Introduction to Climatology

for experts on climate analysis information

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Outline of the lecture

1. Introduction : Climate and Climate System
2. Global Mean Temperature and Radiative Balance
3. Annual Mean Circulation and Horizontal Heating Contrast
4. Seasonal Change and Heat Capacity
5. Introduction of Variabilities
6. Intra-seasonal to Interannual Variability
7. Decadal Variability
8. Global Warming
9. Summary

basic states (items 2–4)

Variabilities (items 5–8)

1. Introduction :
Climate and Climate System

Weather and Climate

Weather

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.

What is 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/our-mandate/weather
https://public.wmo.int/en/about-us/frequently-asked-questions/climate

Climate and Climate System

What is Climate?

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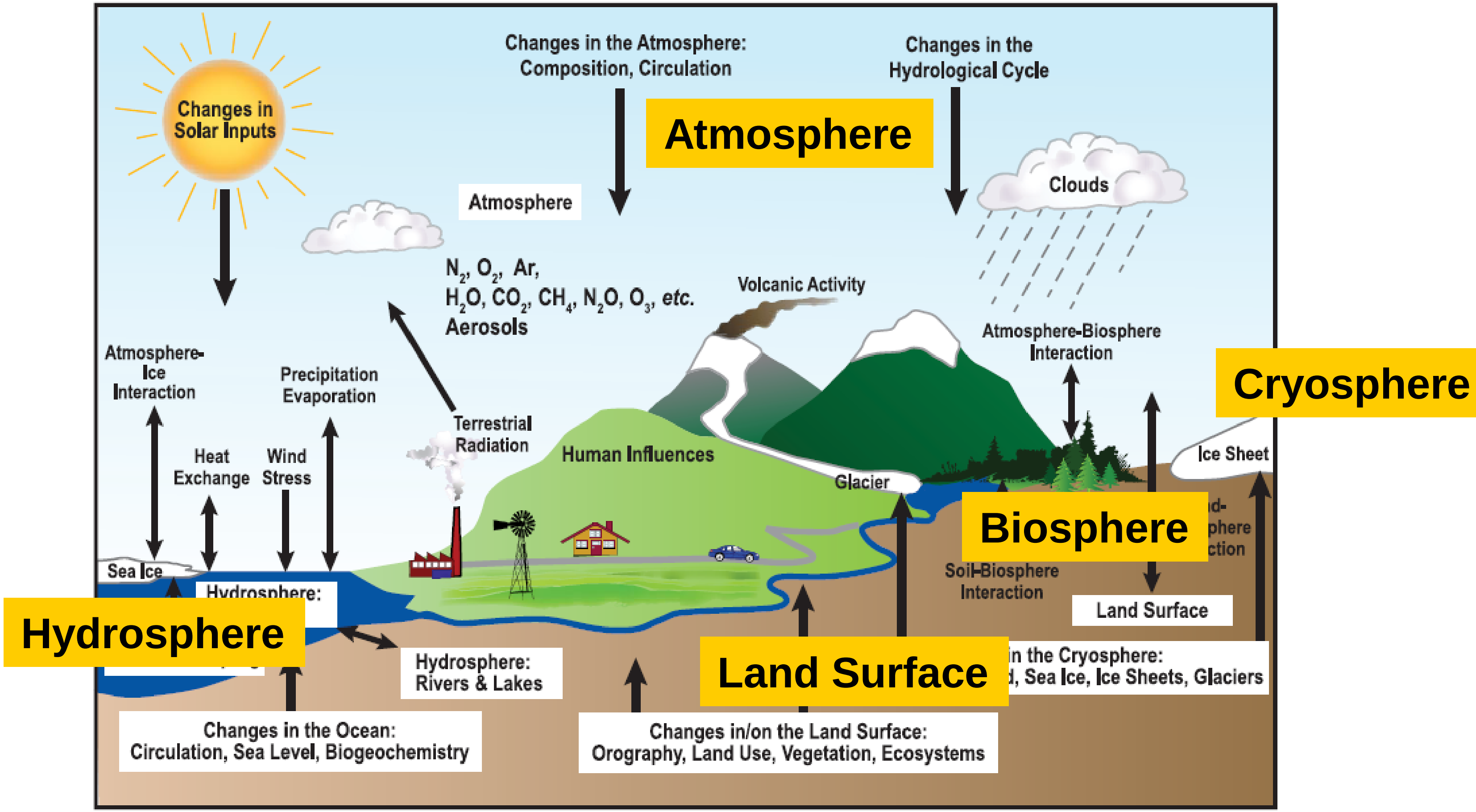
What is the Climate System?

The climate system consists of five major components: the atmosphere the hydrosphere, the cryosphere, 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.

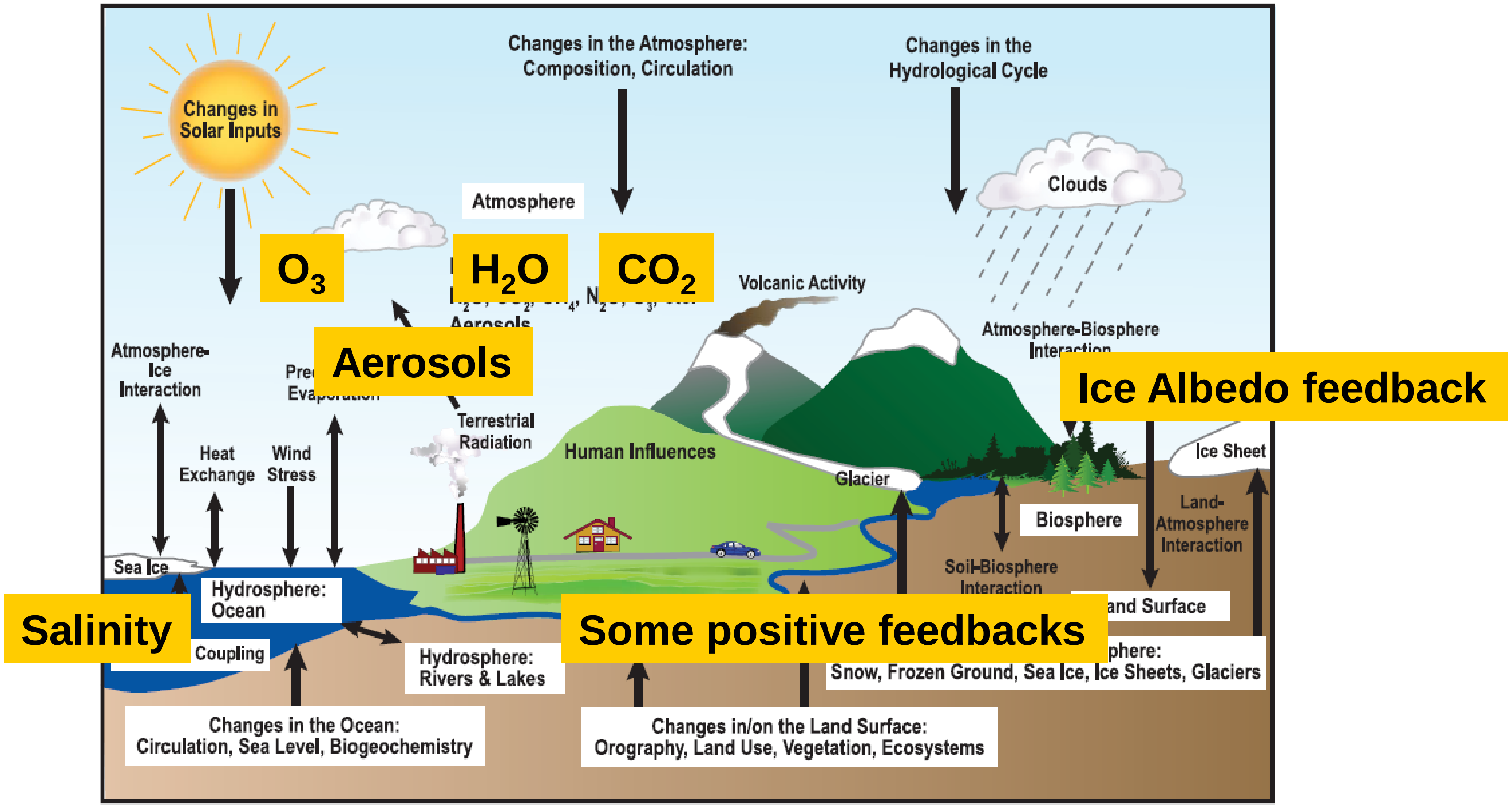
https://public.wmo.int/en/about-us/frequently-asked-questions/climate

Climate System



These components interact on various spatial and temporal scales through the exchanges of heat, momentum, radiation, water and other materials.

Climate System



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

Climate System has many Compositions, and is a very complex system !

The Climate System is described using science

- The climate system is described by an equation system consisting of fluid dynamics, radiation transfer, turbulence, dry/moist convection... , and the interactions among components.
  - Current climate models are collections of our understandings of the climate system.
- Building simpler approximation systems by selecting important processes and reducing spatiotemporal dimensions has helped to elucidate the essence of the climate system.
  - For example, wave dynamics inherent in the system also serves as a powerful concept.

The purpose of this lecture

- To know how climate is formed and its variability is caused
- By using these simpler approximation systems, simple images and powerful tools to explain some of the basic concepts of climatology

2. Global Mean Temperature and Radiative Balance

- 0 / 1 dimension (spatial and temporal average)
  - Circulation (horizontal movement) is not included.
- Basically only the radiation process is considered, whereas the concept of convection are handled in a very simple form.

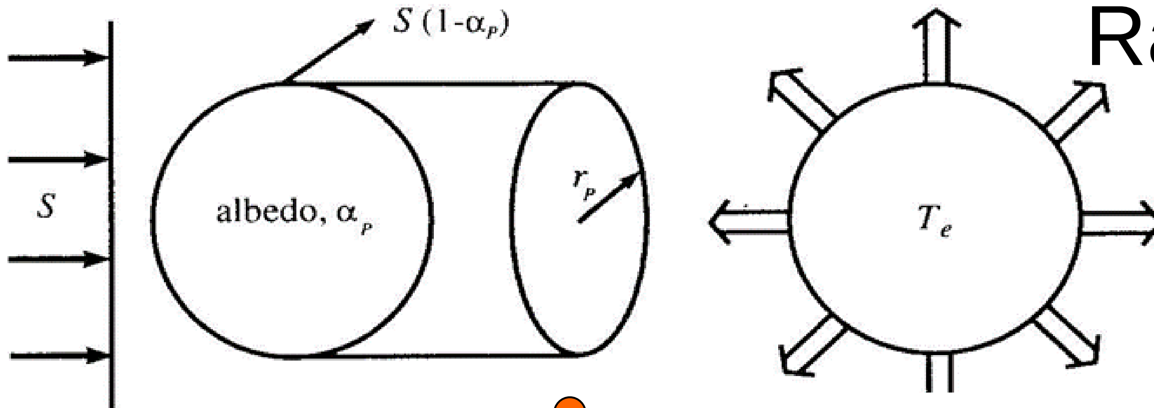
0-dimensional average Temperature
(almost equilibrium state)

Reflection

Earth

Terrestrial Radiation

Solar Radiation



Absorption = Emission

> Warming of Climate System

< Cooling of Climate System

almost in equilibrium state

Earth's temperature from space

obtained by the radiative energy balance

Solar

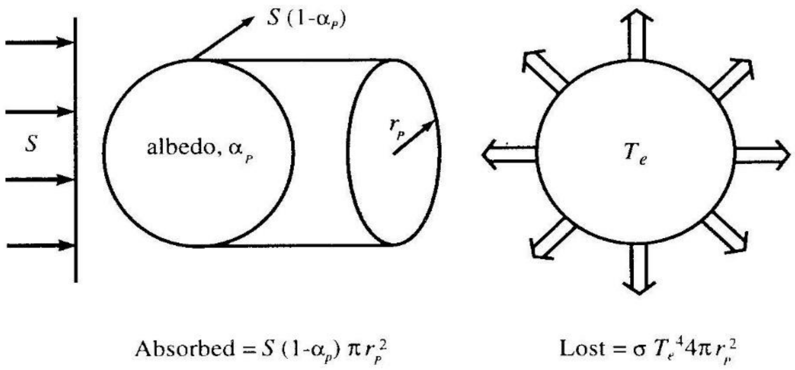
Solar constant $S \approx 1370\,Wm^{-2}$

insolation at the top of the atmosphere :

$$\frac{S}{4} \approx 342 Wm^{-2}$$

planetary albedo $\alpha_P \approx 0.31$

absorption $\frac{S}{4}(1-\alpha_P) \approx 235 Wm^{-2}$



Solar absorption

= Terrestorial emission

$$T_e^* = \sqrt[4]{\frac{S(1-\alpha_P)}{4\sigma}} \approx 254K \approx -19°C$$

Terrestrial

equibrium radiative temperature T_e^*

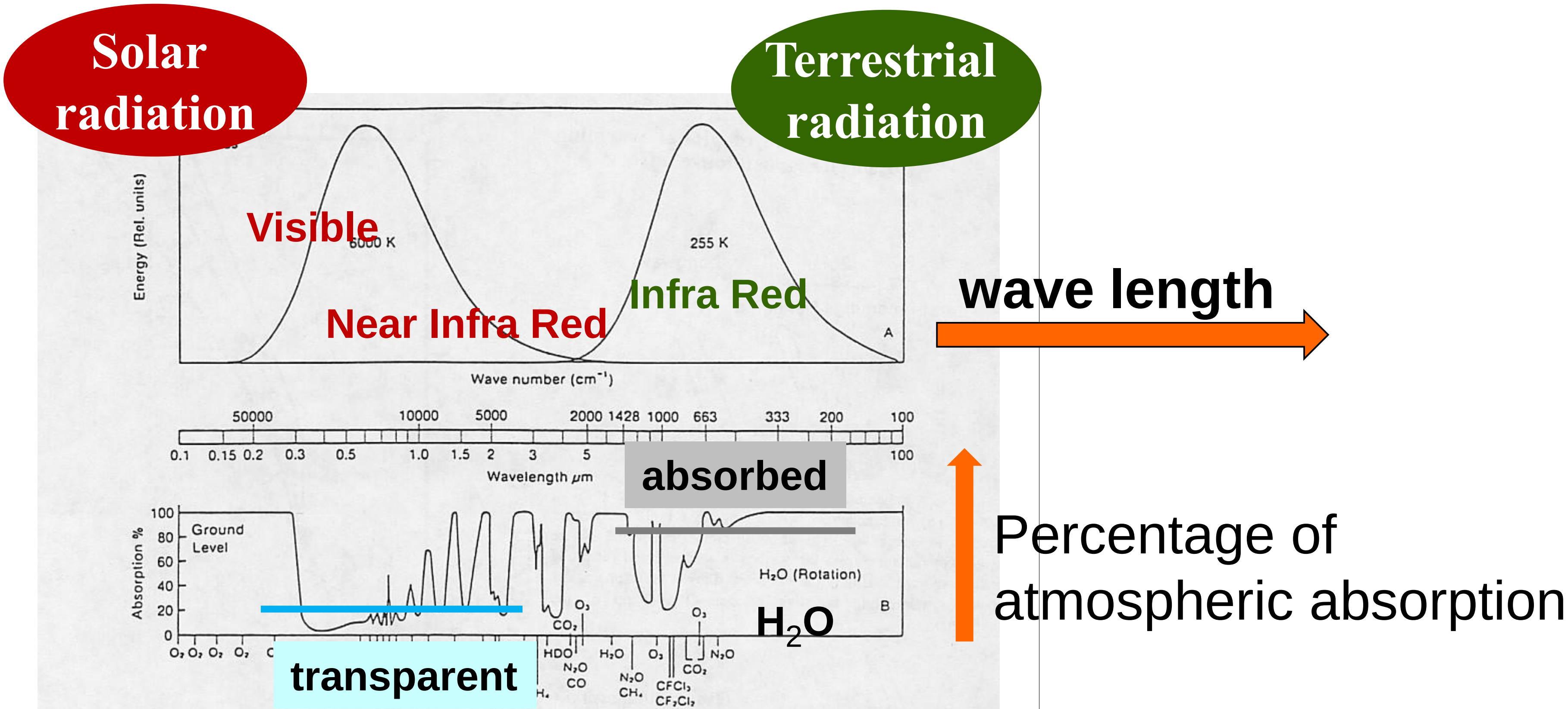
emission σT_e^{*4} ← **black body**

Real World:

Surface Temperature ≒ 15° C

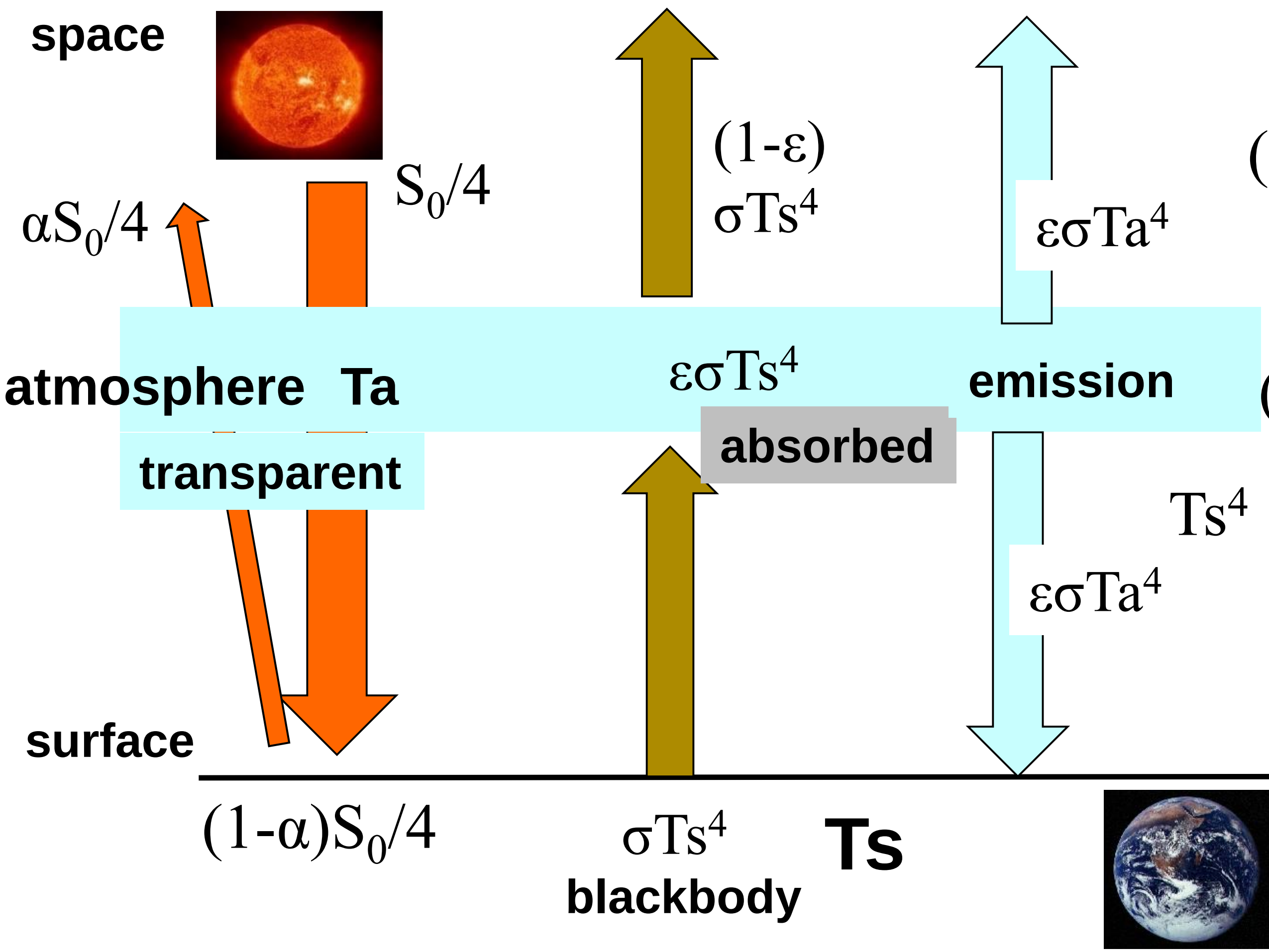
Something is wrong

Absorption of solar radiation and Emission of the earth



(*a*) Spectral distribution of long-wave emission from blackbodies at 6000 K and 255 K, corresponding to the mean emitting temperatures of the Sun and Earth, respectively, and (*b*) percentage of atmospheric absorption for radiation passing from the top of the atmosphere to the surface. Notice the comparatively weak absorption of the solar spectrum and the region of weak absorption from 8 to 12 μm in the long-wave spectrum [from *MacCracken and Luther*, 1985].

A simple Model of Green House Effect



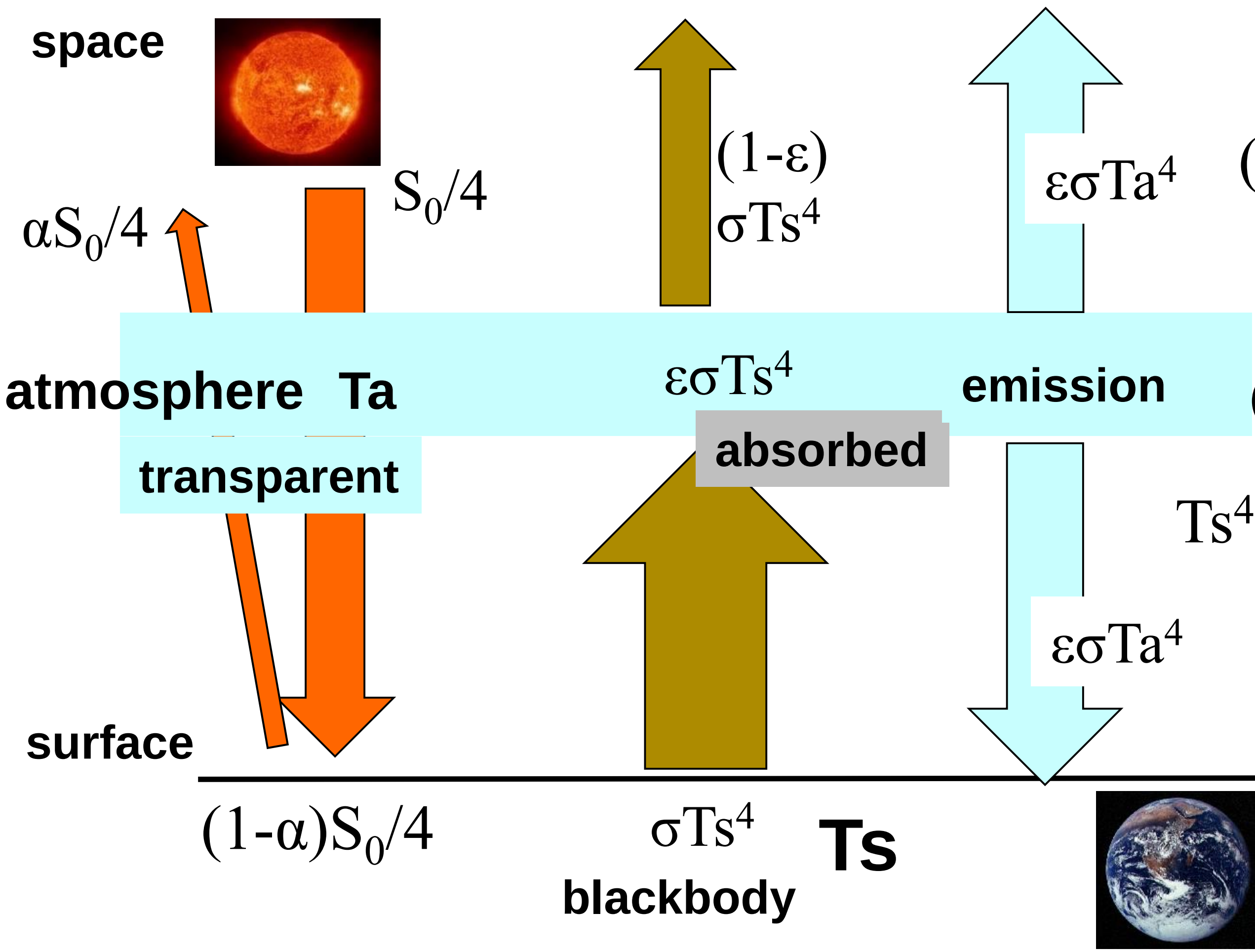
$$(1-\alpha)S_0/4 + \varepsilon\sigma Ta^4 = \sigma Ts^4$$

$$2\,\sigma Ta^4 = \sigma Ts^4$$

$$(1-\alpha)S_0/4 = (2-\varepsilon)/2\ \sigma Ts^4$$

$$Ts^4 = (1-\alpha)S_0/4/\sigma \times 2/(2-\varepsilon)$$

A simple Model of Green House Effect



$$(1-\alpha)S_0/4 + \varepsilon\sigma Ta^4 = \sigma Ts^4$$

$$2\ \sigma Ta^4 = \sigma Ts^4$$

$$(1-\alpha)S_0/4 = (2-\varepsilon)/2\ \sigma Ts^4$$

$$Ts^4 = (1-\alpha)S_0/4/\sigma \times 2/(2-\varepsilon)$$

S0=1370
α=0.31
σ=5.67E-8

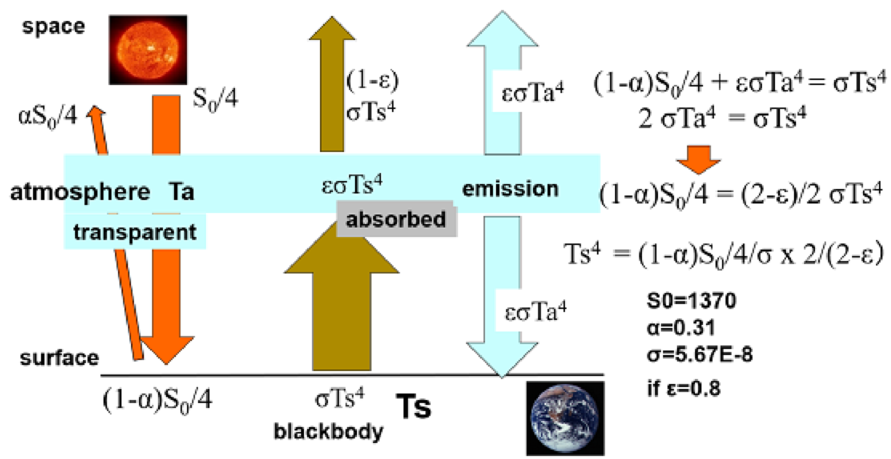
if ε=0.8

Ts = 289K = 16℃

Summary : Global Mean Surface Temperature

- The global mean surface temperature can be obtained close to reality by using a very simple system.
- In the system, consideration should be given to solar radiation, earth radiation, planetary albedo, and an atmosphere whose absorption rate depends on wavelength.

