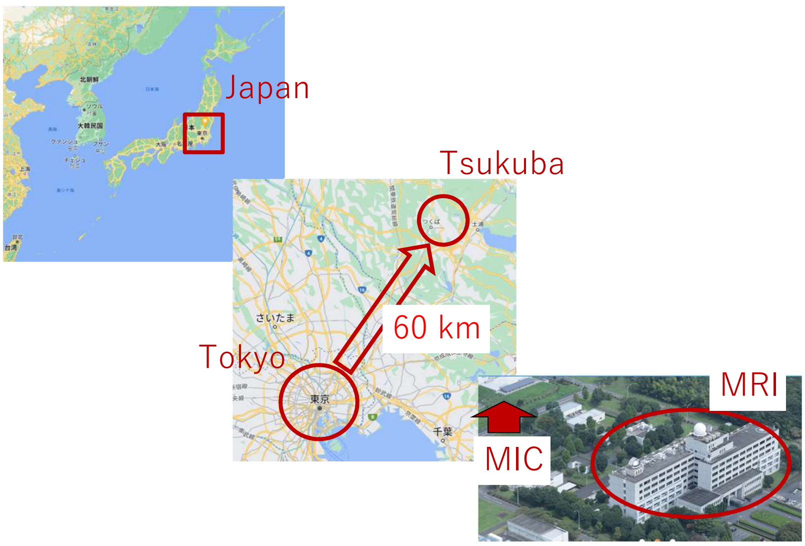
2024/01/29 at JMA HQ
TCC lecture

Introduction to climate

HOSAKA Masahiro
Climate and Geochemical Research Department
Meteorological Research Institute
Japan Meteorological Agency

mhosaka@mri-jma.go.jp

Self-Introduction and about MRI



Self-Introduction and about MRI

My name is HOSAKA Masahiro and I belong to Meteorological Research Institute.

The research subject of our laboratory is global warming. My present main job is management of our laboratory.

During my career, I have studied climate, and modeled land surface processes in our climate model.

Type 1

Format of slides

Title here

What I want to say most about this slide

Divided into 4 areas

"Main Contents"

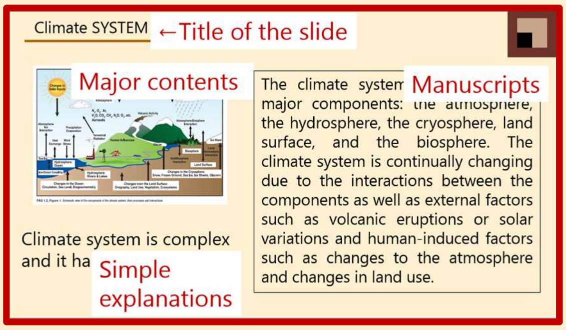
- During my presentation using "type 1 ", please mainly look at the left side (the "title" and "main content").
- If you don't understand what to say with this slide, look at the top right.
- The explanation for this slide is in the bottom right corner. Please read it when you have missed something or want to review it later.

Explanation :
a kind of manuscript

Color
Black: Normal
Blue: Emphasis
Red: Strong Emphasis
Grey: Comment

Type 2

Format of slides



Standard slide format in today's lecture consists of a title, contents, explanations, and manuscripts.

Before starting this lecture, I confess that I am NOT good at English and I DON'T think my pronunciation is good.

I briefly considered having Ms. Sone translate simultaneously while I am explaining in Japanese. If I did that, the amount of explanation would be less and Ms. Sone would be tired. This method is impractical. I could be as happy as you were.

However, if my poor English interferes with your understandings, it is not good.

(cont.)

Outline

1. What is climate ?	Some of basic concepts Difference with weather	40min
2. Radiative Balance	Equilibrium state 0 dim and 1 dim(vertical)	30min
3. Basic States	Annual Mean Seasonal Cycle	25min
4. Variability	Examples of Variabilities	25min
5. Global Warming	Longer time scale Climate system behavior in response to human activity (external forcing)	20min

Outline of today's lecture

11:00-12:30

Lunch?

14:00-15:30

Part 1: What is climate ?
Focusing on the difference with weather

- The time and spatial scale is larger than that of weather.
- System
  - ✓ The climate system contains various elements. They interact in complex ways.
  - ✓ There is a lot of internal variations and their scales vary.
  - ✓ The climate system is in a state of near equilibrium, with heat and water budgets roughly balanced.
  - ✓ The climate system varies around the averaged state due to internal variations and external forcing.
- Predictability
  - ✓ Due to chaos in the atmosphere, ensemble/probabilistic predictions are needed for climate prediction. (1st kind predictability)
  - ✓ Forecasting beyond seasonal time scale requires coupled atmosphere-ocean models as changes in ocean will have affects. (2nd kind predictability)

Part 2: Radiative Balance

- As an example of how the equilibrium state in the climate system is determined, we investigated the global average surface temperature.
- The Earth's temperature is approximately determined by the balance between solar radiation and terrestrial radiation. However, the temperature is much lower than the actual surface temperature.
- Due to the presence of GHG s , which are transparent to solar radiation and absorb and emit terrestrial radiation, the equilibrium temperature at the Earth's surface is higher.
- The higher the GHG concentration, the higher the equilibrium surface temperature. This corresponds to the ongoing global warming.
- It is possible to explain realistic atmospheric temperature distribution, the greenhouse effect, and global warming by using a simple system that includes radiation, convection and greenhouse gases.

Part 1. What is climate?

Before starting this lecture ...

At first, please talk freely what you think that climate is.

What is the difference between weather and climate ?
meteorology

Free Talk (10min)

Any comment is OK!

Please feel free to comment

To introduce yourself, please let us know your name, country, and what kind of models and data you have used in your climate-related work.

The definition of weather by 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





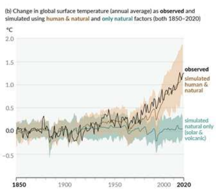


An example of what weather is.

The definition of climate by WMO:

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



statistics

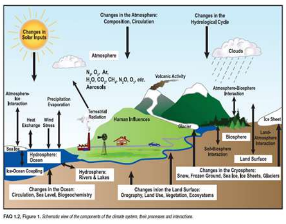
global mean
surface air temperature

An example of what climate is.

The definition of climate system by WMO:

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



Schematic view of climate system

AR4 FAQ1.2 Fig.1

An example of what climate system is.

The climate system is a complex one, composed of many elements.

Difference between weather and climate

Every person has different answers.

I will take a moment to express just my opinion from now on.

From now on, I will talk about climate of my thoughts.

Difference between weather and climate

Key Players

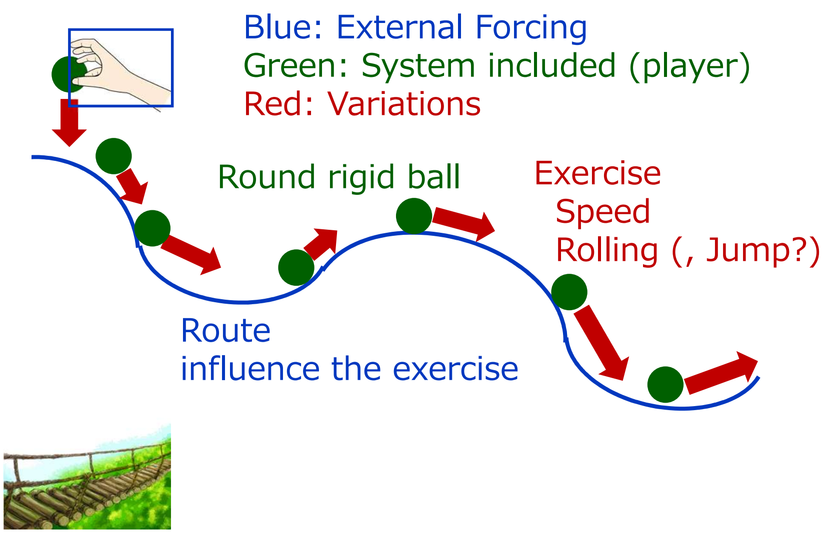
Player	Related Concepts
Atmospheric Convection	Chaos; Unstable atmosphere and Solar radiation 1st kind of predictability
Ocean	Huge Capacity External Forcing ⇒ one of System components 2nd kind of predictability
Human Activities	External Forcing Anthropogenic greenhouse gases

Key words:

- Scale (time and space)
- System considered / players included
- internal variations / external forcing / equilibrium state

- I think that the difference between weather and climate is related to the concepts mentioned here.
- I can not explain it systematically.
- I hope you can feel something from my unclear explanation.

System, players, internal variations and external forcing

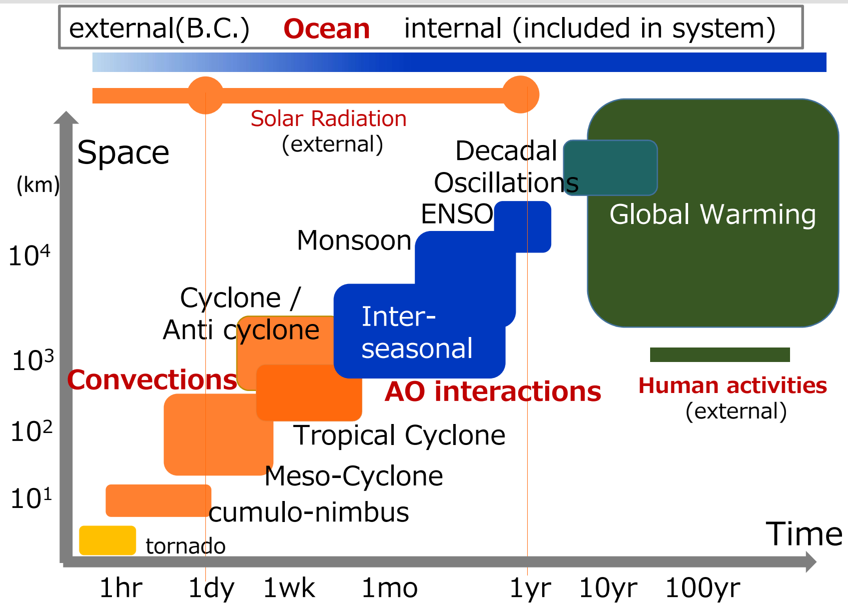


Route that changes depending on exercise

We deal with internal variations of some systems that are subject to external forcing.

As the scale becomes larger and longer, from weather to climate, the systems we consider become more complex.

Internal Variations



There are various internal variations on various scales in time and space in the climate system.

These internal variations are forced by external forcing.
The ocean acts as an external forcing (boundary condition) on shorter time scales, but varies as part of a system on longer time scales.

Convection / Chaos in the atmosphere

- 1st kind of predictability
- Is determinism possible, or is ensemble/probability required?

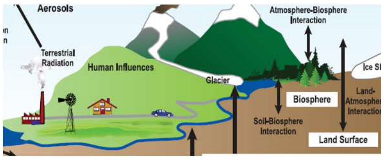
Reference information

In case of land surface and/or river models,...

Some of you may be used to land surface and/or river models.
They may be surprised at the behavior of atmospheric models.

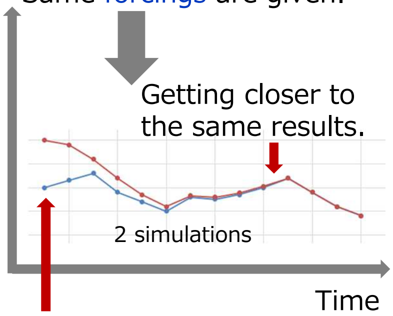
If your specialty is "water resources" or something, ...

External forcing
Atmospheric information
precipitation etc.



A land surface and/or river model

Same forcings are given.



Initial values are different.

Some people refer to these models as slaves to external forcing.

The behavior of the land surface/river models is controlled by atmospheric forcing.

Some of the participants may be familiar with the land surface models or river models.
I think they may be surprised by the behavior of atmospheric models.

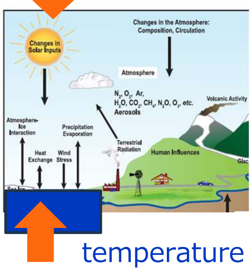
The behavior of river models is controlled by atmospheric forcing.

In case of atmospheric models,...

If you are used to land surface and/or river models, you may be surprised at the behavior of atmospheric models.

An atmospheric model

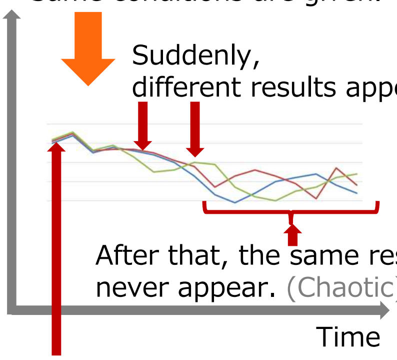
Solar radiation



temperature

Ocean condition

Same conditions are given.



Initial values are different but very close.

Atmospheric models run wild without being controlled by external forces.

If there is even a slight difference in the conditions, the behavior of the system will become completely different after a certain point, even if the external forcing is exactly the same.

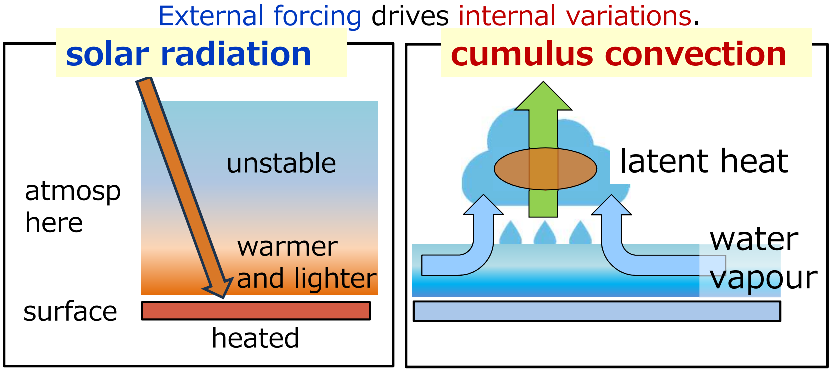
Why?

Atmosphere

It is "unstable" because it is heated from bottom and the convection is strengthened by latent heat.

positive feedback

External forcing drives internal variations.



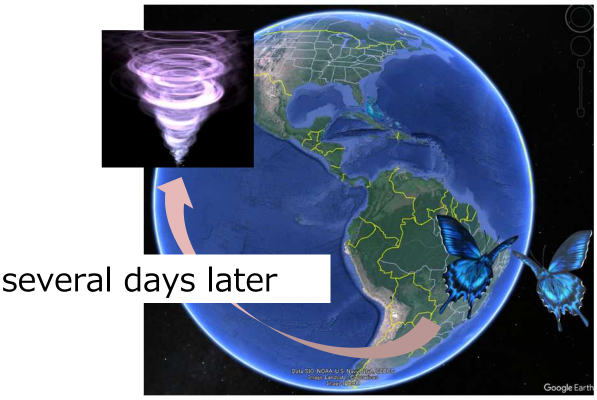
Atmospheric characteristics : unstable and chaotic

[Read the top left]

The atmosphere is unstable vertically because it is warmed from the bottom, and stronger convection occurs due to the phase change of water vapor and the release of latent heat during convection. This makes the atmosphere chaotic.

Atmosphere is unstable and it is chaotic.

Philip Merrilies titled Lorenz's presentation, "Does the flapping of a butterfly's wings in Brazil cause a tornado in Texas?"



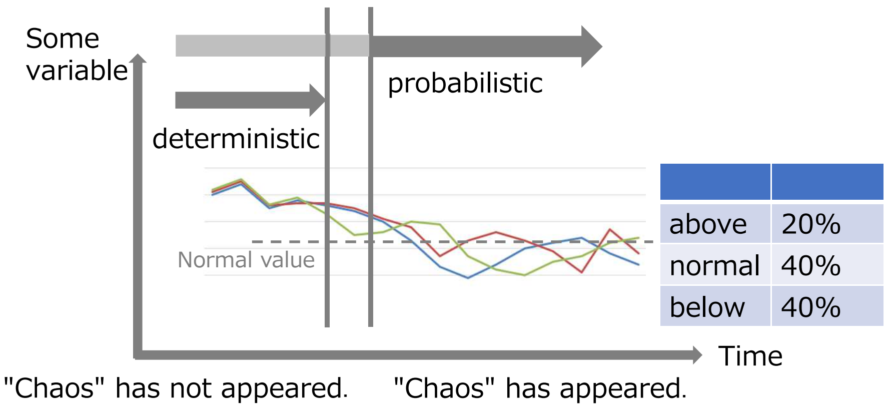
Since then, this has been called "butterfly effect".

Atmospheric dynamics is chaotic.

Lorenz was the first to point out "Chaos" by using Lorenz' system.

In the atmosphere, slight differences in the initial state can greatly change the subsequent state.

