TCC lecture 2022/11/09

Basics of Global Warming

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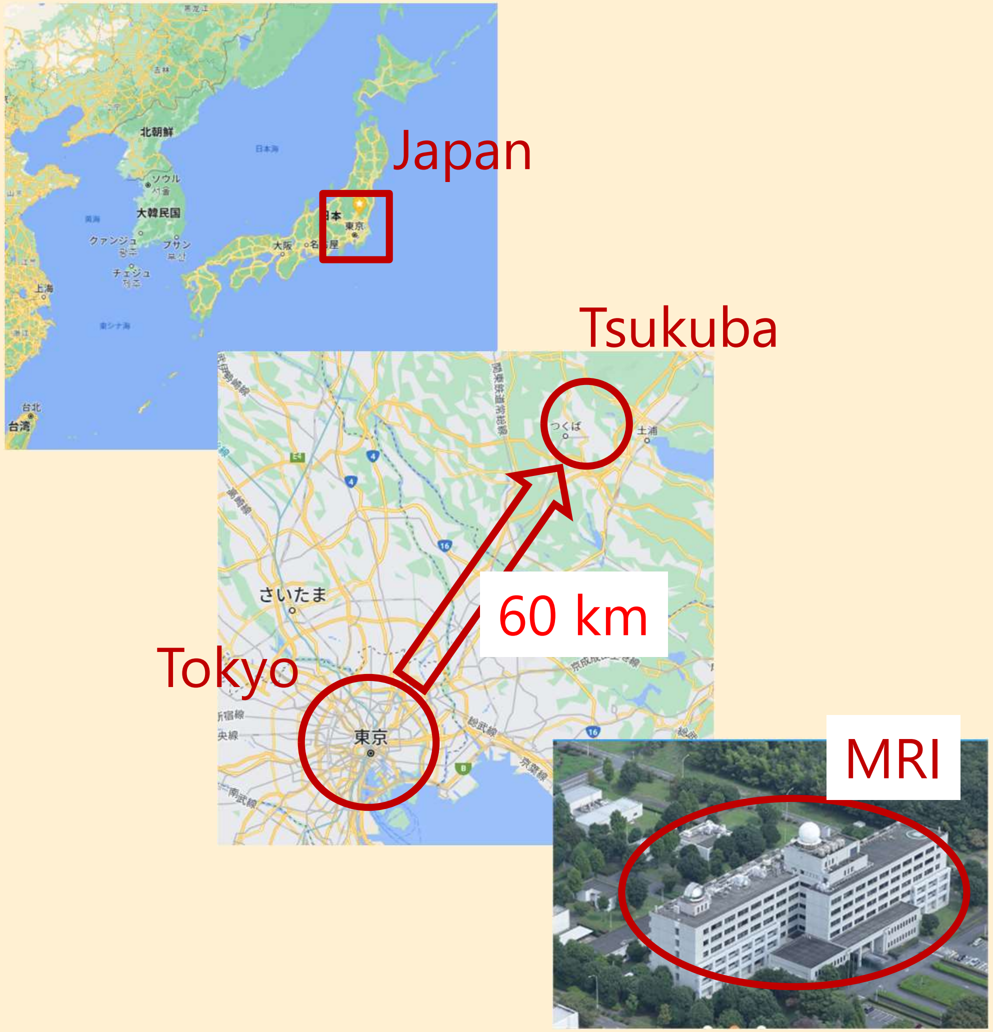
Self-Introduction and MRI



My name is HOSAKA Masahiro and I am belong to Meteorological Research Institute. Our institute is located in Tsukuba, which is about 60 km north of Tokyo.

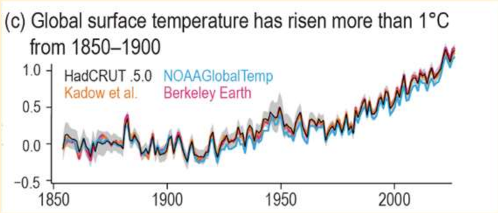
Our laboratory is focused on Global Warming.

My main current job is management, but so far I have studied climate, and have modeled land surface processes in our climate model.

If you have chances to visit Japan, please come to our Institute. I will welcome you.

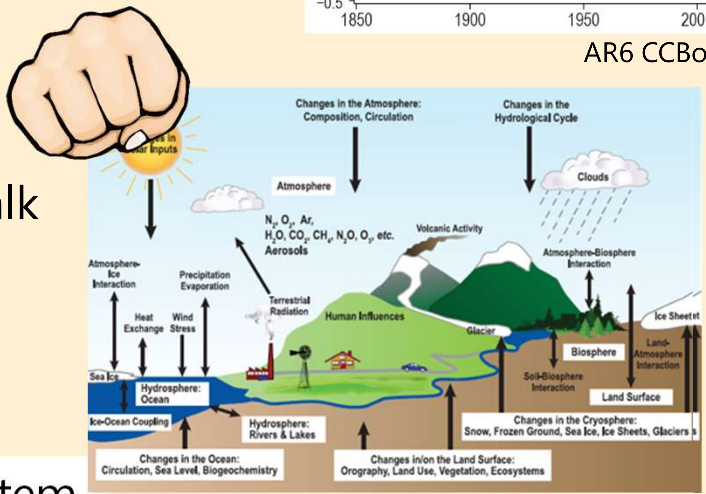
Overview

GHG emission
(GHG concentration)



AR6 CCBox1 Fig.1

1st talk



Climate System

AR4 FAQ1.2 Fig.1

2nd talk

Climate system is complex!
So many processes follow.

Today I am going to have a lecture on "Basics of Global Warming".

I think that the explanation of global warming can be divided into two talks.

The first talk is an increase in surface temperature due to the enhancement of the greenhouse effect. This can be explained using simple systems.

The second talk is the complex climate system's response to it. There are many players, mechanics and phenomena.

I don't know your background very well, so I'll start with the basics of the first story. I know some people think it's too easy, but, please forgive me.

Outline

- Introduction:
  Climate System and Global Warming
- Part 1: Global Warming as enhancement of greenhouse effect
  - Review of basic physics and energy budget
  - Greenhouse effect and GW using energy equilibrium models
- Part 2: Global Warming as the complex climate system's responses
  - Players
  - Mechanisms
- Summary and Conclusion

First, I will show a brief introduction about climate system.
Next, I will explain part 1. Review of basic physics, and greenhouse effect and the enhancement using simple models.
Next, I will move to part 2. In the climate system, they are so many players and mechanisms, so I will show you some of them.
Finally, summary and conclusion.

Introduction:
Climate System and Global Warming

Weather

WMO:

Weather describes short term natural events - such as fog, rain, snow, blizzards, wind and thunder storms, tropical cyclones, etc. - in a specific place and time.

https://public.wmo.int/en/our-mandate/weather

First, let's define weather, climate, and the climate system.

WMO's WWW site says:
(read left)

Climate

Climate, sometimes understood as the average weather, is defined as the measurement of the mean and variability of relevant quantities of certain variables (such as temperature, precipitation or wind) over a period of time, ranging from months to thousands or millions of years. Climate in a wider sense is the state, including a statistical description, of the climate system.

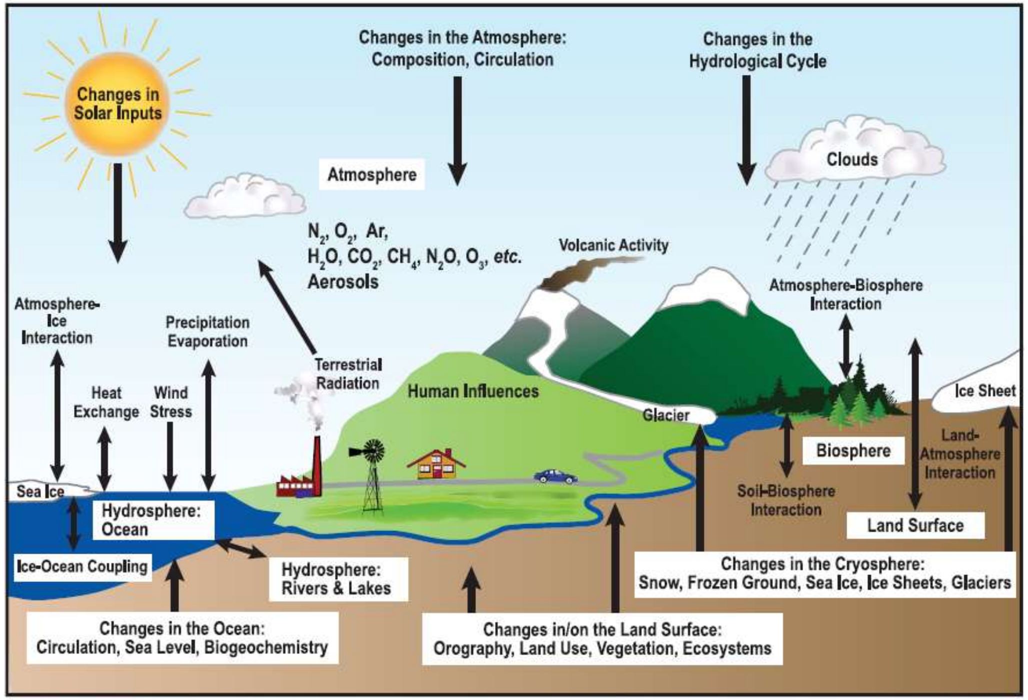
https://public.wmo.int/en/about-us/frequently-asked-questions/climate

Next, move to climate.

(read left)

At the end, there is a phrase "climate system".

Climate SYSTEM



FAQ 1.2, Figure 1. *Schematic view of the components of the climate system, their processes and interactions.* AR4 FAQ1.2 Fig.1

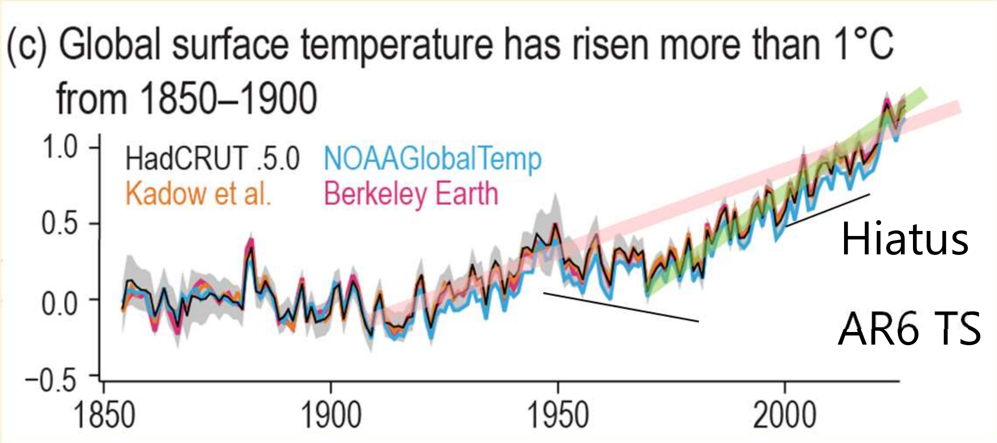
The climate system consists of five major components: the atmosphere, the hydrosphere, the cryosphere, the land surface, and the biosphere. The climate system is continually changing due to the interactions between the components as well as external factors such as volcanic eruptions or solar variations and human-induced factors such as changes to the atmosphere and changes in land use.

https://public.wmo.int/en/about-us/frequently-asked-questions/climate

Climate system is complex.

It has many players and processes.

Global mean surface temperature



AR6 CCBox1 Fig.1

Change in global average surface temperature
Based on the average value of 1850-1900.

The temperature is rising steadily, but not consistently, probably due to internal variabilities.

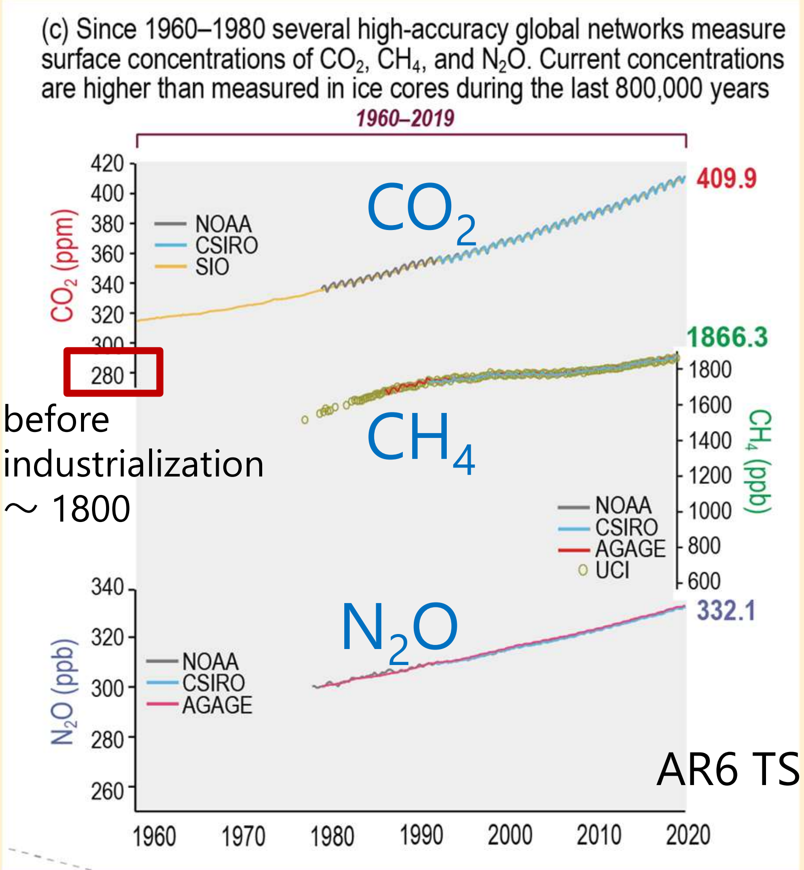
The figure shows past changes in global mean surface temperature based on observations from the mid-19th century to 2020. The vertical axis is the global mean surface temperature, where the baseline is the average of 1850-1900. We can see that it has been steadily increasing since around 1980 or 1920.

The temperature peaked in 1950 and then declined. Also, after a sharp rise in 1990s, it slowed down in 2000s, which is called Hiatus. These are believed to be the effects of internal variabilities.

It sounds like a joke now, but back in the 1970s, it was said that an ice age was coming.

Concentration of greenhouse gases

carbon dioxide
methane
nitrogen dioxide



AR6 TS Fig.9 (c)

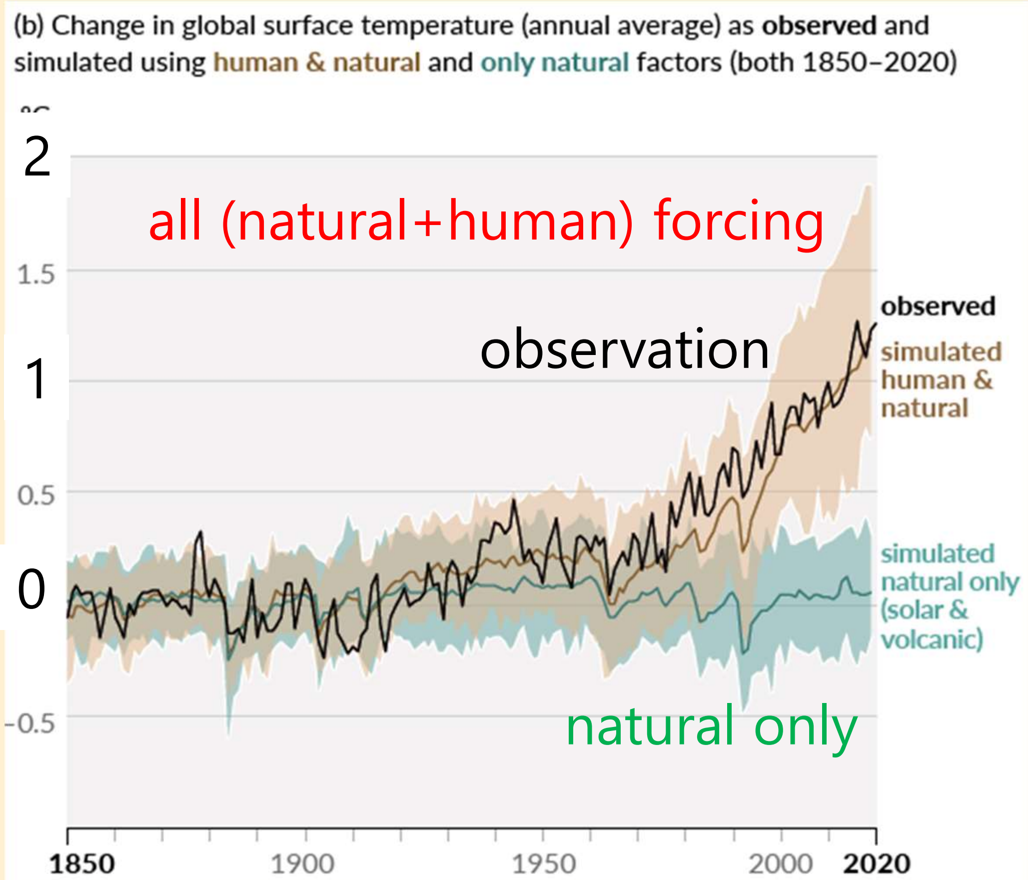
Observed concentrations of CO_2, CH_4, N_2O, the major anthropogenic greenhouse gases, have been increasing.

The figure shows the observed concentrations of CO_2, CH_4, and N_2O from the mid-20th century to 2020.
These gases are known to be the major greenhouse gases of anthropogenic origin.
Since the atmosphere is well-mixed, on average over a relatively large area, it is almost uniform over the entire globe.

We can see that they have been steadily increasing since the past.

CO_2 concentration is said to be about 280 ppm before industrialization.

Global mean surface temperature



AR6 SPM Fig.1 (b)

Ongoing global warming has been caused by anthropogenic forcing.

