# Modelling the Climate
# “a modelling perspective on climate change”
# Part 1

## AE4-E40 Climate Change

A. Pier Siebesma
KNMI & TU Delft
Multiscale Physics Department
The Netherlands
Contact: siebesma@knmi.nl

Koninklijk Nederlands
Meteorologisch Instituut
*Ministerie van Verkeer en Waterstaat*

www.knmi.nl

National Institute for weather, climate research and seismology

Climate:

observing, understanding and predicting changes in our climate system

Questions:

- how does our climate change
- what are the causes of climate change
- what will our future climate be like

# Key Questions

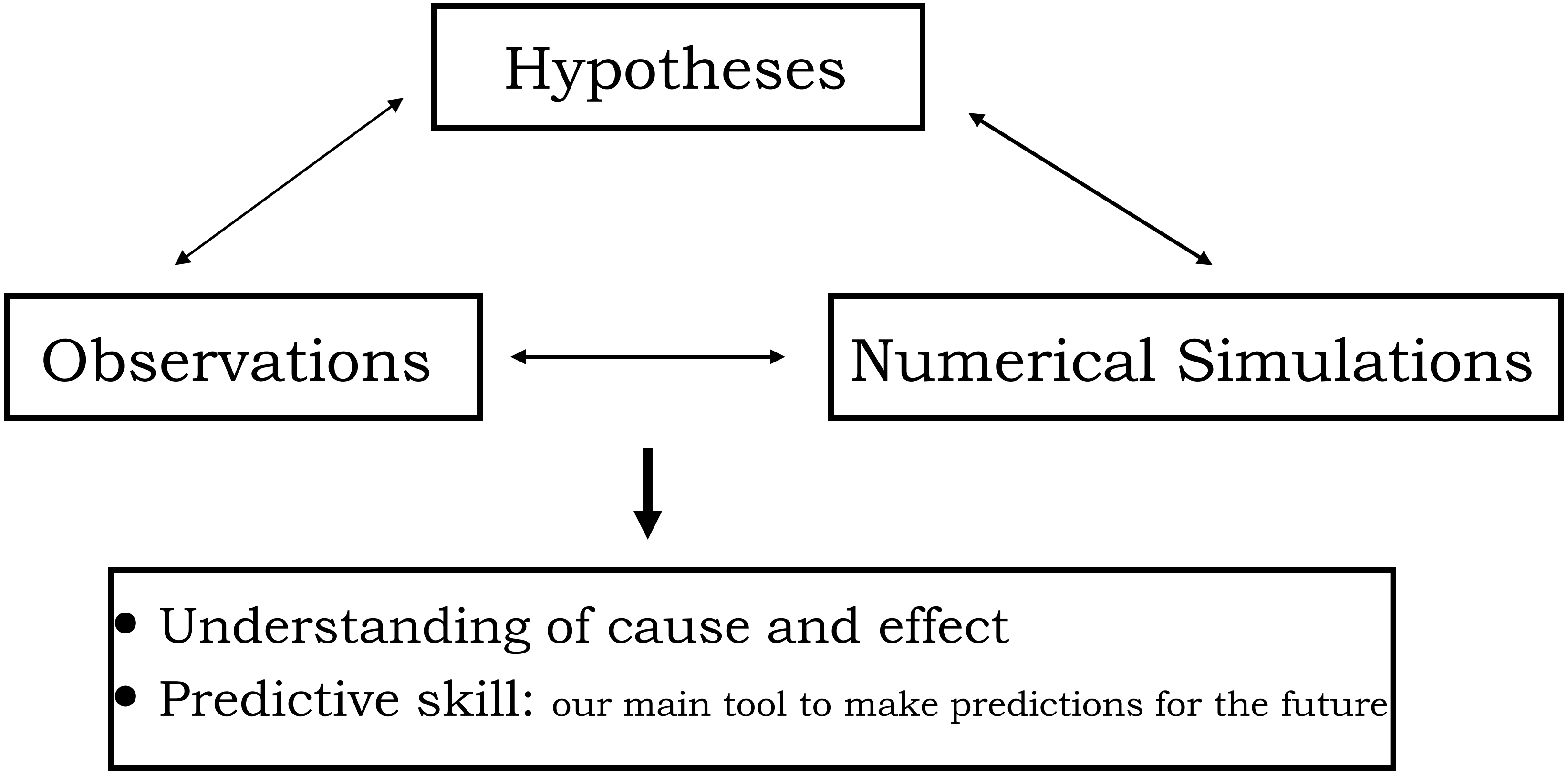
- What is a climate model?
- Why use them?
- What types of climate models are there?

# What is a climate model?

- A mathematical representation of the many processes that make up our climate.

- Requires:
  - Knowledge of the physical laws that govern climate
  - Mathematical expressions for those laws
  - Numerical methods to solve the mathematical expressions on a computer (if needed)
  - A computer of adequate size to carry out the calculations

# Why Numerical climate simulations ?



# Important climate model components

- Radiation
  - as it drives the system each climate model needs some description of the exchange of shortwave and longwave radiation
- Dynamics
  - the movement of energy in the system both in the horizontal and vertical (winds, ocean currents, convection, bottom water formation)
- Surface processes
  - the exchange of energy and water at the ocean, sea-ice and land surface, including albedo, emissivity, etc.
- Chemistry
  - chemical composition of the atmosphere, land and oceans as well as exchanges between them (e.g., carbon exchanges)

# Model resolution

- Depending on our question we need to decide how to divide the Earth in our model and how often we need to calculate the state of the system.
  - Choices in space are 0-d (point), 1-d (e.g., 1 vertical column), 2-d (1 vertical layer, latitude and longitude), and 3-d (many layers, lat and lon)

- Examples:
  - A global energy balance model treats the Earth as one point and has no time resolution
  - Weather forecast models calculate the weather every few minutes every 10 km.

# 2.

*The Simplest Climate Model:*

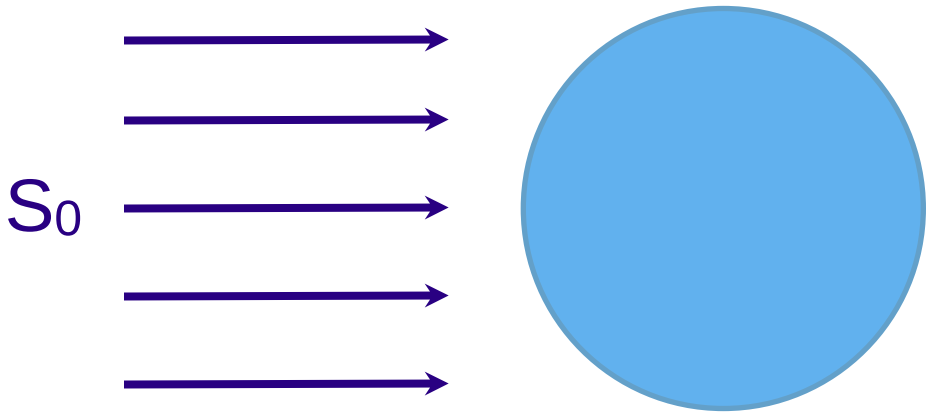
*0-dimensional energy balance model*

# Energy Absorbed by the Atmosphere (1)

**1) How much energy is reaching the top of the atmosphere from the sun?**

- The solar flux received at the top of the atmosphere from the sun depends on the distance of the Earth from the sun. The average value of this flux is called the solar constant, $S_0$, and has a value of 1367 $Wm^{-2}$. Note that this value varies as the orbit of the Earth around the sun is not a perfect circle.

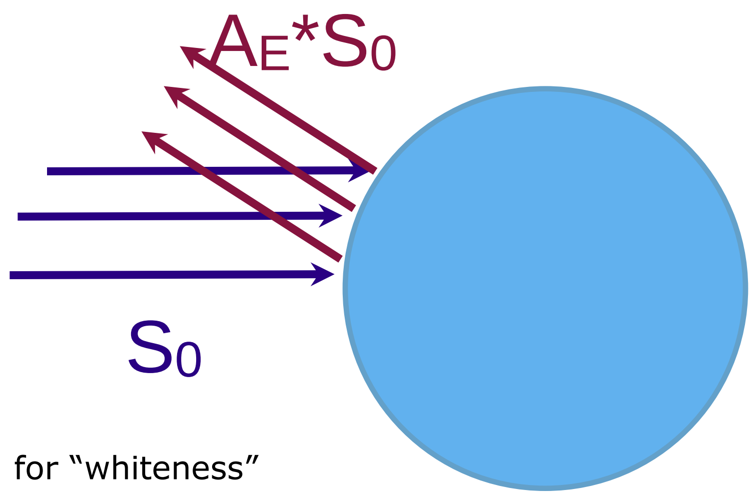
1367 $Wm^{-2}$



# Energy Absorbed by the Atmosphere (2)

## 2) How much energy is directly reflected back to space?

- Some of the solar flux arriving on Earth is directly reflected back to outer space by clouds and the Earth surface. Clouds have a very high albedo* (up to 0.8). Taking all reflectors (clouds, ground, sea) together, the Earth has an albedo of approximately 0.3. Hence only 70 % of the solar flux arriving on earth is available to the system.

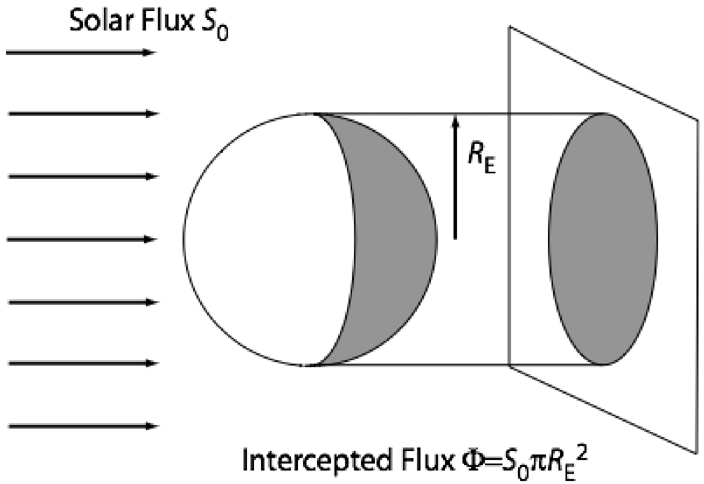



Albedo comes from a Latin word for “whiteness”

# Energy Absorbed by the Atmosphere (3)

**3) What is the total energy absorbed by the Earth?**

- The flux we used so far describes the energy per unit area, hence we now know how much energy per square meter is available to the Earth from solar radiation. To calculate the total energy absorbed we need to multiply the flux with the area that intercepts that radiation. As we can see, that area (the shadow area) is a disk with the radius of the Earth: $\pi R_e^2$



# Energy Absorbed by the Atmosphere (4)

$$E_{in} = \left(S_0 - AS_0\right) \cdot \pi R_E^2$$

Total energy absorbed

Solar flux at TOA

Reflected flux

Area of a disk with radius of the earth

or after some minor rearrangement:

$$E_{in} = S_0\left(1 - A\right) \cdot \pi R_E^2$$

# Energy Emitted by the Atmosphere (1)

**1) How much energy is emitted per unit area from the Earth?**

For a good estimate of this number, we can assume that the Earth is a blackbody. By making that assumption we can now use the Stefan-Boltzmann law to calculate the flux of longwave (infrared) radiation as:

$$F_E = \sigma T_E^4 \qquad \sigma = 5.67 \cdot 10^{-8} \frac{W}{m^2 K^4}$$

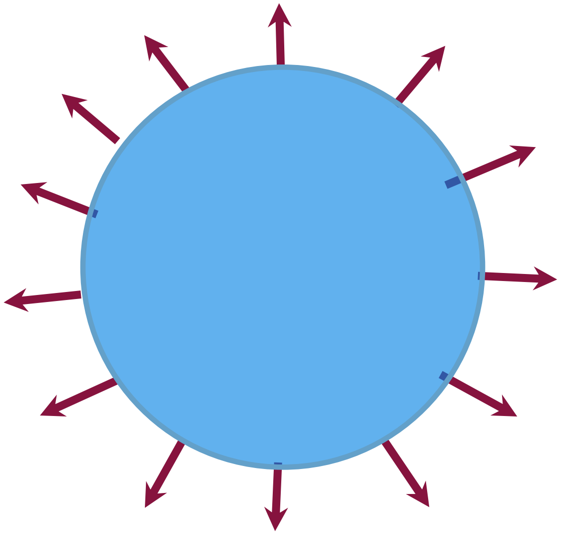
where σ is the Stefan Boltzmann constant and $T_E$ the temperature at which the Earth emits radiation.

# Energy Emitted by the Atmosphere (2)

**2) How much energy is emitted in total from the Earth?**

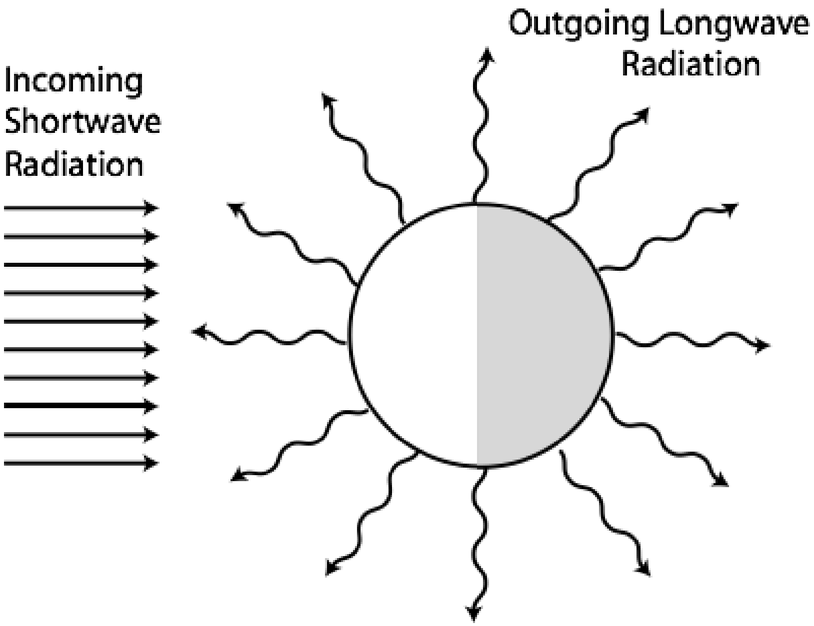
- Again, to find the total amount of energy emitted by the Earth we need to multiply the flux with the area over which energy is emitted. Longwave radiation is emitted from the entire Earth surface and hence:

$$E_{out} = \sigma T_E^4 \cdot A_E = \sigma T_E^4 \cdot 4\pi R_E^2$$



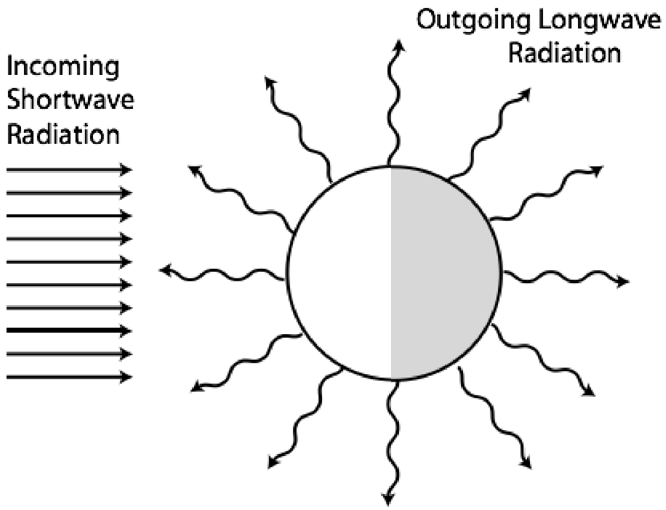
# Earth's Radiative Balance (1)