Differences in terms of forecasting



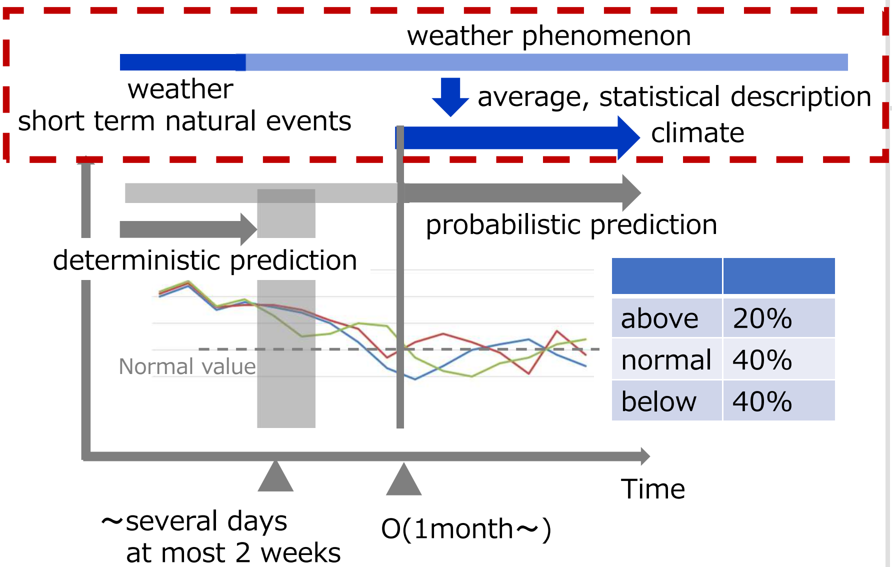
Longer prediction must be probabilistic.

Forecasting the weather can be done deterministically since chaotic properties have not yet appeared.

On the other hand, longer time forecasts, including climate forecasts, need to be expressed probabilistically.

Just my opinion

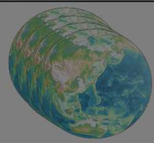
Difference between weather and climate



- As defined by WMO, weather is short term natural events.
- The time scale is almost less than 1 week.
- The weather is always present, and its average and statistical description are climate.
- The time scale of climate is approximately 1 month or longer.

From Sato-san's slide (modified)

al NWP Global Models at JMA

	Global Spectral Model (GSM)	Global EPS (GEPS)	Seasonal EPS (JMA/MRI-CPS3)
Domain			
Horizontal resolution	approx. 13 km	approx. 27 km (up to 18 days) approx. 40 km (up to 34 days)	Atmosphere: approx. 55 km Ocean: approx. 25 km
Forecast length (initial hours)	264 hours (00,12 UTC) 132 hours (06,18 UTC)	5.5 days (06,18 UTC), 11 days (00 UTC) 18 days (12 UTC) 34 days (12 UTC on Tue. and Wed.)	7 months (00 UTC)
Ensemble size	1	51 (up to 18 days), 25 (up to 34 days)	5
Main Products	Typhoon Forecasts, Three-hourly Forecasts, Daily Forecasts, Aviation Weather Forecasts and Warnings	Typhoon Forecasts, One-week Forecasts, Early Warning Information on Extreme Weather, Two-week Temperature Forecasts, One-month Forecasts	Three-month Forecasts, Warm/Cold Season Forecasts, El Niño Outlook
Initial conditions	Hybrid 4D-Var	Global Analysis + SV + LETKF	Atmos.: Global Analysis＋BGM Ocean: 4D-Var + perturbations calculated using 4DVAR minimization history
SST Sea Surface Temperatures conditions	Anomaly-fixed SST (MGDSST)	Anomaly-fixed SST and ensemble-mean SST by CPS3 after 6 days (two-tier method)	Predicted SST in the fully coupled model (one-tier method)

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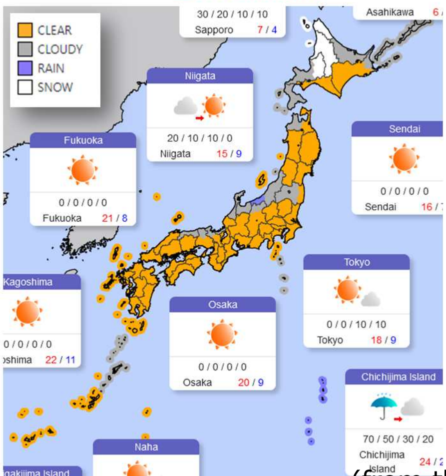
Images of short-range forecasts and long-range forecasts

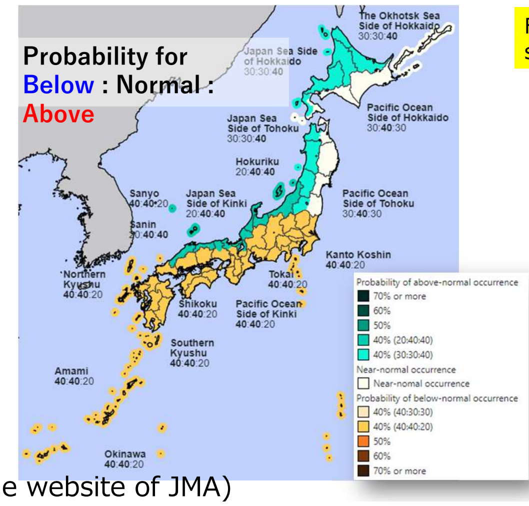
Short-range forecast

- States weather parameters (temperatures, precipitation, …) as they are expected
- Achievable in **deterministic** way

Seasonal forecast

- States expected **deviations** from climate values
- Achievable only in **probabilistic** forecasting





From Natori-san's slide (modified)

(from the website of JMA)

Ocean / Huge capacity and longer time scale

- Boundary Condition ⇒ Predicted Variables
- 2nd kind of predictability

Ocean

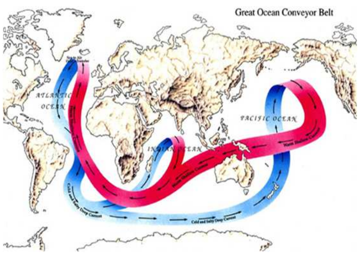
It has huge capacity and much longer time scale.

Huge Storage

Quantity	Ratio
Heat Capacity	1000
Total Mass	200

Ocean / Atmosphere

Conveyor Belt



Global circulation
More than 1000 years for one cycle

Physics: Dynamics (wind, density, salinity), diffusion.
Consists of seawater and sea ice.
Carbon and nitrogen cycles for climate projection

The ocean plays a very important role in the climate system.

The ocean is characterized by huge capacity, more than 100 times larger than the atmosphere. The time scale is very long.

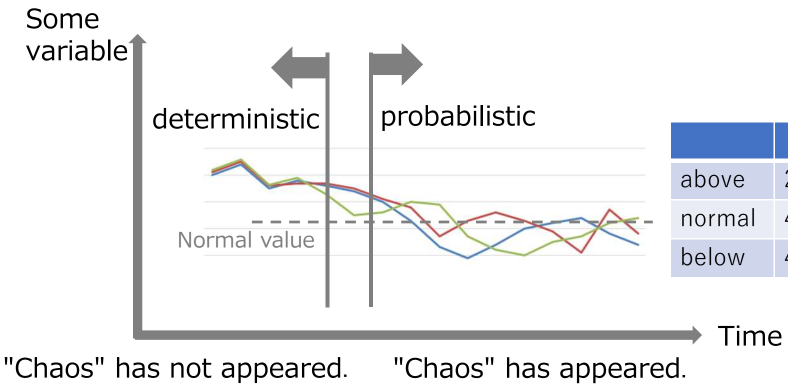
Ocean is sometimes treated constant at weather prediction.

In climate, the ocean plays a very important role as storage, approaching a state of balance through long-term changes.

Reposted just for review

Differences in terms of forecasting

Forecast



above	20%
normal	40%
below	40%

※JMA uses ensemble forecasts in order to make predictions more accurate, even for short-term forecasts.

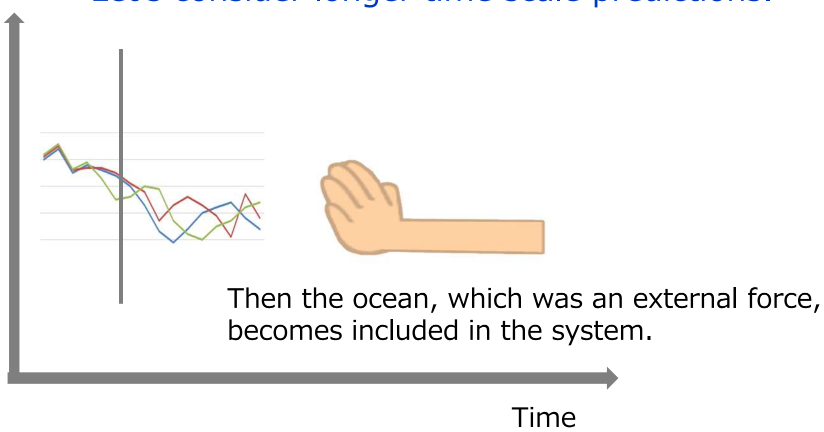
Longer prediction must be probabilistic.

Forecasting the weather can be done deterministically since chaotic properties have not yet appeared.

On the other hand, longer time forecasts, including climate forecasts, need to be expressed probabilistically.

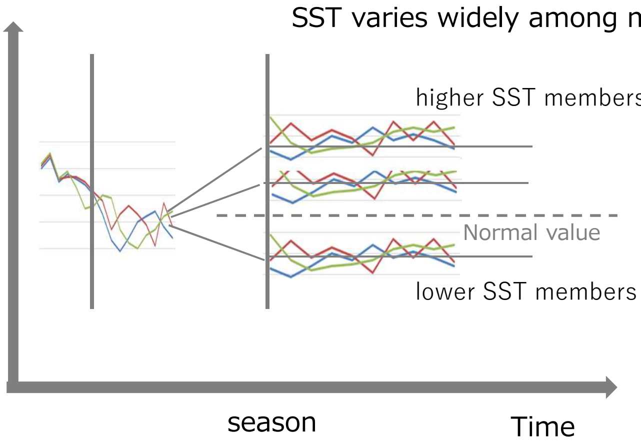
More longer term forecast

Let’s consider longer time scale predictions.



More longer term forecast

Coupled Atmosphere-Ocean Model is needed, where ocean conditions are predicted variables.

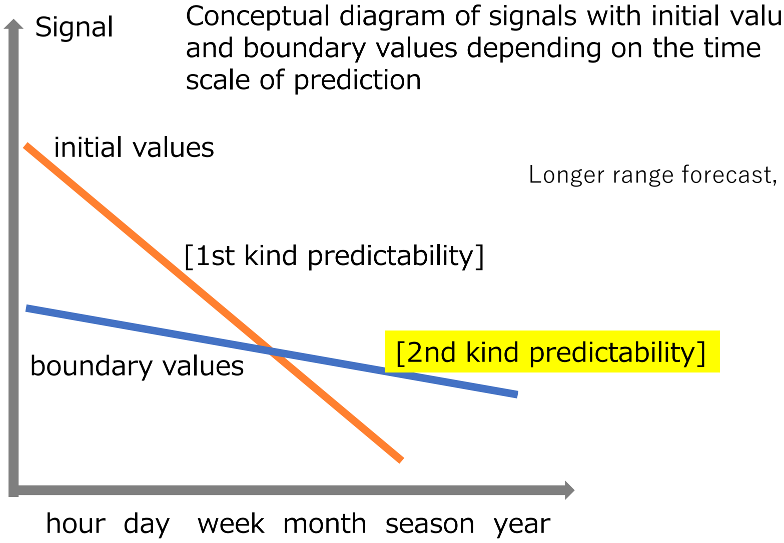


above	50%
normal	30%
below	20%

On time scales longer than months, internal variabilities include those of ocean and land.

The 2nd kind predictability

Conceptual diagram of signals with initial values and boundary values depending on the time scale of prediction



For longer forecasts, in addition to the the predictability due to internal variations in the atmosphere, the predictability due to changes in the ocean, which was a boundary condition, appears. Prediction accuracy becomes more difficult to maintain.

From Sato-san's slide (modified)

al NWP Global Models at JMA

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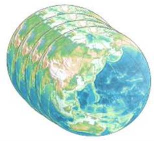
Domain			
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Reference information

Balance and Equilibrium

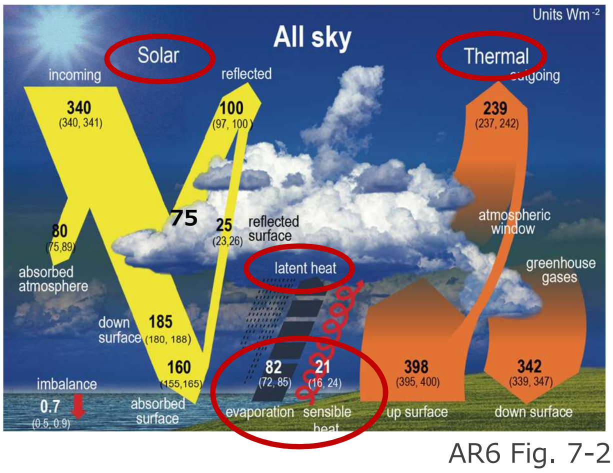
In the climate system, heat, water and momentum are roughly balanced and in a state close to equilibrium.

You will experience this in the next section.
Here is a brief introduction.

Reference information: Balance or Equilibrium (1)

Global Energy Balance

Annual mean



AR6 Fig. 7-2

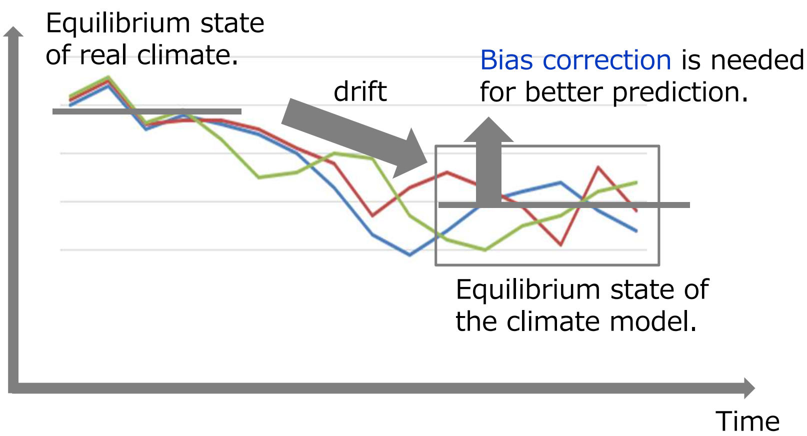
Radiation (solar, terrestrial) , Convection (latent heat), Turbulence (sensible/latent heat)

The climate is approximately at equilibrium state, which is determined by energy balance.

This figure is a very basic representation of the climate system.
This is a figure of energy that is zero-dimensional in time and space, and is an annual average, with the horizontal direction being the global average and the height direction not taken into account.
Solar radiation and terrestrial radiation are particularly important, and turbulence and latent heat release in cumulus clouds also play a role.

Reference information: Balance or Equilibrium (2)

In addition, there are model biases ...



Climate models are not perfect, so the equilibrium state differs from that of the real Earth.

As the model integrates over time, it moves from the initial state (near the equilibrium state of the real atmosphere) to the model's equilibrium state.

Maybe SKIP here (Section 5: Global Warming Section)

The climate system has many elements (players) with unique properties and roles.
Here are some examples of the key players.

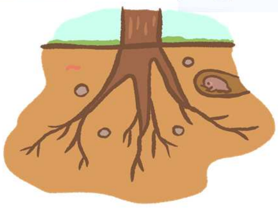
Other players and their characteristics

- Land surface
- Manor components in the atmosphere
- Cloud
- Snow and Ice

Maybe SKIP here

Land surface

various land covers



Physics: Heat and water flows/fluxes in vegetation, snow, soil.
River for climate
Carbon and nitrogen cycles for climate projection

Heat and water flows are important in the weather, but the carbon cycle also plays a role in the climate system.

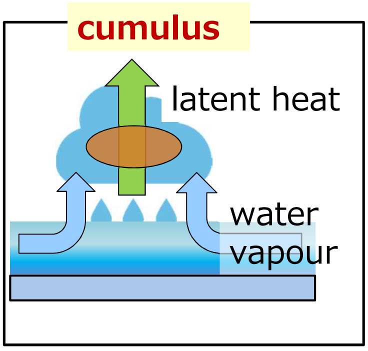
The land is covered with vegetation, snow and ice, lake, and bare land, and has different topography.

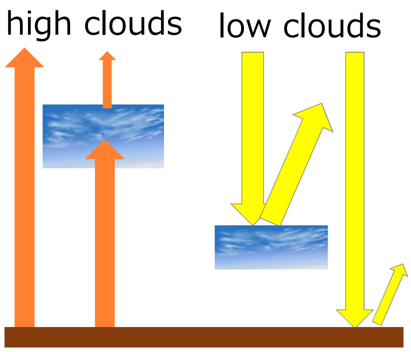
It is strongly connected to the atmosphere through water and heat cycles in the weather system.