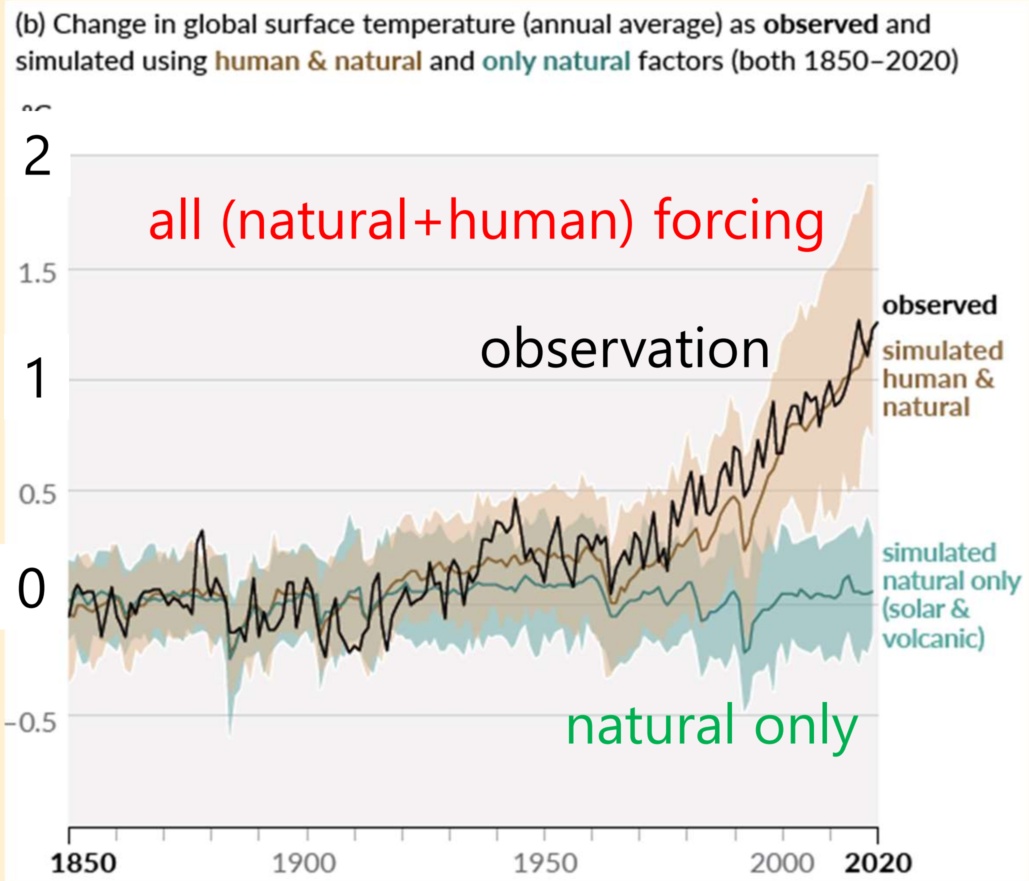
This figure shows the global mean surface temperature from the mid-19th century to 2020.
Solid black line is the observations.

Others are the results of many climate model calculations.

The warm color hatch is the results of applying all natural and anthropogenic forcings, and the solid line is the average of all models.

The cold color hatch is the results of giving only natural forcing, and the solid line is the average of all models.
(cont.)

Global mean surface temperature



AR6 SPM Fig.1 (b)

Ongoing global warming has been caused by anthropogenic forcing.

(cont.)

Climate models remain imperfect. However, they reproduce reality fairly well. By combining the results of many models, we believe that the results can be trusted.

Based on these results, it is believed that the ongoing global warming is caused by anthropogenic forcings, including greenhouse gas emissions.

Summary: Introduction

Global warming is occurring due to human influence such as GHG emissions. Because the climate system is a complex system, the impact goes beyond rising surface temperatures.

- Climate is understood as the averaged weather and as the state of the climate system.
- The climate system is composed of various elements that interact in complex ways under external forces.
- Since industrialization, anthropogenic emissions of greenhouse gases have increased the concentrations.
- Surface temperatures have also increased steadily, especially in recent years.
- Climate model results show that the increase in surface temperature, or ongoing Global Warming, is due to anthropogenic emissions of greenhouse gases.

Part I:
Global Warming as an Enhancement of the Greenhouse Effect

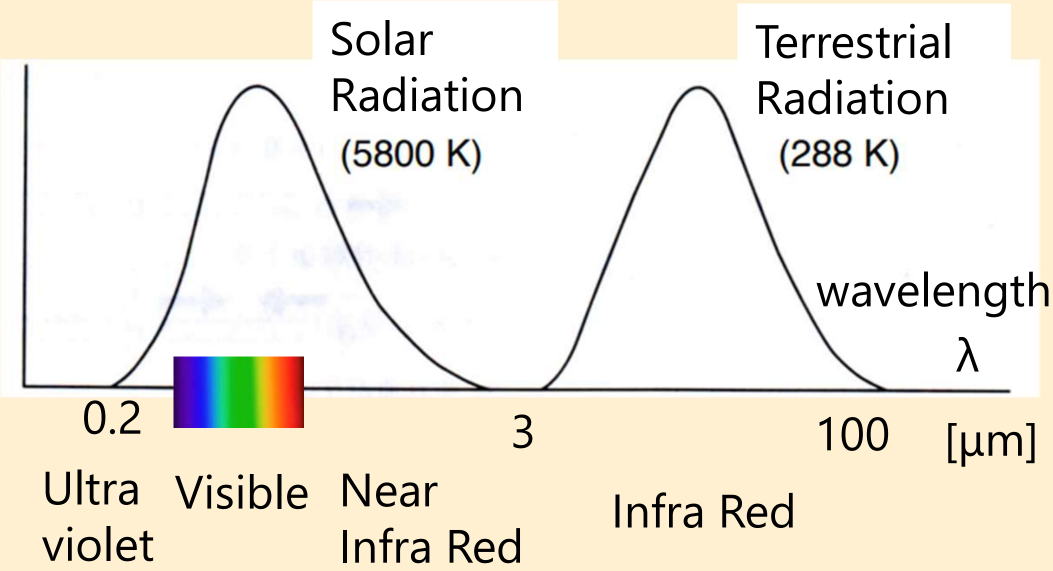
Review of
Basic physics
and Energy budget of the Earth

Before explanation of a main subject, we will review basic physics and energy budget of the earth.

Solar/Terrestrial Radiation,
Radiation scattering/absorption of the atmospheric molecules,
and Energy budget will be explained.

Solar/Terrestrial Radiation

Spectral distribution



Radiation energy [W/m^2] = σT^4

σ: Stefan Boltsmann Constant

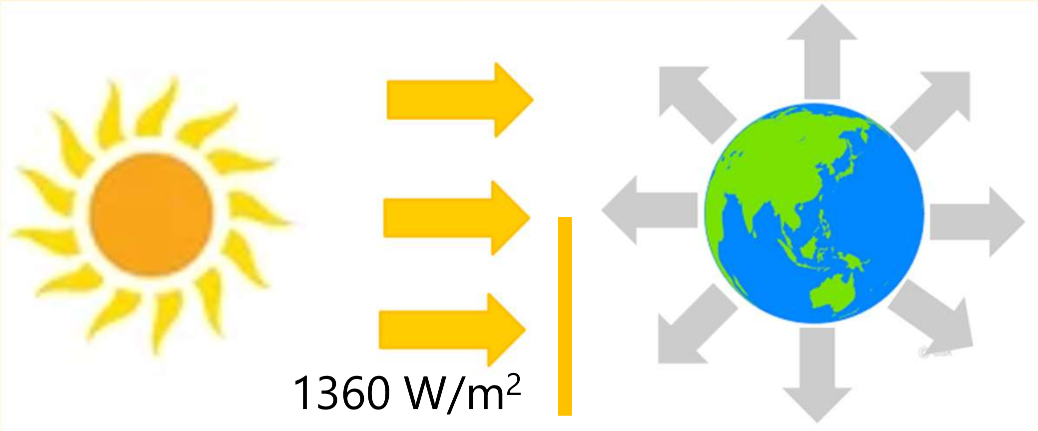
5.67×10^{-8} W/m^2/K^4

The surface temperature of the sun is about 6000 K and that of the earth is much lower.

Objects emit radiation with wavelengths bands that correspond to their temperature. The higher the temperature, the shorter the wavelength. Its intensity distribution almost follows the Planck function.

Radiation energy also corresponds to its mean temperature.

Solar/Terrestrial Radiation



very long distance

The radiation energy is enormous, but distance to the earth is long,

At the Earth distance, the energy flux is about 1360 W/m^2.

The Earth also emits radiation that corresponds to its mean temperature.

Composition

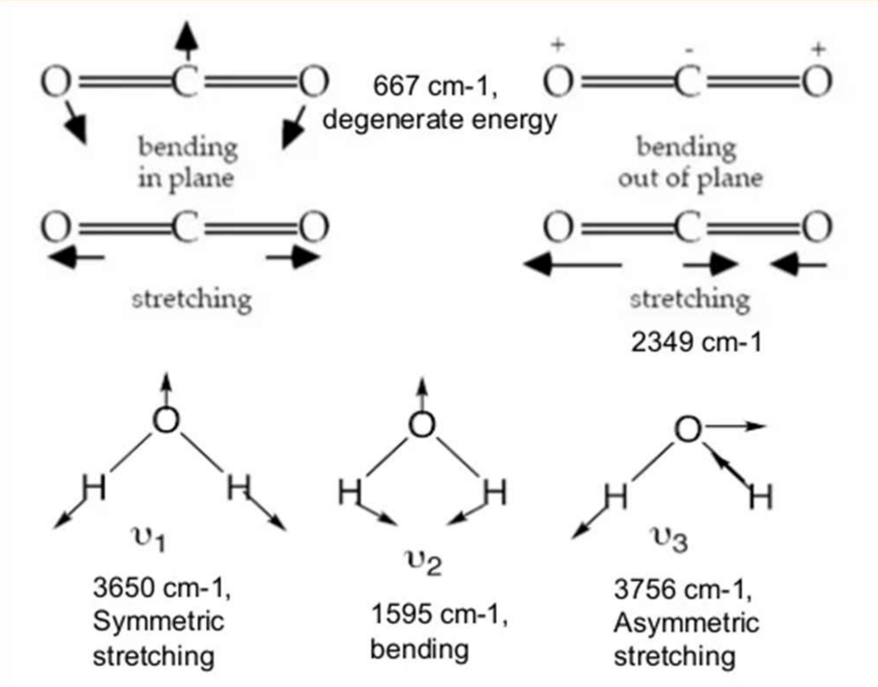
Proportions and concentrations of major gases and greenhouse gases

molecule	propotion	concentration
N_2	78.1%	
O_2	20.9%	
Ar	0.9%	
CO_2	0.03%	411 ppm
CH_4		1877 ppb
N_2O		332 ppb

Let's look at the composition of the Earth's atmosphere. N_2 and O_2 are the most common, and they and Ar account for more than 99.9%. CO_2 is only about 0.03%. The concentrations of other greenhouse effect gas are very small.

Rmark: H_2O and O_3 are not listed here because they vary greatly from place to place.

Absorption of light by gas molecules



Various motion forms of triatomic molecules and examples of absorption wavelengths (CO_2, H_2O)

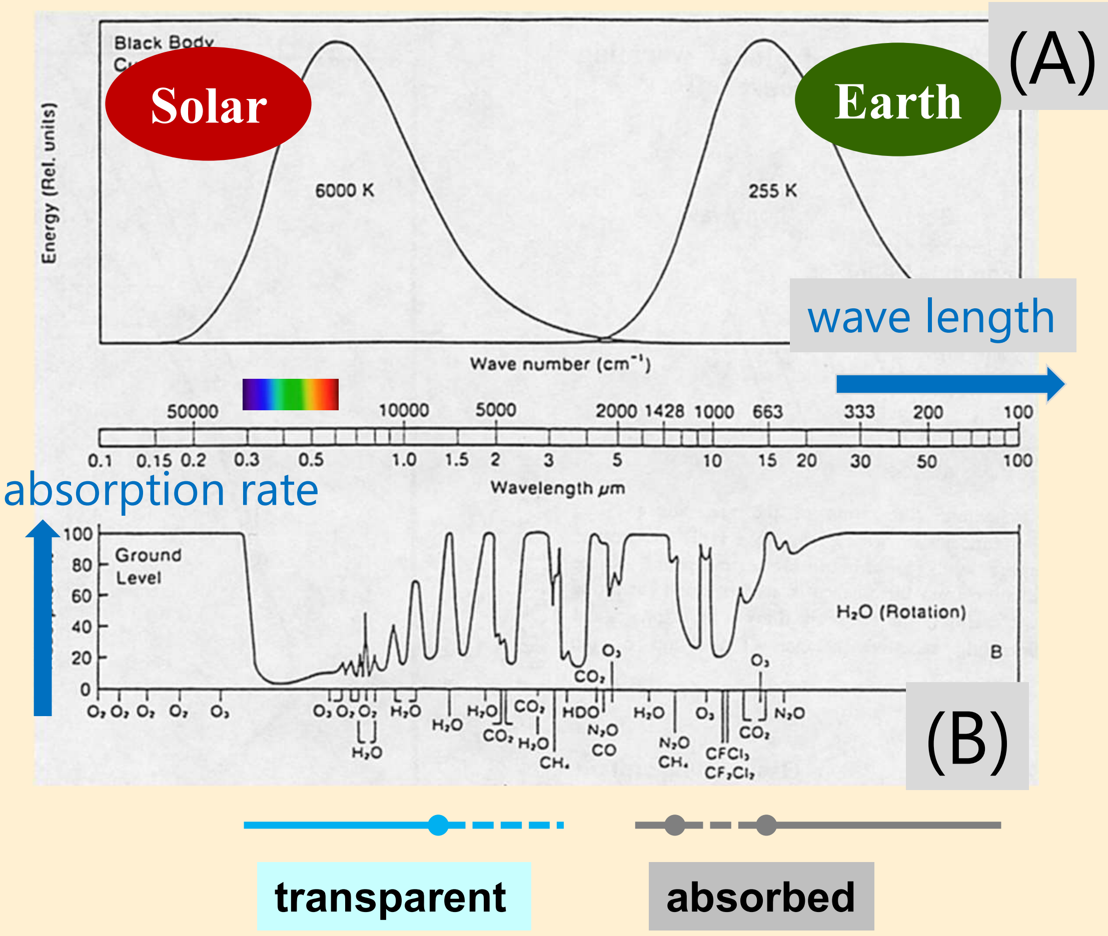
N_2 ,O_2 and Ar etc. hardly absorb any radiation.
※Exception: oxygen absorption in ultraviolet light etc.

Gas molecules absorb radiation of specific wavelengths unique to each molecule, and at the same time transition to a higher energy level.

Transitions rarely occur in monatomic (He, Ar) and isonuclear diatomic molecules (N_2, O_2). Radiation absorption by them is limited.

On the other hand, polyatomic molecules such as CO_2, H_2O, and O_3 are capable of energy transition with various rotations and vibrations, and absorb radiation in the near-infrared and infrared regions in particular. Then, it transitions to a lower energy level and emits radiation.

Absorption of radiations by atmosphere

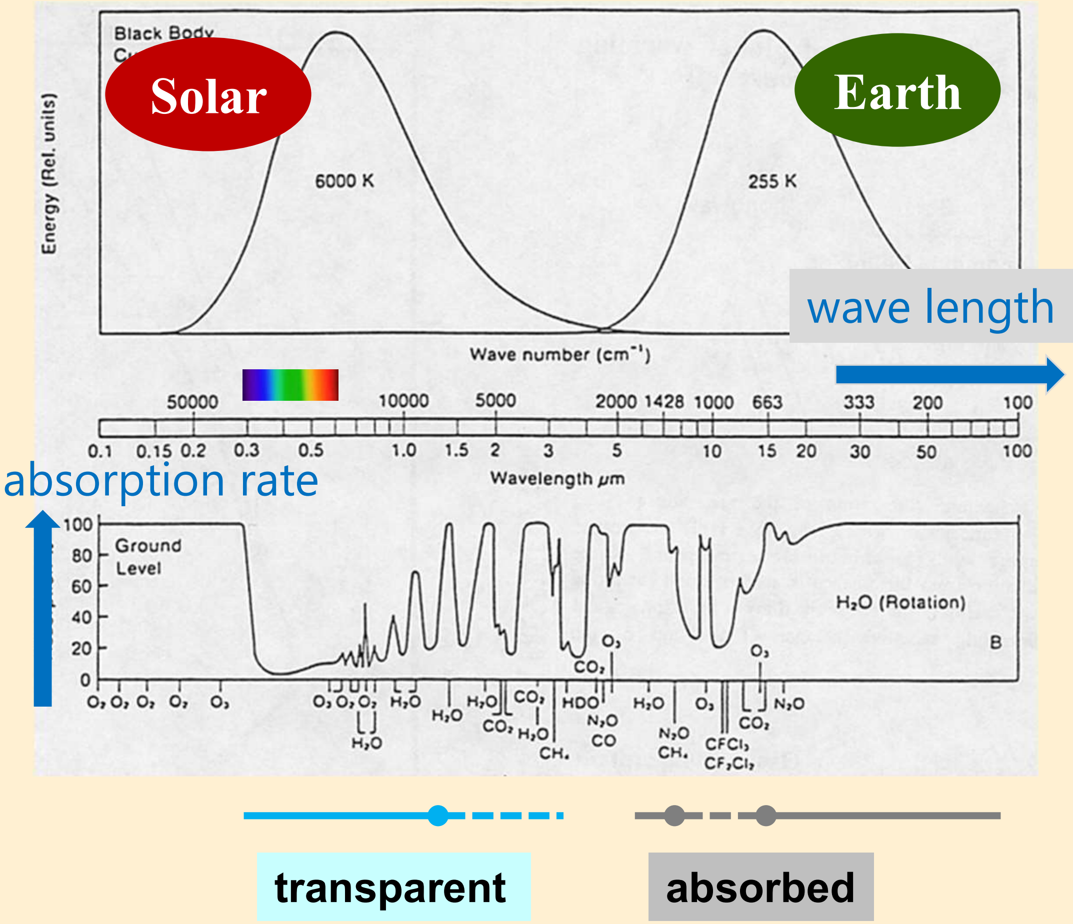


In these figures, the horizontal axis is the wavelength, and the visible region is colored in rainbow.

The upper A shows the emission of blackbody radiation at 6000 K and 255 K.

The bottom B shows the absorption rate when radiation of each wavelength passes through the atmospheric layer. Molecular symbols such as H_2O and CO_2 are written on B. At wavelengths where the absorption lines of these molecules exist, the absorption rate is high.
(cont.)