✓ Remark: If you set ε larger, you can get larger Ts. It corresponds to the global warming.



Radiative Equilibrium and Radiative-Convective Equilibrium

vertical (one dimensional) radiative transfer model

the effect of Convection

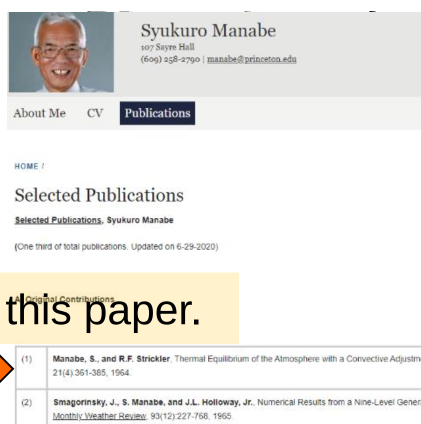
Thermal Equilibrium of the Atmosphere with a Convective Adjustment

2021 Nobel Prize in Physics

SYUKURO MANABE AND ROBERT F. STRICKLER

General Circulation Research Laboratory, U. S. Weather Bureau, Washington, D. C.

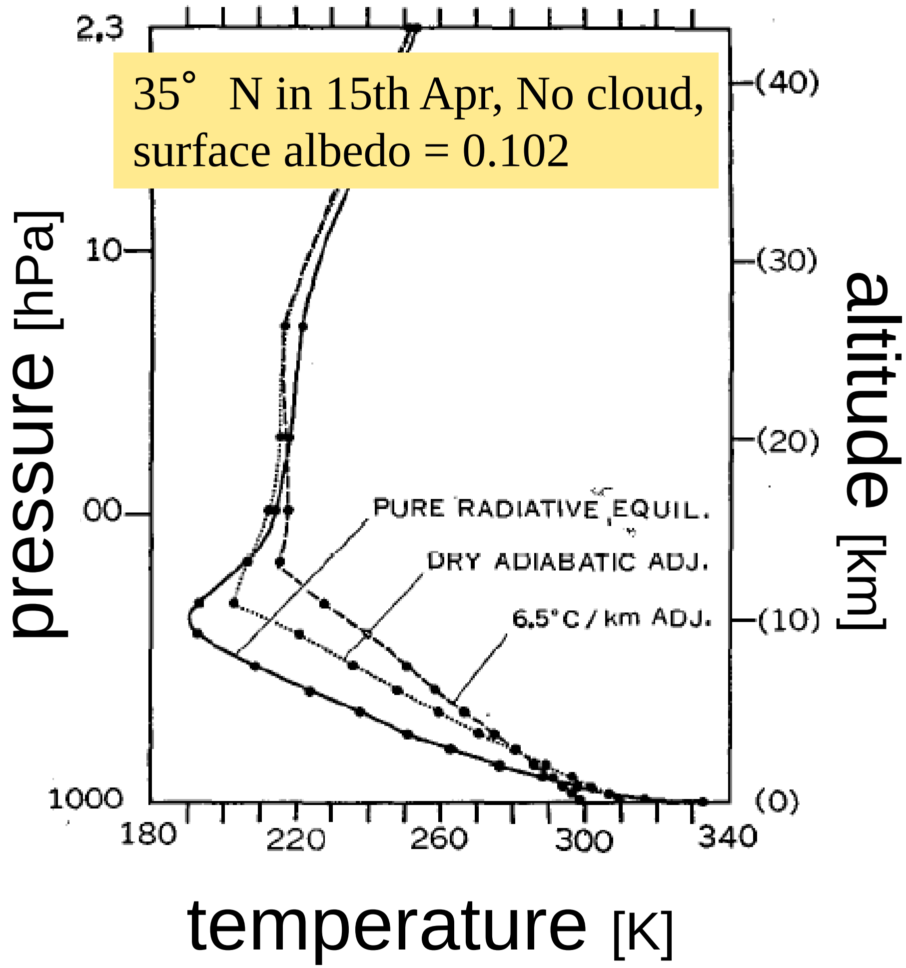
d 19 December 1963, in revised form 13 April 1964)



The 1st one is this paper.

Dr. Manabe's Selected Publications
https://scholar.princeton.edu/manabe/pubs
The 1st one of the list is this paper

Radiative Equilibrium and Radiative-Convective Equilibrium

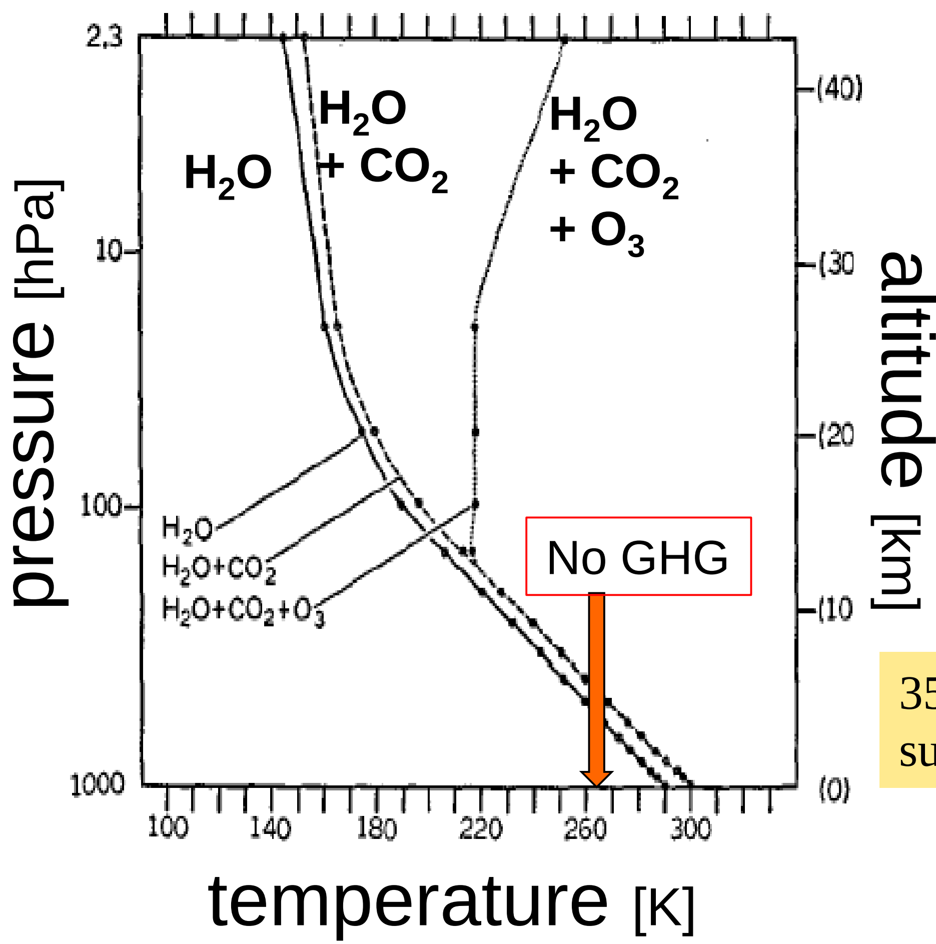


Radiative heating tends to create vertical instability between heated ground and cooled atmosphere.

⇒ To obtain realistic vertical temperature profile, it is necessary to introduce the effect of convection

Radiation Equilibrium Only
⇒ with dry adiabatic adjustment
(10K/km)
or with critical convective lapse rage
(6.5K/km)

Radiative-Convective Equilibrium
- Effect of greenhouse gases -

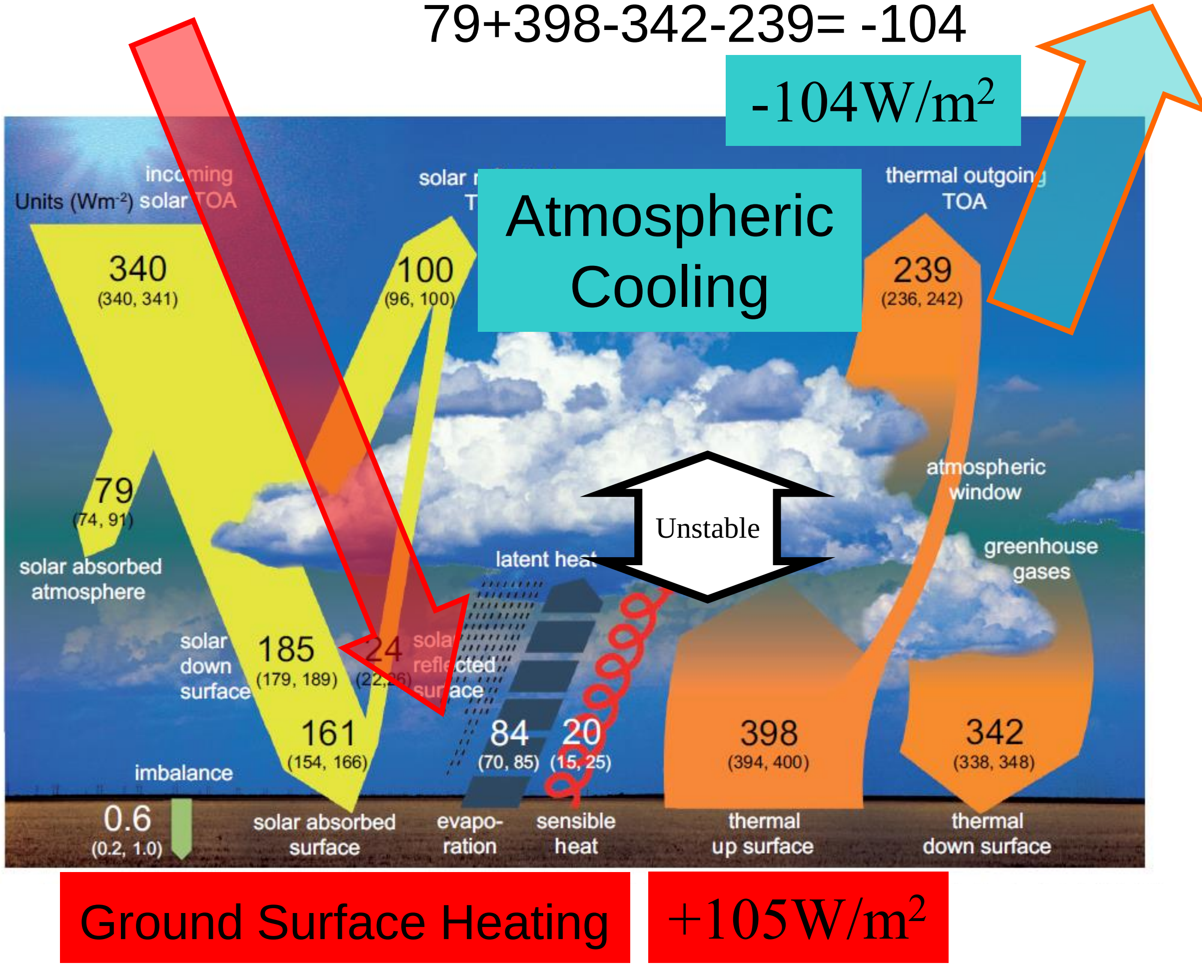


- H_2O is the strongest greenhouse gas.
- O_3 heating is required to represent the realistic temperature profile in the stratosphere.

35° N in 15th Apr, No cloud, surface albedo = 0.102

Energy Budget - vertical heat transport -

79+398-342-239= -104



161+342-398=105

IPCC AR5 (2014)

In the real climate system, the surface of the earth is heated by 105W by radiation. Atmosphere is just as cooled.

Vertical instability is eliminated by vertical heat transport in convective and turbulence processes.

Summary : Radiative-Convective Equilibrium

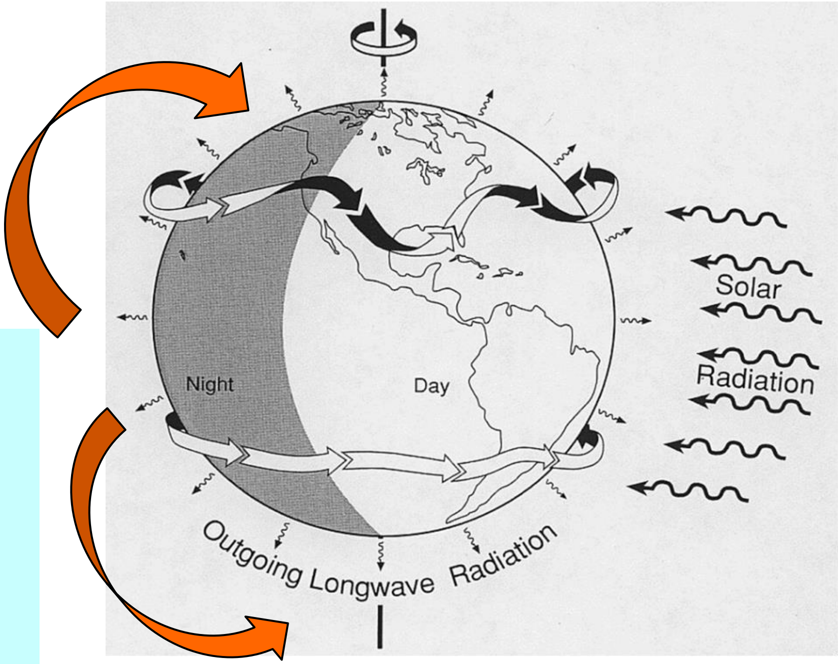
- The vertical one-dimensional temperature profile can be reproduced fairly well by the radiation transfer equation in the atmosphere containing greenhouse gases, with the effect of convection (turbulence) simply.
- It is suggested that water vapor is the strongest greenhouse effect gas.
- In order to reproduce the peak temperature of the stratosphere, it is necessary to consider solar radiation absorption by ozone.

3. Annual Mean Circulation and Horizontal Heating Contrast

Circulation (motion) is introduced in this section.

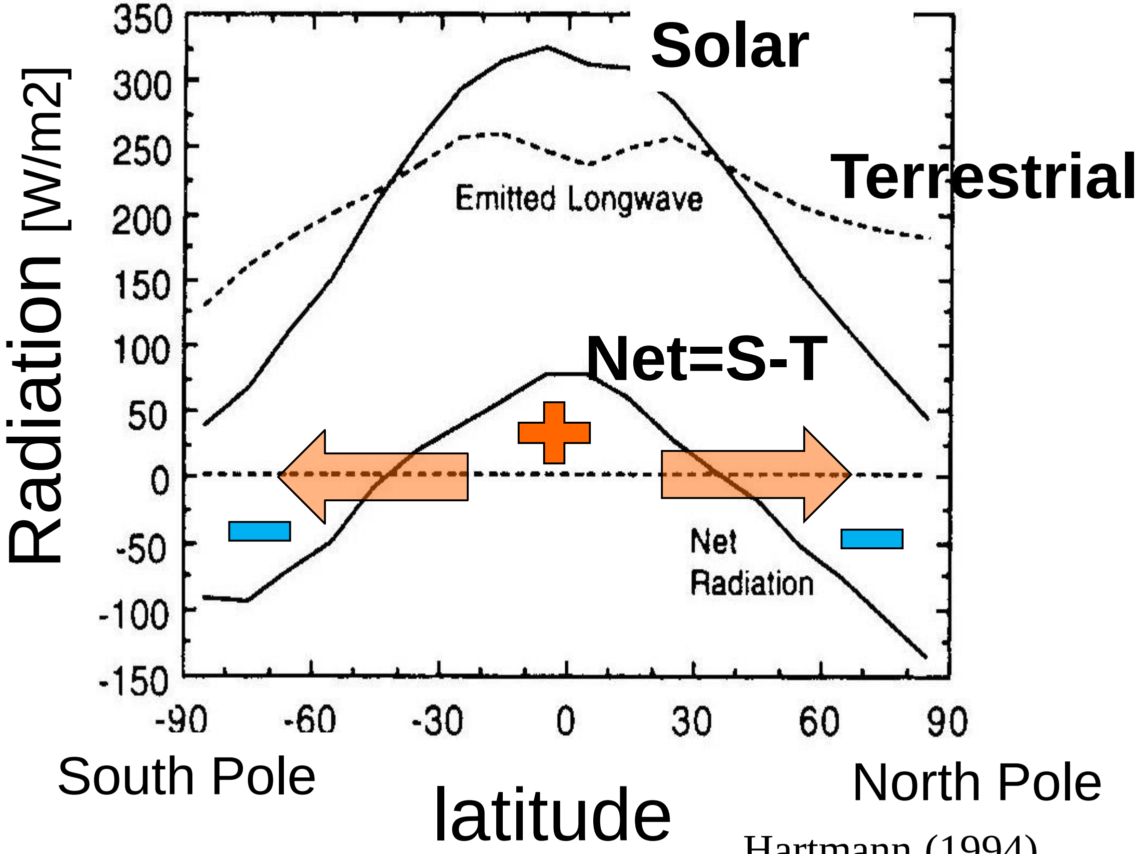
Horizontal heat transport associated with circulations in the atmosphere and ocean reduces horizontal heat imbalance due to radiation.

The main topics are the latitudinal circulations due to North-South energy imbalance.



Remark:
The large-scale circulation structure in the longitude direction is limited.
Because the rotation period (1day) is shorter than the time scale of radiation (O(10days)),
Exception is Walker circulation, and we will be back on the topic of El Nino.

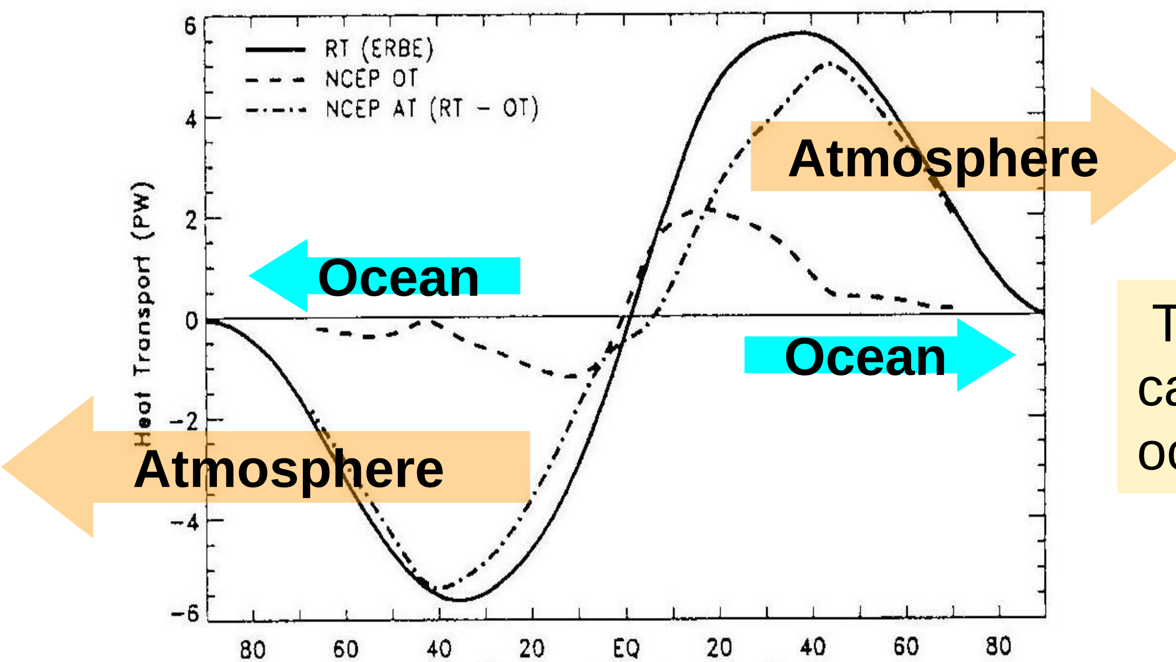
Latitudinal heating contrast of Annual mean radiation balance



Hartmann (1994)

Energy transport by the atmosphere and ocean

Integration from the South Pole of Net radiation absorbed in the Earth



South Pole latitude North Pole

The atmospheric circulation carries more energy than the ocean circulation.

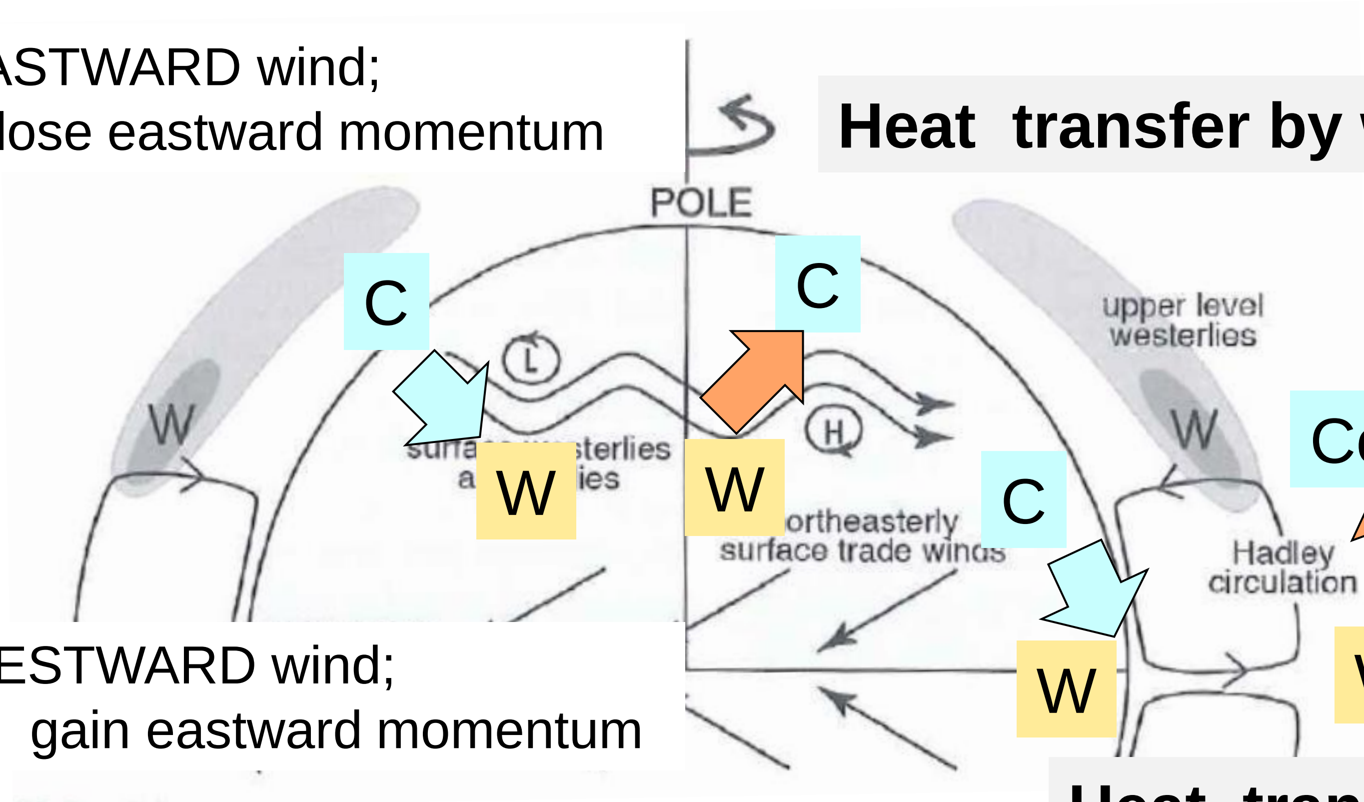
Trenberth and Caron (2001)

Observed atmospheric general circulation

EASTWARD wind;
⇒lose eastward momentum

mid-high lat

Heat transfer by waves.



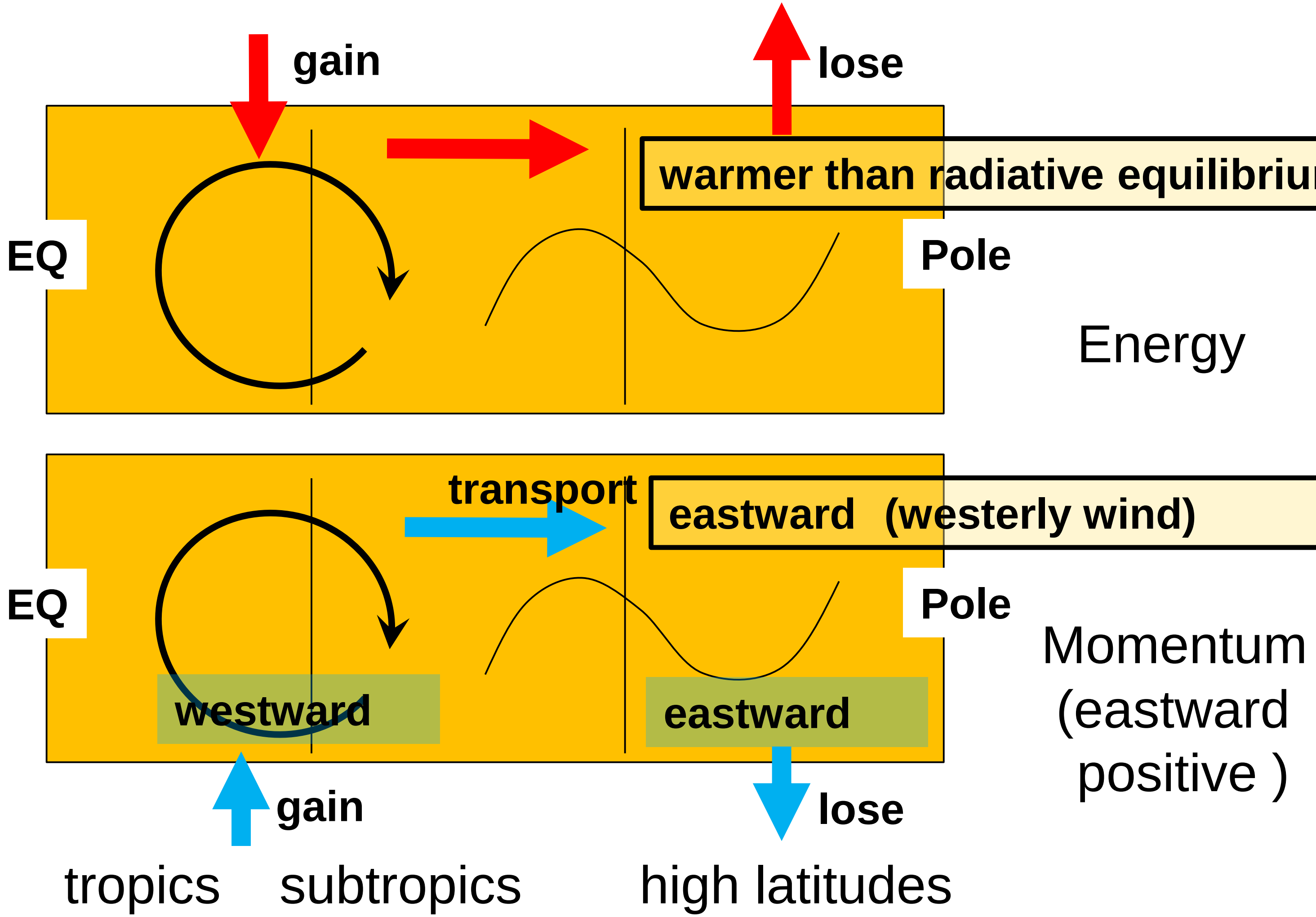
WESTWARD wind;
⇒ gain eastward momentum

low lat

Heat transfer by direct circulation.

