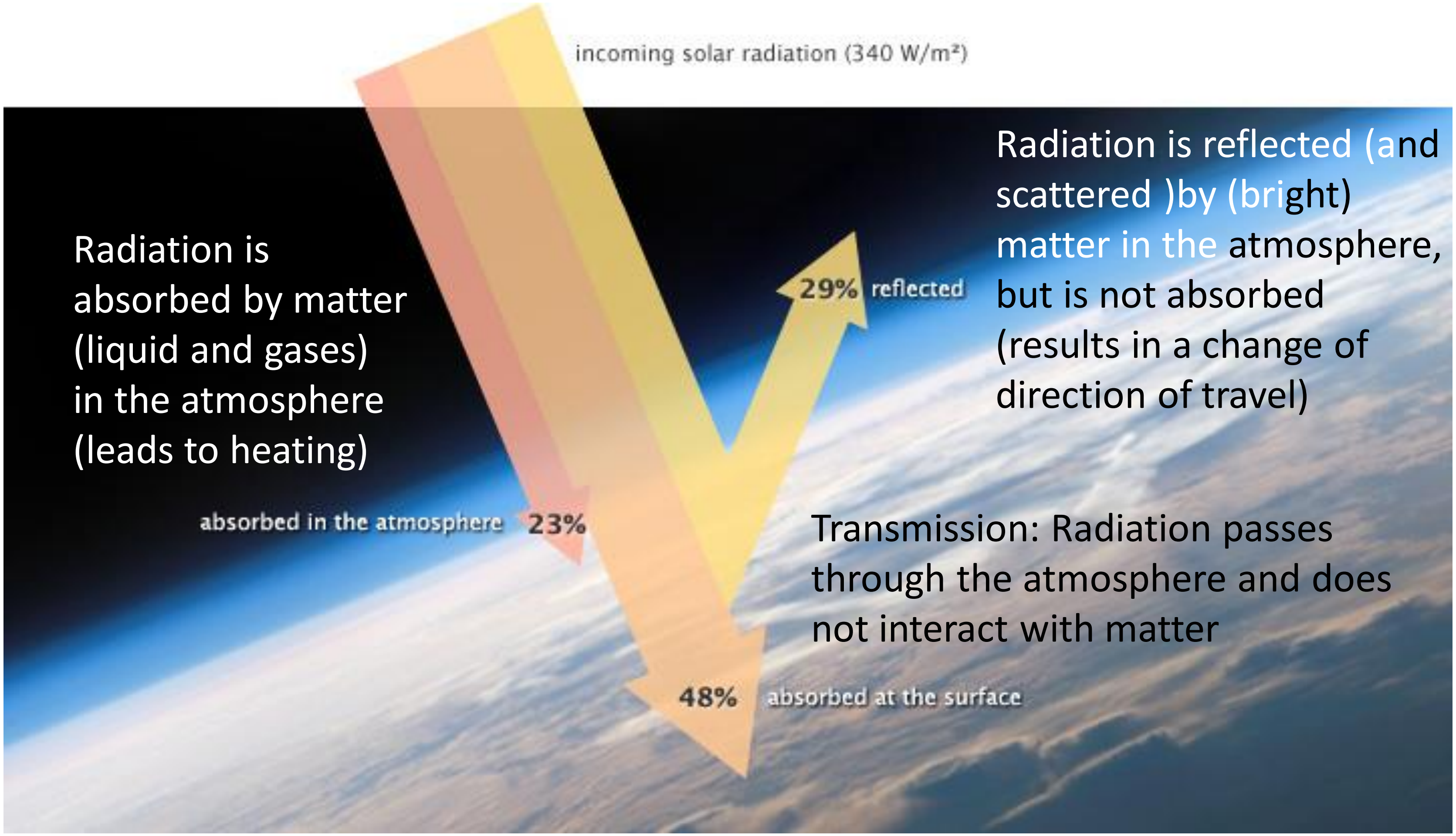




Key points (2)

- The solar constant (or TSI = flux (per second) of the radiative energy from the Sun at the ToA of the earth) is ~1360 W m^{-2}
- The actual insolation at the ToA of the Earth depends on 4 geometrical and/or astronomical parameters:
- The self-rotation of the Earth (1/2 decrease in the incoming solar radiation)
- The spherical shape of the Earth (1/2 decrease in the incoming solar radiation)
- The shape of the orbit of the Earth (yearly variation of the energy)
- The tilt of the Earth's axis (seasonal variation of the energy)
- The Incident solar energy at the ToA of the earth is ~ 340 W m^{-2} (global and annual average)

Climate & Earth’s energy budget



Radiation is absorbed by matter (liquid and gases) in the atmosphere (leads to heating)

Radiation is reflected (and scattered)by (bright) matter in the atmosphere, but is not absorbed (results in a change of direction of travel)

Transmission: Radiation passes through the atmosphere and does not interact with matter

NASA illustration by Robert Simmon. Astronaut photograph [ISS013-E-8948](ISS013-E-8948).

Earth's energy balance

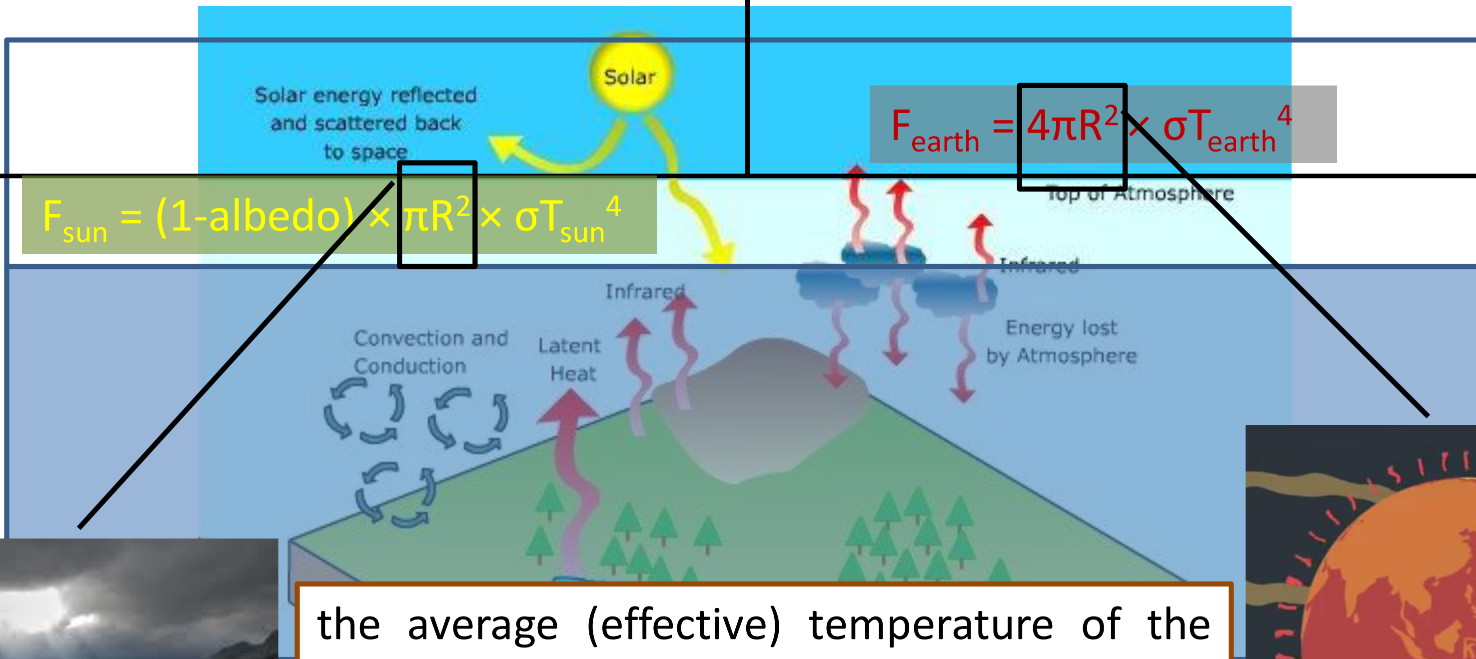
Absorbed solar energy = Emitted terrestrial energy

$$(1\text{-albedo}) \times \pi R^2 \times \sigma T_{sun}^4 = 4\pi R^2 \times \sigma T_{earth}^4$$

$$T_{earth} = 255\ K\ (= -18\ C)$$

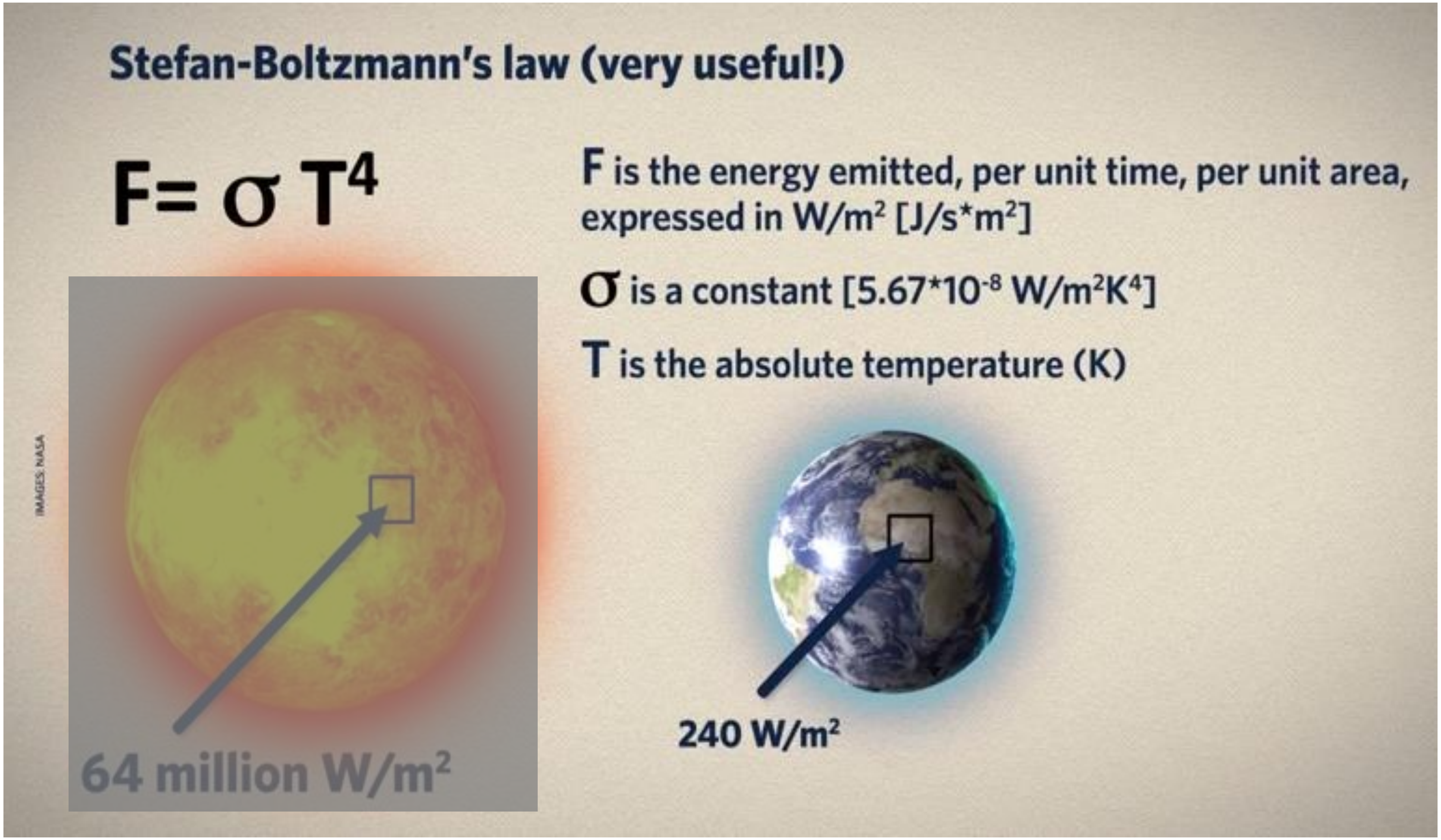
$$F_{earth} = 4\pi R^2 \times \sigma T_{earth}^4$$

$$F_{sun} = (1\text{-albedo}) \times \pi R^2 \times \sigma T_{sun}^4$$



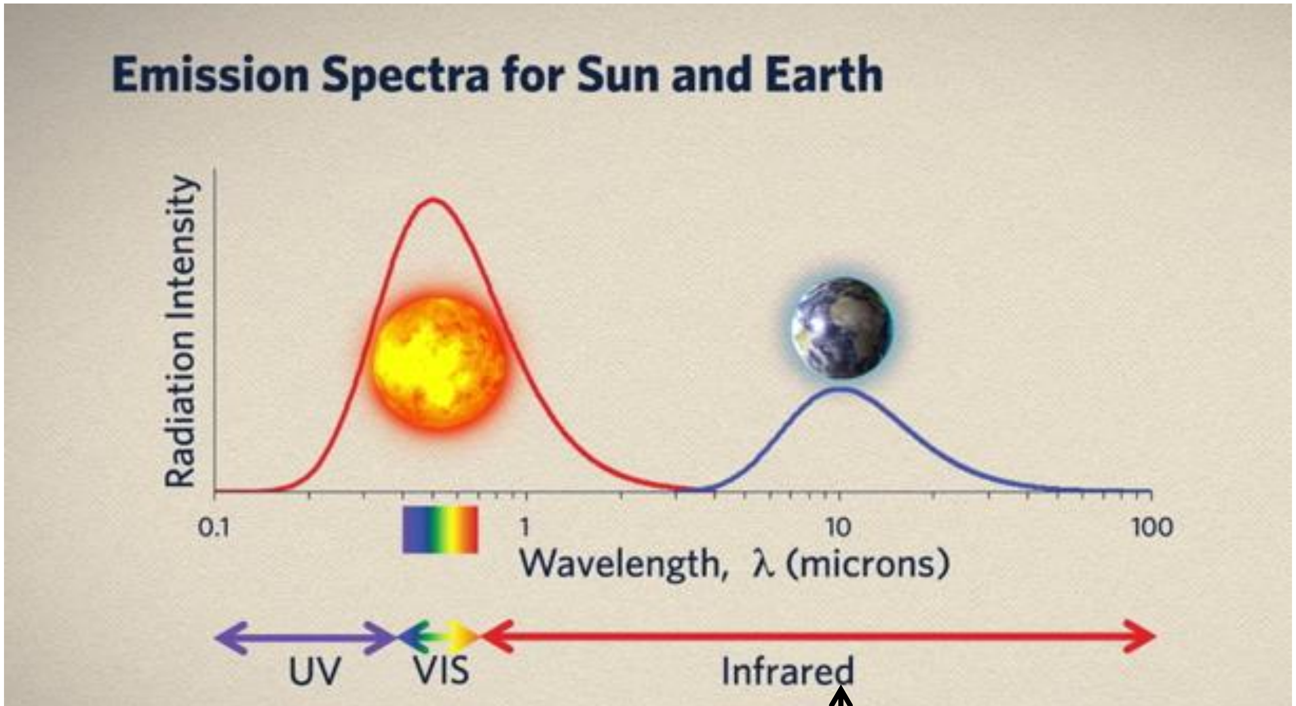
the average (effective) temperature of the earth, at which it emits the amount of radiation to bring its energy budget into balance

Emitted Energy from the ToA of Earth



The radiative energy emitted from the ToA of the earth is ~ 240 Watts m^{-2}

Spectrum of the energy emitted at the ToA of Earth



T_{earth} = 255 K (-18 °C) ... Wien's law ... 11.4 μm

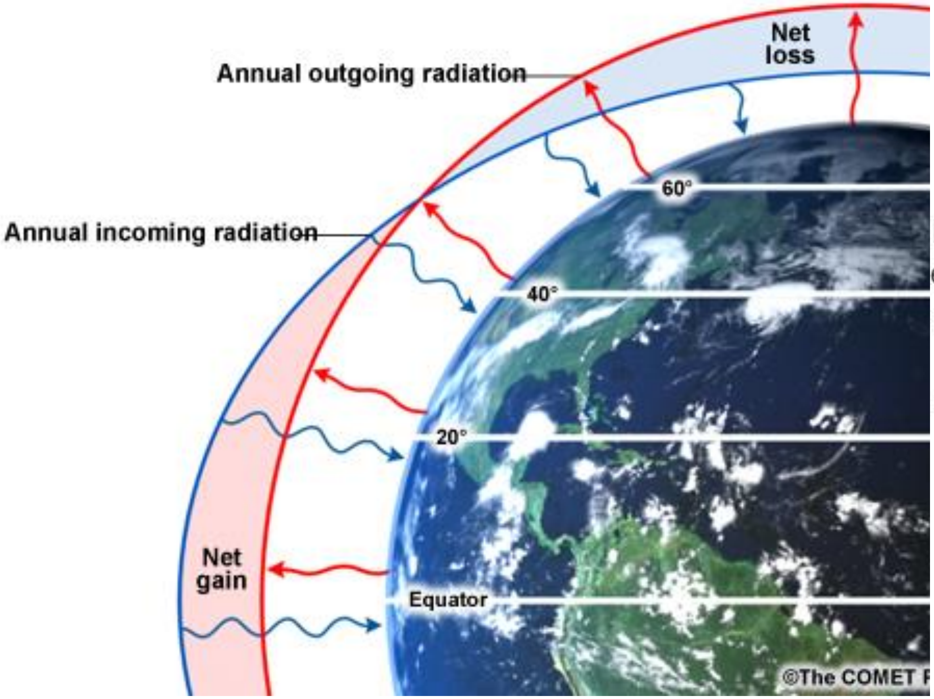
$$\lambda_m = 2897 / T$$

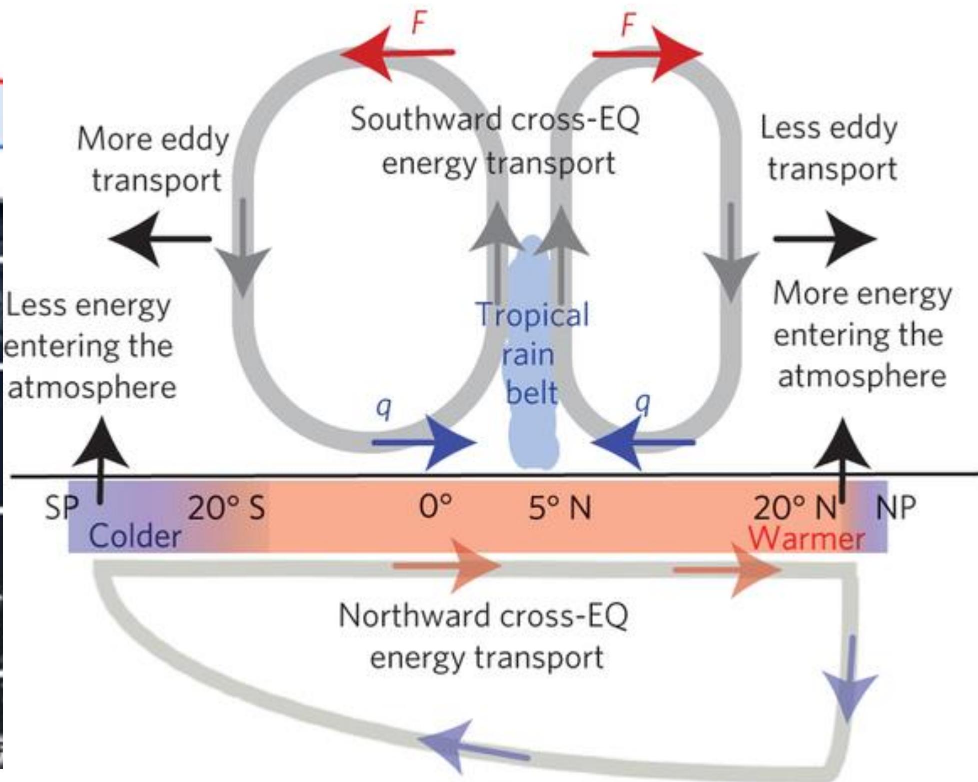
The radiative energy of the earth is mainly in the infrared region of the electromagnetic spectrum (longwave/terrestrial)

Geographical distribution of the earth's energy budget

"The global circulation of air drives some of the Earth's ocean currents and helps to redistribute the solar energy that reaches Earth, moderating climate and impacting environments for all life on Earth."

Lessons 1-2



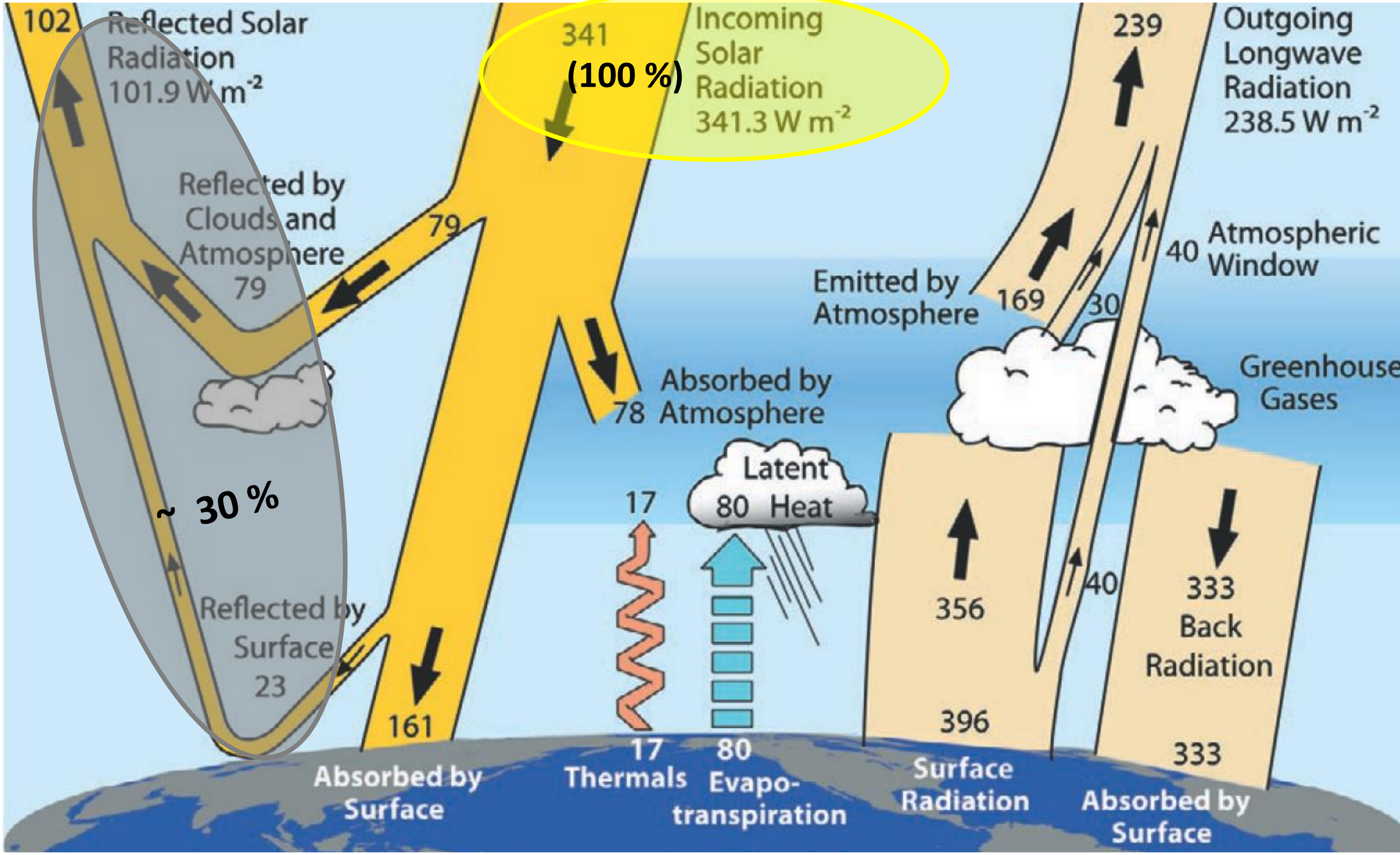


(left) The tropics defined by net gain in radiation compared with deficits at the poles.
(right) "Heat is released from the ocean to the atmosphere ... The atmosphere responds through eddy energy transports ... "(Frierson et al., 2013, Nature Geoscience)

Key points (3)

- The outgoing radiative energy (ORE) at the ToA of the earth must balance the incident solar energy
- The temperature at the ToA of planet earth under this condition is relatively stable and ca. -18 °C and shapes the ORE at ca. 240 W m^{-2} (average global value)
- The radiation of earth occurs in infrared wavelengths of light, i.e. it radiates energy across the range of 3 – 70 μm in the electromagnetic spectrum. Its peak radiation is in the wavelength of 11.4 μm
- The flow of incoming and outgoing energy is Earth's energy budget.
- Which are the processes that interfere with radiation within the atmosphere of the Earth (i.e. from the surface to the the ToA)?
- Which are the amounts of energy exchanged during these processes?