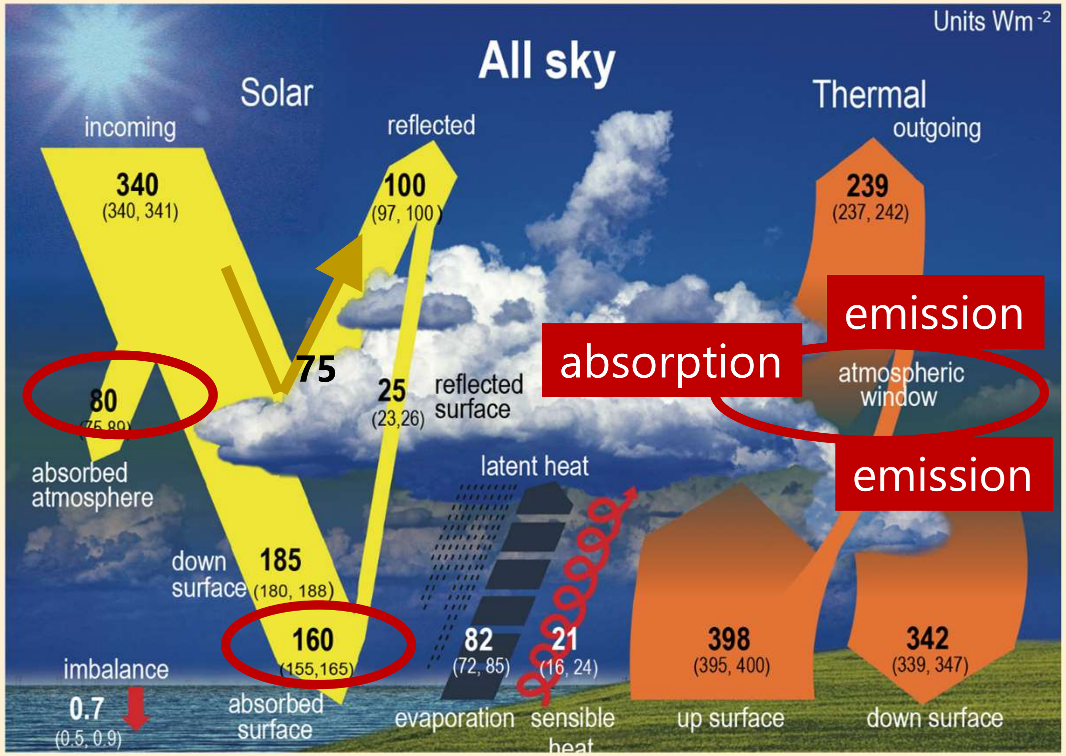
Absorption of radiations by atmosphere



(cont.)
In the wavelength band of solar radiation, absorption is generally low, depending on the wavelength band. On the other hand, in the wavelength band of terrestrial radiation, the absorption rate is generally high.

It turns out that greenhouse gases absorb very little solar radiation and a significant amount of terrestrial radiation.

Global Energy Budget



AR6 Fig. 7-2

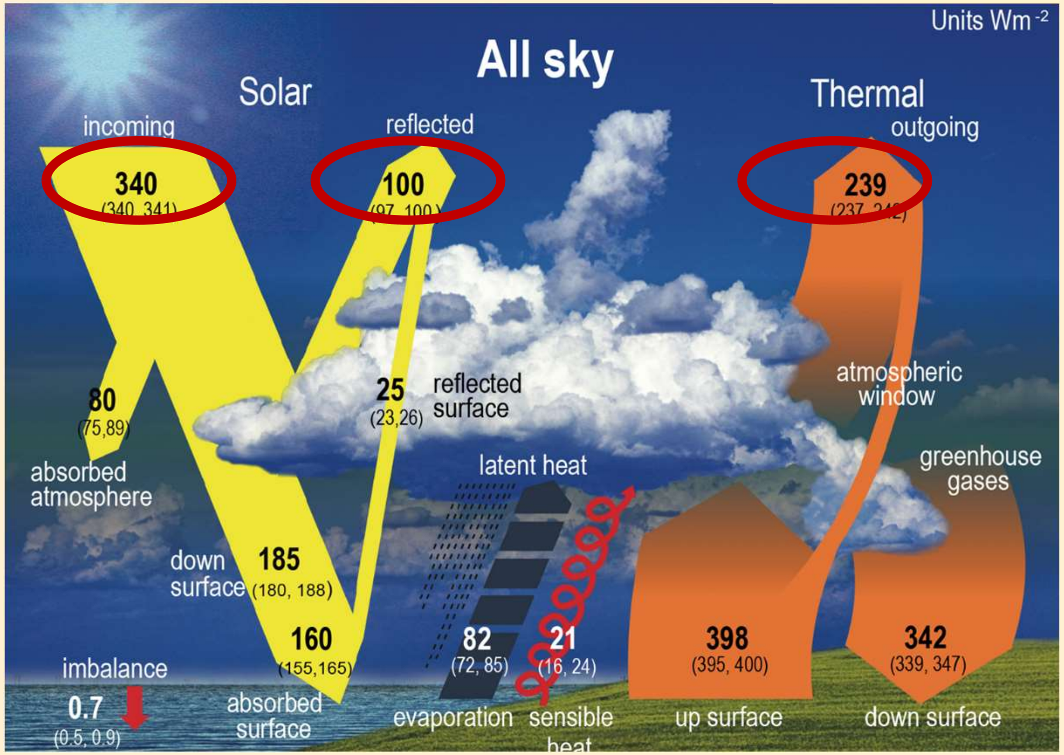
Before finishing the introduction, let me show you a figure of the global energy budget.

In this figure, yellow arrows represent solar radiation, and orange arrows represent terrestrial radiation. The values are global mean energy fluxes and the unit is W/m^2.

As shown in the previous slide, solar radiation is poorly absorbed in the atmosphere. However, it is highly absorbed at the surface.
The radiation emitted from the surface is largely absorbed by the atmosphere. After that, the atmosphere emits upward and downward terrestrial radiation. (cont.)

Global Energy Budget

AR6 Fig. 7-2



- The planetary albedo, the global reflectance of solar radiation, is 0.3 in present climate. (100/340 ≒ 0.3)
- The energy budget is approximately balanced. (340-100 ≒ 239)

(cont.)
Anyway, now, I want you to remember only two things following.

[1] In present climate, about 30% of the radiation from the Sun is reflected by the Earth. The global reflectance of solar radiation is called the planetary albedo.

The planetary albedo may change due to climate change, however, for the next discussion, we assume it to be 30%.

[2] Earth radiation is 239 W/m^2, which is approximately equal to 340-100. The solar radiation entering the earth and the terrestrial radiation leaving the earth are approximately balanced.

Summary: Review of basic physics and global energy budget

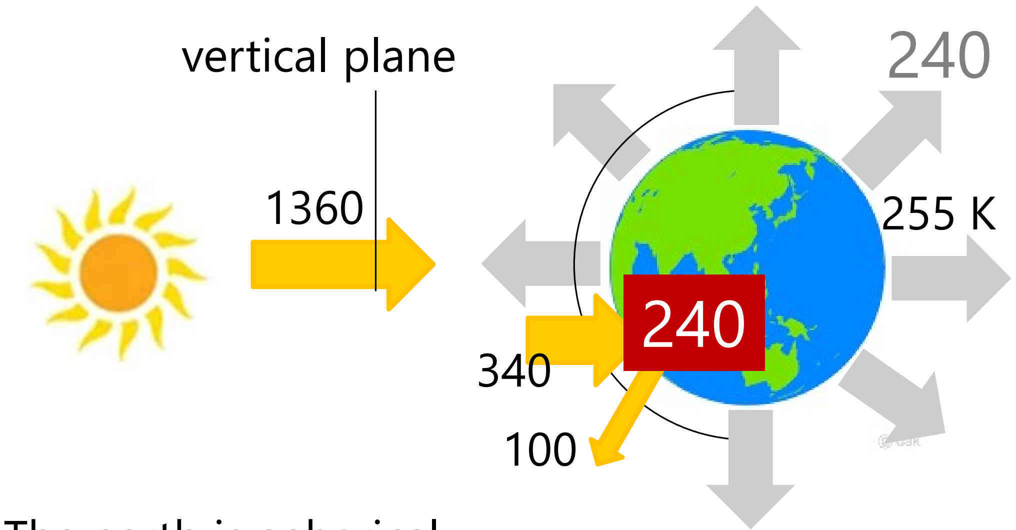
The earth absorbs solar radiation and emits terrestrial radiation, but at different wavelengths. In the Earth's atmosphere, minor constituents absorb terrestrial radiation well.

- Basic physics
  - The sun has a temperature of about 6,000 K and emits visible and near-infrared radiation.
  - The Earth has a temperature of about 250 K and emits infrared radiation.
  - Polyatomic molecules, such as CO_2 and CH_4, which exist in small amounts in the atmosphere, have absorption lines especially in the near-infrared and infrared wavelength regions.
  - The atmosphere absorbs little solar radiation, but it absorbs terrestrial radiation well.
- Global energy budget
  - The energy balance of the Earth's atmosphere is almost in equilibrium.
  - Note that 30% of solar radiation is reflected without being absorbed by the atmosphere or the surface.

Essence of Global warming:
Rise in surface temperature due to increase in GHG

Equilibrium temperature of the Earth,
Greenhouse effect,
and Global warming as enhancement of greenhouse effect

Earth's temperature in balance with solar radiation



The earth is spherical
⇒ 1360/4 = 340 ;
Planetary albedo=0.3
⇒ 340 x (1-0.3) = 240

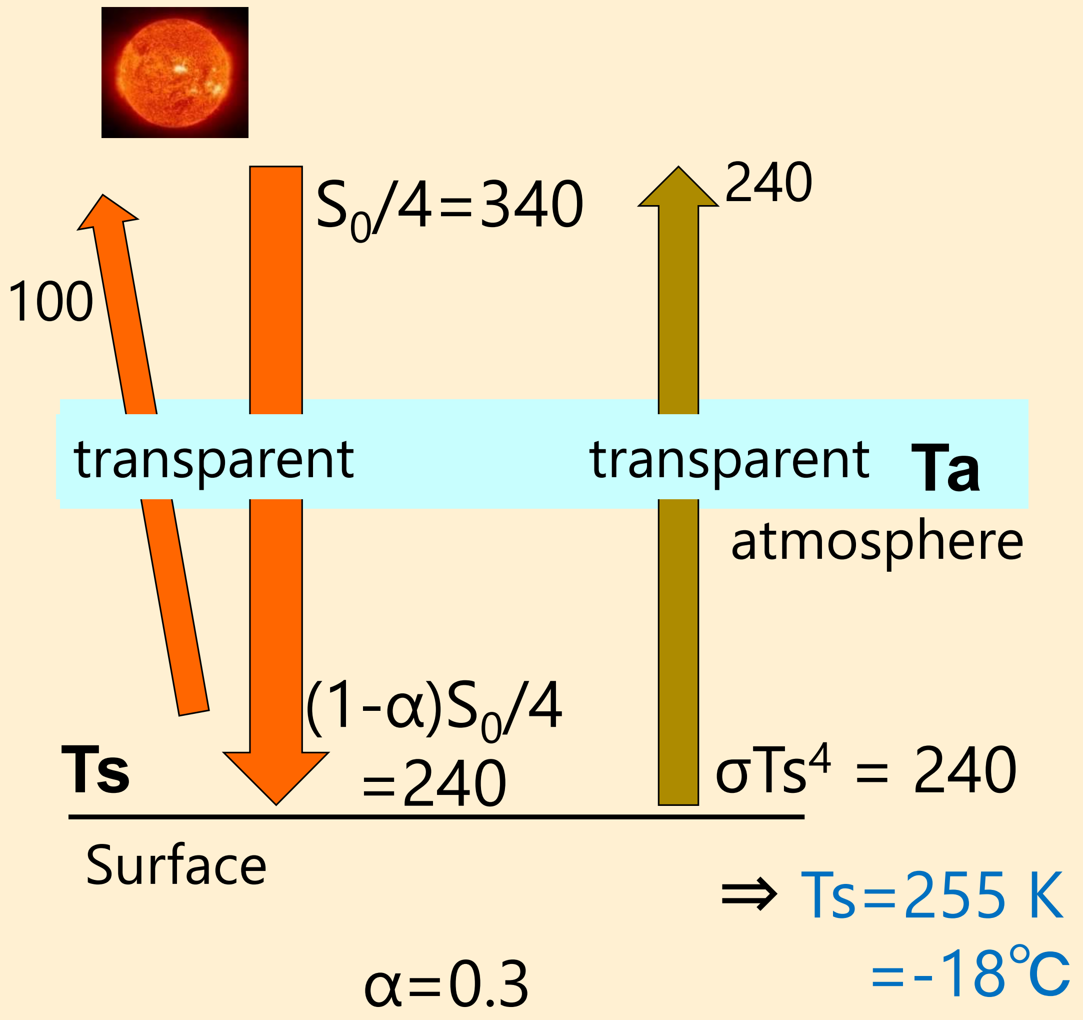
Energy balance:
⇒ $\sigma T^4 = 240$, where $\sigma = 5.67 \times 10^{-8}$
⇒ **T = 255 K**

TOO COLD

Consider the temperature of the earth.

Solar radiation reaches the earth from the sun. The radiation flux to the vertical plane is 1360 W/m^2. However, since the earth is spherical, the earth's average is 340 W/m^2, which is 1/4. Assuming a planetary albedo of 0.3, 100 W/m^2 will be reflected. The remaining 240 W/m^2 warms the earth.
If this energy continues to enter, the earth will get hotter and hotter. But in reality, the Earth emits invisible Earth radiation to balance the energies.
Considering that the temperature of the Earth is uniform and emits 240 W/m^2 in blackbody radiation, the corresponding temperature of the Earth is 255 K.

Earth's surface temperature with a transparent atmosphere

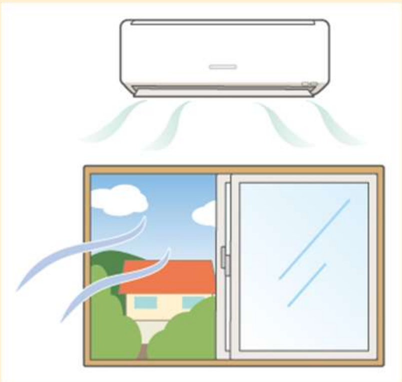


For a moment, let us consider the surface temperature of the Earth, assuming a parallel-plate atmosphere.
There is radiation from the Sun and the Earth reflects 30%. The Earth's surface emits as much energy as it receives. For simplicity, consider the atmosphere to be transparent to solar radiation.
As a first step, in this slide, let's assume that the atmosphere does not absorb any terrestrial radiation either.
In this case, the situation is the same as the case without atmosphere.
The surface radiation is 240 W/m^2 and the surface temperature remains 255 K.

In order to raise the temperature…

Cold night

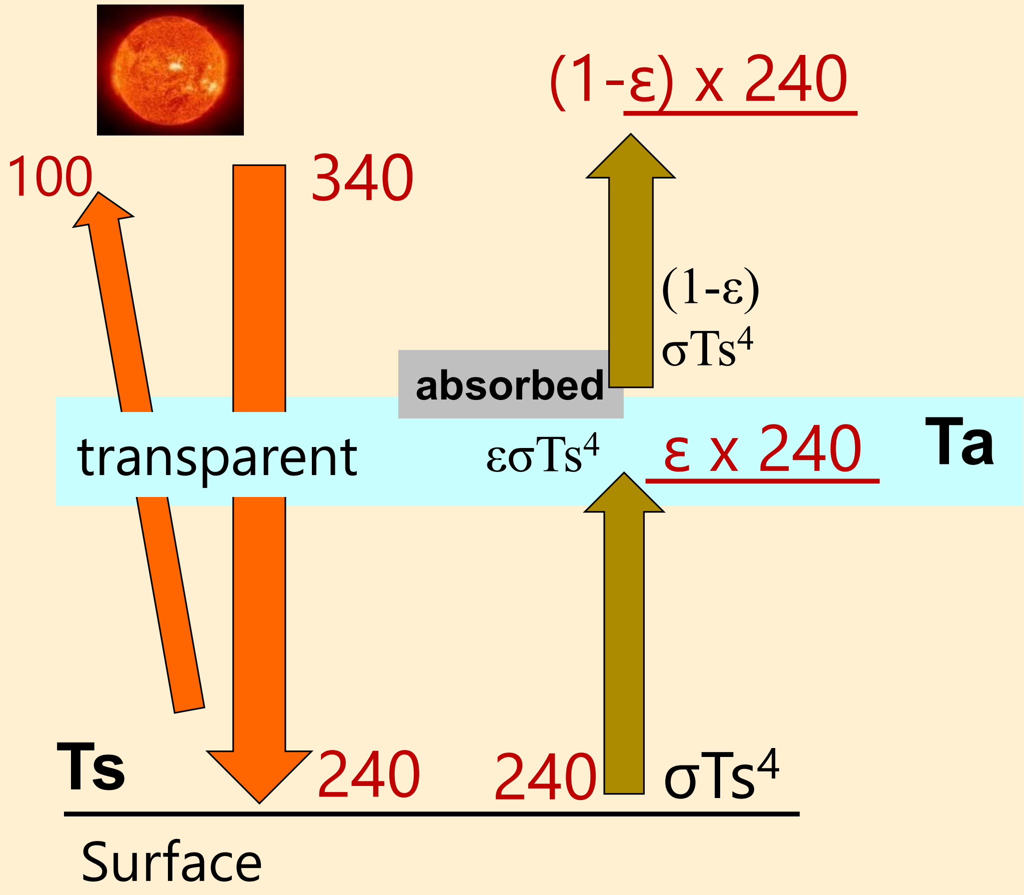
“To prevent heat from escaping” is important.



Air conditioning is less effective if the window is open.

The temperature of 255K is too low for us. How can the earth raise the temperature? These are the figures I used to explain global warming to children. In Japan, if we don't wear anything at night when the temperature is low, our body will get cold and we will catch cold. However, if we use a comforter, our body temperature will be kept and we will be able to sleep warmly. This is a very good way to prevent heat from escaping.
In another example, even if we turn on the air conditioner to lower the temperature on a hot day, the temperature will not drop if the window is open. However, if we close the windows, we can keep the temperature low easily.
To keep the temperature high, it is important to prevent heat from escaping.