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

Energy and Momentum transport by atmospheric general circulation

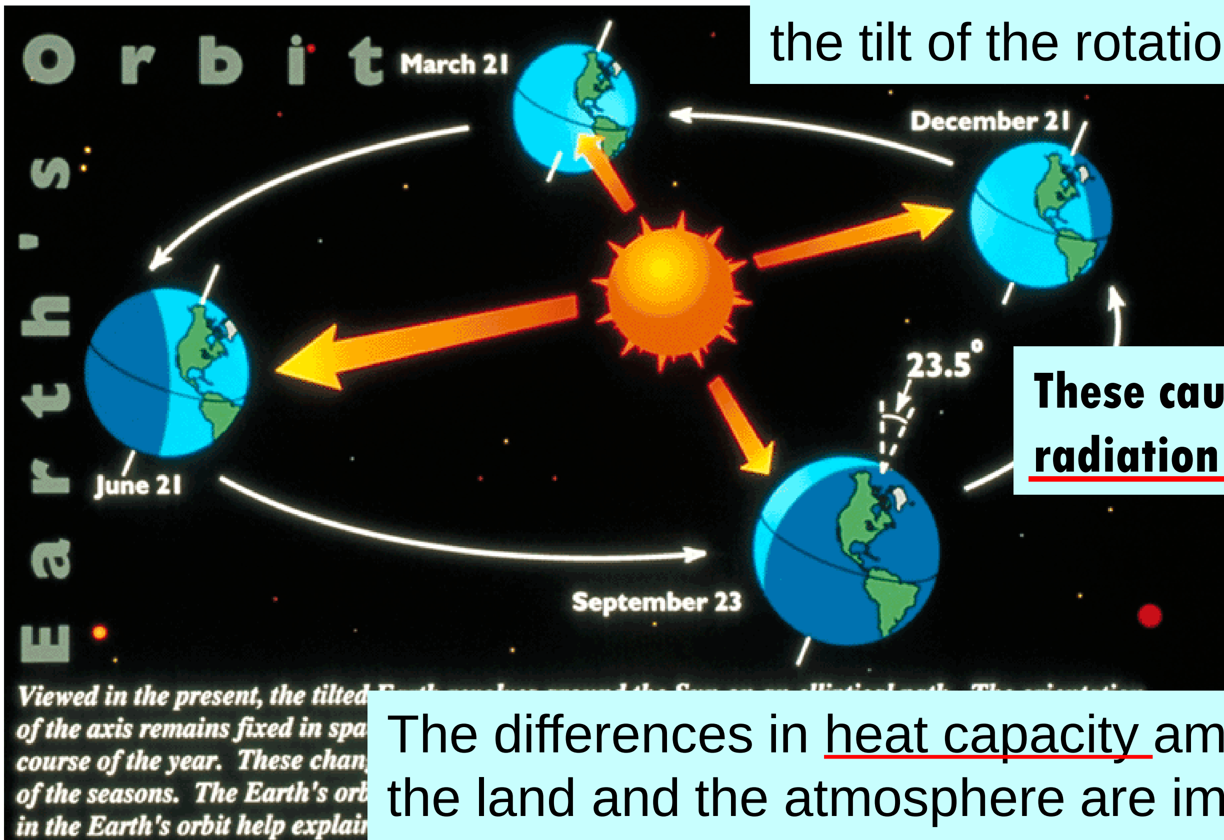


Summary :
Elimination of Horizontal Heating/Momentum Imbalance

- Net radiation is positive at low latitudes, while negative at high latitudes.
- This imbalance is compensated for by heat transport by atmospheric and ocean circulation, and atmospheric heat transport is larger than ocean one.
- At low latitudes, the contribution of transport by the Hadley circulation is dominant,
- while at medium and high latitudes, the contribution of transport by waves is dominant.
- The circulation also transports momentum.
- The latitudinal transport of heat and momentum has a great influence on the distribution of the mean state.

4. Seasonal Change and Heat Capacity

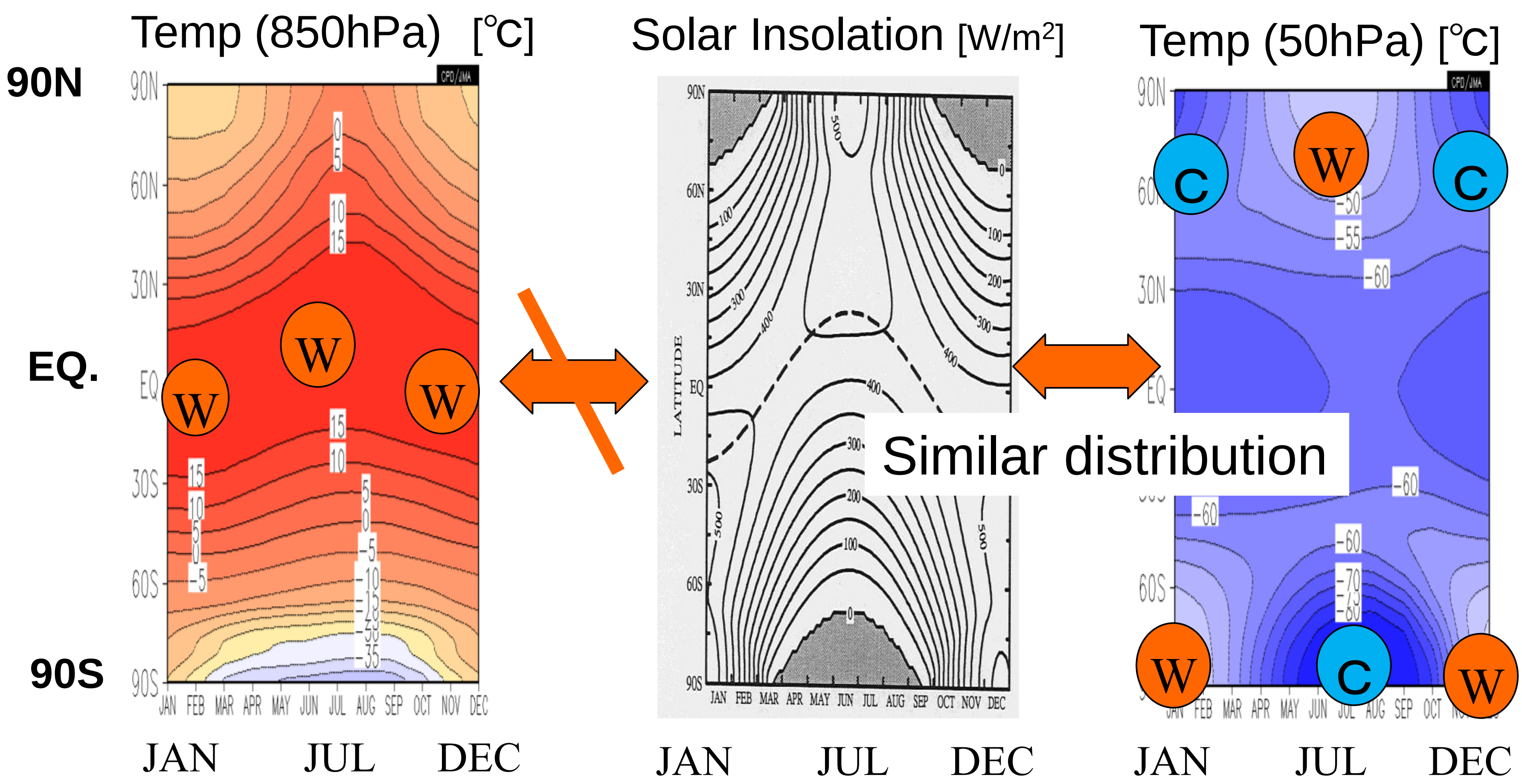
Seasonal change is caused by the revolution of the earth and the tilt of the rotation axis.



These cause seasonal changes in solar radiation at each latitude.

The differences in heat capacity among the ocean, the land and the atmosphere are important. They **give great characteristics to seasonal changes.**

Seasonal Change of Solar Insolation and Temperature



海洋の大きな熱容量

オゾン加熱
熱容量小

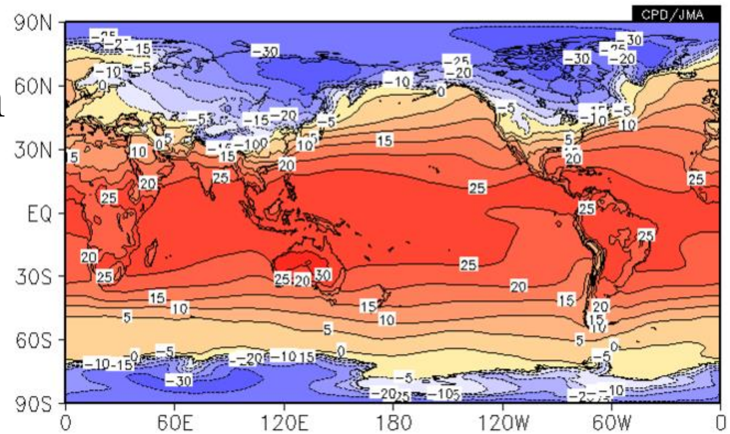
Heat Capacity of atmosphere and ocean

	Atmosphere	Ocean
Density	1.2-1.3kgm^{-3}	10^3kgm^{-3} / atm. x 800
Mass(per 1 m^2)	（Top ～ Surface） 10^4kgm^{-2}	（Surface ～10m depth） 10^4kgm^{-2}
Specific heat	10^3Jkg^{-1}K^{-1}	4×10^3Jkg^{-1}K^{-1} / atm. x 4
Heat capacity (per 1 m^2)	（Top ～ Surface） 10^7JK^{-1}m^{-2}	（Surface ～ 2.5m depth） 10^7JK^{-1}m^{-2}

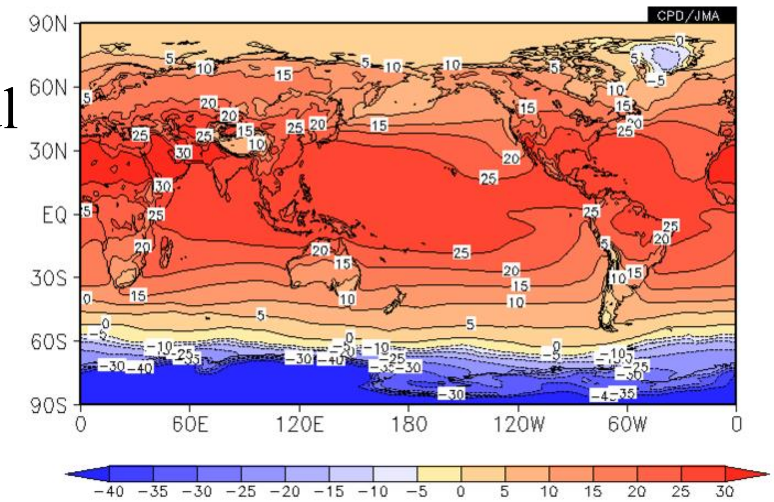
Heat capacity of the atmosphere is the same as that of ocean with 2.5m depth

Jan-Jul contrast of surface temperature [°C]

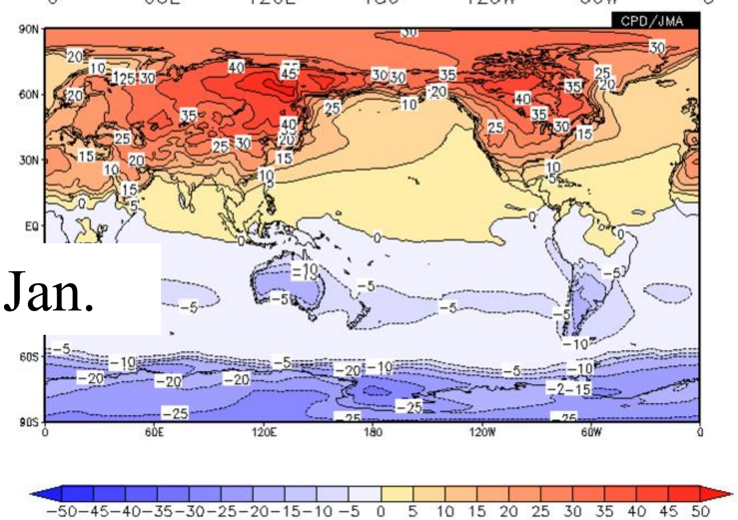
Jan



Jul



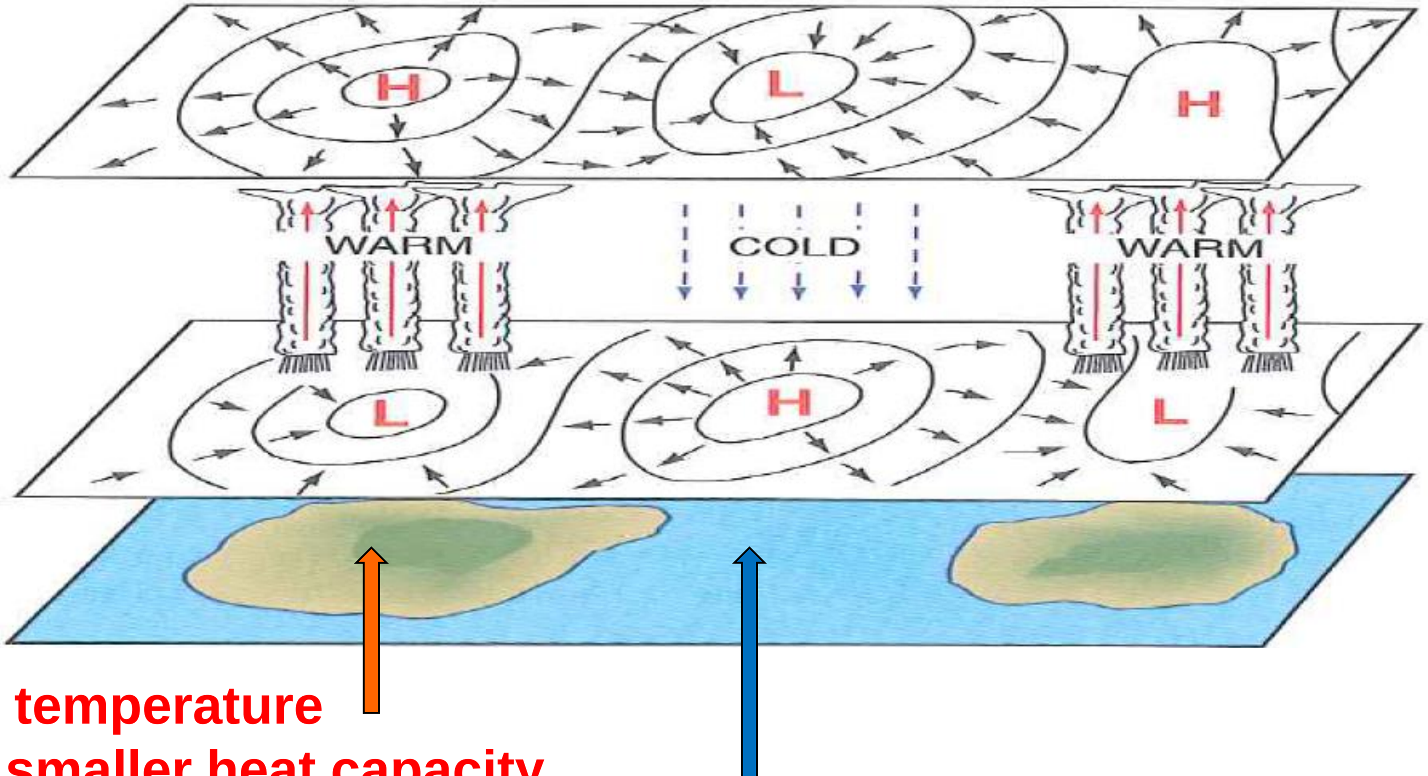
Jul - Jan.



The heat capacity of land is much smaller than that of ocean.

Larger temperature contrast over lands
Winter: land temp. < ocean temp.
Summer: land temp. > ocean temp.

Monsoon circulation

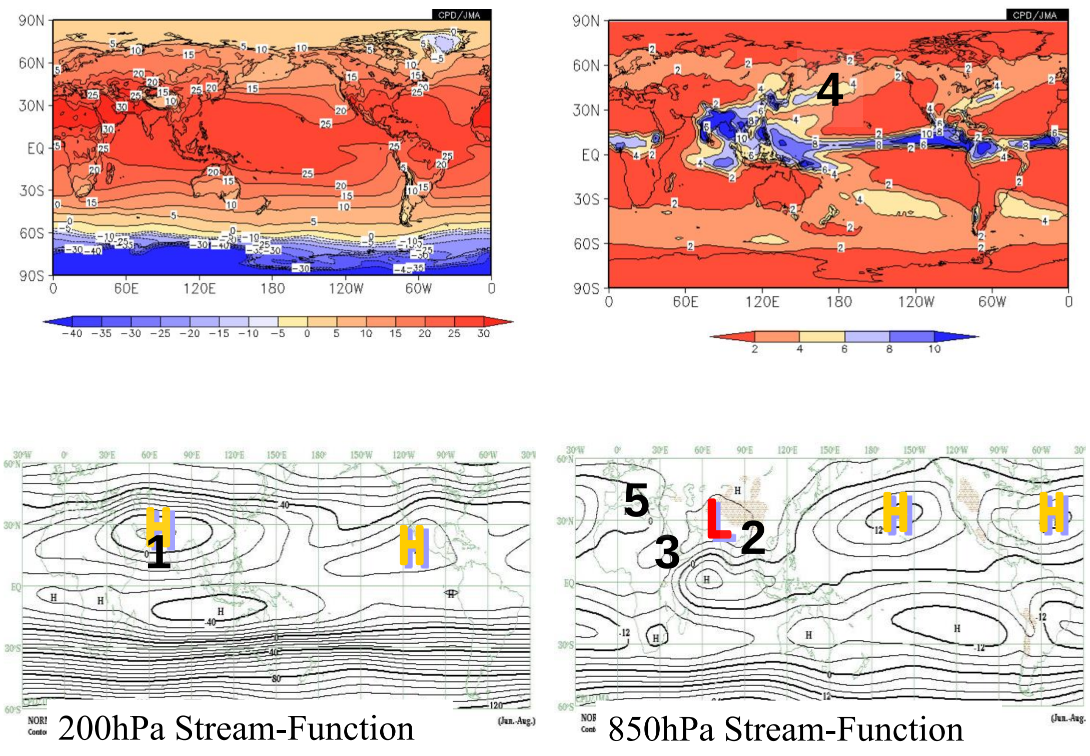


Higher temperature
due to smaller heat capacity

Lower temperature
due to larger heat capacity

the summer hemisphere

Monsoon circulation

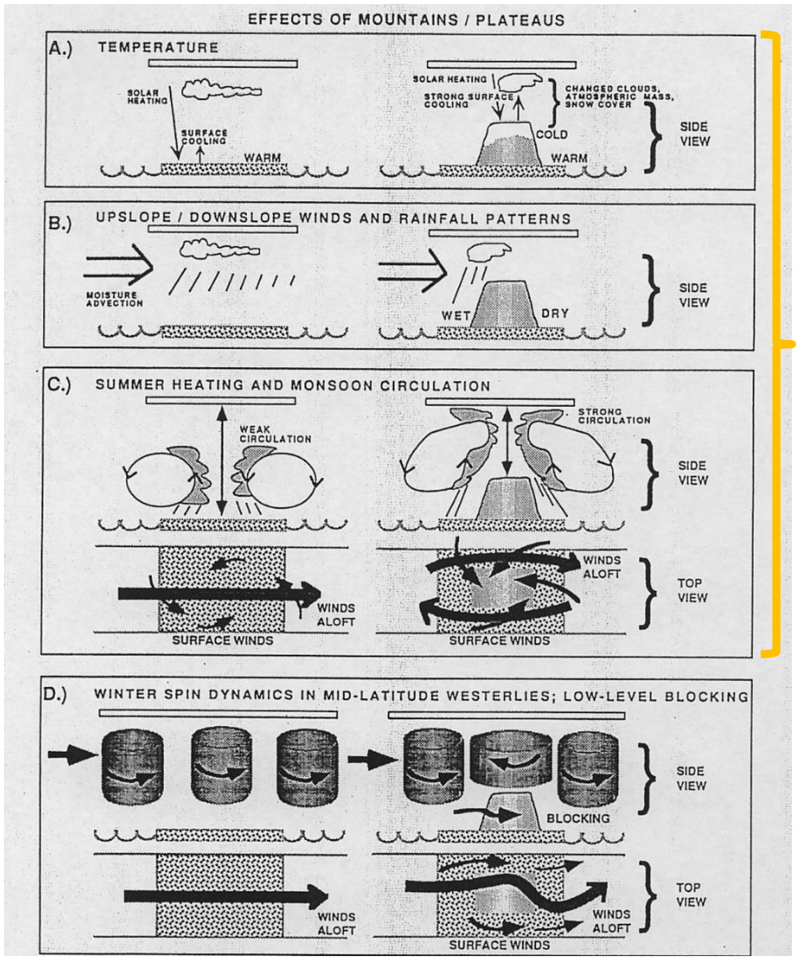


A concentrated subtropical rainfall forms a typical summer monsoon

1. an upper-level anti-cyclonic circulation,
2. a monsoon trough
3. a low-level jet
4. a subtropical rainfall band expanding north eastward
5. extensive downward motions causing dry region in the north westward

in the northern hemisphere

Role of orography on climate



Mountains also have impacts on not only the time-averaged atmospheric circulation, but also seasonal changes in local climate through thermal and dynamical processes.

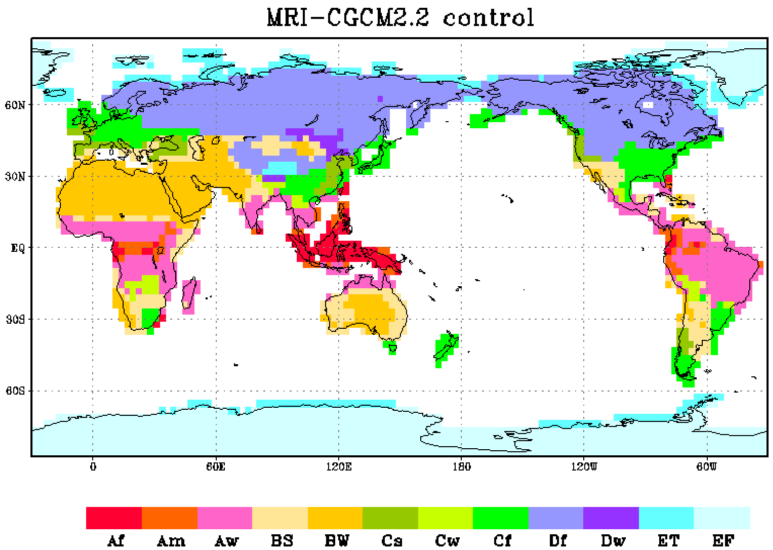
thermal effects

dynamical effect

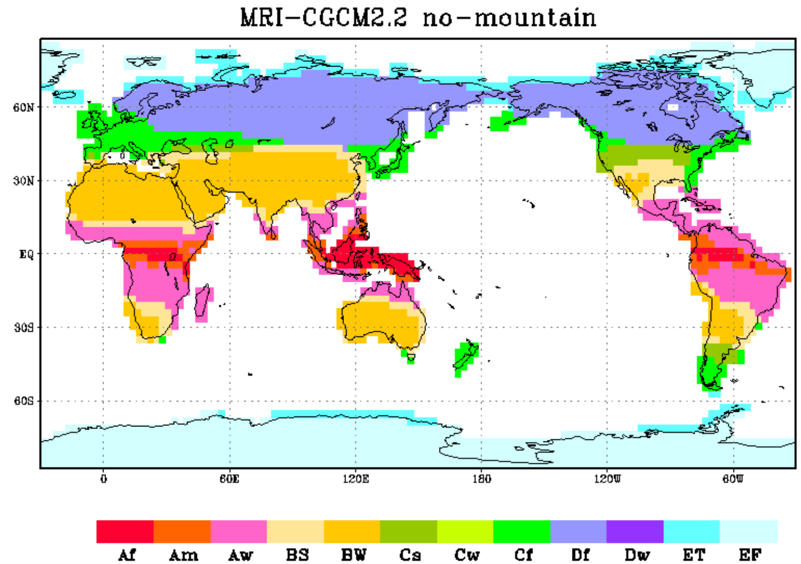
Kutzbach et al. (1993) J.Geology

Role of orography on climate

Simulation by Climate Model



Simulation by Climate Model without mountain



Kitoh (2005)

Mountains would be responsible for the real world climate of humid summer and somewhat cold winter in the eastern parts of the continents.

Summary : Seasonal Change and Heat Capacity

- Due to the orbital elements of the earth, seasonal changes in shortwave radiation occur, which leads to seasonal changes.
- In seasonal changes, the magnitude of heat capacity has a great influence on the amplitude and spatial distribution of changes in physical quantities.
- The characteristic monsoon circulation is created mainly by the difference in heat capacity between land and ocean.
- Mountains also have impacts on seasonal changes through thermal and dynamical processes.

5. Introduction of Variabilities

Characteristics of Variabilities

- Origin
- Time Scale

Powerful Tool for understanding Variabilities

- Waves
  - ✓ IGW (Inertial Gravity Waves)
  - ✓ Rossby Wave

Origin of variabilities

- **Natural origin**

  external: land-sea distribution, orography, solar constant,
  orbital variations, volcano

  internal: internal mode, air-sea interaction, ...