Climate & Earth's annual energy budget

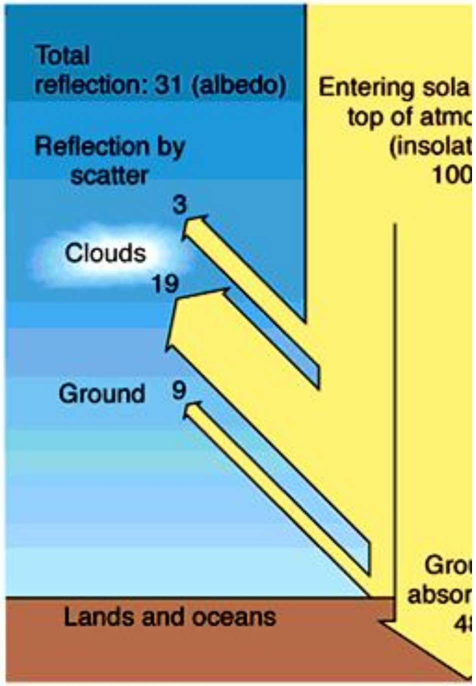


Important Note: Determining exact values for energy flows in the Earth system is an area of ongoing climate research. Different estimates exist, all with some uncertainty. Estimates (of the reflected sunlight and thermal infrared energy radiated by the atmosphere and the surface) come from satellite observations, ground-based observations, and numerical weather models. ***These numbers are from IPCC, 2007, updated with [Trenberth et al., 2009]***

Reflection of Incoming solar radiation

Earth's Albedo: the fraction (0-1 or %) of solar radiation reflected back to space by:

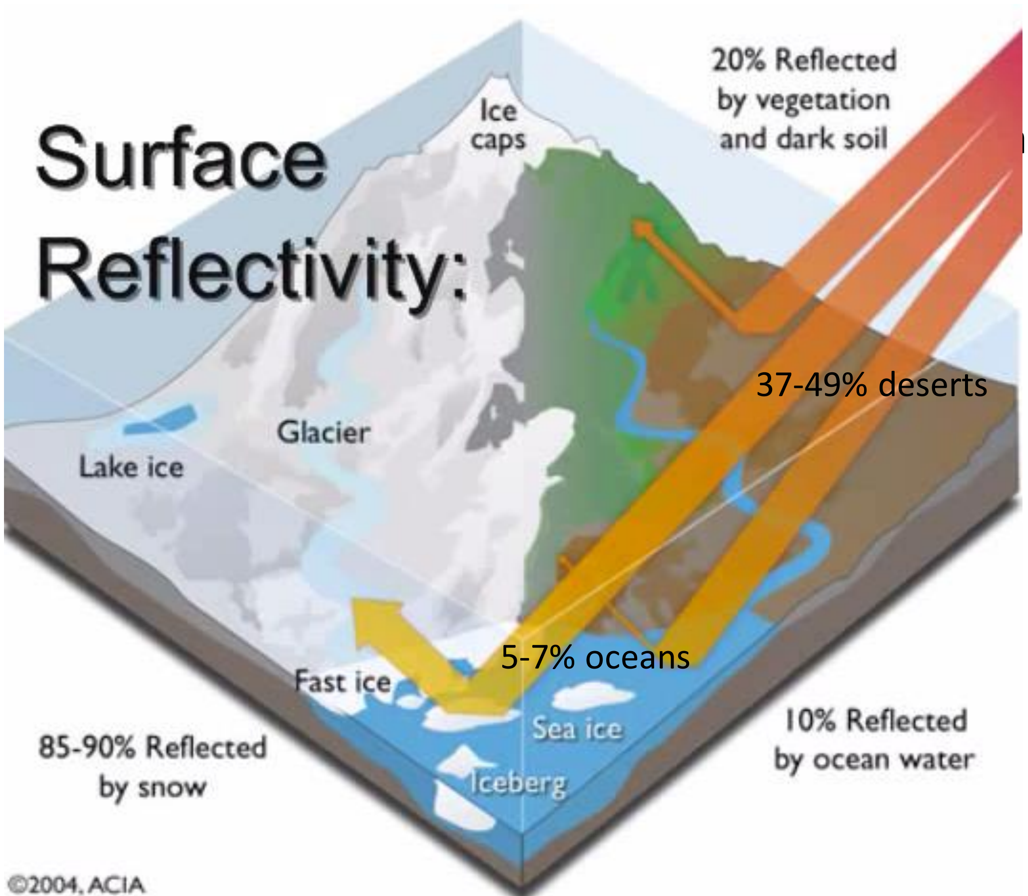
1. **Surface**
2. **Clouds**
3. **Particles** (or aerosols: any liquid, solid or mixed particle suspended in the air)

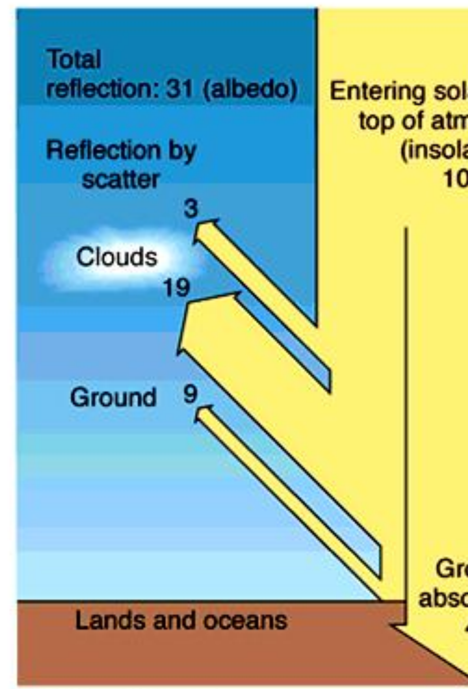


Reflection of Incoming solar radiation

Earth's Albedo: the fraction (0-1 or %) of solar radiation (at all wavelengths) reflected back to space by:

rticle





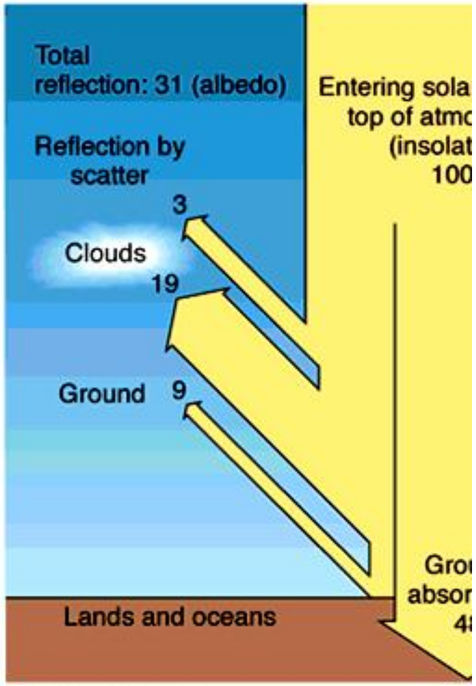
Reflection of Incoming solar radiation

Earth's Albedo: the fraction (0-1 or %) of solar radiation reflected back to space by:

2. **Clouds**

Parameters that control cloud reflectivity:

i. Cloud thickness (thick clouds are more reflective)
ii. Size of water droplets (small are more reflective)
iii. Number of water droplets (the more the number the more reflective)



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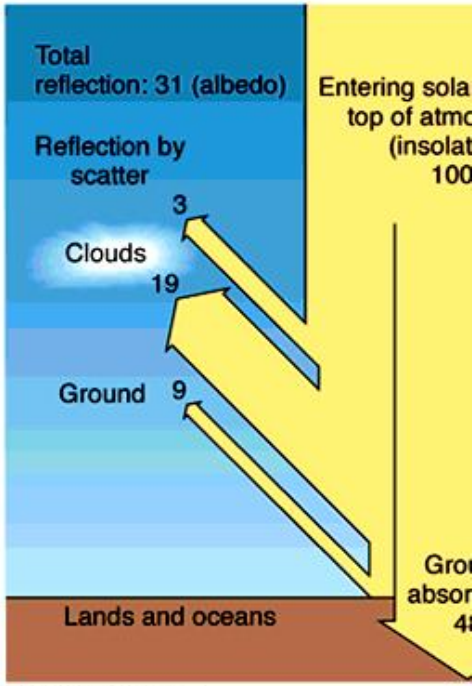
CCN



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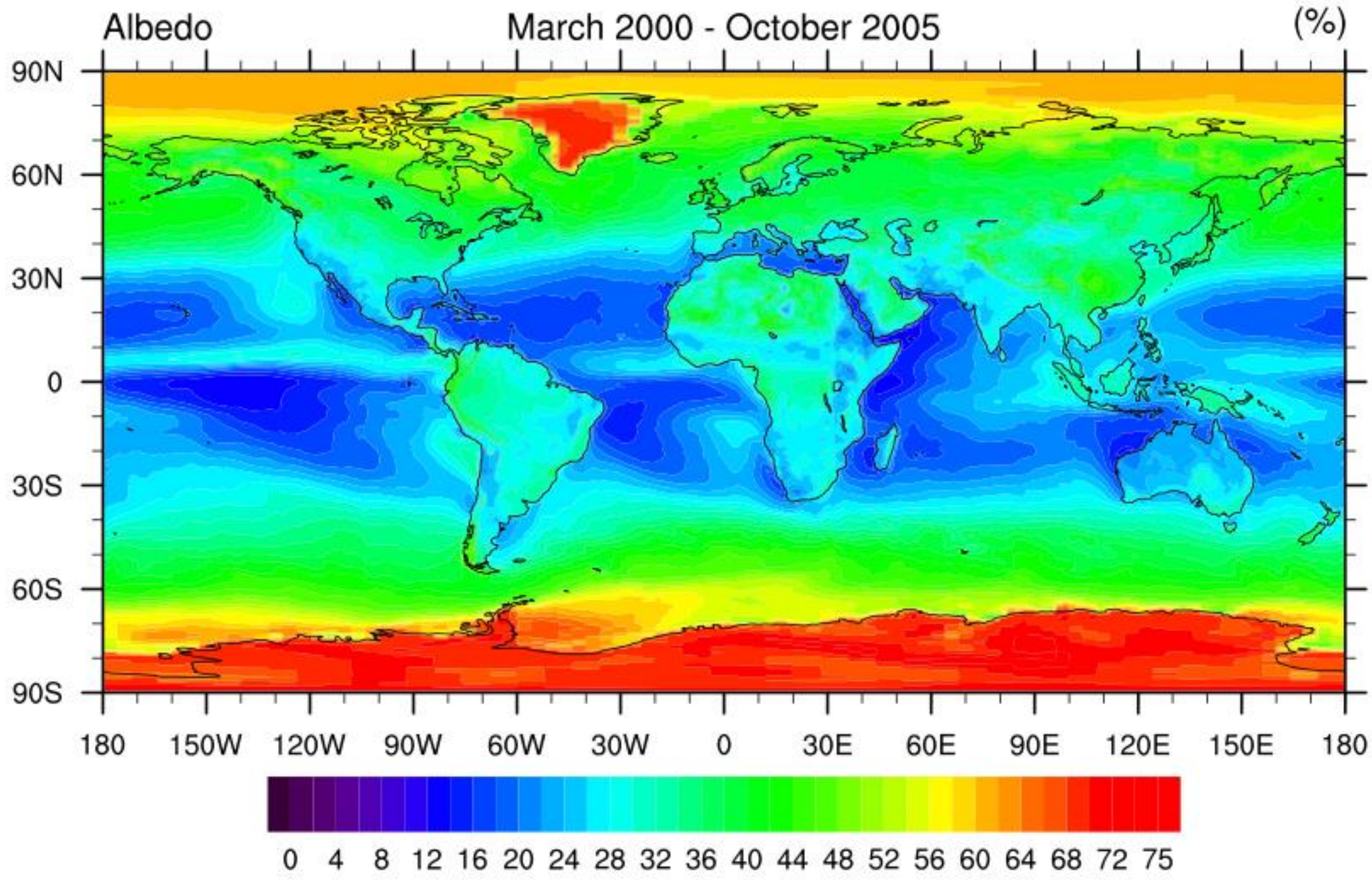
Parameters that control aerosol optical properties (e.g. Single Scattering Albedo):

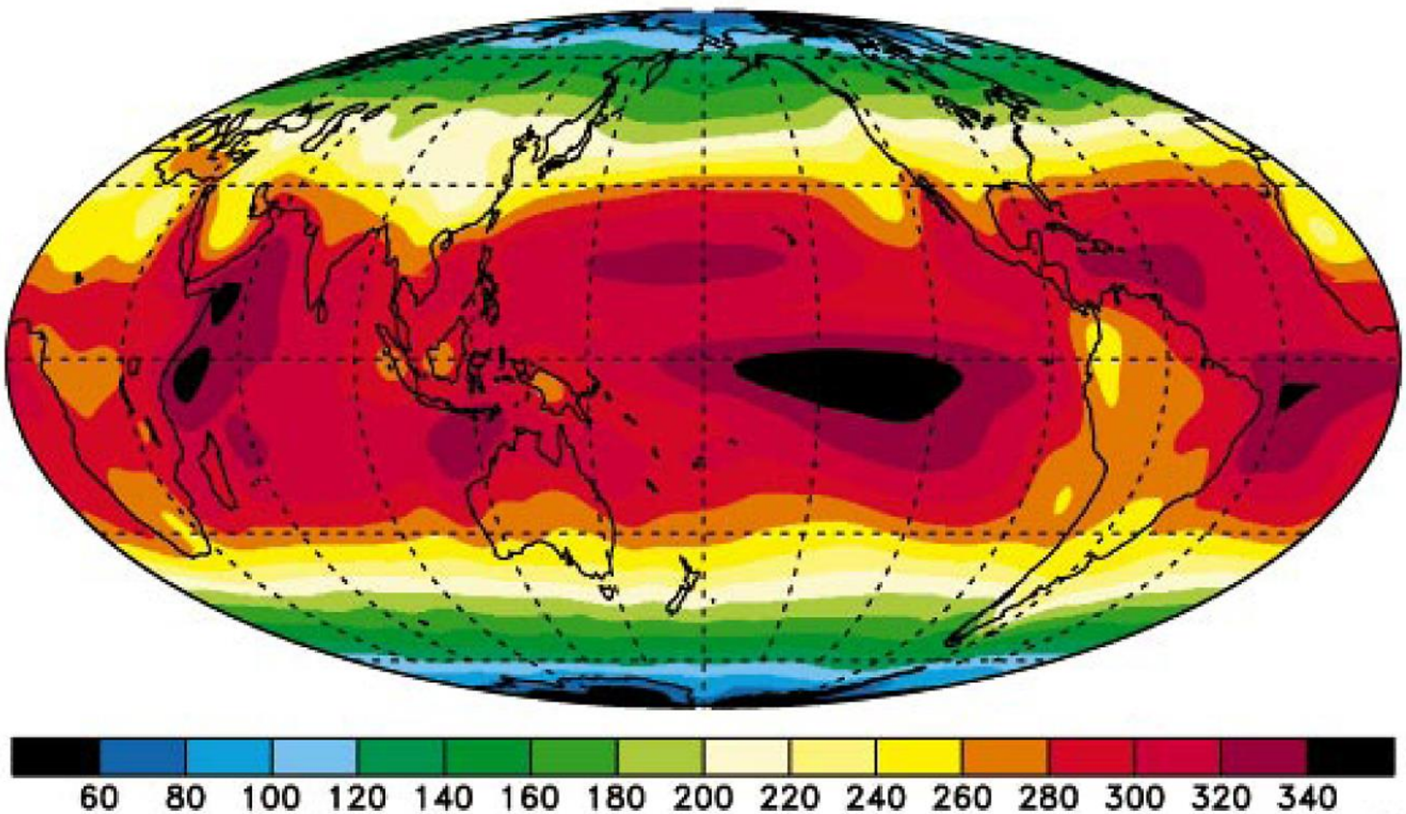
i. Size of particles
ii. Shape of a particle (anisotropy)
iii. Chemical composition (color) of particles (e.g. black carbon absorbs radiation; sulfate, nitrate particles scatter radiation)

Global distribution of the total average albedo



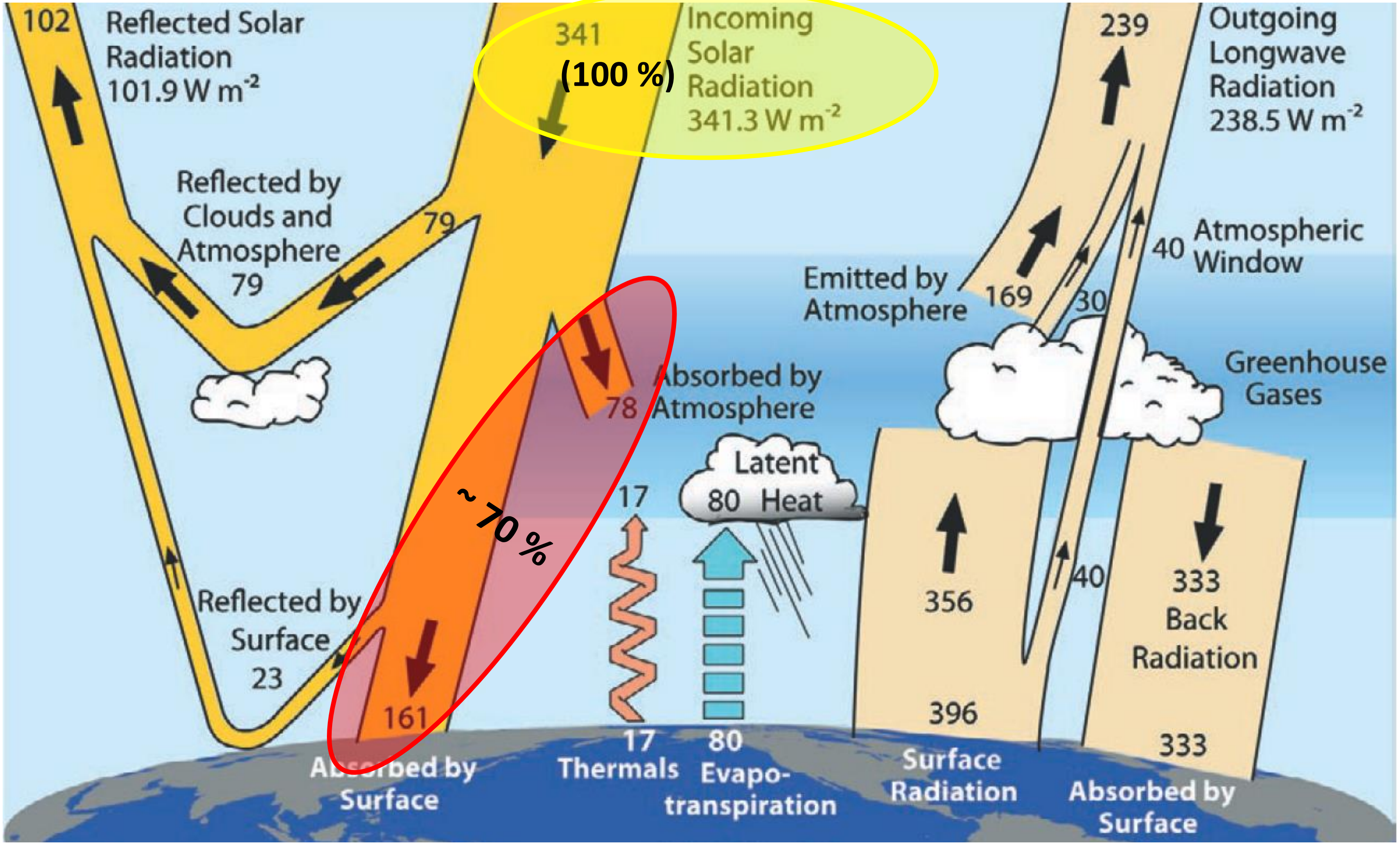
Note: A factor of 5 difference in absorption at the poles compared to the equator

Net Incoming solar radiation at the ToA (~70% of incident solar radiation)



Annual mean net incoming solar radiation at the top of the atmosphere that is absorbed by the Earth (in W m^{-2}). Figure from [Trenberth and Stepaniak (2003)](). Copyright 2003 American Meteorological Society (AMS).

Climate & Earth's annual energy budget



Important Note: Determining exact values for energy flows in the Earth system is an area of ongoing climate research. Different estimates exist, all with some uncertainty. Estimates (of the reflected sunlight and thermal infrared energy radiated by the atmosphere and the surface) come from satellite observations, ground-based observations, and numerical weather models. ***These numbers are from IPCC, 2007, updated with*** ***[Trenberth et al., 2009]***

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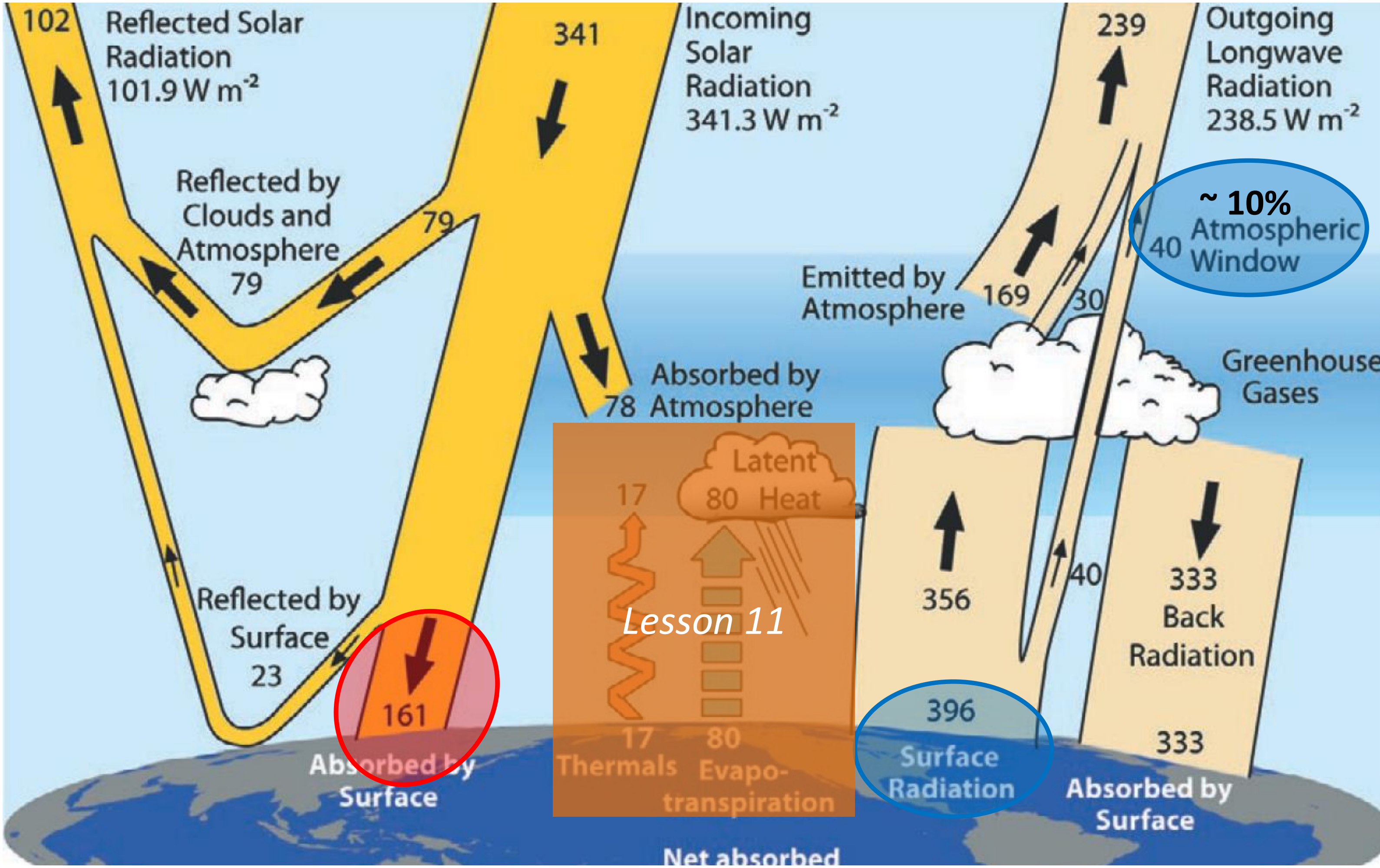

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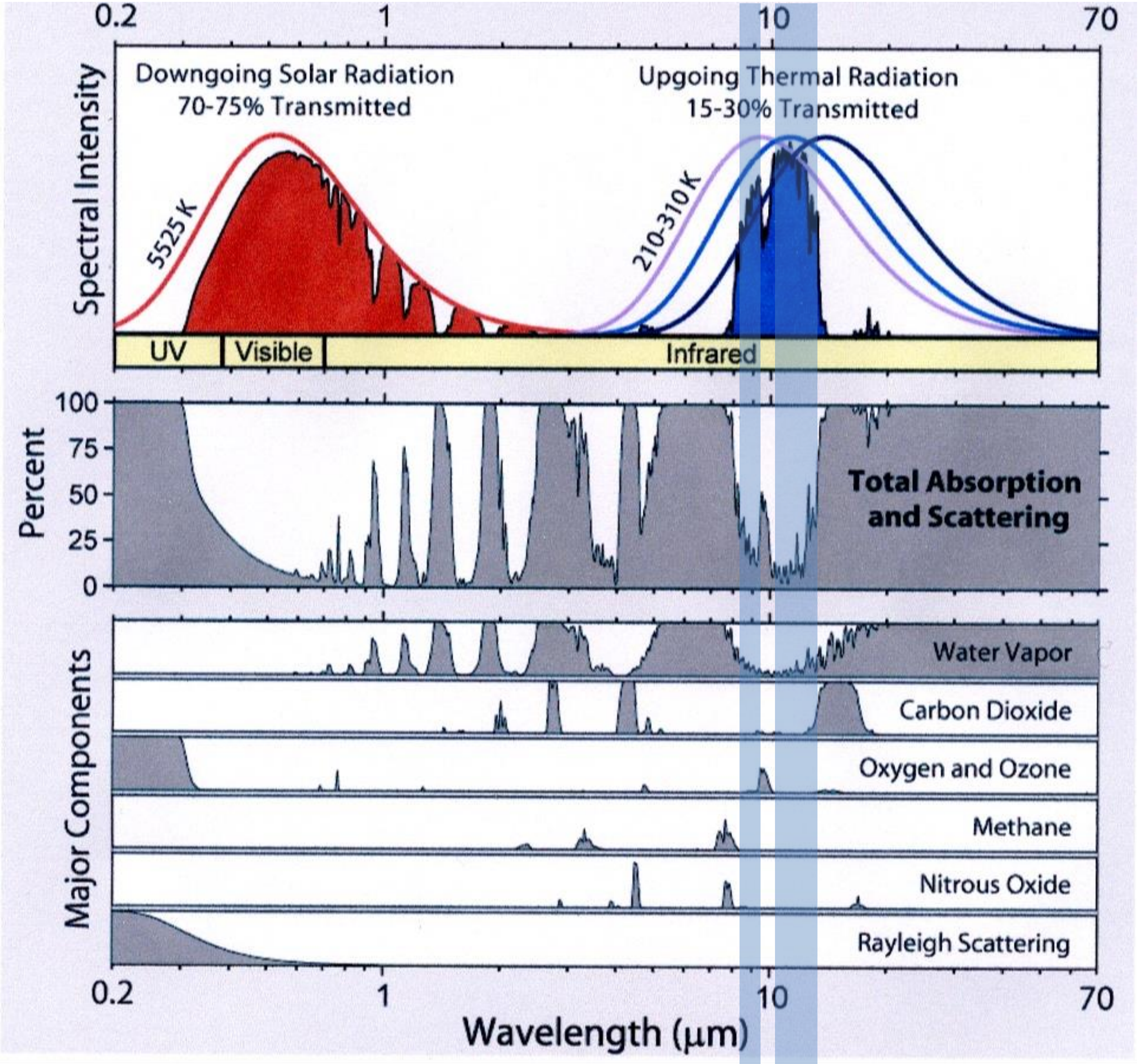
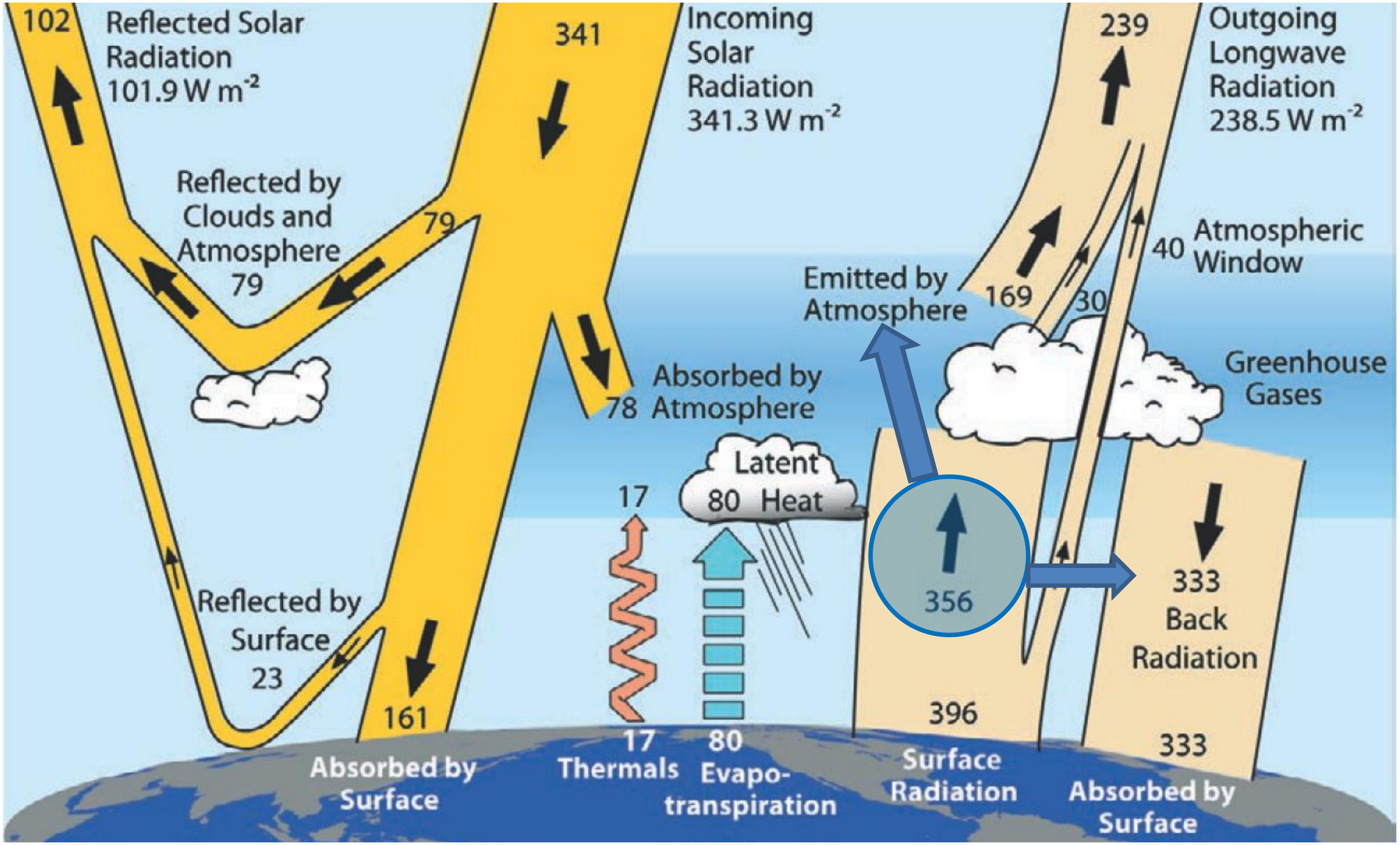
Radiation transmitted by the atmosphere