In addition, in the climate system, Rivers that carry water into the ocean should be treated. Carbon and nitrogen cycles also play important roles in the global warming issue.

Maybe SKIP here

Cloud





Changes in high clouds and low clouds have different effects on the climate.

Clouds have very special roles in both weather and climate.

Clouds, in weather, cause water phase changes and atmospheric heating.

Cloud has a large impact on the climate through radiation, and clouds are a major source of uncertainty in global warming projections.

Maybe SKIP here

Minor Components in the atmosphere

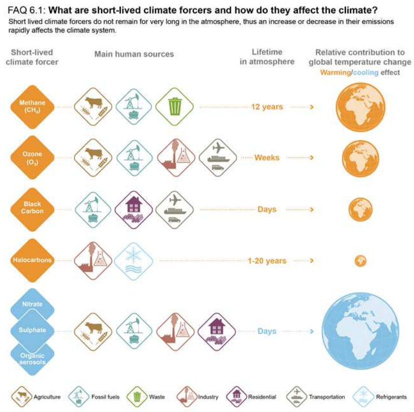
Tracers

Ozone, Metan, CO2, ...

Aerosols

Black carbon, Sulfate, Sea solt, ...

If there were no aerosols, there would be almost no clouds.



AR6 FAQ6.1 Fig.1

Most of them are short lived, but ...
Each has very unique characteristics and roles in the climate system.
and complicates the climate system.

Advection, chemical reaction, change in forms and dynamics

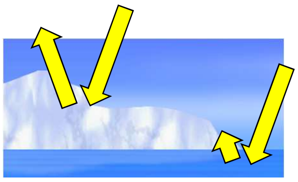
Minor atmospheric components play very important roles in both weather and climate.

Water can condense in the atmosphere because of aerosols. Although it is rarely dealt with explicitly, it is also very important in weather.

Its importance increases in the climate system because it causes changes clouds.

Maybe SKIP here

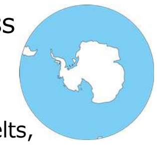
Snow and Ice



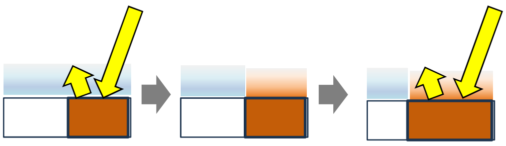
High albedo

High reflectance of solar radiation

Huge amount of mass



If all of Antarctica's ice melts,
sea water levels will rise by 60m globally.
For Greenland, it is 6m.



Ice (Snow) albedo feedback

Very strong positive feedback affect climate change.

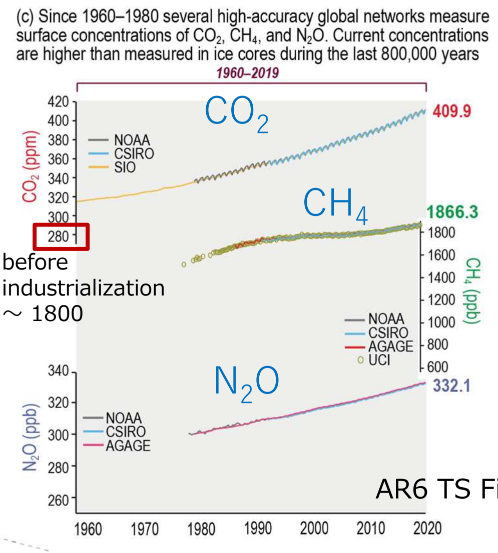
Snow and ice also have unique roles in the weather / climate systems.

Snow and ice play the role of keeping the surface temperature below zero degrees in the weather system.

Due to its high reflectance (albedo) of solar radiation, it has a large impact on the climate system through radiation, including positive ice-albedo feedback.

In addition,

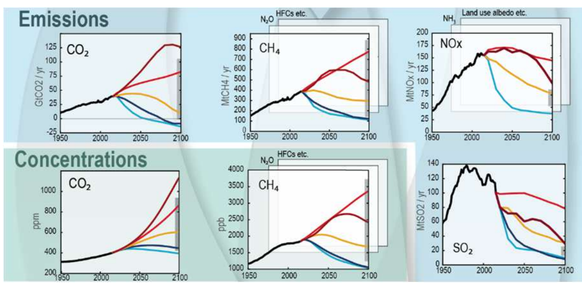
Human activities



AR6 TS Fig.9 (c)

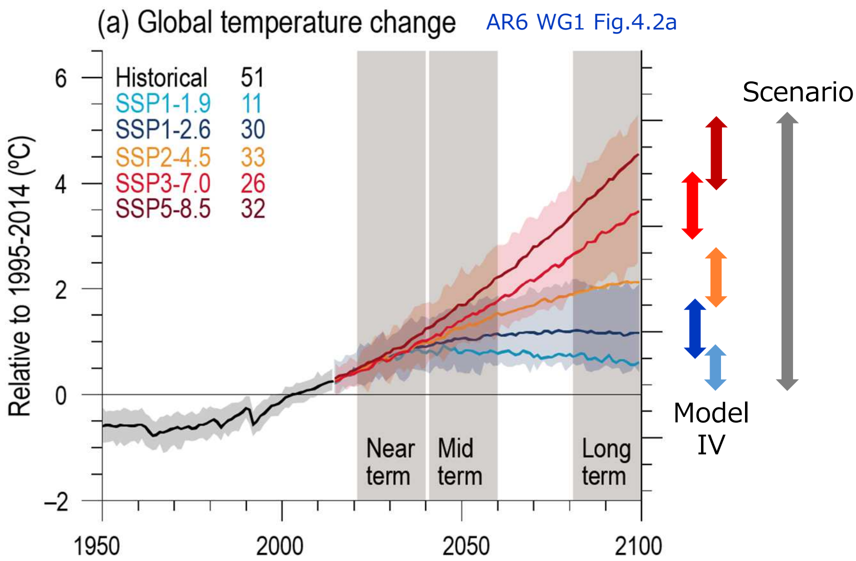
Observed concentrations of CO_2, CH_4, N_2O, the major anthropogenic greenhouse gases, have been increasing.

In the future, the emissions are expected to decrease, although they may continue to increase.



AR6 Fig.TS4

Much more longer term "projection"



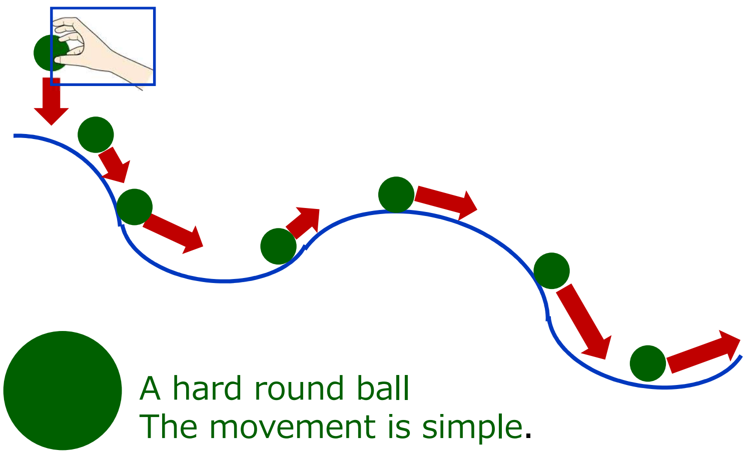
In long-term global warming projections, external anthropogenic forcing determines the uncertainty.

For long-term predictions such as those extending to the end of this century, the uncertainty due to external forcing from human activities is greater than that due to internal variability.

Summary: What is climate ?
Focusing on the difference with weather

- The time and spatial scale is larger than that of weather.
- System
  - ✓ The climate system contains various elements. They interact in complex ways.
  - ✓ There is a lot of internal variations and their scales vary.
  - ✓ The climate system is in a state of near equilibrium, with heat and water budgets roughly balanced.
  - ✓ The climate system varies around the averaged state due to internal variations and external forcing.
- Predictability
  - ✓ Due to chaos in the atmosphere, ensemble/probabilistic predictions are needed for climate prediction. (1st kind predictability)
  - ✓ Forecasting beyond seasonal time scale requires coupled atmosphere-ocean models as changes in ocean will have affects. (2nd kind predictability)

Responses for external forcings and internal variations

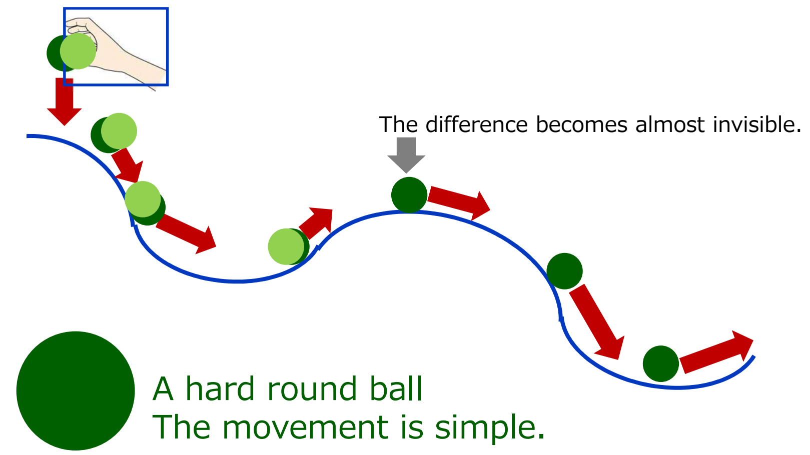


In case of land surface / river models...

A round, hard ball moves regularly while changing its speed (internal variability) according to its course(external forcing).

Responses for external forcings and internal variations

In case of land surface / river models...

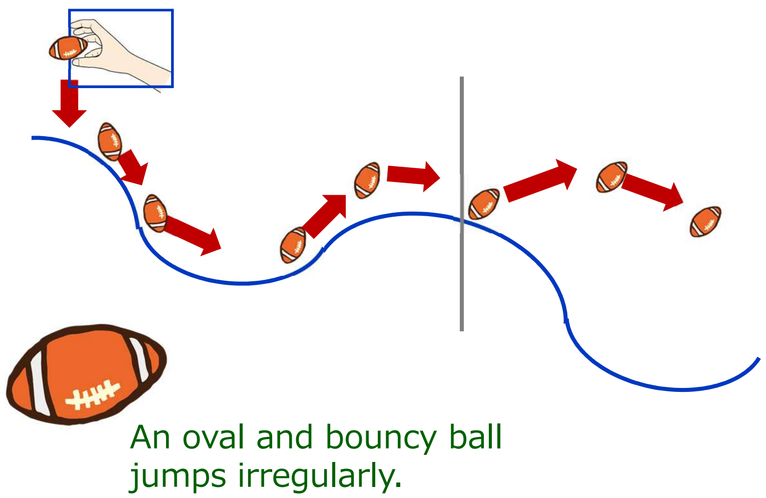


A round, hard ball moves regularly while changing its speed (internal variability) according to its course(external forcing).

Even if there were slight differences in conditions, they would eventually behave the same.

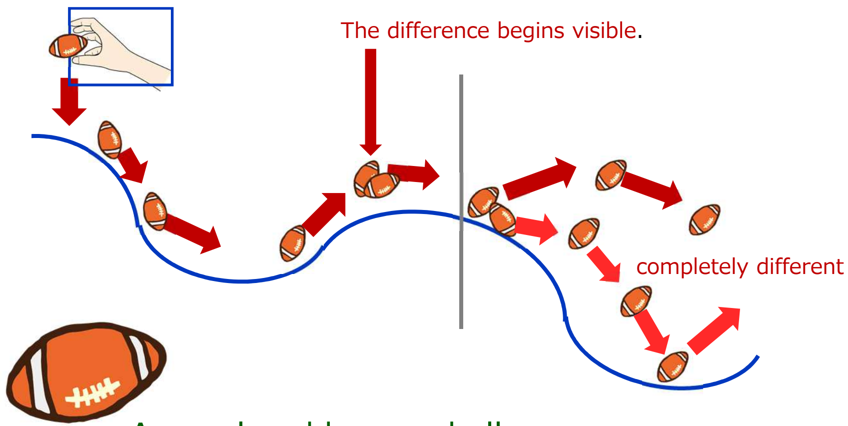
Responses for external forcings and internal variations

In case of atmosphere



An oval bouncing ball irregular course, it will move in a fairly irregular manner.

Responses for external forcings and internal variations



An oval and bouncy ball
jumps irregularly.

In case of atmosphere

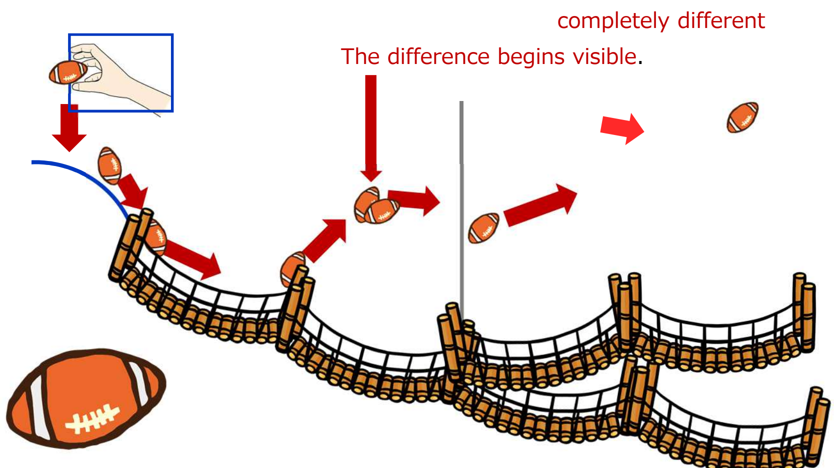
An oval bouncing ball irregular course, it will move in a fairly irregular manner.

If there were slight differences in conditions, they would behave completely differently.

After that, they never be similar.

jumps irregularly.

Responses for external forcings and internal variations



An oval and bouncy ball
jumps irregularly.

In case of atmosphere

If there were slight differences in conditions, they would behave completely differently.

After that, they never be similar.

Outline

Outline of today's lecture

1. What is climate ?	Some of basic concepts Difference with weather	40min
2. Radiative Balance	Equilibrium state 0 dim and 1 dim(vertical)	30min
3. Basic States	Annual Mean Seasonal Cycle	30min
4. Variability	Examples of Variabilities	25min
5. Global Warming	Longer time scale Climate system behavior in response to human activity (external forcing)	20min

11:00-12:30
Lunch?
14:00-15:30

How to determine the mean state.
- focusing on surface temperature -

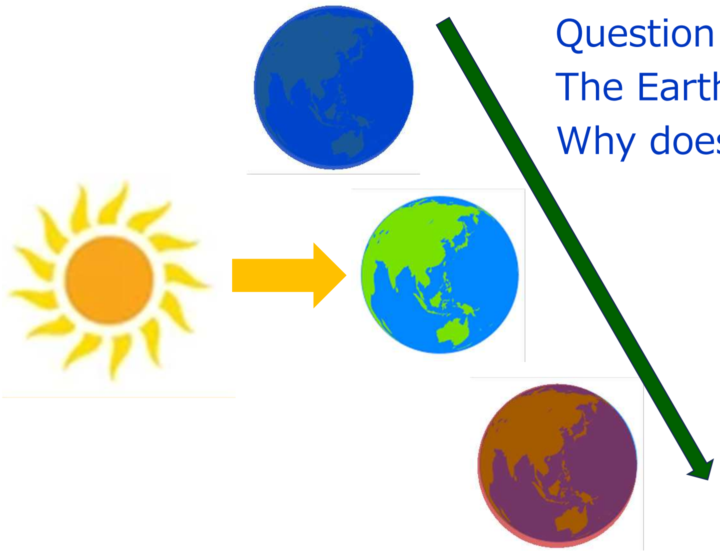
Please experience
how the mean state is determined

This part does Not deal with internal variations.

Part 2. Radiative Balance

- Review of basic physics (radiation)
- Greenhouse effect
  - 0-dim model
  - Manabe's 1-dim Model

How to decide Earth's temperature ?

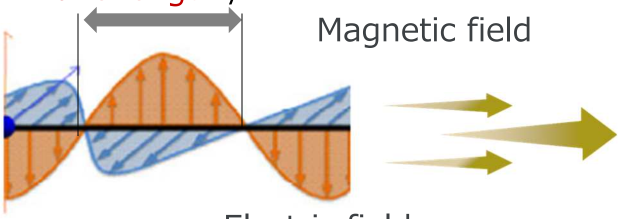


Question:
The Earth is heated by solar radiation.
Why doesn't it heat up endlessly?