- **Anthropogenic origin**

  emission of greenhouse gases, destruction of ozone layer, land surface modification,,, (main factors of current climate changes)

Time scales of climate variabilities

- **Days to intra-seasonal variability**
  Blocking, Quasi-stationary Rossby wave
  Madden-Julian Oscillation (MJO)
- **Seasonal to interannual climate variability**
  El Nino/Southern Oscillation (ENSO)
  monsoon variability
  modes of variability (NAO, PNA, WP patterns)
- Decadal to interdecadal climate variability : O(10yr)
- Ocean thermohaline circulation : O(4000yr)
- Glacial and interglacial, and more

N.B. climate system is not in equilibrium

Waves as introduction of GFD

"Wave" is a powerful tool for describing and predicting time evolution. It is inherent in the system of GFD.

For example, when you throw a stone into a calm water surface, waves (anomaly of height and velocity on the surface) are created. If you look at the initial state, you may predict/imagin the time progress of the anomaly, by using "waves dynamics".

Waves: shallow water linear equations in rotating system

- West/eastward IGWs (Inertial gravity waves) and Rossby waves exist as normal modes.

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

$$\frac{\partial u}{\partial t} - fv = -g\frac{\partial h}{\partial x} - bu,$$

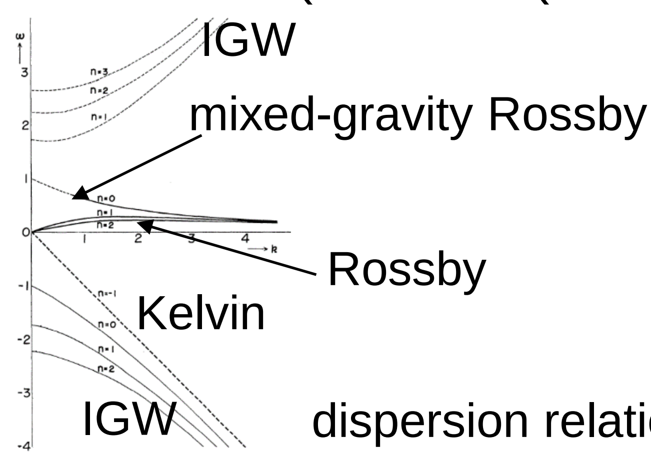
$$\frac{\partial v}{\partial t} + fu = -g\frac{\partial h}{\partial y} - bv.$$

- In the equatorial β plane($f = \beta y$), Kelvin waves and mixed Rossby gravity waves also exist. (Matsuno (1966), Gill(1980))

$$i\omega u - yv + ik\phi = 0$$

$$i\omega v + yu + \frac{d\phi}{dy} = 0$$

$$i\omega\phi + iku + \frac{dv}{dy} = 0$$



dispersion relationship

Waves: linear primitive equation model

- By means of vertical normal modes, a multi-level primitive equation model can be reduced to sets of shallow water equations characterized by various equivalent depths.
  - ✓ Therefore, IGWs and Rossby waves exist in the system.
- Remark: In the real world, latent heating exists. We sometimes have to consider modulation. The phase speed in the real world is slower than that of theory.

Waves: Rossby waves

- Climate often deals with large-scale phenomena, where Rossby waves, also known as planetary waves, are often important.
- The phase velocity of Rossby waves is negative (westward) regardless of wavelength, but the group velocity (velocity of wave packet) is positive (eastward) for short wavelengths waves.
- If the flow velocity in the base field cancels with the phase velocity, the effective phase velocity becomes zero (stationary wave).

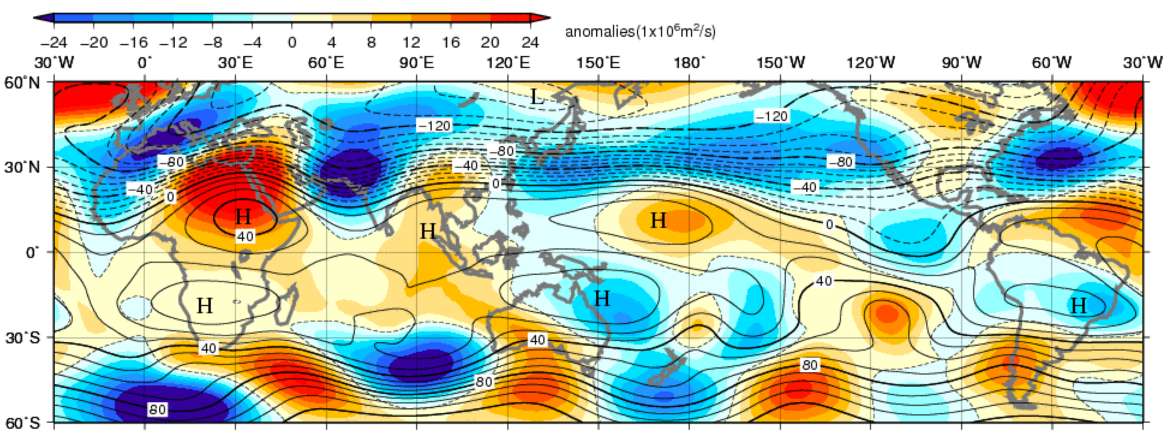
6. Intra-seasonal to Interannual Variability

Quasi-stationary Rossby waves

Rossby waves are

- large scale waves in the atmosphere and ocean.
- obey the conservation law of potential vorticity.
- are dispersive and propagate westward (longer wave is faster).
- are stationary if phase speed is the same as westerly wind which advects the waves.

Group velocity of stationary Rossby wave packet is eastward.
Stationary Rossby wave packet tends to propagate trapped by Jet streams.

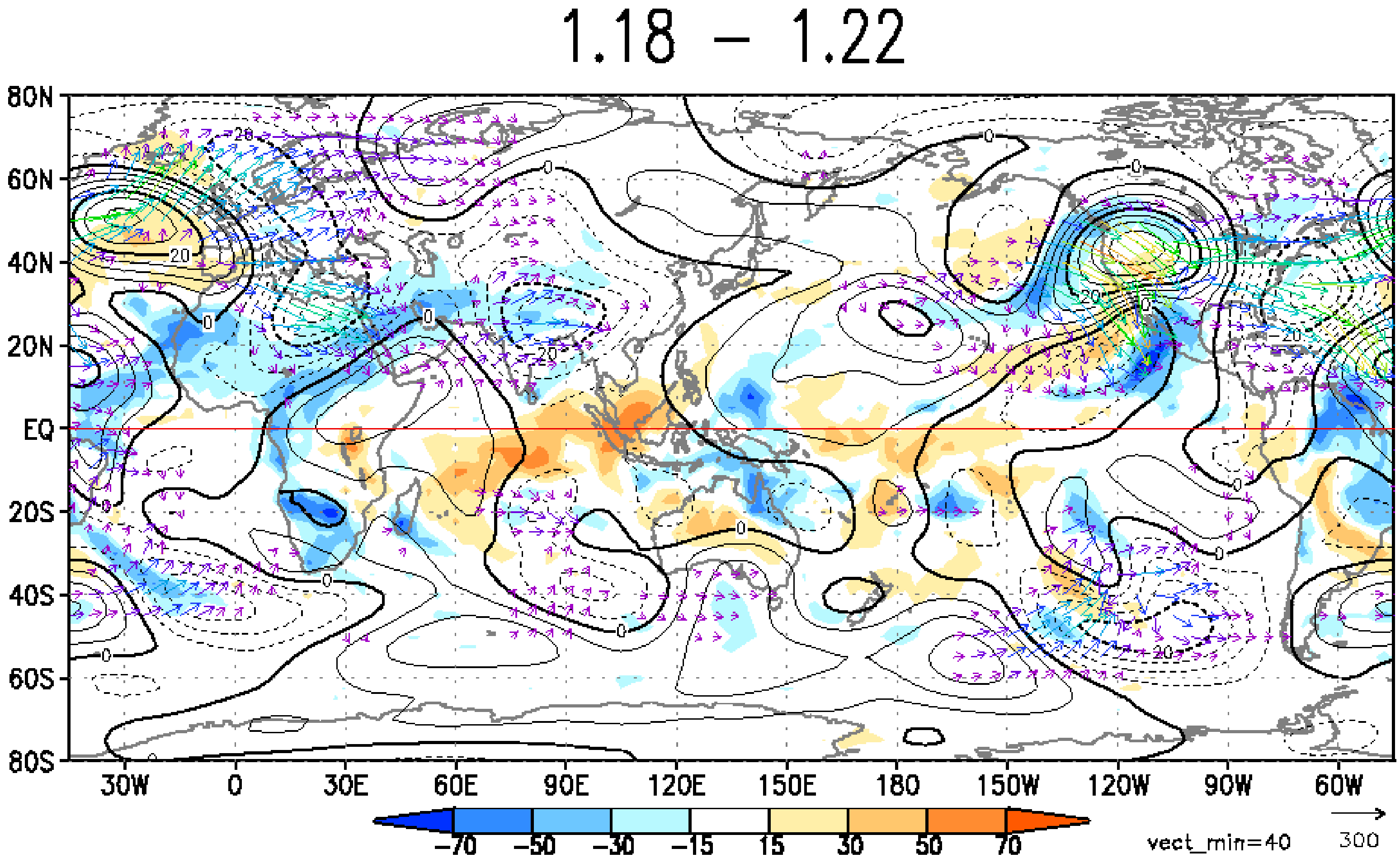


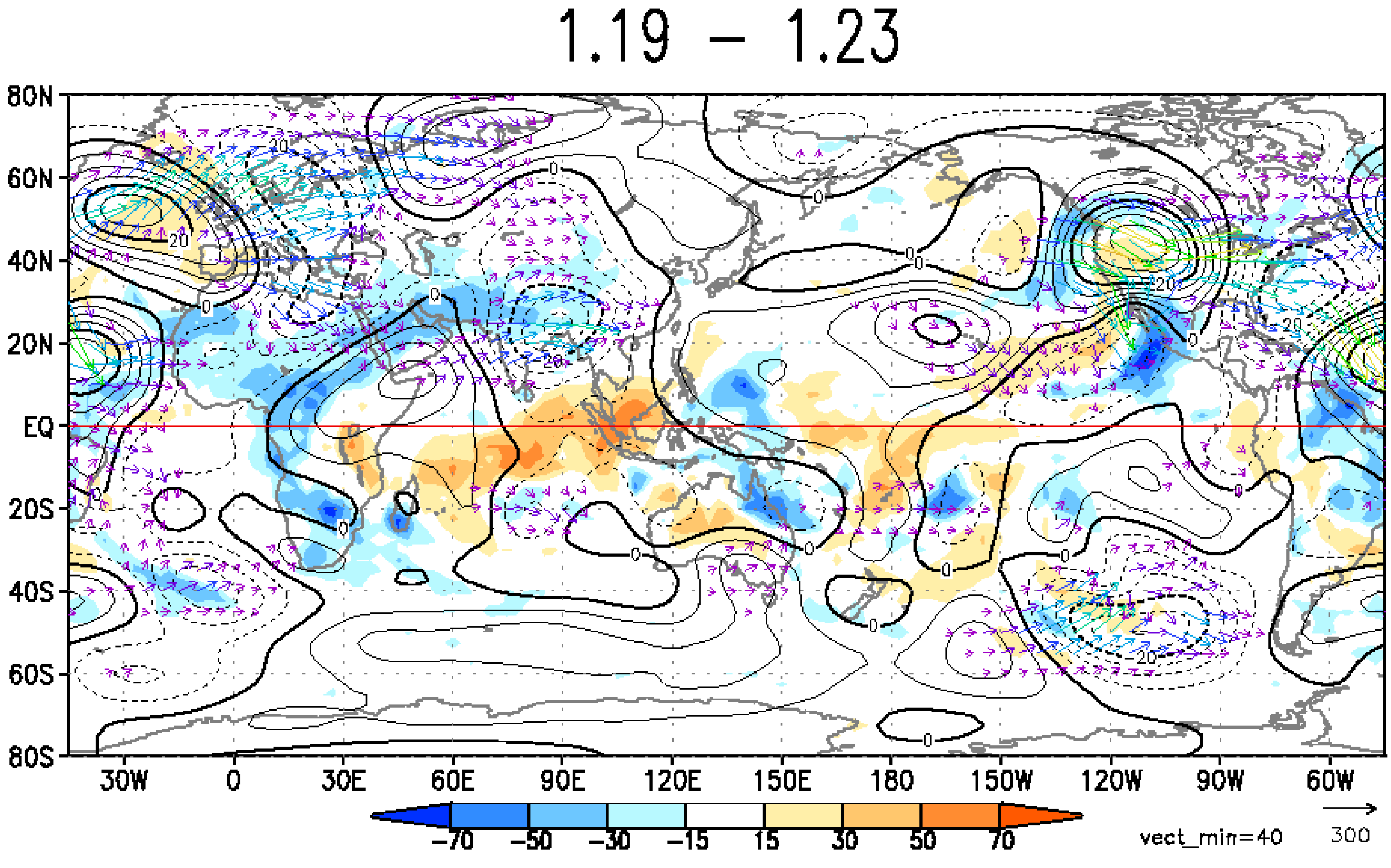
Five day mean 200 hPa stream function and anomaly (26Jan.2005–30Jan.2005) CPD/JMA
The contours show the stream function at intervals of 10x10^6 m^2/s, and the shading shows stream function anomalies.
Anomalies are deviations from the 1981–2010 average.

2005/1/26-1/30

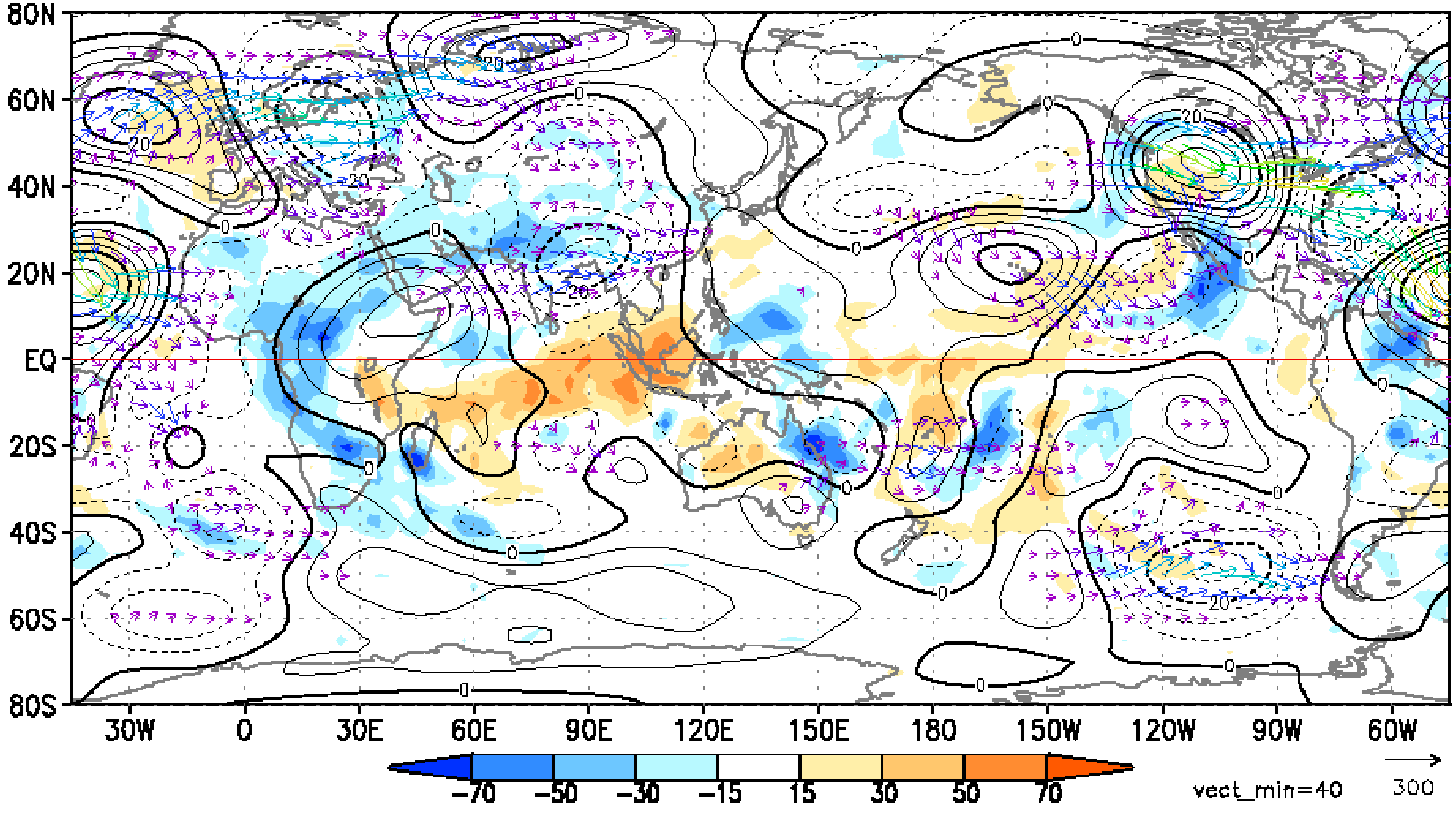
Blocking over the North Atlantic and Rossby wave trains along the Asian jet

5-day mean stream function anomalies at 200hPa 2005.1.18-




1.19 – 1.23
80N
60N
40N
20N
EQ
20S
40S
60S
80S
30W
0
30E
60E
90E
120E
150E
180
150W
120W
90W
60W
-70
-50
-30
-15
15
30
50
70
vect_min=40
300

1.20 – 1.24



80N
60N
40N
20N
EQ
20S
40S
60S
80S
30W
0
30E
60E
90E
120E
150E
180
150W
120W
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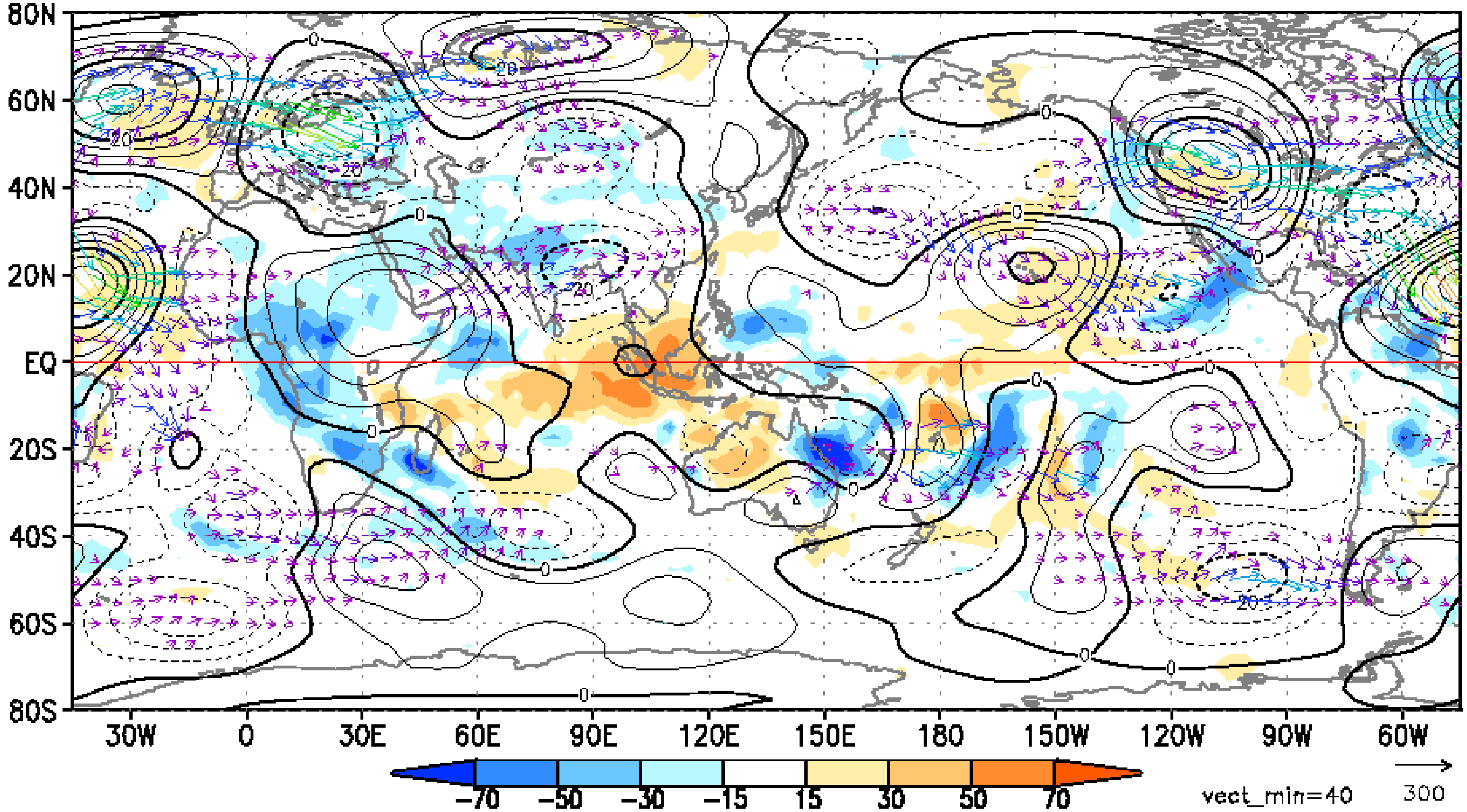
-70
-50
-30
-15
15
30
50
70
vect_min=40
300

1.21 – 1.25


80N
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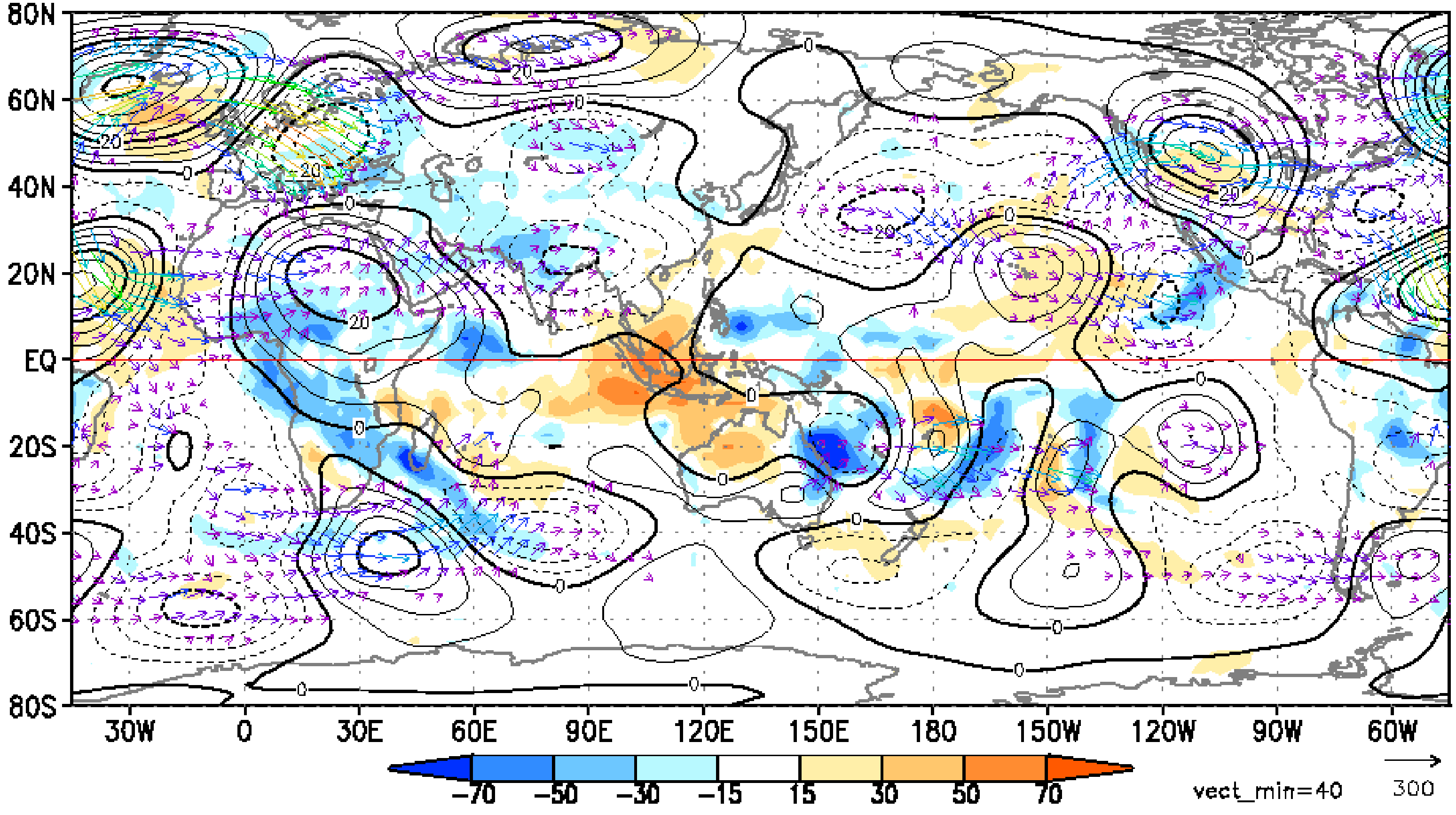
90W
60W
-70
-50
-30
-15
15
30
50
70
vect_min=40
300