Earth's surface temperature with a grey atmosphere

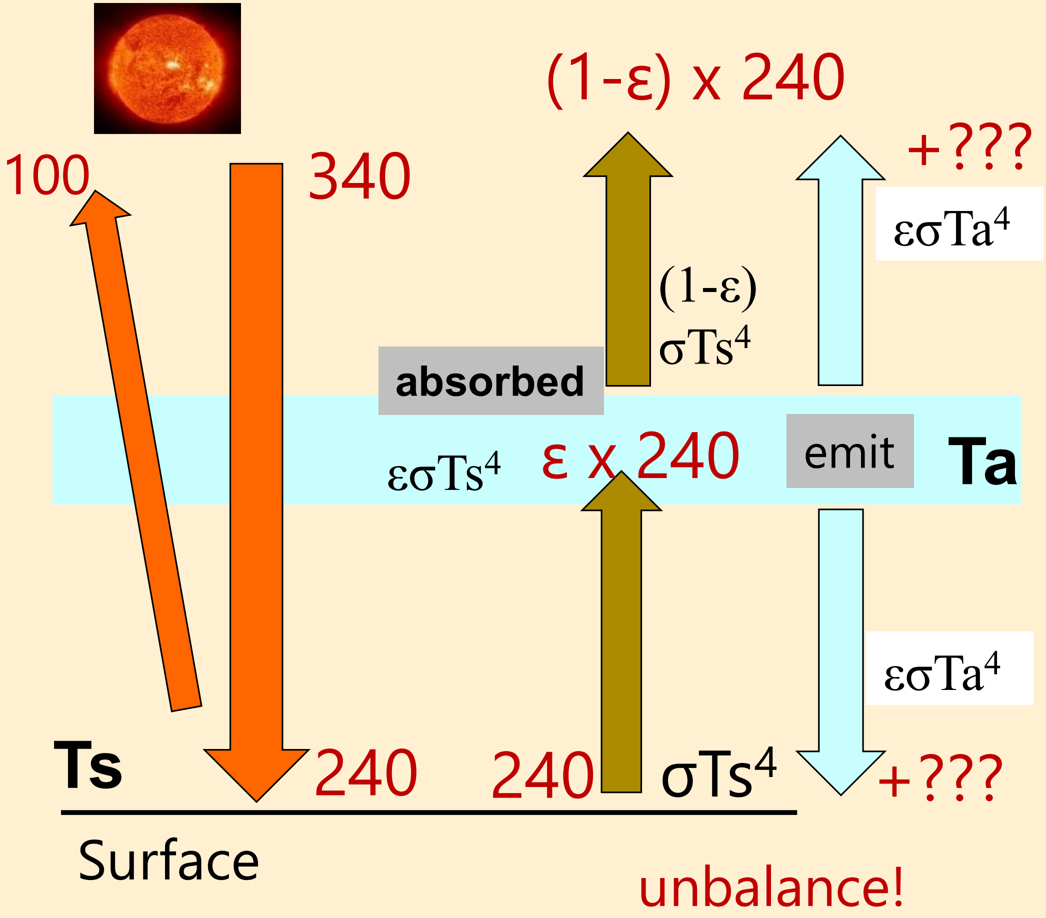


Now let's change the properties of the atmosphere in the parallel-plate atmosphere.

Let us assume that the atmosphere absorbs terrestrial radiation by a fraction ε. The rest surface terrestrial radiation goes straight out into space.
The terrestrial radiation leaving the earth has become less than the solar radiation entering the earth, 240. Heat will accumulate in the earth.

On the other hand, the atmosphere is warmed by the absorption of radiation.

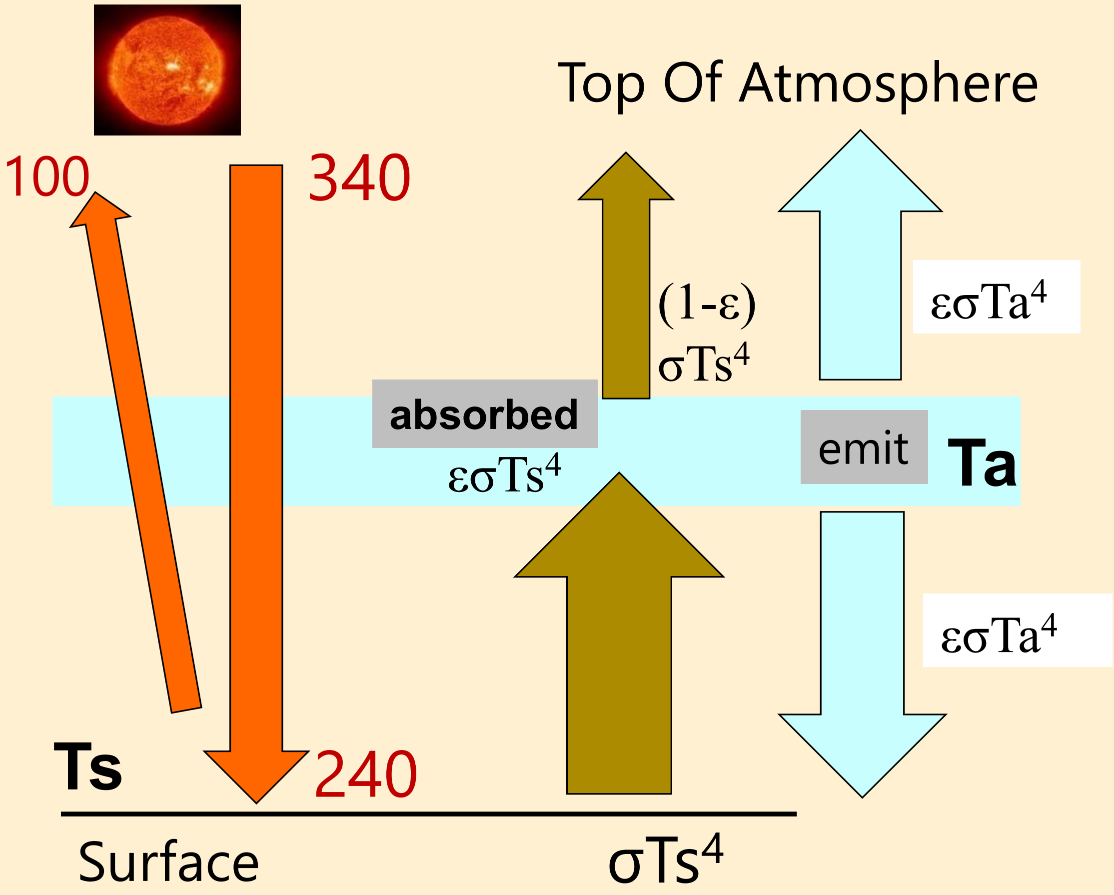
Earth's surface temperature with a grey atmosphere



As the atmosphere absorbs the radiation, the temperature of the atmosphere increases. In reality, the atmosphere emits terrestrial radiation corresponding to its temperature Ta.
However, according to Kirchhoff's law, it emits radiation not at σTa^4, but multiplied by ε, which is the same as the absorbing rate .

Anyway, Now the ground surface heat is out of balance.

Earth's surface temperature with a grey atmosphere



If this continues, it will never end.
Let's find the final equilibrium state.
The equations for balance in the equilibrium state:

TOA: $240 = (1-\varepsilon)\sigma Ts^4 + \varepsilon\sigma Ta^4$

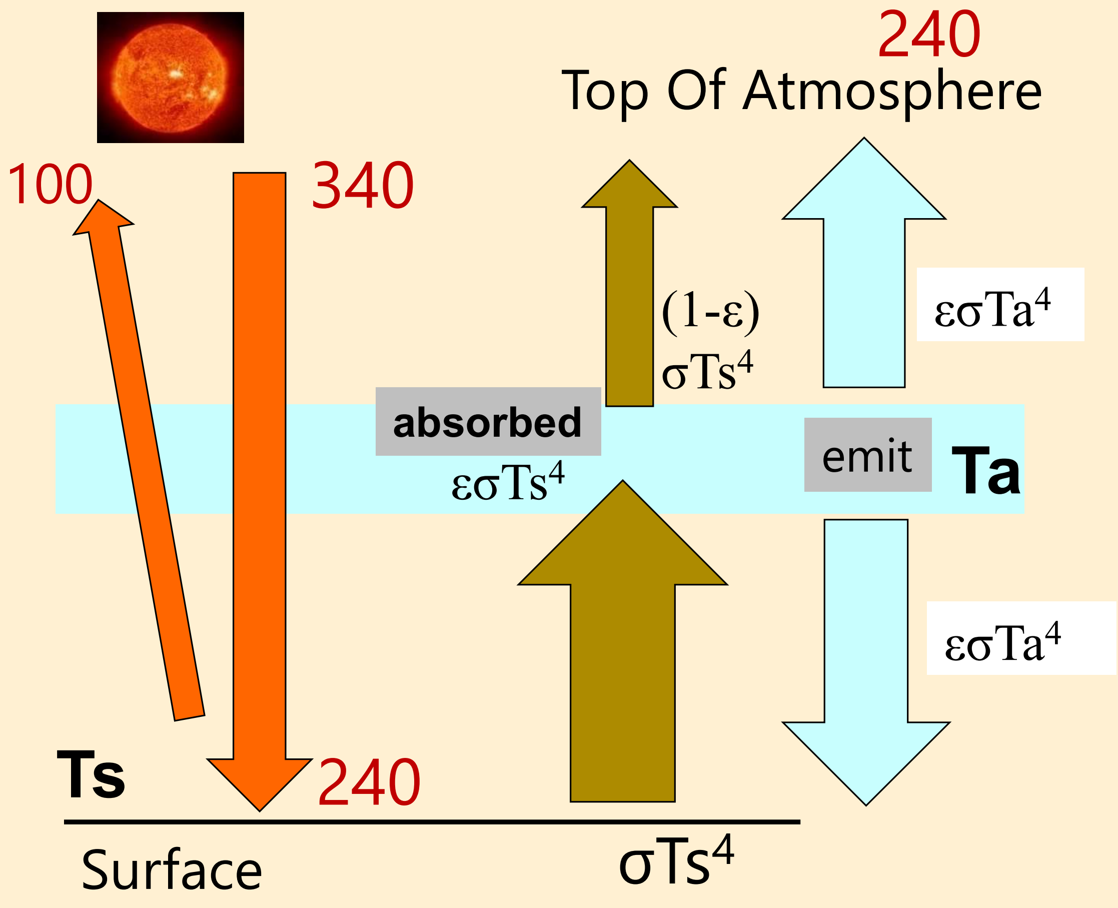
Atmosphere: $\varepsilon\, \sigma\, Ts^4 = 2\, \varepsilon\, \sigma\, Ta^4$

Surface: $240 + \varepsilon\, \sigma\, Ta^4 = \sigma\, Ts^4$

By solving the equations, we can get the answer: $\sigma\, Ts^4 = 240 \times 2 / (2-\varepsilon)$

ε	Ts [K]	Ts [℃]	σTs^4
0.7	284	11	369
0.8	290	17	400
0.9	296	23	436
1.0	303	30	480

Earth's surface temperature with a grey atmosphere



ε	Ts [K]	Ts [℃]	σTs^4
0.7	284	11	369
0.8	290	17	400
0.9	296	23	436
1.0	303	30	480
real	288	15	398

The solution for ε = 0.8 is very close to the real earth.
Remark: This model is so simple that it doesn't make much sense.

It can be seen that the higher the absorption of terrestrial radiation by the atmosphere, the higher the surface temperature.

Radiative Equilibrium and Radiative-Convective Equilibrium

2021 Nobel Prize in Physics

Thermal Equilibrium of the Atmosphere with a Convective Adjustment

1964

SYUKURO MANABE AND ROBERT F. STRICKLER

General Circulation Research Laboratory, U. S. Weather Bureau, Washington, D. C.
(Manuscript received 19 December 1963, in revised form 13 April 1964)

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

1967

SYUKURO MANABE AND RICHARD T. WETHERALD

Geophysical Fluid Dynamics Laboratory, ESSA, Washington, D. C.
(Manuscript received 2 November 1966)

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Selected Publications, Syukuro M

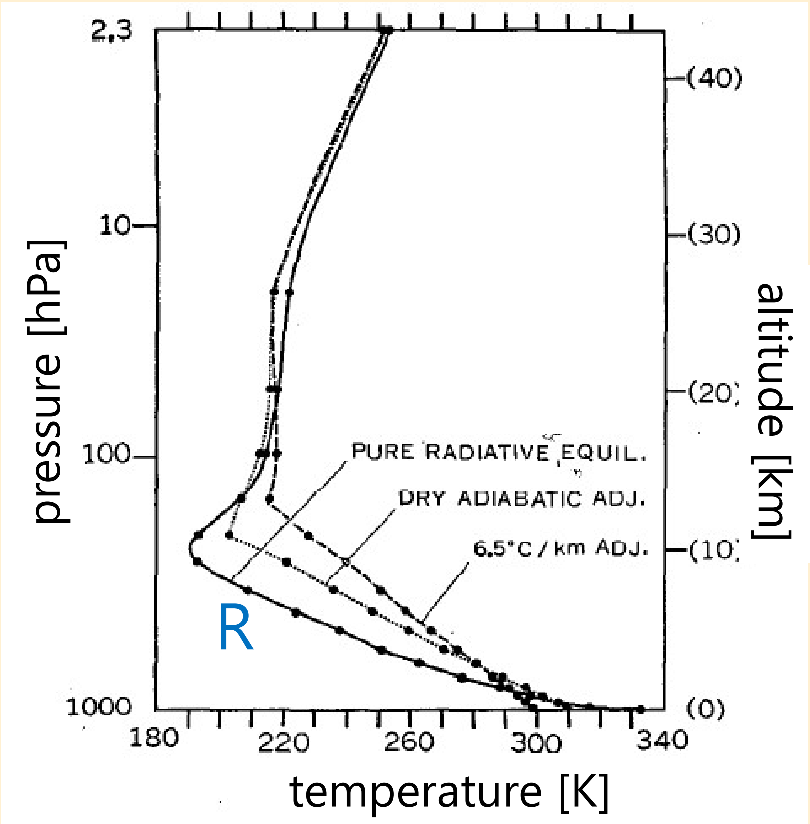
(One third of total publications. Upd

Dr. Manabe's Selected Publications
https://scholar.princeton.edu/manabe/pubs

Now let's move on to the vertical one-dimensional system, the radiative equilibrium model, and the radiative-convective equilibrium model.
Last year, Dr. Manabe was awarded the Nobel Prize for the first time in the field of meteorology and climate.

He is known for his many studies using three-dimensional climate models. But at the beginning of his career, he used such simple systems to study the greenhouse effect and global warming. He himself says that these papers are favorite ones.

Radiative Equilibrium and Radiative-Convective Equilibrium



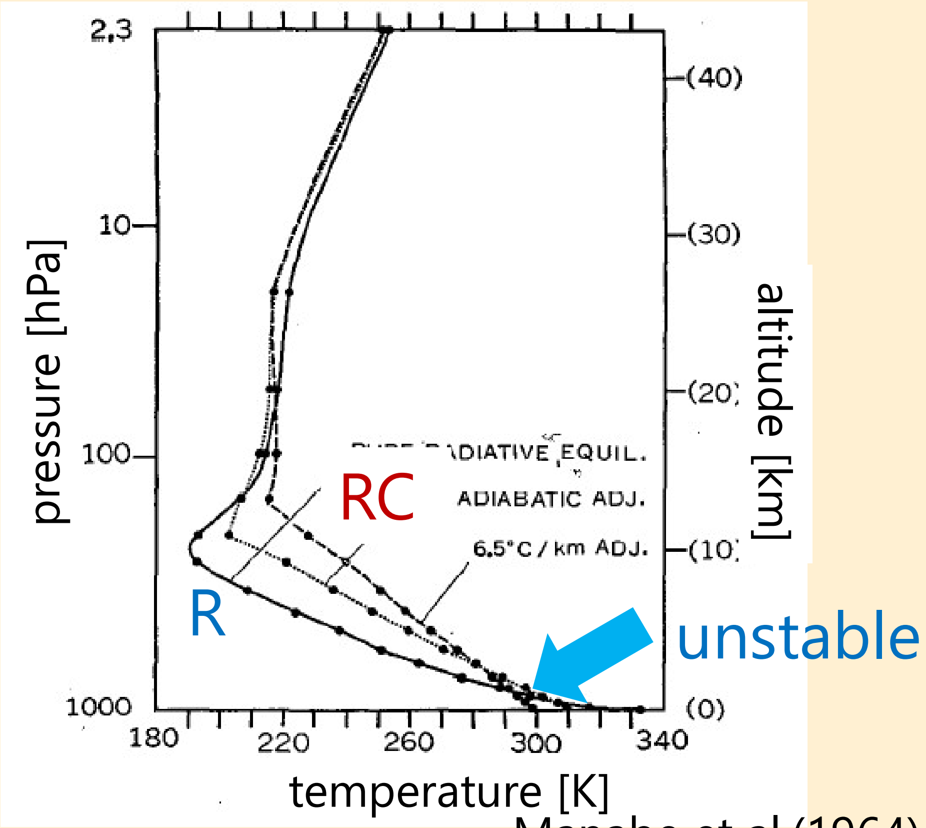
Manabe et al.(1964)

Remark: the condition is not global mean.
No cloud, 35N, 15th Apr, albedo=0.12

This figure shows the vertical distribution of temperature obtained by solving the vertical one-dimensional radiative equilibrium model and the radiative convective equilibrium model. The horizontal axis is temperature and the vertical axis is height.

A vertical one-dimensional radiative equilibrium model is a model in which radiative transfer equations are established given the composition of the atmosphere in the vertical direction.
This solution is the bottom, R-marked distribution.
(cont.)

Radiative Equilibrium and Radiative-Convective Equilibrium



Manabe et al.(1964)

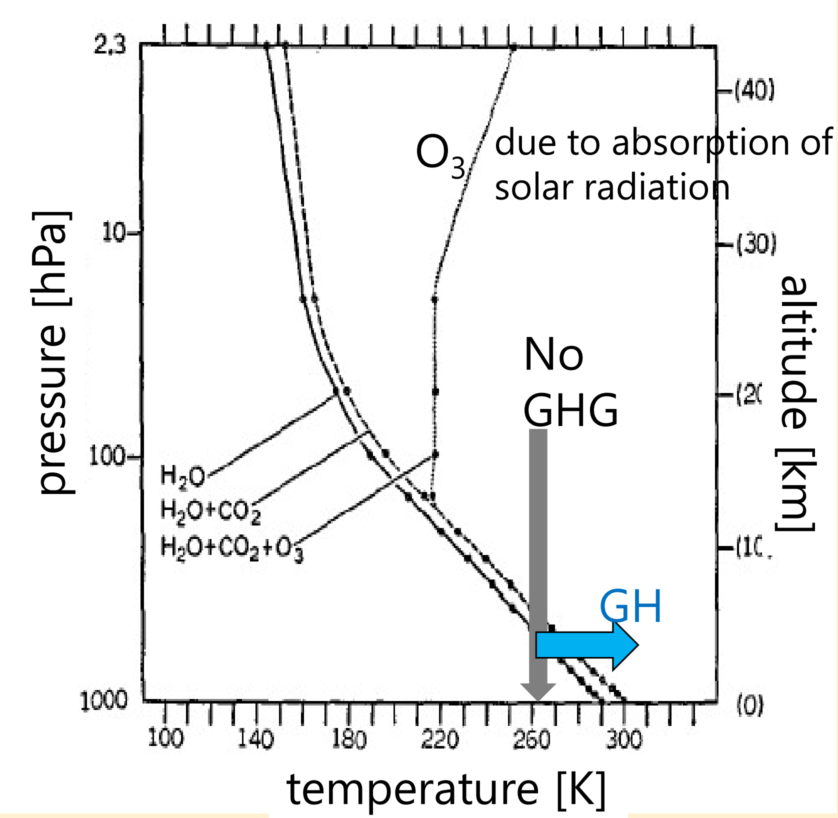
R cannot be realized due to instability.