On average the energy absorbed and emitted by Earth have to balance, as otherwise the system would heat or cool indefinitely. We can calculate the temperature the Earth emits at by assuming a balance of incoming and outgoing energy:




$$E_{in} = E_{out}$$

# Earth's Radiative Balance (2)




$$E_{in} = E_{out}$$

$$S_0\left(1 - A\right) \cdot \pi R_E^2 = \sigma T_E^4 \cdot 4\pi R_E^2$$

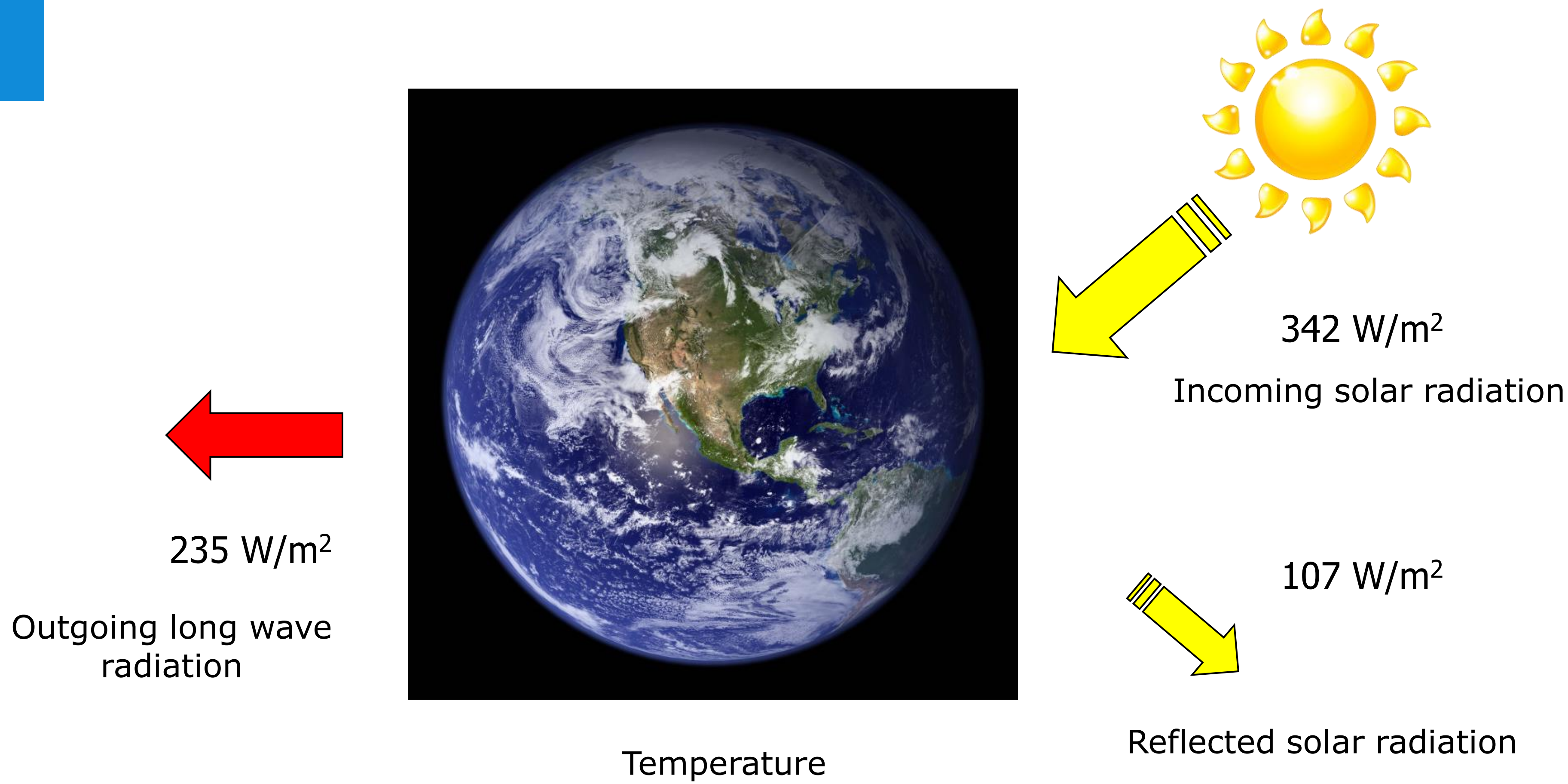
$$\frac{S_0}{4}\left(1 - A\right) = \sigma T_E^4$$

$$T_E^4 = \frac{S_0\left(1 - A\right)}{4\sigma}$$

$$T_E = \sqrt[4]{\frac{S_0\left(1 - A\right)}{4\sigma}} \approx 255K = -18^\circ C$$

The world's simplest climate model

# Global Energy Balance Summarized



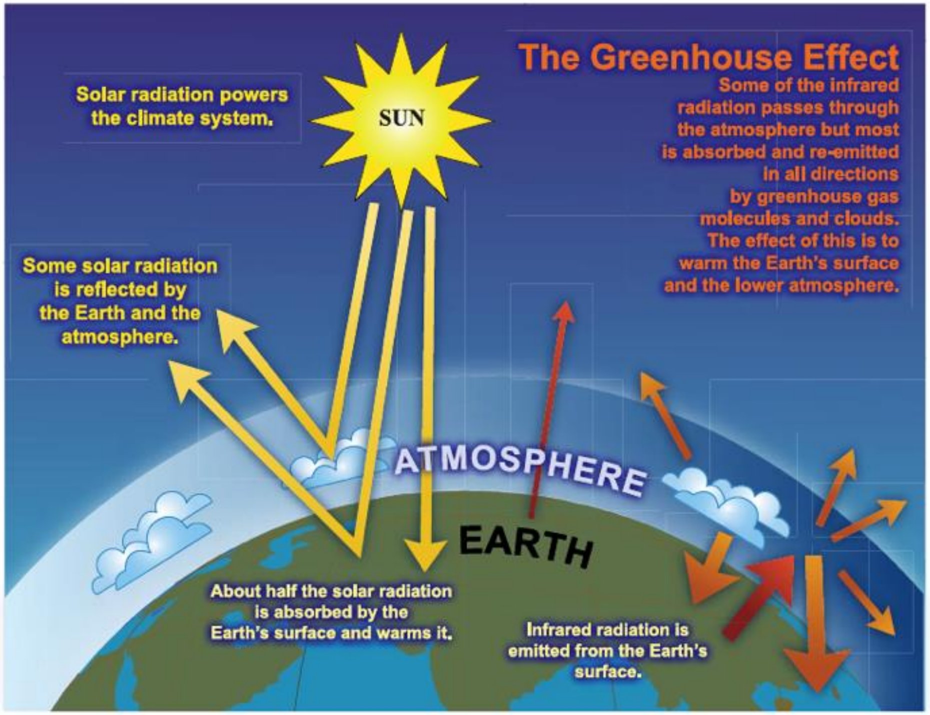
# Remarks

- We calculated that the temperature at which the Earth emits radiation is about -18$^o$C.
- If the Earth had no atmosphere, this would be the mean temperature at the surface.
- We know the observed mean surface temperature is about +15$^o$C.
- Hence the presence of the atmosphere increases the surface temperature by 33$^o$C.
- This is due to the Earth greenhouse effect, the magnitude of which can be calculated as:

$$\Delta T_g = T_S - T_E = 15^\circ C - \left(-18^\circ C\right) = +33^\circ C$$

# The Greenhouse Effect
# How does it work?

- The atmosphere contains gases that absorb the infrared radiation emitted from the surface and then re-emit it from the atmosphere in all directions.
- Some of this radiation will therefore be emitted downwards and be an additional source of energy at the surface, which leads to a warming at the surface!

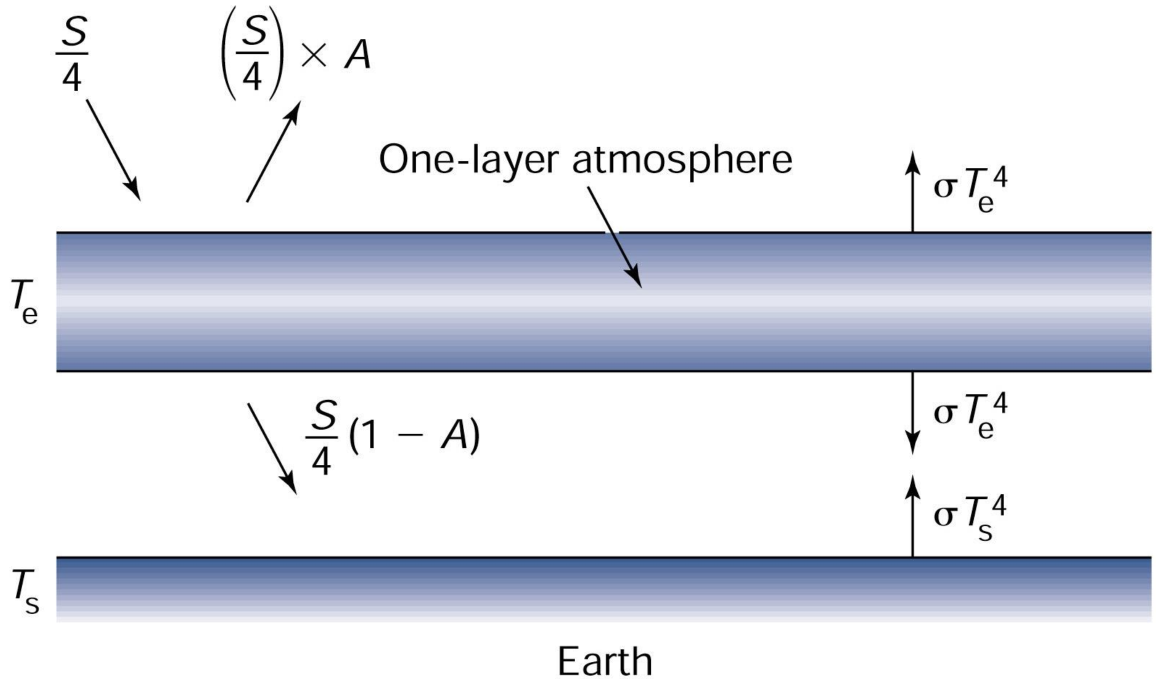



Source: IPCC, 2007

# The Greenhouse Effect
# The one-layer atmosphere (1)

We assume:

- The atmosphere to be a single layer that covers the Earth
- that the atmosphere has its own temperature $T_e$ that is different from the surface temperature of the earth $T_S$.
- that the atmosphere behaves like a black body



# The Greenhouse Effect
# The one-layer atmosphere (2)

Surface Energy Balance: $$\sigma T_s^4 = \frac{S}{4}(1-A) + \sigma T_e^4 \qquad (1)$$

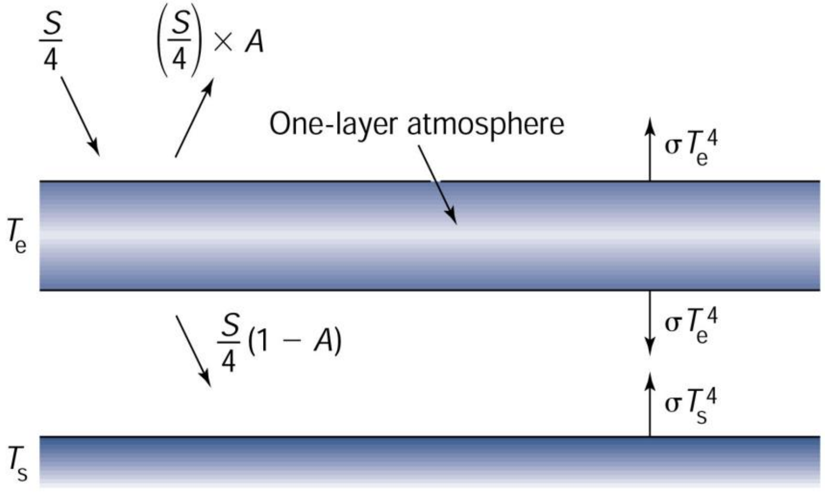
Atmosphere Energy Balance: $$\sigma T_s^4 = 2\sigma T_e^4 \qquad (2)$$

(2) in LHS of (1)

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

Divide (2) by σ and take 4th root:

$$T_S = \sqrt[4]{2} \cdot T_e$$



# The Greenhouse Effect
# The one-layer atmosphere (3)

So we have two equations for the two temperatures:

$$T_S = \sqrt[4]{2} \cdot T_e$$

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

The surface temperature is about 1.19 times the atmosphere temperature:

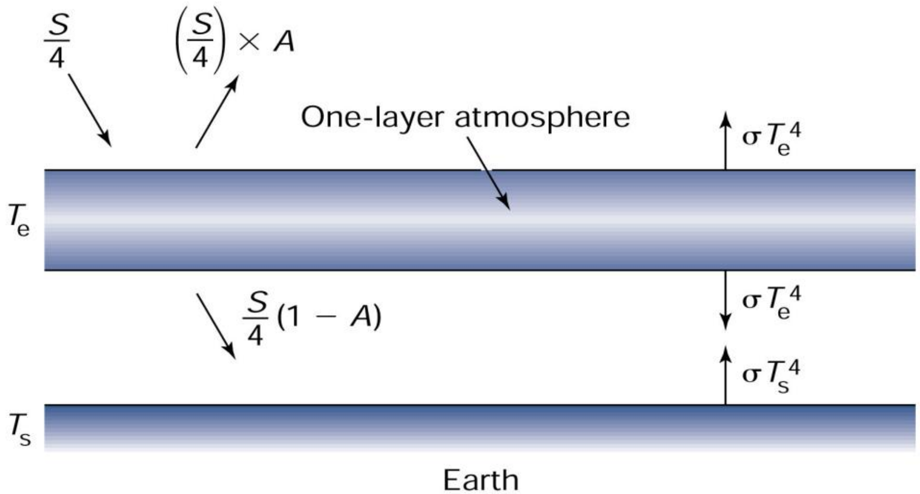
The greenhouse effect!

The same equation as before:

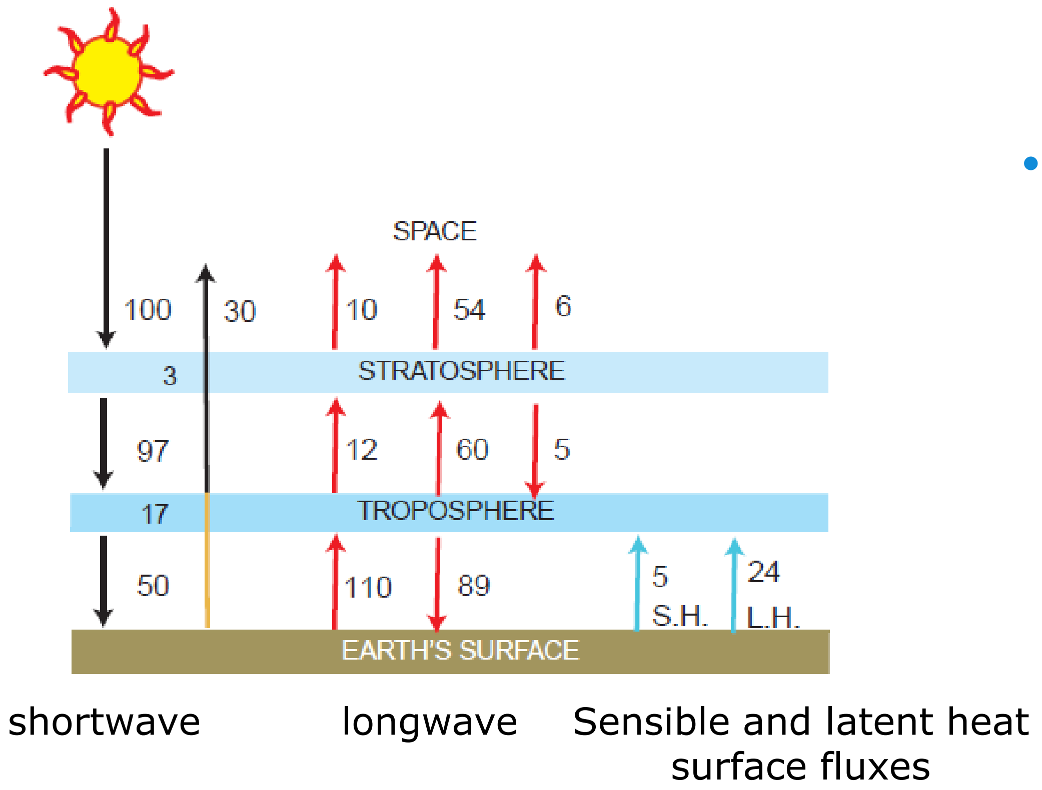
$T_e = 255K$

This gives a surface temperature of 303K and therefore a greenhouse effect of 48K!