1.22 – 1.26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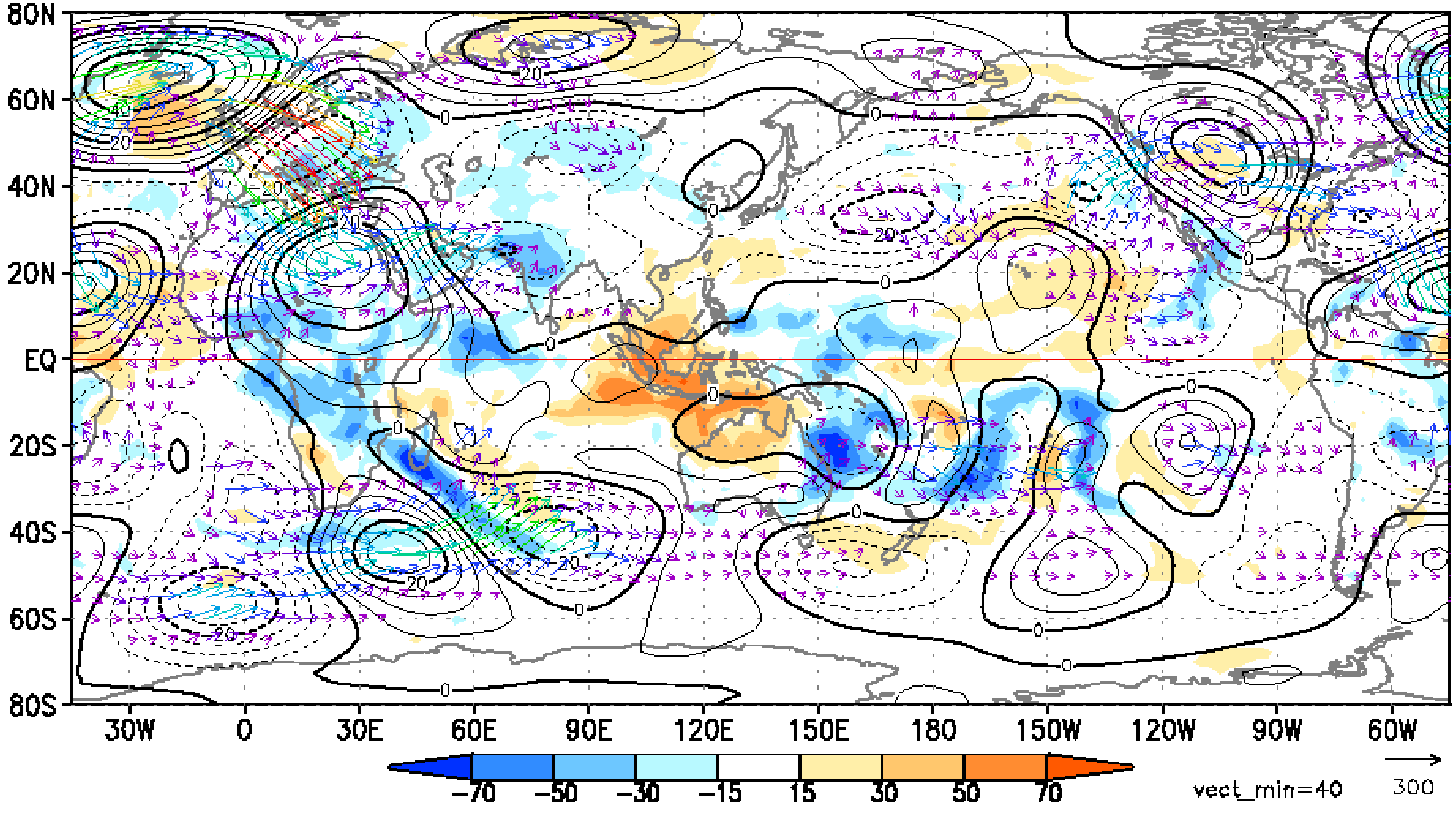
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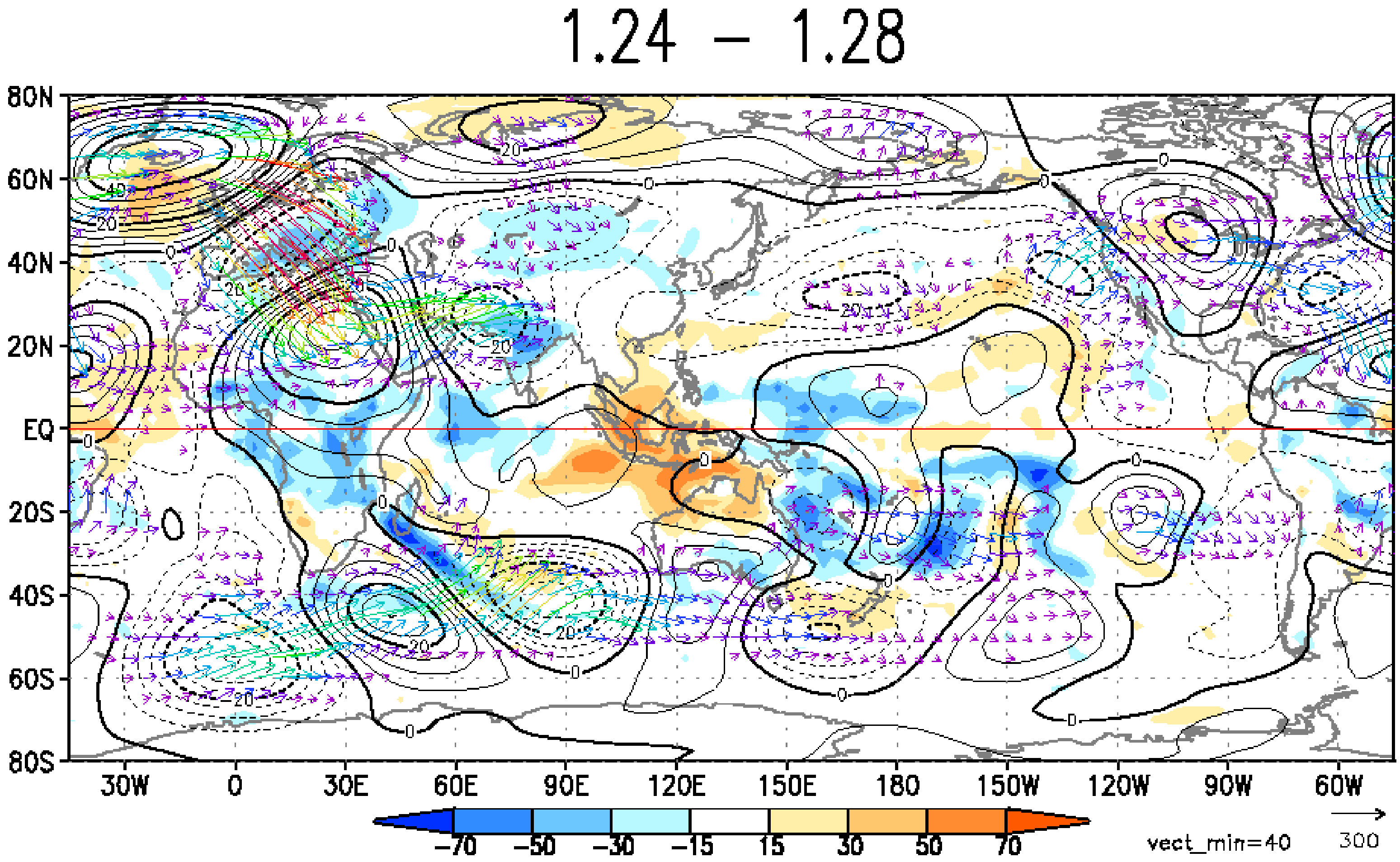

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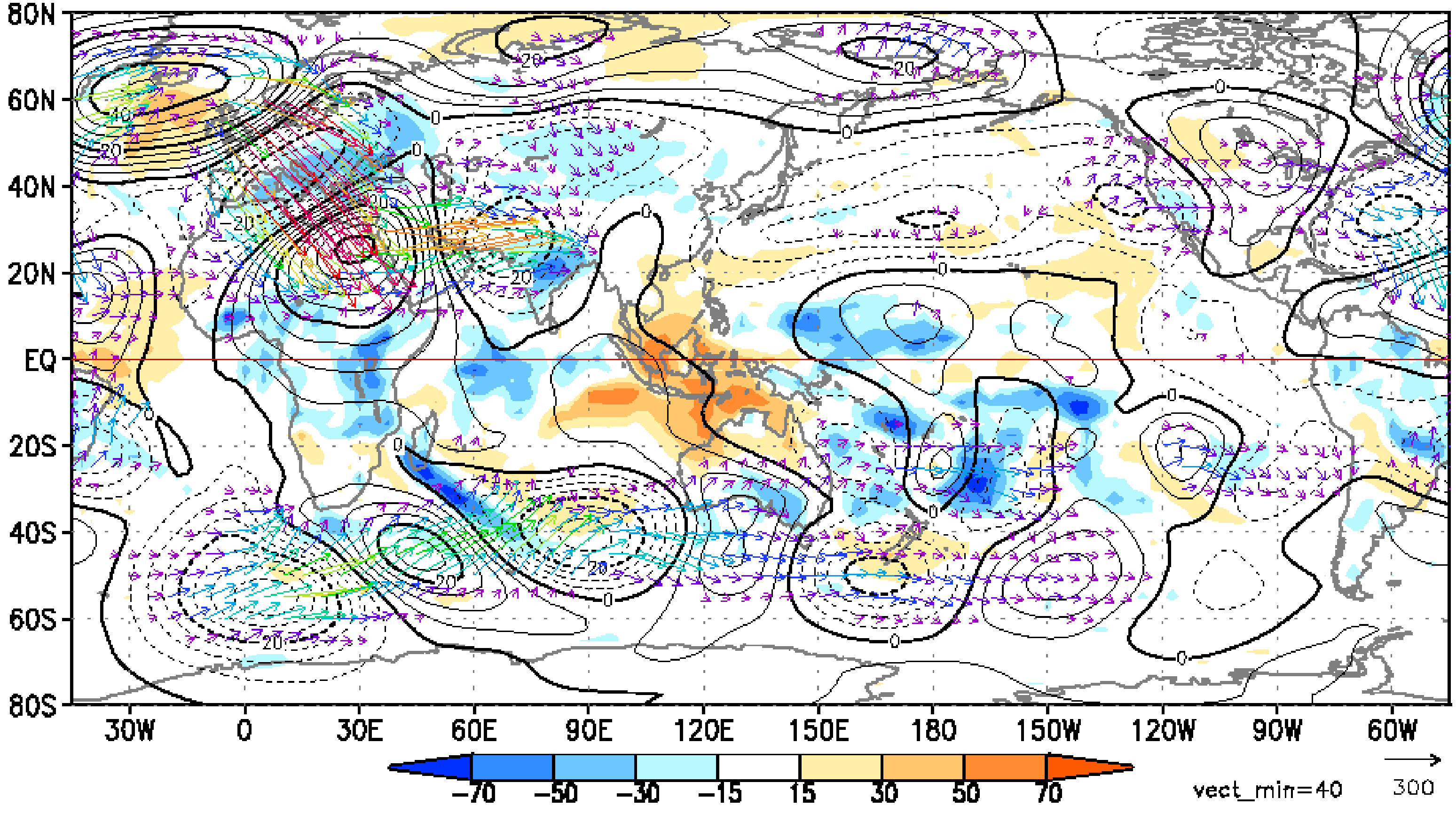

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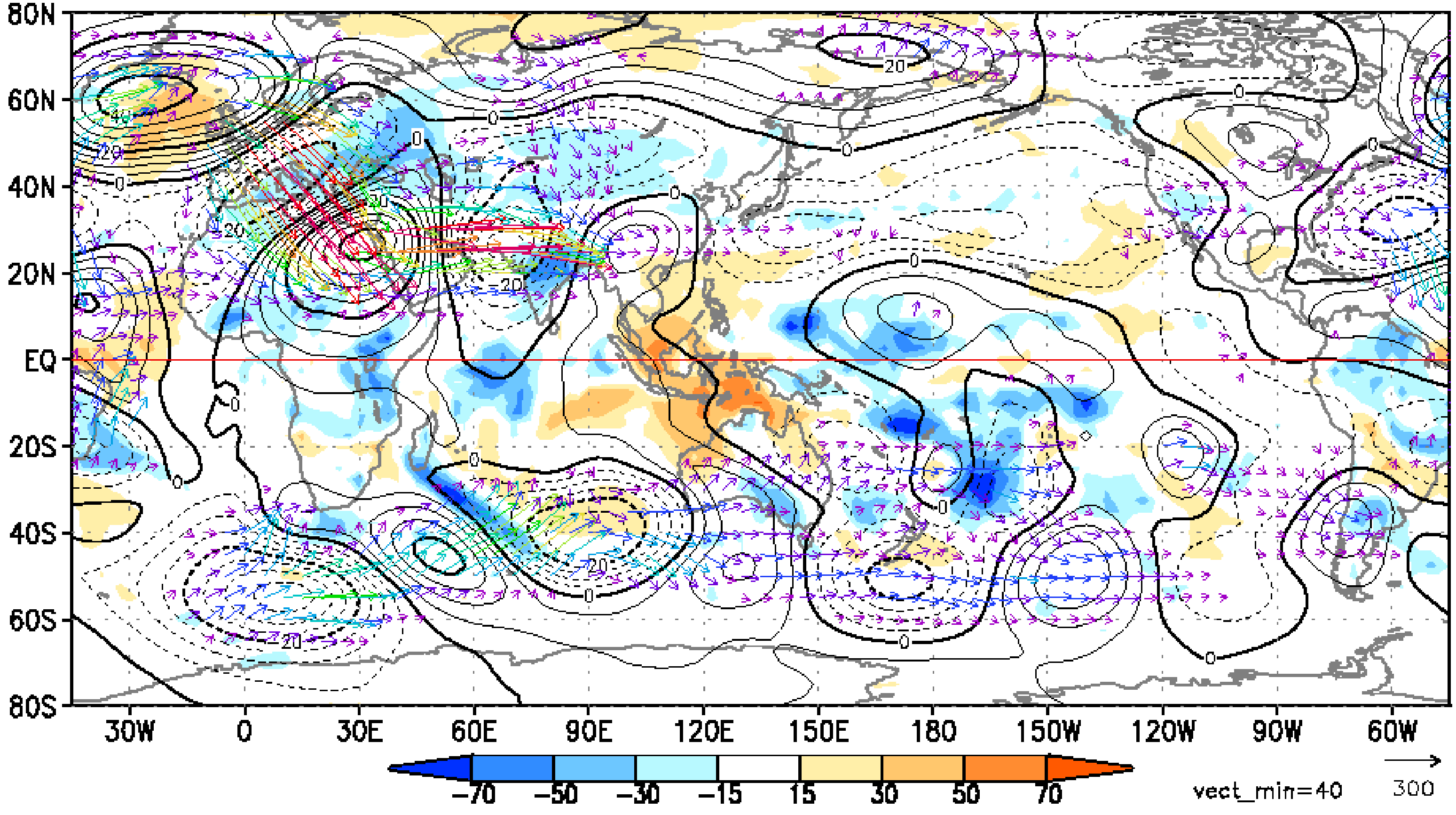

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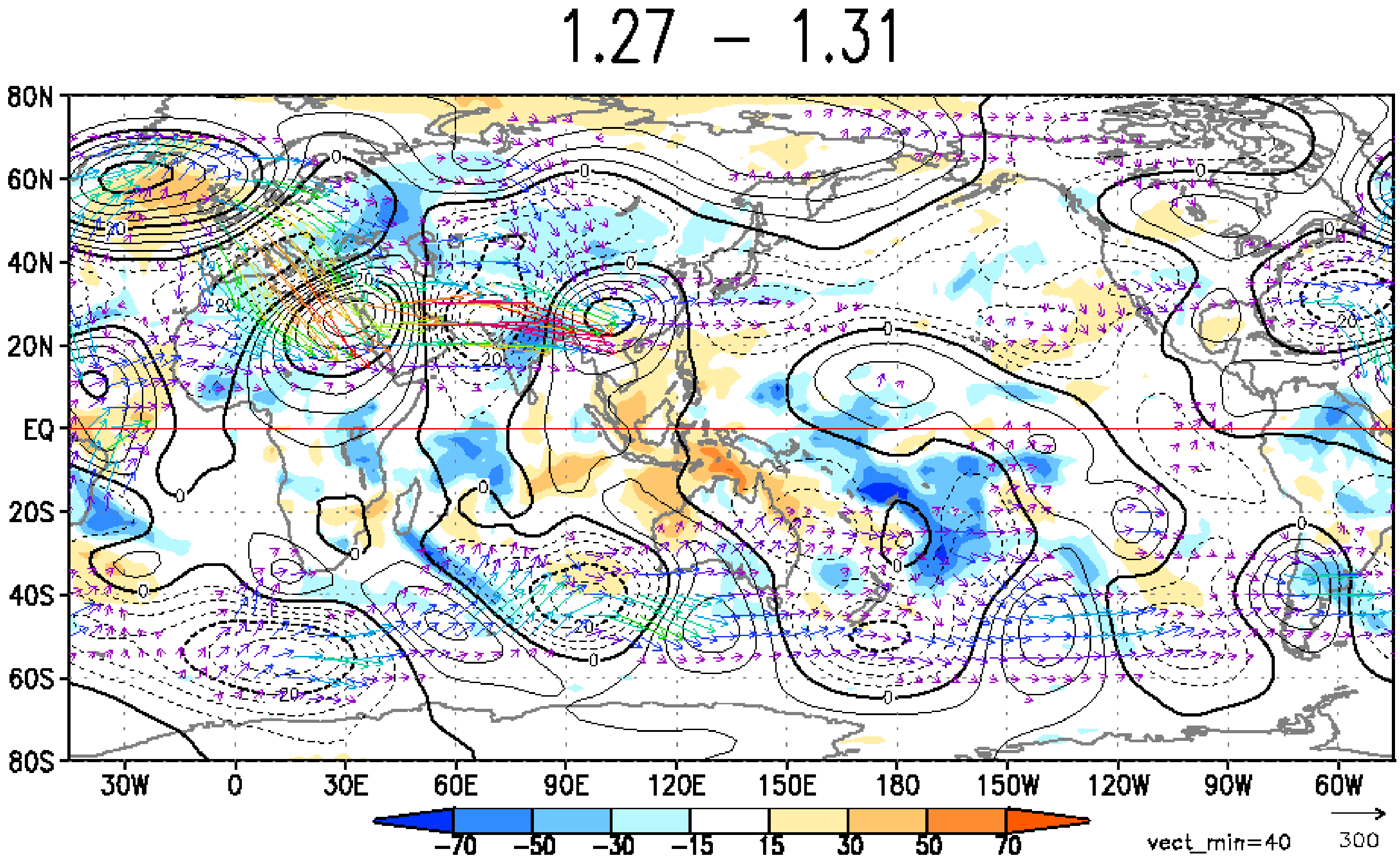
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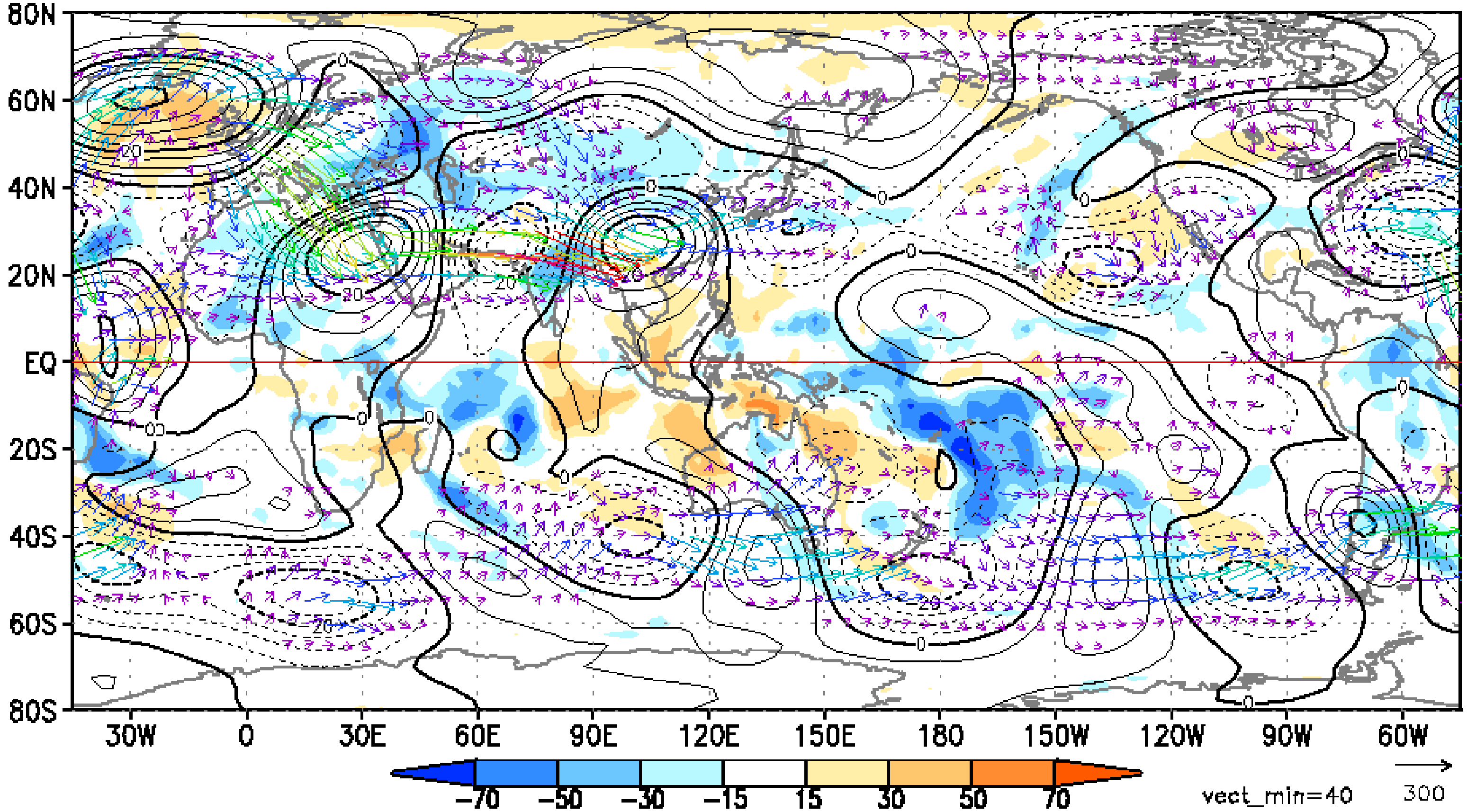
1.28 – 2.1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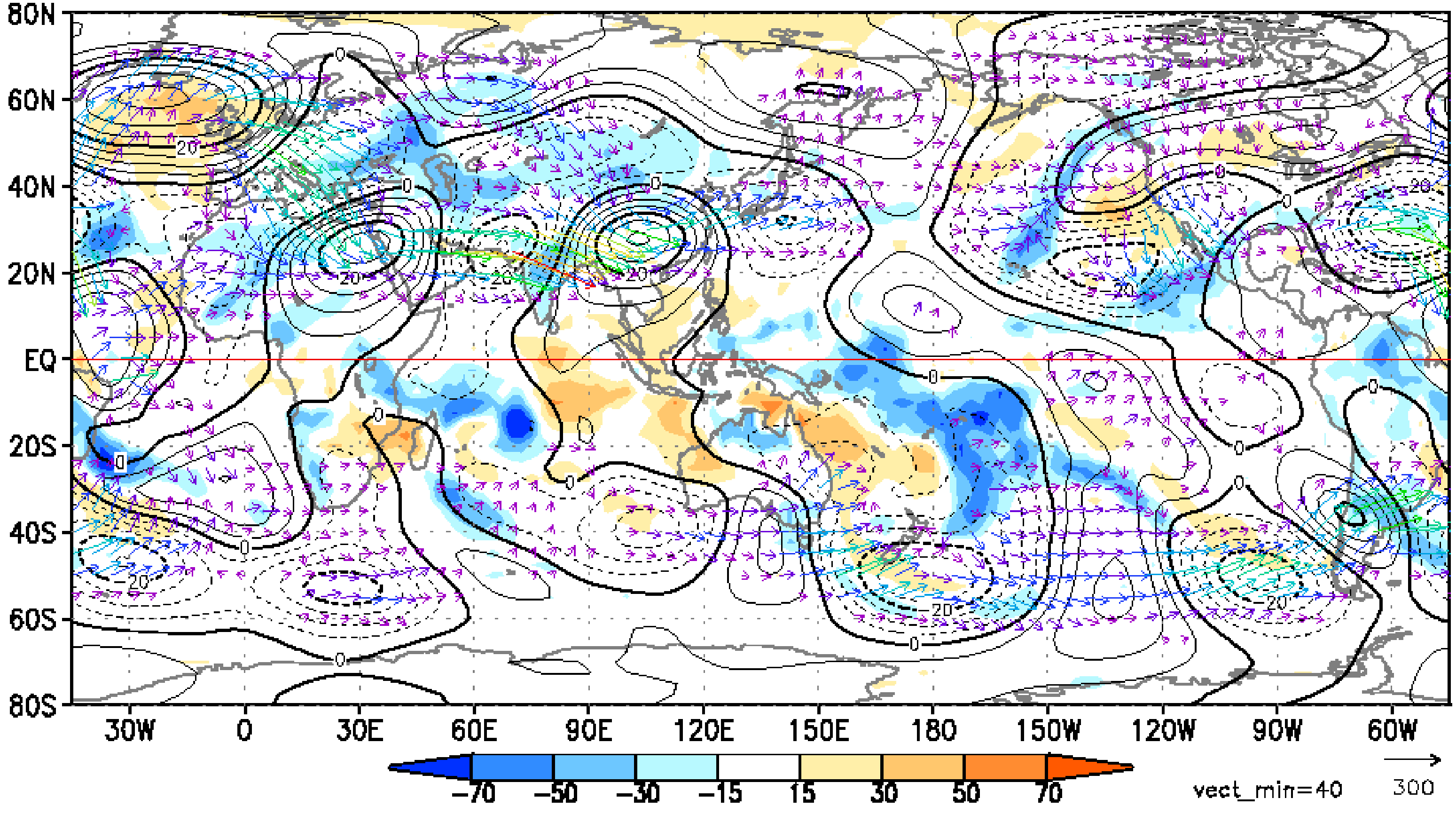
1.29 - 2.2