Electromagnetic Wave

Electromagnetic waves are radiation and light

Combination of electric and magnetic fields

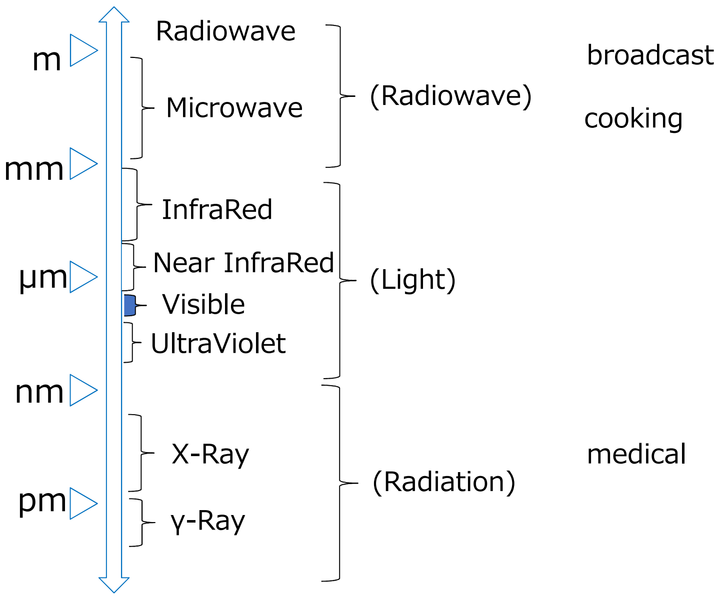


Very high speed
Travels at the speed of light in a vacuum
c ≒ 300,000,000 m/s

There are very fast waves all around us that are mostly invisible and inaudible.
It is created by electric and magnetic fields.

Since they are waves, they have "wave length"s.

Light is a kind of Electromagnetic Waves



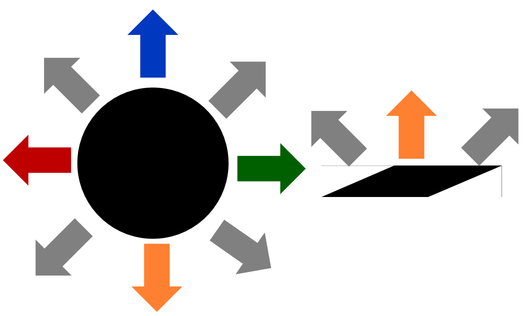
Electromagnetic waves in a certain wavelength band are light.

There are various types of electromagnetic waves with different wavelengths.

Light includes infrared, visible, and ultraviolet rays.

Human eyes can see only visible.

All objects shine and radiate.



Energy spectrum

$$I'(\lambda, T) = \frac{2hc^2}{\lambda^5} \frac{1}{e^{hc/\lambda kT} - 1}$$

Total Energy $I \fallingdotseq \sigma T^4$

I:radiance
T:temperature
λ : wave length
h: Planck const
c: light speed
k: Boltzman const

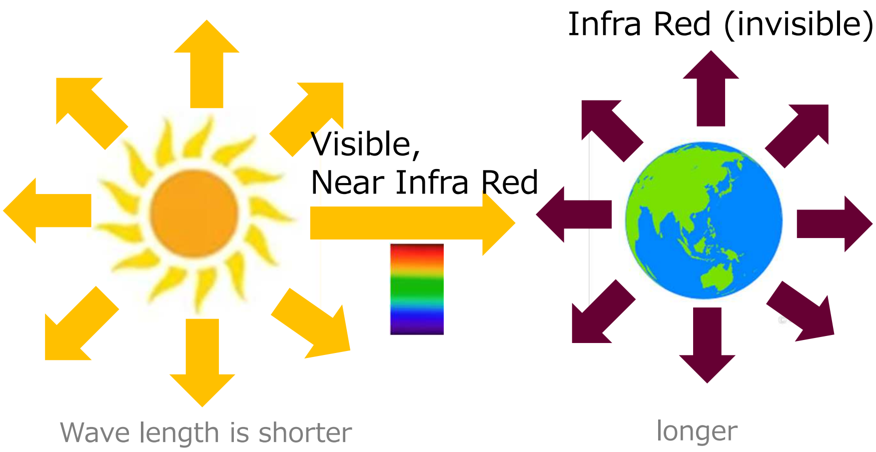
All objects radiate. The higher the temperature, ...

All objects radiate.

The higher the temperature, the shorter and more intense the energy emitted.

Total energy is proportional to the fourth power of temperature

Both the Sun and the Earth also radiate



Energy per unit surface area/unit time $I \fallingdotseq \sigma T^4$

Both the sun and the earth emit energy.

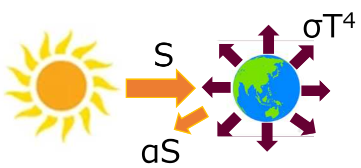
Some of the sun's radiation is visible to the human eyes,

the Earth's radiation is invisible .

Equation for Earth's temperature

$$C\ dT/dt = (1-\alpha)S - \sigma T^4$$

Change in the earth energy	Solar radiation (Const)	Terrestrial radiation



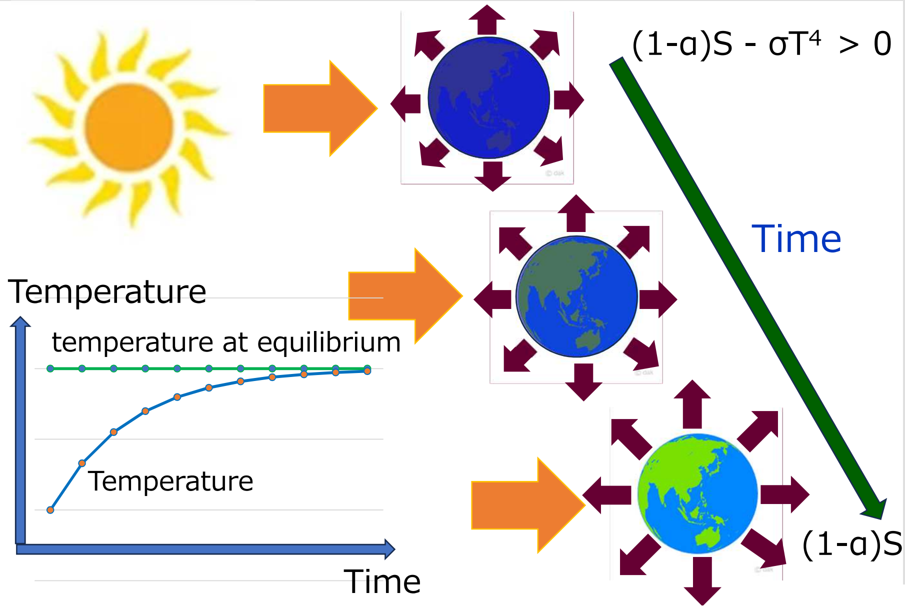
- T: Earth's temperature
- S: Radiation energy from the sun (1360)
- α: Earth's reflectance (0.3)
- σ: Stefan Boltzman const
- t: Time
- C: Earth heat capacity

The Earth's temperature changes according to the equation on the left.

The Earth's temperature increases due to heat from the sun and decreases due to heat leaving the earth.

It changes according to the equation on the left.

Changes in Earth's temperature



The temperature approaches the equilibrium temperature and becomes constant.

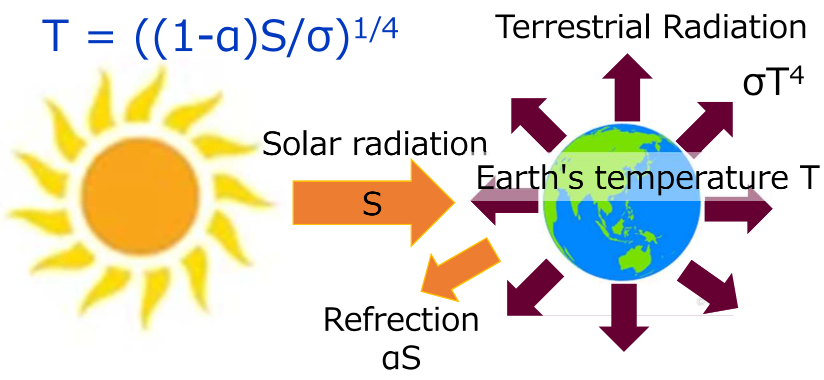
If the initial temperature is low, the temperature will gradually increase as shown on the left and reach the equilibrium temperature.

Balance at equilibrium temperature

Equation:

$C\, dT/dt = (1-\alpha)S - \sigma T^4 \quad \rightarrow 0$

$T = ((1-\alpha)S/\sigma)^{1/4}$



It is the temperature of the Earth as seen from space, which is very low.

Earth's Equilibrium temperature

Set S=1360, a=0.3

$T = ((1-\alpha)S/\sigma)^{1/4}$
≒ 255K
≒ **-18℃**

This is very low!

Green House Effect: 0-dim model

Composition of the Earth's atmosphere

molecule	proportion of mass	concentration	
N_2	78.1%		not GHG
O_2	20.9%		not GHG
Ar	0.9%		not GHG
CO_2	0.03%	411 ppm	GHG
CH_4		1877 ppb	GHG
N_2O		332 ppb	GHG

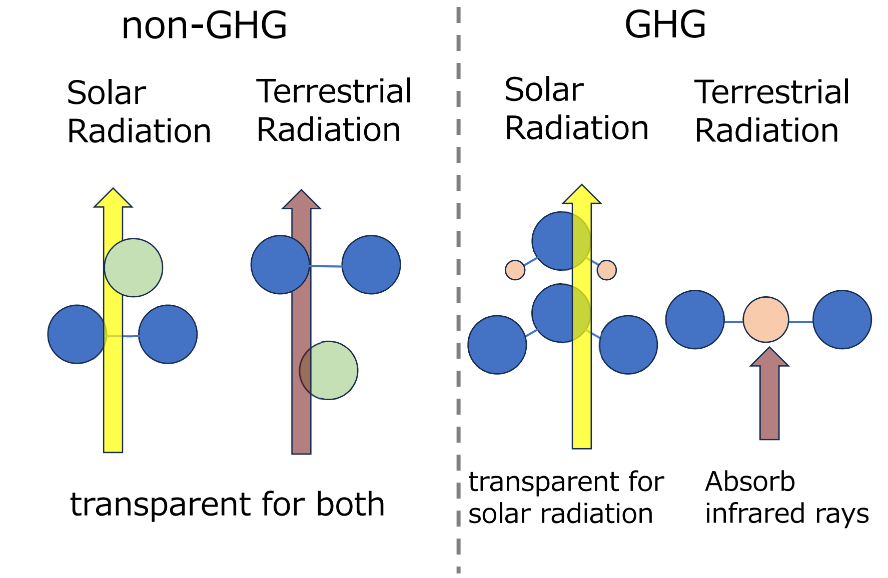
Most gases in the Earth's atmosphere have no greenhouse effect.

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 GHG.

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

Characteristics of GHG

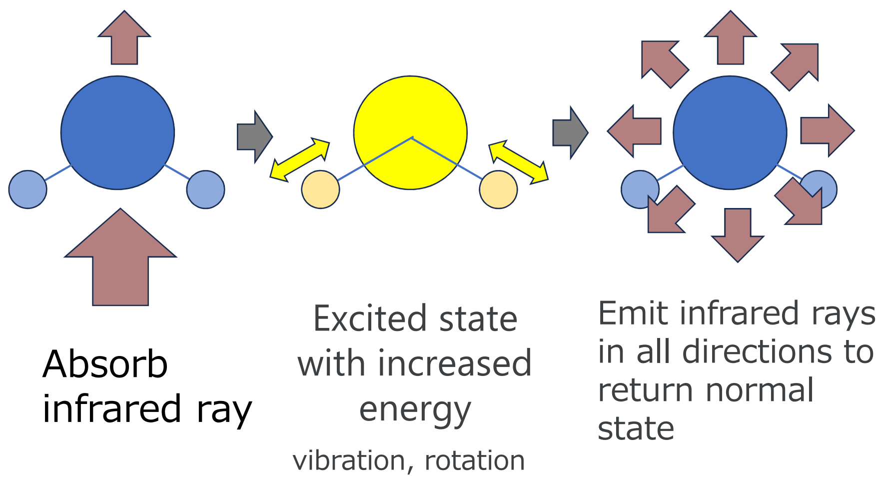
Green House effect Gas



GHGs are transparent to solar radiation and absorb the terrestrial radiation.

Non-GHG are transparent to both solar and terrestrial radiation.
On the other hand, GHG allow solar radiation to pass through, but absorb terrestrial radiation at specific wavelengths.

Characteristics of GHG

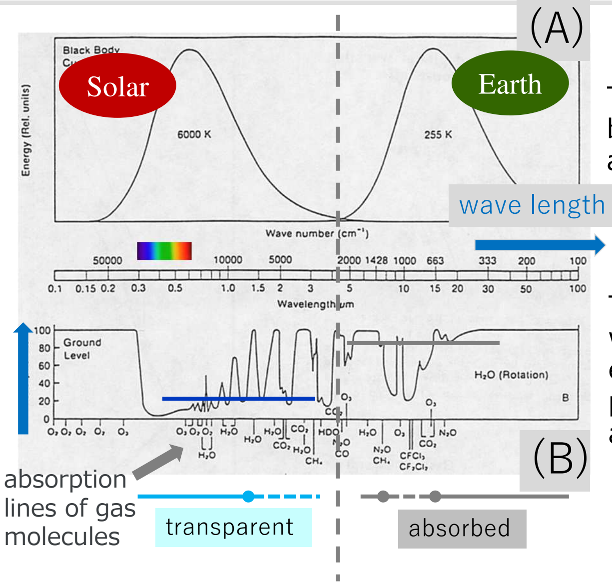


The wavelength of waves absorbed depends on the kind of gas.

GHGs emit energy downwards.

GHGs absorb infrared radiation, become excited, and then return to their original state by emitting infrared radiation in all directions.

Remark: Absorption by atmosphere



The emissions of blackbody radiation at 6000 K and 255 K.

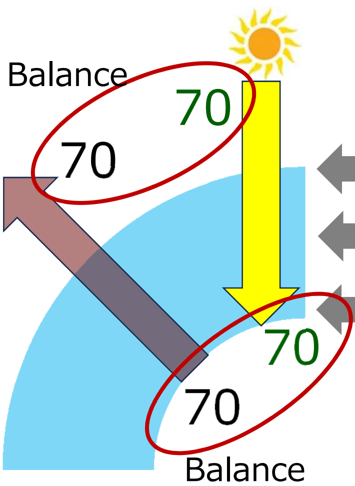
The absorption rate when radiation of each wavelength passes through the atmosphere.

※ Not completely transparent about solar radiation, but the difference is clear.

About the next few pictures

Let the energy reaching the earth from the sun be 100. Receives 70 = 100 - reflected 30.

※ For simplicity, reflective arrows are omitted.



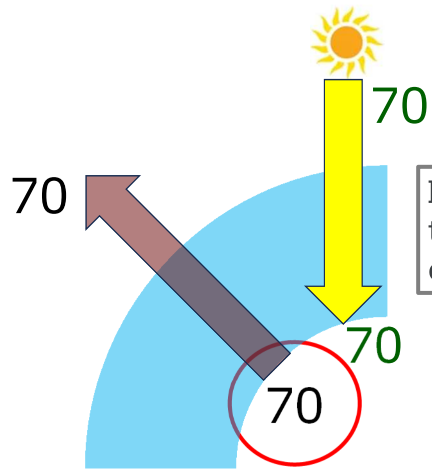
TOP Boundary between space and atmosphere

Atmosphere

BOTTOM Boundary between surface and atmosphere

As we have seen, after enough time, the energies balance out.
So, at both TOP and BOTTOM, upward and downward energies are balanced.
In the current figure, 70-70=0 at both boundaries.

no GHGs

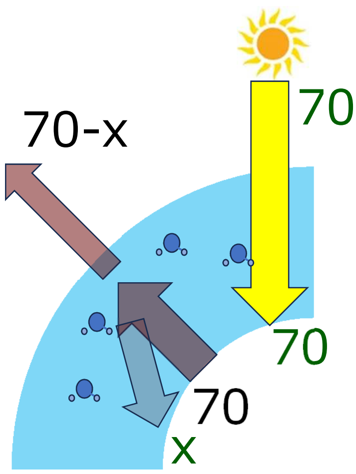


In both TOP and BOTTOM, the upward and downward energies are balanced by 70.

The temperature of the earth's surface is -18 ℃, which radiates energy 70.

The values of all fluxes are 70.
The surface temperature is -18 ℃, corresponding to 70.

Add GHGs, the balance is out.



GHGs absorb infrared radiation from the earth's surface and radiate it upward and downward.