Larger than observed!!



# Remarks



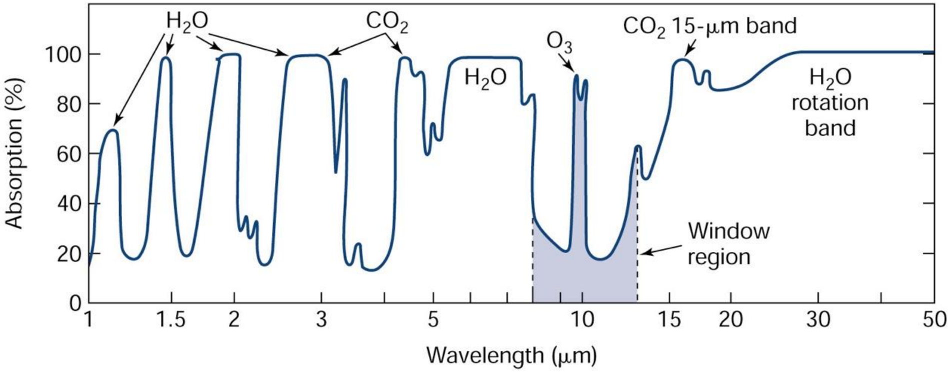

- Strength of Greenhouse effect is determined through by
  - ease with which solar radiation penetrates through the atmosphere (left column)
  - difficulty with which terrestial (longwave) radiation is transmitted through the the atmosphere (middle column)

- Main contributor of longwave trapping (clouds and water vapor 80%, CO2, O3, NOx, CH4 remaining 20%)
- Greenhouse effect not only maintains warm surface temperature, it also limits the diurnal cycle in surface temperature.

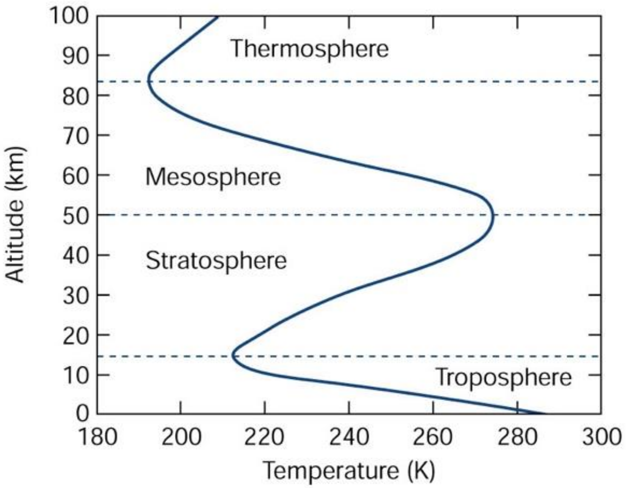
# Limitations of the one layer atmosphere model

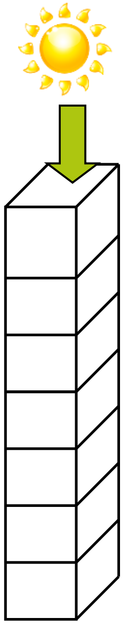
- Atmosphere does not behave as a black body and has a complex absorption spectrum for long wave radiation
- The atmosphere has a well defined vertical thermodynamic structure that is primarily the result of the interaction of the atmosphere with radiation
- Surface latent and sensible heat fluxes have an additional surface cooling effect. (radiative-convective equilibrium)

This requires a sophisticated 1-dimensional radiative transfer model





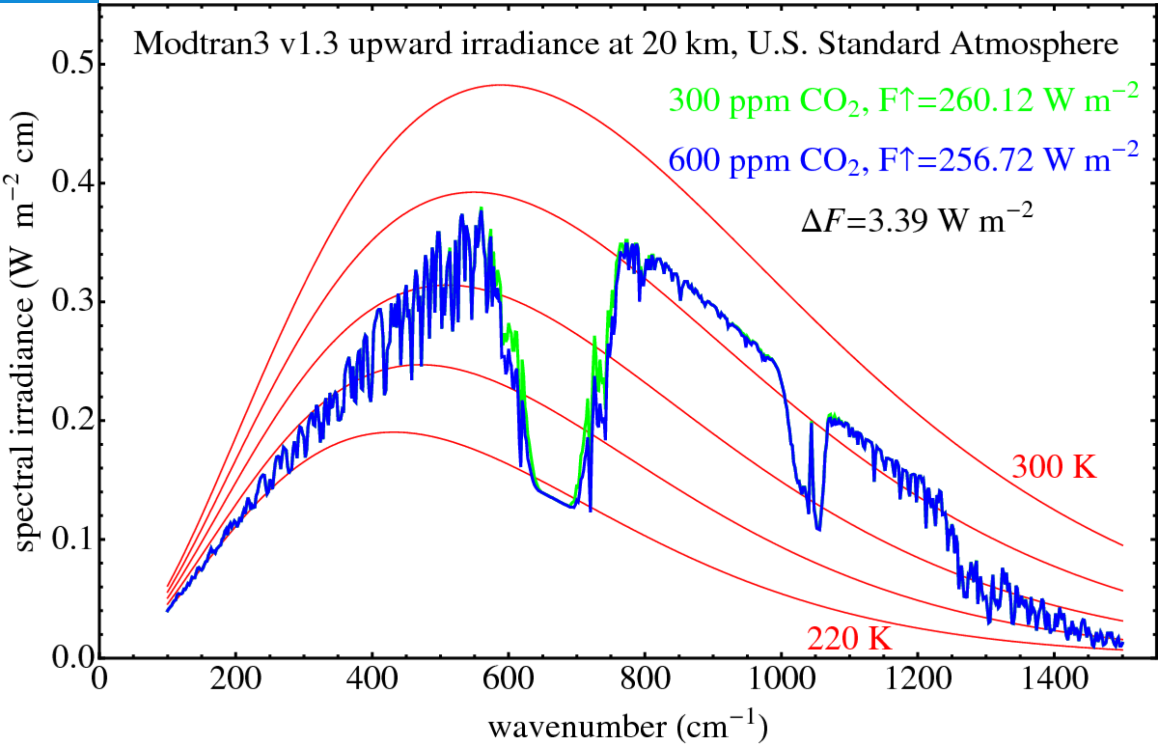


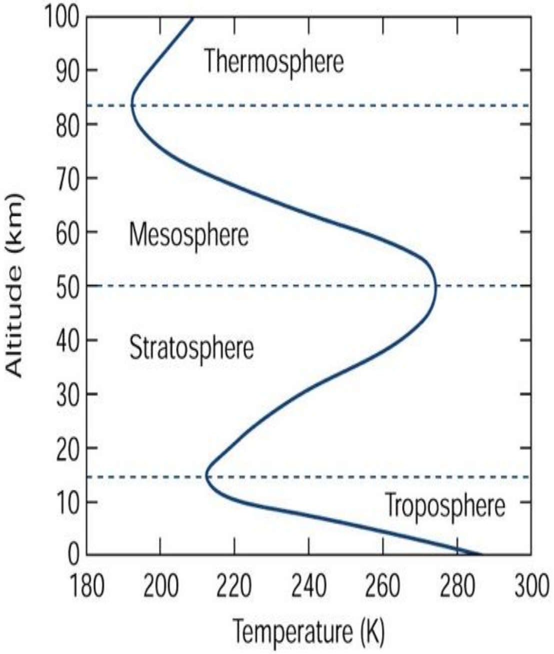



# 3.

*1-dimensional Radiative Transfer Model*

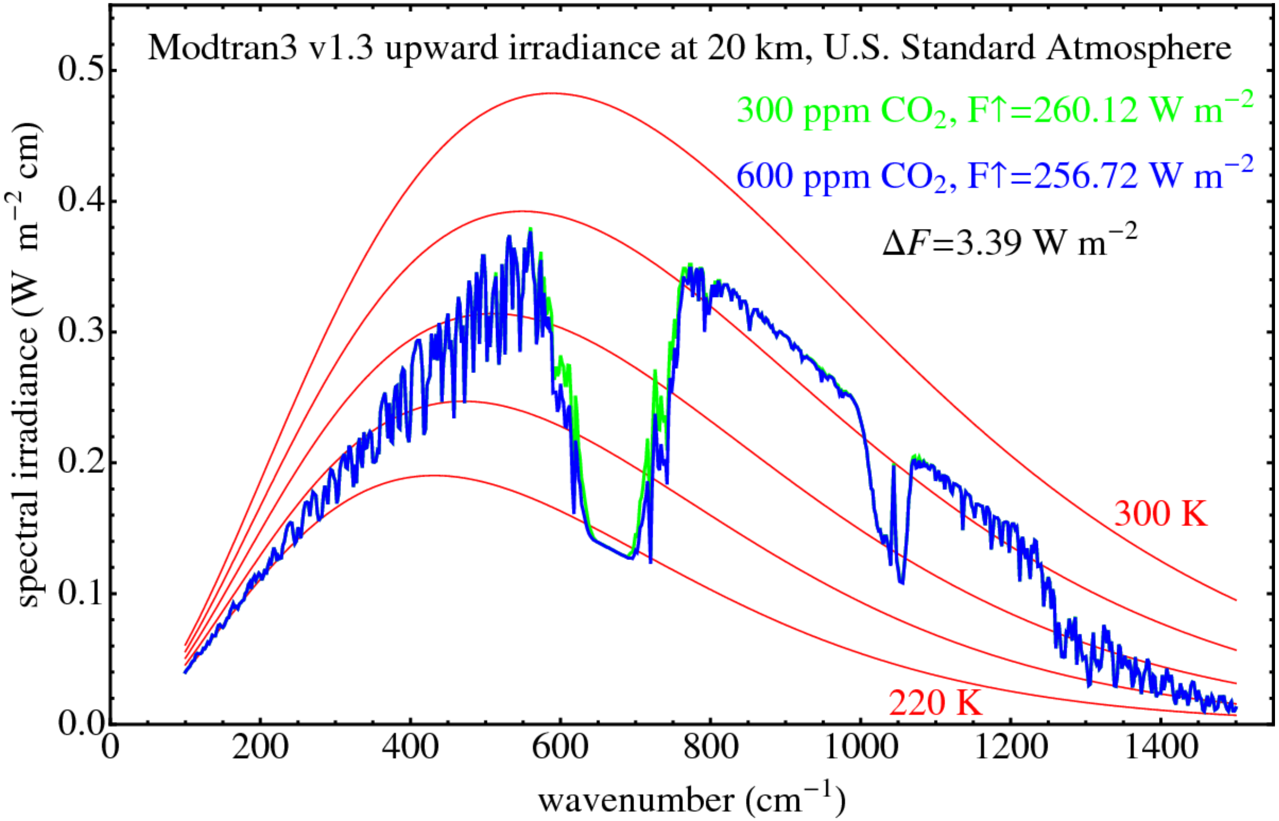
# Example of a radiative transfer calculation (1)




- Note that the that in certain parts of the electromagnetic spectrum the Earth resembles a blackbody, while in others it does not.
- This is due to the effect of absorption and re-emission of longwave radiation by greenhouse gases!

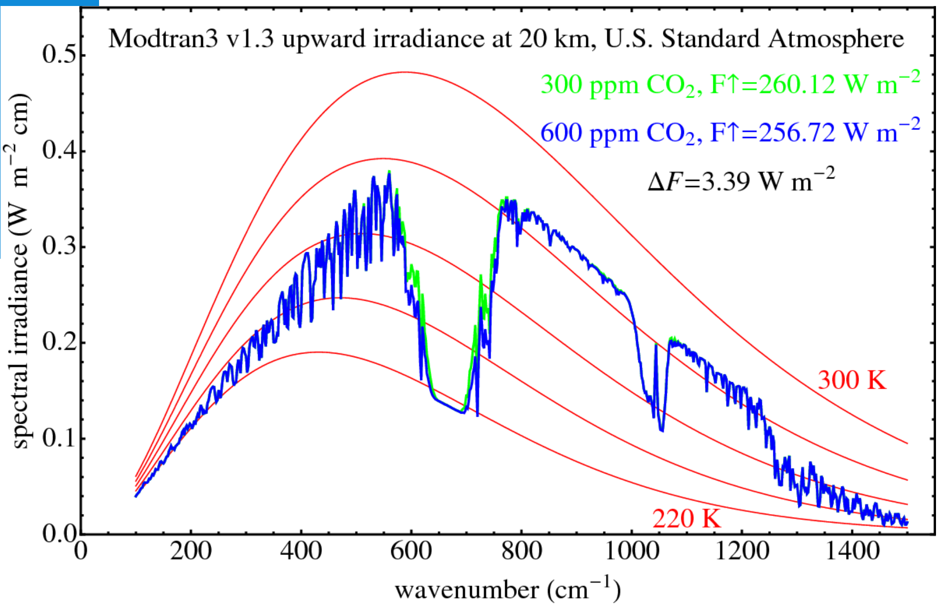
# Example of a radiative transfer calculation (2)

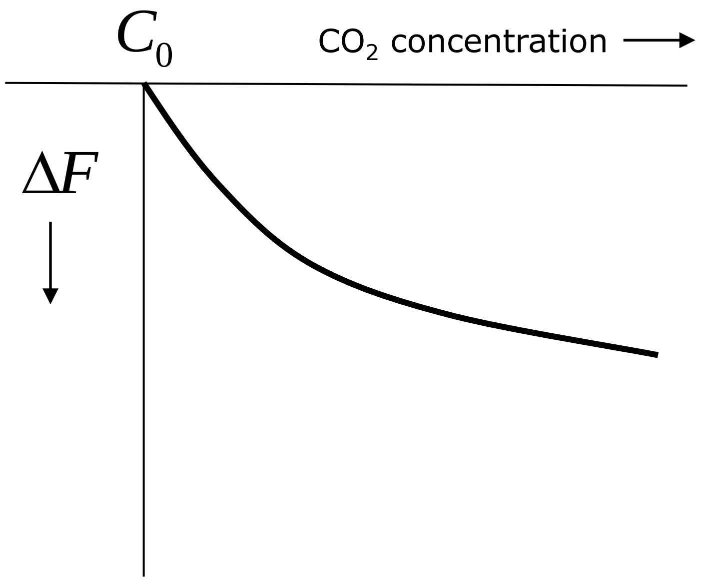



$$\Delta F \approx 3.39 W m^{-2}$$

- RTM can be used to calculate the change in outgoing longwave radiation at the atmosphere.
- Doubling of CO2 traps more infrared radiation which leads to a decrease of outgoing longwave radiation ( DF). This decrease is known as the radiative forcing (more on this later).