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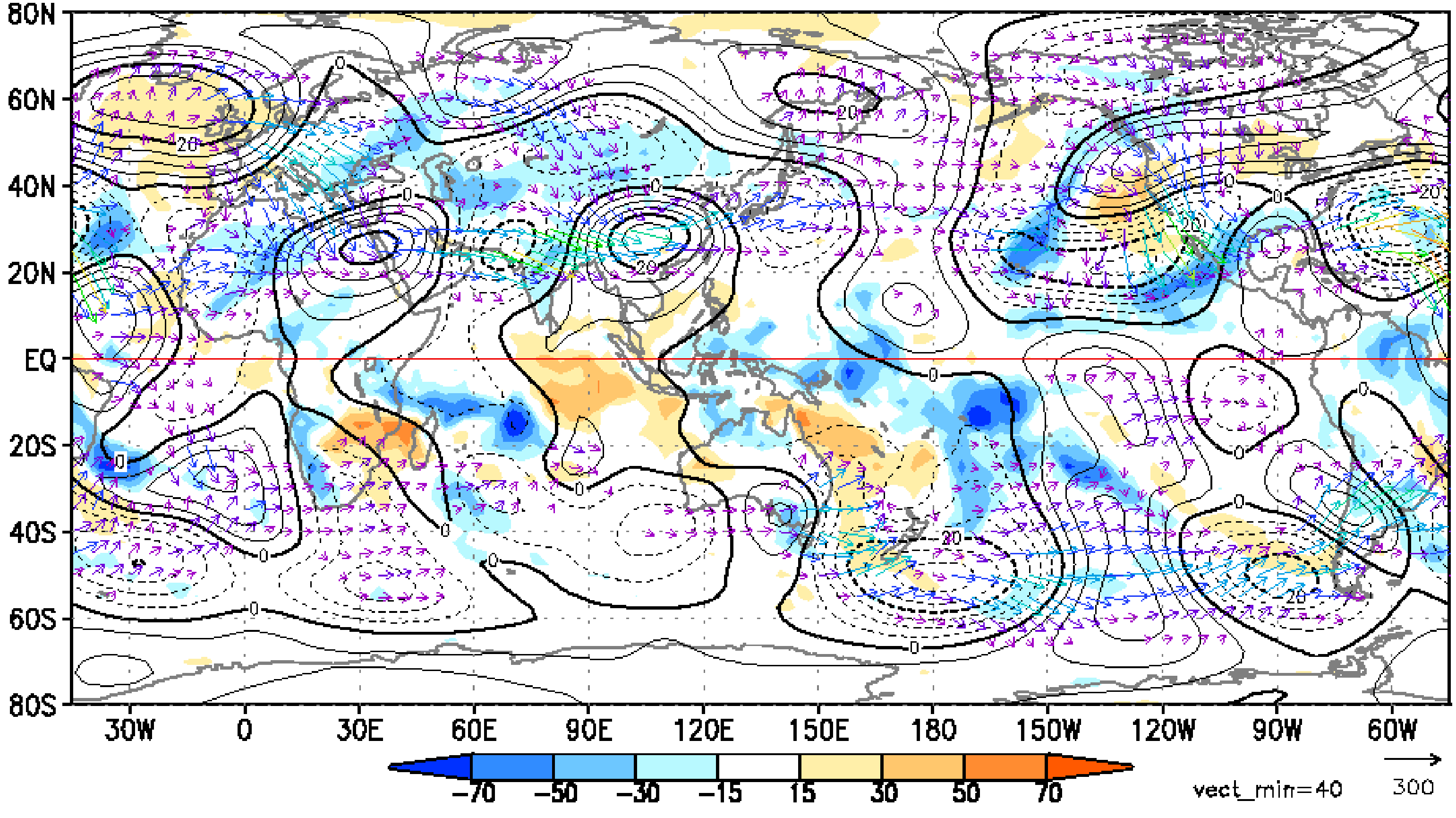
1.30 – 2.3



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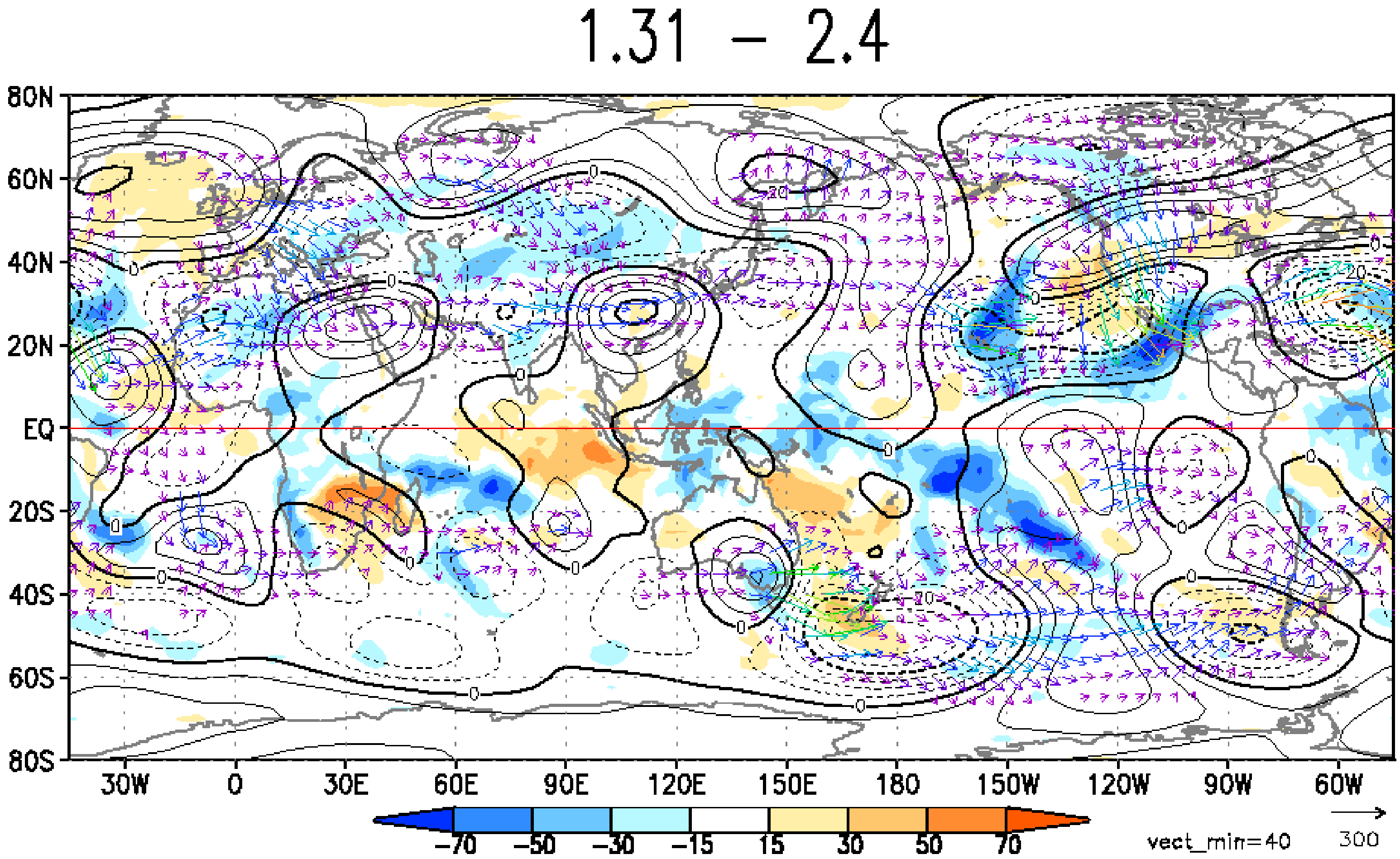
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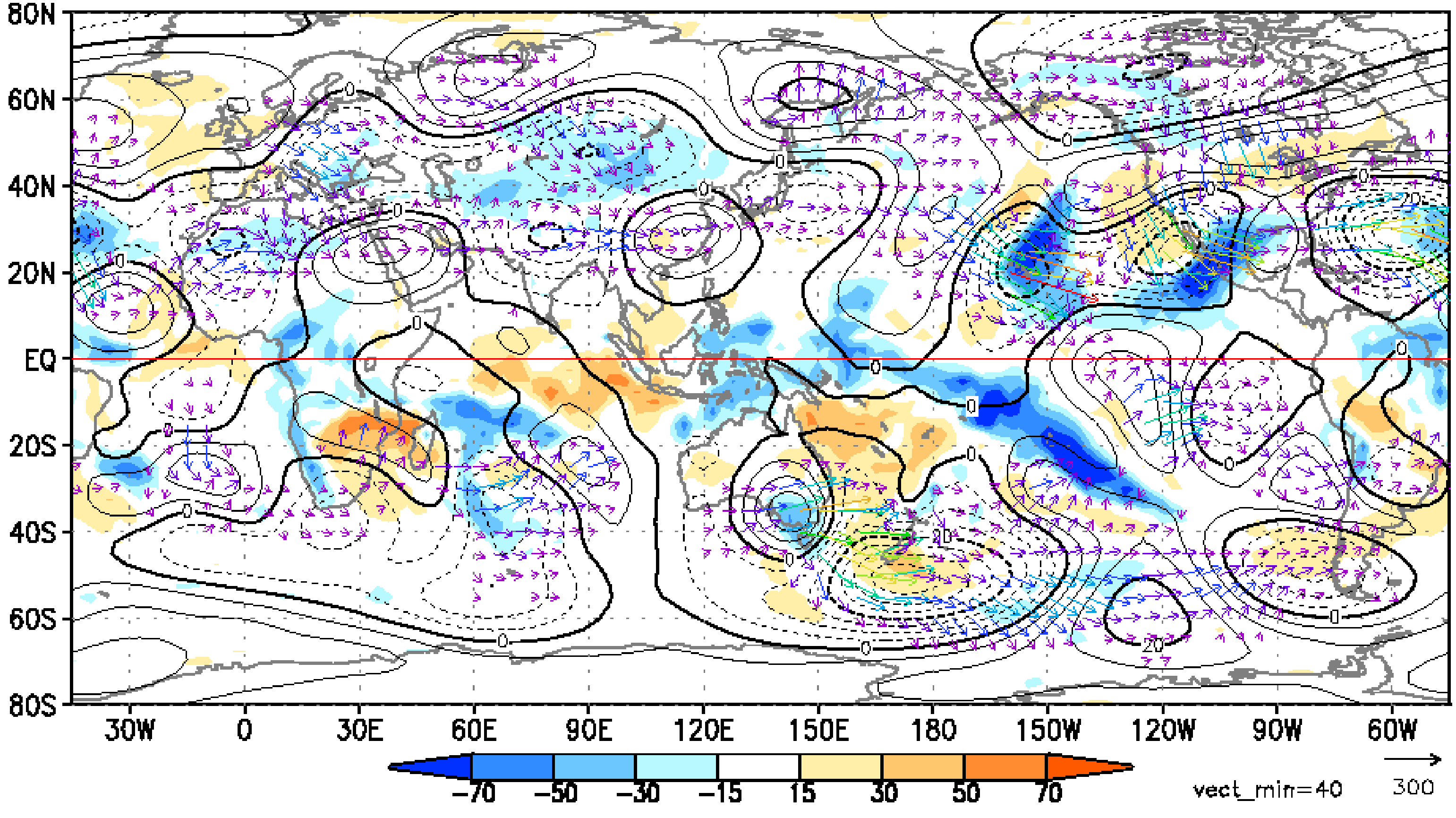
2.1 – 2.5



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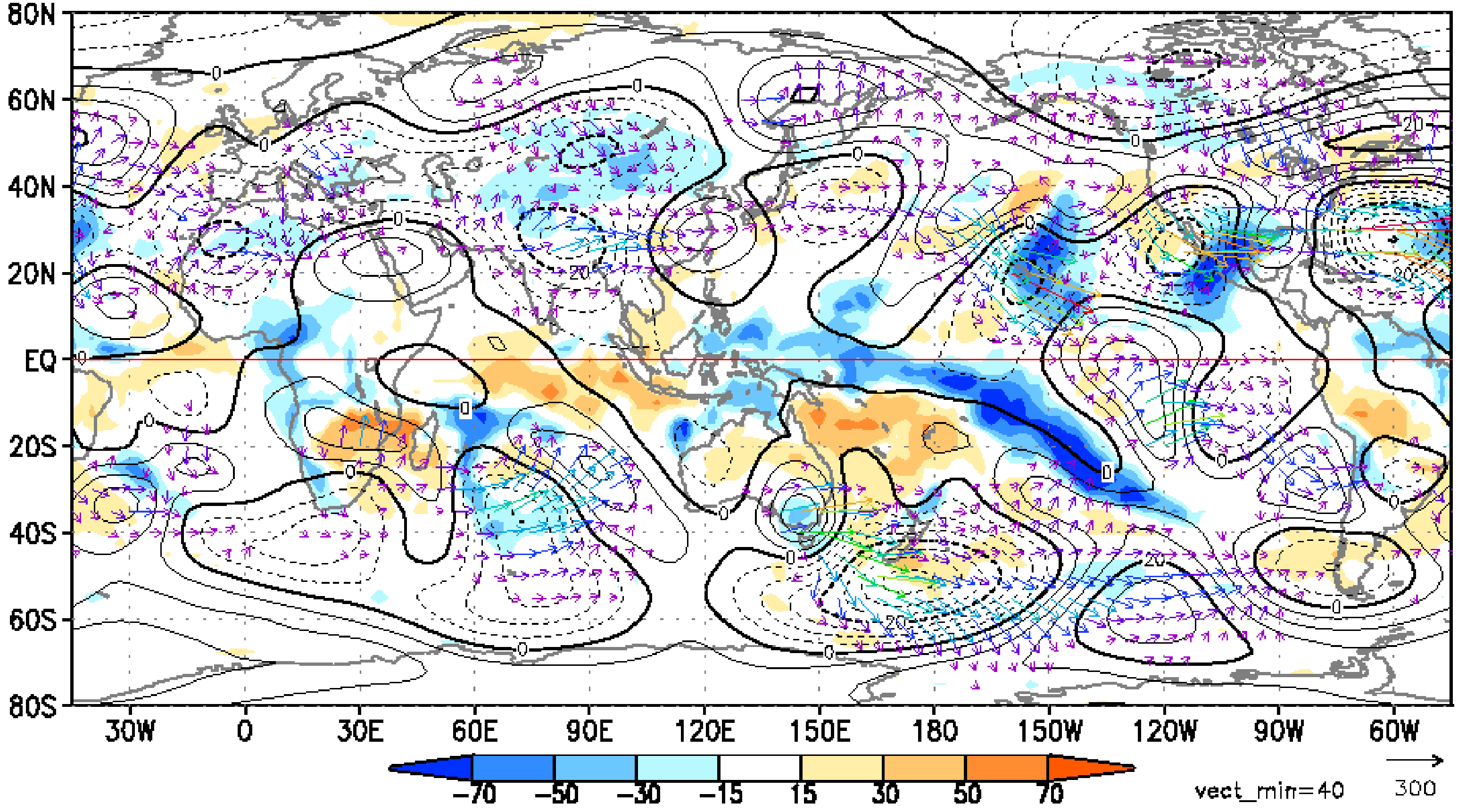
2.2 – 2.6



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vect_min=40
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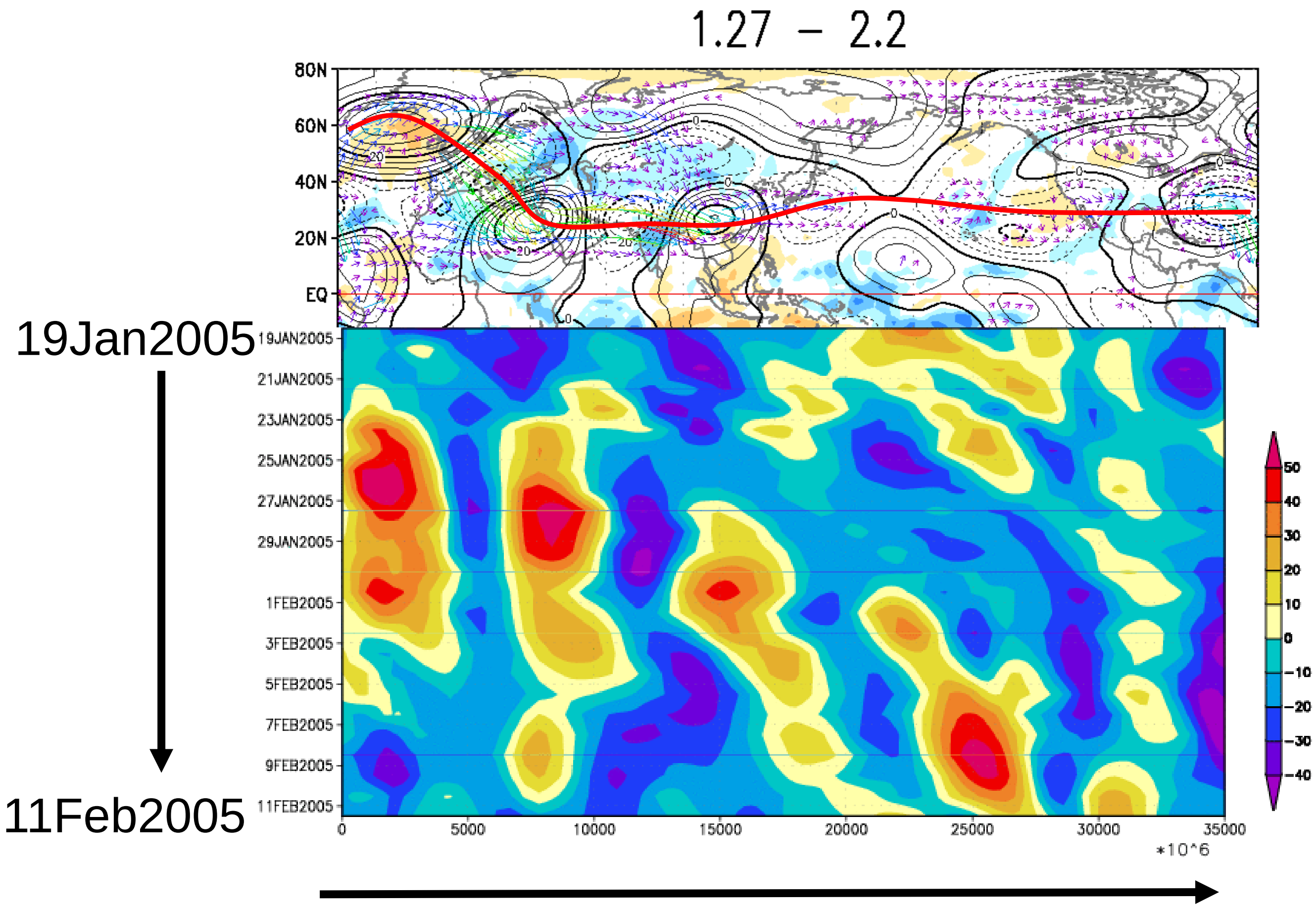
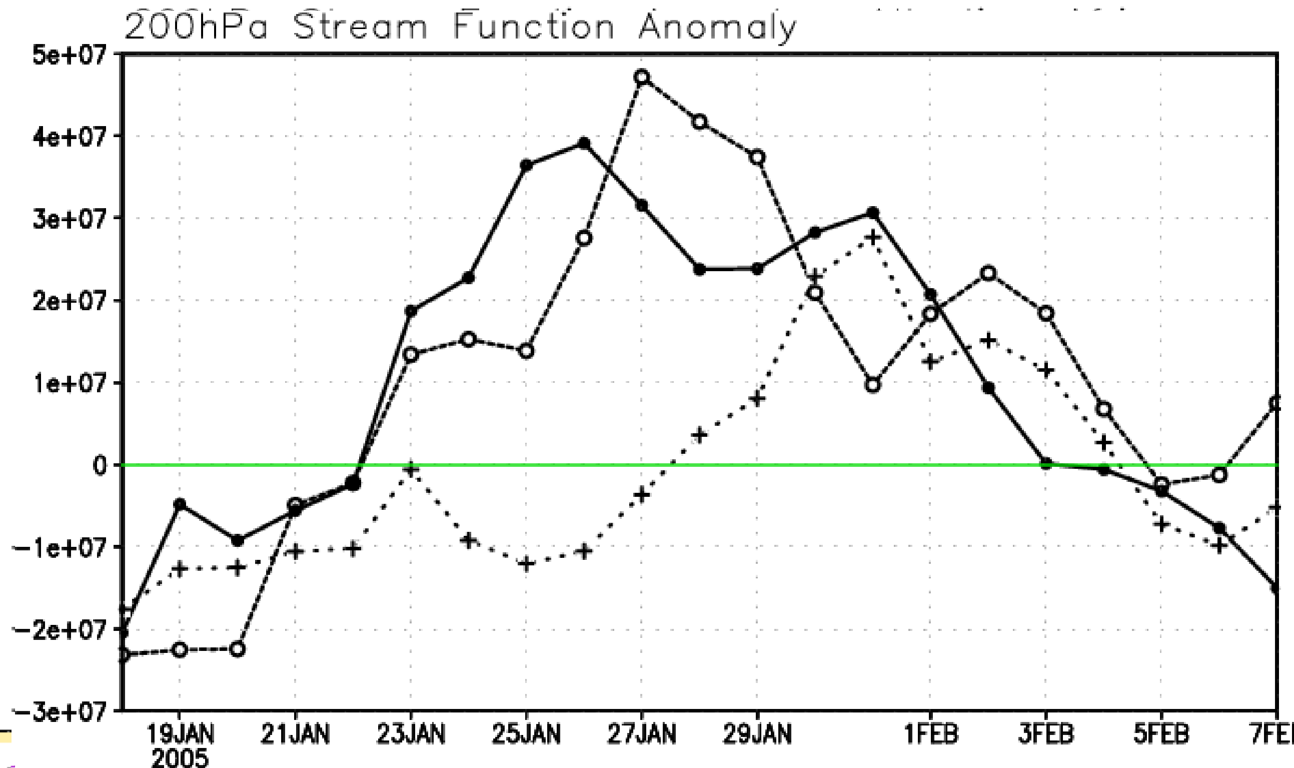
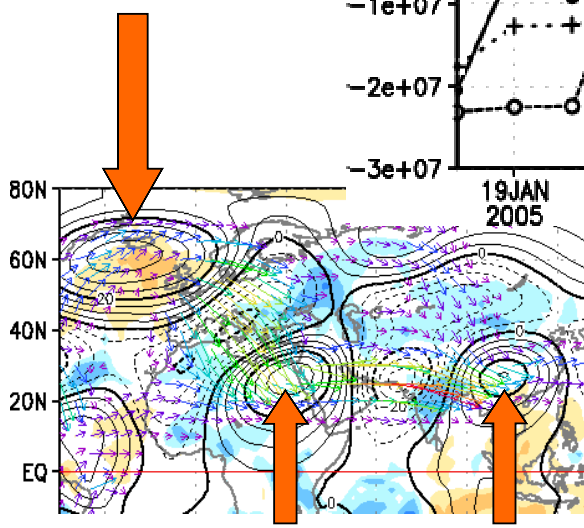
Blocking over the North Atlantic and Rossby wave trains along the Asian jet

Time cross section of stream function anomalies at 200hPa
x-axis : distance along the red line from a base point (60W,60N)



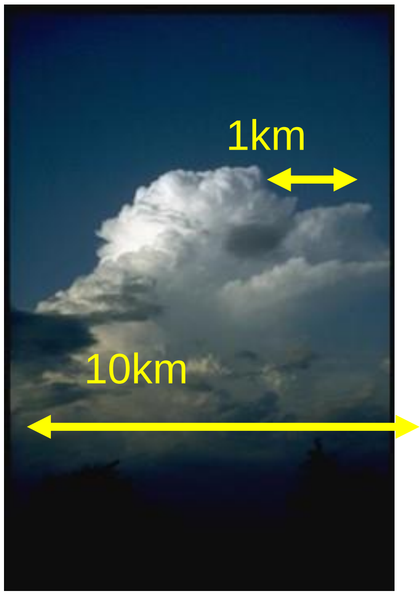
Decay of Blocking due to Rossby wave radiation

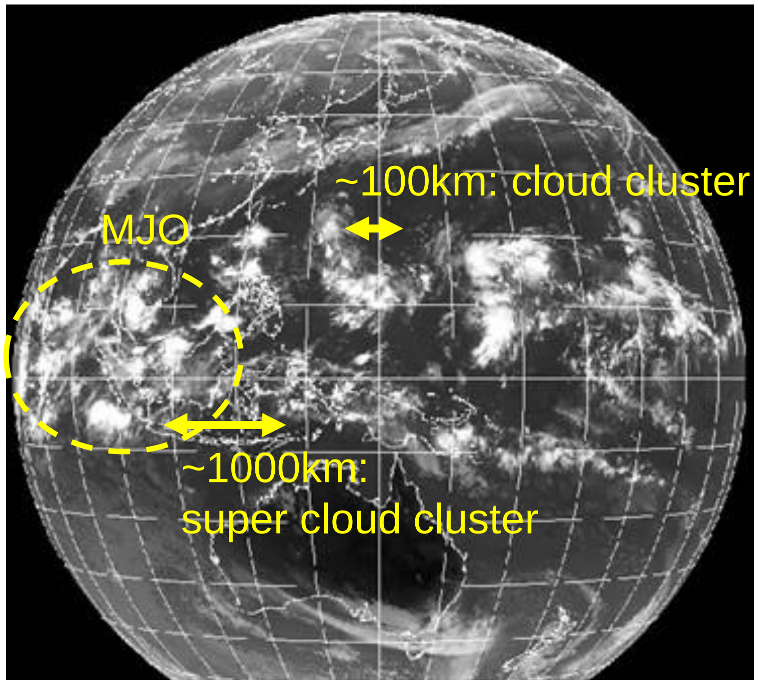




Madden-Julian Oscillation (MJO) and equatorial waves

Multi-scale clouds in the tropics



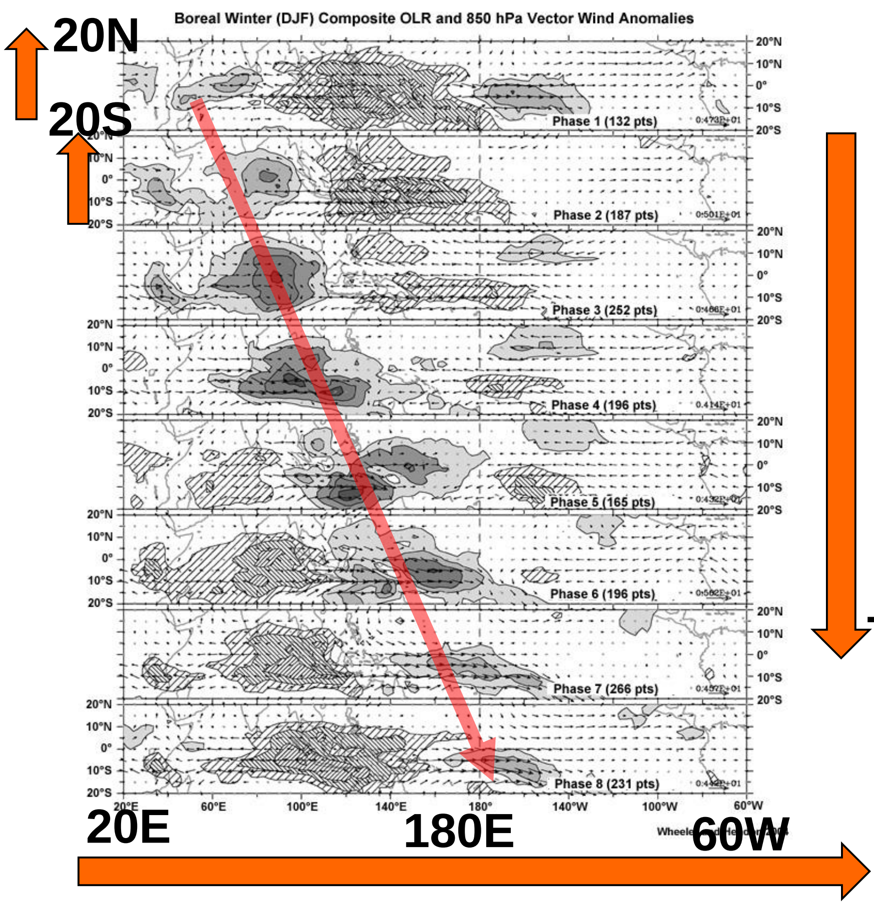


Outgoing Longwave Radiation (OLR) from MTSAT JMA at 00 UTC Oct. 5, 2005

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

Madden-Julian Oscillation (MJO)

DJF composite OLR anomaly (shading ; ΔOLR < 0)



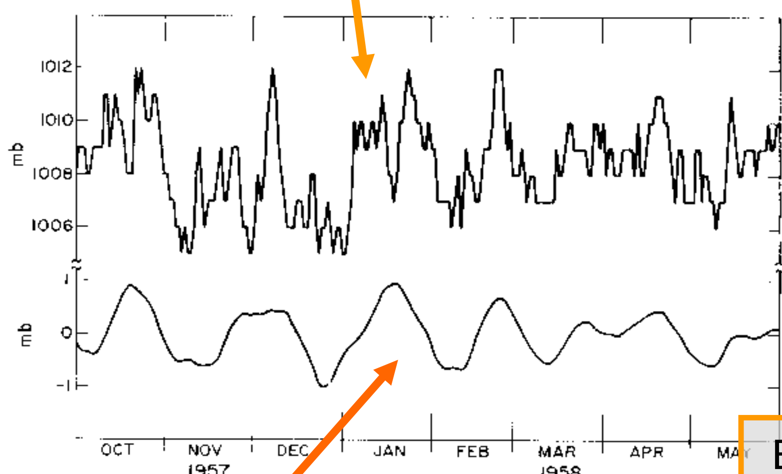
A broad area of active cloud and rainfall propagates eastwards around the equator at intervals of between about 30-60 days.