Modified from Rohde, Global Warming Art, 2007

Climate & Earth's annual energy budget



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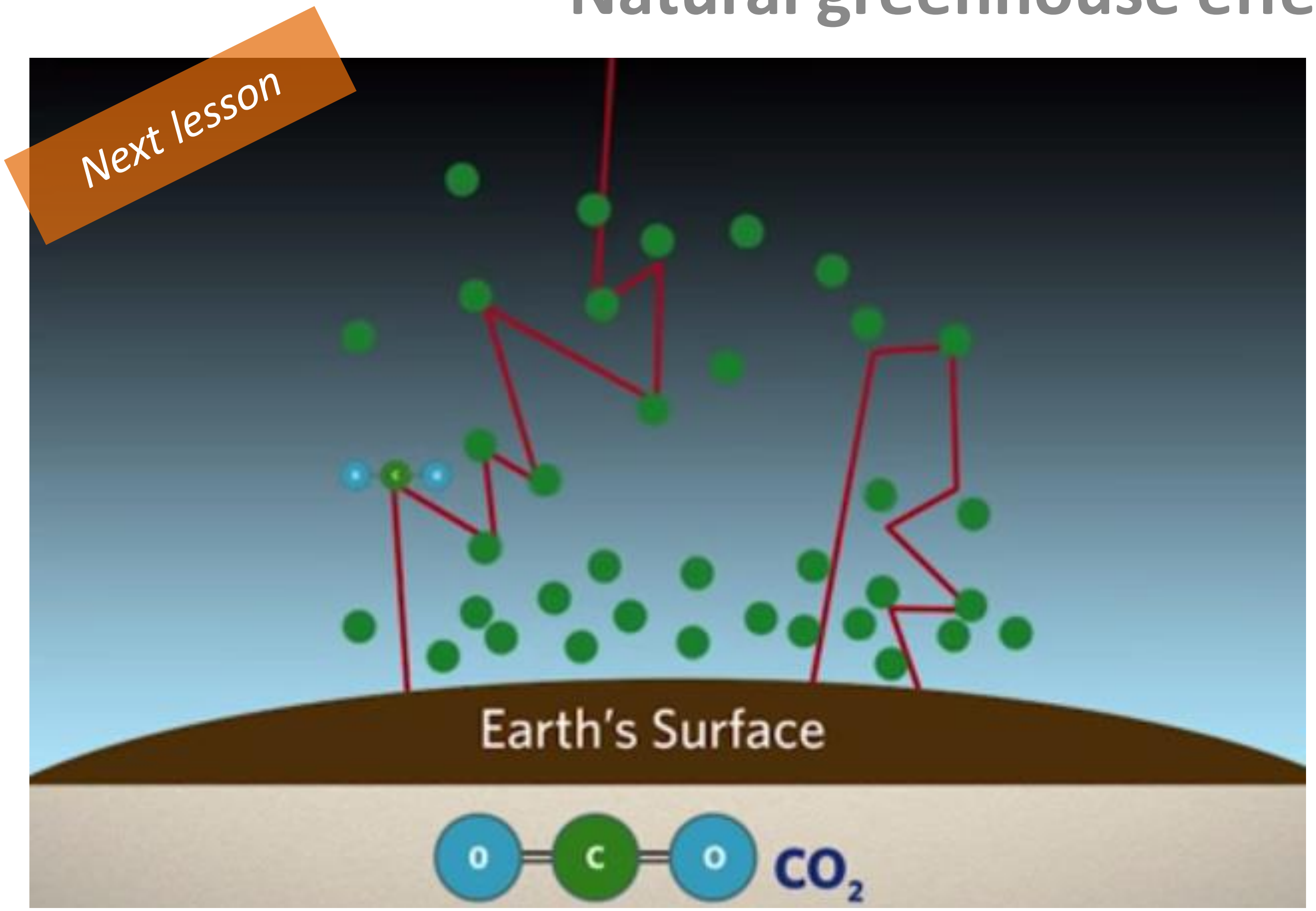
Radiation absorbed by the atmosphere (1)

Natural greenhouse effect

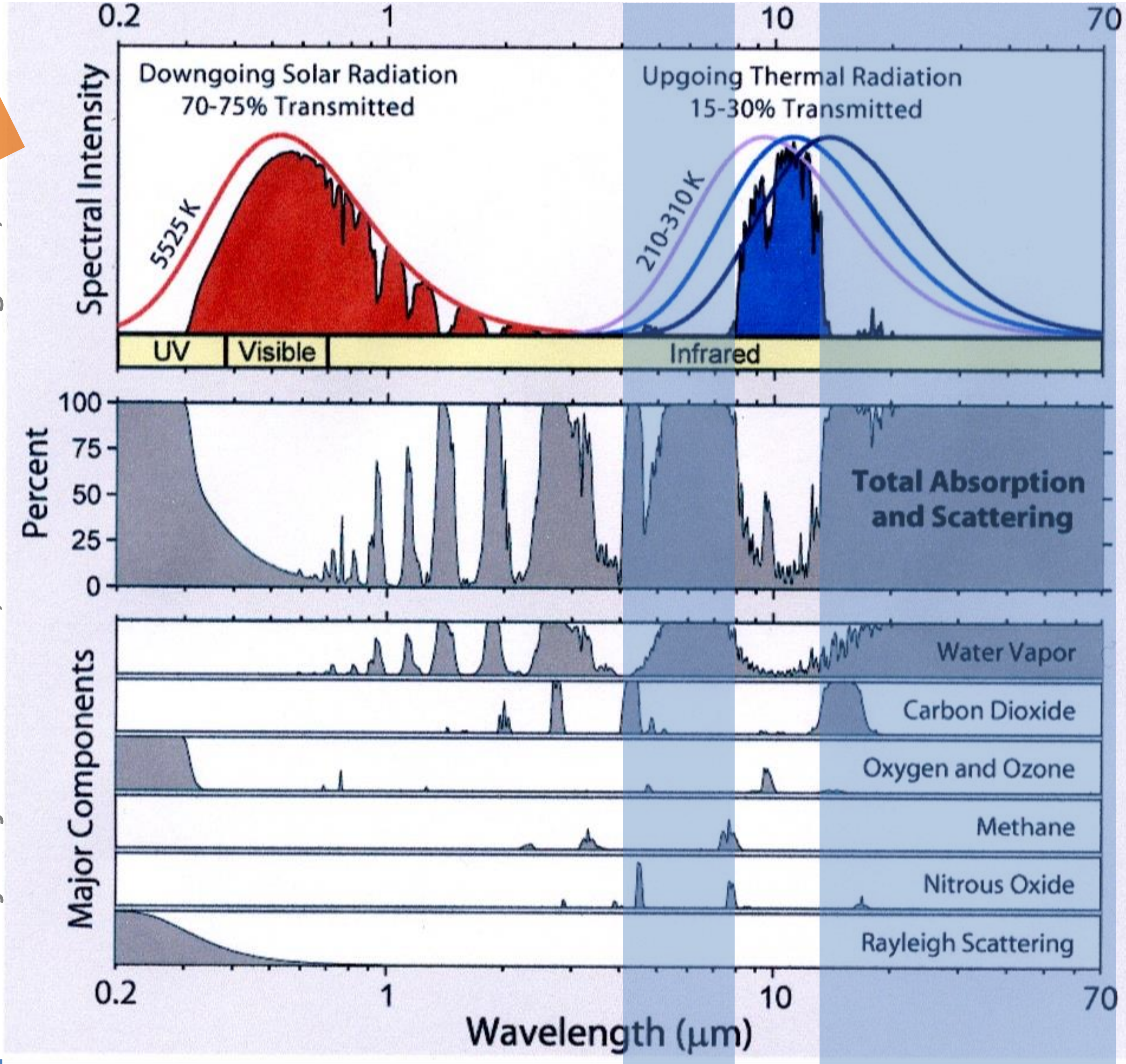


Some atmospheric gases (e.g. CO_2, CH_4, H_2O) absorb terrestrial (long-wave) infrared radiation. Then, their temperature rises and they radiate infrared energy upwards or towards the surface of the earth or at the surface of another gas molecule (and so on). Thus, the earth receives additional amounts of energy (than the solar)

and is habitable, i.e. the atmosphere raises temperature by about 33 °C (from -18 °C at ToA to 15 °C at the its surface)

Radiation absorbed by the atmosphere (1)

Next lesson



Modified from Rohde, Global Warming Art, 2007

Radiation absorbed by the atmosphere (2)

Cloud greenhouse forcing

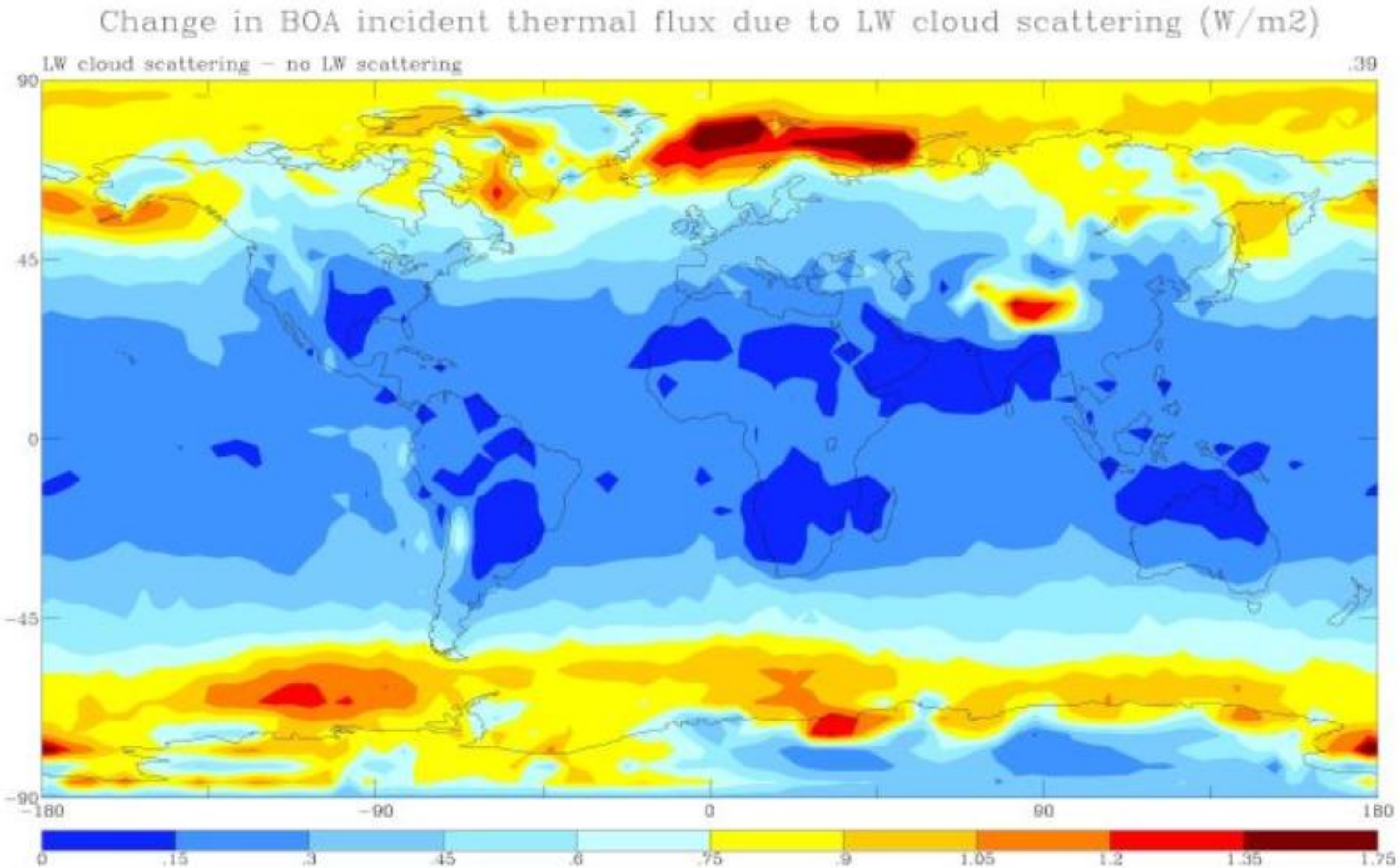
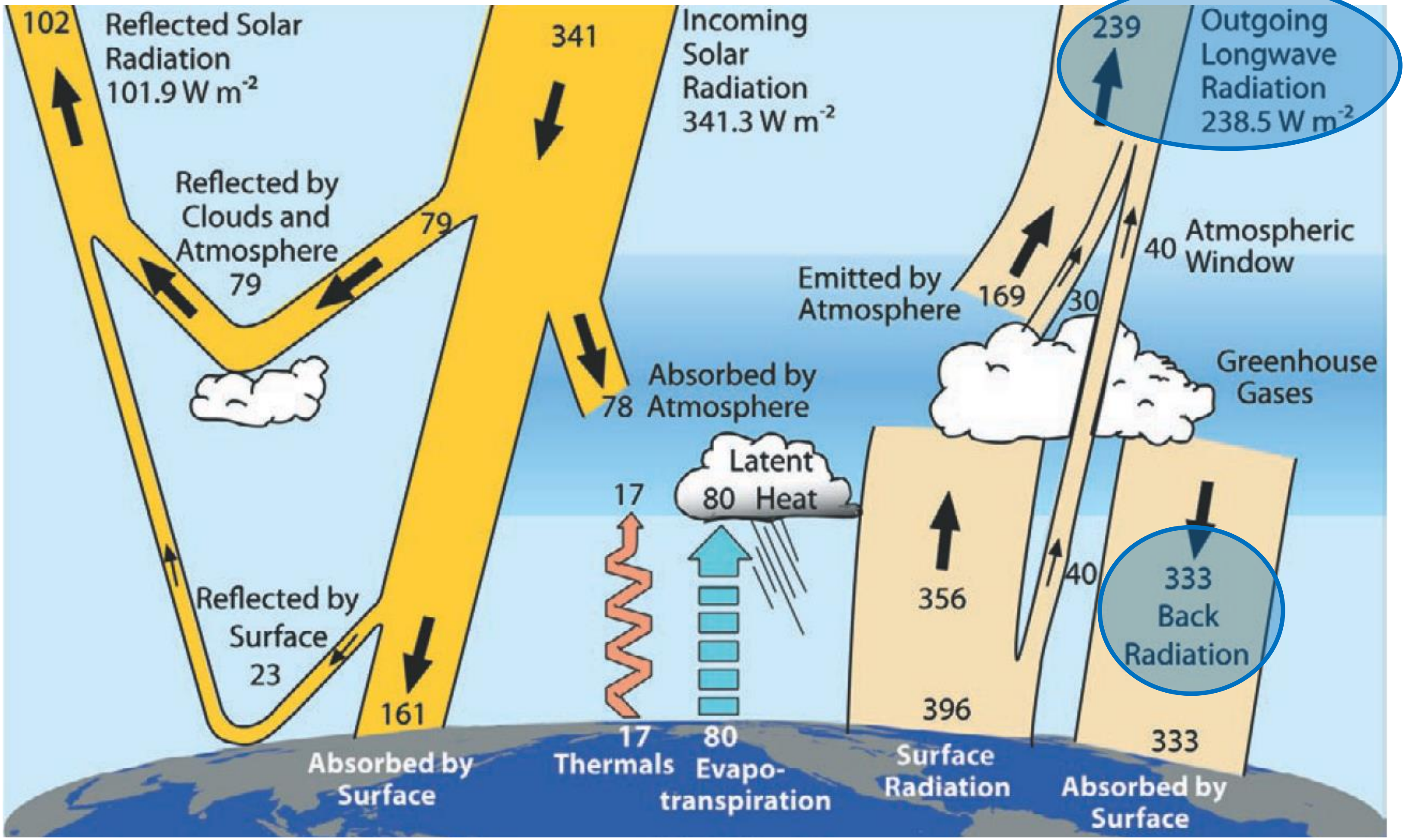


Figure 4. Change in BOA incident thermal flux due to longwave cloud scattering. The BOA fluxes are computed using the standard GISS 4 × 5 GCM control run with the SI200 radiation. Downwelling flux enhancement by downward reflection of upwelling radiation due to the longwave cloud multiple scattering effect is shown as a positive quantity. The global annual mean BOA incident flux increase due to longwave cloud multiple scattering is 0.39 W/m^2.

Climate & Earth's annual energy budget



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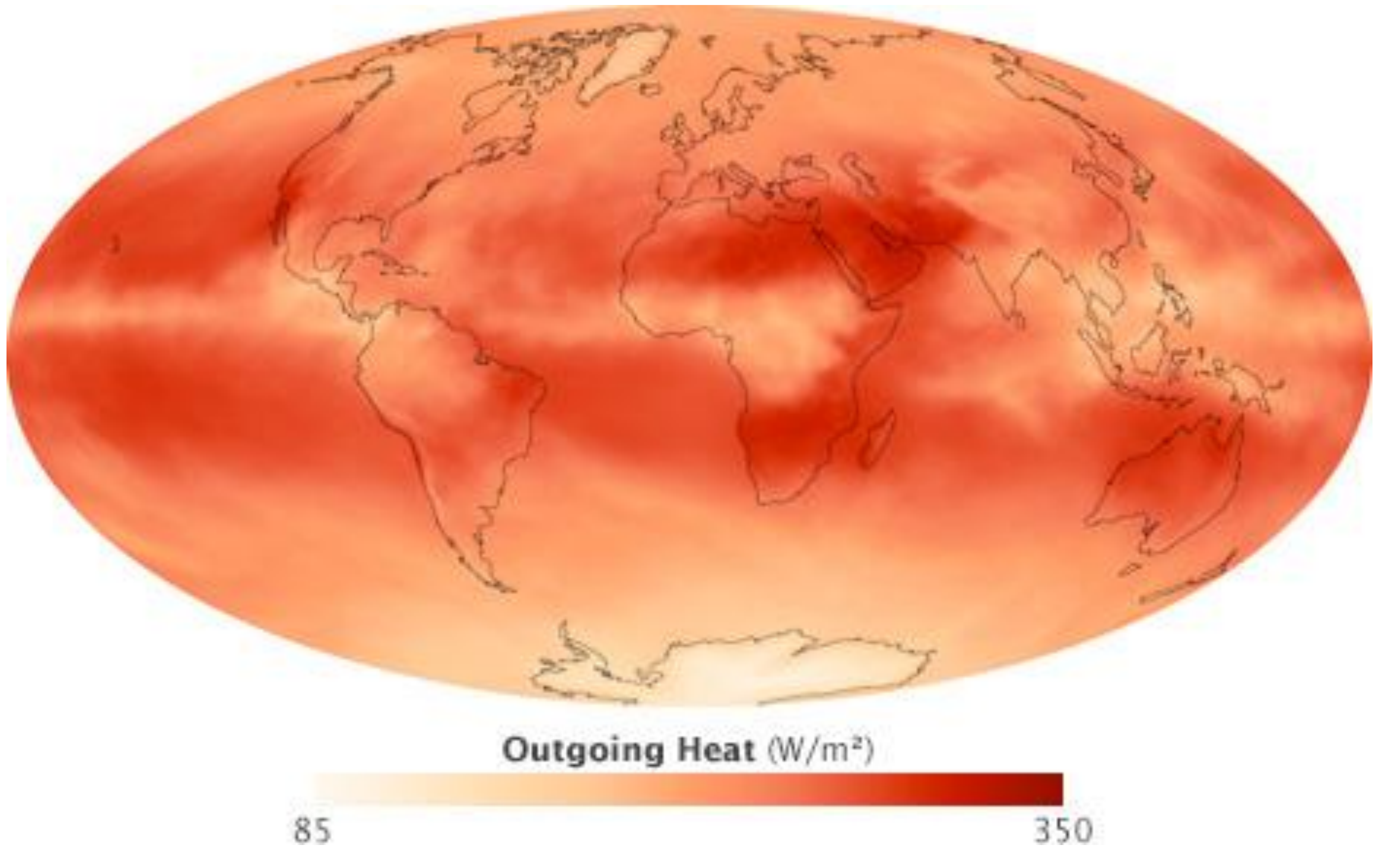
Net Outgoing long-wave radiation at the ToA



Absorbed sunlight is balanced by heat radiated from Earth's surface and atmosphere. This satellite map shows the distribution of thermal infrared radiation emitted by Earth in September 2008. Most heat escaped from areas just north and south of the equator, where the surface was warm, but there were few clouds. Along the equator, persistent clouds prevented heat from escaping. Likewise, the cold poles radiated little heat. (NASA map by Robert Simmon, based on CERES data.)

Key points (4)

- The incident solar radiation (average global value 340 Wm^{-2}) is only partly transmitted downwards. Around 30% is reflected back to space (albedo of the earth) mainly by clouds (~60%), but also by the ground surface and aerosols.

- Most of the incoming solar radiation (~67%) is absorbed by the surface of the earth, which is heated and emits energy by radiation, thermals and evapotranspiration. A small part of the radiative flux (~10%) is transmitted back to space.

- Most of the emitted energy from the surface to the atmosphere (terrestrial/ long-wave/ infrared) is absorbed by certain gases (e.g. CO_2, CH_4, N_2O), which are heated and emit long-wave radiation. By this process (natural greenhouse effect), the Earth becomes habitable with a mean global air temperature of about 15 °C.

- Is the Earth system balanced?

Observing the Earth's energy budget

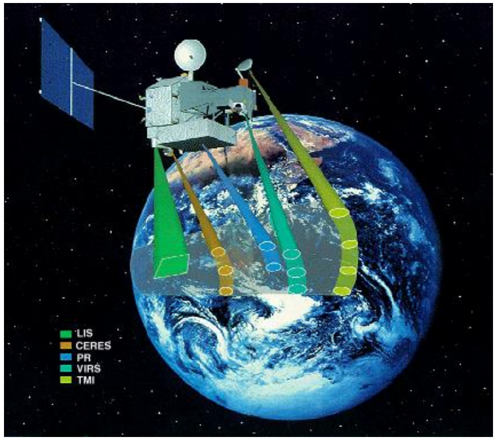
Space applications lessons

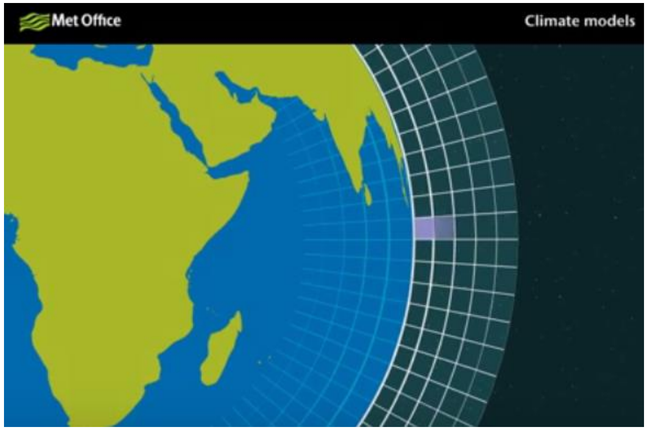
Types of approaches:

Satellite missions: a set of instruments that measure radiative energy flows, are mounted on satellites moving in orbits of different inclination around the Earth.

Numerical models: a set of mathematical and physical equations (including energy flows) that are known to describe the climate system, within each point of an imaginary net (multiple layers of cells) covering the globe (or only specific regions).

Ground-based observations: remote sensing satellite ground stations for radiation measurements





http://apcg.space.noa.gr

UV-MFR instrument for radiation measurements

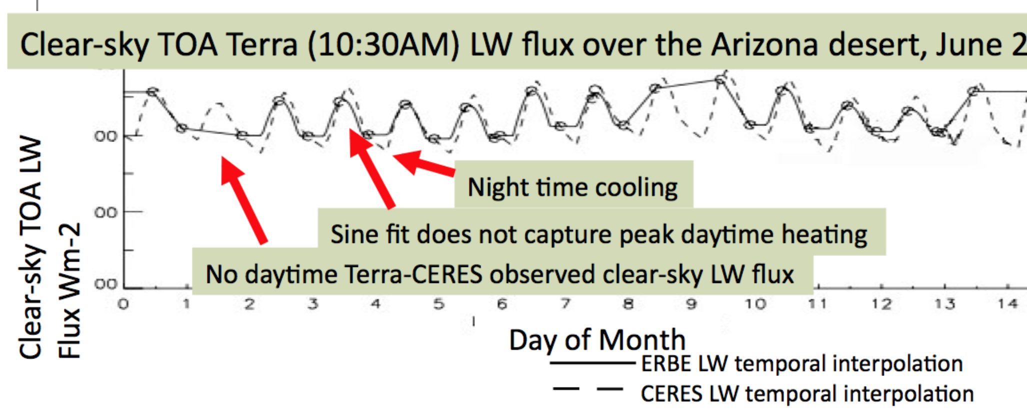
Observing the Earth's energy budget

Big Projects/Experiments:

[ERBE - The Earth Radiation Budget Experiment]: the first multi-satellite mission (three Earth-orbiting satellites); from 1985 to 2005 (1989); operator: NASA

[CERES - Clouds and the Earth's Radiant Energy System]: one of the highest priority scientific satellite instruments developed for NASA's Earth Observing System; 1st launch on 1997; instruments are currently flying on the Terra, Aqua and Suomi-NPP satellites.

Trenberth et al. (2008)
DOI:10.1175/2008BAMS2634.1:
"Some differences arise from real changes in the climate such as changes in albedo from reduced snow and ice cover,
as well as changes in atmospheric circulation and clouds"
"changes in albedo ... arise from the improved CERES instruments and processing"
"Increases in surface evaporation appear to be real"

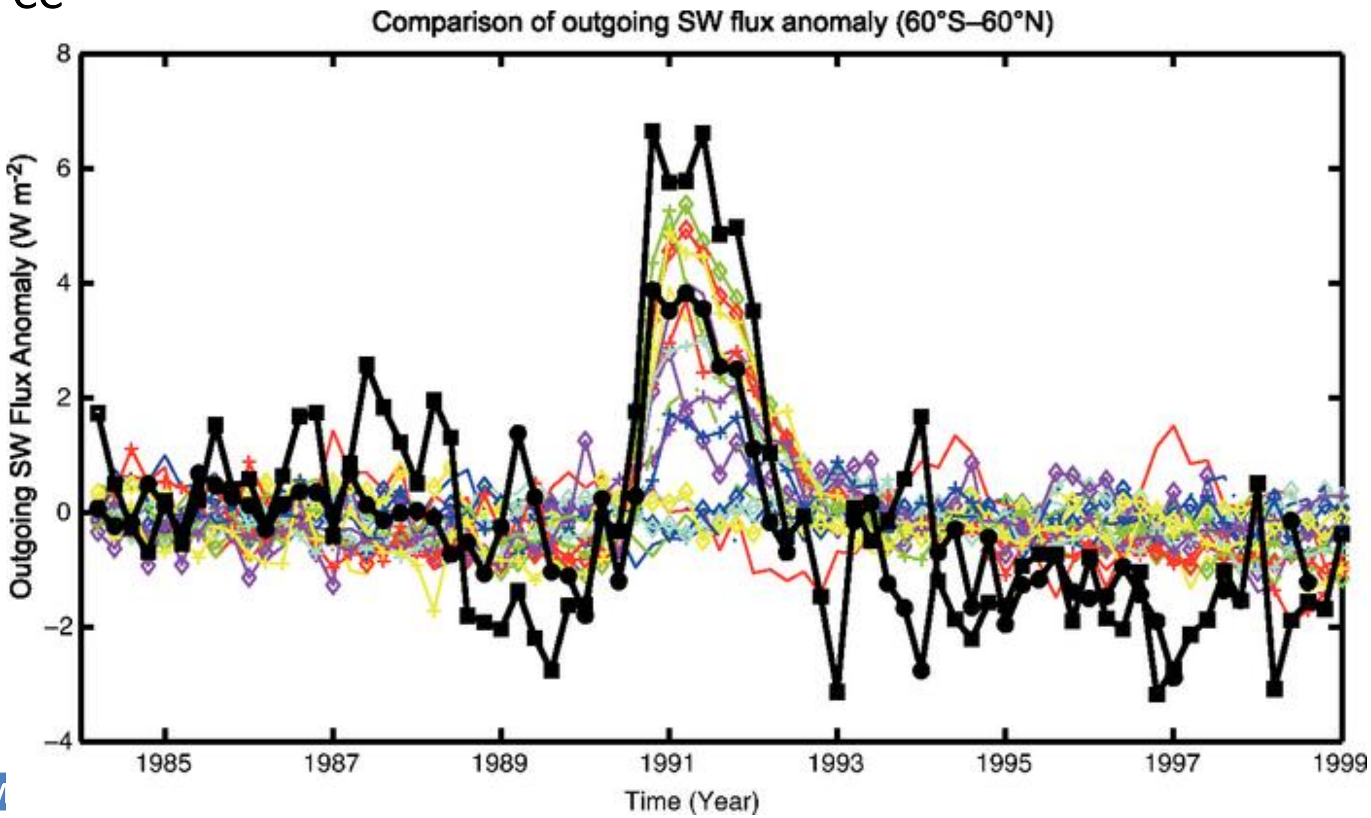


Observing the Earth’s energy budget

Big Projects/Experiments:

PCMDI - Program for Climate Model Diagnosis and Intercomparison: multi-model ensemble of results on climate phenomena; established in 1989 (LLNL, California); extensive analysis of these simulations provide an important scientific basis for the IPCC

Comparison of outgoing shortwave radiation flux anomalies (in W m^{-2}, calculated relative to the entire time period) from several models in the MMD archive at PCMDI (coloured curves) with ERBS satellite data (black with stars; Wong et al., 2006) and with the ISCCP flux data set (black with squares; Zhang et al., 2004). The comparison is restricted to 60°S to 60°N because the ERBS data are considered more accurate in this region.