# Example of a radiative transfer calculation (3)




RTM calculations indicate $$\Delta F \approx 5.35 \times \ln\left(\frac{C}{C_0}\right) \quad Wm^{-2}$$

Pre-industrial concentration $C0_2$ = $C_0$= 285 ppm

Present day concentration $C0_2$ (2010) = 389 ppm

Doubled concentration $C0_2$ (20??) = 570 ppm

| $C0_2$ (ppm) | $\Delta F$ ($Wm^{-2}$) |
|---|---|
| 285 | 0 |
| 389 | 1.75 |
| 570 | 3.7 |

# What is Radiative Forcing?

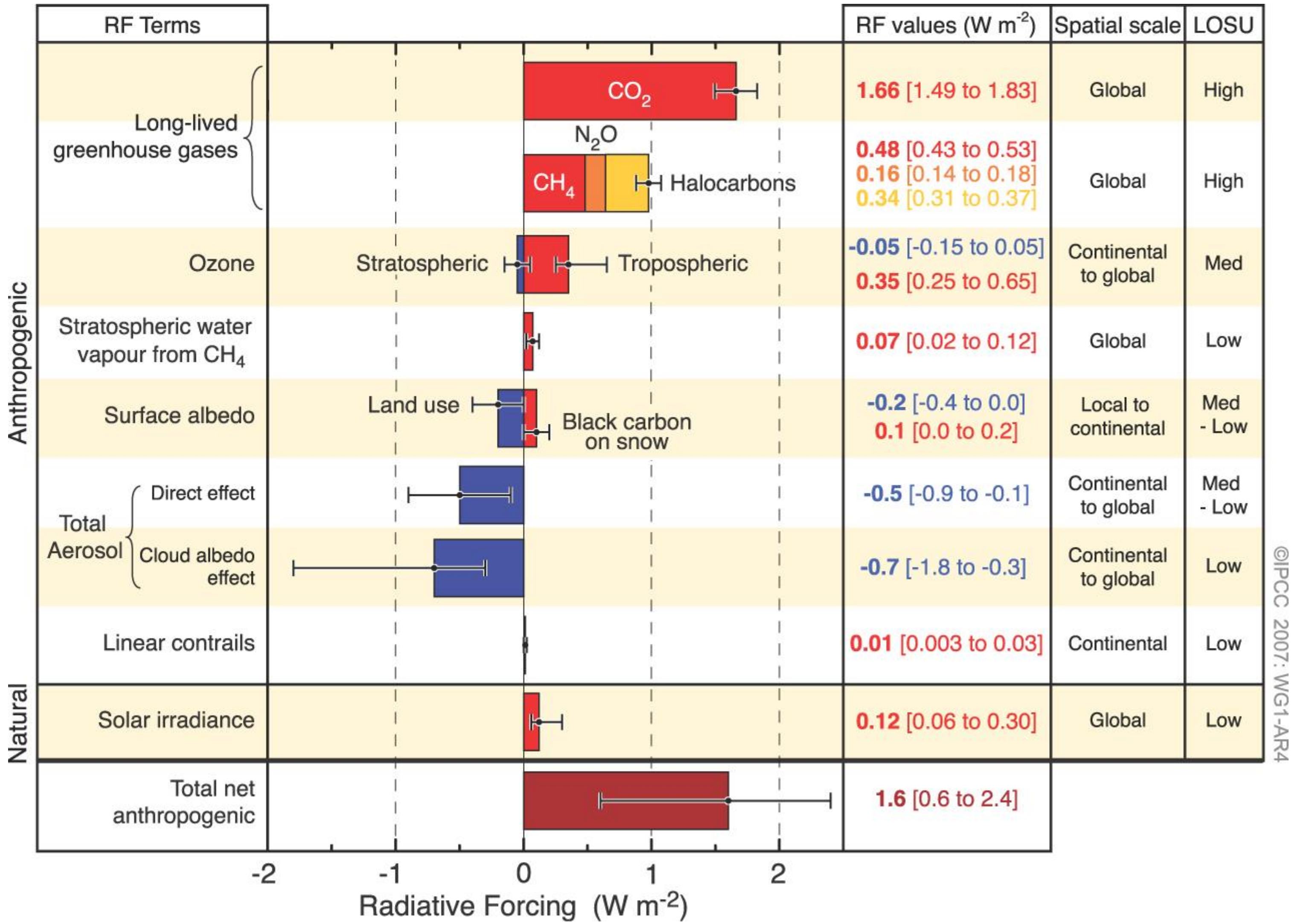
Definition:

"Radiative forcing is a measure of the influence a factor (think $CO_2$) has in altering the balance of incoming and outgoing energy in the Earth-Atmosphere system and is an index of the importance of the factor as a potential climate change mechanism. In this report (IPCC 2007) radiative forcing values are for changes relative to preindustrial conditions defined at 1750 and are expressed in watts per square meter ($W/m^2$)."

Remark: We have just calculated the radiative forcing for $CO_2$

Other important radiative forcings that are quantified in the IPCC report:

# Radiative Forcing Components (Source IPCC 2007)



# Droplet concentration and Radiation:

# "Indirect" aerosol effect

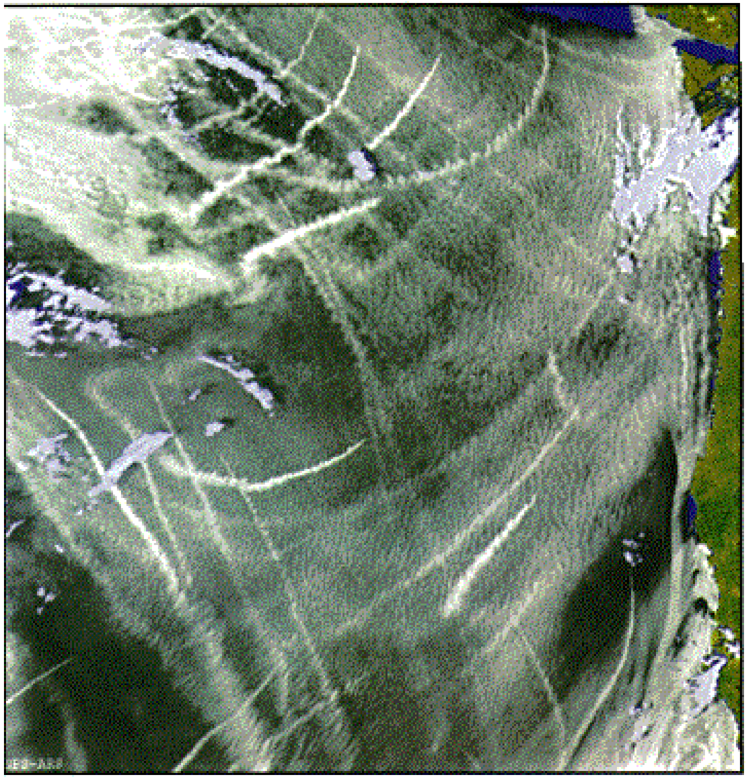


Figure 1: Ship tracks off the coast of Washington

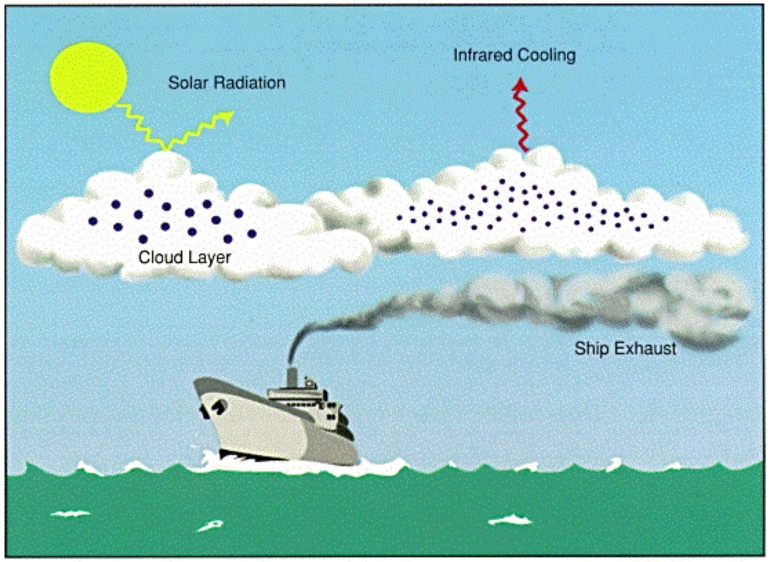
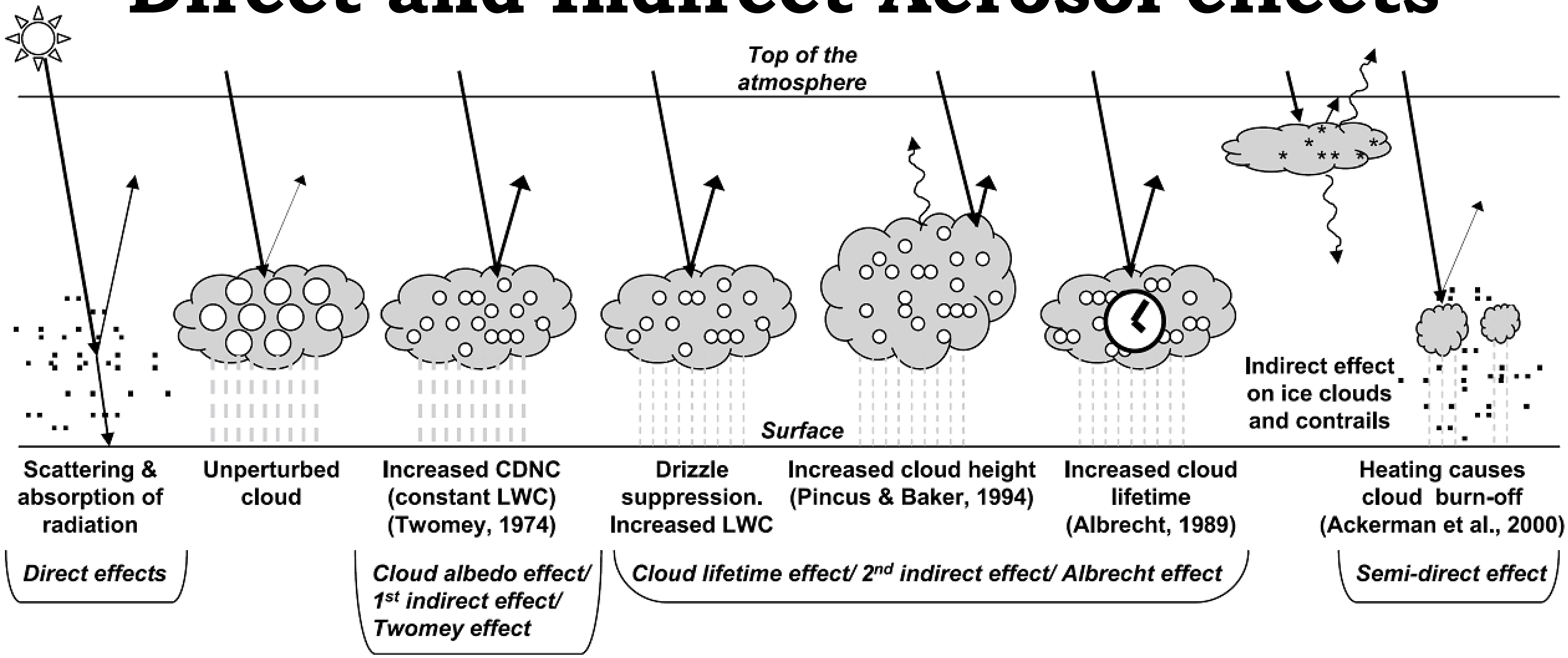



Figure 2: Illustration depicting the effects of aerosols from ship exhaust on cloud reflectivity

# Direct and Indirect Aerosol effects

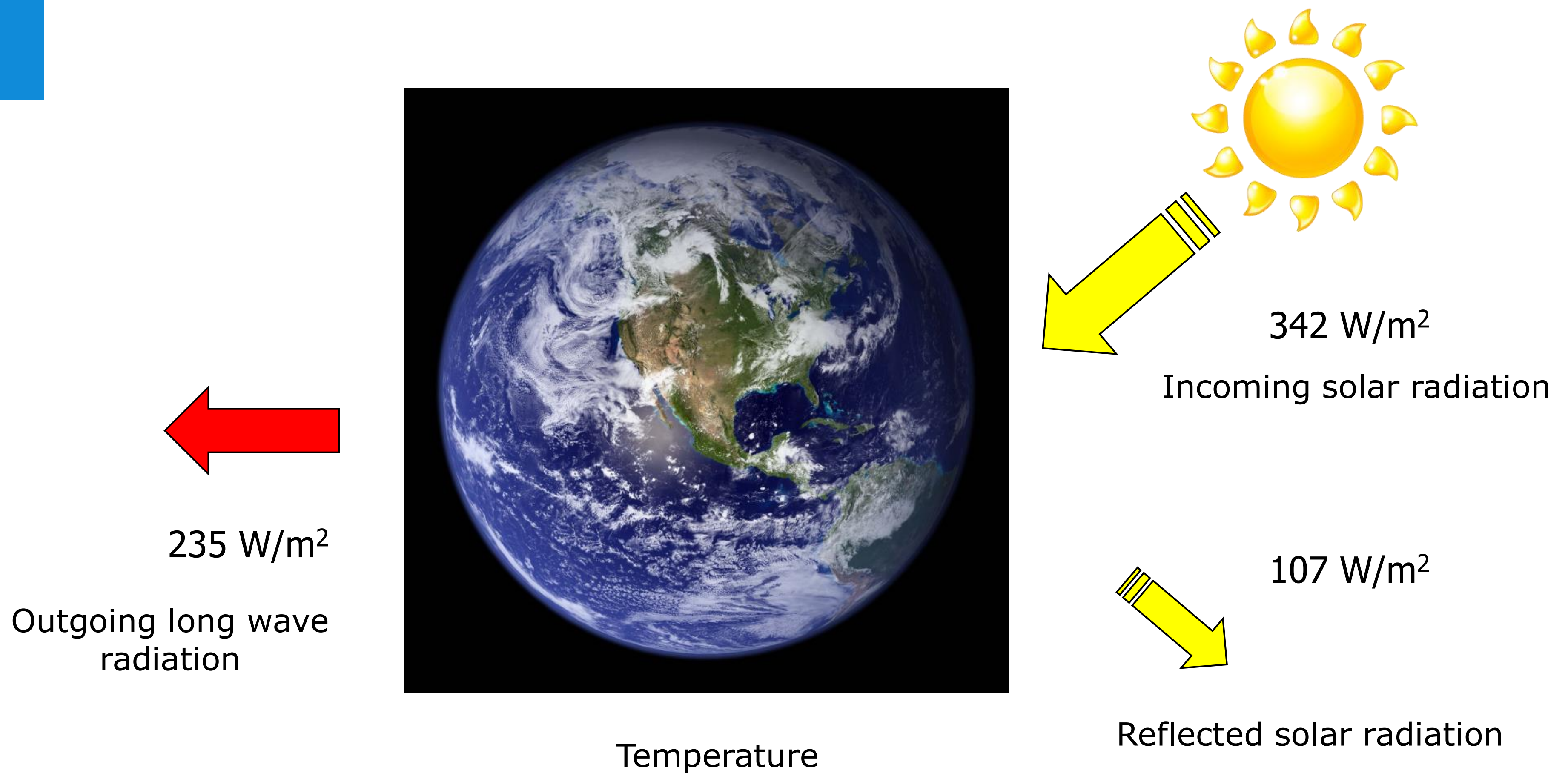



Remark: There is a thin line between forcing and response (or feedback). A certain degree of response is needed to evaluate the indirect effects of aerosols since they need to affect the clouds, the radiative properties and their lifetime. So is this a forcing or a response or feedback?? The debate on this continues until this day.