8 phases

Wheeler and Hendon(2004)

Madden-Julian Oscillation (MJO)

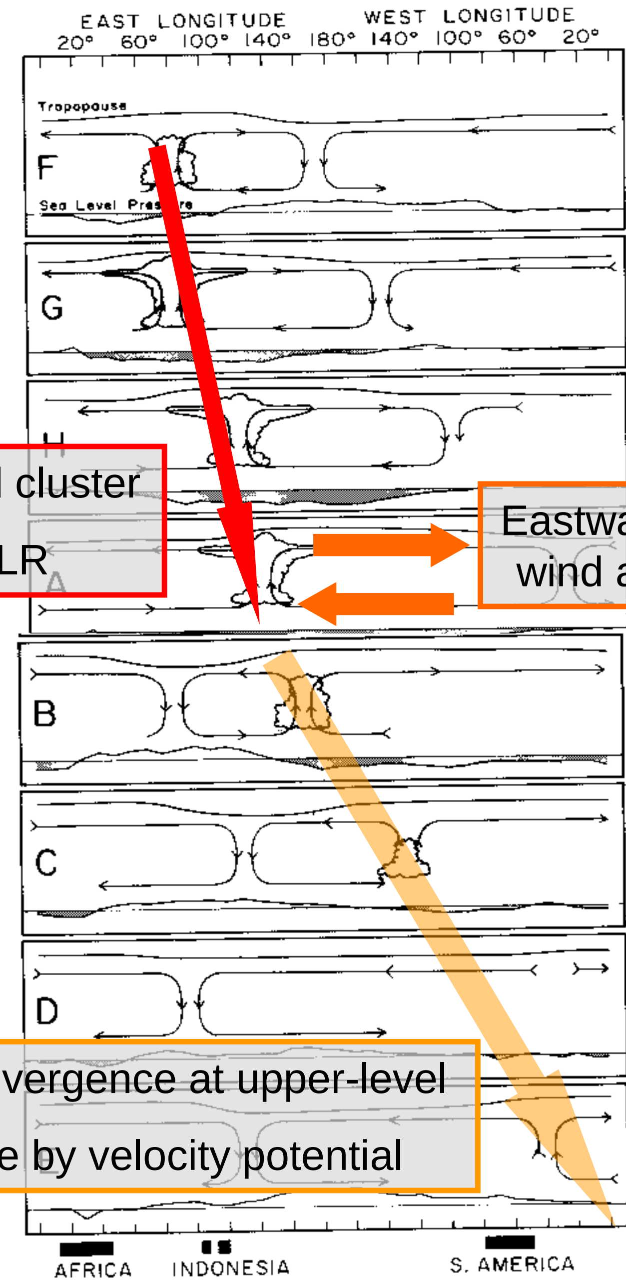
Surface pressure at Canton Iceland (3S, 172W)



10月 12月 2月 4月

After applying band-pass filter around 45 days

Eastward super cloud cluster detectable by OLR



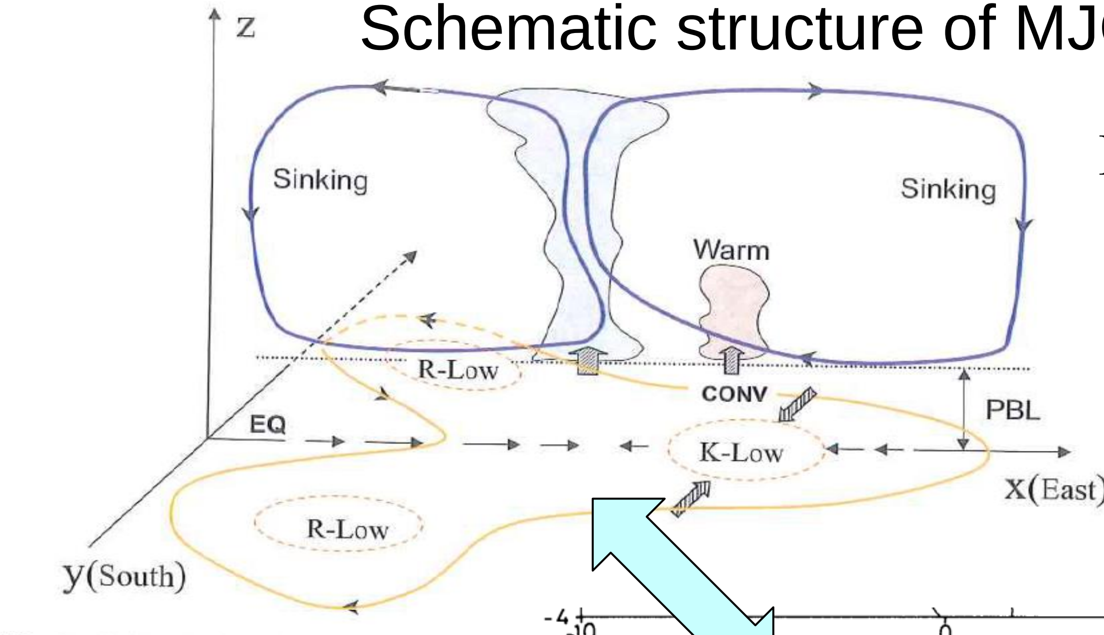
Eastward zonal wind anomaly

Eastward divergence at upper-level detectable by velocity potential

Madden and Julian (1972)

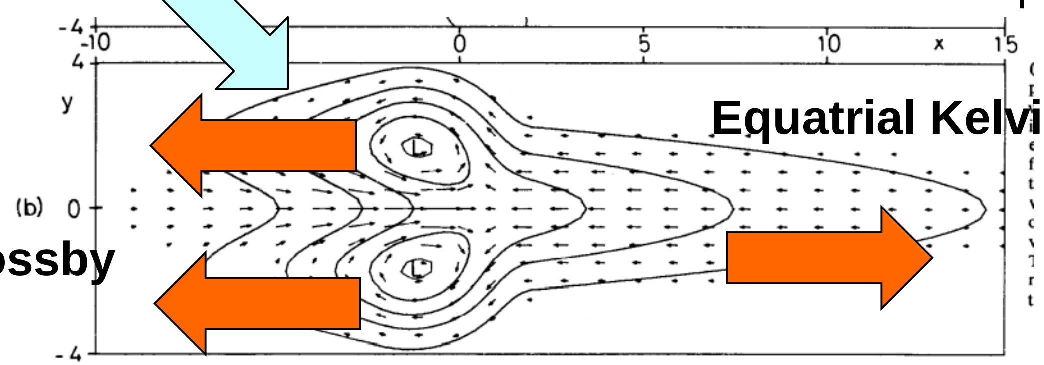
Madden-Julian Oscillation (MJO)

Schematic structure of MJO



From Wang (2005)

Linear theory of equatorial waves
shallow water equatorial β

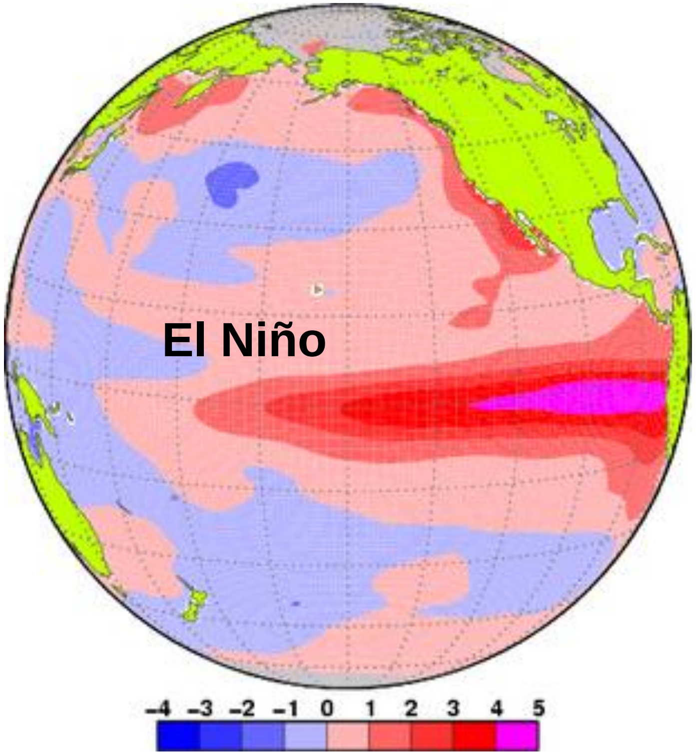


Equatrial Kelvin

Equatrial Rossby n=1

Gill (1980)

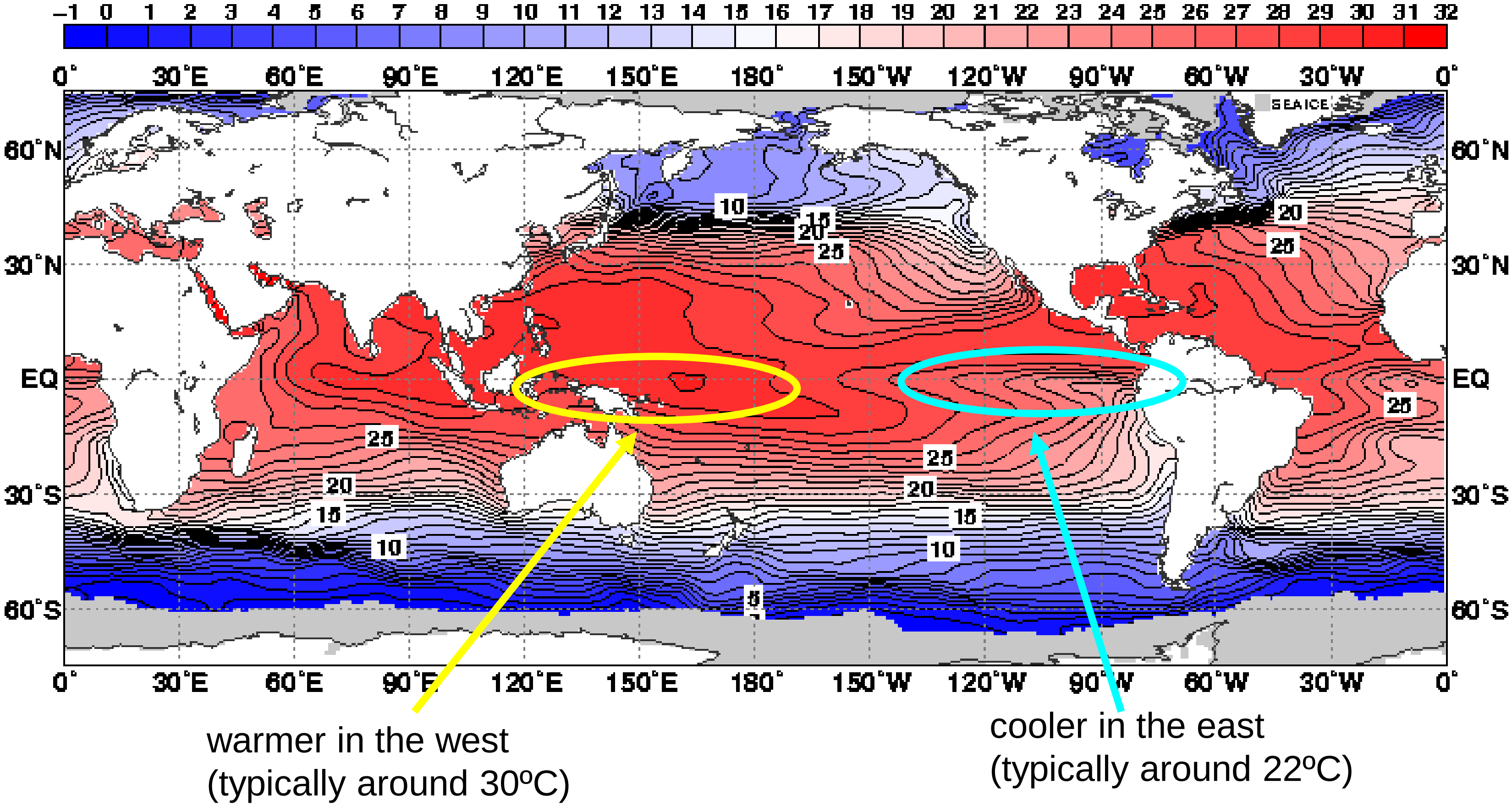
Interannual Variability
El Niño and Southern Oscillation (ENSO)



El Niño/La Niña is important !!

1. Predominant inter-annual climate variability
2. Big Impact on the world climate
3. Predictable with one or two seasons lead time

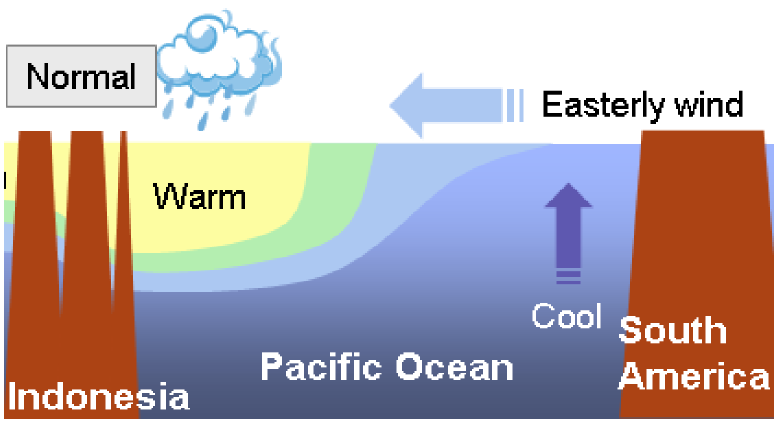
Sea surface temperature (SST)



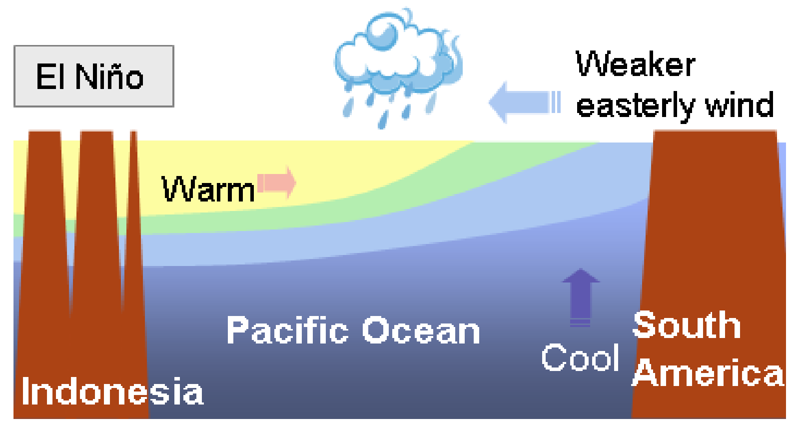
1-month mean sea surface temperature observed in July 2005 when the conditions in the equatorial Pacific Ocean stayed close to normal.

Atmosphere-ocean interaction during El Niño

Normal condition



El Niño condition



Warmer SST in the eastern Pacific → Eastward shift of active convection

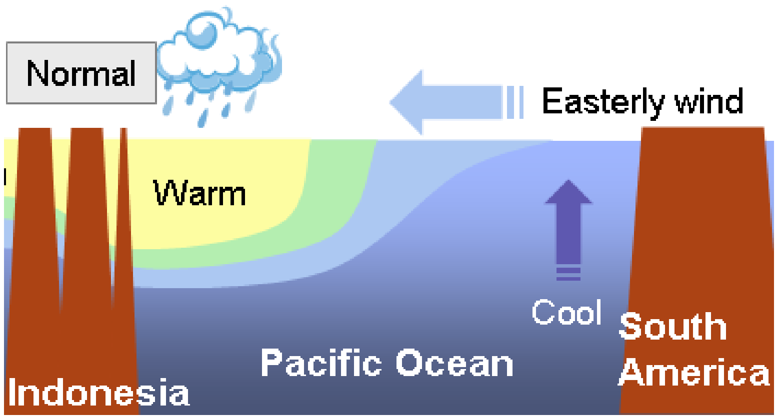
Eastward shift of active convection ↓ Weaker easterly trade wind

Weaker easterly trade wind → Eastward shift of warm water

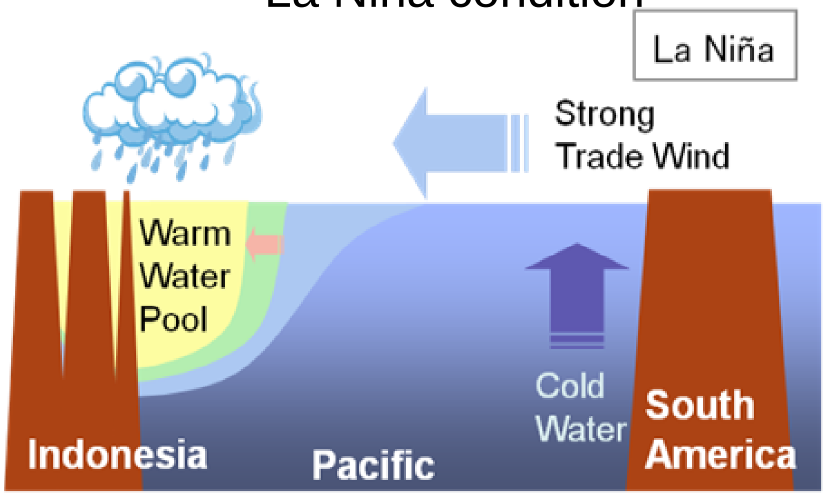
Eastward shift of warm water ↑ Warmer SST in the eastern Pacific

Atmosphere-ocean interaction during La Niña

Normal condition



La Niña condition



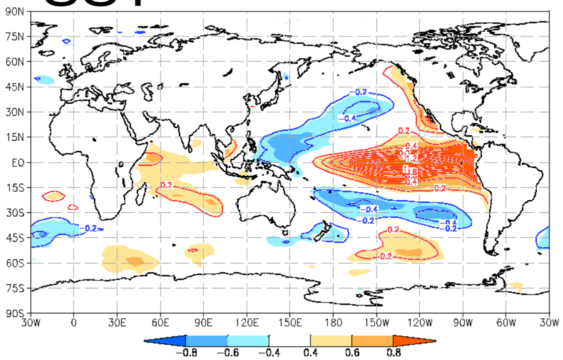
Colder SST in the eastern Pacific → Westward shift of active convection

↑ ↓

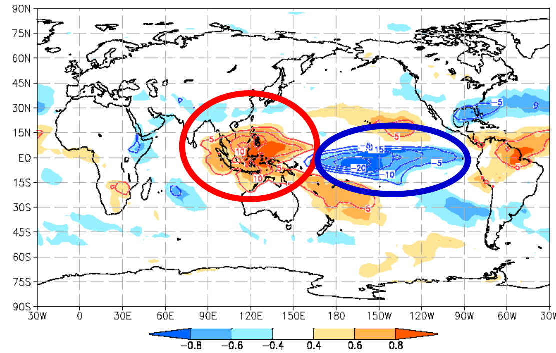
Westward shift of warm water ← Stronger easterly trade wind

Statistical relationship between NINO.3 and atmospheric circulation fields in DJF

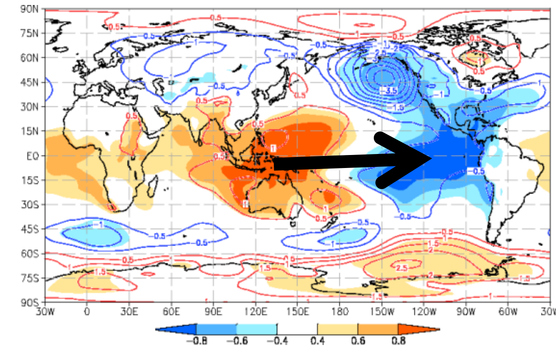
SST



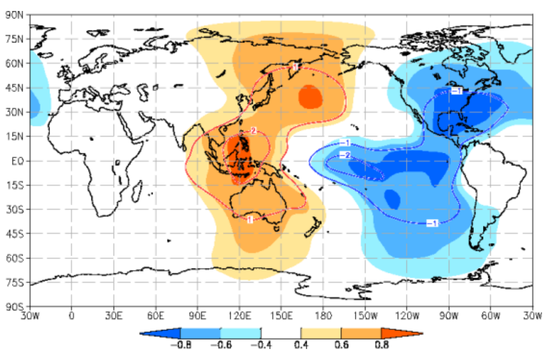
OLR



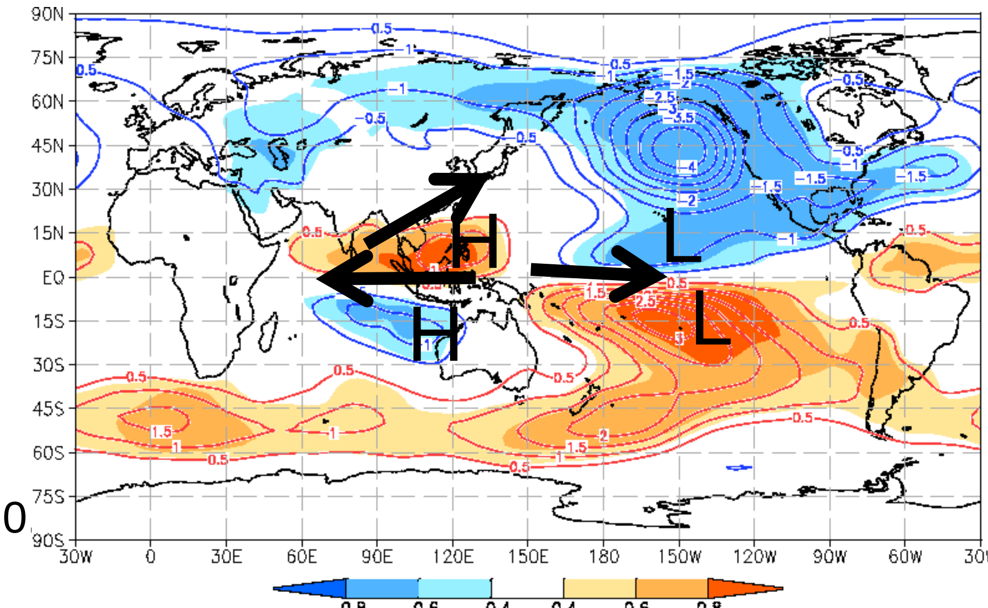
Sea Level Pressure



Velocity Potential at 200hPa



Stream Function at 850hPa

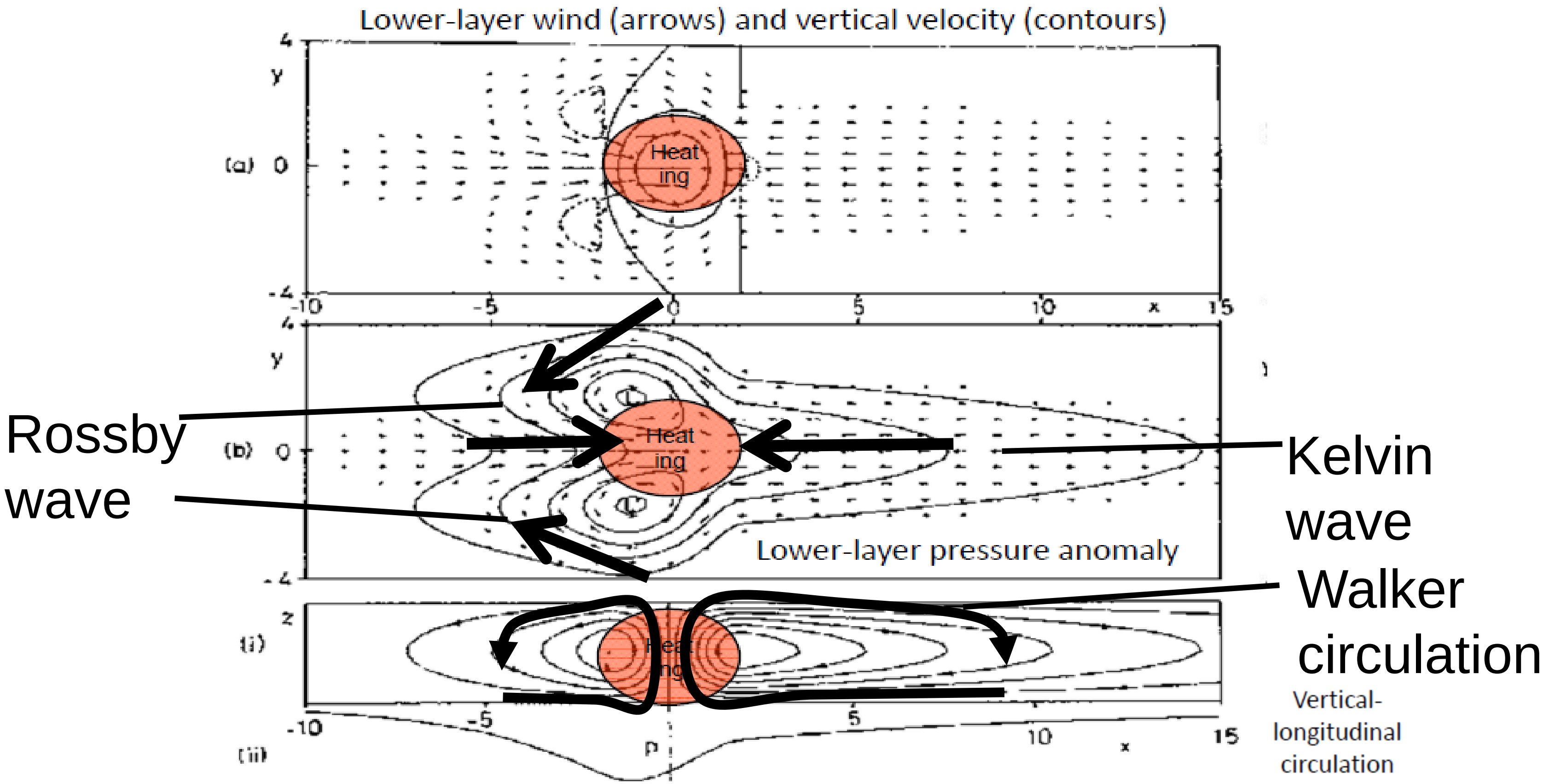


Contours show atmospheric circulation anomalies when normalized NINO.3 is+1.0
Shadings show correlation coefficients.