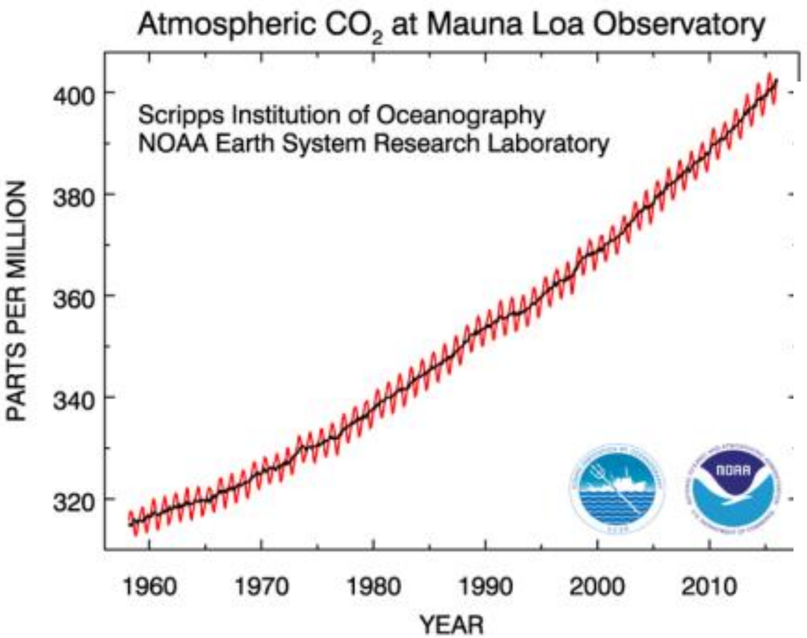


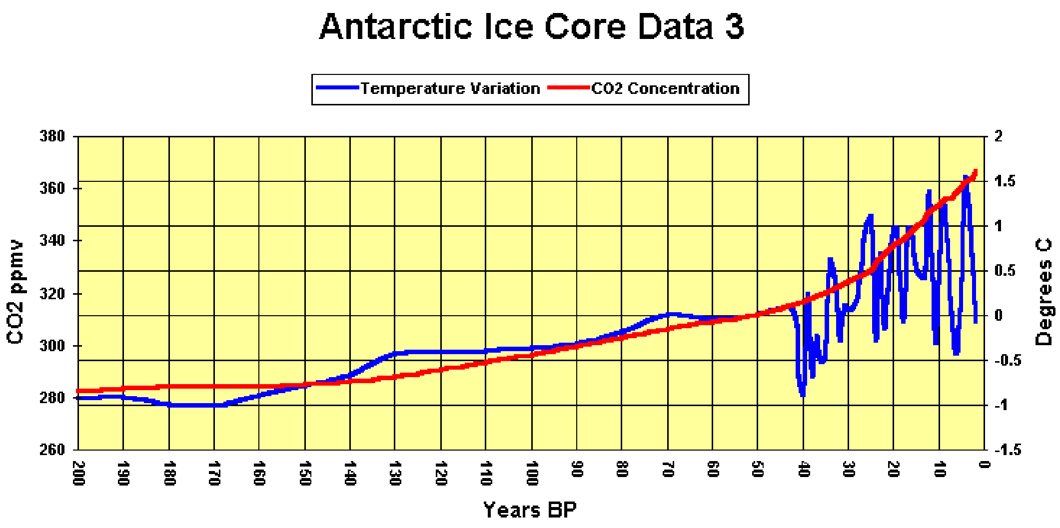
Observing the Earth's energy budget

Big Projects/Experiments:

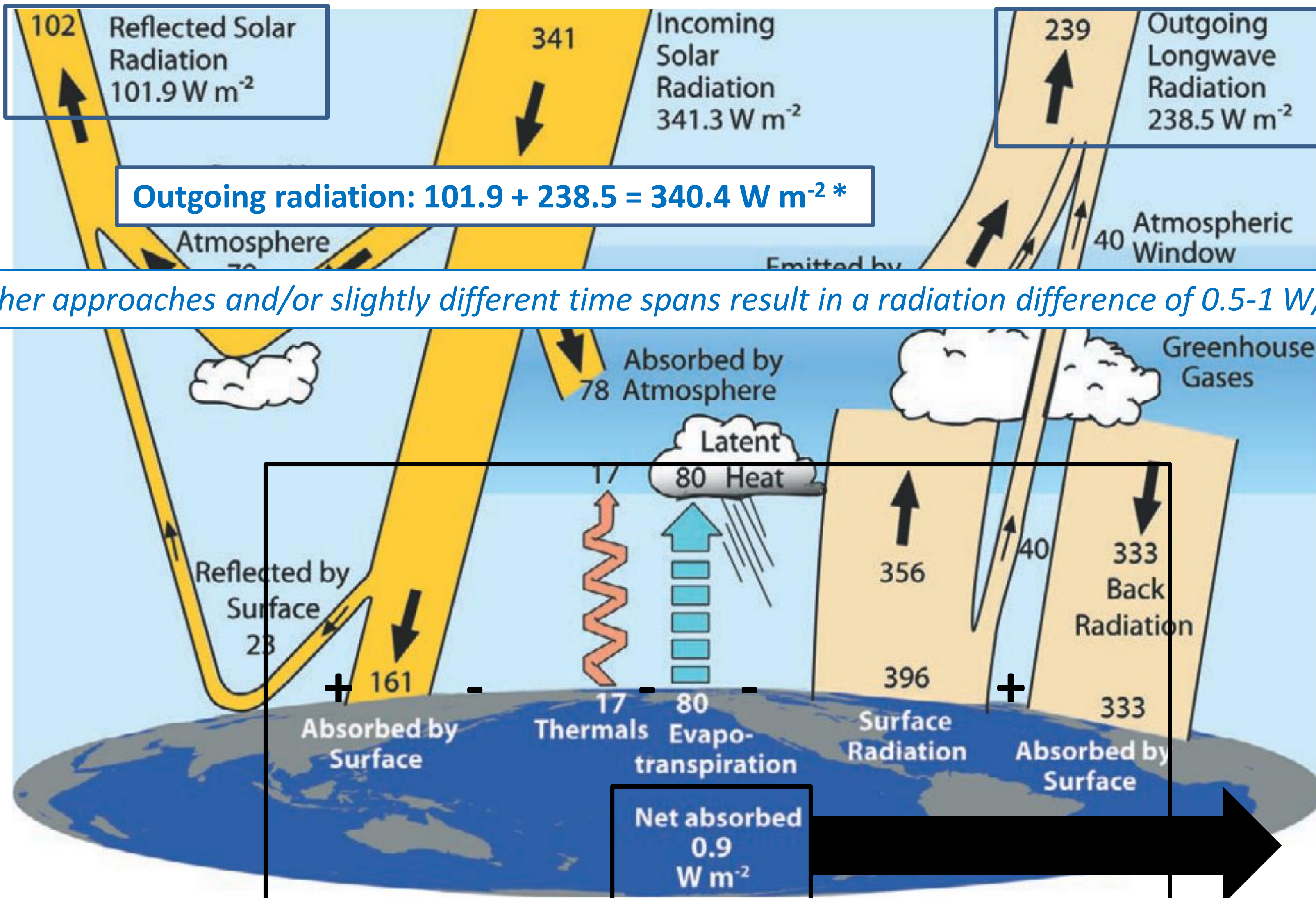
* MLO - Mauna Loa Hawaii Observatory: is a premier atmospheric research facility that monitors gases and radiation since the 1950's; The undisturbed air, remote location, and minimal influences of vegetation and human activity are ideal for studying climate change.

* West Antarctic Ice Sheet (WAIS) Divide: greenhouse gases (CO2), temperature etc. measurements during glacial and interglacial periods; since 2005; a paleoclimate record





Earth's energy budget: balance /imbalance

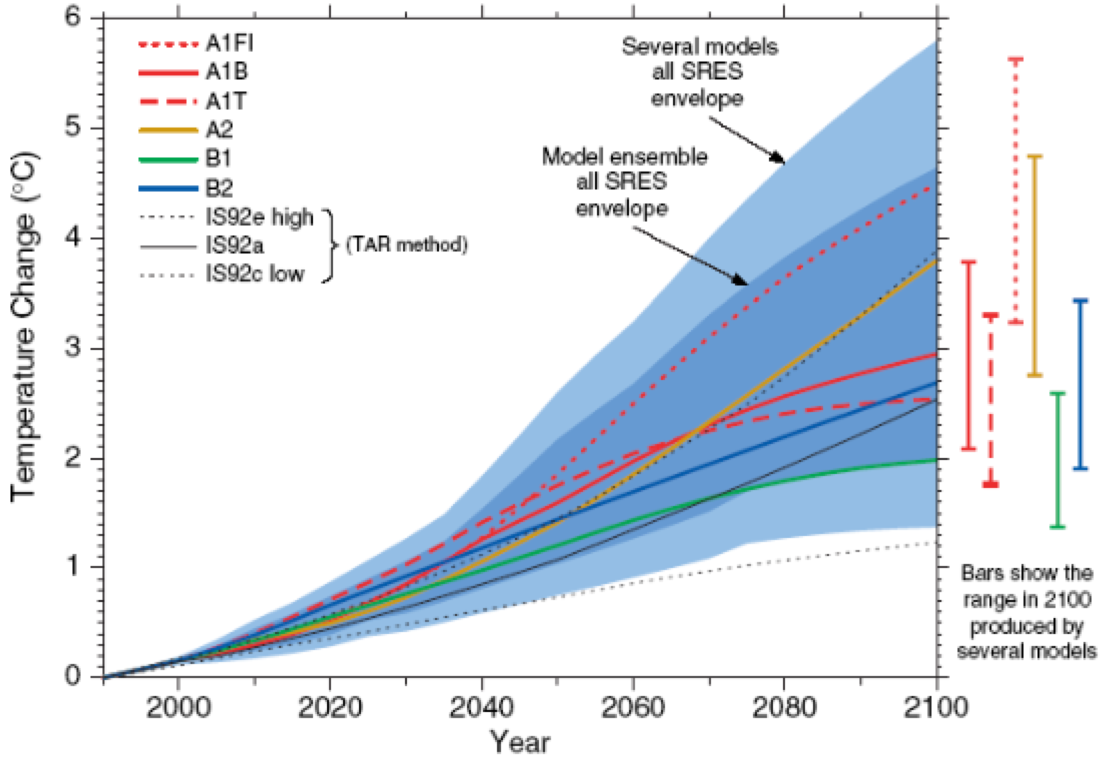


Outgoing radiation: 101.9 + 238.5 = 340.4 W m^{-2} *

** other approaches and/or slightly different time spans result in a radiation difference of 0.5-1 W/m^2*

Temperature change due to the imbalance in the Earth's energy budget

FUTURE TEMPERATURE PROJECTIONS
FROM CLIMATE MODELS (IPCC, 2001)

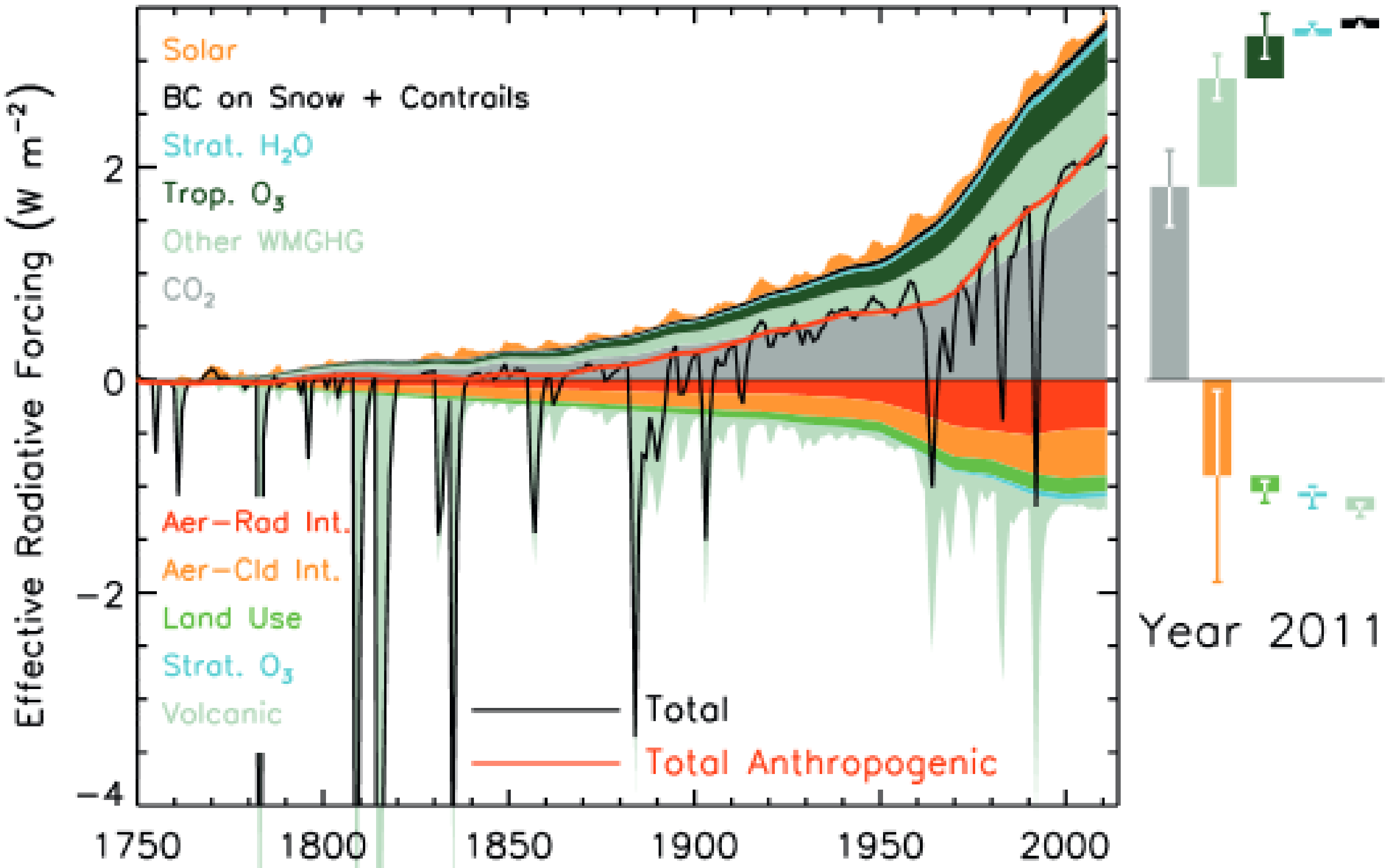


Previous lesson

Key points (5)

- Big satellite experiments continuously observe the incoming and outgoing global radiation fluxes with decreasing uncertainties
- Ground-based measurements of greenhouse gases and surface temperature give knowledge about their temporal variation from the past and up to now
- Independent climate model runs and climate model ensembles are verified by measurements and predict the future climatic conditions
- The Earth system is imbalanced, thus the mean global atmospheric temperature increases
- Why the Earth system is imbalanced?

Variations/Forcings in the Earth's energy budget



Source: http://www.climatechange2013.org/images/report/WG1AR5_Chapter08_FINAL.pdf

Variations/Forcings in the Earth’s energy budget

1. Natural influence: Solar luminosity

Nature **443**, 161-166 (14 September 2006) | doi:10.1038/nature05072

Variations in solar luminosity and their effect on the Earth's climate

P. Foukal[1], C. Fröhlich[2], H. Spruit[3] & T. M. L. Wigley[4]

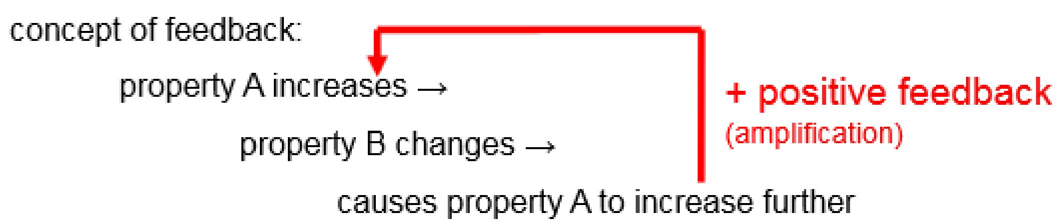
Variations in the Sun's total energy output (luminosity) are caused by changing dark (sunspot) and bright structures on the solar disk during the 11-year sunspot cycle. The variations measured from spacecraft since 1978 are too small to have contributed appreciably to accelerated global warming over the past 30 years. In this Review, we show that detailed analysis of these small output variations has greatly advanced our understanding of solar luminosity change, and this new understanding indicates that brightening of the Sun is unlikely to have had a significant influence on global warming since the seventeenth century. Additional climate forcing by changes in the Sun's output of ultraviolet light, and of magnetized plasmas, cannot be ruled out. The suggested mechanisms are, however, too complex to evaluate meaningfully at present.

Top

Variations/Forcings in the Earth's energy budget

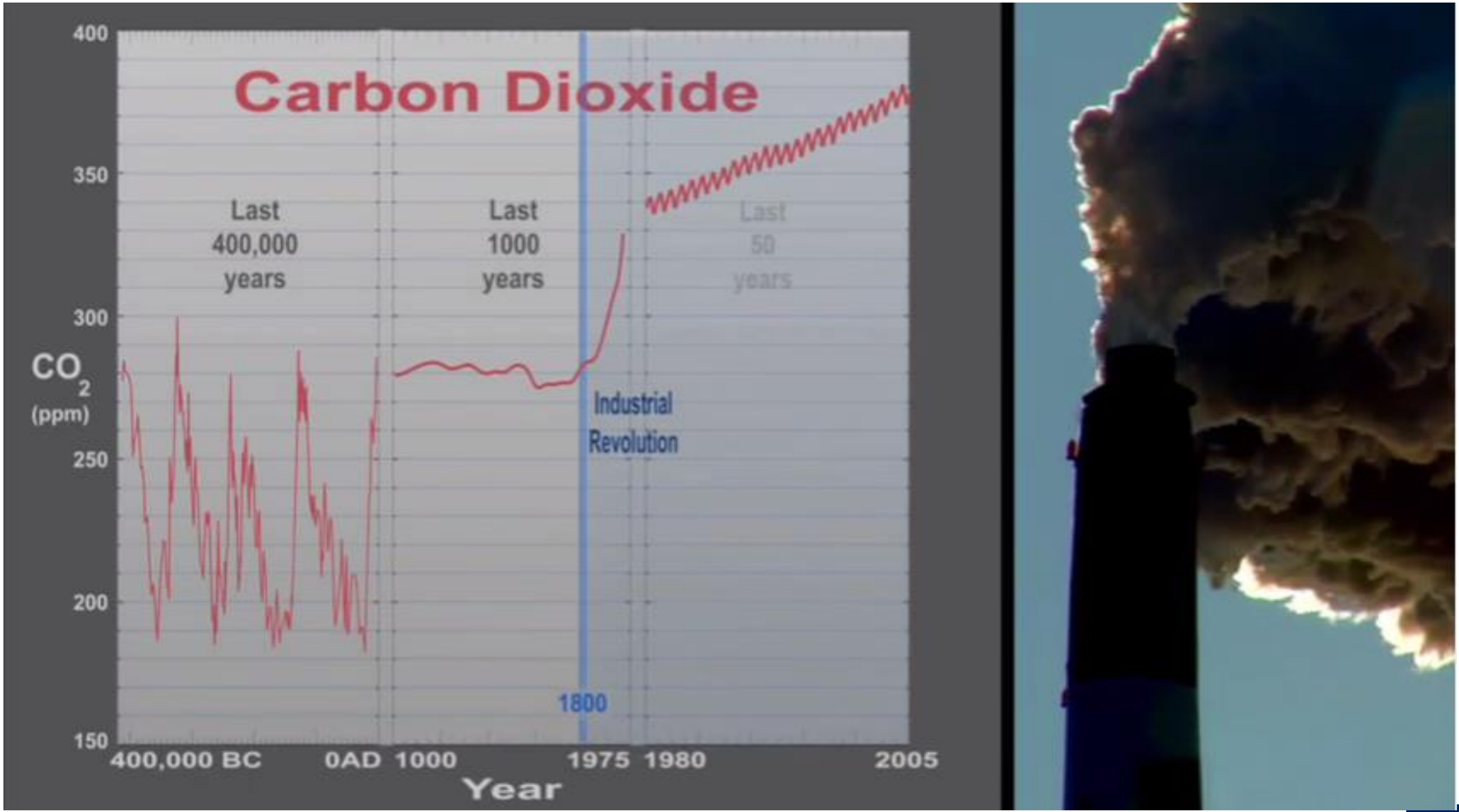
2. Natural influence: Incident solar radiation

When the earth is closer to the sun, it is warmer,
Release of CO_2 from the ocean to the atmosphere
The exchanges of energy between air – sea differentiate
Changes in the sea ice (melting) , biosphere (deforestation)
The air temperature is further increased



Variations/Forcings in the Earth's energy budget

3. Anthropogenic influence: Industrial revolution



Variations/Forcings in the Earth's energy budget

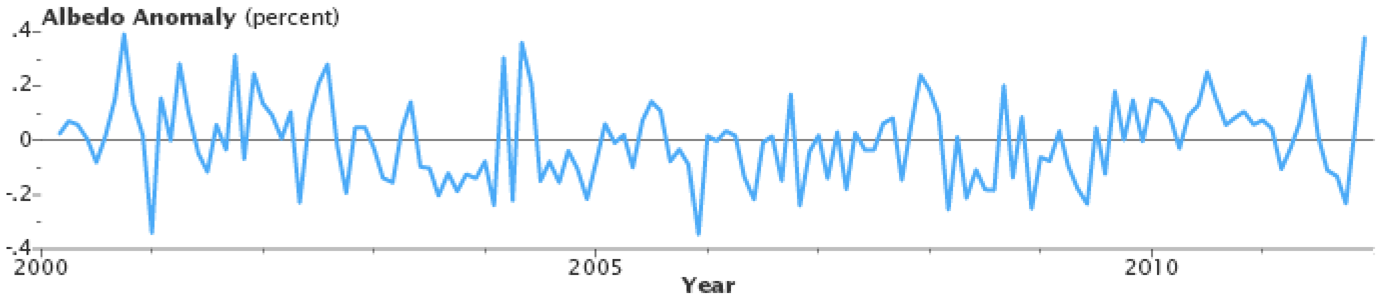
4. Anthropogenic influence: changes in the earth's reflectivity (albedo)

Taken across the planet, no significant global trend appears

BUT

At the North Pole, reflectivity decreased markedly, a result of the declining sea ice on the Arctic Ocean and increasing dust and soot on top of the ice

an increase in reflectivity in the western tropical Pacific and reduced reflectivity in the central Pacific—patterns consistent with a shift from El Niño to La Niña



Variations/Forcings in the Earth's energy budget

5. Atmospheric aerosols and global radiation

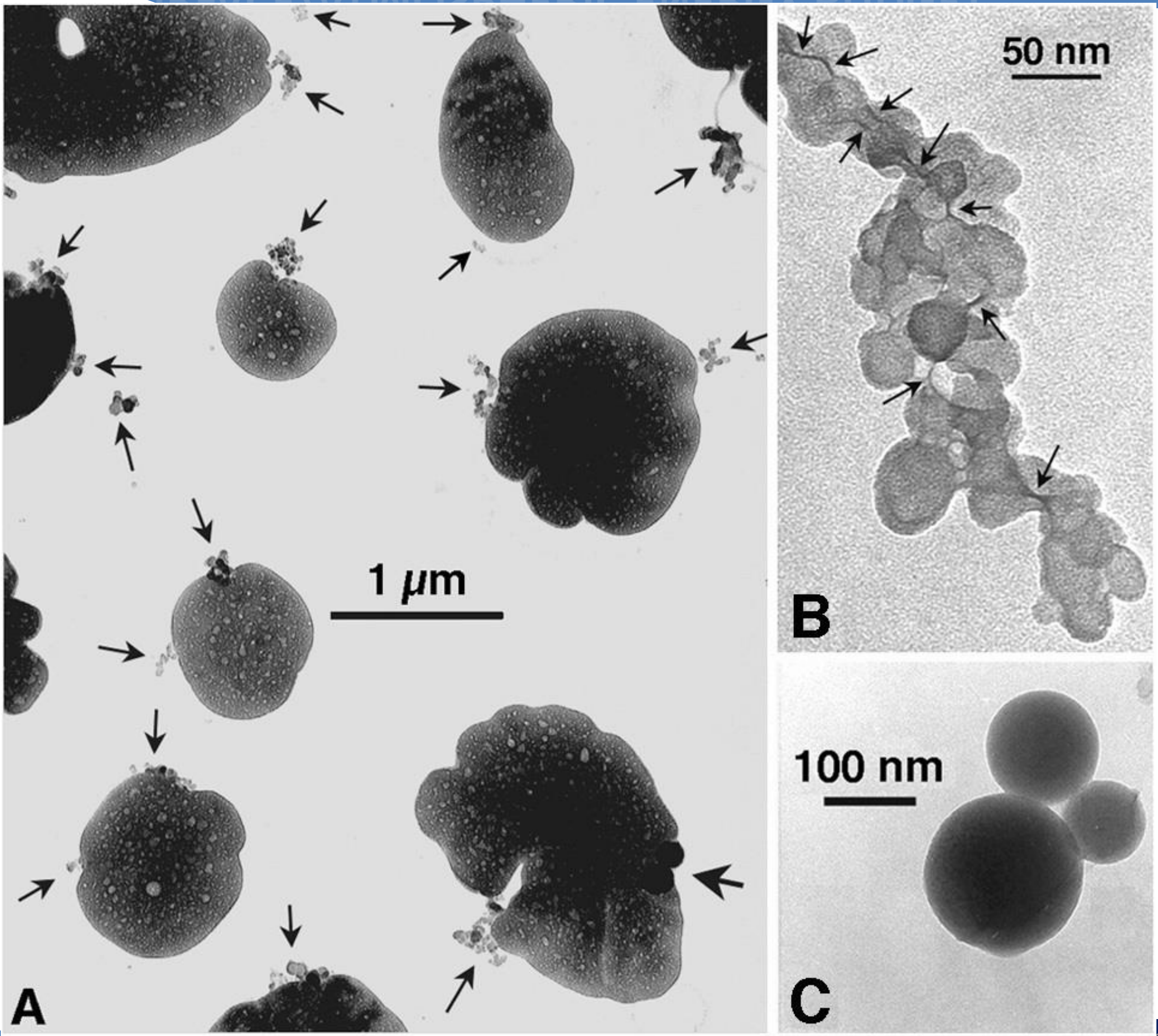
Aerosols are suspended particles in the air which are small enough to resist gravitational sedimentation (i.e. they remain afloat despite the force of gravity acting on them).