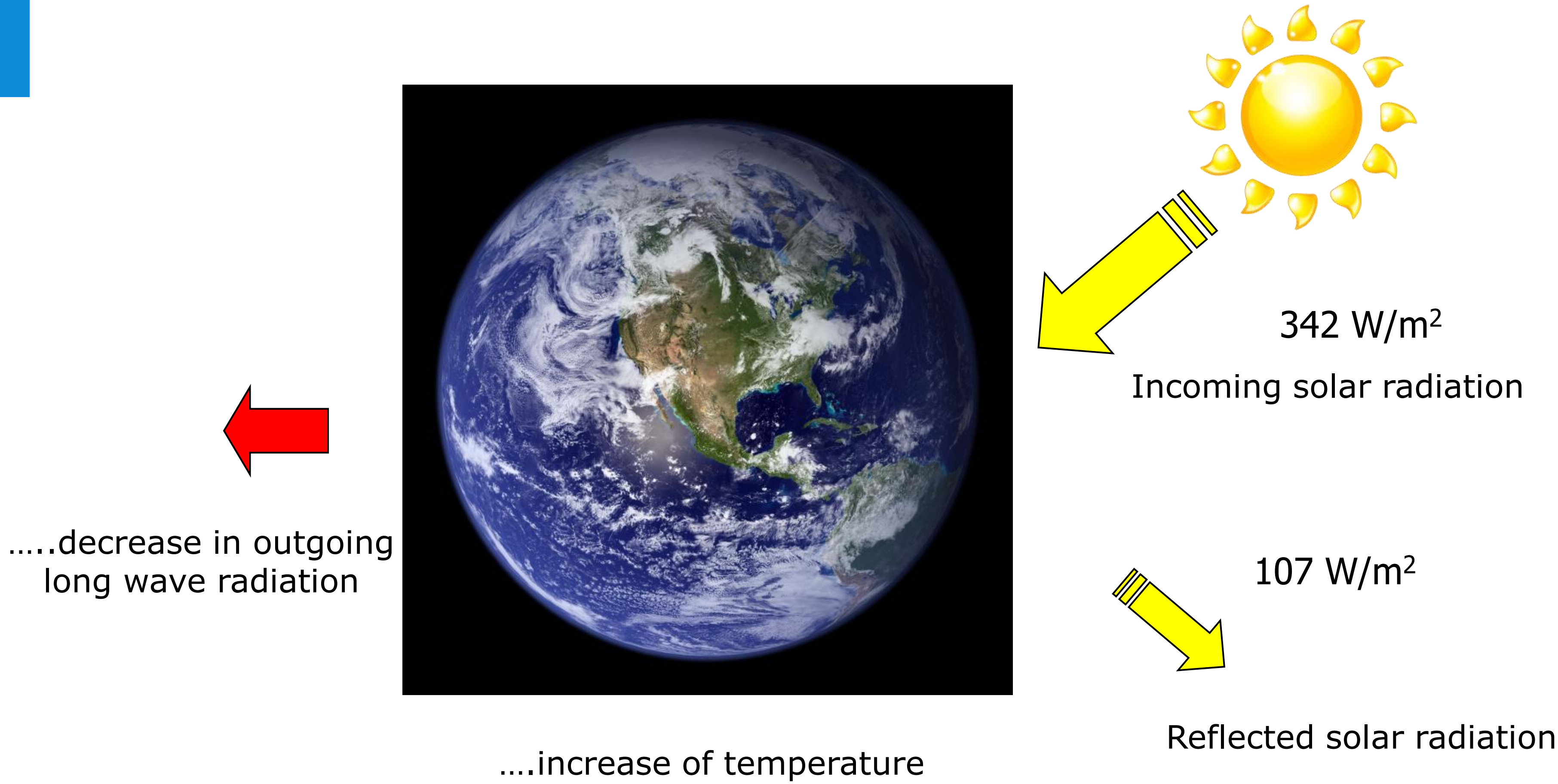
# Radiative Forcing: final remarks

- A useful concept that allows to quantify the relative strengths of the forcings to which the Earth-Atmosphere system has to respond.
- As the time window over which the radiative forcing is evaluated is increasing it will reduce the natural contributions as cyclic changes (solar 11 yr cycle) and vulcanic eruptions.
- Note that the determination of the radiative forcings can only be done with the help of models. It is impossible to vary the factors independently and also to keep the Earth’s surface temperature constant

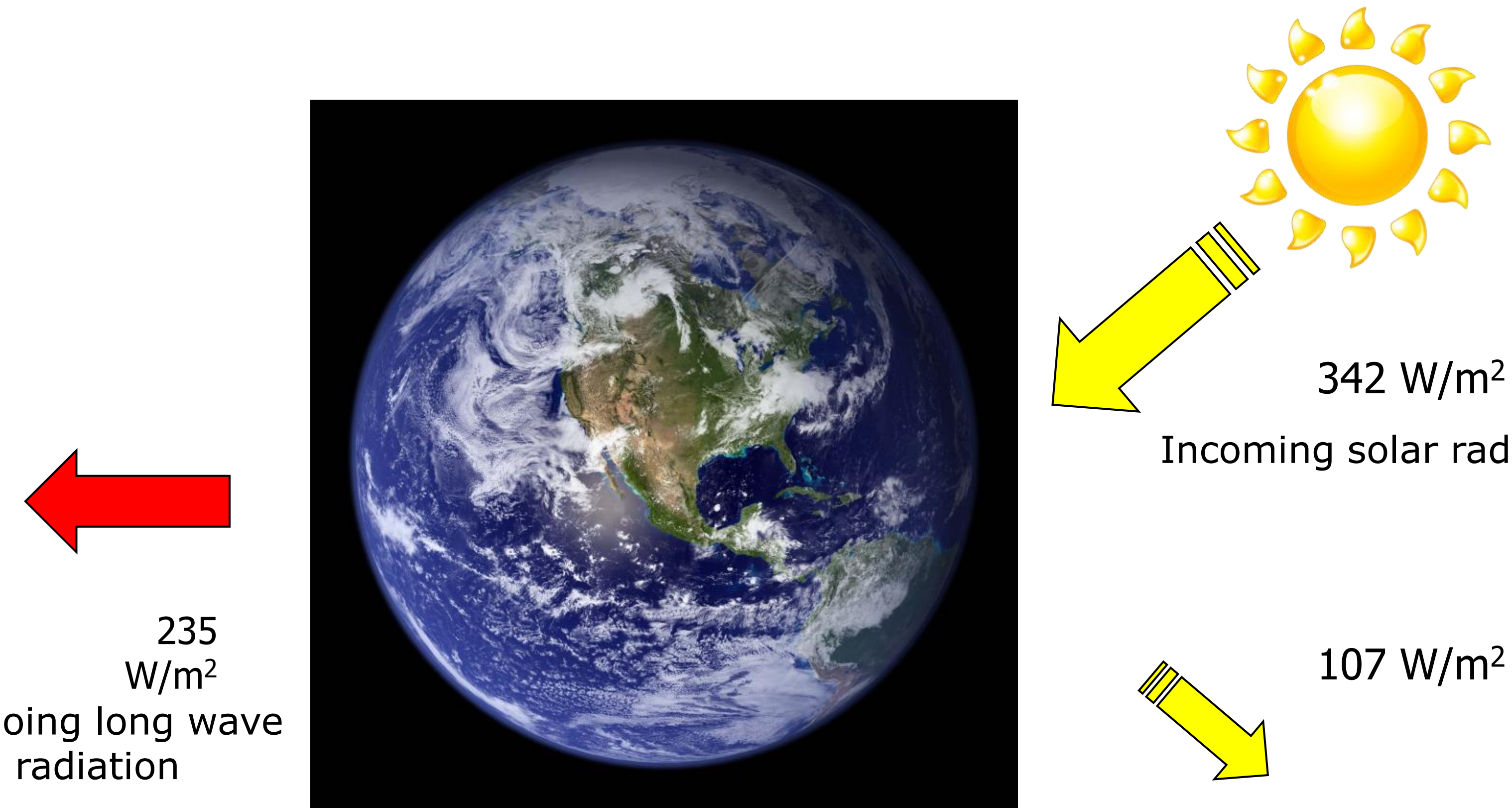
# Global Energy Balance



# Increase of Greenhouse Gases.......

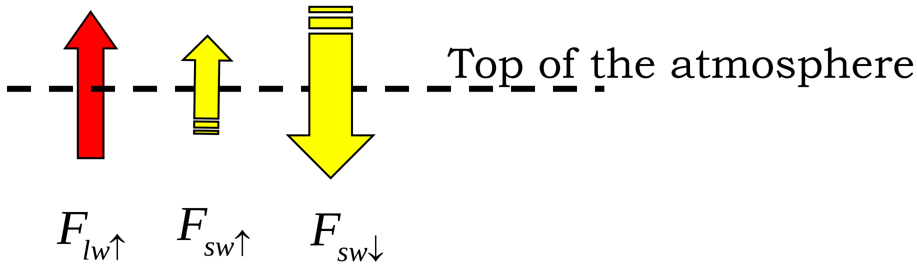


# ……restored new Equilibrium



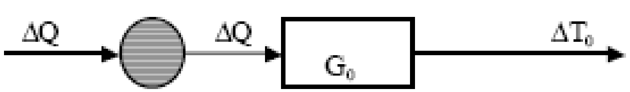

Higher equilibrium temperature

**Can we, given the radiative forcing, calculate this change of Temperature if $CO_2$ concentrations are doubled assuming a otherwise static climate?**




$$R = F_{sw\downarrow}(1-A) - F_{lw\uparrow} \approx 0$$
$$= \frac{S}{4}(1-A) - \sigma T^4 \approx 0$$

R: net radiation at the TOA




$$o \approx \delta R = \Delta Q + \frac{\partial R}{\partial T_s}\Delta T_s = \Delta Q + \lambda_p \Delta T_s$$

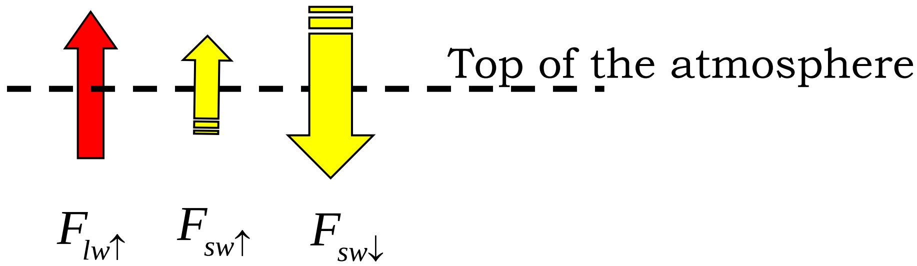
Radiative Forcing

Zero feedback gain

If we now apply a radiative forcing $\Delta Q$ (for instance a CO2 doubling) the radiative equilibrium in a static climate can only be restored by increasing the temperature by an amount:

$$\delta R \approx \frac{\partial R}{\partial T_s}\Delta T_s$$

$\Lambda$ Planck Factor: change in TOA LW radiation per Kelvin.

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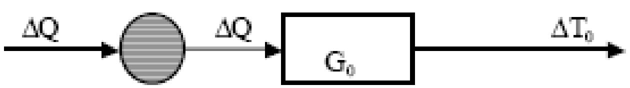



$$o \approx \delta R = \Delta Q + \frac{\partial R}{\partial T_s}\Delta T_s = \Delta Q + \lambda_p \Delta T_s$$

Radiative Forcing

Zero feedback gain

$$\lambda_P = \frac{\partial R}{\partial T_s} = 4\sigma T_s^3 = \frac{F_{lw\uparrow}}{T_s}4$$

$$\cong \frac{235x4}{280} \cong -3.4\,Wm^{-2}K^{-1}$$ Planck Parameter

$$\Delta Q = 3.7 Wm^{-2}$$ Forcing for 2XCO2

$$\Delta T_{s,P} \equiv -\Delta Q / \lambda_P = 1.1K$$ Direct Warming

## Can we calculate the change of Temperature if $CO_2$ concentrations are doubled assuming a otherwise static climate?

- Yes assuming everything else remains constant the temperature will increase by 1.1 K.

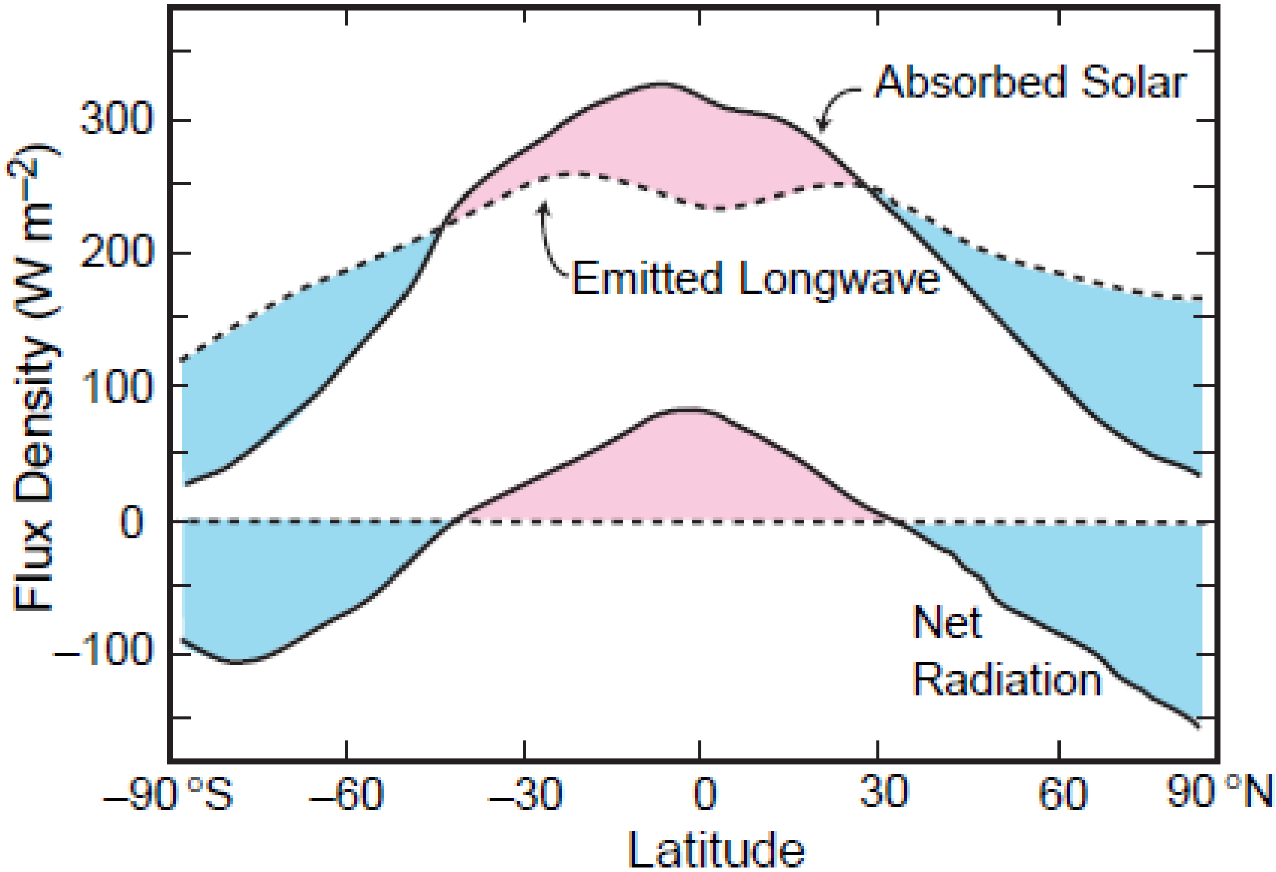
- This so called direct enhanced Green House effect is well accepted and there is little debate on this number.