RC is more realistic.

(cont.)
The temperature gradient in this lower layer is so large that the air near the surface is lighter than the air above it. Therefore, the distribution R is not realized, due to the instability.

On the other hand, the radiative-convective equilibrium model is a model that adds the effect of convection. The temperature gradient of 6.5 K/km in the troposphere. Its temperature distribution is the one at the top, marked RC. This distribution RC is considered more realistic than R.

Radiative-Convective Equilibrium



Manabe et al. (1964) Fig. 6c

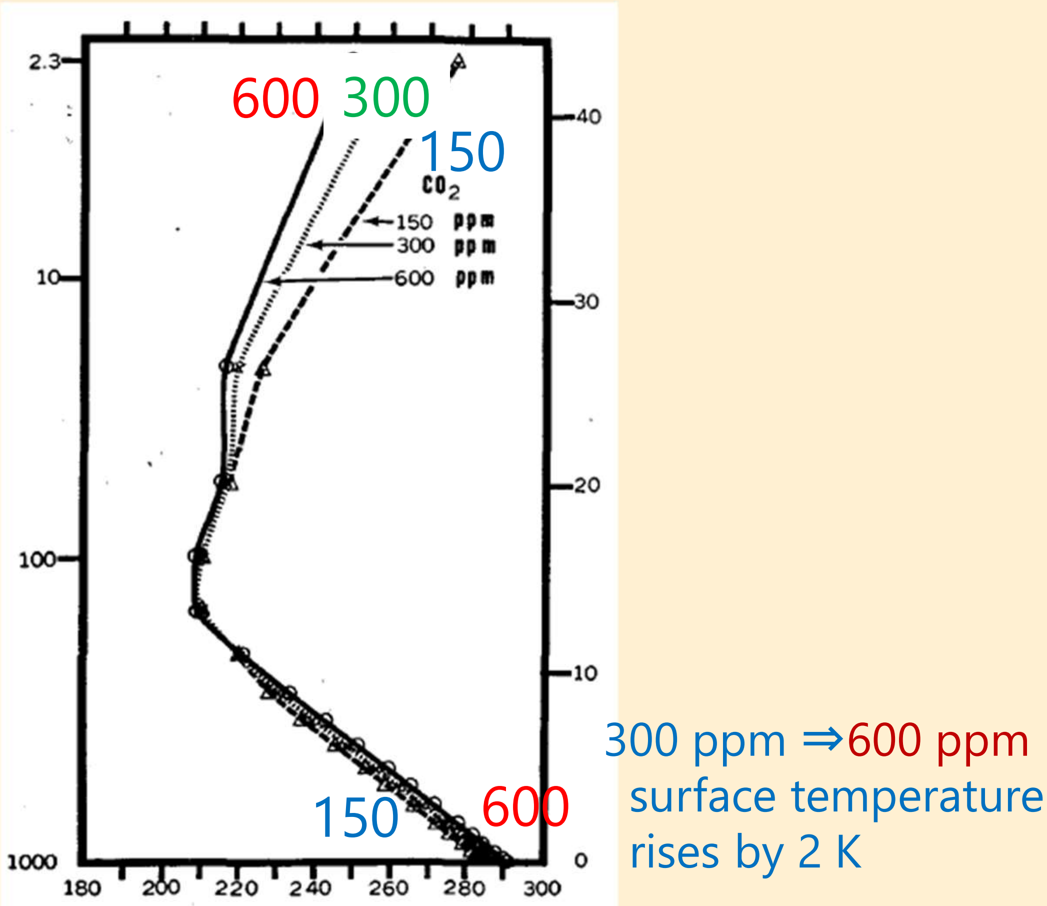
H_2O, CO_2, O_3 cause greenhouse effect, and H_2O effect is the largest.

This figure shows the vertical distribution of temperature obtained by changing the types of greenhouse gases using the radiative-convective equilibrium model. Without greenhouse gases, the surface temperature would be about 260 K.

Adding H_2O, CO_2, and O_3 raises the surface temperature. This corresponds to each greenhouse effect. You can see the the greenhouse effect of H2O is the largest.

We can also see that the stratosphere is formed due to the presence of O_3. Note, however, that this is due to the absorption of solar radiation by ozone.

CO_2 doubling



Manabe et al. (1967) Fig. 16

The figure shows the temperature distribution obtained by the vertical one-dimensional radiative-convective equilibrium model when CO_2 concentration is set to 300 ppm, which is close to the value at that time, half, and double.

Under conditions of doubling CO_2 concentration, the surface temperature was shown to rise by about 2 K.

They also showed that the more greenhouse gases, the cooler the stratospheric temperature.

Summary : Essence of Global warming

While solar radiation is efficiently received at the surface, as the atmosphere absorbs the terrestrial radiation, it prevents heat to escape, so the surface temperature rises by more than 30 K. Greenhouse gases concentration increases and intensification of this effect cause global warming.

- Using some simple thermal equilibrium models, it is shown that GHG increases the surface temperature and that increasing GHG contributes to global warming.
- Parallel plane atmospheric model
  - The greenhouse effect increases the surface temperature by more than 30 K.
  - Increasing the amount of greenhouse gases will further increase the temperature of the Earth's surface.
- Vertical one-dimensional radiative-convective equilibrium model
  - Greenhouse gases increase the temperature of the troposphere.
  - Increased concentrations of greenhouse gases increase surface temperatures.
  - Doubling the amount of greenhouse gases increases the surface temperature by about 2 K.

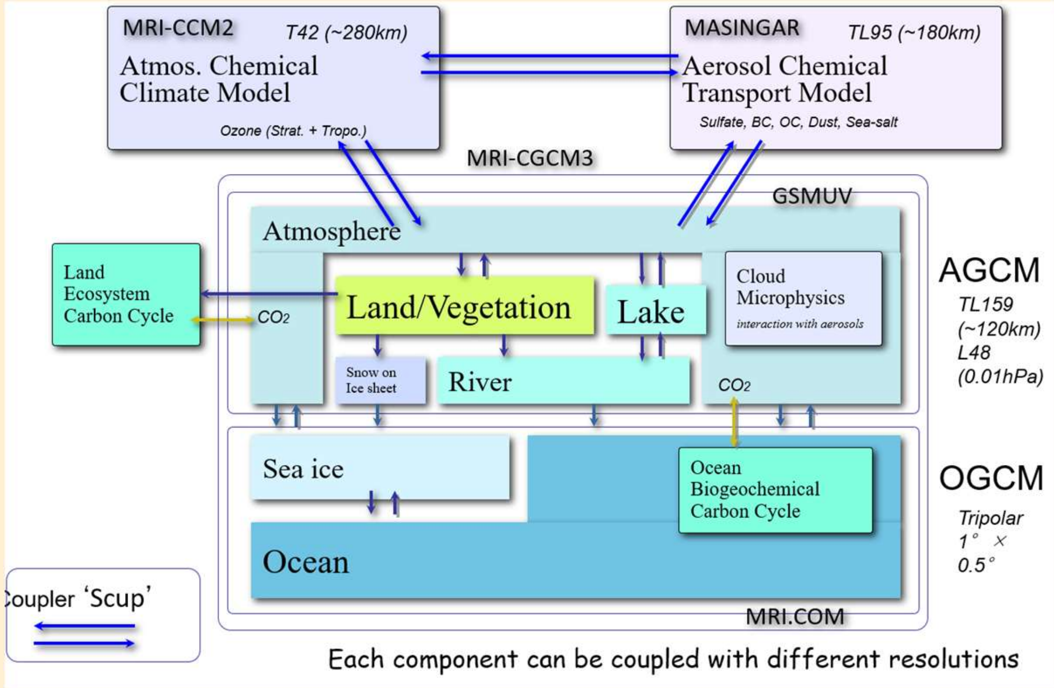
Part 2:
Global warming
as the complex climate system’s responses
to the enhancement of the greenhouse effect

Climate System is complex.
It has so many players and so many mechanisms.

Many characteristic players in the climate system and some important concepts

Climate model's components or key players,
Global energy budget,
Response to External forcing,
Internal variabilities
and Increase of Extreme events

MRI-ESM 2 : an example of Climate Model



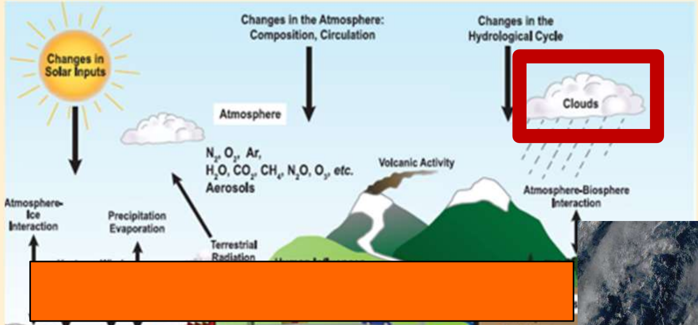
Schematic figure of MRI-ESM 2 as an example of climate models
It consists of atmospheric, ocean, chemical and aerosol models.
They have many characteristic variables.

The figure shows the structure of the climate model of the Meteorological Research Institute as an example of climate models.

The atmospheric model includes the land surface and ecosystem models.
The ocean model includes the sea ice model and the marine biochemical model.
Chemical reactions in the atmosphere are handled by the atmospheric chemical model, and aerosols in the atmosphere are handled by the aerosol model.

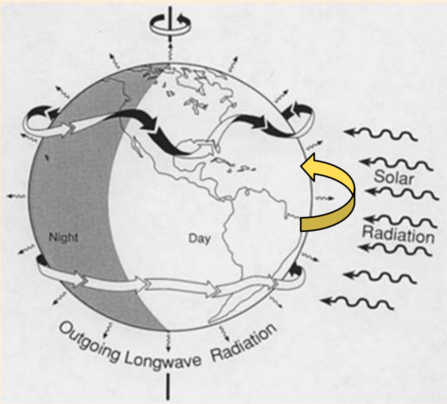
Component models shown here have many variables that act as unique players with different characteristics.

Atmosphere



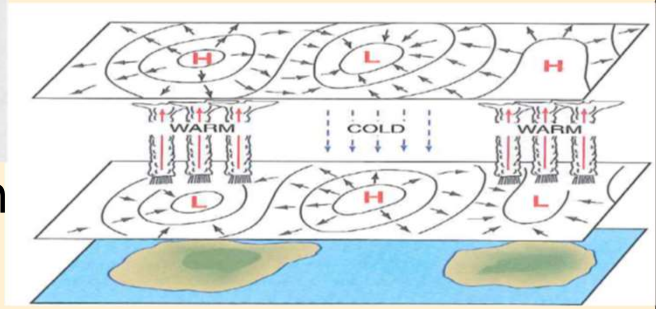
unstable
weather
cloud

Heated from below during daytime



general circulation

global circulation

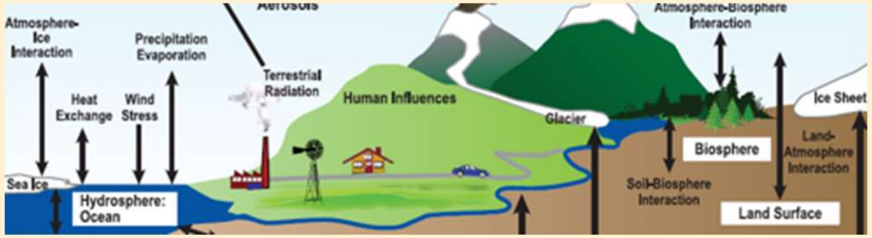


monsoon

The atmosphere is inherently unstable because it warms from below during the day. Severe weather can occur when water vapor condenses and changes phases, releasing heat of condensation.
As we will see later, cloud modifies radiation budget, it is a major factor of uncertainty in climate prediction.

At larger spatial scales, the atmosphere has atmospheric general circulation, such as Hadley circulation.
Also, since the land has a smaller heat capacity than the ocean, monsoon circulation can also be seen, in which the direction of circulation (wind) changes depending on the season.

Land / Sea surface



Land surface
- heterogeneity
- memory (heat/moisture)
- carbon

Sea surface
- supply of water vapour

Snow and ice
- high albedo
- reflect most of solar radiation

Land surface is characterized by land height, vegetation and land cover such as forests, grasslands, and deserts. Their heterogeneity greatly affects weather and climate.
Soil, which stores heat and moisture, have longer timescales than atmosphere. Since vegetation and soil store carbon, land surface has an important role in the carbon cycle.

Sea surface, surface of the ocean, has a smaller temperature change and a larger supply of water vapor than land surface.

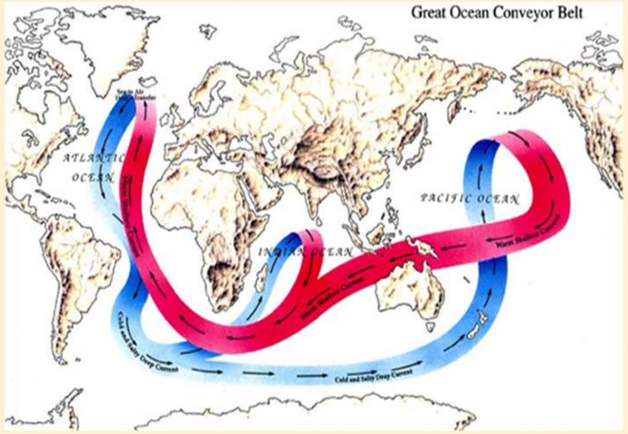
On land and sea surfaces, snow and ice exist and they have high albedo.

Ocean

Huge storage

Total heat capacity ～ 1000 times
Total mass ～ 300 times
of the atmosphere

Ocean can store large amount of heat and carbon.



Long timescale

Conveyor Belt: Global circulation below about 1000 meters depth
; more than 1000 years for one cycle

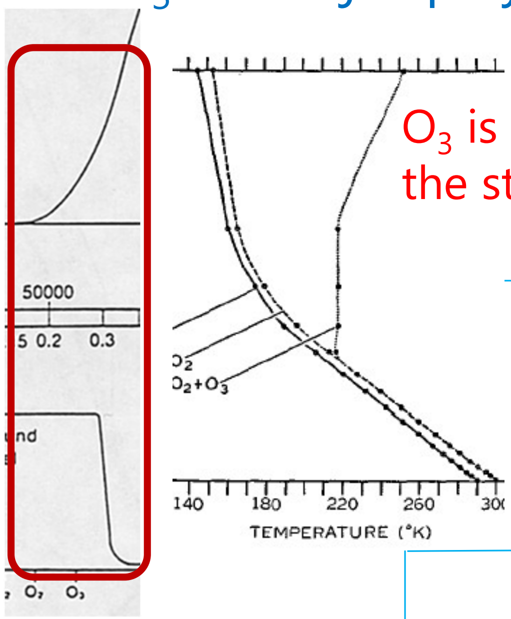
The ocean covers about 70% of the globe and has an average depth of about 4,000 m. The heat capacity is huge. The heat capacity of 2.5 m ocean is almost equal to that of the entire atmosphere. The timescale required for the global thermohaline circulation called a conveyor belt to go around is more than 1,000 years. For these reasons, the time scale of ocean phenomena is much longer than that of the atmosphere.

The ocean also absorbs and stores heat and carbon when the atmosphere is warm and its carbon concentration is high.

Chemistry

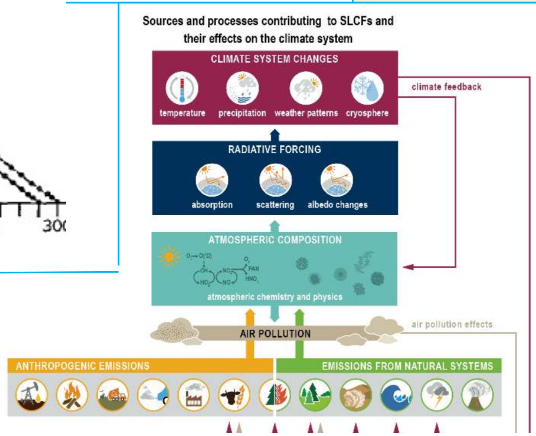
Various substances
Various chemical reactions

O_3 : A major player



O_3 is needed for the stratosphere

Solar ultraviolet is absorbed by O_3



SLCFs has attract attention

AR6 Fig. 6-1

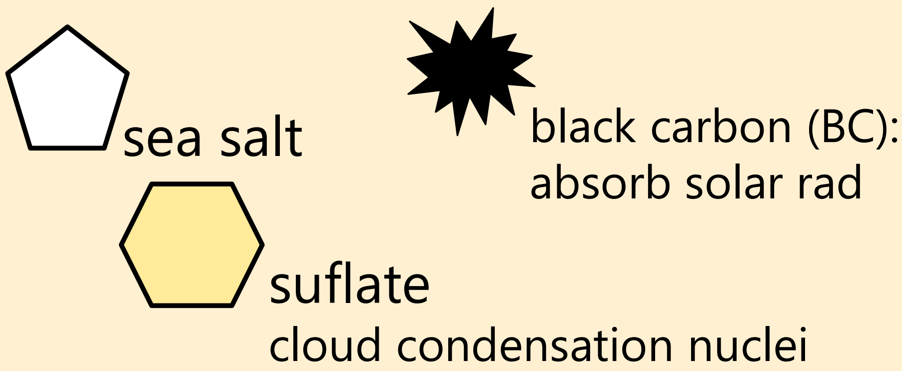
Various substances such as O_3, sulfur compounds, nitrogen compounds, hydrocarbons, and halides, exist as trace components in the atmosphere, and they are generated and destroyed by chemical reactions.

O_3 is well known for absorbing harmful ultraviolet radiation and producing a temperature maximum at an altitude of about 50 km.

Recently, short-lived climate forcers (SLCFs) have attracted attention for their impact on global warming and the environment.

Aerosols

Various unique players



Sulfate, which acts as cloud condensation nuclei, affects the radiation budget by changing cloud lifetime and cloud optical properties.
Remark: Cloud is uncertainity factor,
and aerosols affects on cloud.