Aerosols can be solid, liquid, or a combination of both. They typically range in size from 0.1 to 10.0 micrometers. (PM10).

The main sources of aerosols are dust from the land surface (e.g. deserts), sea surface (liquid droplets and solid sea-salt particles), volcanoes, forest fires, and anthropogenic combustion.

Effects on radiation:
Directly reflect, scatter, absorb (mainly) sunlight
Indirectly affect the reflectance, scattering and absorption of clouds.

Small soot and sulfate aerosols are seen in these microscope slides. Trapped in the atmosphere, these tiny particles can have an important effect on climate.
Credit: Mihály Pósfai, Arizona State University



Variations/Forcings in the Earth's energy budget

5. Atmospheric aerosols and global radiation

<u>Effects on radiation</u>:
Directly reflect, scatter, absorb (mainly) sunlight
Indirectly affect the reflectance, scattering and absorption of clouds.

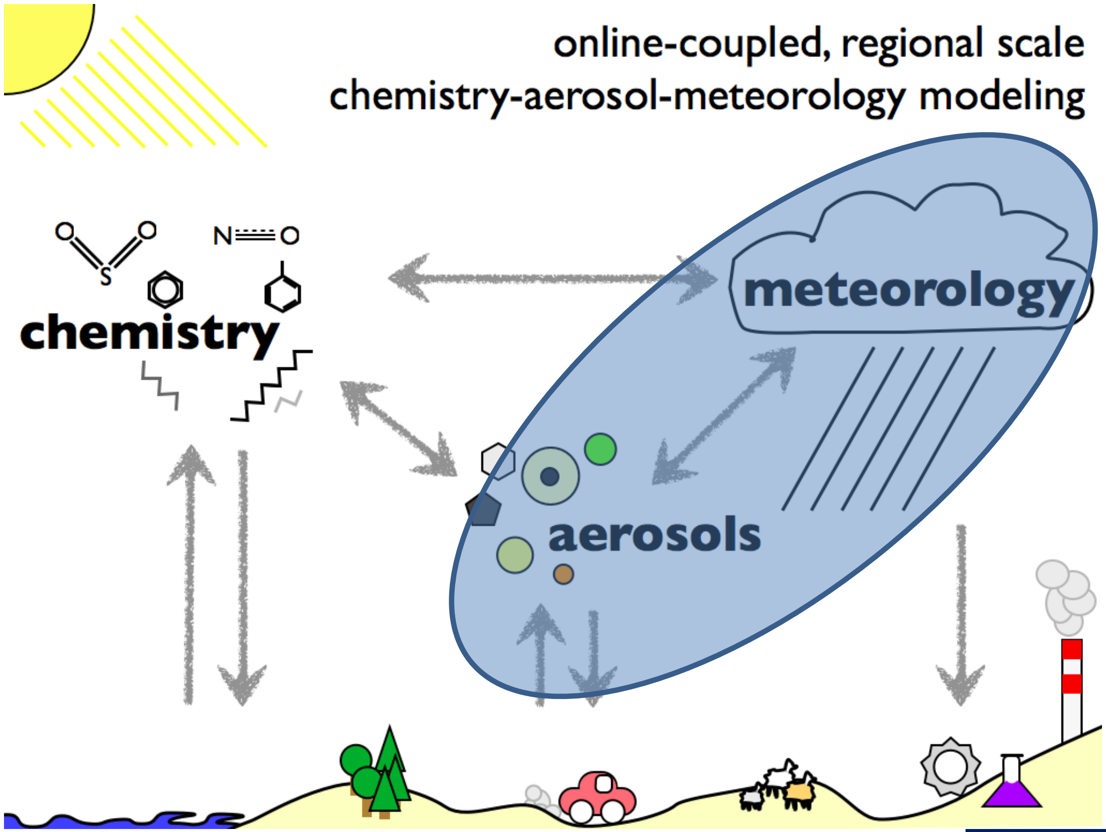
Key points (6)

- The energy and temperature of the Earth system can be influenced by several (*natural* and/or anthropogenic) parameters and processes:
- *Solar luminosity (changes in the incoming solar radiation)*
- *The distance of Sun – Earth (increase in CO_2 levels)*
- Changes in Earth's reflectivity (changes in the incoming solar radiation)
- Industrial revolution (increase in CO_2 levels)
- Aerosol radiative forcing (changes in the incoming solar radiation)
- How the different chemical components/types of aerosols affect the radiative budget of the earth?
- Which is the total (and total anthropogenic) radiative forcing of the Earth now?

Modelling the radiative forcing of aerosols

Simulated atmospheric processes:

Emissions (natural & anthropogenic)
Atmospheric chemistry
Transport
Interaction with radiation
Interaction with clouds
Deposition



Modelling the radiative forcing of aerosols

Simulated atmospheric processes:

B. Vogel et al.: The comprehensive model system COSMO-ART

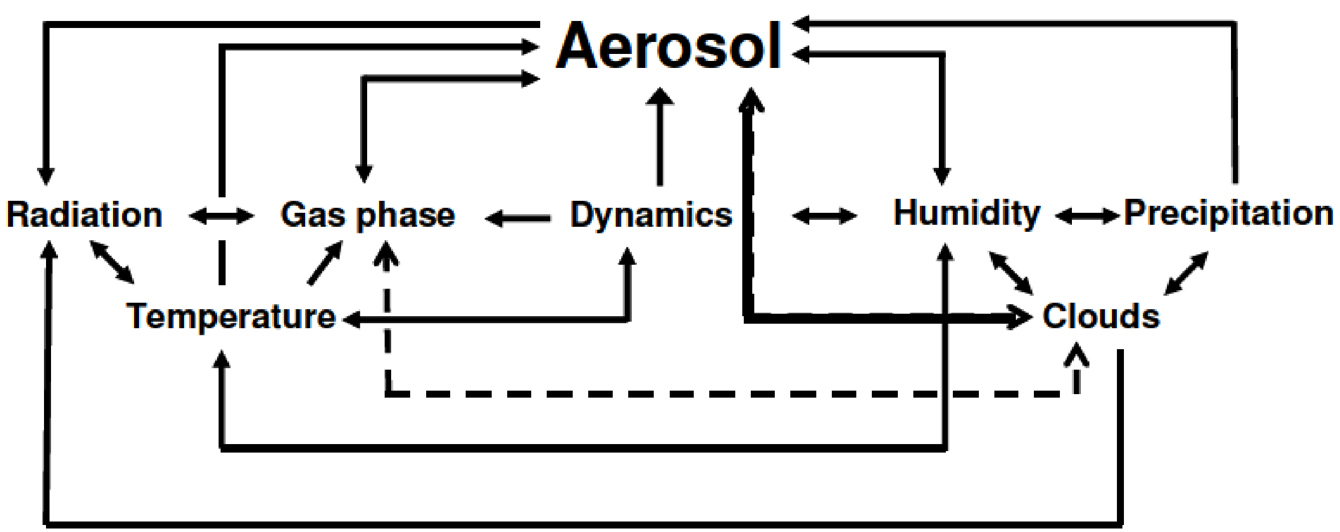
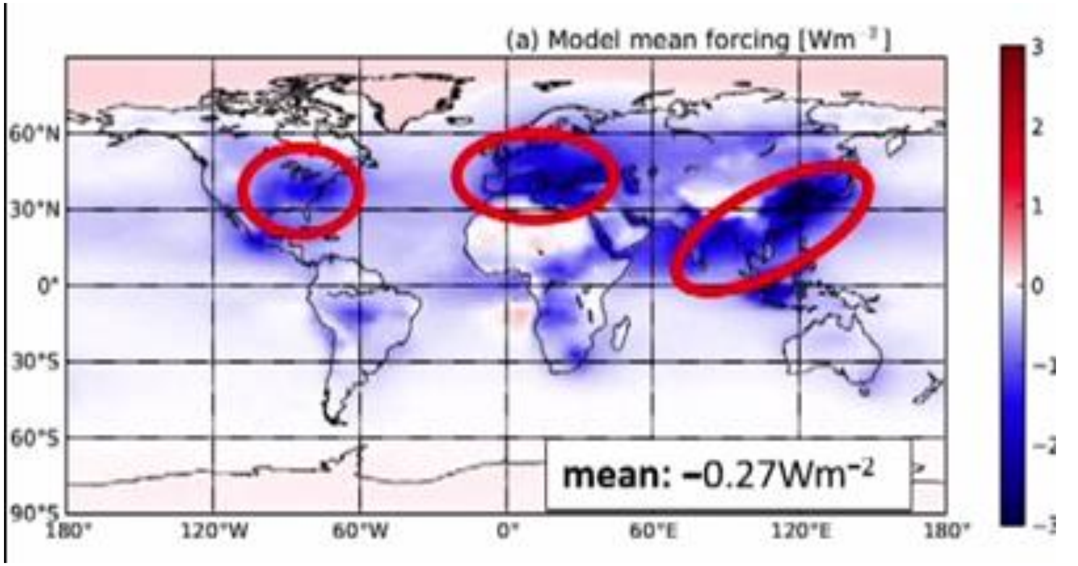


Fig. 3. Feedback processes that are included in the model runs. The dashed lines indicate interactions that are not taken into account.

Modelling the radiative forcing of aerosols

Simulated atmospheric processes:

Emissions (natural & anthropogenic)
Atmospheric chemistry
Transport
Interaction with radiation
Interaction with clouds
Deposition



AEROCOM phase II (ensemble of 16 models)
Highest direct aerosol forcing for densely populated areas

Approaches:

from simple climatologies to
Interactive schemes (large CPU time)

Indirect effects of aerosols on radiation are prone to large uncertainties

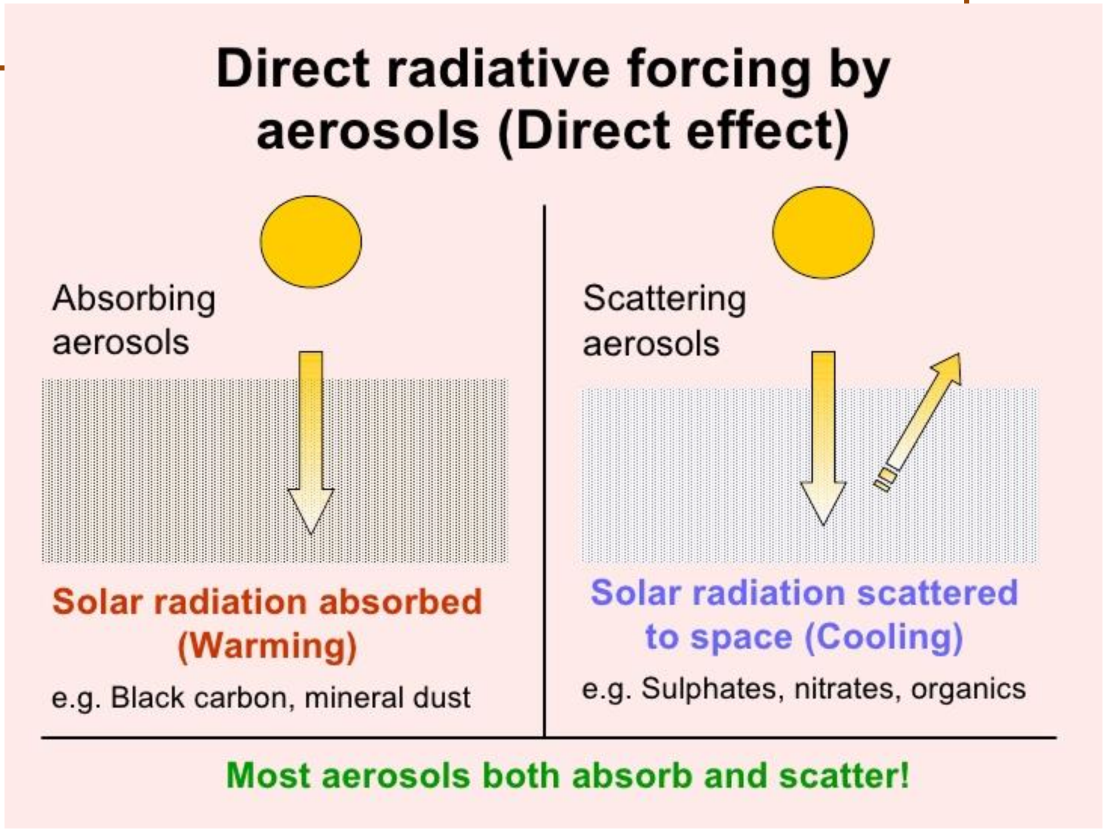
Direct radiative forcing of aerosols

Direct effect:

aerosols scatter (mainly) sunlight, increasing albedo, cooling the atmosphere (on the global scale).

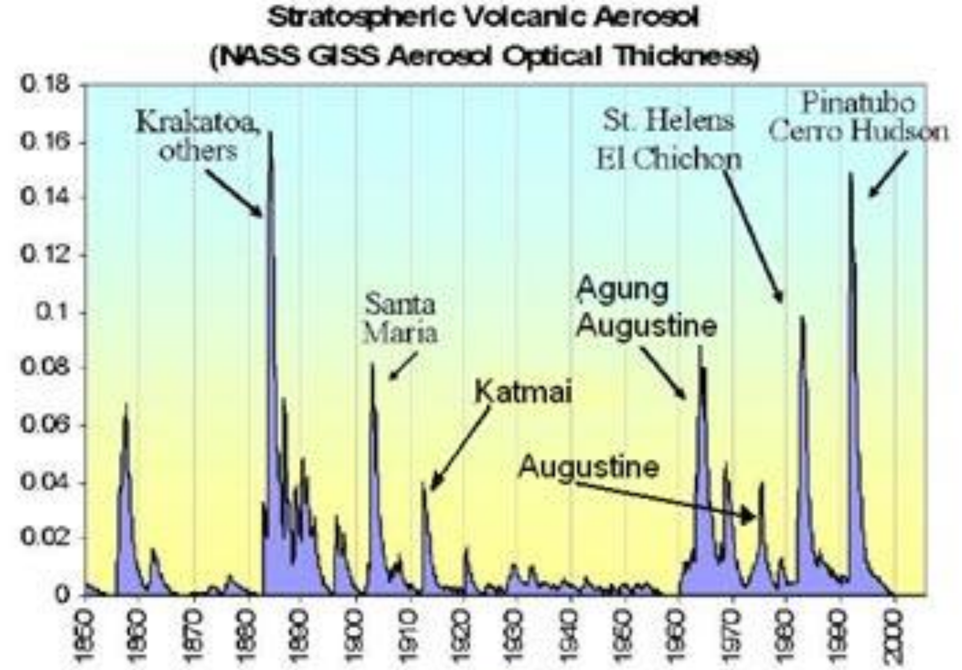
Black carbon effect:

if aerosols have black carbon (soot) inside, they can be heated by sunlight, warming the atmosphere (on the local scale).



i. Direct radiative forcing of VOLCANIC aerosols

Volcanic eruptions can inject millions of tons of dust and gaseous sulfur dioxide into the stratosphere, which evolves to sulfate aerosols, i.e. effective scatterers of solar radiation.



Volcanic aerosols in the high atmosphere block solar radiation and increase cloud cover leading to widespread cooling, especially significant in summer

i. Direct radiative forcing of VOLCANIC aerosols

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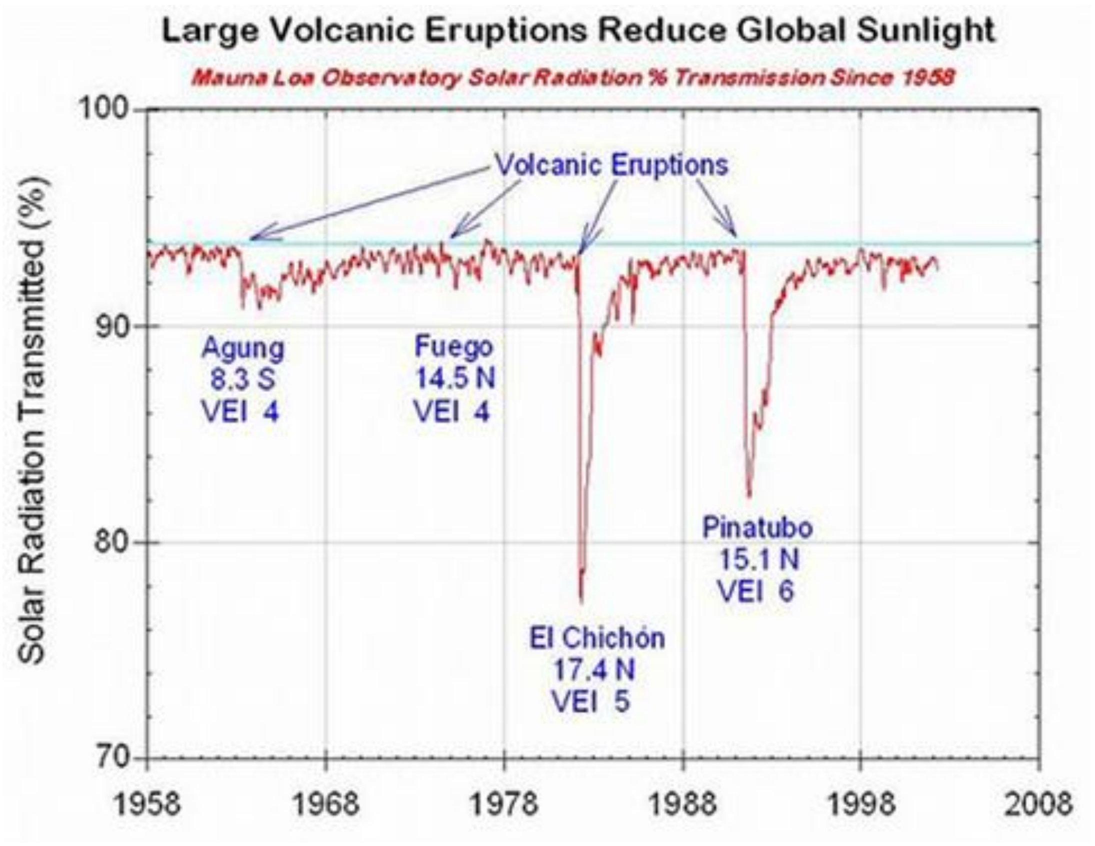
Mount Pinatubo 1991:

20 millions tons SO_2

20-30 % decline in the solar radiation reaching the surface of the earth

0.5 °C drop in average global air temperature



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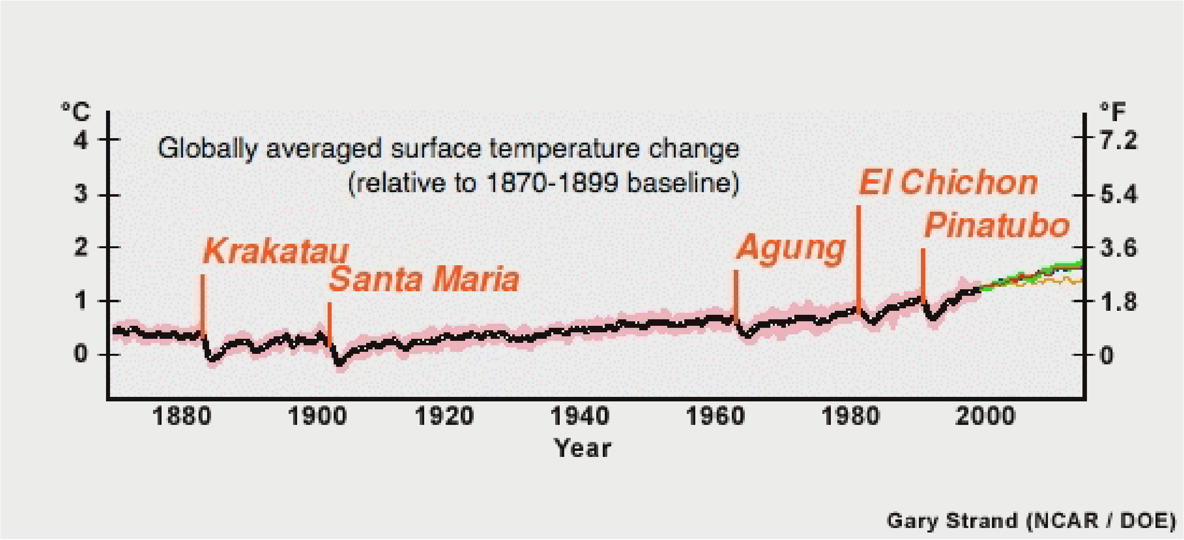
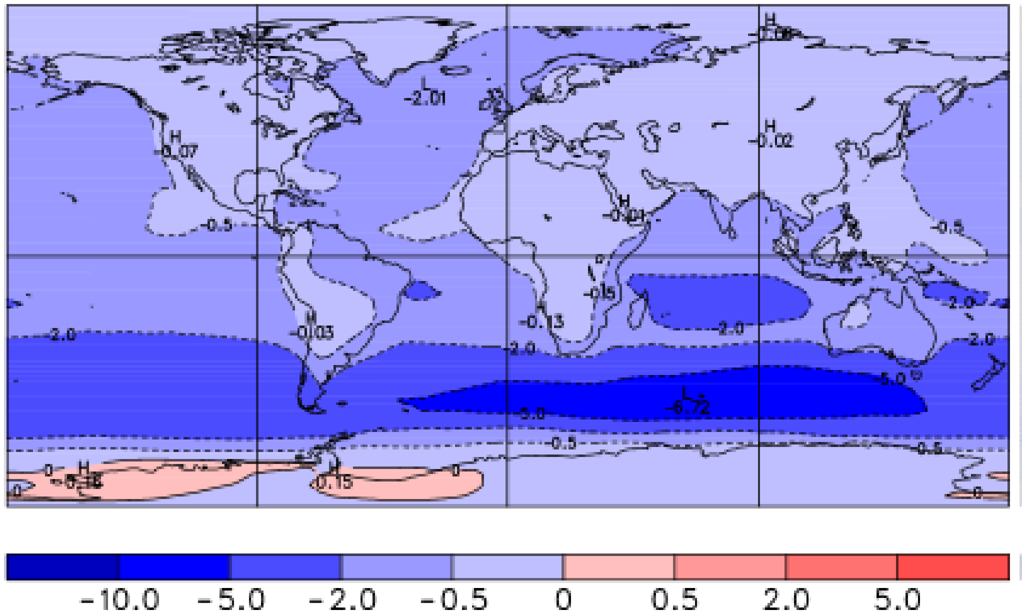


ii. Direct radiative forcing of SEA-SALT aerosols

The sea salt aerosol is non-absorbing in the visible region with a single scattering albedo close to unity and partly absorbing in the long wave region.

Sea-salt dominates the light extinction in remote marine environments.

Geo-engineering: Among proposed mechanisms for counteracting global warming through solar radiation management is the deliberate injection of sea salt acting via marine cloud brightening and the direct effect of sea-salt aerosols.



Seasonal mean global distributions of sea salt forcing for clear sky columns in the simulations for June–August (JJA) (Ma et al., 2008)

iii. Direct radiative forcing of BIOMASS BURNING aerosols

"Summer 2007 reflects the daily T_{max} that are projected to occur in the **latter part of the 21st century**"
Founda & Giannakopoulos., 2009

"This period was an **all time record hot summer,** combined with a prolonged drought period and strong winds" *Founda & Giannakopoulos., 2009*

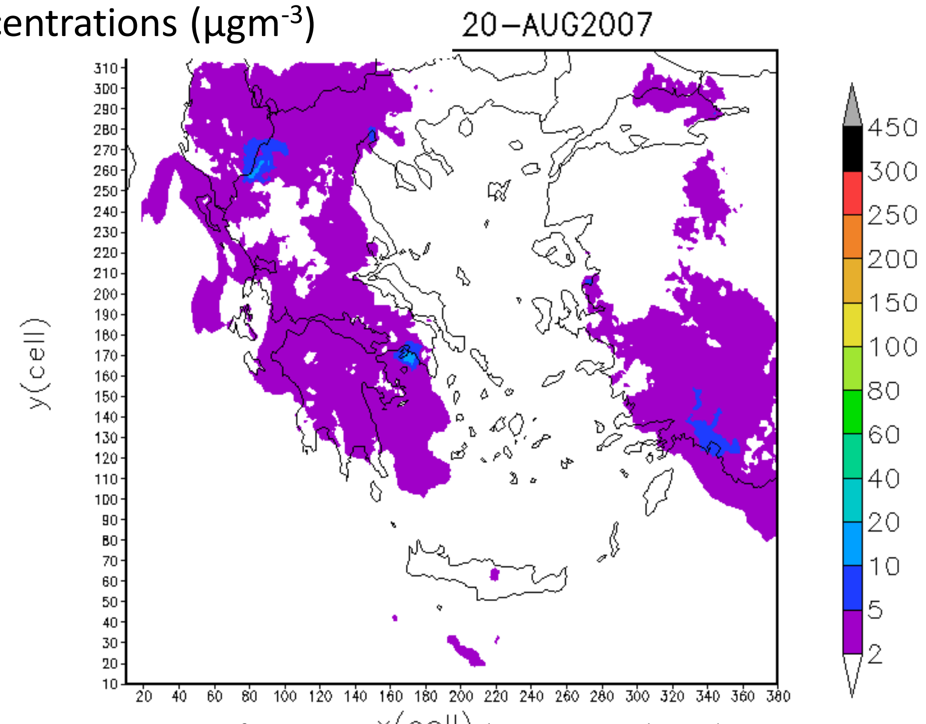
"**64 people** lost their lives"
Founda & Giannakopoulos., 2009

"**2700 km²** of forest, olive groves and farmland were destroyed by the fires"
Liu et al., 2009

"Greece suffered the **worst forest fires** in the past 50 years"
Liu et al., 2009

iii. Direct radiative forcing of BIOMASS BURNING aerosols

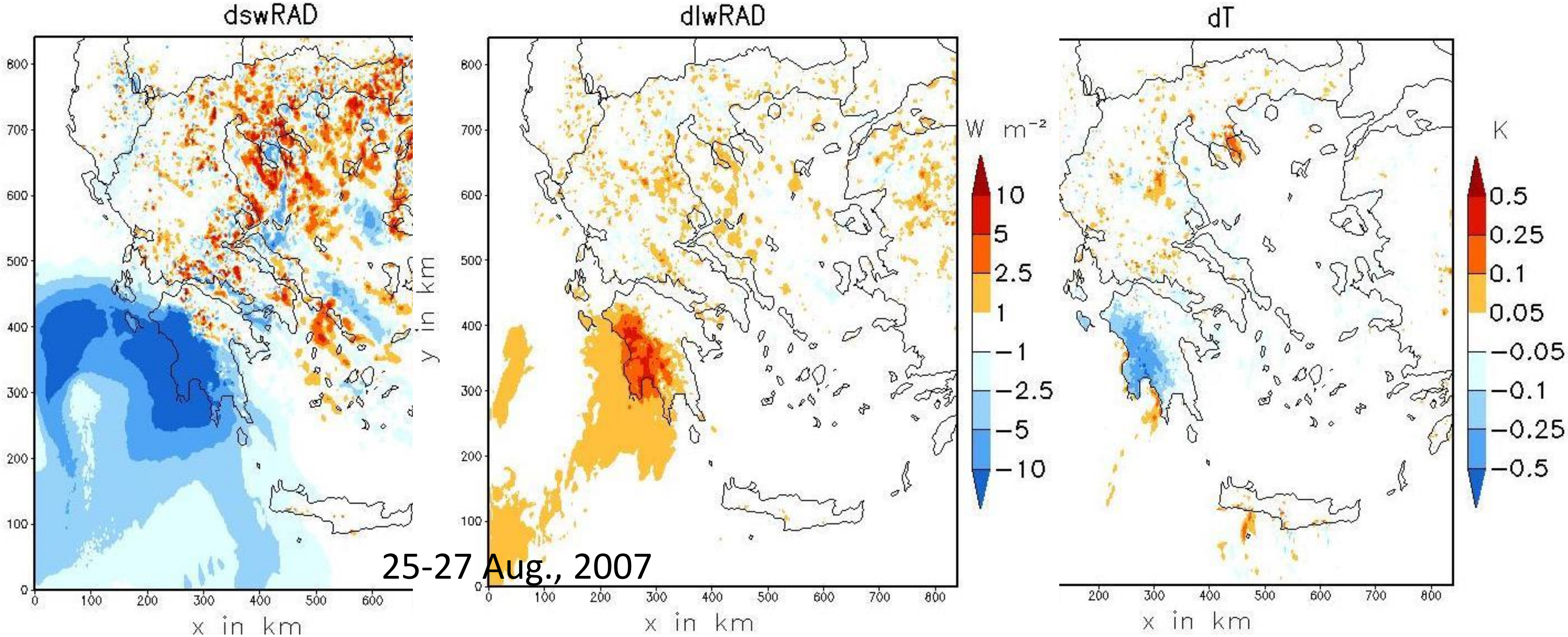
Daily average Total Carbon concentrations (μgm^{-3})



- **OC** increases 15 to 60 times over fire spots (Euboea and Peloponnese, respectively).
- The fire-induced aerosols reach the area during the peak fire period and account for the 45% of total surface **PM$_{10}$** (and 5% during Sept.,1).
- Secondary **inorganic aerosols** are also affected, but their increases are small in absolute numbers (3-day-average value up to +2 μgm^{-3}).