- However our climate system  is not static but is a dynamical system that contains many feedbacks. This requires full 3-dimensional dynamical modeling

# 4.

*General Circulation Models*

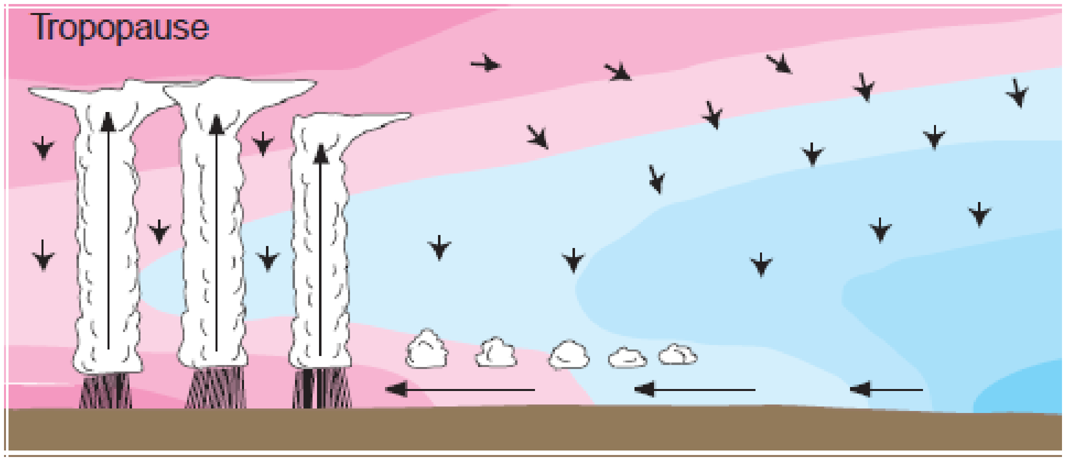
## Imbalance of the net radiative balance as a function of latitude



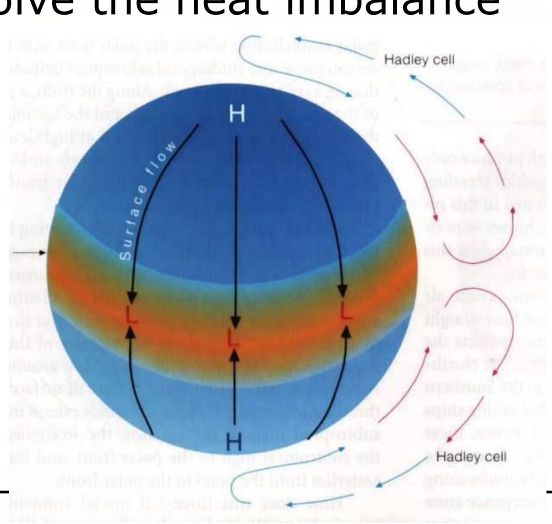

Net warming in the tropics and a net cooling toward the poles

That’s why it is warmer in the tropics than at the poles……….

This induces upward motion (convection) in the tropics and subsiding (downward) motion toward the poles

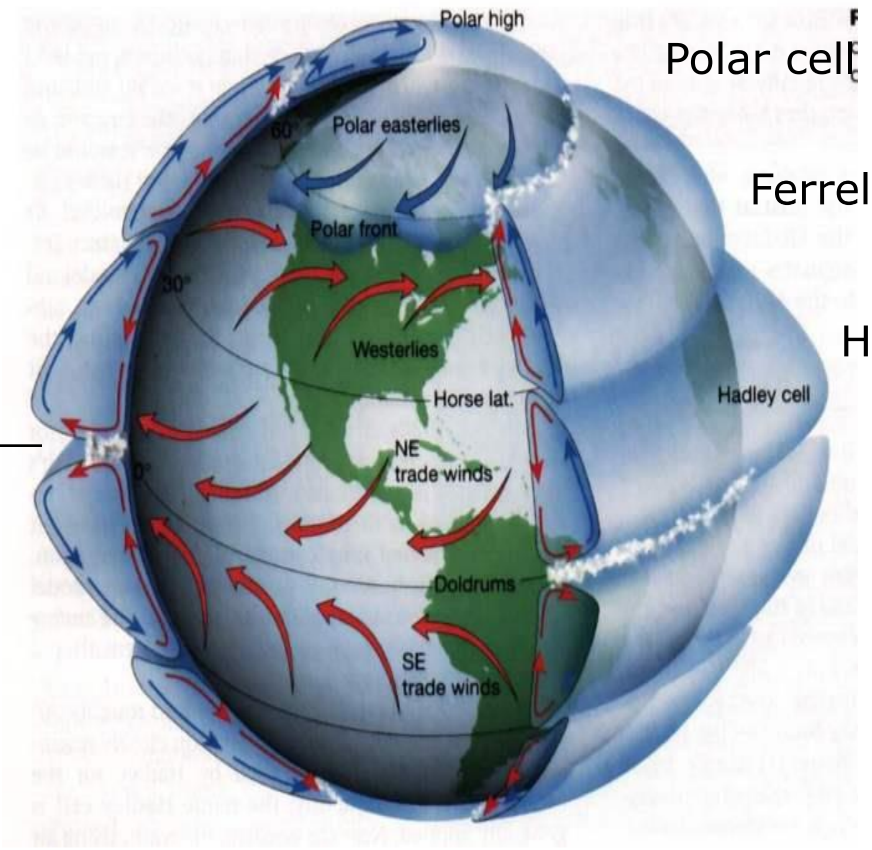



And sets up heat transport from the equator to the poles to resolve the heat imbalance




In absence of rotation of the earth……

# Switching on rotation: three cells



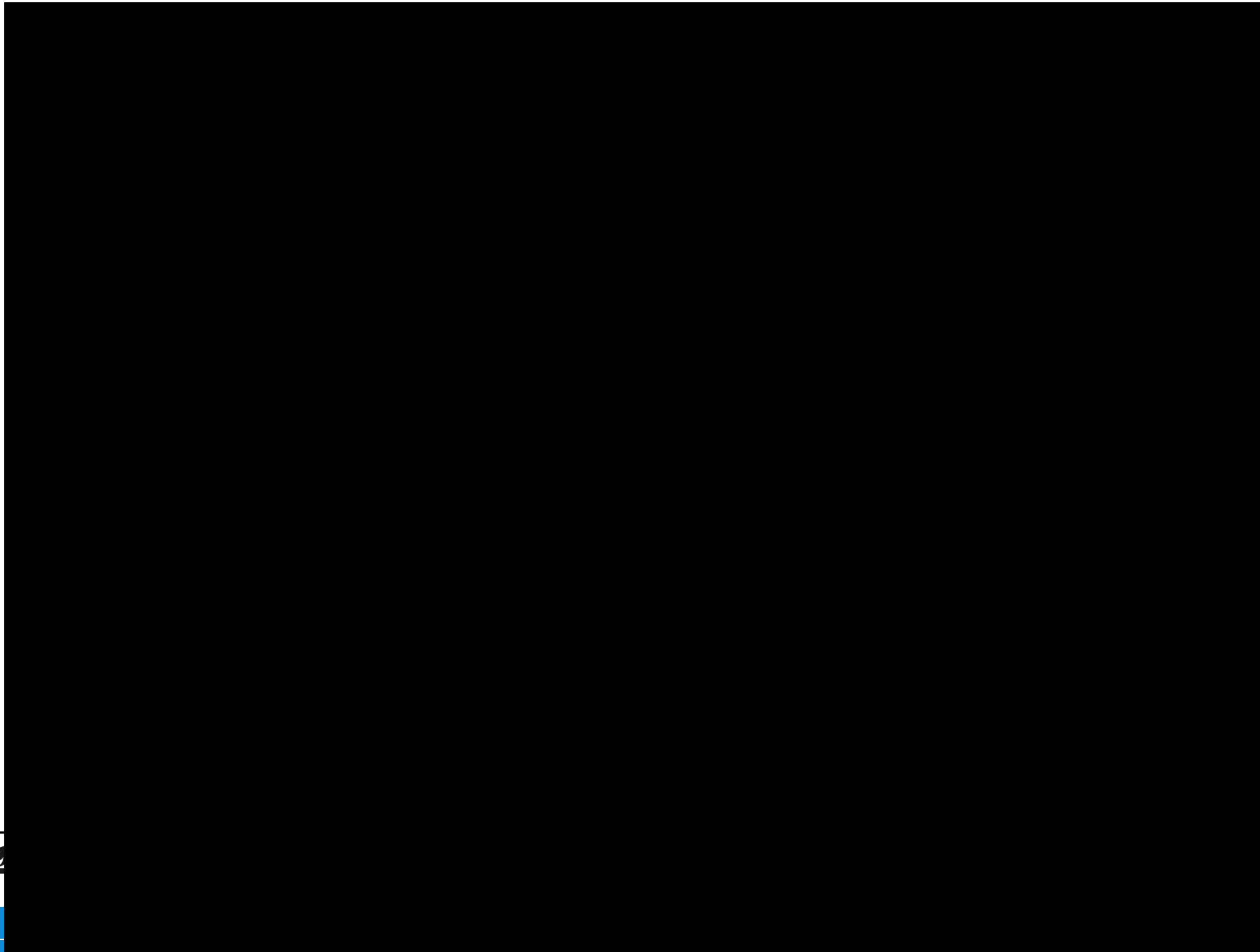

Polar cell

Ferrel cell

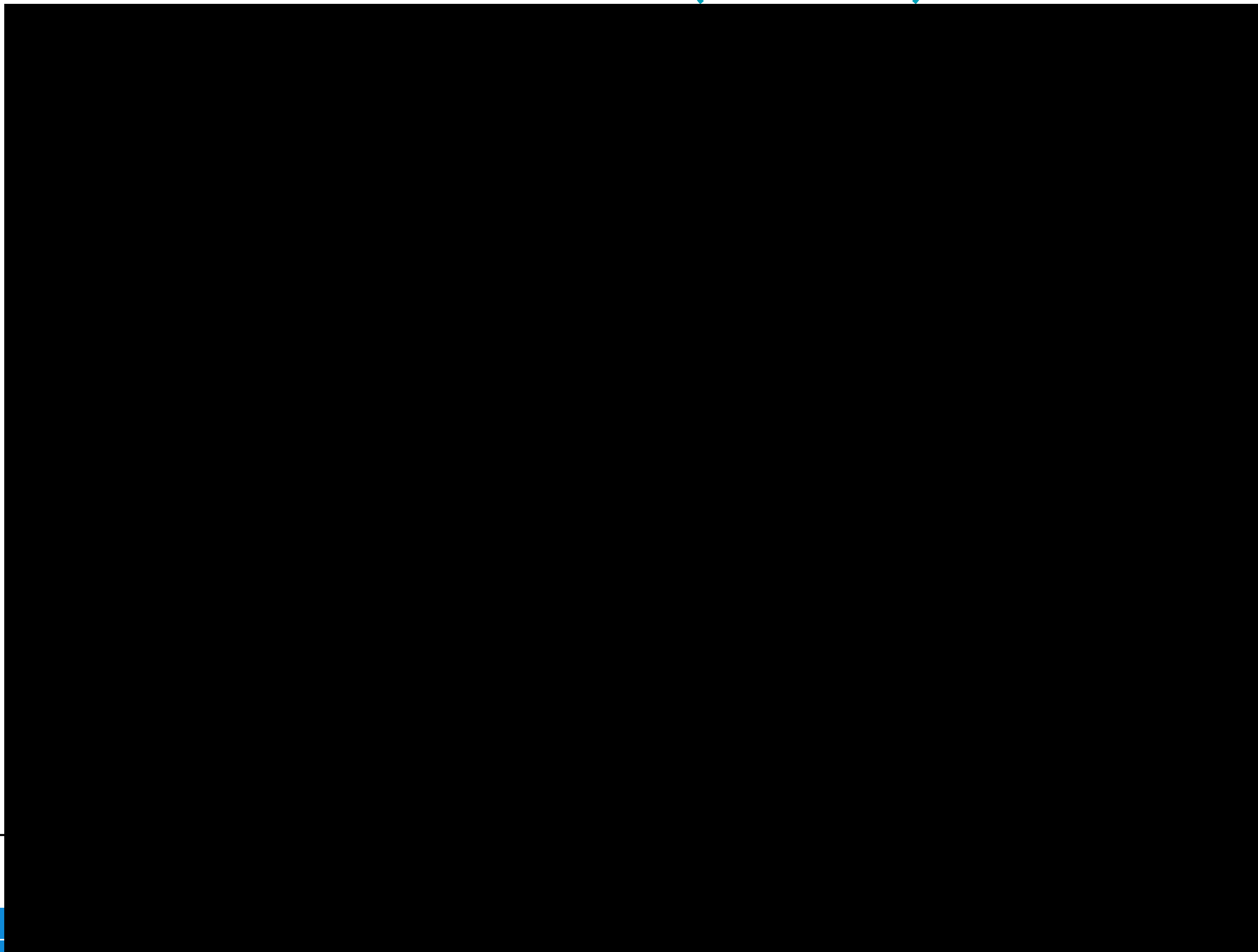
Hadley cell

Intertropical Convergence Zone (ITCZ)

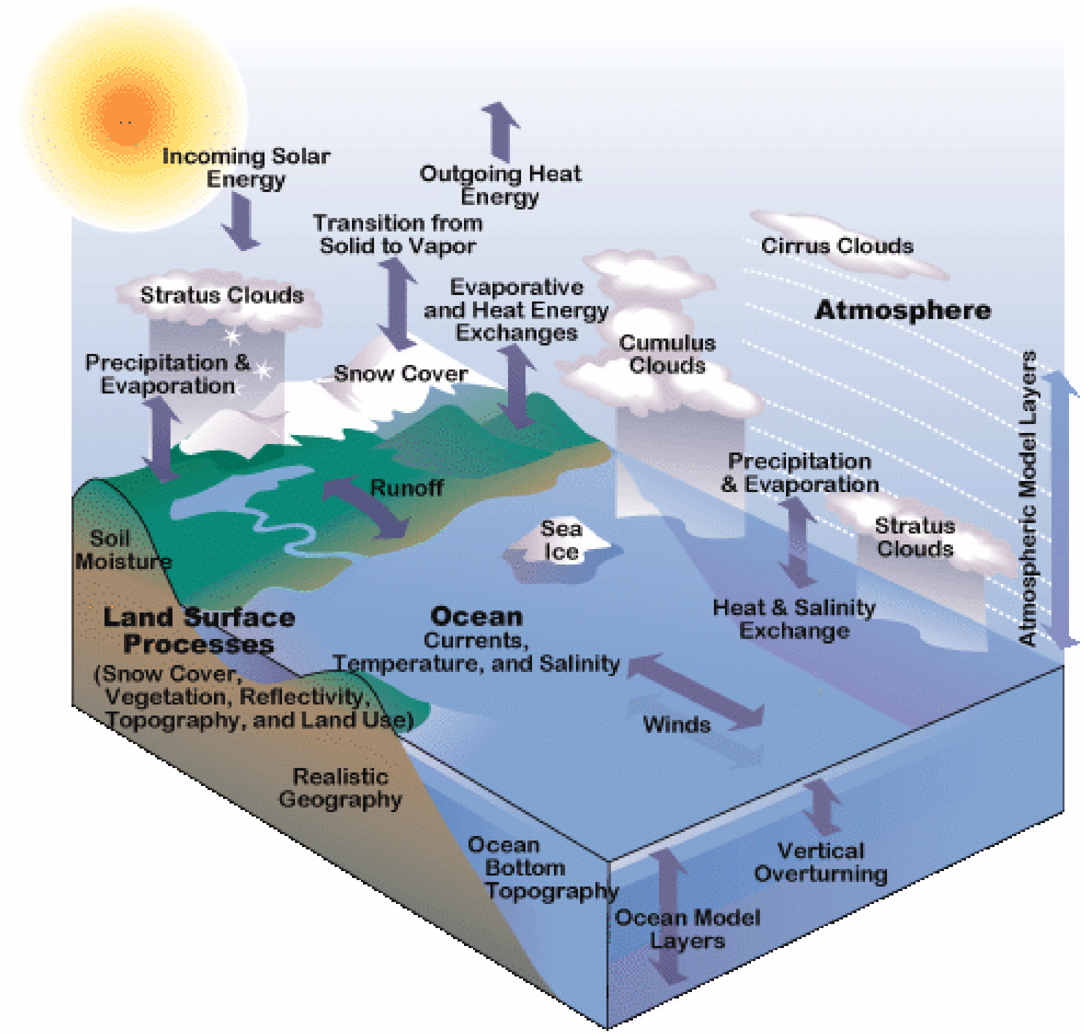
# Atmospheric Circulations as seen by geostationary satellites (infrared)