Some aerosols, such as BC, change properties while suspended

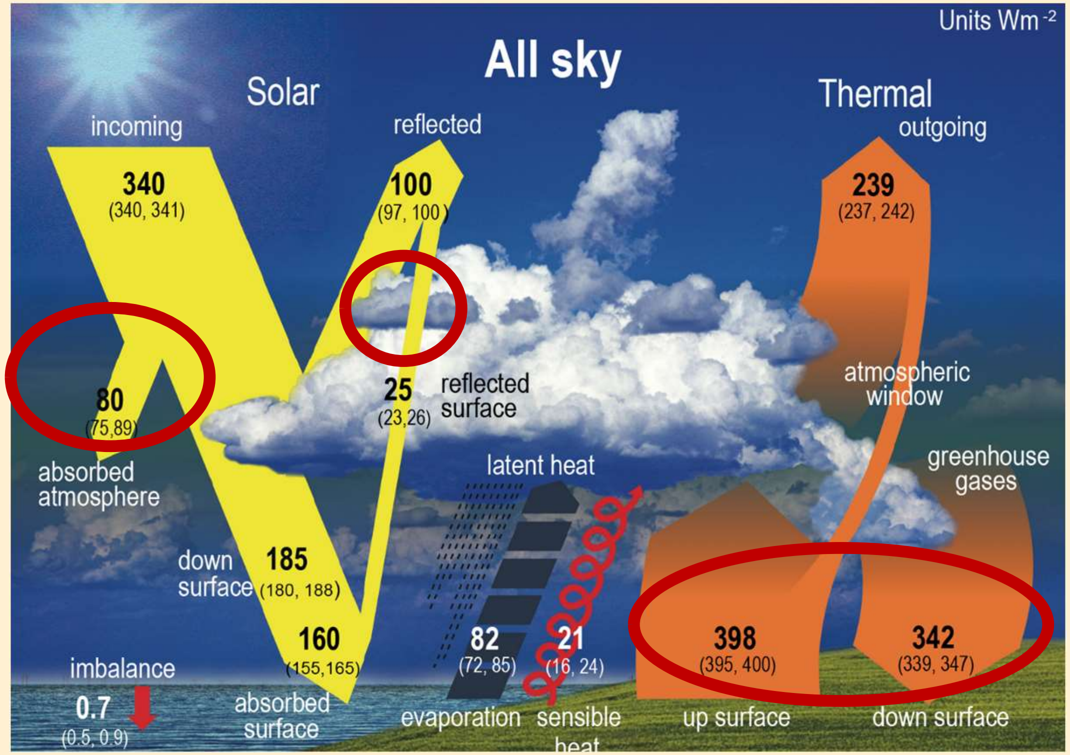
Aerosols, such as sulfates, nitrates, organic aerosols, black carbon, soil particles, sea salt particle, are suspended in the atmosphere. Aerosols absorb and scatter solar radiation, thus affecting the radiation budget.

Aerosols such as sulfates act as cloud condensation nuclei, and the amount affects the optical properties and the lifetime of the cloud, so through these changes in cloud, also affects the radiation budget.

In addition, aerosol’s dynamics is still poorly understood. Therefore, aerosols are major factors of uncertainty in global warming predictions.

Global Energy Budget

The topic will change.
Imbalance of global energy budget mainly due to ocean heat storage



AR6 Fig. 7.2

Let's look again at this figure of the global energy budget.

After taking the lecture part 1, now, you will notice that the atmosphere is almost transparent to solar radiation, but it absorbs terrestrial radiation better, resulting in large upward and downward fluxes of terrestrial radiation in the lower atmosphere.

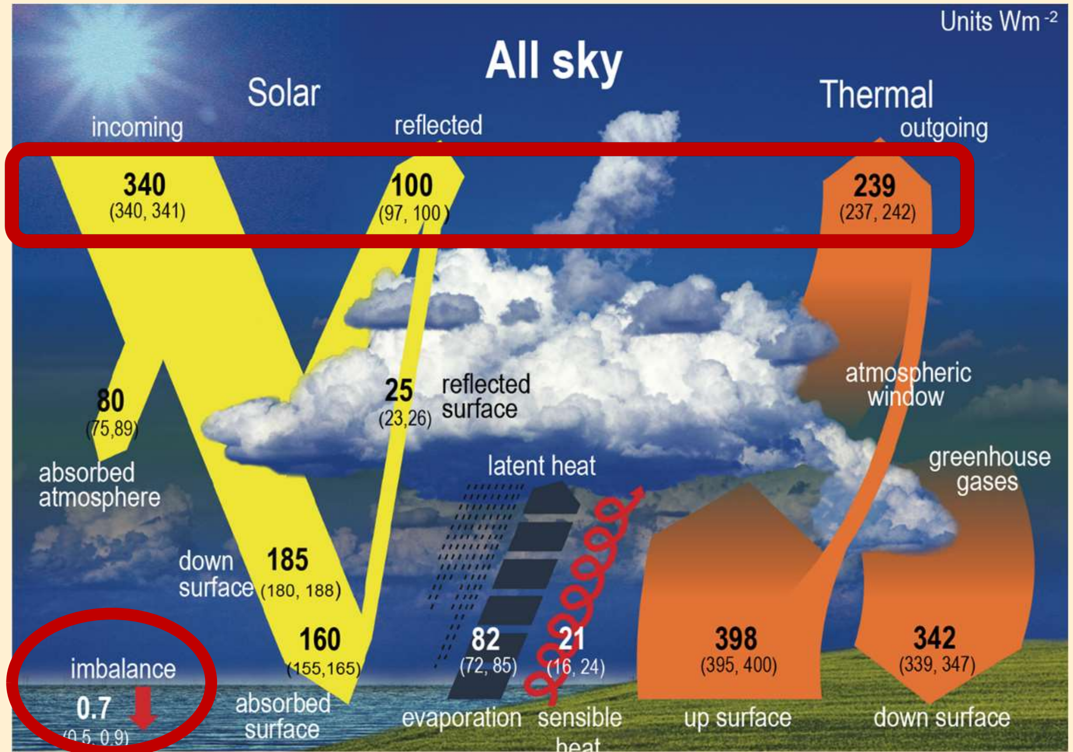
(cont.)

transparent

absorbed
⇒ large fluxes

Global Energy Budget

out of equilibrium



AR6 Fig. 7.2

Earth's energy is slightly out of equilibrium.
It warms below the surface.

Now I will focus on the imbalance.

In the radiation balance at the top of the atmosphere (TOA), the energy is not balanced by 340-100-239=1 W/m^2.

At the surface, thre is also an imbalance of 0.7 W/m^2 .

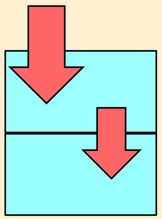
Remark: The heat capacity of the atmosphere is very small, so the value of 1 at TOA is actually 0.7.

Destination of energy absorption

Component	1993–2018	
	Energy Gain (ZJ)	%
Ocean	263.0 [194.1 to 331.9]	91.0
0–700 m	151.5 [114.1 to 188.9]	52.4
700–2000 m	82.8 [59.9 to 105.6]	28.6
>2000 m	28.7 [14.5 to 43.0]	10.0
Land	13.7 [12.4 to 14.9]	4.7
Cryosphere	8.8 [7.0 to 10.5]	3.0
Atmosphere	3.8 [3.2 to 4.3]	1.3
TOTAL	289.2 [220.3 to 358.1] ZJ	
Heating Rate	0.72 [0.55 to 0.89] W m^{-2}	

Table 7.1 (AR6)

Most of the energy absorbed by the earth is stored in the ocean. About half of them are in the deep sea.



This table shows the destination percentage of the earth's heat absorption. As we have seen, the earth absorbs heat by about 0.7 W/m^2.
Ocean heating accounts for more than 90%, with land heating at 5%, melting of snow and ice at 3%, and atmospheric heating at only 1%.

By ocean depth, about 50% remain shallower than 700 m, while the remaining 40% reach deeper ocean.

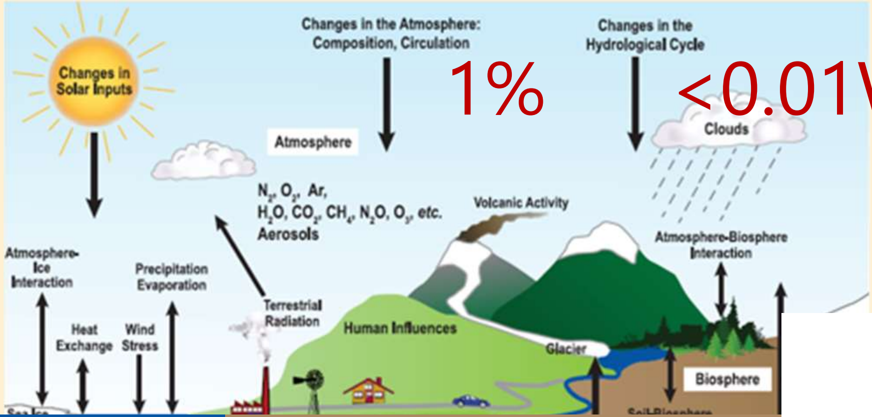
GW situation warms the top of the ocean, implying that it penetrates deeper due to ocean circulation and thermal diffusion.

Table 7.1 | Contributions of the different components of the global energy inventory for the periods 1971–2018, 1993–2018 and 2006–2018 (Box 7.2 and Cross-Chapter Box 9.1). Energy changes are computed as the difference between annual mean values or year mid-points. The total heating rates correspond to Earth's energy imbalance and are expressed per unit area of Earth's surface.

Component	1971–2018		1993–2018		2006–2018	
	Energy Gain (ZJ)	%	Energy Gain (ZJ)	%	Energy Gain (ZJ)	%
Ocean	396.0 [285.7 to 506.2]	91.0	263.0 [194.1 to 331.9]	91.0	138.8 [86.4 to 191.3]	91.1
0–700 m	241.6 [162.7 to 320.5]	55.6	151.5 [114.1 to 188.9]	52.4	75.4 [48.7 to 102.0]	49.5
700–2000 m	123.3 [96.0 to 150.5]	28.3	82.8 [59.9 to 105.6]	28.6	49.7 [29.0 to 70.4]	32.6
>2000 m	31.0 [15.7 to 46.4]	7.1	28.7 [14.5 to 43.0]	10.0	13.8 [7.0 to 20.6]	9.0
Land	21.8 [18.6 to 25.0]	5.0	13.7 [12.4 to 14.9]	4.7	7.2 [6.6 to 7.8]	4.7
Cryosphere	11.5 [9.0 to 14.0]	2.7	8.8 [7.0 to 10.5]	3.0	4.7 [3.3 to 6.2]	3.1
Atmosphere	5.6 [4.6 to 6.7]	1.3	3.8 [3.2 to 4.3]	1.3	1.6 [1.2 to 2.1]	1.1
TOTAL	**434.9 [324.5 to 545.3] ZJ**		**289.2 [220.3 to 358.1] ZJ**		**152.4 [100.0 to 204.9] ZJ**	
Heating Rate	**0.57 [0.43 to 0.72] W m^{-2}**		**0.72 [0.55 to 0.89] W m^{-2}**		**0.79 [0.52 to 1.06] W m^{-2}**	

Remark: Equilibrium or NOT

Remark: you may be confused, we will reconfirm from the point of view of thermal equilibrium.



1%

<0.01W/m^2

5%

3%

90%

The total imbalance < 1 W/m^2

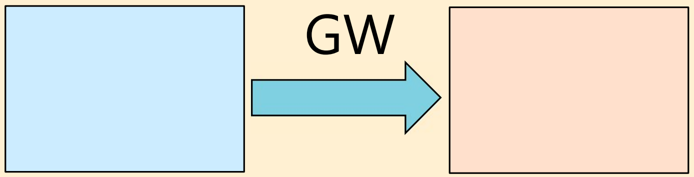
GW can be considered essentially as thermal equilibrium.

On the actual earth, it is used to heat the ocean etc. (transient response)

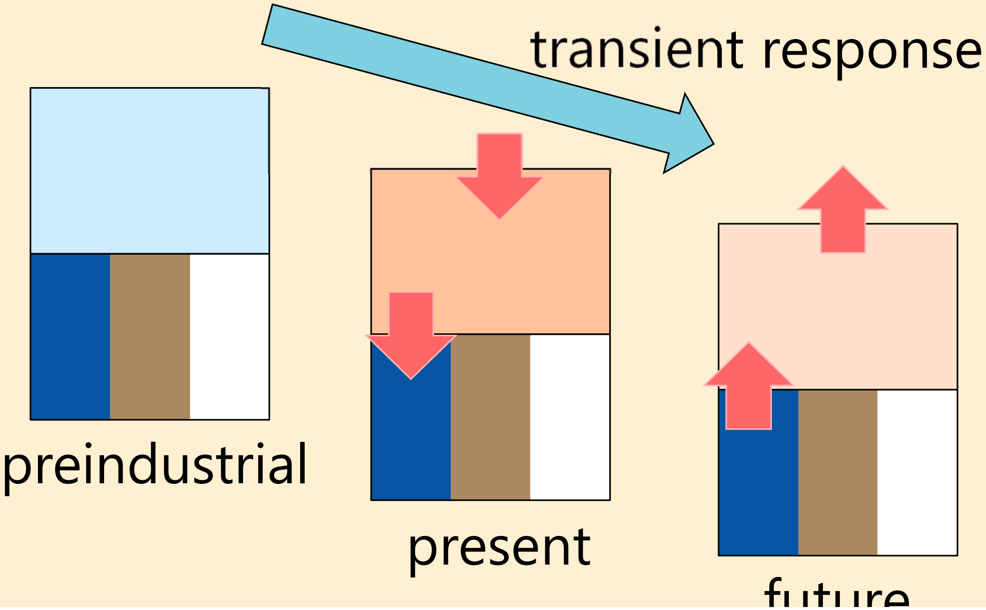
As mentioned in Part 1, global warming can be thought of as thermal equilibrium to a first approximation. The current imbalance is only 0.7 W/m^2. The heat capacity of the atmosphere is very small.

However, considered in a higher order approximation, it is not in equilibrium. On the actual earth, it is used to heat the ocean and land, and to heat and melt snow and ice.

Remark: Equilibrium or NOT



Global warming can basically be considered in terms of thermal equilibrium as shown in part 1.



If we consider a higher order approximation, we see a transient response

The solar radiance energy entering the earth has NOT changed. The terrestrial radiation leaving the earth into space has decreased. As a result, the Earth is warming in total.

In the future, if the concentration of greenhouse gases in the atmosphere decreases, the heat accumulated in the ocean should return to the atmosphere, and the amount of terrestrial radiation emitted from the earth should increase accordingly.

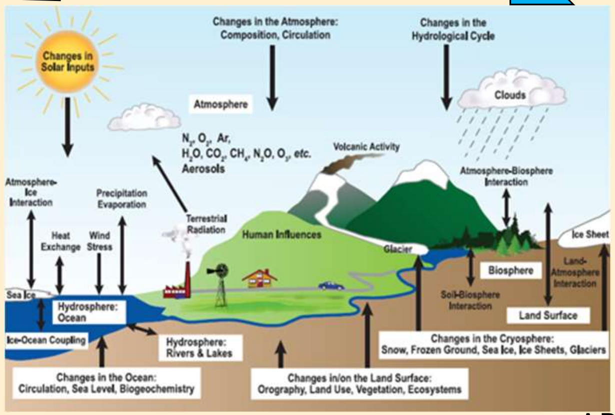
External forcings on climate system

The topic will change.
External forcings and Internal variabilities

natural

seasonal change,
11-year cycle
(solar radiation)

volcano eruption
(aerosol)



AR4 FAQ1.2 Fig.1

Climate System

GHG emission
(GHG concentration)

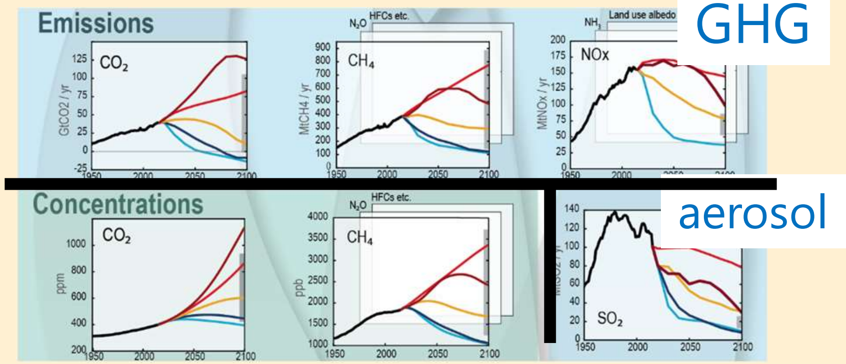
Land Use
(GHG concentration)

anthropogenic

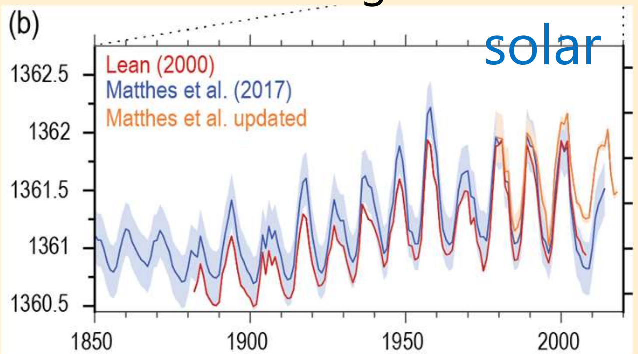
For example, emissions of greenhouse gases and aerosols due to human activities, solar radiation and its fluctuations, and volcanic eruptions are considered external forcings on climate system.

Part of climate change is a response to these external factors.

External Forcings



AR6 Fig.TS4



AR6 Fig.2.2(b)

Global warming is the result of the climate system's response to external forcing, especially GHG aerosol emissions. External forcing is a determining factor in global warming.

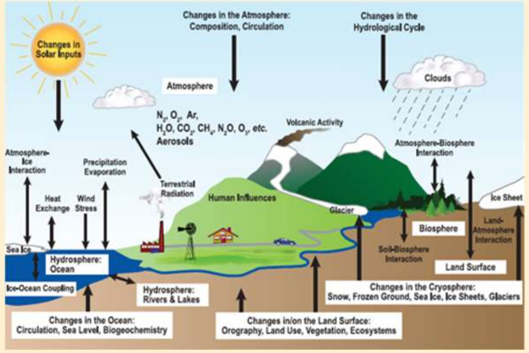
The figure shows past and future emissions of anthropogenic GHGs and sulfate aerosols (future scenario), GHG concentrations, and past solar radiation.

GHG emissions and their concentrations have increased in the past. Future changes represent scenarios, and there are some cases (red, 8.5 W/m^2 scenario to light blue, 1.9 W/m^2). Since the amount of surface temperature rise varies greatly according to the difference in these scenarios, it can be said that the emission of greenhouse gases is the factor that determines the course of global warming.