Athanasopoulou et al., 2014, Atmos. Environ.

iii. Direct radiative forcing of BIOMASS BURNING aerosols



- The **short-wave** radiative forcing at the surface is negative, reaches -20 (-50) W m^{-2} (hourly) over the fire spots and decreases down to 5-20 (10-50) W m^{-2} downwind.
- The positive forcing on the net upward **long-wave** flux, is +10 W m^{-2}.
- These changes modify the diabatic heating of the atmosphere by **-0.5 (-5) K** at 2m above surface

Athanasopoulou et al., 2014, Atmos. Environ.

iv. Direct radiative forcing o

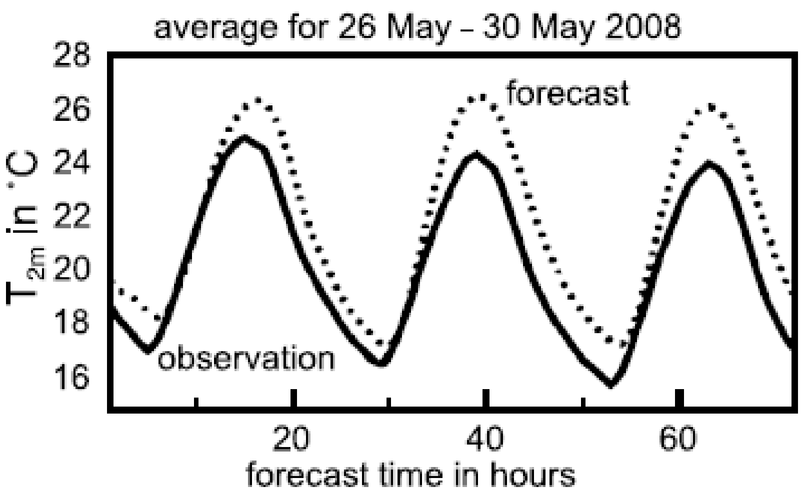
Atmos. Chem. Phys., 12, 4045–4063, 2012
www.atmos-chem-phys.net/12/4045/2012/
doi:10.5194/acp-12-4045-2012

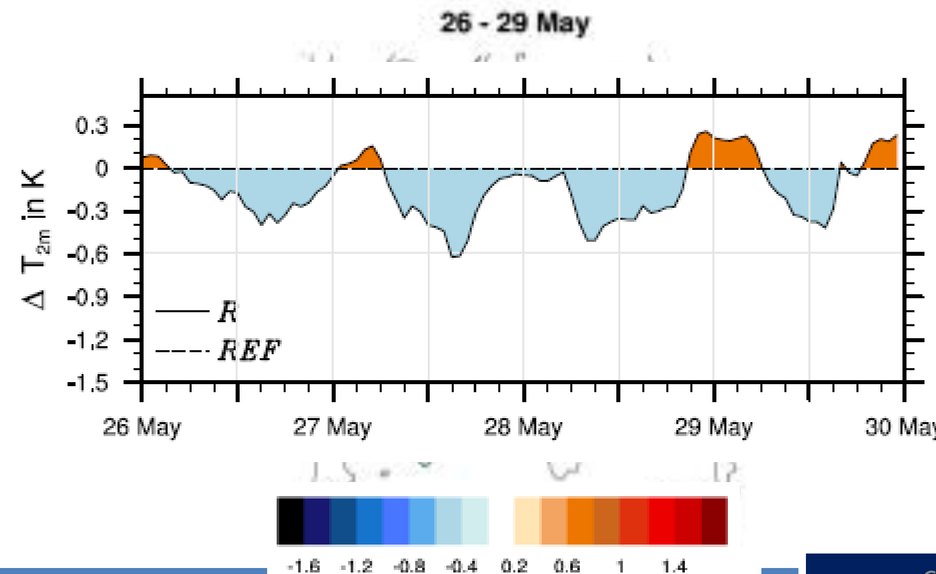
Saharan dust event impacts on cloud form Western Europe

M. Bangert[1], A. Nenes[2,3], B. Vogel[1], H. Vogel[1], D. Barahona[4,5], V. A. Karydis[2], P. Kumar[3,6], C. Kottmeier[1], and U. Blahak[7]

This had a significant impact on the cloud optical properties, causing a reduction in the incoming short-wave radiation at the surface up to $-75\,\mathrm{W\,m^{-2}}$. Including the direct interaction of dust with radiation caused an additional reduction in the incoming short-wave radiation by 40 to $80\,\mathrm{W\,m^{-2}}$, and the incoming long-wave radiation at the surface was increased significantly in the order of $+10\,\mathrm{W\,m^{-2}}$.

The strong radiative forcings associated with dust caused a reduction in surface temperature in the order of -0.2 to -0.5 K for most parts of France, Germany, and Italy during the dust event. The maximum difference in surface temperature was found in the East of France, the Benelux, and Western Germany with up to -1 K. This magnitude of temperature change was sufficient to explain a systematic bias in numerical weather forecasts during the period of the dust event.



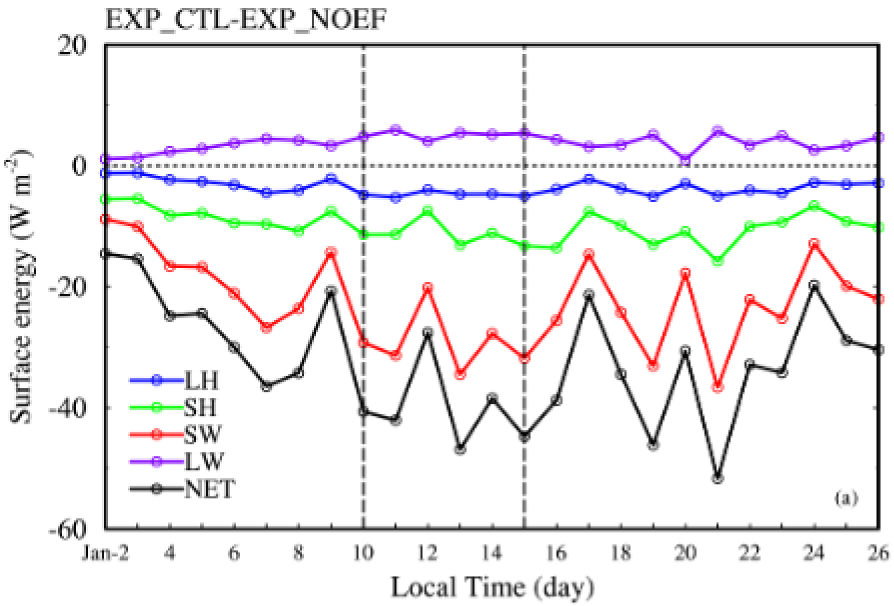


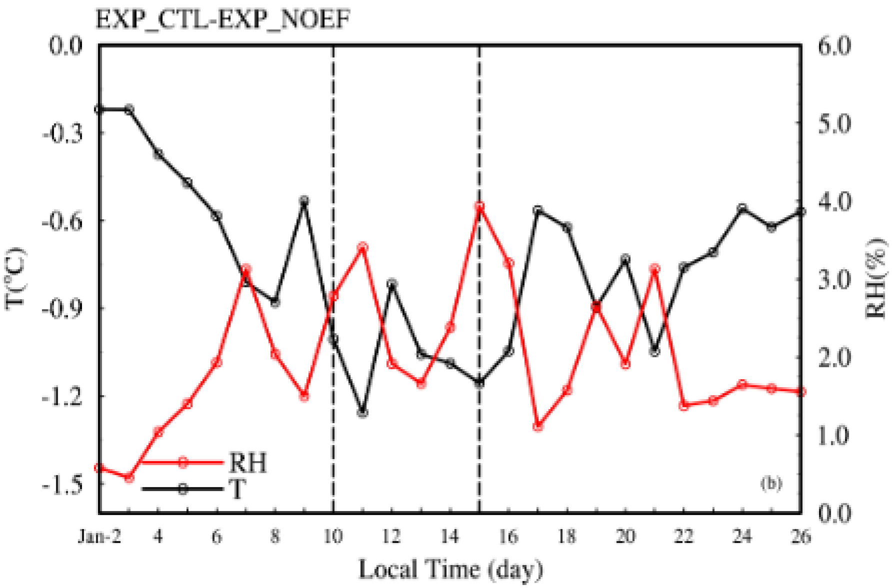
v. Direct radiative forcing of HAZE

"Smog Blankets Chinese Cities"
Buildings are seen in heavy haze in Beijing's central business district, January 14, 2013.
PM2.5 ~ 900 micrograms per cubic meter. The World Health Organization recommends maximum daily level of PM 2.5 = 20 micrograms per square meter.

v. Direct radiative forcing of HAZE

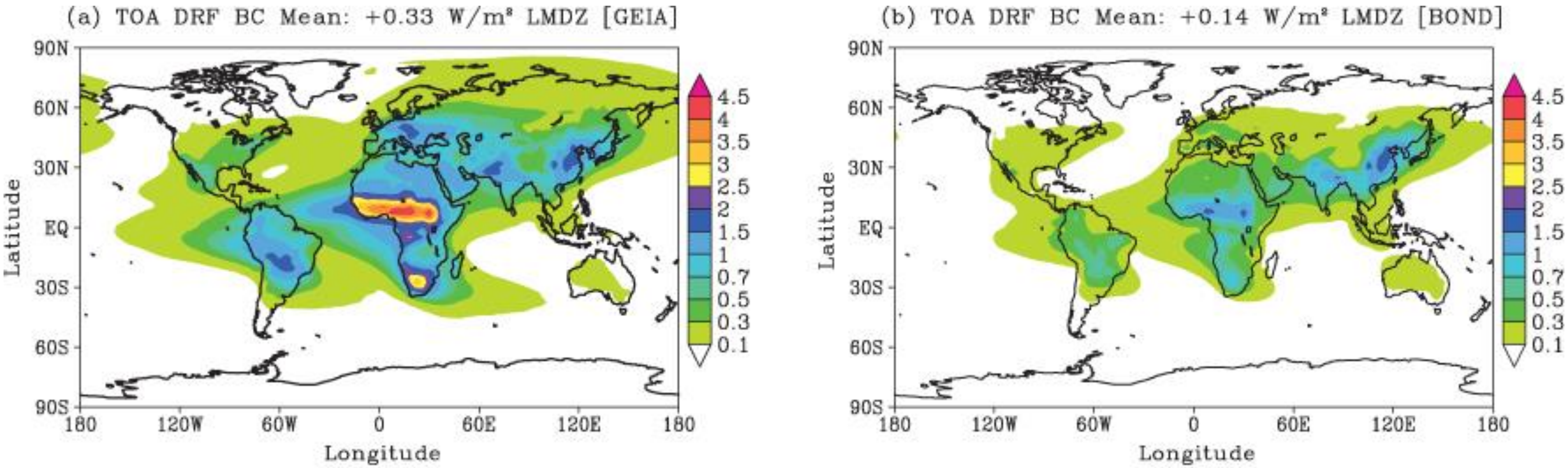
Y. Gao et al.: Modeling the feedback between aerosol and meteorological va





http://www.atmos-chem-phys.net/15/4279/2015/acp-15-4279-2015.pdf

vi. Direct radiative forcing of Black Carbon



Tellus B. Fatima et al., 2012

Cloud forcing: albedo (cooling) vs. greenhouse (warming)

Depends on: Temperature (altitude), thickness *and makeup of particles.*

Figure 3. Cirrus clouds transmit most of the incoming shortwave radiation, but they trap some of the outgoing longwave radiation. Their cloud greenhouse forcing is greater than their albedo forcing, resulting in a net warming of the Earth.

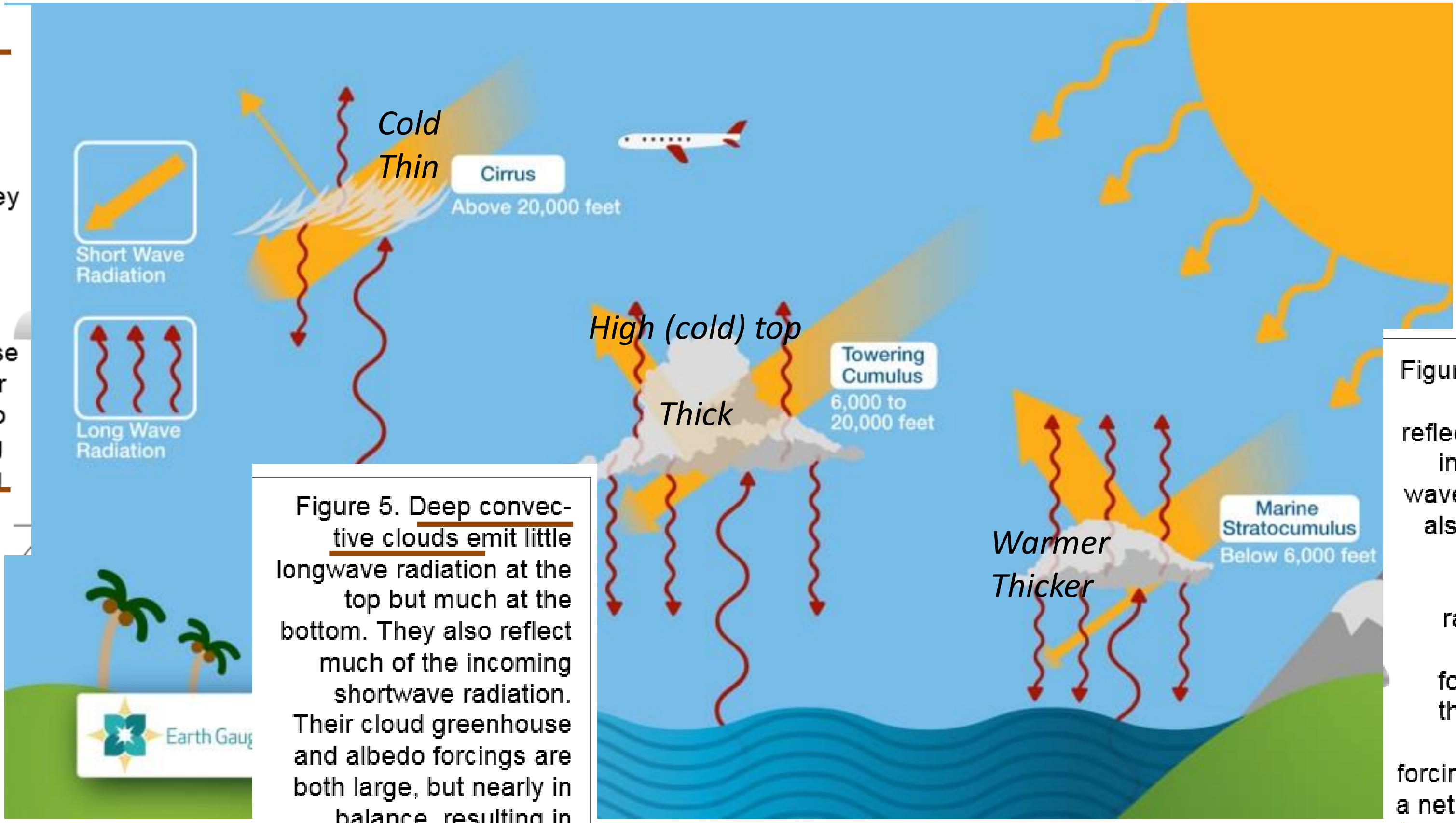


Figure 5. Deep convective clouds emit little longwave radiation at the top but much at the bottom. They also reflect much of the incoming shortwave radiation. Their cloud greenhouse and albedo forcings are both large, but nearly in balance, resulting in neither warming nor cooling.

0

Figure 4. Stratocumulus clouds reflect much of the incoming shortwave radiation but also reemit large amounts of longwave radiation. Their cloud albedo forcing is larger than their cloud greenhouse forcing, resulting in a net cooling of the Earth.

The overall effect of all clouds together is negative (cooling the Earth).

Lesson 9

Indirect radiative forcing of aerosols

Atmospheric aerosol particles also serve as cloud condensation nuclei (CCN) and ice forming nuclei (IN) that are the seed particles for formation of cloud liquid drops and ice crystals, and thus changes in the aerosol are expected to change cloud processes and properties, thereby contributing to an indirect aerosol radiative forcing*:

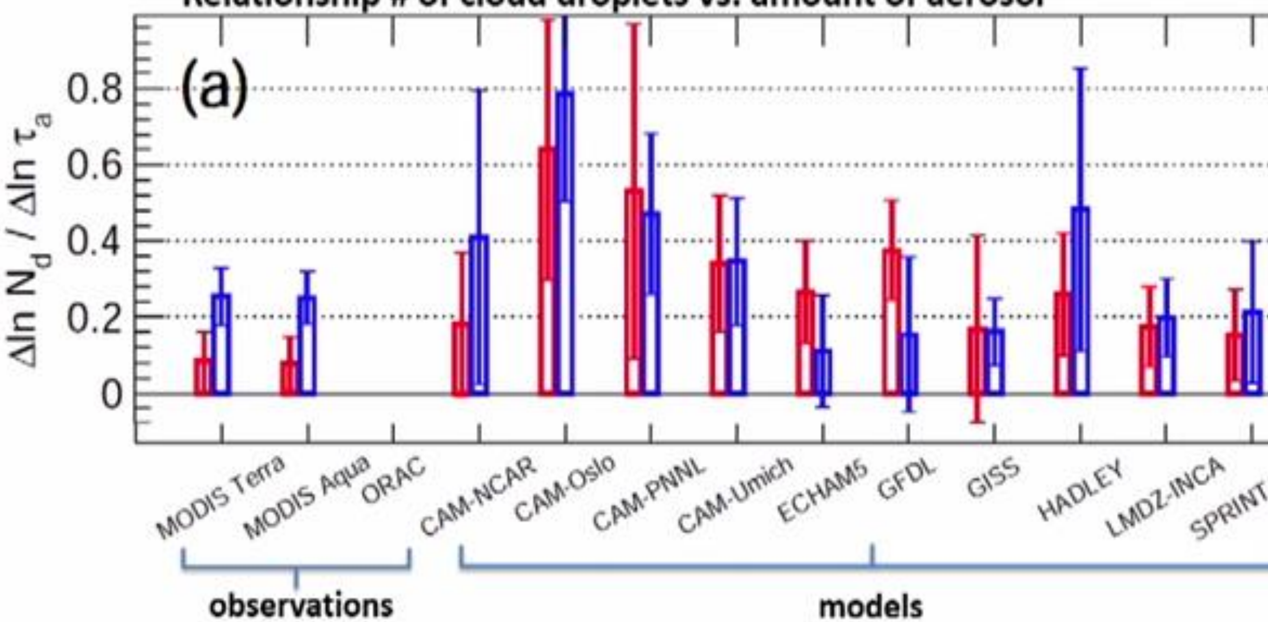
More and smaller droplets (1st indirect effect)

Increased cloud brightness

Decreasing precipitation rate (2nd indirect effect)

Increased cloud lifetime (2nd indirect effect)

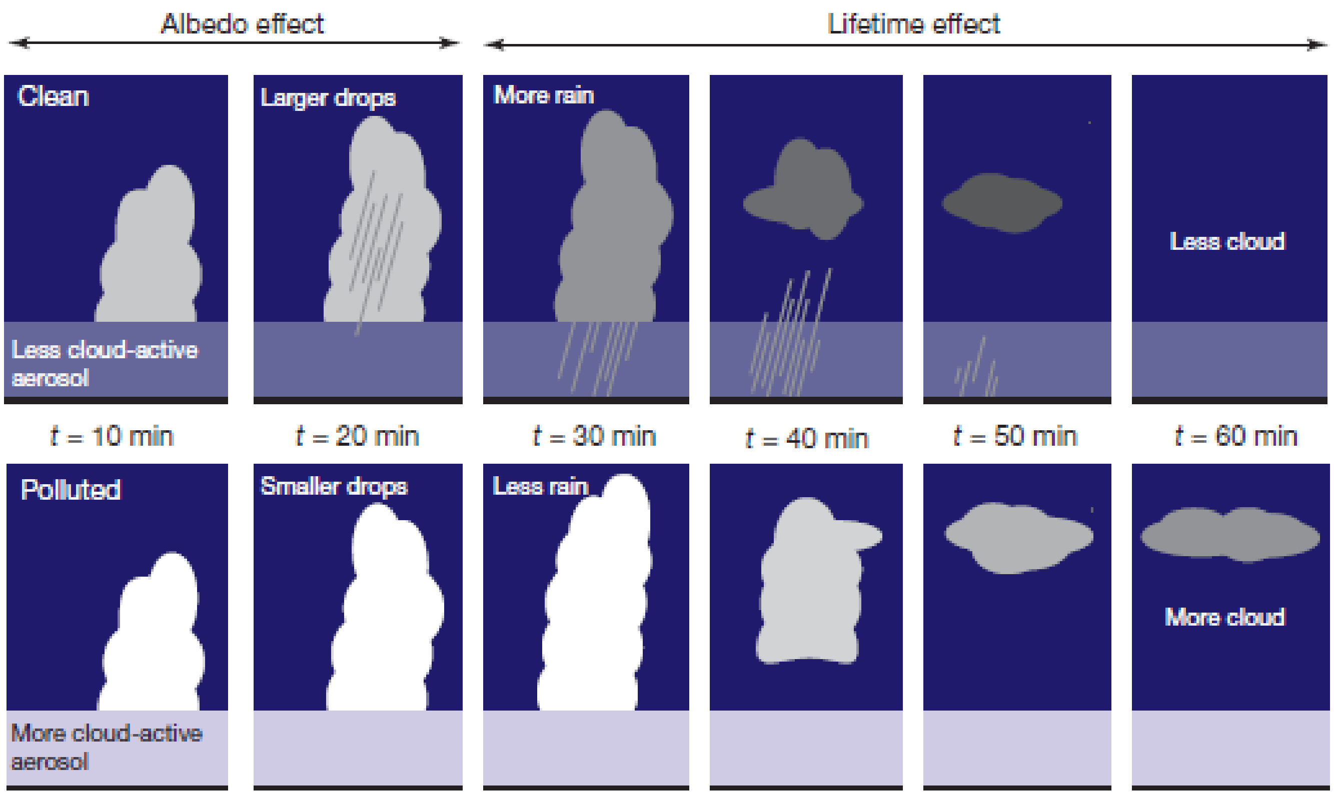
Relationship # of cloud droplets vs. amount of aerosol



Quaas et al. (2009): 3 satellite datasets and 10 models – AEROCOM I

** There are a lot of conflicting results to these common findings, due to the complexity of these processes and the individual atmospheric conditions*

Indirect radiative forcing of aerosols

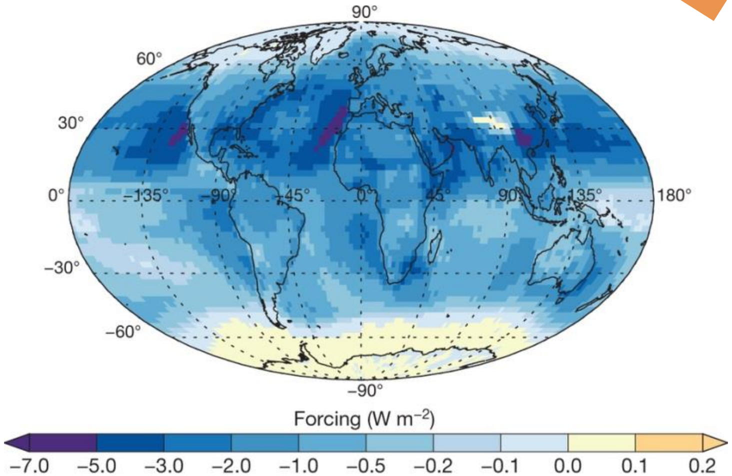


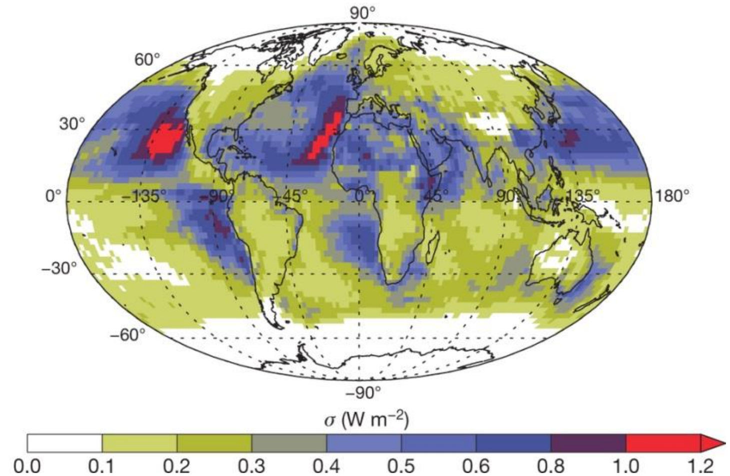
NASA: "Less than a third of the models participating in the Fourth Intergovernmental Panel on Climate Change (IPCC) included indirect aerosol effects, even in a very limited way, and those considered only sulfate aerosols."