# Atmospheric Circulations as seen by geostationary satellites (infrared)



# General circulation models




Processes to include

# Atmospheric model Component

$$\frac{du}{dt} - \left(f + u\frac{\tan\phi}{a}\right)v = -\frac{1}{a\cos\phi}\frac{1}{\rho}\frac{\partial p}{\partial\lambda} + F_\lambda$$ E-W wind

$$\frac{dv}{dt} + \left(f + u\frac{\tan\phi}{a}\right)u = -\frac{1}{\rho a}\frac{\partial p}{\partial\phi} + F_\phi$$ N-S wind

$$g = -\frac{1}{\rho}\frac{\partial p}{\partial z}$$ vertical balance

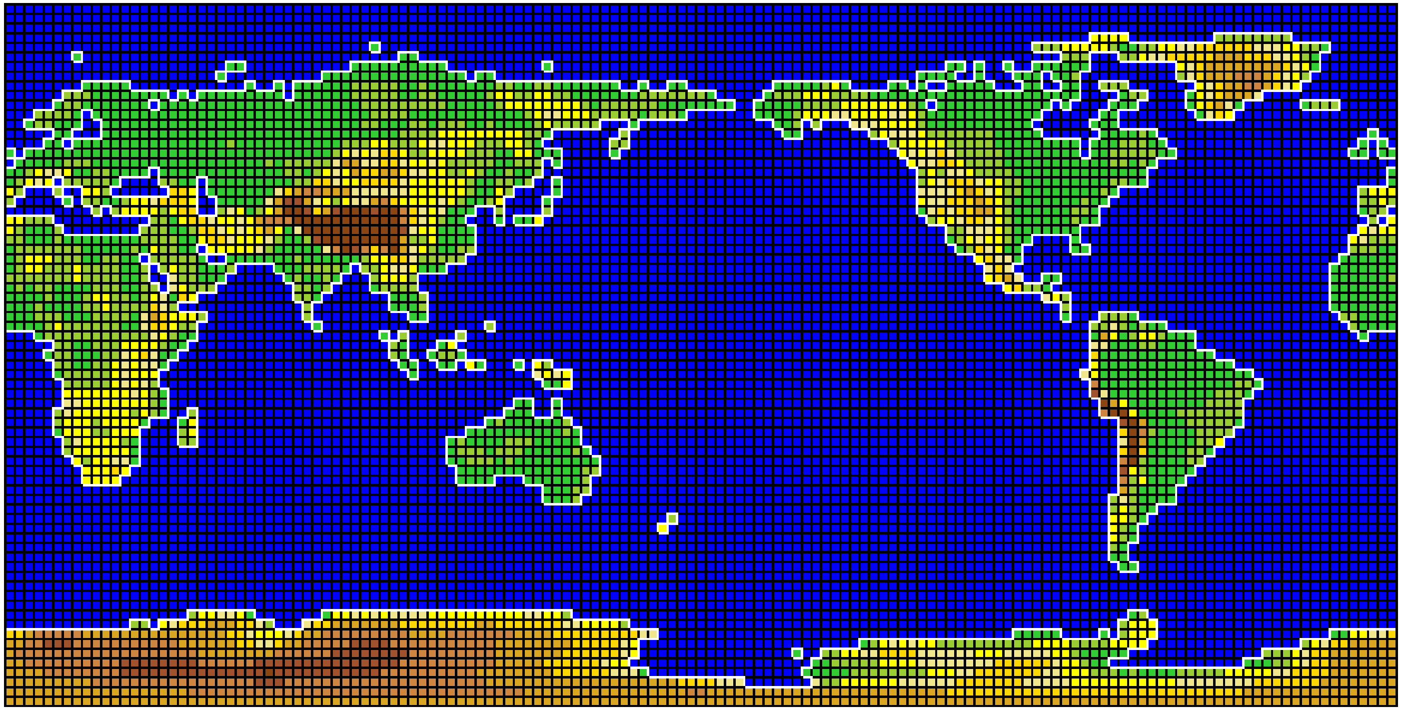
$$\frac{\partial\rho}{\partial t} = -\frac{1}{a\cos\phi}\left[\frac{\partial}{\partial\lambda}(\rho u) + \frac{\partial}{\partial\phi}(\rho v\cos\phi)\right] - \frac{\partial}{\partial z}(\rho w)$$ mass

$$c_p\frac{dT}{dt} - \frac{1}{\rho}\frac{dp}{dt} = Q$$ Temperature

$$p = \rho RT$$ Ideal Gas

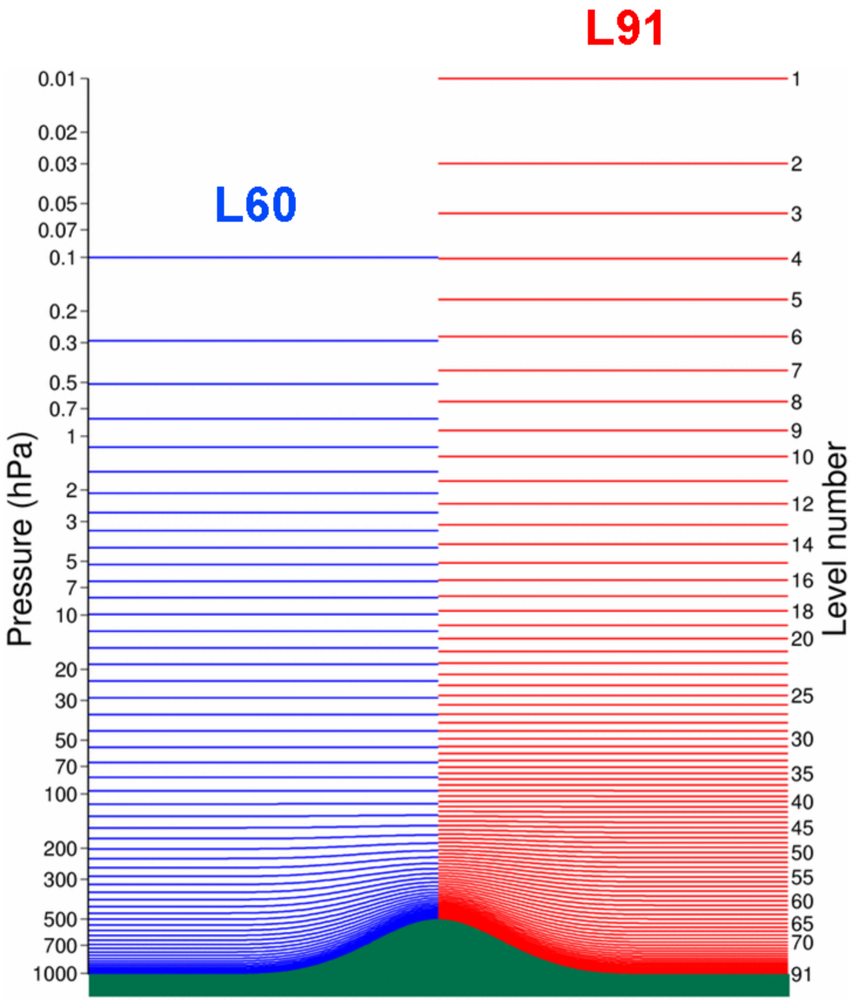
6 equations for 6 unknowns (u,v,w,T,p,ρ) - Moisture often added as 7th equation

# Atmospheric models - dicing up the world



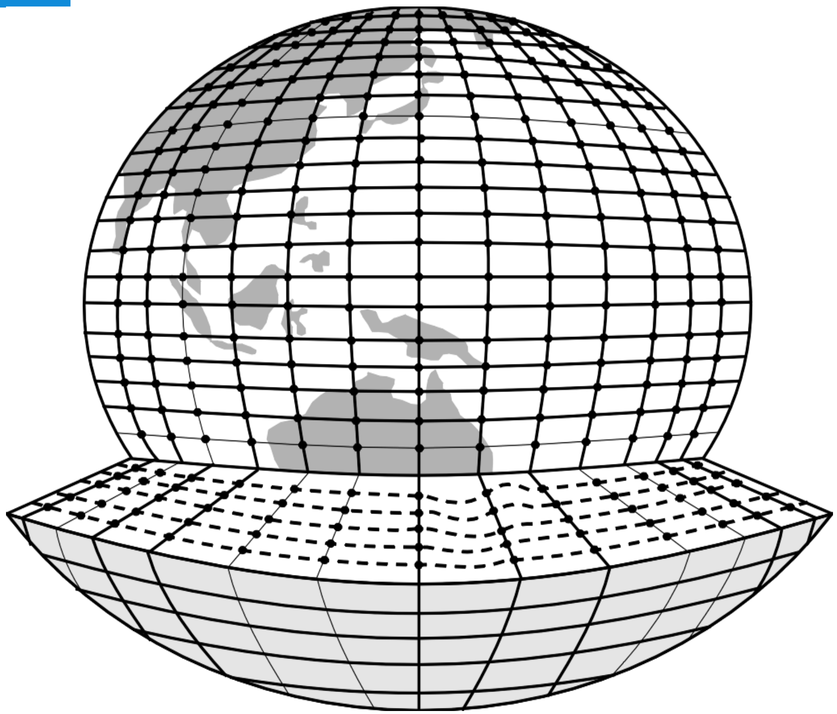
2.5 deg x 2.5 deg grid

# Atmospheric models - dicing up the world




Vertical levels

# Atmospheric models - dicing up the world



How many calculations does an atmospheric model alone have to perform:

2.5 x 2.5 degrees -> about 10,000 cells

30 layers in the vertical -> about 300,000 grid boxes

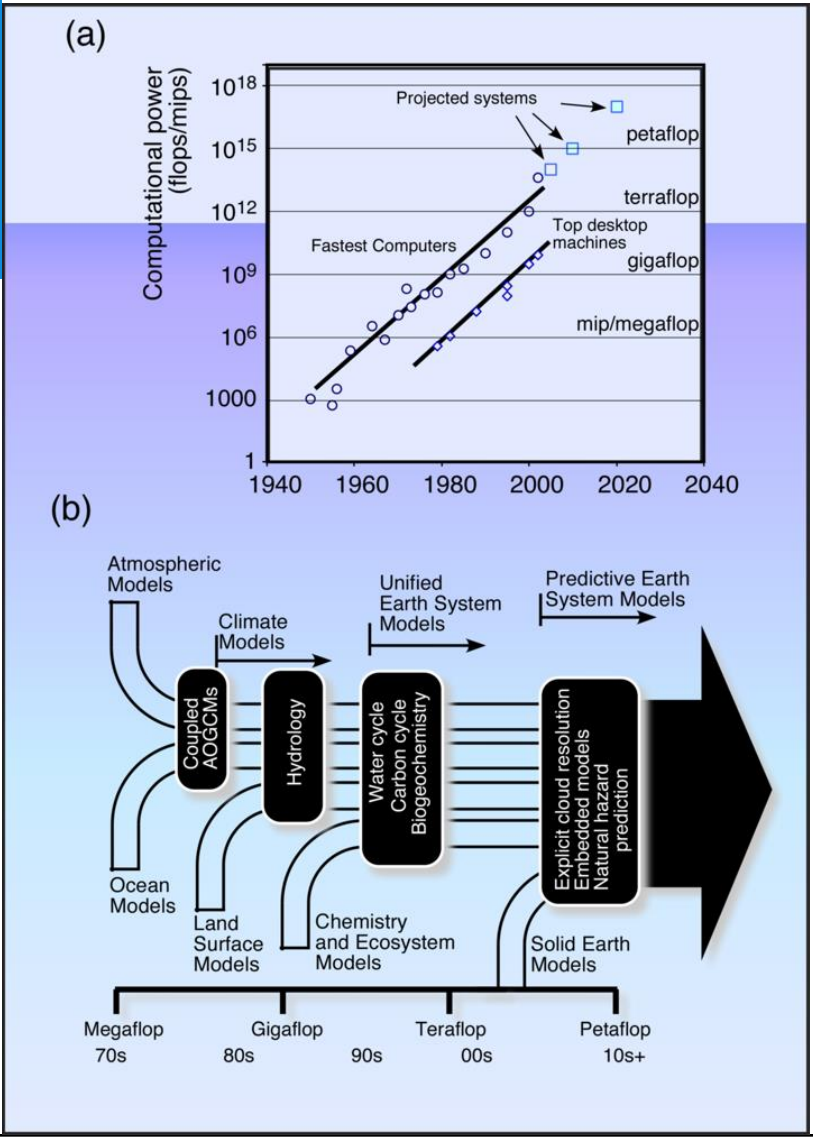
At least 7 unknowns -> about 2.1 million variables

Assume 20 calculations (low estimate) for each variable -> about 42 million calculations per time-step

Time step of 30 minutes -> about 2 billion calculations per day

100 years of simulation -> 73 trillion calculations

# Climate Computing

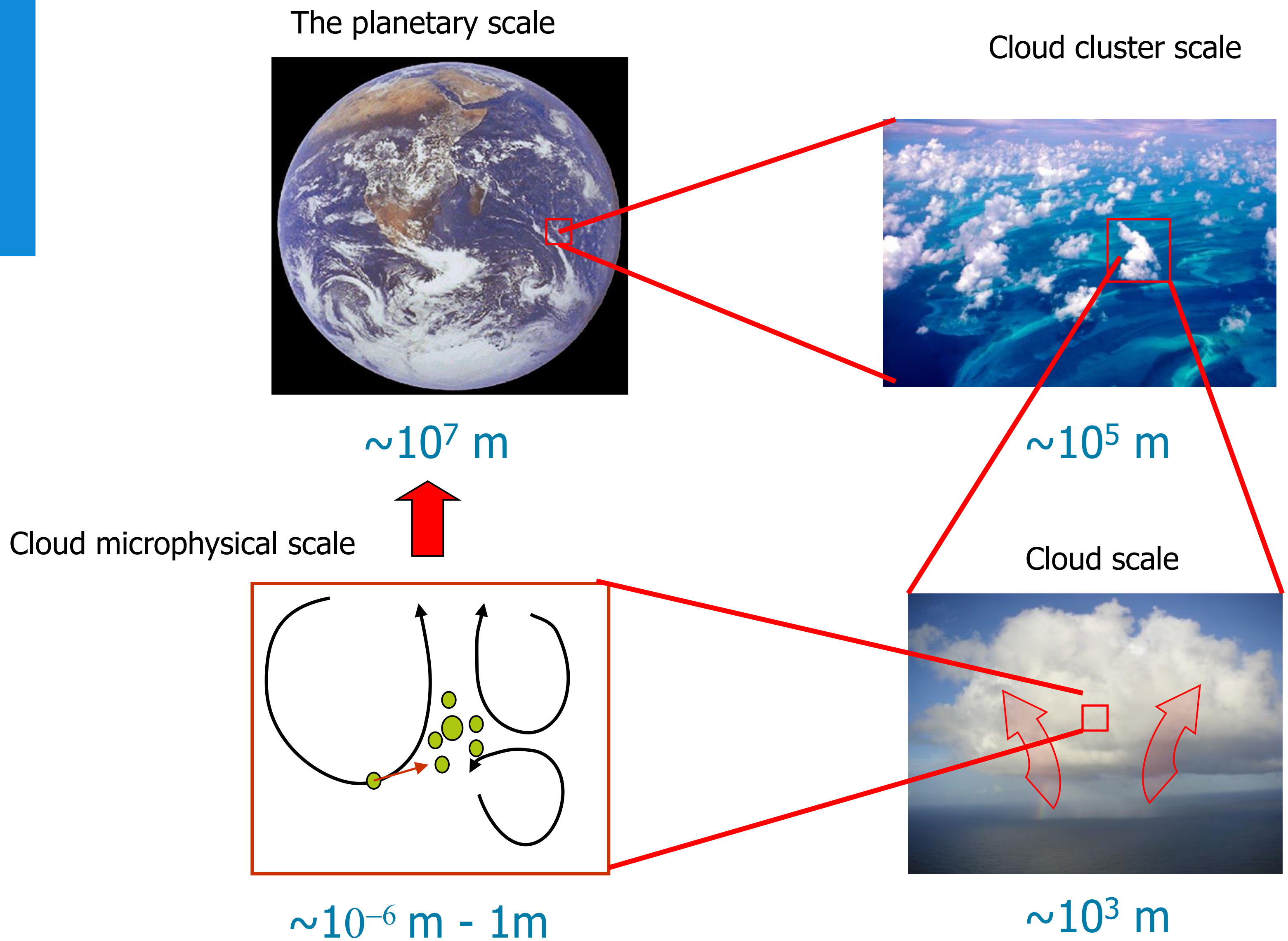



Climate modelling requires the use of the most powerful supercomputers on Earth, and even with those we have to simplify the models.