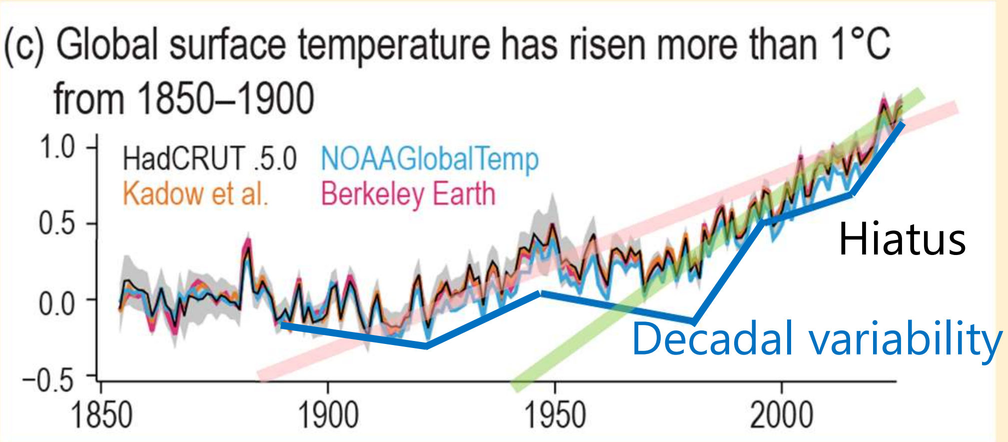
Solar radiation has an 11-year cycle, but the amplitude is small, so can be considered almost constant.

Internal variabilities (IV)

Various time-spatio scale



AR4 FAQ1.2 Fig.1



AR6 CCBox1 Fig.1

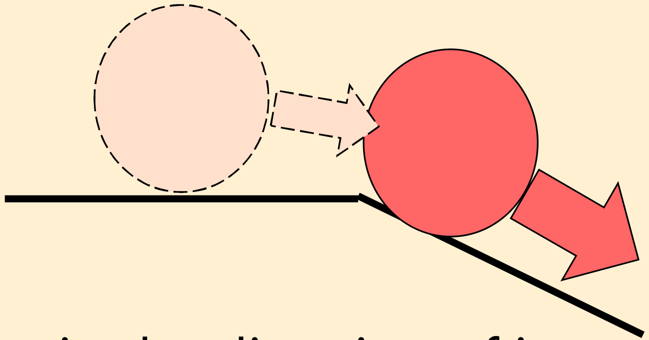
※Interannual variability is also IV.

On the other hand, phenomena that are independent of external forcings are called internal variabilities. Since the climate system is a complex system, it has various IVs. The timescales of them also vary. Meteorological phenomena such as cyclones have relatively short timescales, whereas phenomena such as ENSO and decadal variability, which involve oceanic variabilities with long time constants, span from seasons to decades.

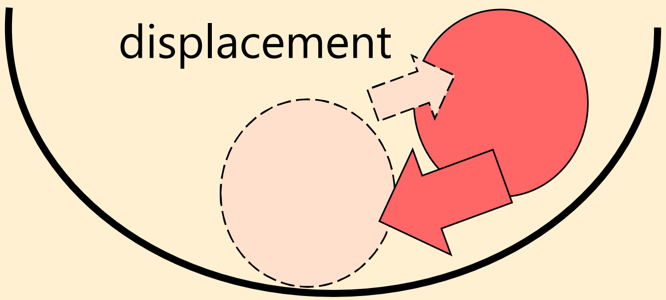
When considering global warming as a response signal to external forcing, IVs are often thought of as noise. It can sometimes interfere with the detection of changes due to global warming.

Feedback

The topic will change.
An important concept, FEEDBACK



Acts in the direction of increasing displacement: Positive feedback



Acts in the direction of decreasing displacement: Negative feedback

When a system changes, the mechanism inside the system that strengthens (weakens) the change is called positive (negative) feedback.

When greenhouse gases increase and surface temperatures rise, several responses occur. Some responses have the effect of further increasing the surface temperature(positive feedback), while others have the effect of suppressing the increase (negative feedback).

Increase in extreme weather

The topic will change. EXTREME

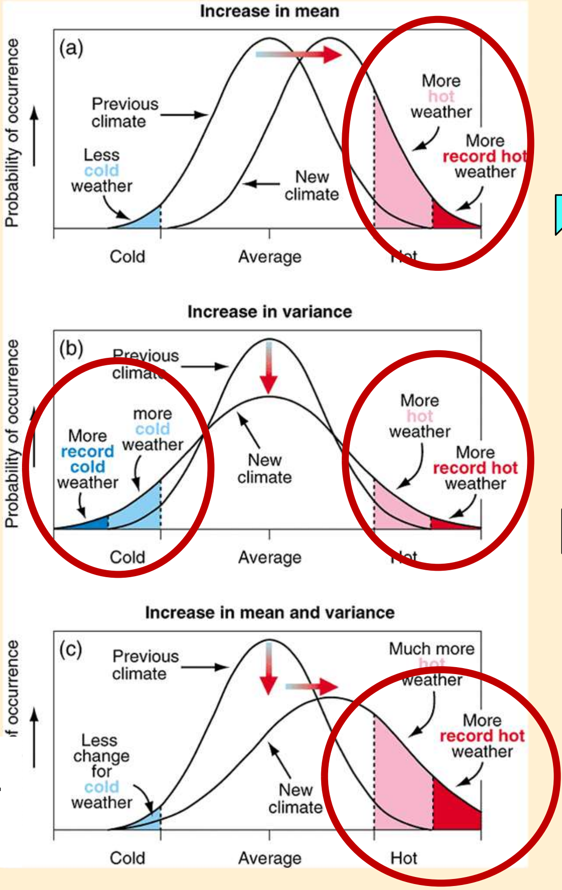


Fig.2-32 (TAR)

Mean changes and increased variability frequently cause "extreme weather in the present climate".

In these figures, the horizontal axis is the physical quantity, such as temperature, and the vertical axis is the frequency. It represents the frequency distribution of the phenomenon.

The figure above shows the case where the mean increases but the variance remains the same. In this case, events with large values that did not occur in previous climates will occur more frequently.

The middle figure shows the case where the mean remains the same, but the variance increases. In this case, both high-valued and low-valued phenomena will occur more frequently.

Increase in extreme weather

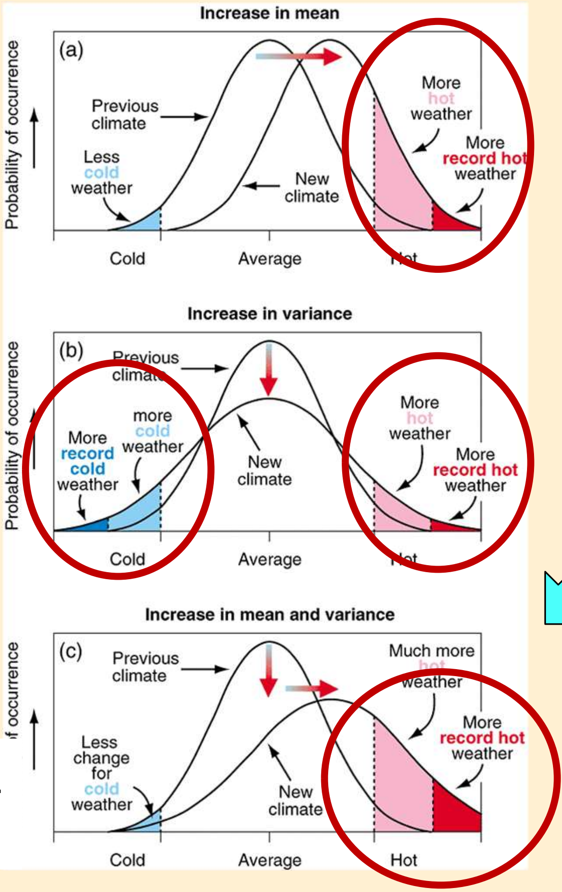


Fig.2-32
(TAR)

Mean changes and increased variance frequently cause "extreme weather in the present climate".

The figure below shows the case where the mean increases and the variance also increases. Phenomena with large values will increase significantly.

Global warming changes both the mean and the variance. In particular, it seems that there are many phenomena in which the variance increases. These mean more anomalous phenomena for us who have become accustomed to previous climate conditions.

Summary: players and concepts

The climate system consists of various components, each with different properties.

- The climate system has subsystems such as atmosphere, land surface, ocean, aerosol, and chemistry, and there are players with various characteristics in those subsystems.
- For example, the ocean is a system with a huge heat capacity. As global warming progresses, there has been a slight imbalance in the heat budget, most of which is due to heat flux into the ocean.
- Global warming is the response of the climate system to the external force of human-induced greenhouse gas emissions. The climate system also has processes with internal variability and feedback, and behaves in complex ways.
- In global warming, there are many phenomena in which not only the mean value changes but also the variance increases. They cause frequent occurrence of phenomena that are regarded as extreme weather in the current climate.

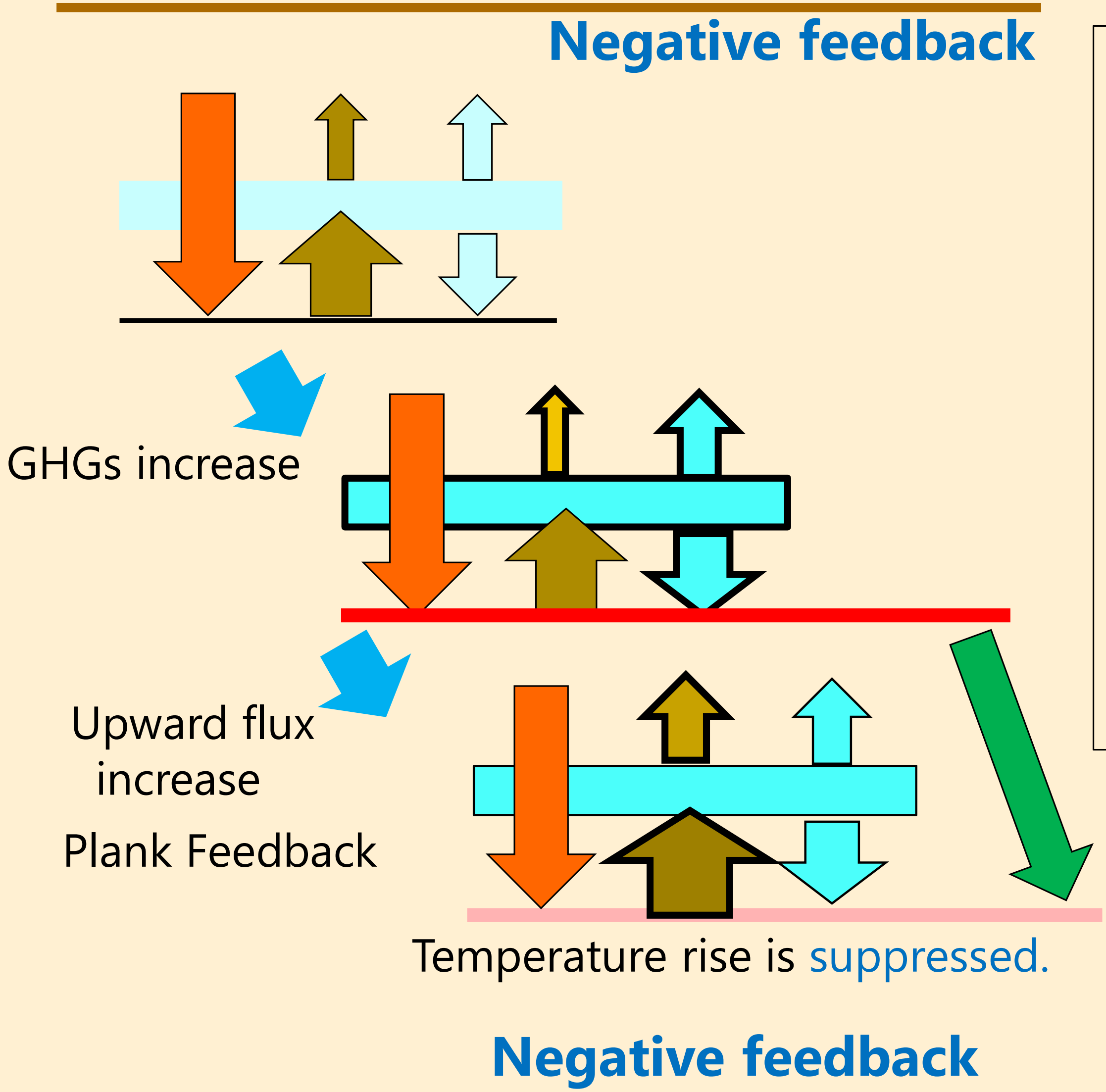
Climate system mechanisms in global warming

Here are some of the many processes.

After anthropogenic greenhouse gas increases cause surface temperature increases, several process mechanisms with feedback occur.

Planck Feedback

Remark:
This is the mechanism presented in Part 1

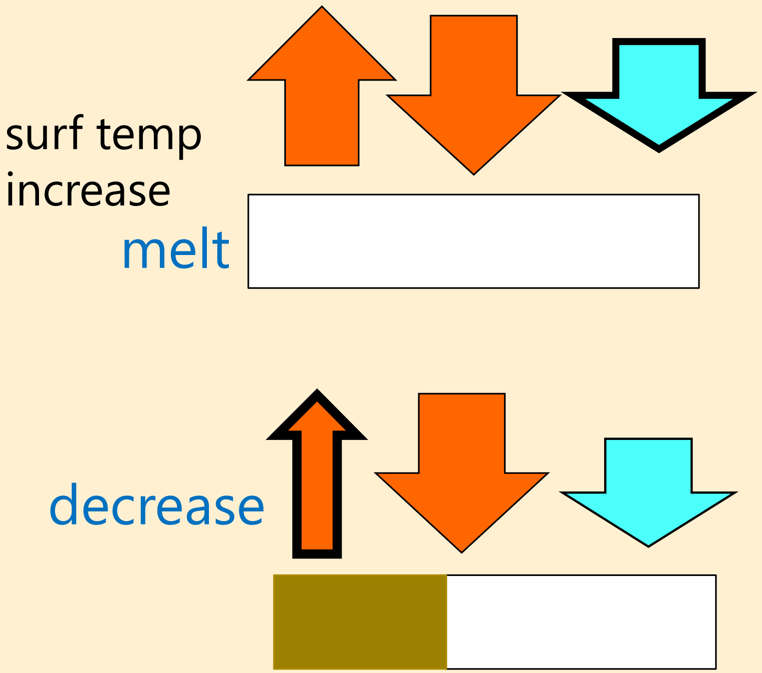


This is the mechanism presented in Part 1.

Atmosphere with increased greenhouse gases absorb more of the terrestrial radiation, causing the upper atmosphere to heat up.
Then more energy to enter the surface.
Therefore, the surface temperature rises, the energy emitted upward increases, and a state of equilibrium is reached with the surface temperature increase suppressed.

Ice-Albedo Feedback

Positive Feedback



Solar radiation input increase
⇒ melt more

Positive Feedback

Ice albedo feedback is well known as localized but very strong positive feedback.

Ice albedo feedback is a mechanism in which as the surface temperature rises, the surface snow/ice melt, the albedo (reflection) decreases, and the surface temperature rises further.

Not only is it locally warmer, but it also causes an increase in global mean solar incidence as the planetary albedo decreases.

Ice-Albedo Feedback causes..

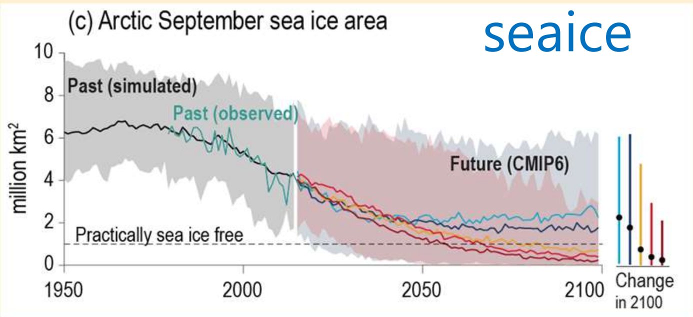
- Land Snow / Sea ice
  - ☐ Decrease in snowfall, snow amount
  - ☐ Shortening of the snow cover period
  - ☐ Shrinking sea ice extent
- Glacier and Ice sheet
  - ☐ Melting　(⇒ sea level rise)

Ice albedo feedback occurs in snow cover, sea ice, glaciers, and ice sheets.

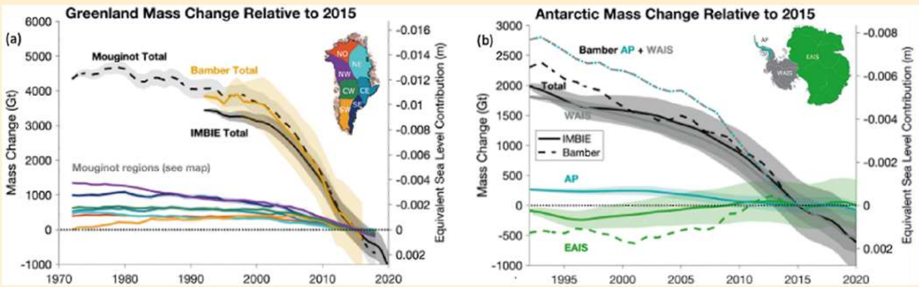
It is well known that the sea ice extent in the Arctic Ocean in summer has decreased significantly.

The spring snow melts earlier and the snow cover period is getting shorter. Snowfall and snow amount are also decreasing.

It is also known that the melting of ice sheets will cause a very large sea level rise.



TS fig8c (AR6)



ice sheet

fig. 9_16 (AR6)

Water Vapor Feedback

Positive Feedback

GHGs increase

Rise in air temperature as well as surface increases

Rise in saturated water vapor pressure (7%/K)

WV is GHG

Rise in water vapor

Rise in air temperature

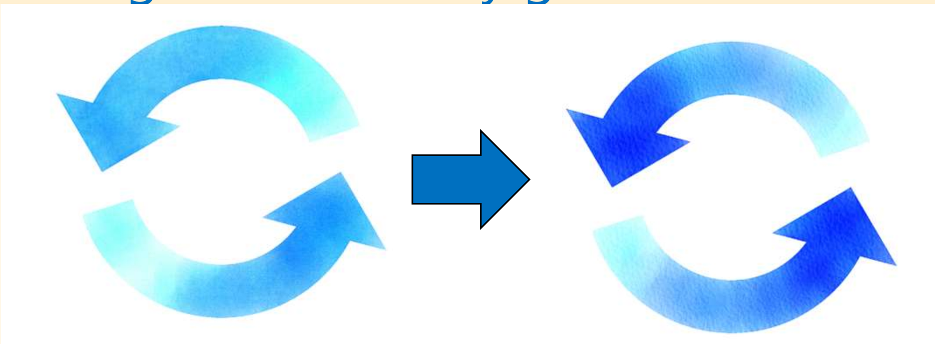
Positive Feedback

Water vapor feedback is also a strong positive feedback.