Lesson 9

Indirect radiative forcing of aerosols

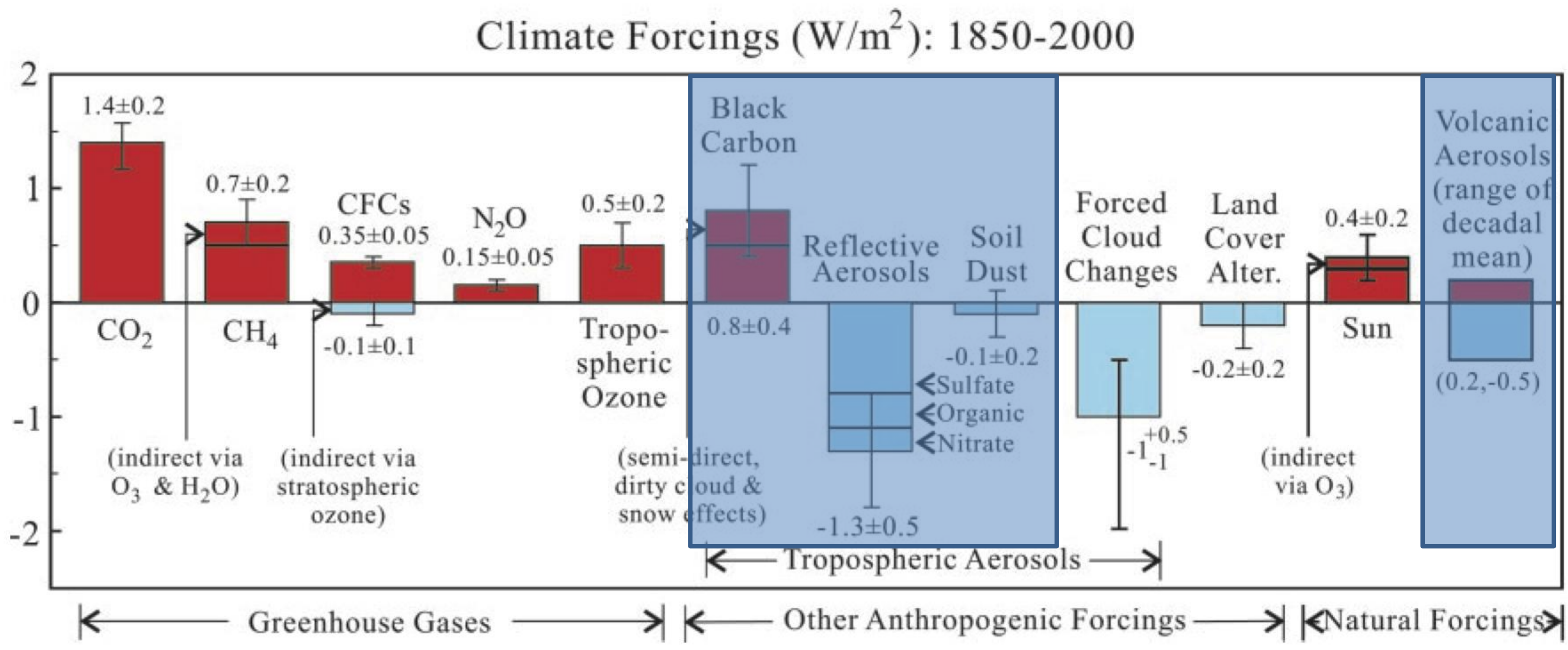
"The effect of anthropogenic aerosols on cloud droplet concentrations and radiative properties is the source of one of the largest uncertainties in the radiative forcing of climate over the industrial period. This uncertainty affects our ability to estimate how sensitive the climate is to greenhouse gas emissions. ...
... improved measurements and evaluation of simulated aerosols in polluted present-day conditions will not necessarily result in commensurate reductions in the uncertainty of forcing estimates."





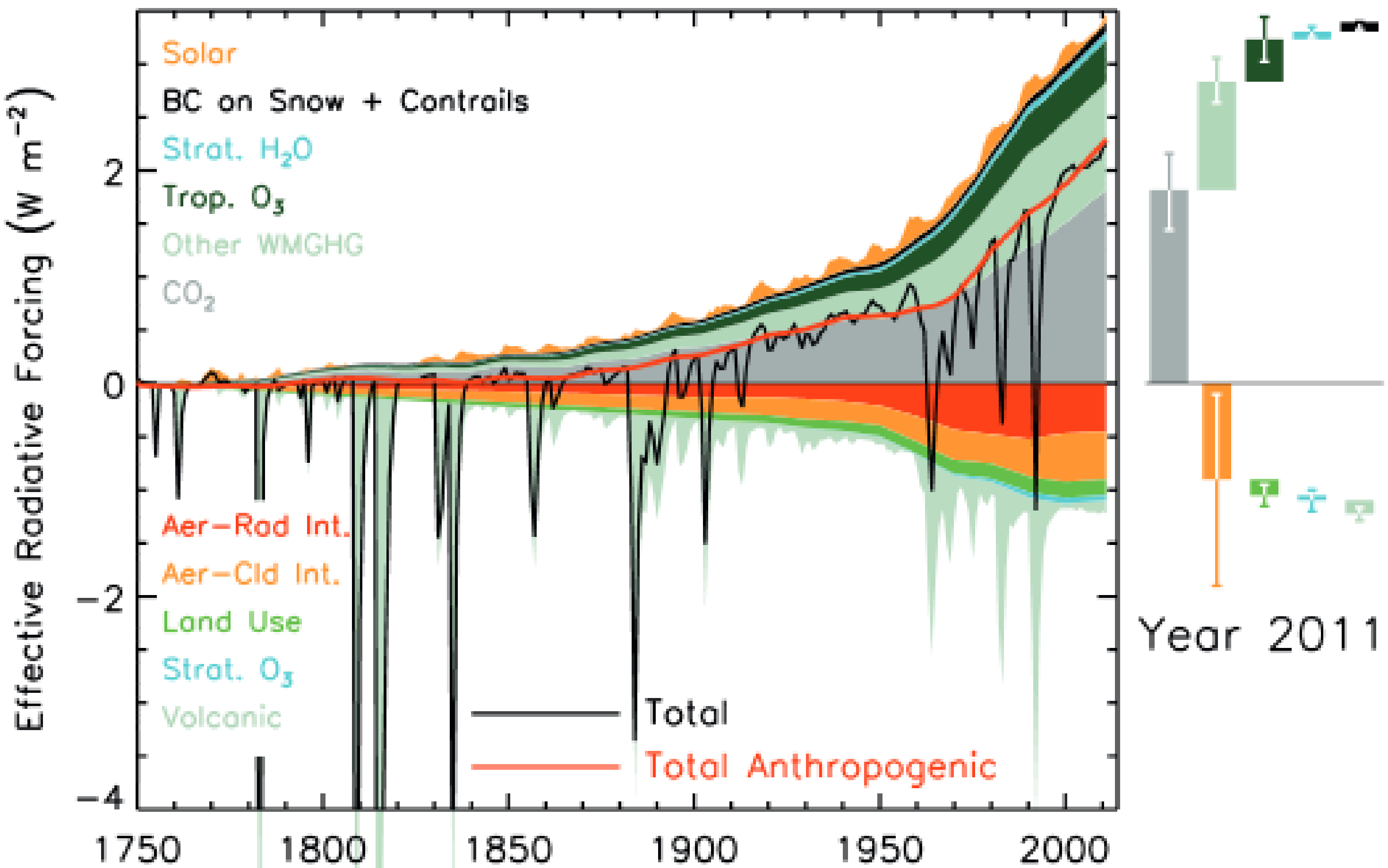
[Carlslaw et al., 2013, NATURE]

Aerosol forcing in the Earth's energy budget



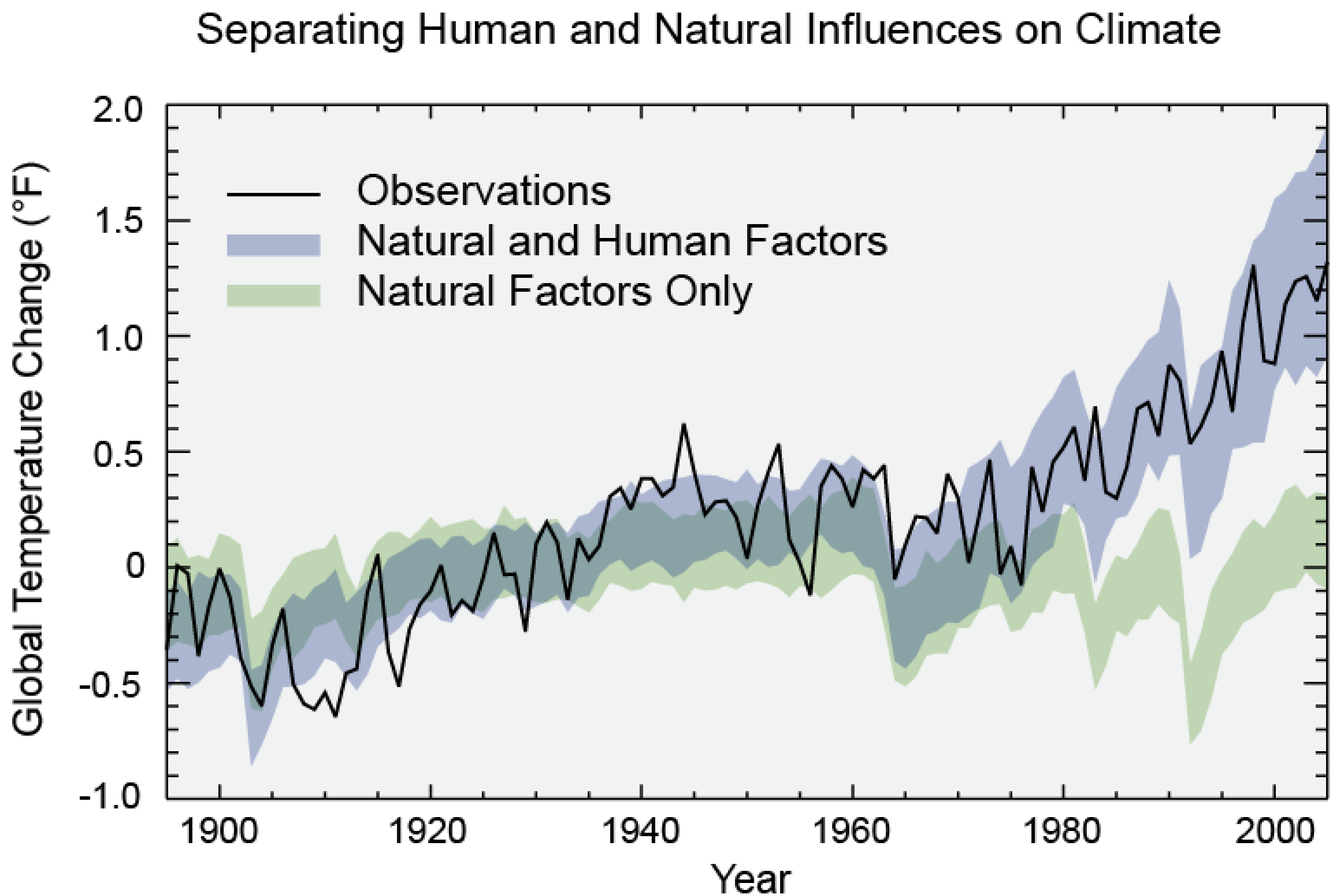
The atmospheric aerosols in total have a negative radiative forcing

Total influences in the Earth's energy budget



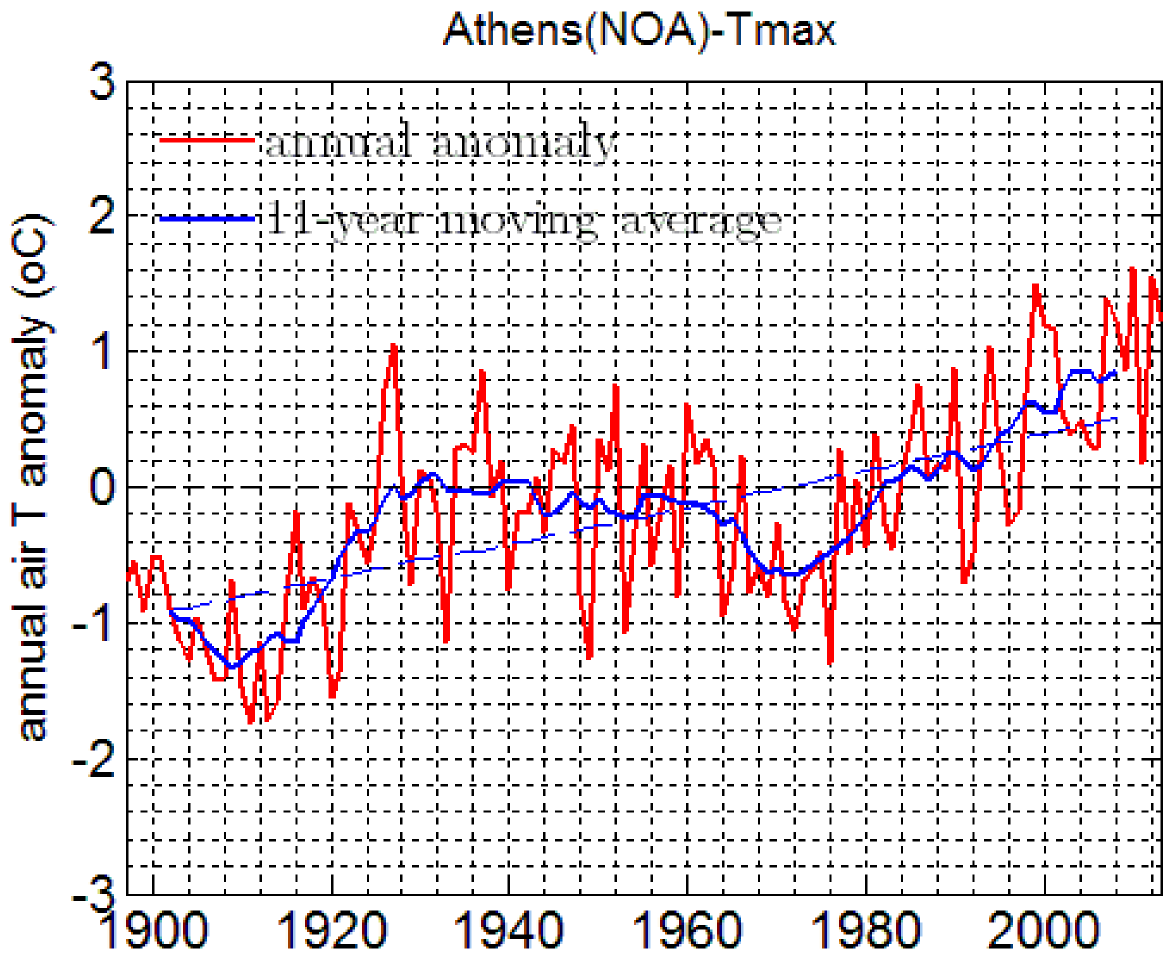
Previous lesson

The total (and total anthropogenic) radiative forcing is positive



Previous lesson

The rise in atmospheric temperature has mainly anthropogenic origin



The Institute of Environmental Research and Sustainable Development (IERSD/NOA) holds the oldest and most complete climatic records in Greece.

Key points (7)

- Most of the components and types of aerosols (volcanic, sea-salt, dust, forest fires, haze,) in the atmosphere scatter the incoming solar radiation, thus on average cause a radiative cooling. (The effect of aerosols on the long-wave radiation is smaller)
- Exception is the black carbon, which is a highly absorbing of the incoming solar radiation, thus warms the atmosphere, causing a radiative warming
- The indirect effects of aerosols on clouds are highly uncertain, though estimated to be negative (i.e. cause a radiative cooling of the atmosphere)
- The total aerosol radiative forcing of the Earth is negative. The net cloud forcing is also negative
- The total (and anthropogenic) radiative forcing of the Earth is positive
- The anthropogenic radiative forcing of the Earth outweighs the effect of natural aerosols on radiation

Summary (1)

- The Sun radiates energy across the wavelength range of 0.1 – 4 μm (max. 0.5 μm). The quantity that arrives at the top of the atmosphere (ToA) of the Earth (perpendicular to the solar rays) is about 1360 W/m^2, and this is known as the solar constant (S_0) or total solar irradiance (TSI).
- The Incident solar energy (actual insolation) at the ToA of the earth is temporally and spatially modified (by the rotation, shape, orbit, tilt) to be around 340 W m^{-2} (global and annual average)
- To maintain the (long-term) stability of earth's temperature (T), the planet must radiate to space a flux of energy (F) sufficient to just balance the input from the sun (radiative energy balance). The respective values at ToA are T~-18C and F~240 Wm-2.

Summary (2)

- The 30% of the incident solar energy is reflected back to space, mainly by the clouds (plus by the ground and aerosol surface).
- Most of the incoming solar energy is absorbed by the ground surface, which is warmed and emits energy through long-wave radiation (plus through thermals and evapotranspiration).
- Apart from a 10%, which is transmitted back to space, the rest amount of energy is absorbed by the greenhouse gases and the clouds, which are warmed and emit long-wave radiation upwards, downwards and towards other gases (and so on). This is the natural greenhouse effect, which warms the earth system by about 34 C (T_{earth} ~ 15 C).

Summary (3)

- The Earth system is imbalanced, thus the mean global atmospheric temperature increases (findings of satellite, ground and model experiments)
- The climate forcing to the earth system is caused by the greenhouse gases (natural: H_2O, CO_2 and anthropogenic: CO_2, CH_4, N_2O etc.), other anthropogenic influences (direct and indirect aerosol effects) and natural influences (volcanic eruptions, solar luminocity, clouds). From those, aerosols (including volcanic) and clouds have a negative radiative forcing.
- The total (and anthropogenic) radiative forcing of the Earth is positive.
- The anthropogenic radiative forcing of the Earth outweighs the effect of natural aerosols on radiation.

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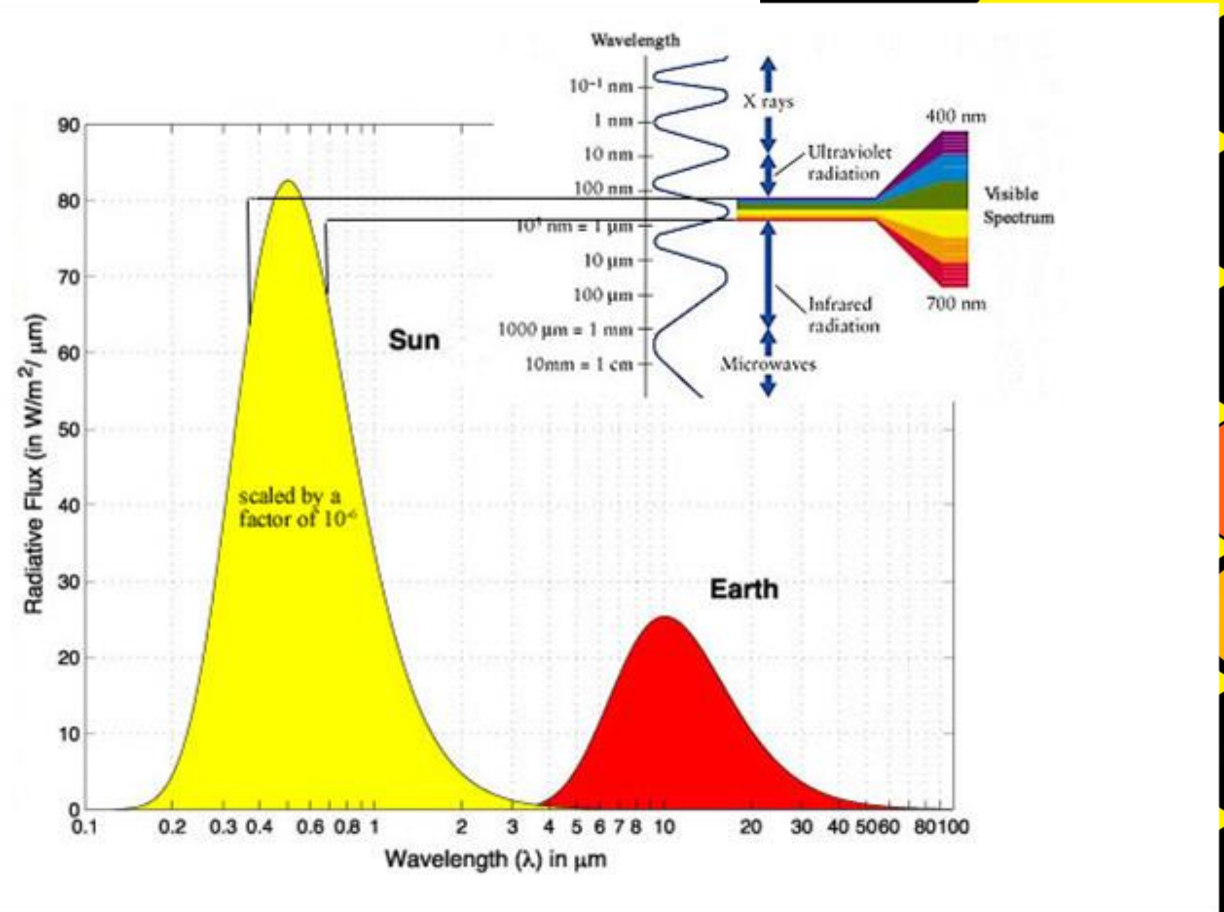
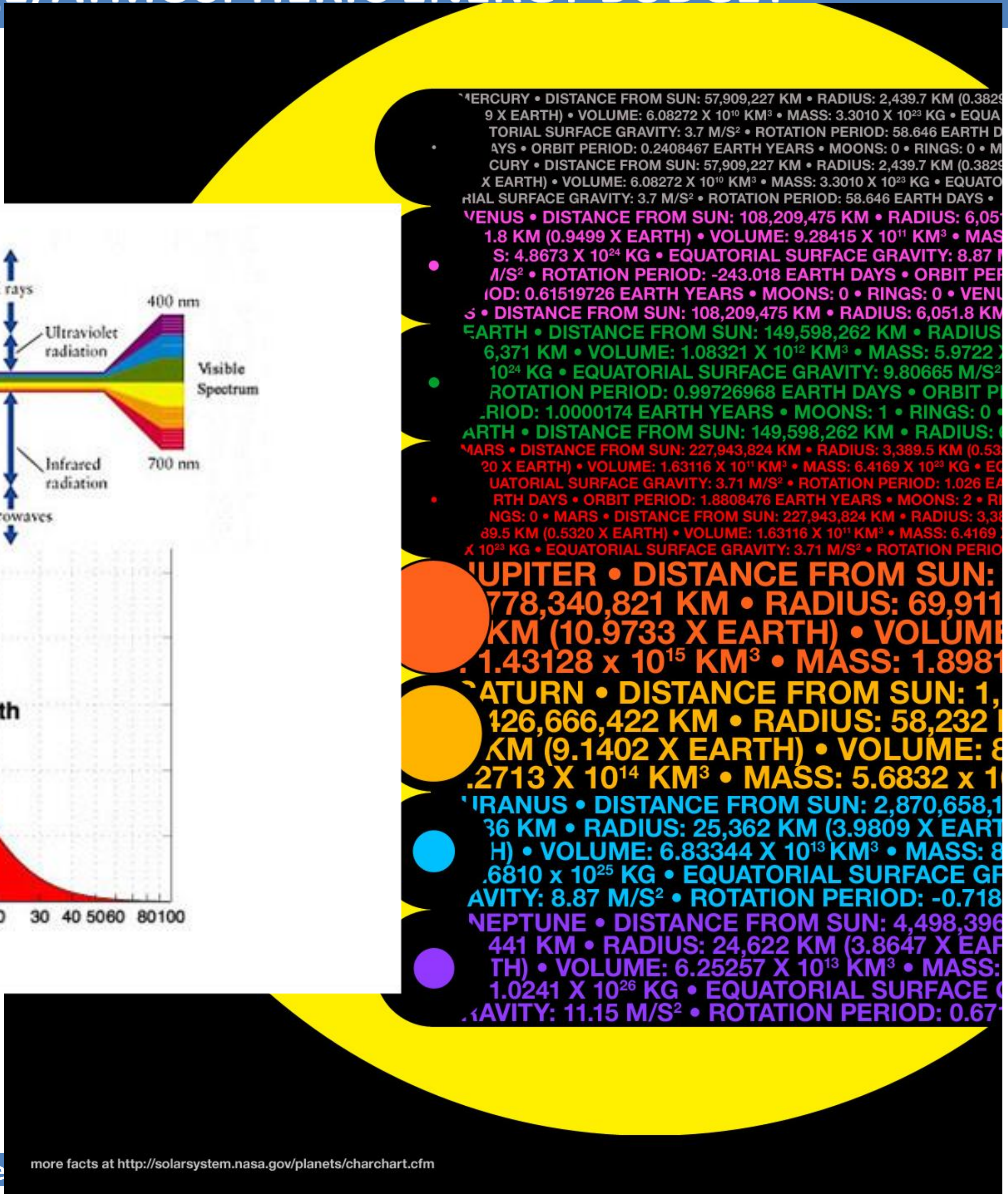
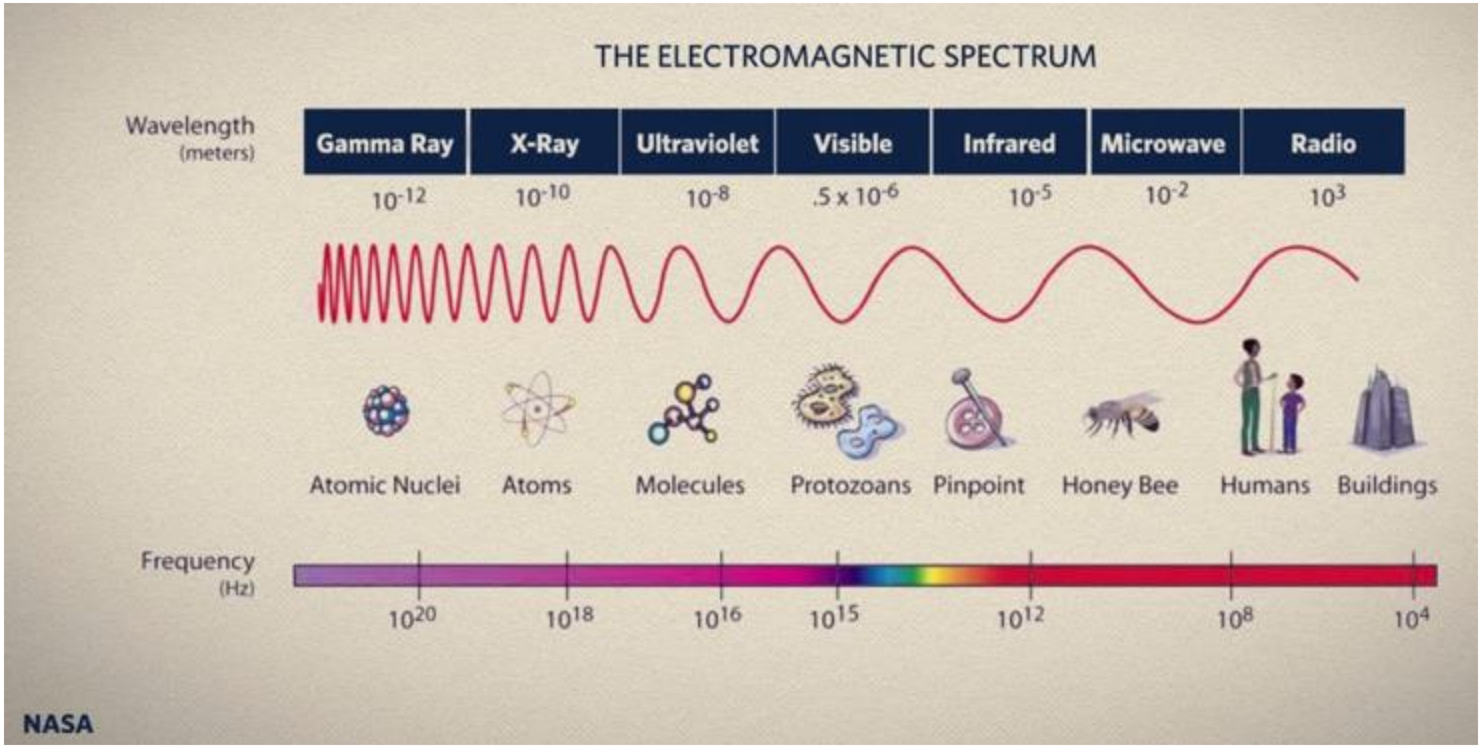
Backup slides