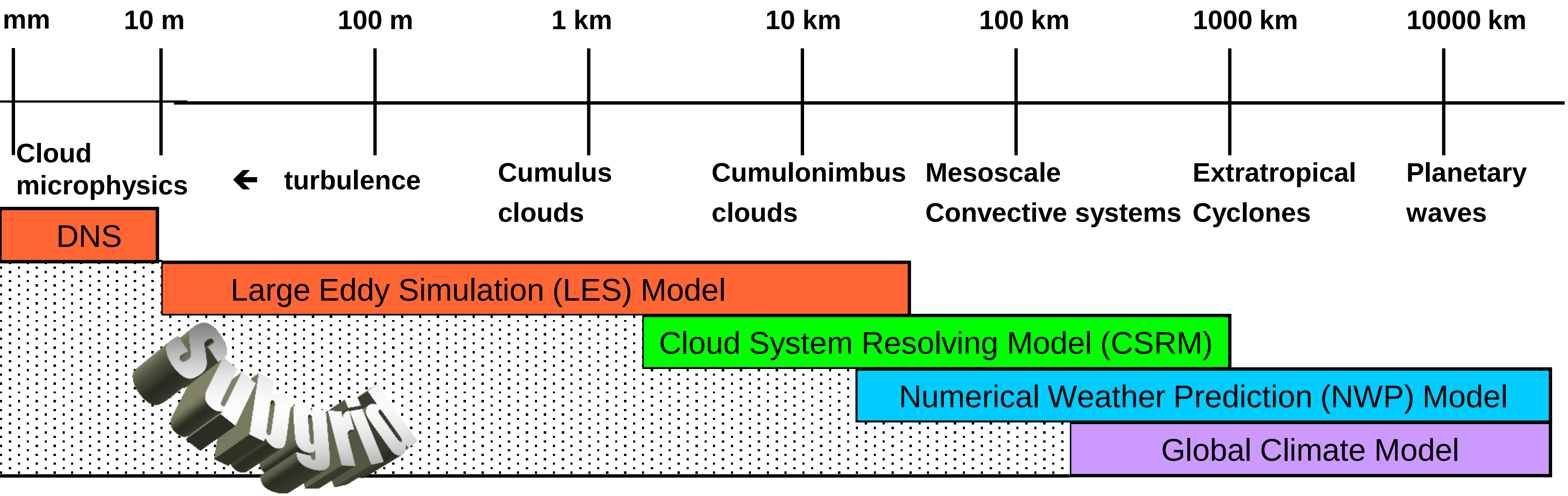
Climate modelling is therefore constrained by the computer capabilities and will be for the foreseeable future.

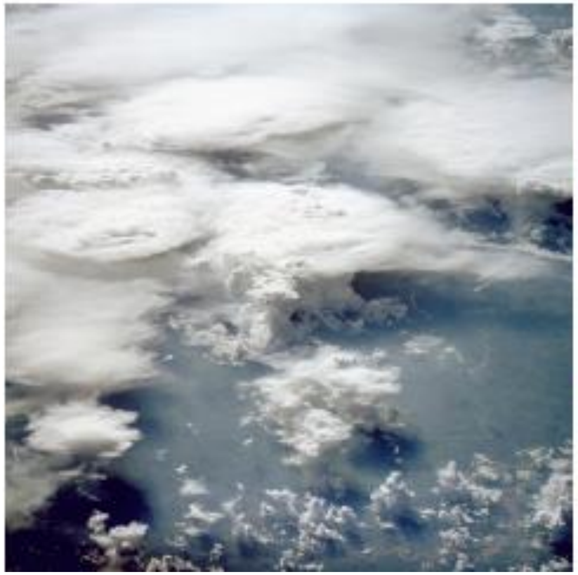
McGuffie and Henderson-Sellers, 2005

# The climate system : A truly multiscale problem

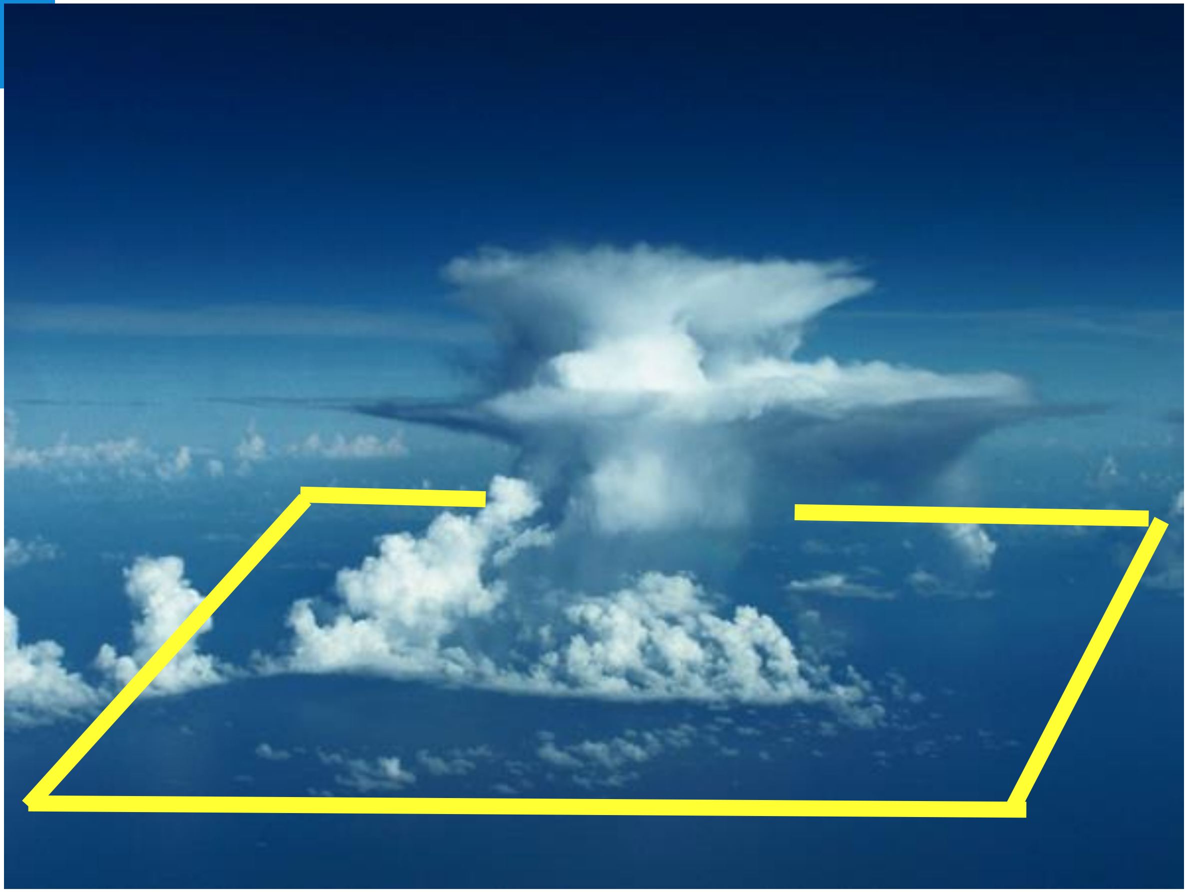


# No single model can encompass all relevant processes



# Parametrization



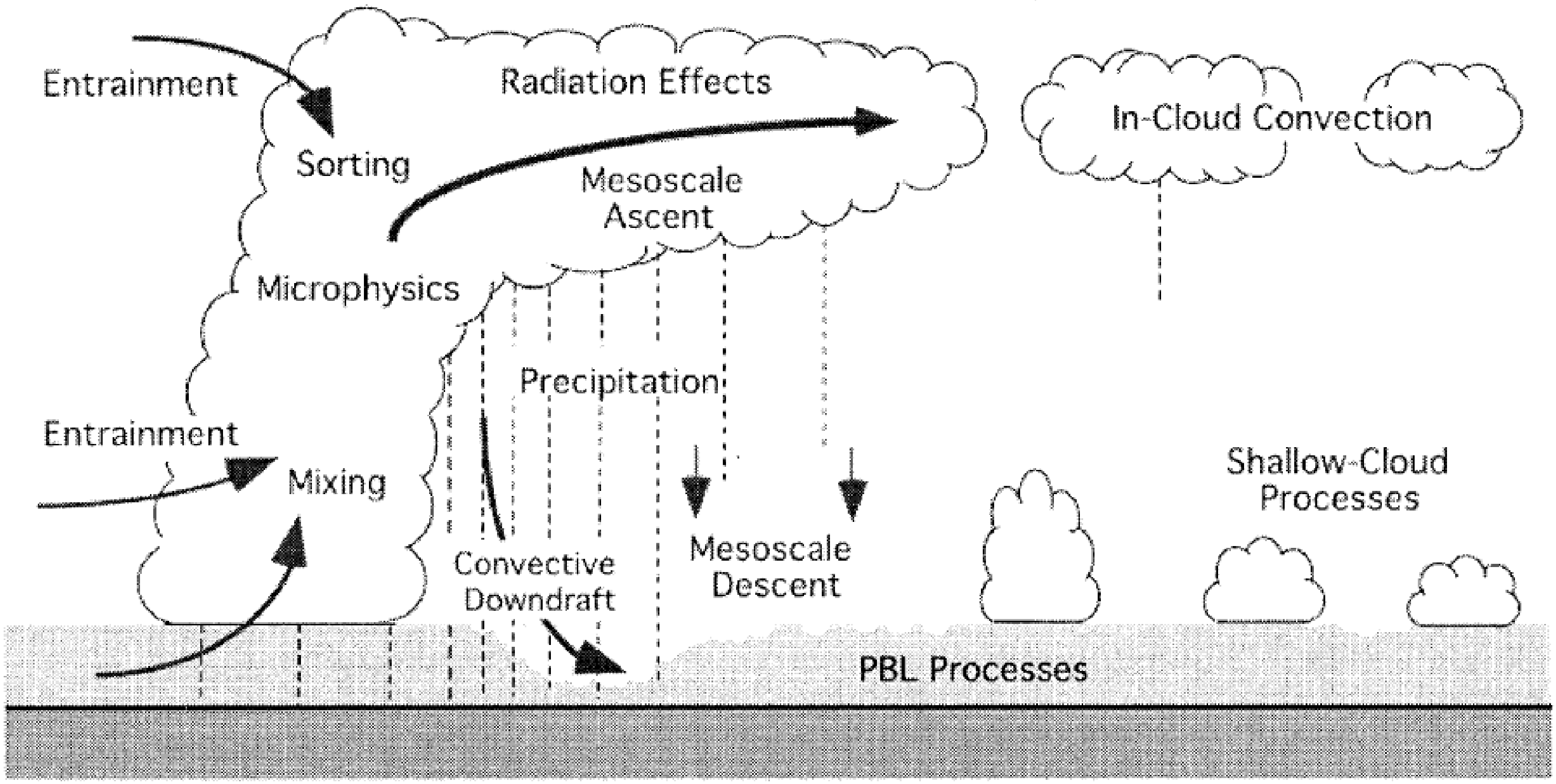
Grid-box size is limited by computational capability

Processes that act on scales smaller than our grid box will be excluded from the solutions.

We need to include them by means of parametrization (a largely statistical description of what goes on “inside” the box).

Similar idea to molecules being summarized statistically by temperature and pressure, but much more complex!

# Parametrization




Examples for processes that need to be parametrized in the atmosphere

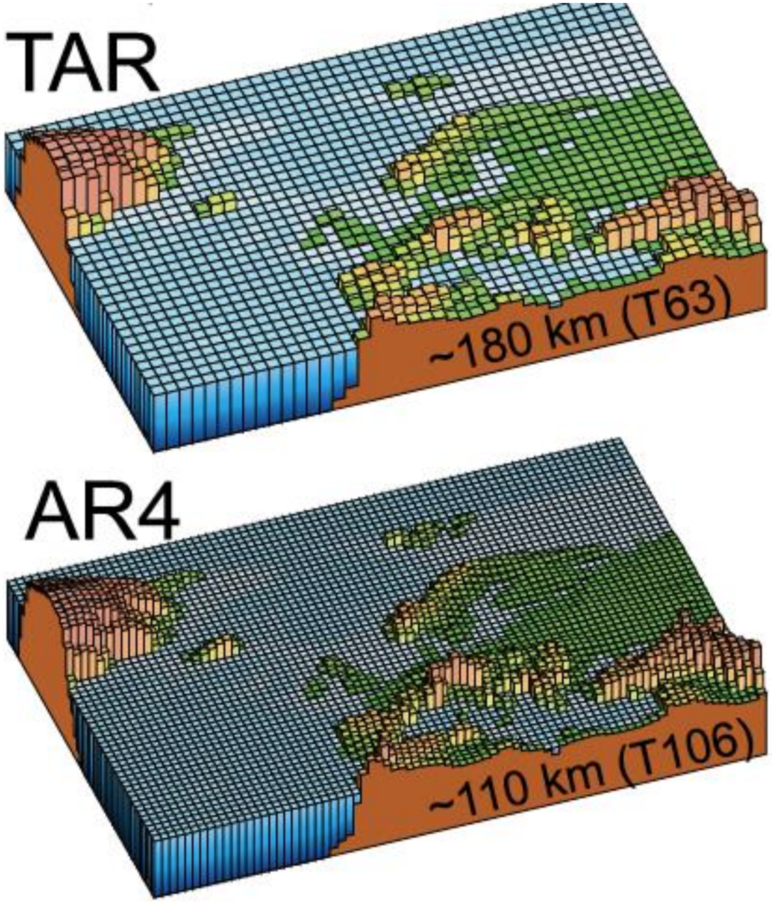
# Parametrization

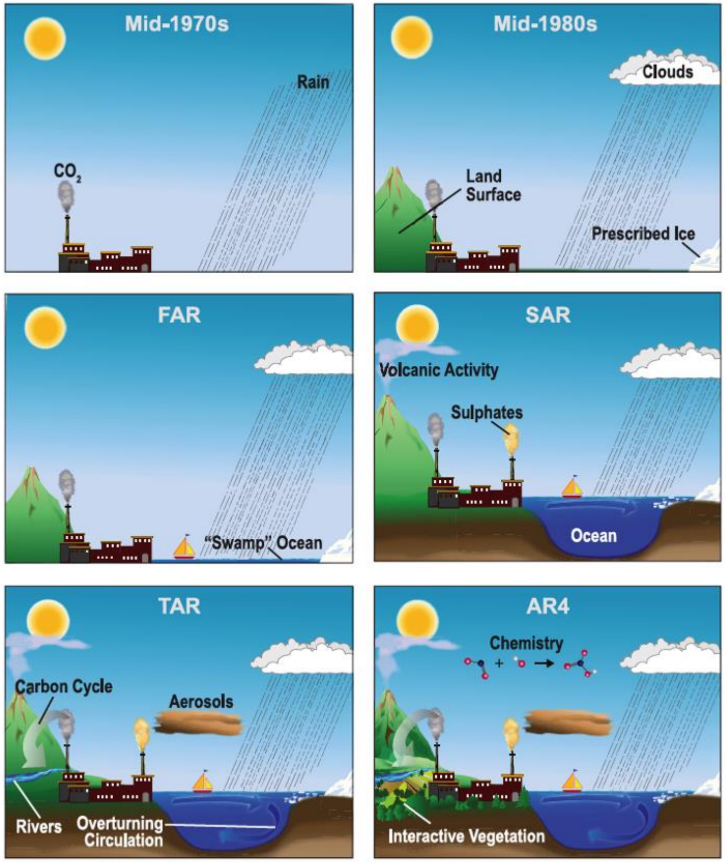
As parametrizations are simplifications of the actual physical laws, their (necessary) use is an additional source of model uncertainty.

# History of model complexity

2001

2007




Source: IPCC, 2007

- Tomorrow:

  Climate Models at work!!