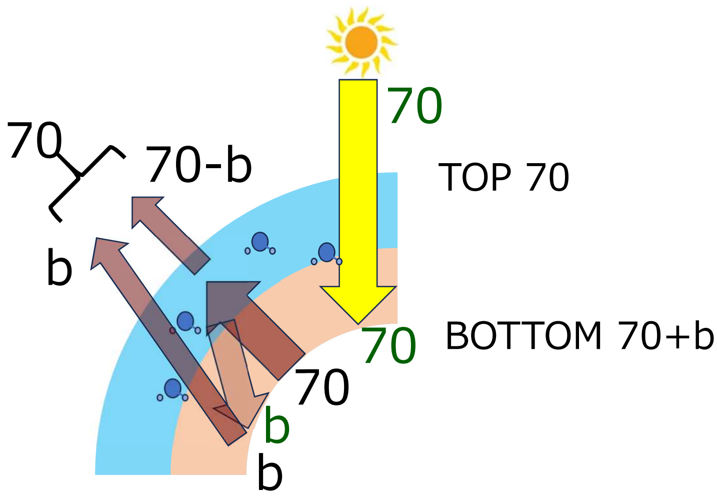
The energy is not balanced at both TOP and BOTTOM.

The surface temperature will rise to a state of equilibrium.

Add GHGs, the balance is out.

When GHGs are added, they absorb upward infrared radiation from the earth's surface and radiate it upward and downward. As a result, energy balances are out at TOP and BOTTOM. The surface temperature will rise until the next equilibrium state is reached.

New equilibrium state



If b≒44, the corresponding temperature is 15 ℃.

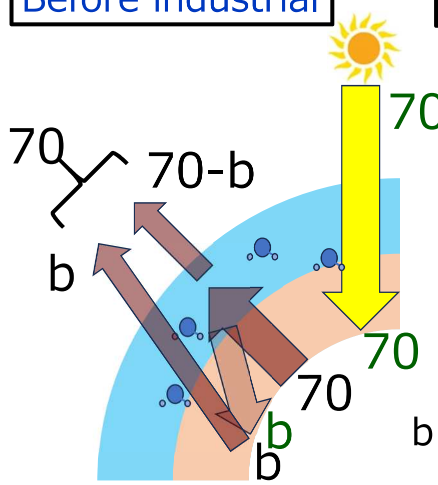
In the new equilibrium state, the surface temperature will be higher.

In the new equilibrium state, the balanced energies will be 70 at TOP and 70+b at BOTTOM and b > 0.

This is the "Green House Effect".

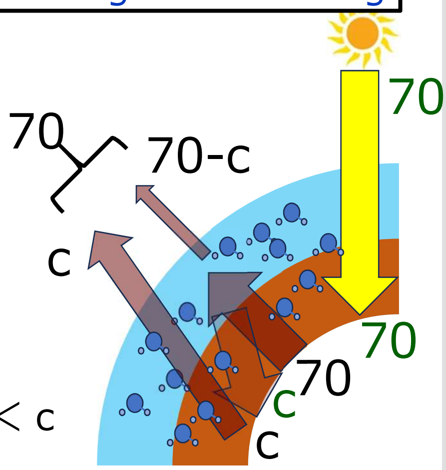
Global Warming

Before industrial



b < c

Under global warming



The more GHG there is, the higher the surface temperature.

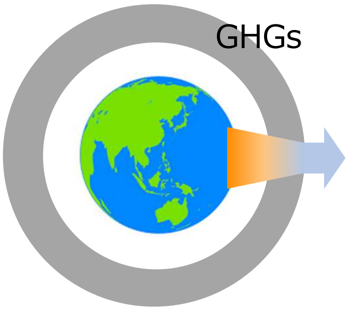
If more greenhouse gases are added, the equilibrium temperature at the Earth's surface will become even higher. (b < c)

Currently, GHG concentrations continue to increase, and surface temperature continues to rise.

Green House Effect

I think there are two possible interpretations.

GHGs prevent heat from escaping from the earth. They act as heat insulator.

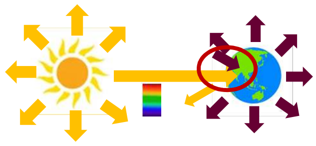


Upward radiation at the surface is now balanced by downward radiation from solar and the atmosphere.

$$T = ((1-a)S/\sigma)^{1/4}$$

▼

$$T = (((1-a)S + A_d)/\sigma)^{1/4}$$



possible interpretations of Green House Effect

(Read left)

Green House Effect: Manabe's 1-dim model

vertical 1-dimensional model

Radiative-Convective Equilibrium Model

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

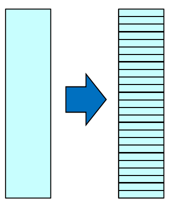
Geophysical Fluid Dynamics Laboratory, ESSA, Washington, D. C.
(Manuscript received 2 November 1966)

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

The first Nobel Prize in the field of weather and climate

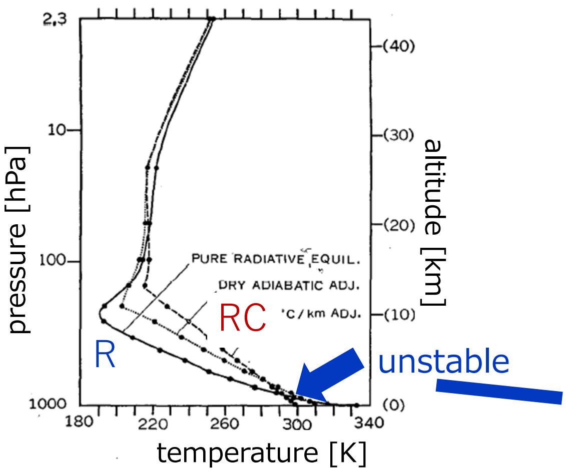
In addition to researches using full climate models, his basic researches were also recognized.

Radiative / Radiative-Convective Equilibrium



R: Radiation only

RC: Effect of convection is included.



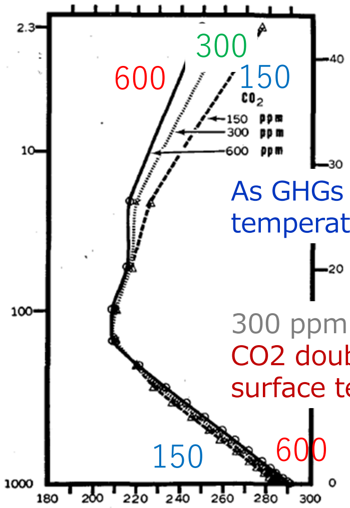
R's profile cannot be realized.

RC's profile is more realistic.

They reproduced the equilibrium temperature vertical profile by using simple 1-dim model.

They divides Earth's atmosphere vertically into layers, supplies greenhouse gases, and solves radiative transfer equations.
However, radiation only model (R) produced an unrealistic vertical profile, so they needed to add the effect of convection (RC).

Radiative-Convective Equilibrium



Manabe et al. (1967) Fig. 16

He investigated Global Warming and showed changes in vertical temperature structure.

Using a simple model, they investigated changes in temperature on the surface and in the atmosphere when the concentration of CO2 changes.

Summary

- As an example of how the equilibrium state in the climate system is determined, we investigated the global average surface temperature.
- The Earth's temperature is approximately determined by the balance between solar radiation and terrestrial radiation. However, the temperature is much lower than the actual surface temperature.
- Due to the presence of GHG s , which are transparent to solar radiation and absorb and emit terrestrial radiation, the equilibrium temperature at the Earth's surface is higher.
- The higher the GHG concentration, the higher the equilibrium surface temperature. This corresponds to the ongoing global warming.
- It is possible to explain realistic atmospheric temperature distribution, the greenhouse effect, and global warming by using a simple system that includes radiation, convection and greenhouse gases.

Outline

1. What is climate ?	Some of basic concepts Difference with weather	40min
2. Radiative Balance	Equilibrium state 0 dim and 1 dim(vertical)	35min
3. Basic States	Annual Mean Seasonal Cycle	20min
4. Variability	Examples of Variabilities	25min
5. Global Warming	Longer time scale Climate system behavior in response to human activity (external forcing)	20min

Outline of today's lecture

11:00-12:30

Lunch?

14:00-15:30

Part 3. Basic States of the atmosphere

- Annual Mean latitudinal energy distribution
- Seasonal Cycle and heat capacity

Basic Physics of the atmosphere

Dynamical Processes and Physical Processes

- Primitive Equations
  - Based on Fluid dynamics
    - Continuity equation
    - Conservation of momentum
  - Thermal energy equation
  - approximated for Earth's atmosphere (rotation, hydrostatic, ...)
- The effects of other physical processes are added
  - Radiation
  - Convection
  - Turbulence
  - Effects due to gravitational waves

The equation system consists of fluid dynamics equations approximated for the Earth's atmosphere. The contributions of other physical processes are added as terms in the equation.

Basic States is determined by ...

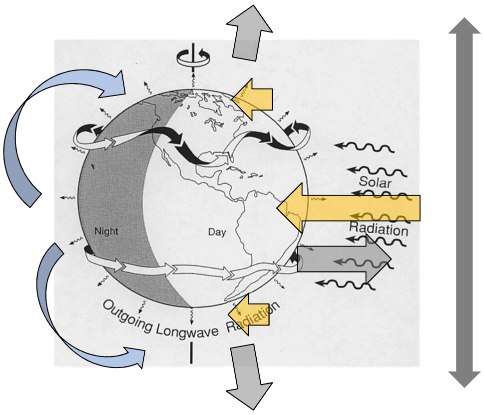
- The mean fields (state, structure) are determined by the balance of the main physical terms included in the equation system.
- As we have seen, radiation is the most important.
- Other physical processes will also appear in the lectures that follow.

Radiation Convection Turbulence

Fluid Dynamics with thermal equations
Advection Waves

Annual mean latitudinal energy distribution

Add a north-south dimension
to the vertical 1-dimension



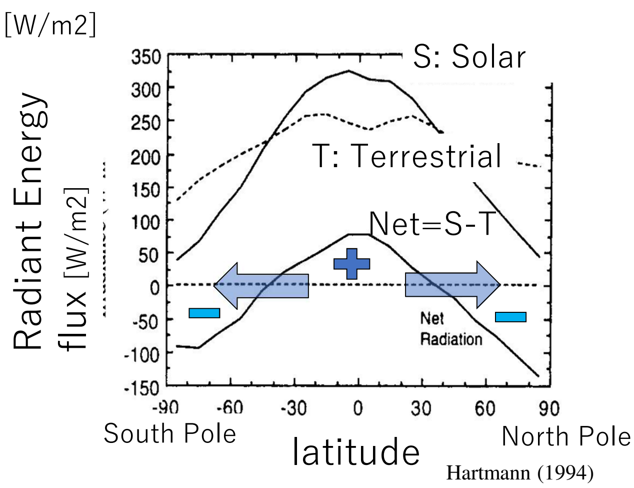
Imbalance of radiant energy

Canceled out by heat transport through the atmosphere and ocean.

Energy balance is still important for annual mean latitudinal state.

[See left]

Annual mean latitudinal energy distribution



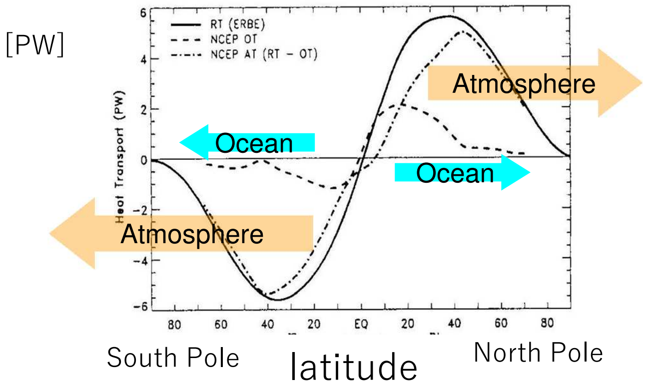
Hartmann (1994)

There is a large contrast in the latitudinal distribution of solar radiation.

For terrestrial radiation, the contrast is smaller.

Therefore, there is an imbalance in the radiated energy at each latitude.

Annual mean latitudinal energy distribution



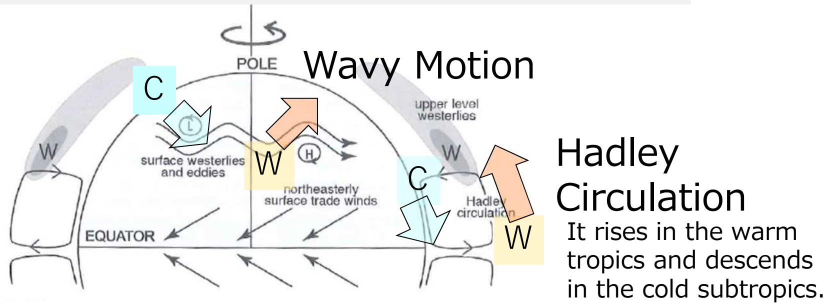
Trenberth and Caron (2001)

This imbalance at each latitude is resolved by heat transport through the atmosphere and ocean.

The atmosphere carries more energy than the ocean.

Annual Mean Atmospheric circulation

Heat transfer by waves at higher latitudes.



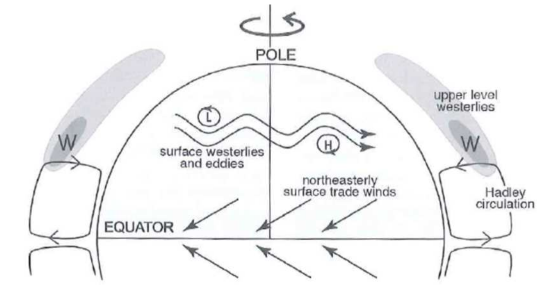
Heat transfer by direct circulation at lower latitudes.

From Marshall J., and R. A. Plumb, 2008: Atmosphere, Ocean, and Climate Dynamics, Academic Press, 319pp.

Latitudinal heat transport by the atmosphere is carried out by mean circulation at low latitudes and by waves at mid-high latitudes.

Comment:
Latitudinal Difference in momentum friction
by the atmospheric circulation

EASTWARD wind; Atmosphere loses eastward momentum at higher latitudes



WESTWARD wind; Atmosphere loses westward momentum at lower latitudes

From Marshall J., and R. A. Plumb, 2008:
Atmosphere, Ocean, and Climate Dynamics, Academic Press, 319pp.

At high latitudes, the wind is westerly, or eastward, in the lower layers, so the atmosphere loses eastward momentum due to friction.

At low latitudes, the Coriolis force causes the wind to be easterly, or westward, in the lower layers, so the atmosphere loses westward momentum due to friction.

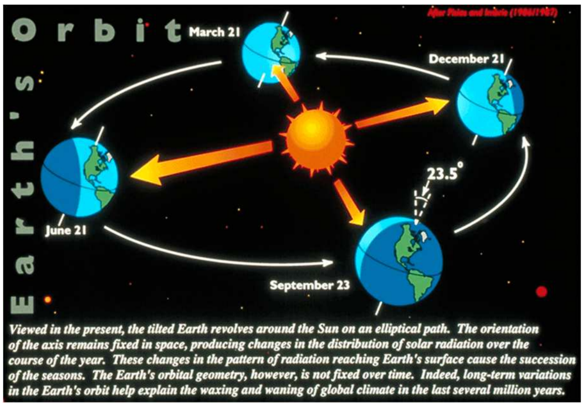
Summary : Latitudinal energy distribution

- The net radiation energy received by the Earth is positive at low latitudes and negative at high latitudes.
- This imbalance is canceled by heat transport by atmospheric and oceanic circulation. Here the heat transfer of the atmosphere is greater than that of the ocean.
- Atmospheric heat transport is dominated by Hadley circulation at low latitudes, while wave transport is dominant at mid- and high latitudes.

Remark: The balance does not mean causal relationship
Solar radiation, which is an external forcing, has a very large latitudinal contrast.
In response to this distribution, a latitudinal contrast in temperature and terrestrial radiation" and heat transport due to the atmosphere and ocean are created, so that the heat budget is balanced at each latitude.

Summary at the beginning

Seasonal Cycle and Heat Capacity

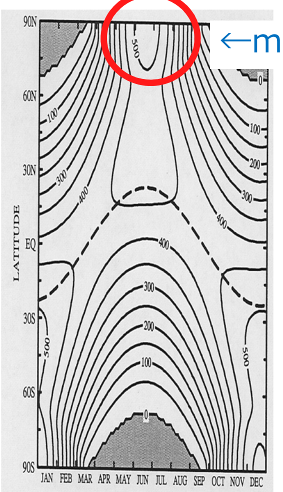


Orbital elements causes the seasonal cycle because the rotation axis is tilted.
The differences in heat capacity among the ocean, the land and the atmosphere affects on the seasonal changes

[Read left]

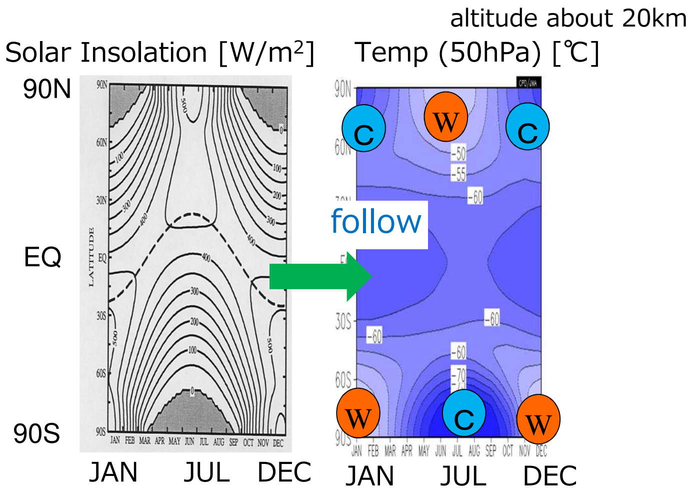
Solar Insolation and Temperature

Solar Insolation [W/m²]



This figure shows the amount of solar radiation per day. The dotted line represents the latitude position of the sun's midpoint.
Annual mean solar radiation is greatest at the equator, but in the seasonal progression, daily solar radiation is not always greater at lower latitudes.
The highest amount of solar radiation per day occurs at the pole of the summer solstice. There is zero solar radiation in the polar regions in winter.