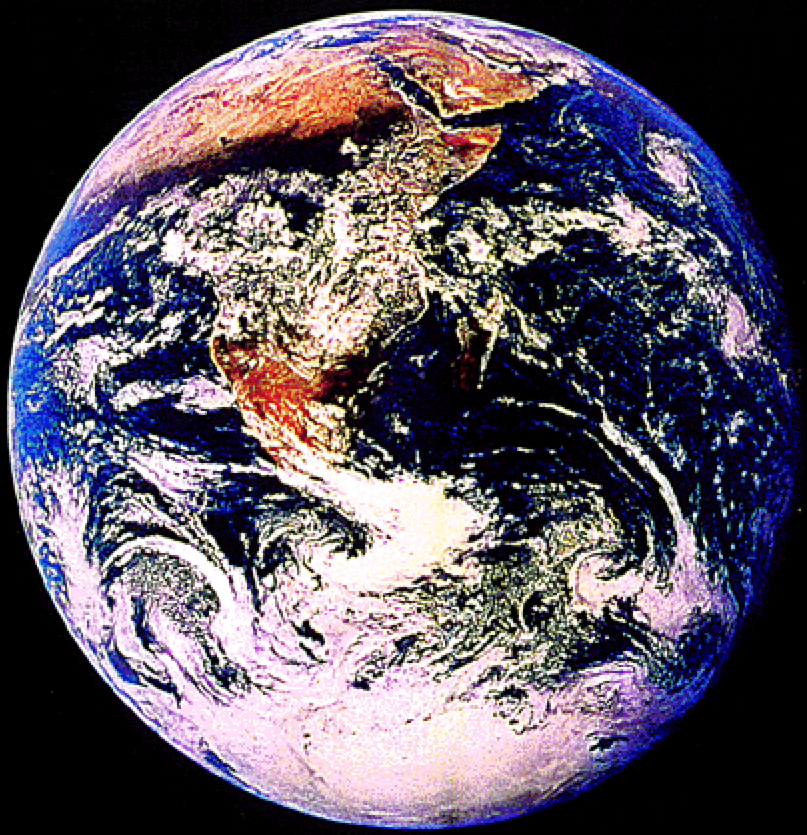
SURFACE/ATMOSPHERIC ENERGY BUDGET






THE ELECTROMAGNETIC SPECTRUM
Wavelength
(meters)
Gamma Ray
X-Ray
Ultraviolet
Visible
Infrared
Microwave
Radio
10-12
10-10
10-8
.5 x 10-6
10-5
10-2
103
Atomic Nuclei
Atoms
Molecules
Protozoans
Pinpoint
Honey Bee
Humans
Buildings
Frequency
(Hz)
1020
1018
1016
1015
1012
108
104
NASA

Earth



Vital Statistics

Radius	6378 km
Surface area	5.1×10^8 km^2
Mass	5.974×10^{24} kg
Density	5.515 g/cm^3
Local gravity	9.87 m/s^2
Escape velocity	11 km/s
Albedo	0.36
Surface temperature	290 K
Length of day	23 h 56 min
Length of year	365.25 days
Distance from the Sun	1.496×10^8 km

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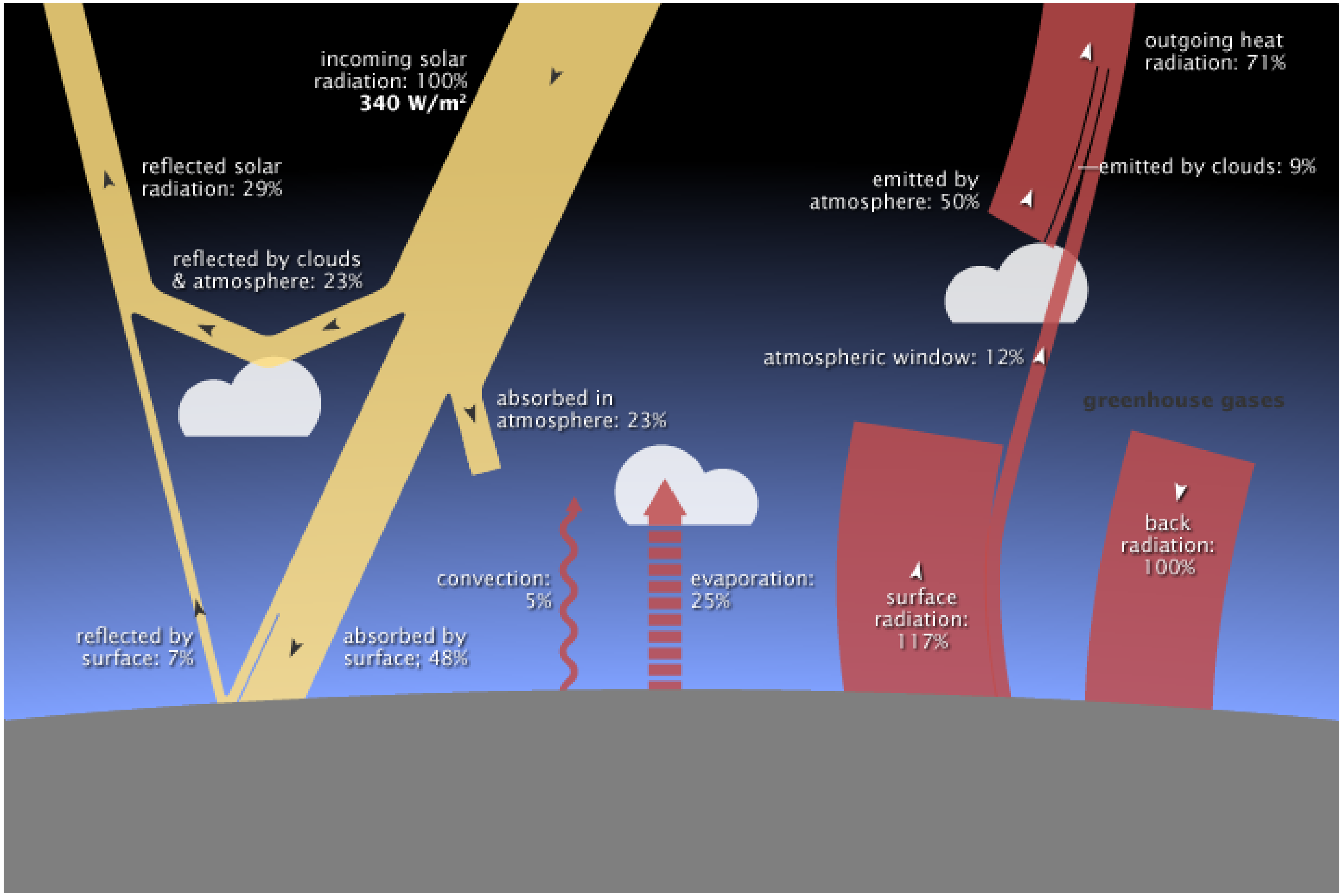
Climate & Earth's annual energy budget



Climate & Earth's annual energy budget

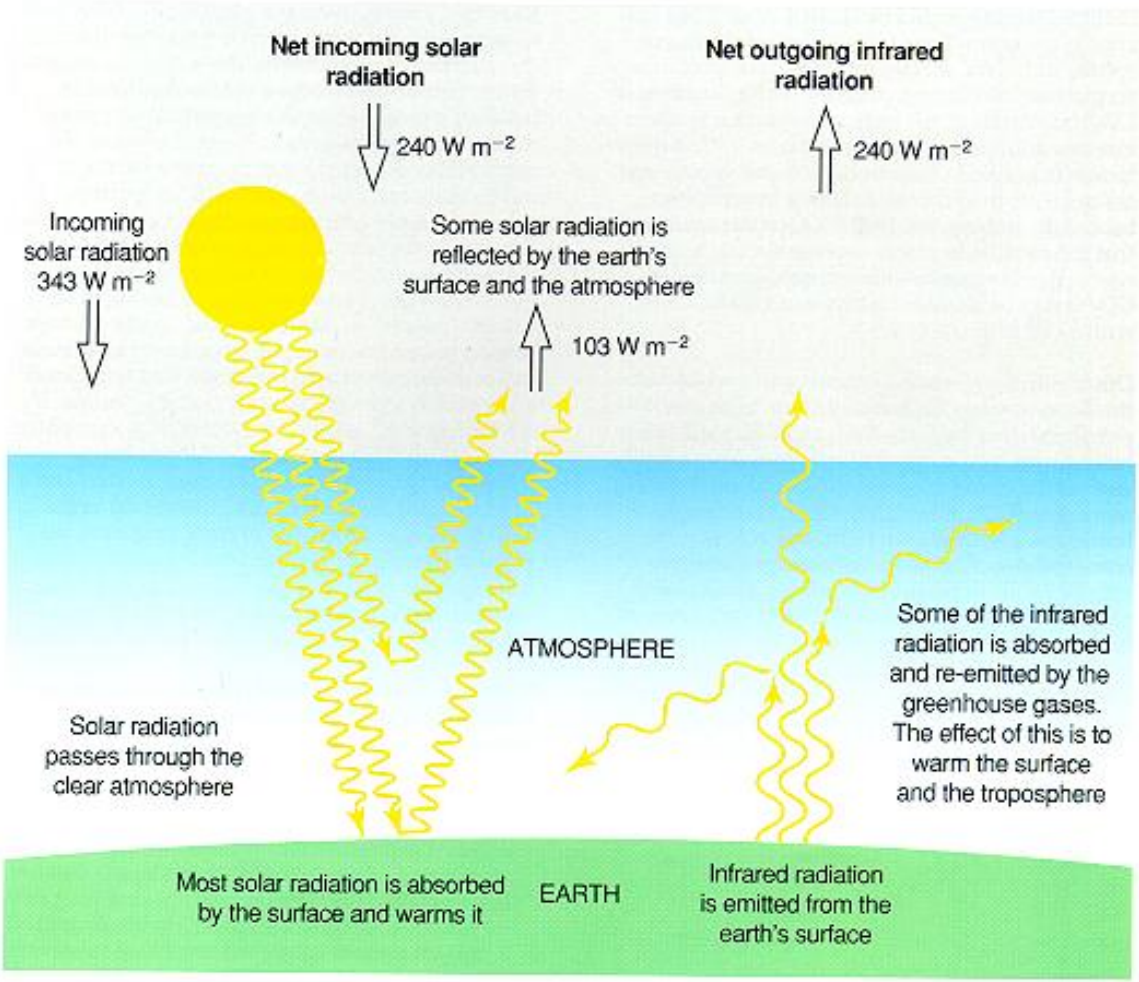
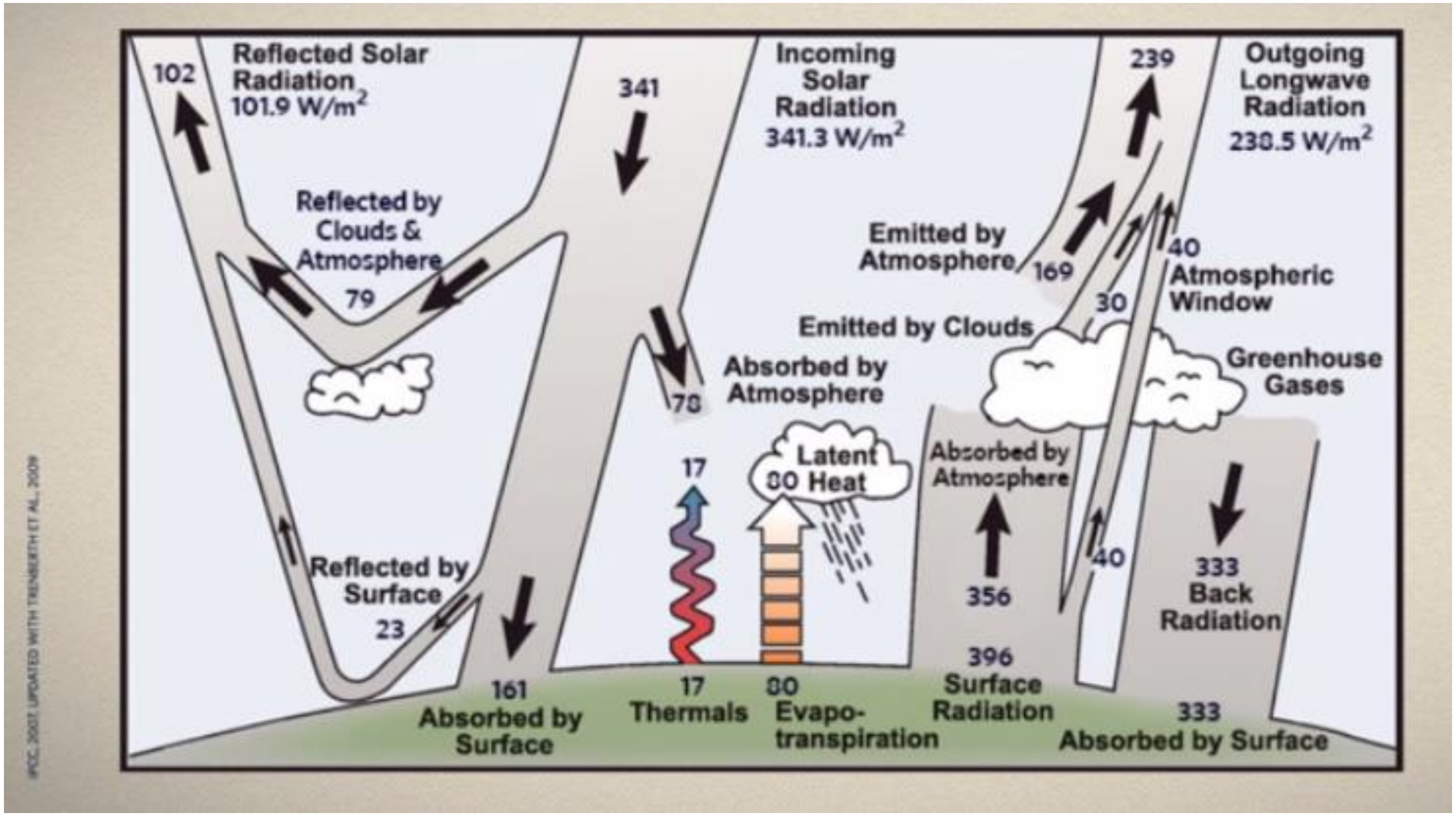
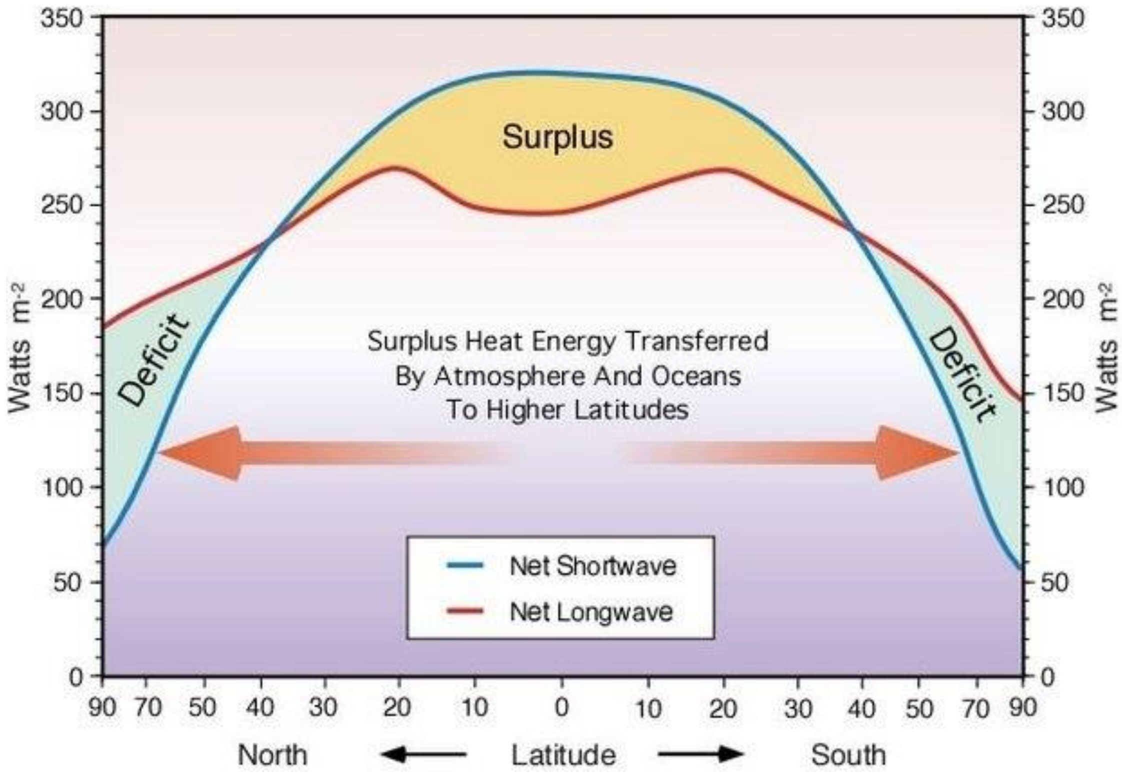


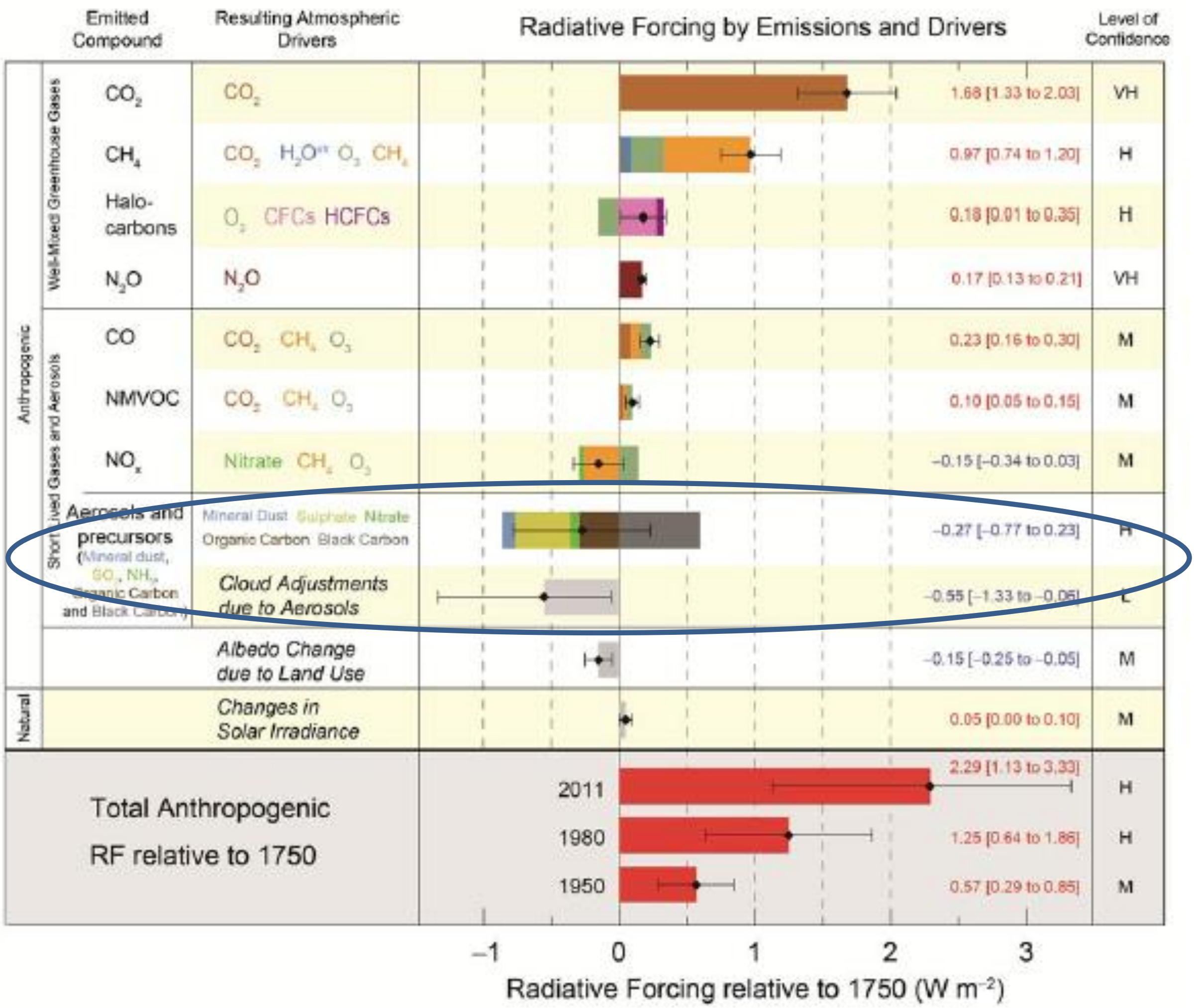
Figure 1. *A simplified diagram illustrating the global long-term radiative balance of the atmosphere. Net input of solar radiation (240 W m^{-2}) must be balanced by net output of infrared radiation. About a third (103 W m^{-2}) of incoming solar radiation is reflected and the remainder is mostly absorbed by the surface. Outgoing infrared radiation is absorbed by greenhouse gases and by clouds keeping the surface about 33 °C warmer than it would otherwise be.*

Climate & Earth's annual energy budget

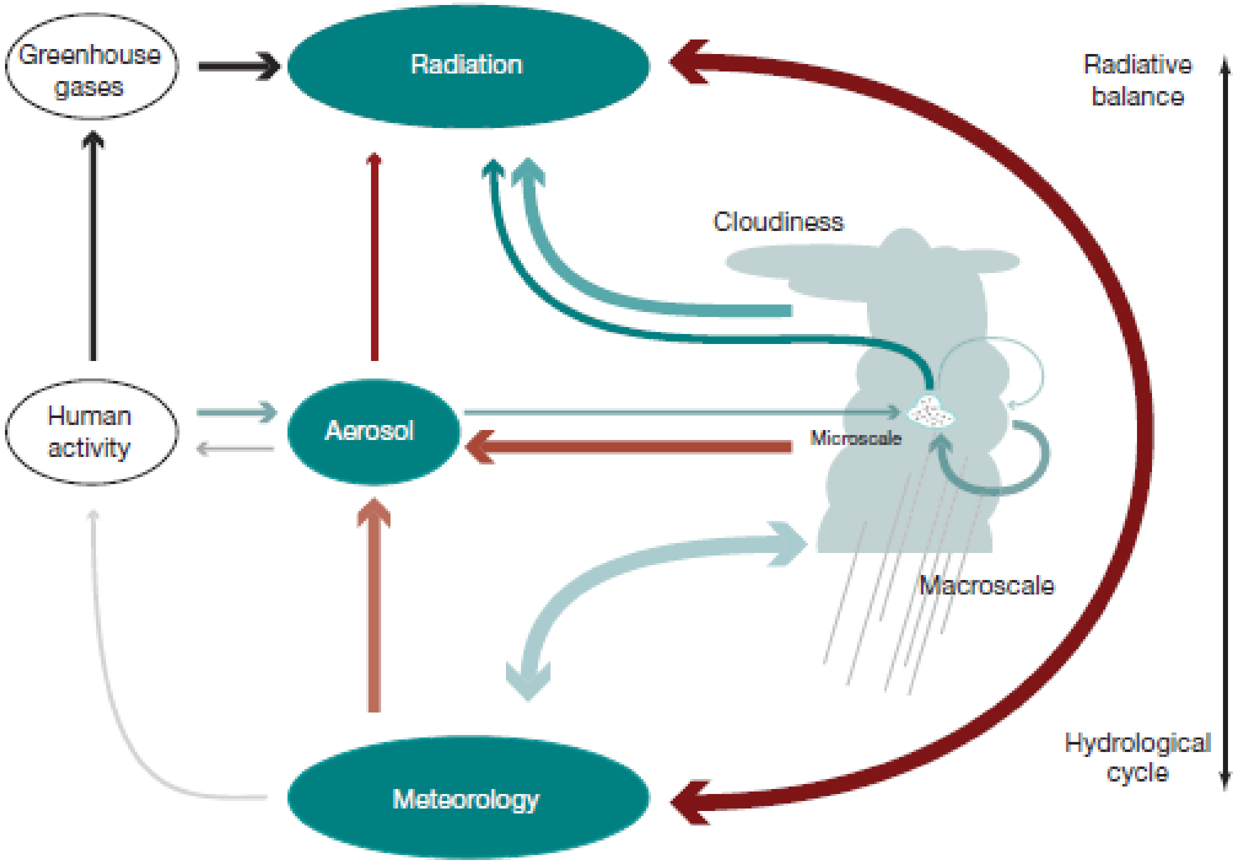



Surplus
Deficit
Deficit
Surplus Heat Energy Transferred
By Atmosphere And Oceans
To Higher Latitudes
Net Shortwave
Net Longwave
Watts m-2
Watts m-2
350
300
250
200
150
100
50
0
90 70 50 40 30 20 10 0 10 20 30 40 50 70 90
North
Latitude
South

Anthropogenic influences in the Earth's energy budget



Aerosol – Cloud interactions



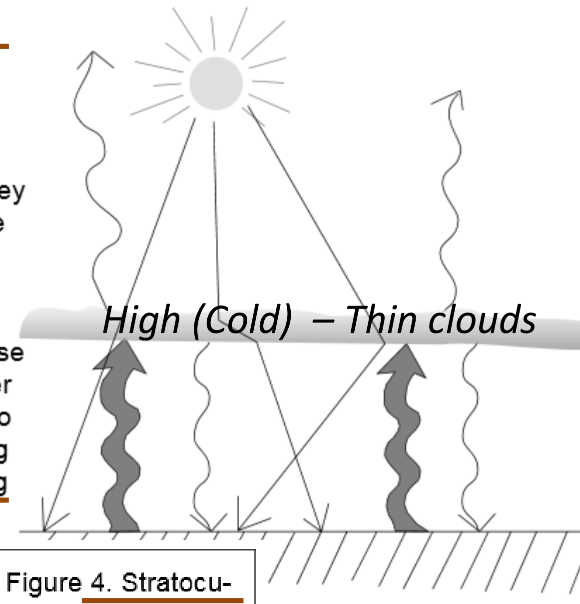
Cloud forcing: albedo (cooling) vs. greenhouse (warming)

Depends on:

Temperature (altitude), thickness *and makeup of particles.*

The overall effect of all clouds together is negative (cooling the Earth).

Figure 3. Cirrus clouds transmit most of the incoming shortwave radiation, but they trap some of the outgoing longwave radiation. Their cloud greenhouse forcing is greater than their albedo forcing, resulting in a net warming of the Earth.



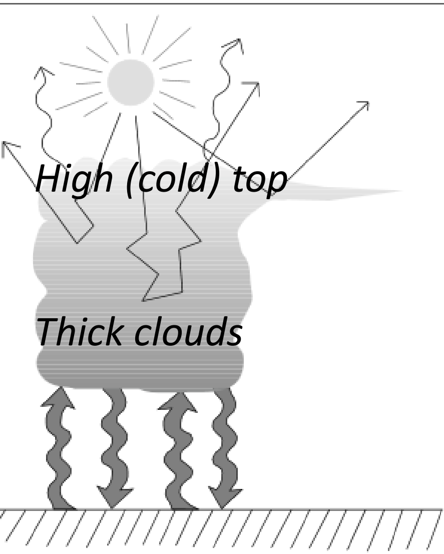


Figure 5. Deep convective clouds emit little longwave radiation at the top but much at the bottom. They also reflect much of the incoming shortwave radiation. Their cloud greenhouse and albedo forcings are both large, but nearly in balance, resulting in neither warming nor cooling.

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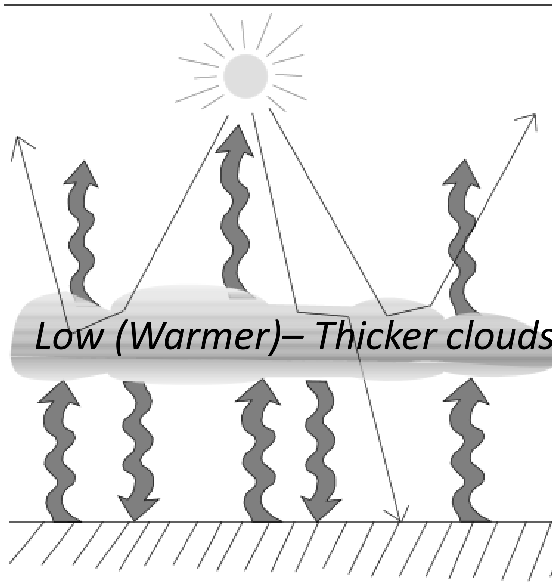

Figure 4. Stratocumulus clouds reflect much of the incoming shortwave radiation but also reemit large amounts of longwave radiation. Their cloud albedo forcing is larger than their cloud greenhouse forcing, resulting in a net cooling of the Earth.

Source: NASA / GATECH

NASA's Solar Dynamics Observatory captured this imagery of a solar flare, as seen in the bright flash. A loop of solar material, a coronal mass ejection (CME), can also be seen rising up off the right limb of the Sun. Image credit: NASA/SDO/Goddard