When anthropogenic greenhouse gases increase and global warming occurs, the temperature of the atmosphere rises. Saturated water vapor increases. Relative humidity, although non-obvious, does not change much. As a result, the amount of H_2O in the atmosphere increases. As already mentioned, H_2O is a greenhouse gas, which further increases the surface temperature.

Water Vapor Increase causes ...

Wet gets wetter, dry gets drier



Intensification of the water cycle on large scales causes wetter in wet regions and drier in dry regions.

Extreme precipitation

Increased water vapor also leads to increased heavy rainfall, extreme precipitation.

More water vapor in the atmosphere enhance the water circulation, if the wind circulation does not change much.

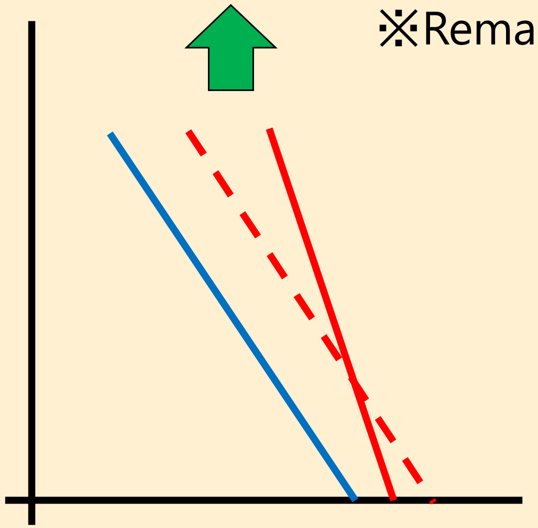
As a result, the amount of precipitation will increase in areas with wet region further. It also results in less precipitation in dry areas. This is called "wet gets wetter, dry gets drier".

There will also be an increase in extreme precipitation events where heavy rain fall at once.

Lapse Rate Feedback

Negative Feedback in low lat region

※Remark: OLR is the same



The Lapse Rate gets smaller at low latitudes due to the increasing convection heating.
Surface temperature rise is smaller to emit the same terrestrial radiation.

In Part 1, including Dr. Manabe's researches, radiative-convective equilibrium model, we assumed that the vertical temperature gradient (Lapse Rate) in the troposphere would not change even with global warming.
However, looking at the results of the climate model, it seems to change differently from that assumption.
At low latitudes, the results show that the middle layer is warmer than the lower layer.
In this equilibrium state, more upward radiation is emitted from the middle layer, so less upward radiation is emitted from the surface. In other words, the rise in ground surface temperature is suppressed.

Lapse Rate Feedback causes...

Decrease in Lapse rate means stratification stabilization.

weakened circulation (wind)

This could, for example, cause a decrease in the number of tropical cyclones.

※Remark: just a possibility

On the other hand

Increase in water vapor content, due to water vapor feedback, causes intensification of water circulation and convection.

weaken each other's changes

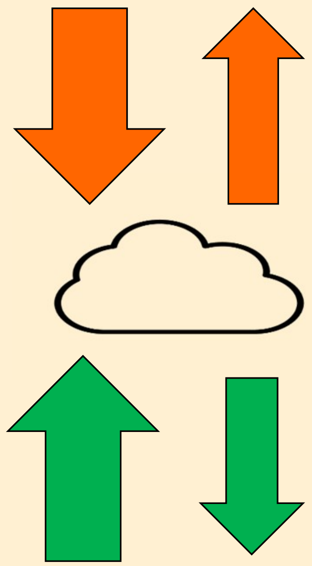
A smaller Lapse rate means that stratification is stabilized.
This could, for example, cause a decrease in the number of tropical cyclones.

Lapse rate feedback works in the opposite direction to water vapor feedback, not only in the direction of changes in surface temperature, but also in the direction of intensity and frequency of weather phenomena.

Cloud Feedback

If global warming causes more clouds, ...

albedo increases
negative feedback



greenhouse effect is enhanced
negative feedback

Consider the case where global warming causes clouds to increase.

More clouds reflect more solar radiation and lower the surface temperature. (negative feedback)

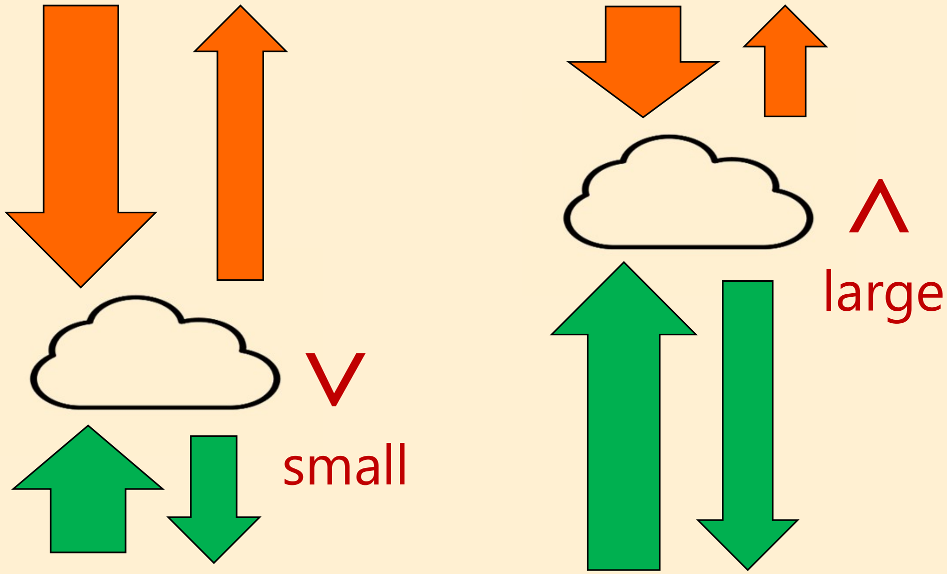
As it absorbs terrestrial radiation, the greenhouse effect intensifies and the surface temperature rises. (positive feedback).

We can see “cancellations occur”.

(cont.)

Cloud Feedback

Not clear, but possibly **positive feedback**



High and low clouds have different effects. Furthermore, It is NOT known whether each cloud will increase or decrease.

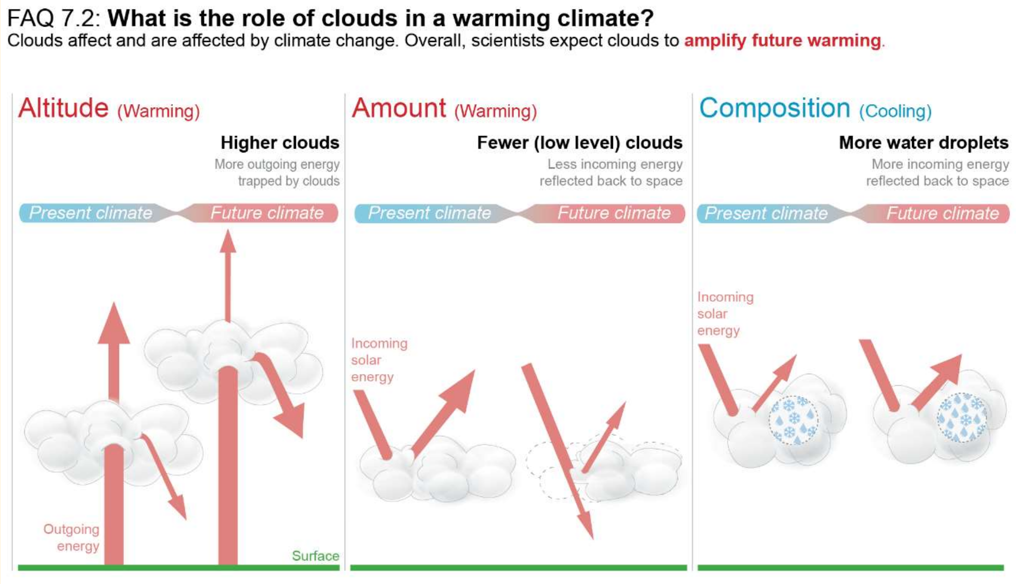
Not clear, but possibly **positive feedback**

(cont.)
For low clouds, the temperature of the cloud is similar to that of the surface of the earth, so the greenhouse effect is not very strong. (negative feedback)
Higher clouds have a stronger greenhouse effect due to lower cloud temperatures. (negative feedback)
In this way, the direction of feedback differs depending on the height of the clouds.

Furthermore, it is not known whether global warming will increase clouds.

Although cloud feedback still adds a lot of uncertainty to forecasts, it is considered to be a positive feedback.

Cloud Feedback



AR6 Fig. FAQ 7.2

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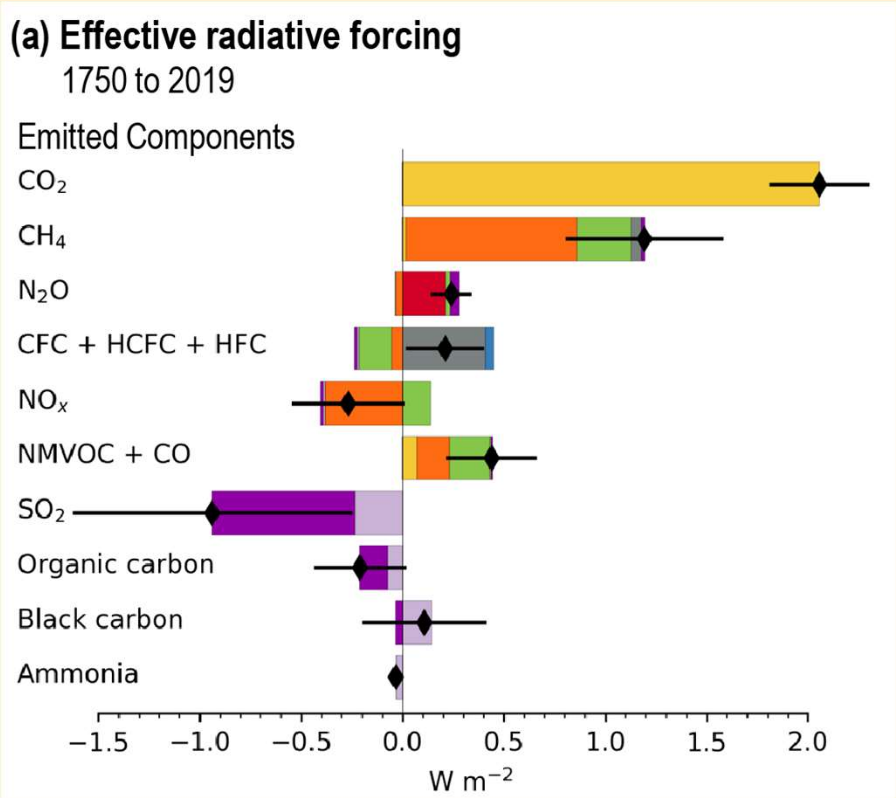
We can see that this is an open question.

Radiative Forcing

Important concepts



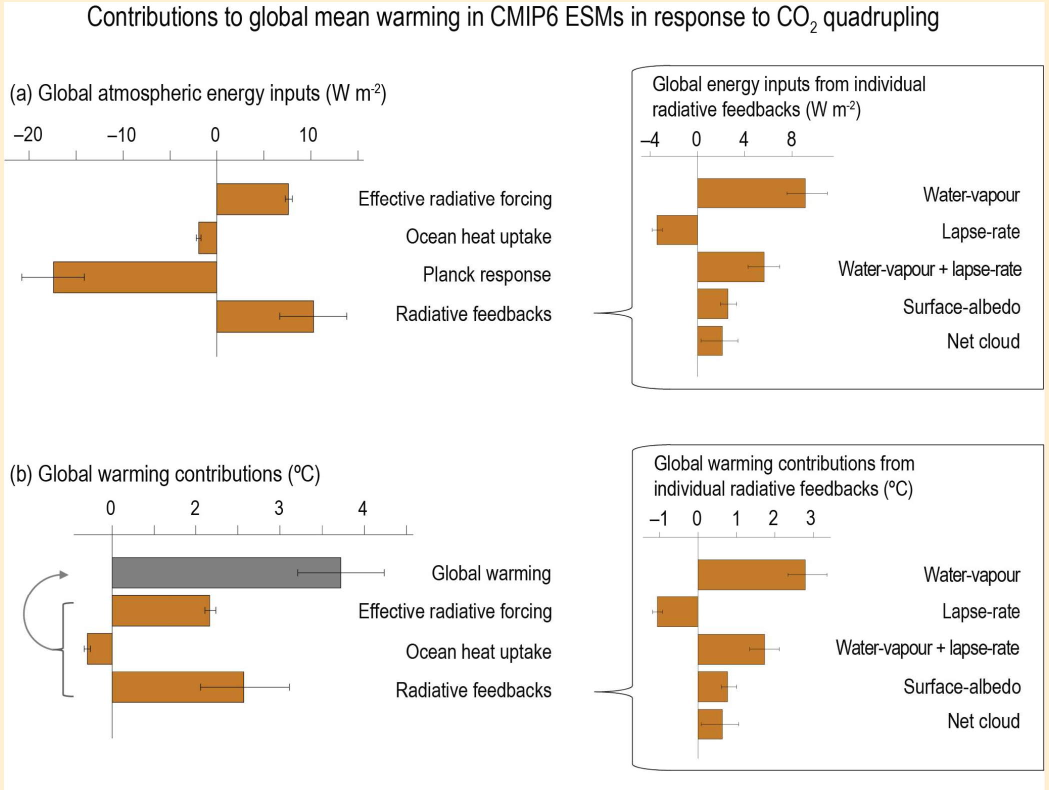
AR6 TS fig.15(a)

Effective radiative forcing at 2019 by GHGs and aerosols. Baseline is at 1750.

Radiative forcing is the amount of change in the radiation balance at the top of the troposphere caused by a factor when the climate system changes due to GHG change.

Higher radiative forcing means that the factor has a greater impact on global warming.

Total radiative forcing is a measure of the impact of GHG on the climate system. Future projections using climate models require future scenarios for GHG, and the total radiative forcing is taken into account in creating future scenarios.



AR6 Fig. 7.20

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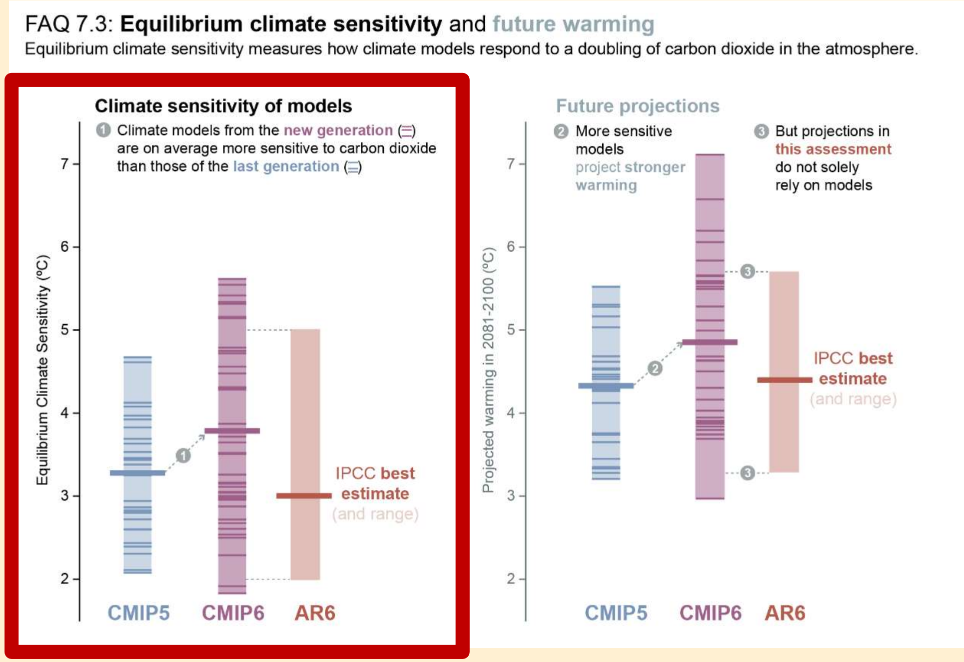
Climate Sensitivity

Important physical quantities that are indicators of the sensitivity



AR6 FAQ 7.3 Fig.1

In CMIP6, some models show big climate sensitivity, and the average and variance increased compared to CMIP5. However, they used paleoclimate and other evidence and obtained smaller value and smaller uncertainties.

Climate sensitivity is a quantity that quantitatively indicates how much the climate system is affected by a certain external factor.

Global warming usually uses changes in global average surface temperature as the impact on the climate system.

In particular, it is generally evaluated in the form of changes in surface temperature (effects on the climate system) against changes in radiative forcing (external factors) when the atmospheric CO_2 concentration is doubled.

ECS (Equilibrium Climate Sensitivity) is said to be almost 3 K, but uncertainty is still high.

Summary: Climate system mechanisms in global warming

A complex climate system has a variety of mechanisms for global warming, which can either enhance or weaken it.

- I showed some of the mechanisms that the complex climate system exhibits after the increase in greenhouse gases causes the surface temperature to rise.
- The Planck response is that an increase in greenhouse gases causes an increase in surface temperature.
- As temperatures rise, the amount of snow and ice on the ground decreases, which causes a decrease in the albedo (the reflectance of solar radiation), further increasing the surface temperature.
- As the temperature rises, the amount of water vapor in the atmosphere increases, which strengthens the greenhouse effect and acts in the direction of raising the surface temperature. This also leads to wetter areas due to enhanced water circulation.
- With warming, the temperature gradient also changes. Temperature gradients are thought to be smaller in low-latitude regions, and this works to reduce increases in surface temperature.
- The increase in clouds due to global warming raises the albedo and increases the greenhouse effect. The contribution of cloud feedback to global warming is unknown, but it is thought to accelerate the increase in surface temperature.

Summary

Summary

- The earth receives radiation energy from the sun while emitting terrestrial radiation, and they are basically balanced.
- The Earth's atmosphere contains greenhouse gases that are nearly transparent to solar radiation and absorb terrestrial radiation. This presence raises the Earth's surface temperature by about 30 K.
- Anthropogenic emissions of greenhouse gases are intensifying the greenhouse effect and causing global warming.
- The climate system is very complex and responds to external forcing in various ways, and has various interactions and internal variability.
- As a result, various changes are taking place, not limited to the increase in surface temperature. This is the global warming.