Solar Insolation and Temperature at high altitude

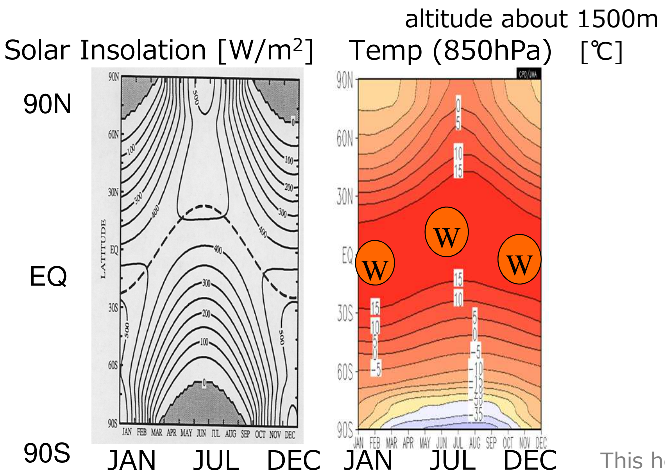


Heat capacity is small at high altitudes.

Ozone absorbs solar radiation and creates a peak temperature at an altitude of about 50 km.

Because of the seasonal variation in heating due to solar radiation absorption and the stratospheric atmosphere has small heat capacity, the seasonal march of the stratospheric temperature follows that of solar insolation.

Solar Insolation and Temperature at lower atmosphere



Surface, especially ocean, has large heat capacity, so they are not similar.

This height is chosen to avoid the masking effect of mountains.

In the troposphere, the distribution of hot equatorial regions and cold polar regions is maintained throughout the year.
This is due to the large heat capacity of the ocean and the fact that the latitudinal distribution of sea surface temperature (SST) has not changed dramatically.

Mass and Heat capacity of atmosphere and ocean

	Atmosphere	Ocean
Mass [kgm^{-2}]	10^4 (Total)	10^4 (Surf ～10 m depth) O(10^6) (Total)
Heat capacity [$JK^{-1}m^{-2}$]	10^7(Total)	10^7 (Surface ～ 2.5 m depth) O(10^9) (Total)

Heat capacity of the atmosphere is the same as that of ocean with 2.5m depth.

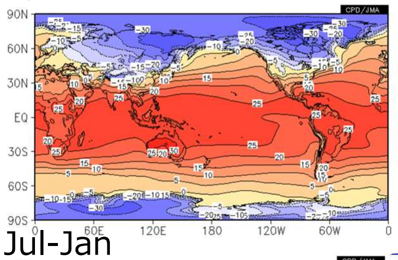
Density [kgm^{-3}]: atm 1.2-1.3, ocean 1000
Specific heat [$Jkg^{-1}K^{-1}$] : atm 10^3, ocean $4x10^3$

The ocean has a much larger mass and heat capacity than the atmosphere.

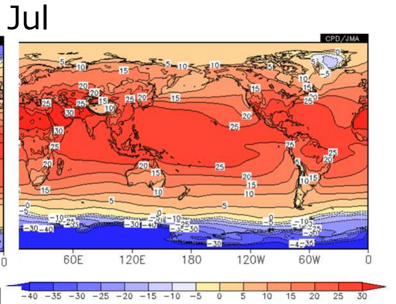
Heat Capacity:
Atmosphere << Land << Ocean

Jan-Jul contrast of surface temperature

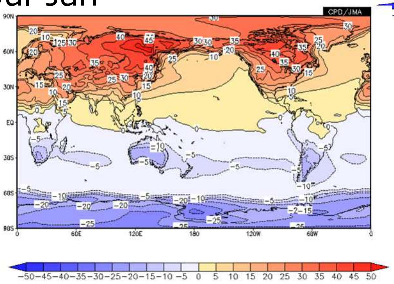
Jan



Jul



Jul-Jan



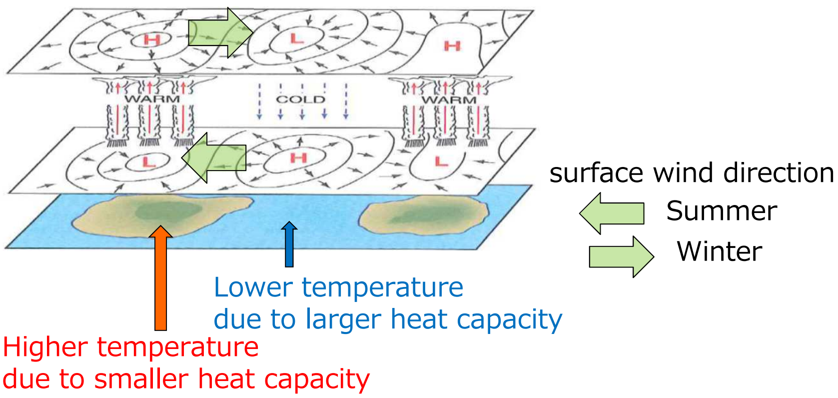
Heat Capacity:
Land << Ocean

"High temperatures at low latitudes and low temperatures at high latitudes", both in summer and winter due to large heat capacity of surfaces.

Compared to the same latitude, the temperature over the ocean is higher in winter and on land in summer, because heat capacity of ocean is larger than that of land.

Monsoon Circulation

Schematic figure of Summer Monsoon

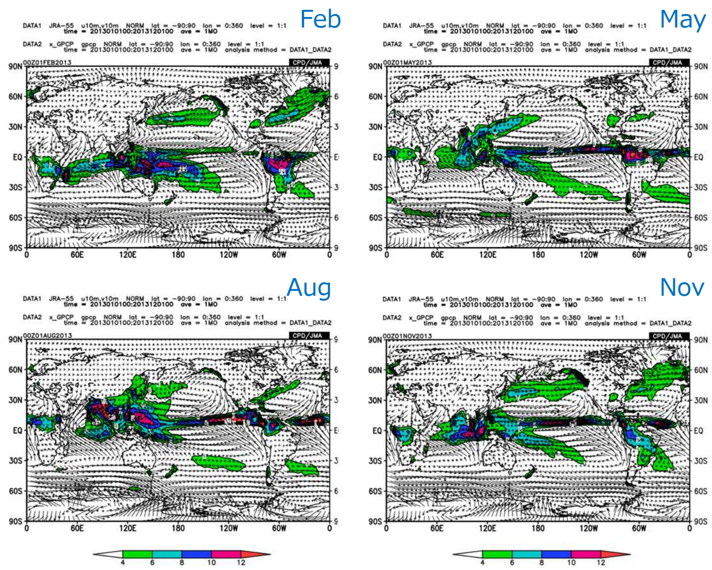


Monsoons occur because of the difference in heat capacity between the ocean and land.

In summer, circulations occur in which the air rises over land and falls over the ocean. Therefore, the wind blows from the sea towards the land in the lower layers. In winter it is the opposite. This is caused by the difference in heat capacity between land and ocean.

Seasonal March of precipitation and surface wind

MAY SKIP



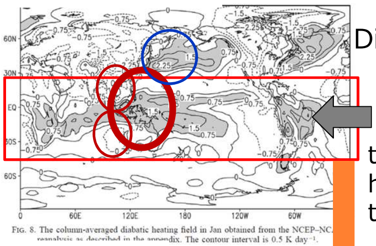
In general, precipitation is more in summer. As the seasons progress, the precipitation belt moves from south to north and then from north to south. There is relatively more precipitation on land in summer and more precipitation on the sea in winter, due to Monsoon.

The surface wind tend to blow into the precipitation area.

MAY SKIP

Local heating in the tropics produces circulation

Real atmosphere

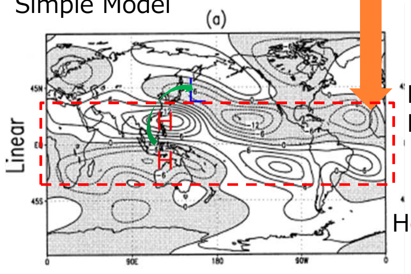


Diabatic heating in Jan.

the area where the heating is given to the linear model

Similar distribution

Simple Model



Linear response to the heating: Eddy stream function at 300hPa

Held et al.(2002)

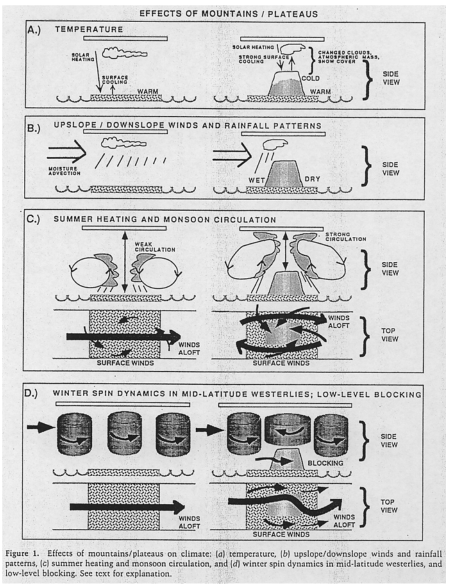
The theory will be shown later in internal variability.

Seasonal heating in the tropics produces responsive circulation as a result of linear wave propagation

Tropical convective heating and circulations are observed.
When a convective heating is applied to a linear model, the waves represented by that model create similar circulations.
This indicates that tropical convective heating and waves create circulation over distance.

MAY SKIP

Effect of orography on climate



Kutzbach et al. (1993)

J. Geology

Orography also influence weather and climate through circulation.

- Higher mountain area has a cooler surface temperature, which affects clouds.
- It creates a forced updraft, making it easier for rain to fall.
- Forced updrafts further intensify summer monsoon precipitation.
- In winter it creates a meandering jet called blocking.

Summary : Seasonal Change and Heat Capacity

- Earth's orbital elements cause seasonal variations in solar radiation absorption, which lead to seasonal variations.
- In seasonal changes, heat capacity has a great influence on the spatial distribution. The value of heat capacity is atmosphere < land area < ocean.
- The monsoon circulation is mainly generated by the difference in heat capacity between land and sea.
- As the season progresses, the precipitation area shifts north-south, and the surface wind changes accordingly.
- Stationary heating in the tropics and topography affect circulation and climate distribution.

Outline

Outline of today's lecture

1. What is climate ?	Some of basic concepts Difference with weather	40min
2. Radiative Balance	Equilibrium state 0 dim and 1 dim(vertical)	30min
3. Basic States	Annual Mean Seasonal Cycle	25min
4. Internal Variability	Examples of Theories Examples of Variabilities	40min
5. Global Warming	Longer time scale Climate system behavior in response to human activity (external forcing)	20min

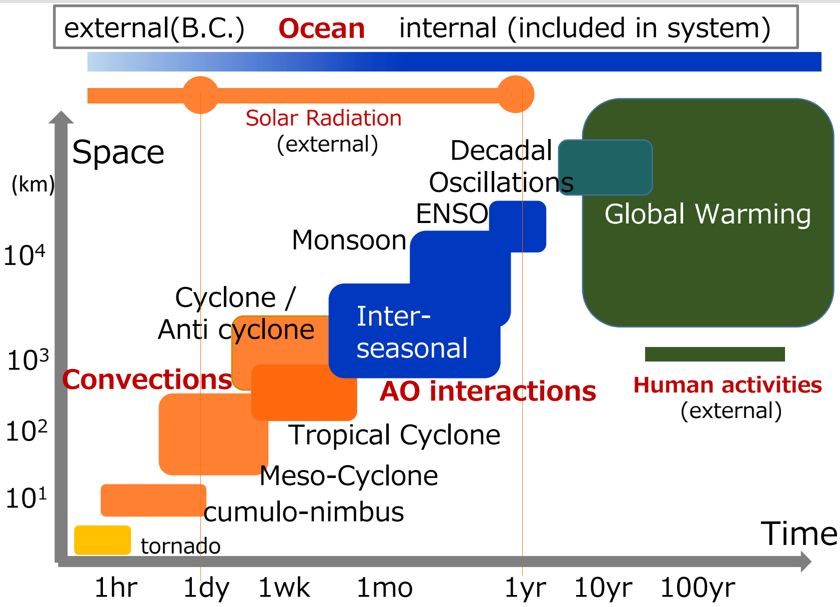
11:00-12:30

Lunch?

14:00-15:30

Part 4. Internal Variabilities

Internal Variations



There are various internal variations on various scales in time and space in the climate system.

External forcing (solar radiation with diurnal and seasonal variations, etc.) and random weather phenomena continuously affect the climate system and cause internal variations. The induced internal variations modify the average climate field and cause other internal variations.

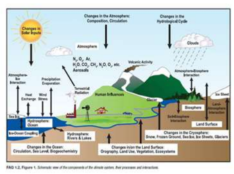
Part 4-1 Examples of physics

Powerful Tools: Physics

Dynamical Processes and Physical Processes in the atmosphere

- Dynamics: Primitive Equations
  - Based on Fluid dynamics
    - Equation of continuity (conservation of mass)
    - Equation of motion
  - Thermal energy equation
  - approximated for Earth's atmosphere (rotation, hydrostatic, ...)
- The effects of other physical processes are added
  - Radiation
  - Convection
  - Turbulence
  - Effects due to gravitational waves

Physics is a powerful tool in describing and predicting internal variations.



※ Climate models are the collection of our physical knowledge about climate.

Powerful Tools: GFD and simple models

In particular, "GFD" is a very powerful tool for describing/predicting the movements of the atmosphere and ocean.

Fluid dynamics — Physics for general fluid

↓ Assumptions: Vertical stratification, rotating system, spherical shell, ...

Geophysically Fluid dynamics — Suitable for describing the atmosphere and ocean

- Internal gravitational waves (origin is Gravity)
- Rossby waves (origin is Earth's Rotation)

↓ Assumptions and simplification

Equational beta-plane shallow water — Gravity and Rossby waves

1-dim linearized shallow water — No Rotation ⇒ Gravity waves only

Powerful Tools for understanding the climate system

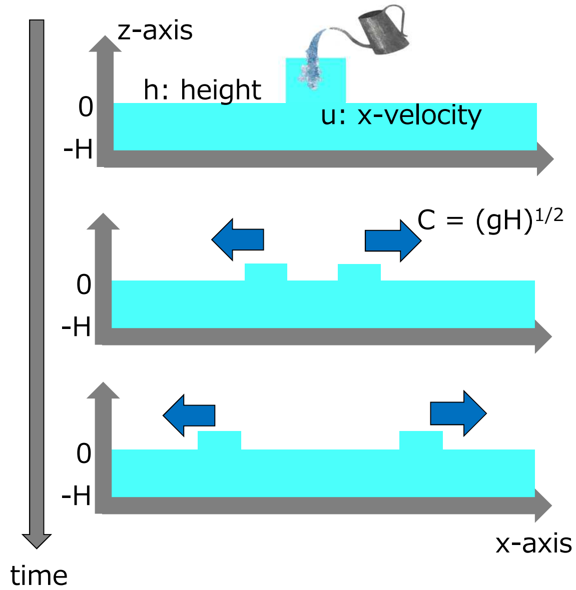
Real Earth	In situ Obs	point	
Real Earth with analysis	Satellie Obs, (Re) Analysis data	wide spread in time and space	phenomenon
GCMs, Climate models	Model	wide spread in time and space	phenomenon simulated, reproduction of reality
GFD		physical concept	
Simple models			exact solution, theory

↑ interpretation

Based on the correspondence between them, theoretical knowledge is used for physical interpretation of the observational data and model reproduction results.

Probably the simplest system

Shallow water system and Gravity waves



Linearized 1-dim shallow water system

$$du/dt = - g\ dh/dx$$
$$dh/dt = - H\ du/dx$$

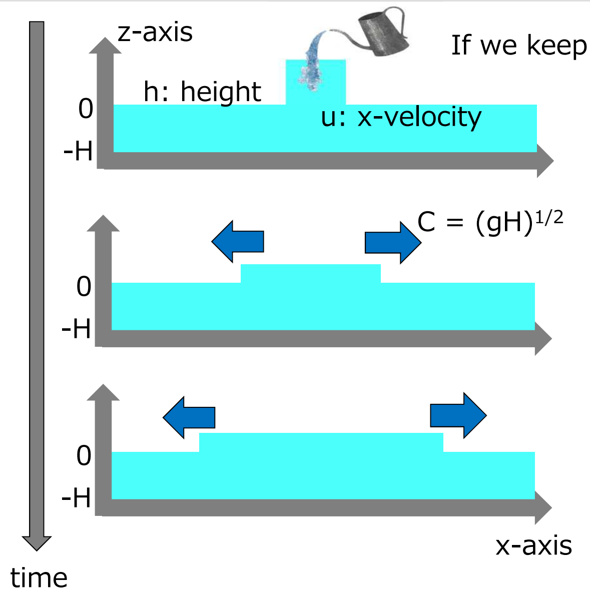
By creating equations that follow the laws of physics, giving initial conditions, calculating and solving them, then we can describe the behavior of a system.

For the simple case shown in the figure, this system can describe the initial anomaly moving to both sides with velocity C by gravity waves (propagation).

This means that such simple movements can be predicted/described by this system.

Probably the simplest system

Shallow water system and Gravity waves

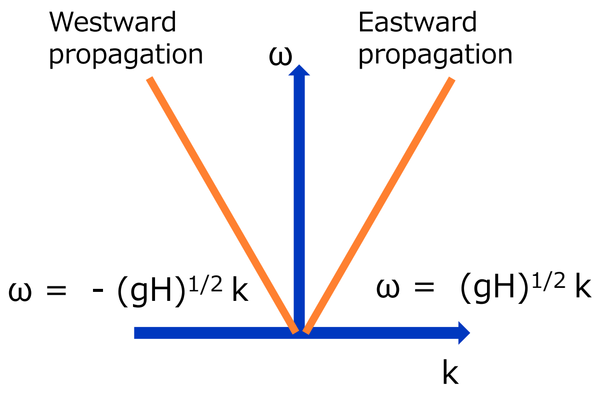


If we keep pouring water, ...

Similarly, we can describe/predict the motion of the system.

Gravitational waves propagate with velocity C.

Dissipation Relationship of Gravity Waves in shallow water system



Linearized 1-dim shallow water system

$du/dt = - g\, dh/dx$

$dh/dt = - H\, du/dx$

$\Rightarrow\ d^2h/dt^2 = gH$

Solution ~ $\exp(i(kx-\omega t))$

ω: frequency (= 2π / period)

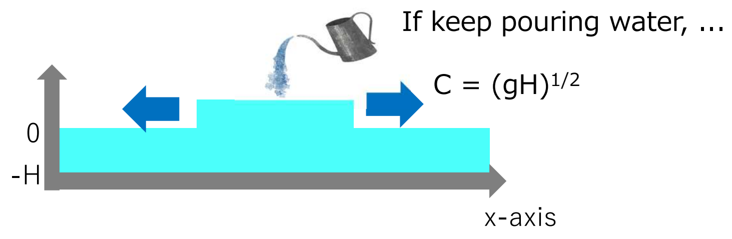
k : wave number (= 2π / wave length)

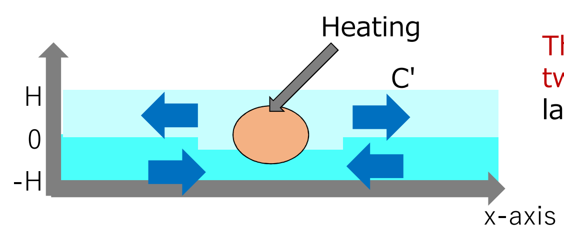
$\Rightarrow \omega = \pm (gH)^{1/2} k$

Phase Verocity: $c = \omega/k = \pm (gH)^{1/2}$

Group Verocity: $c_g = d\omega/dk = \pm (gH)^{1/2}$

Application to motion of two-layer fluid





This system also describes/predicts the motion of a two-layer fluid with heating of the center of the layers.

The solutions are the same except for the wave speed. The speed of the wave depends on the density difference (buoyancy).

Equatorial β-plane shallow water system

Matsuno (1966)

$$\frac{\partial u}{\partial t} - fv + g\frac{\partial h}{\partial x} = 0$$

$$\frac{\partial v}{\partial t} + fu + g\frac{\partial h}{\partial y} = 0$$

$$\frac{\partial h}{\partial t} + H\left(\frac{\partial u}{\partial x}\right) = 0$$

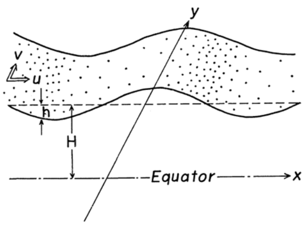


Fig. 1. Model and Coordinates.

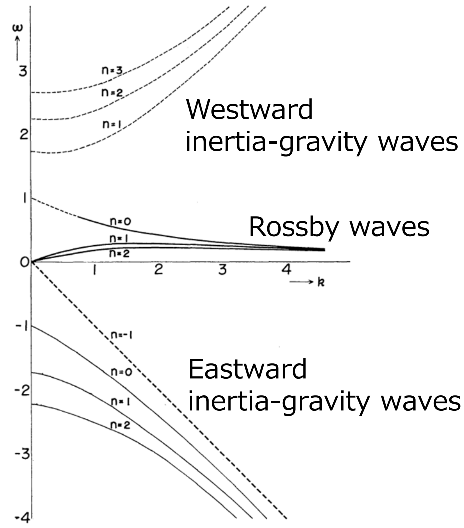
Dissipation Relationship

inertia-gravity waves

$$\omega_{1,2} \fallingdotseq \mp \sqrt{k^2+2n+1}$$

$$\omega_3 \fallingdotseq k/(k^2+2n+1)$$

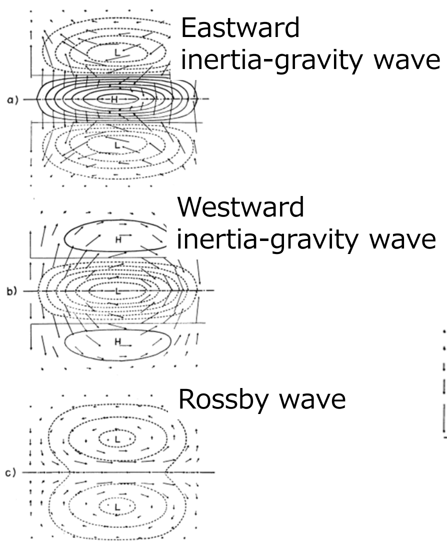
Rossby waves

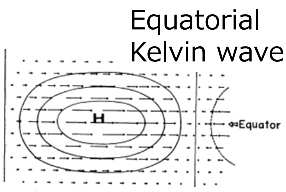


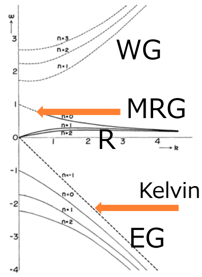
Equatorial β-plane shallow water system

Matsuno (1966)

horizontal structure of waves







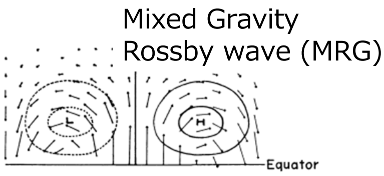
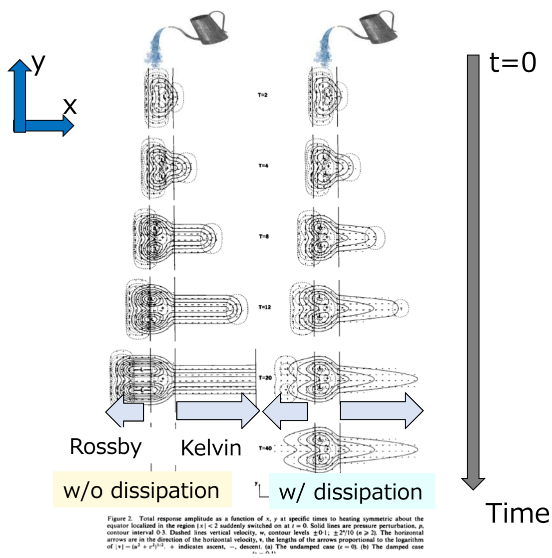


Fig. 7. Rossby type wave ($n=0$ $k=1.0$).

Matsuno (1966), Gill (1980)

Equatorial β-plane shallow water system



Heckley and Gill (1984)

x-y 2dimensional
y=0: Equator
Rotation: Coriolis parameter f=0+βy

$$du/dt - \beta y v = - g\, dh/dx$$
$$dv/dt + \beta y u = - g\, dh/dy$$
$$dh/dt + H\, du/dx + H\, dv / dy = 0$$

Assuming a location near the equator and including rotational effects, the motions of eastward gravitational waves (equatorial Kelvin) and westward Rossby waves are exactly solved.

Application to motion of two-layer fluid

$$\partial u/\partial t + \varepsilon u - \tfrac{1}{2} y v = -\partial p/\partial x$$
$$\tfrac{1}{2} y u = -\partial p/\partial y$$
$$\partial p/\partial t + \varepsilon p + \partial u/\partial x + \partial v/\partial y = -Q$$
$$w = \partial p/\partial t + \varepsilon p + Q.$$

When we applied to two-layer fluids, this simple system can describe the circulation created by heating in the equatorial middle layer.

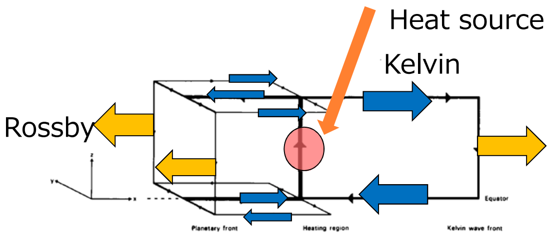
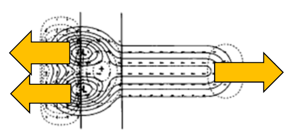


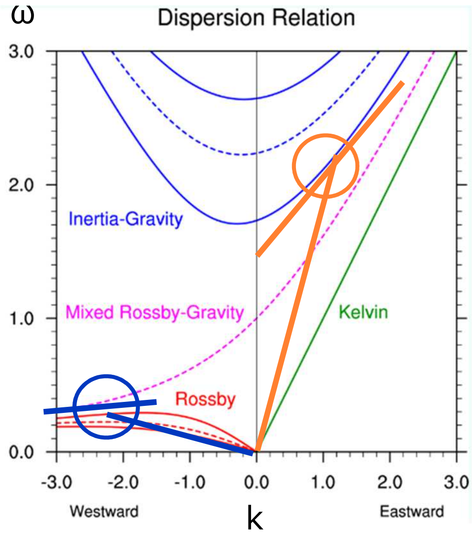
Figure 3. Schematic illustration of the flow field in the absence of damping.

baroclinic mode in 2 layer system

This flow pattern is well known as the Matsuno-Gill pattern. This will be repeatedly shown in several lectures that follow.



Dispersion Relationship



In waves, the relationship between the frequency (1/period) and the wave number (1/wavelength) is important, and this is called the dispersion relationship.

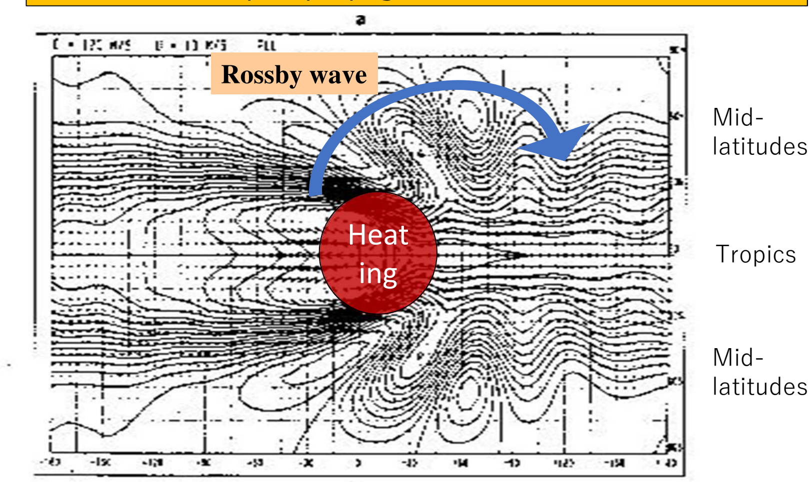
Phase Verocity: $c = U + \omega/k$
Group Verocity: $c_g = U + d\omega/dk$

- Wave packets and energy propagate at group velocity.
- The phase velocity of the Rossby wave is westward, but the group velocity of the short-wavelength Rossby wave packet is eastward.

Impact of tropical heating on circulation in mid-latitudes

From Maeda-san's slide

In the case of a westerly wind basic state, Rossby waves forced in the tropics propagate to the mid-latitudes.



Lim and Chang, 1983

Rossby waves created by convection near the equator can propagate to mid-to-high latitudes.

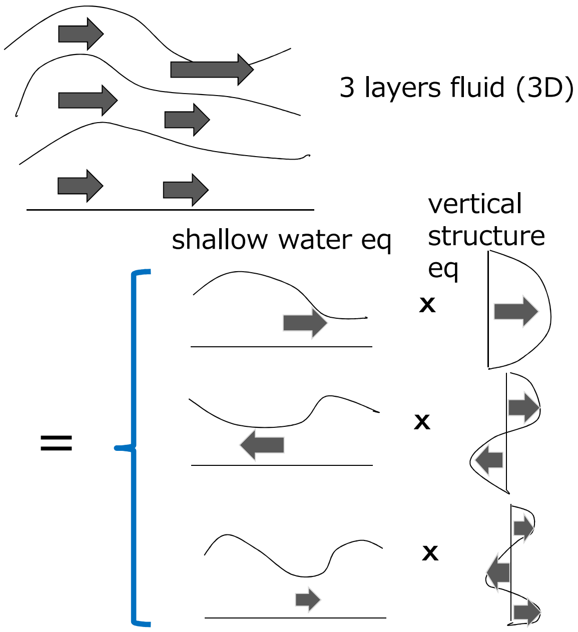
Correspondence with 3D system

SKIP

One of the excellent features of the shallow-water wave system is that it can be matched with a multi-layer system of linear primitive equations.

This figure shows the case of three layers.

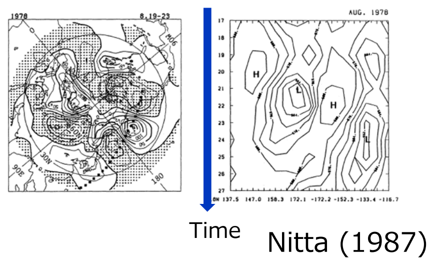
I won't go into details, but the horizontal distribution is expressed by the shallow water wave system, and the vertical distribution is expressed by the vertical structure equation, and the product is taken. By adding the three vertical modes, it is possible to express the motion of a three-layer fluid.



In nature, we sometimes find **internal variabilities**

In nature, that is, in observational data and analytical data, we sometimes find regular distributions or statistical relationships.

Distributions similar to that of theory
- Wavy patterns, Oscillations
- If there is sufficient correspondence, interpretation based on theory is possible.



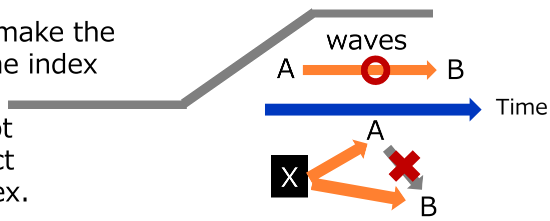
Nitta (1987)

Intra-inter seasonal Variabiltiy	Quasi-stationary Rossby wave, MJO and equatorial waves, AO
Interannual Variability	ENSO, El Nino Modoki, IOD, QBO,
Decadal Variability	PDO, ENSO-Monsoon relation

Teleconnection patterns

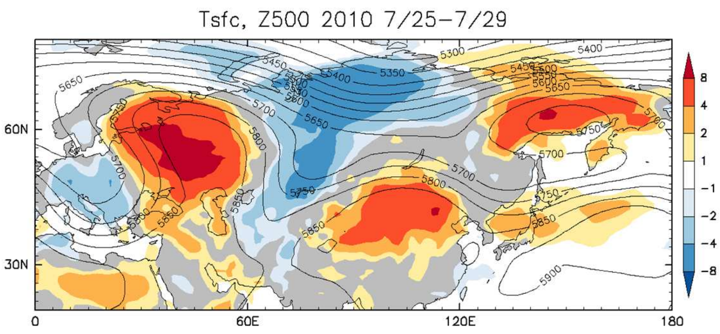
In nature, that is, in observational data and analytical data, we sometimes find regular distributions or statistical relationships.

- ☐ Correlation between atmospheric and oceanic conditions in multiple distant locations
- ☐ ENSO, AO, NAO, AMO, AAO, MJO, PDO, QBO, MQBO, TBO, SAO, IHO, DM (IDO), PJ, PNA, WP, EU, ...
- ☐ Locations, temporal and spatial scales, and detection methods vary.
- ☐ Find some characteristics, decides an index and make the time series, and get related spatial patterns to the index time series. Just a statistical relationship
- ✓ Remark: Even if a correlation is found, it does not necessarily mean that a physical cause-and-effect relationship can be determined. Nature is complex.



Example of Blocking

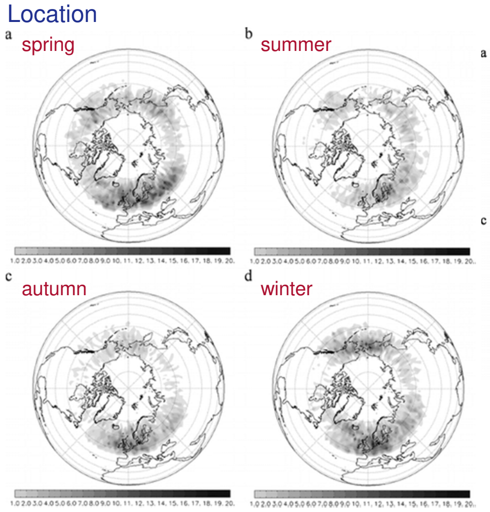
Heatwave by blocking in 2010



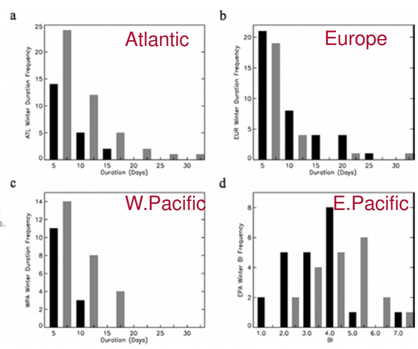
- Eastern Europe: late June to late July
- Western Russia: late July to mid August
  - 38.2℃ at Moscow on July 30 (15℃ higher than climatology)
  - Heavy rainfall and floods over Pakistan
- Hot summer also over Japan

Blocking Climatology

Location



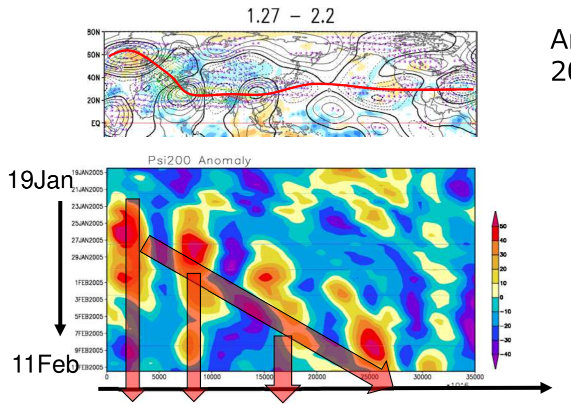
Duration



(Barriopedro et al. 2006)

- Blocking events occur over Atlantic to Europe, and Russia to US
- Sometimes it continues over 30 days

Quasi-stationary Rossby waves



An example:
2005/01-02

the red line of the above panel

Time cross section of stream function anomalies at 200hPa.
x-axis : distance along the red line from a base point.

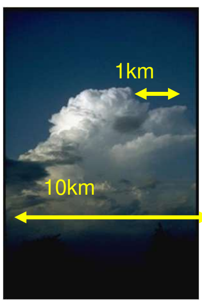
In this example, Rossby waves emitted from a blocking block in the North Atlantic propagating along the Asian jet to the Pacific Ocean.

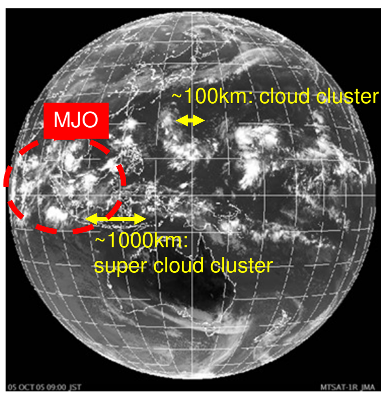
In such cases, if the waves are properly represented in the model, it may be possible to predict them.

An example of intra-seasonal variability:

Madden-Julian Oscillation (MJO)

There are multi-scale clouds in the tropics.





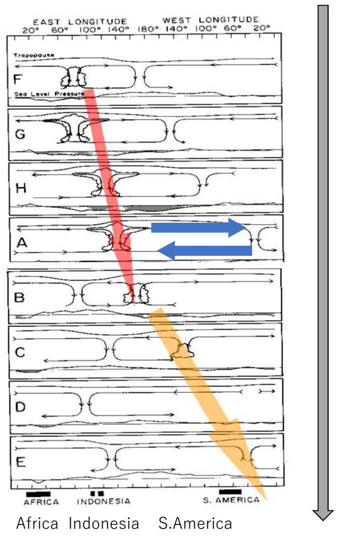
OLR: MTSAT JMA at 00 UTC Oct. 5, 2005

The tropics have clouds and cloud clusters at various spatial scales. MJO is an intraseasonal oscillation in which a 1000 km-scale convective active region circles the Earth in about 30-60 days.

Such 1000 km-scale convection active regions are called super cloud clusters.

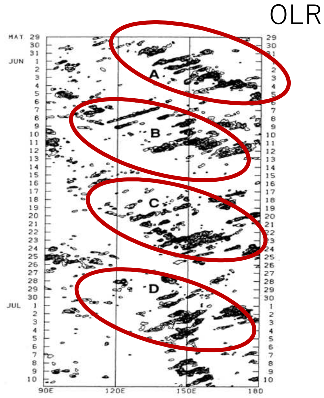
In the tropics, Heavy precipitation -> Deep cloud -> Low cloud-top temperature -> Low OLR

Madden-Julian Oscillation (MJO)



Madden and Julian (1972)

Systems move eastward.
The cycle is about 30-60 days.



Nakazawa (1988)

The left panel shows a schematic diagram of MJO. It is detected in velocity potential in dry regions, as eastward divergence in upper layers, and in OLR in wet regions. The velocity is different in dry and wet regions. The mechanism of eastward movement is equatorial Kelvin waves, which are thought to be modified due to convection.

Schematic structure of MJO

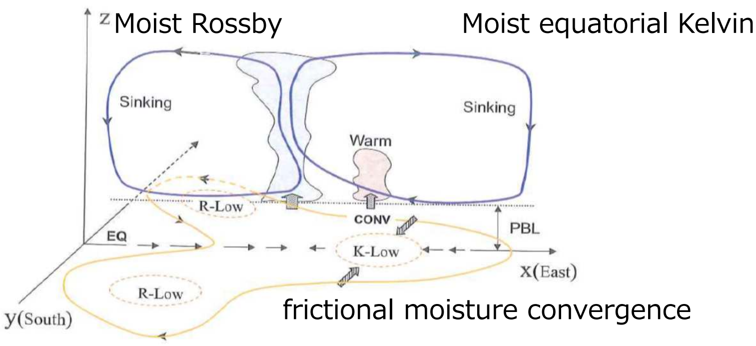
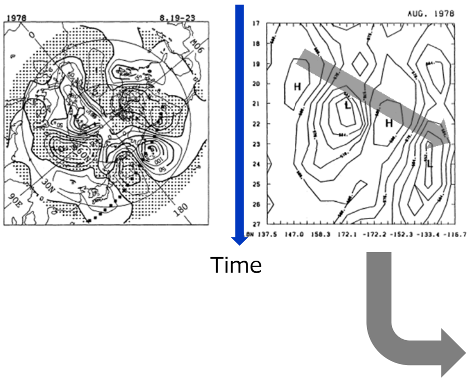


Figure 10.13. Schematic structure of the frictional CID mode, which is the counterpart of observed MJO mode. In the horizontal plane the "K-low" and "R-low" represents the low-pressure anomalies associated with the moist equatorial Kelvin and Rossby waves, respectively. Arrows indicate the wind directions. In the equatorial vertical plane the free-tropospheric wave circulation is highlighted. The wave-induced convergence is in phase with the major convection, whereas the frictional moisture convergence in the "K-low" region is ahead of the major convection due primarily to meridional wind convergence.

From Wang (2005)

Water vapor convergence due to friction occurs on the east side of the convective heating (Kelvin wave response region), causing the heating region to shift eastward.

PJ pattern (Pacific-Japan pattern)



Nitta (1987)

Schematic diagram

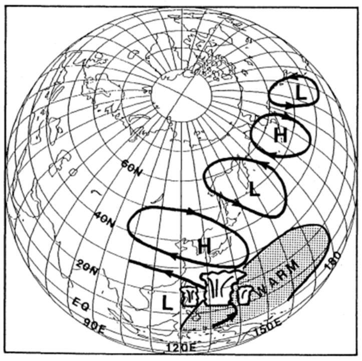


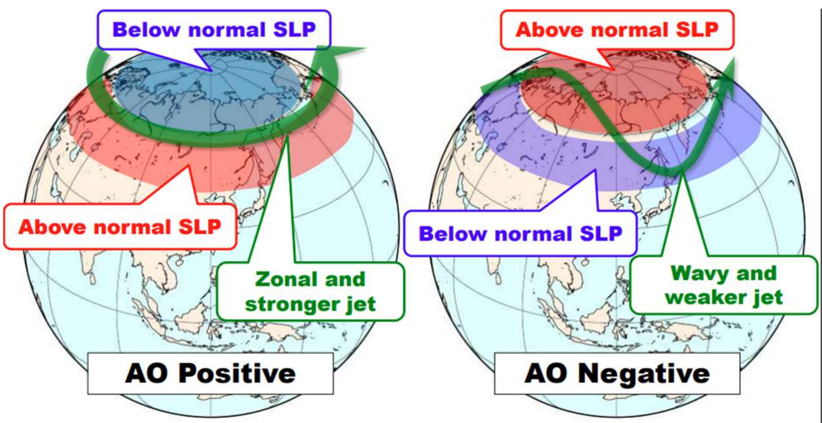
Fig. 18. Schematic pictures showing the relationships between SST anomalies, convective activities and atmospheric Rossby-wave trains.

Interpreted as Rossby-wave

If the convection around the Philippines is weak (strong), the pressure near Japan will become a negative (positive) anomaly and the Ogasawara High will become weaker (stronger).

Arctic Oscillation (AO)

From Maeda-san's slide



A seesaw-like oscillation of pressure anomalies between the Arctic and mid-latitudes which dominates climate variability in boreal winter.

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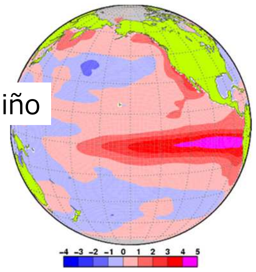
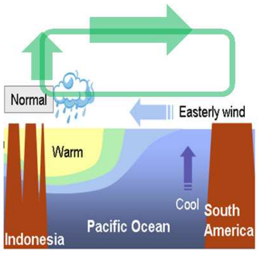
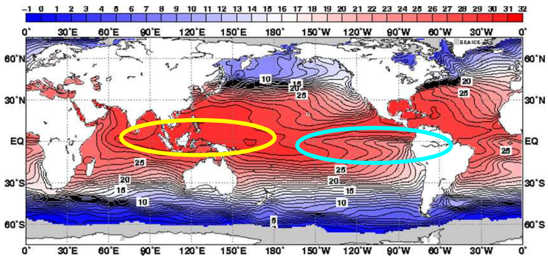
Internal variation with the strongest signal

ENSO (El Niño Southern Oscillation)

El Niño







warmer in the west
(typically around 30ºC)

cooler in the east
(typically around 22ºC)

ENSO is an internal variation of the atmosphere and ocean system in the tropical Pacific Ocean.

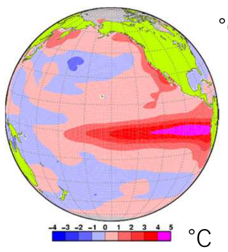
El Nino is warmer than normal condition in the eastern equatorial Pacific, lasting about 6-18 months, at intervals of several years.

Internal variation with the strongest signal

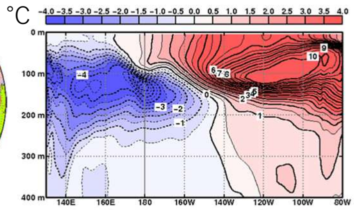
ENSO (El Niño Southern Oscillation)

SST anomalies

Sub surface water temperatures

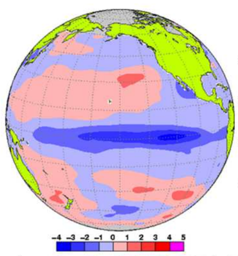


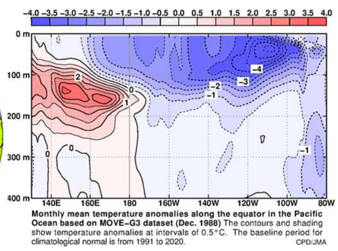
°C



in Nov. 1997

El Nino





in Dec. 1988

La Nina

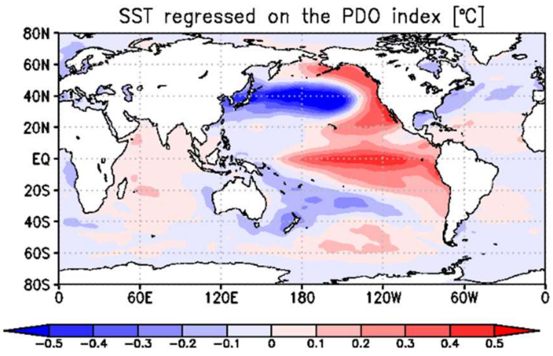
From Maeda-san 's and Umeda-san's slides

Listen to their lecture for details.

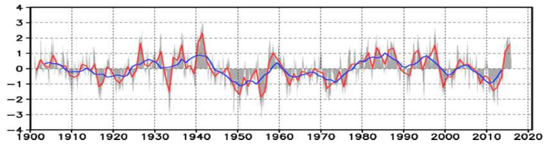
ENSO is an internal variation of the atmosphere and ocean system in the tropical Pacific Ocean.

El Nino is warmer than normal condition in the eastern equatorial Pacific, lasting about 6-18 months, at intervals of several years.

Pacific Decadal Oscillation (PDO)



SST pattern regressed on PDO index



PDO index

Red: annual mean
Blue: 5-year mean

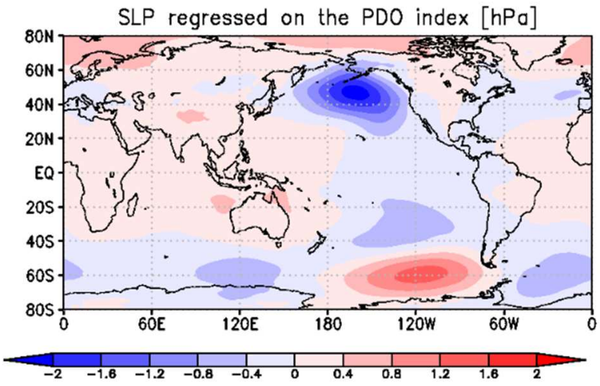
from JMA website

As a major variation in SST observed in the North Pacific, a pattern in which anomalies of opposite signs appear near the central region and along the coast of North America is known.

The sign of index is reversed every ten to several decades.

The cause of PDO is still not clearly understood.

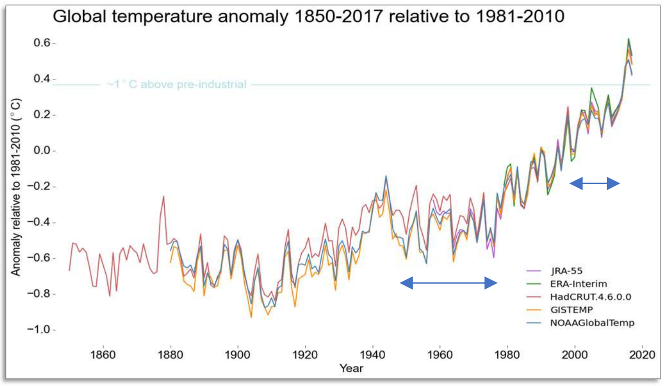
Pacific Decadal Oscillation (PDO)



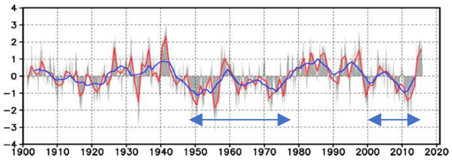
from JMA website

When the PDO index is positive, the Aleutian Low pressure system and the westerly winds in the upper atmosphere tend to become stronger.

Global Warming Slowdown and PDO



PDO index



Phases of global warming slowdown ("hiatus") tends to correspond to the negative phase of PDO index.

Summary

- The climate system has characteristic internal variabilities on various time scales.
- Physics, especially GFD and waves, is a useful tool for interpreting internal variabilities.
- In short-time variations, atmospheric waves are often important, such as MJO and wave-like patterns.
- The ocean is involved in internal variations over long time scales. ENSO is a typical one and has a great impact on the global climate.