Some simple solutions for heat-induced tropical circulation

Quarterly Journal of the Royal Meteorological Society
Volume 106, Issue 449, July 1980, Pages: 447–462, A. E. Gill

Symmetric Heating Anomaly about the equator



Lingering impacts of ENSO through change in SST in Tropical Indian Ocean (TIO)

SST in TIO tends to raise associated with El Nino with one-season lag

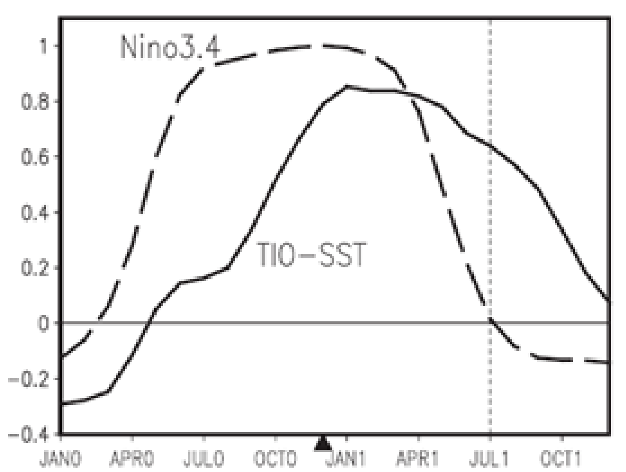
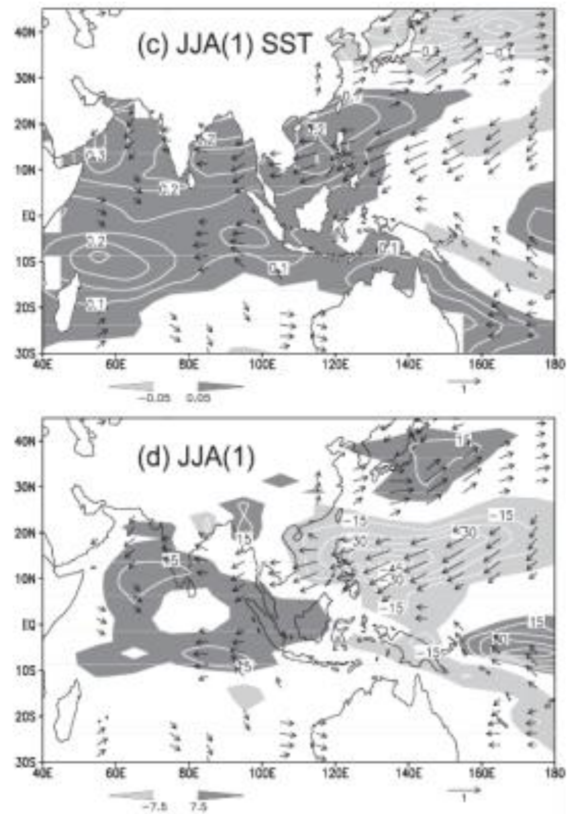


Fig. 1. Correlation of tropical Indian Ocean (40-100°E, 20°S-20°N) SST (solid) with the Nino3.4 (170°W-120°W, 5°S-5°N) SST index for Nov(0)-Dec(0)-Jan(1). Numerals in parentheses denote years relative to El Nino: 0 for its developing and 1 for decay year. The dashed curve is the Nino3.4 SST auto-correlation as a function of lag. The black triangle denotes Dec(0), the peak phase of ENSO.

Warm SST in TIO has impact on atmospheric circulation in Asia Pacific region in JJA



Precipitation anomaly (mm/month)

Xie et al.(2009)

El Niño Modoki & CP El Niño

Nature,2009

The El Niño with a difference

Karumuri Ashok and Toshio Yamagata

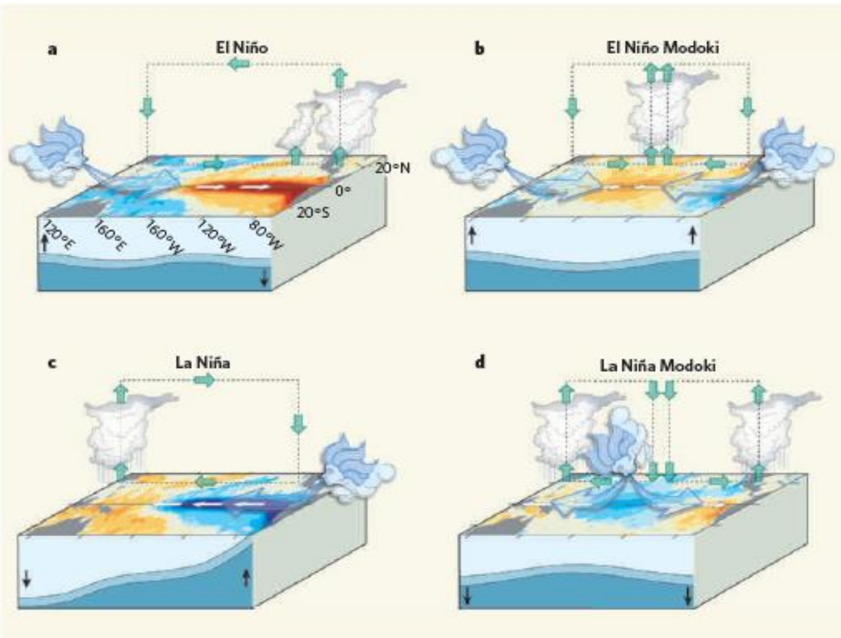


Figure 2 | Anomalous conditions in the tropical Pacific. a, An El Niño event is produced when the easterly winds weaken; sometimes, in the west, westerlies prevail. This condition is categorized by warmer than normal sea surface temperatures (SSTs) in the east of the ocean, and is associated with alterations in the thermocline and in the atmospheric circulation that make the east wetter and the west drier. **b,** An El Niño Modoki event is an anomalous condition of a distinctly different kind. The warmest SSTs occur in the central Pacific, flanked by colder waters to the east and west, and are associated with distinct patterns of atmospheric convection. **c, d,** The opposite (La Niña) phases of the El Niño and El Niño Modoki respectively. Yeh *et al.*[3] argue that the increasing frequency of the Modoki condition is due to anthropogenic warming, and that these events in the central Pacific will occur more frequently if global warming increases.

Nature,2009

El Niño in a changing climate

Sang-Wook Yeh[1], Jong-Seong Kug[1], Boris Dewitte[2], Min-Ho Kwon[3], Ben P. Kirtman[4] & Fei-Fei Jin

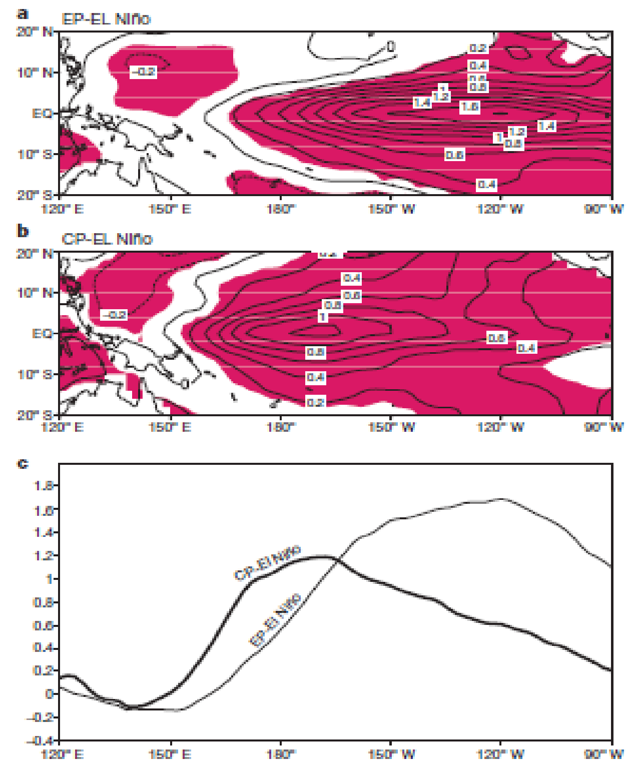
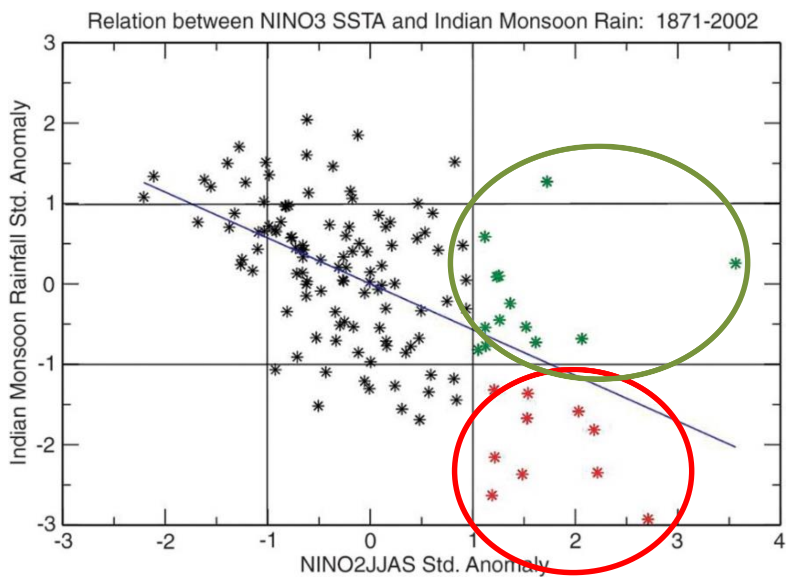


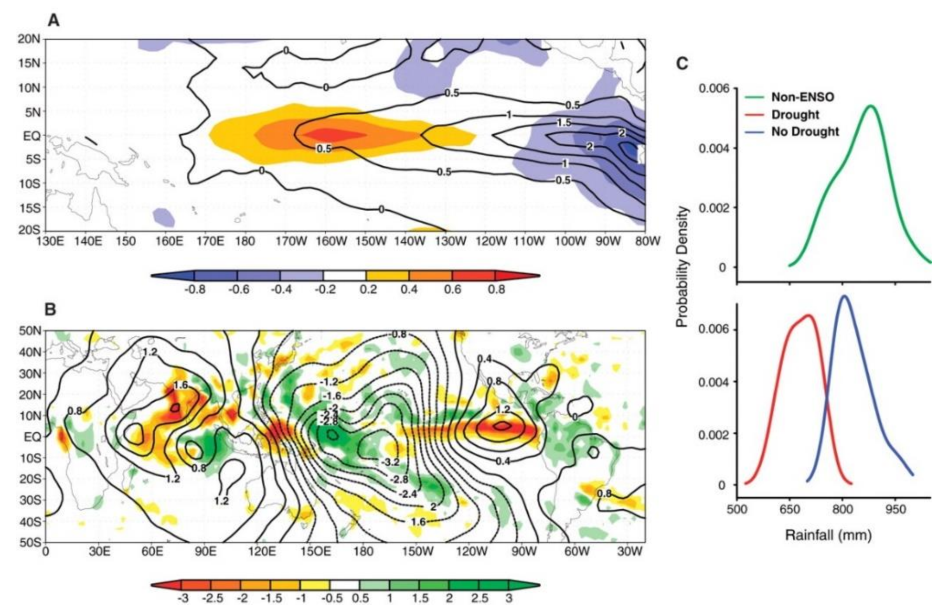
Figure 1 | Deviations of mean SST for the two characteristics of El Niño from the 1854–2006 climatology. a, The EP-El Niño; **b,** the CP-El Niño. The contour interval is 0.2 °C and shading denotes a statistical confidence at 95% confidence level based on a Student's *t*-test. **c,** The zonal structure for the composite EP-El Niño (thin line) and CP-El Niño (thick line) averaged over 2 °N to 2 °S.

ENSO-Monsoon relation

Severe droughts in India have always been accompanied by El Niño events. SST anomalies in the central equatorial Pacific are more effective in focusing drought-producing subsidence over India.



Plot of standardized, all-India summer [June to September (JJAS)] monsoon rainfall and summer NINO3 anomaly index. Severe drought and drought-free years during El Niño events (standardized NINO3 anomalies > 1) are shown in red and green, respectively.



(**A**) Composite SST difference pattern between severe drought (shaded) and drought-free El Niño years. Composite SST anomaly patterns of drought-free years are shown as contours. (**B**) Composite difference pattern between severe drought and drought-free years of velocity potential (contours) and rainfall (shaded). (**C**) PDF of all-India summer monsoon rainfall from severe-drought (red curve) and drought-free (blue curve) years associated with El Nino occurrence and from the non-ENSO years (green curve). SST and velocity potential composite differences are based on 1950 to 2004, rainfall composites are based on 1979 to 2004, and PDFs are based on 1873 to 2004.

Kumar et al.(2006)

A dipole mode in the tropical Indian Ocean

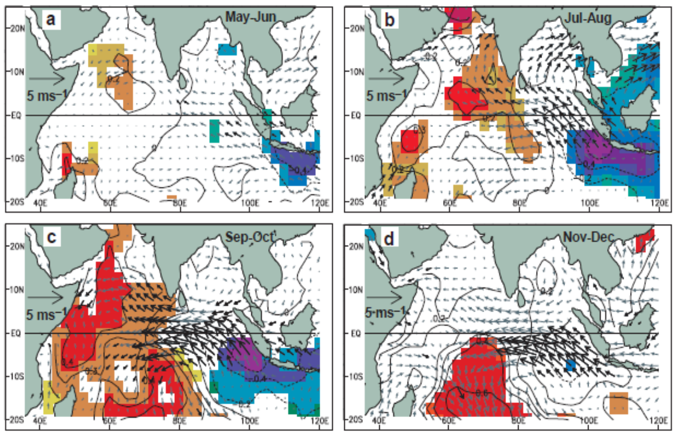


Figure 2 A composite dipole mode event. **a–d**, Evolution of composite SST and surface wind anomalies from May–June (**a**) to Nov–Dec (**d**). The statistical significance of the analysed anomalies were estimated by the two-tailed *t*-test. Ano exceeding 90% significance are indicated by shading and bold

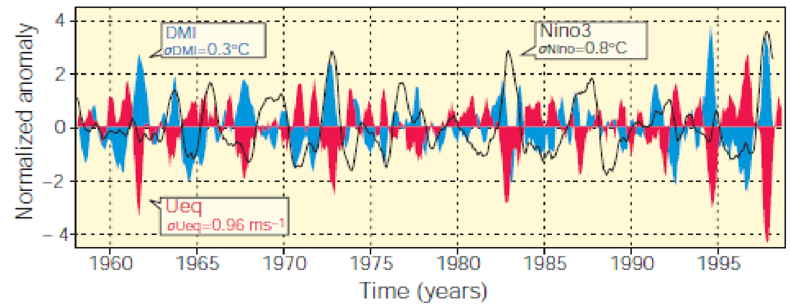
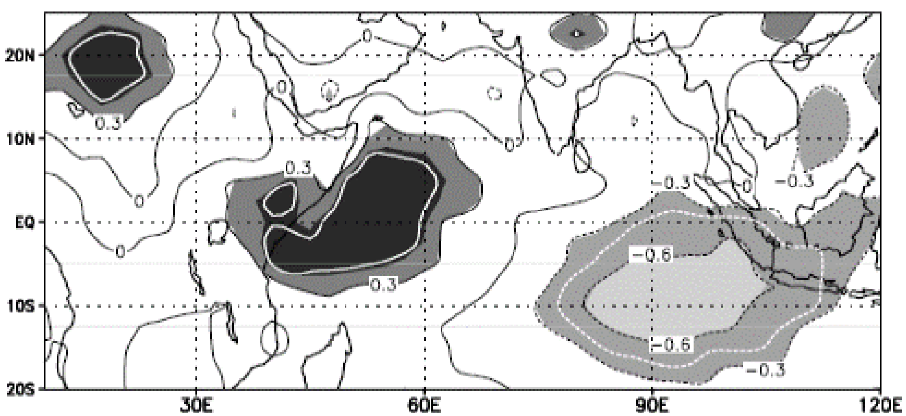


Figure 1 Dipole mode and El Niño events since 1958. Plotted in blue, the dipole mode index (DMI) exhibits a pattern of evolution distinctly different from that of the El Niño, which is represented by the Nino3 sea surface temperature (SST) anomalies (black line). On the other hand, equatorial zonal wind anomalies U_{eq} (plotted in red) coevolves with the DMI. All the three time series have been normalized by their respective standard deviations. We have removed variability with periods of 7 years or longer, based on harmonic analysis, from all the data sets used in this analysis. In addition, we have smoothed the time series using a 5-month running mean.



Saji et al., Nature 1999

Figure 4 Rainfall shifts northwest of the OTCZ during dipole mode events. The map correlates the DMI and rainfall to illustrate these shifts. The areas within the white curve exceed the 90% level of confidence for non-zero correlation (using a two-tailed *t*-test).

Indian Ocean Dipole mode

Possible Impacts of Indian Ocean Dipole model events on global climate

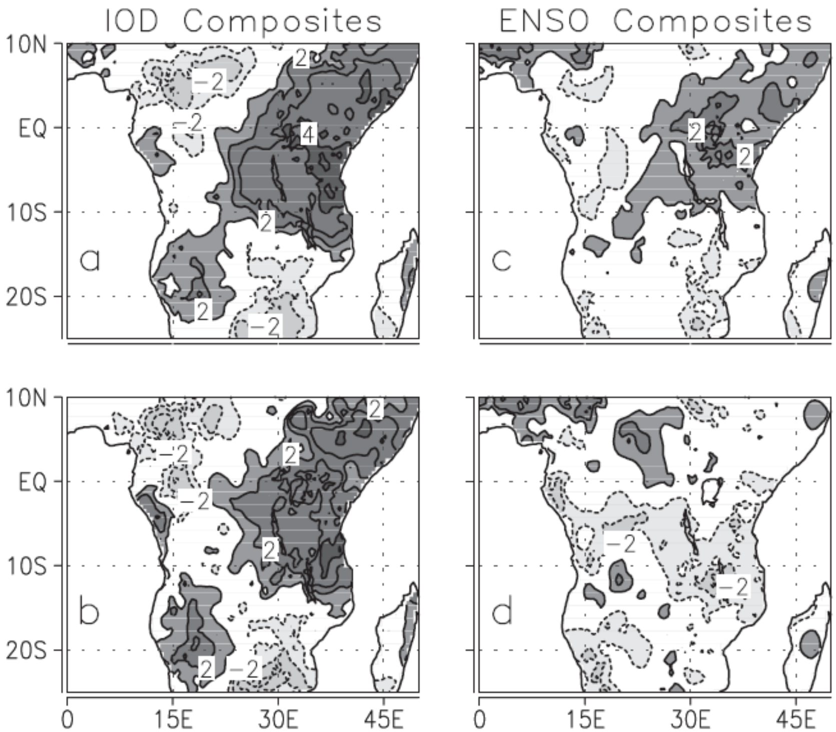


Fig. 1. Composite OND rain anomaly over Africa for (a) 19 IOD events, (b) 11 ENSO-independent IOD events, (c) 20 ENSO events and (d) 12 IOD-independent ENSO events. The composite anomaly was normalized by the standard deviation of rain during OND. Contours given at ±1, ±2, etc.

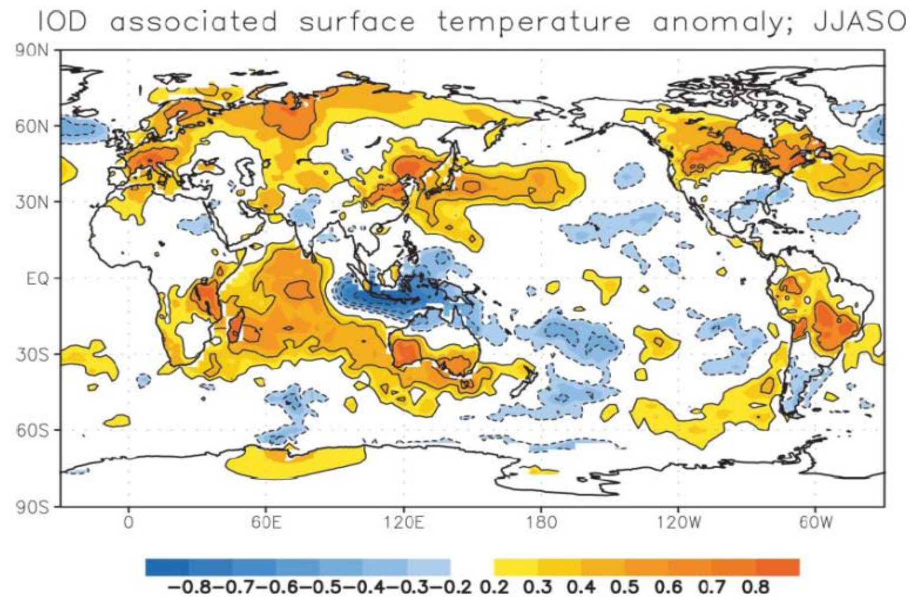
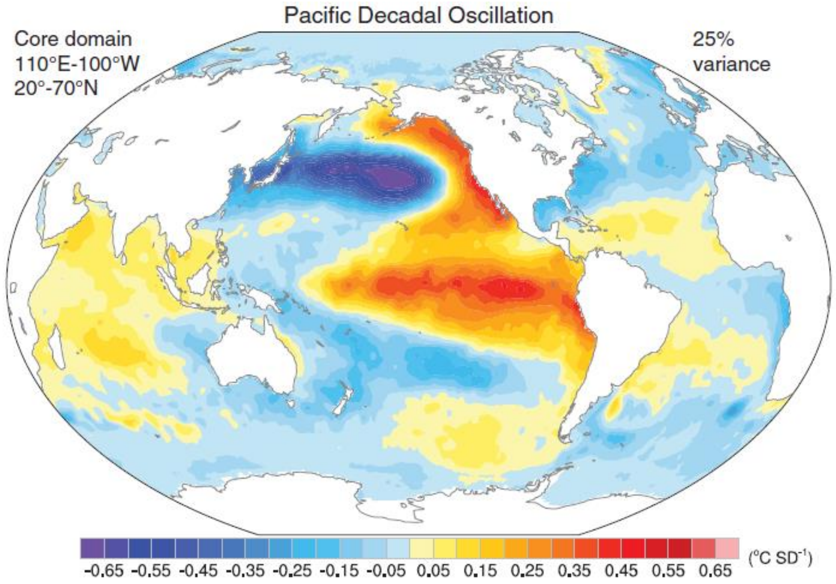


Fig. 21. Partial correlation of land and sea-surface temperature on DMI independent of Nino3 during JJASO

Saji et al.(2003)

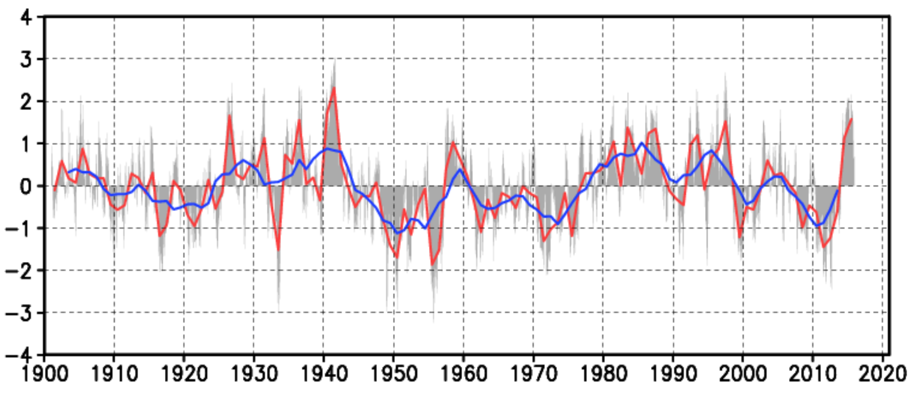
Decadal Oscillation

Pacific Decadal Oscillation (PDO)



Trenberth and Fasullo (2013)

SST pattern regressed on PDO index



PDO index

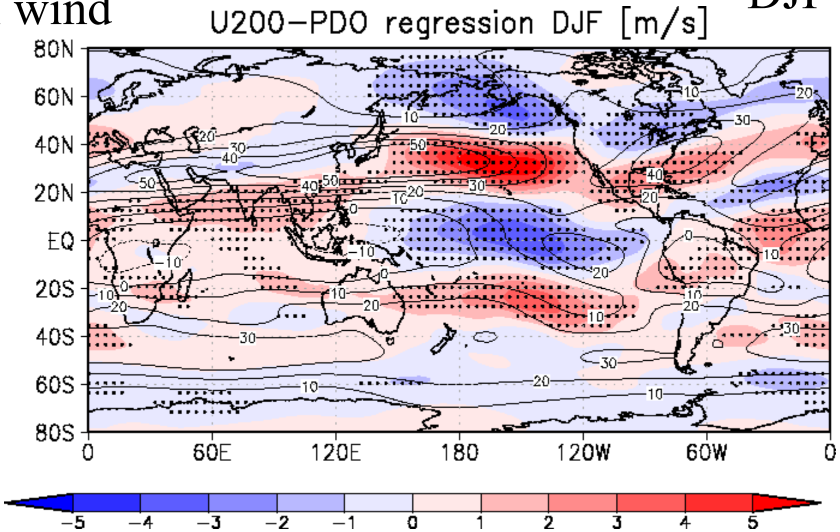
(from JMA website)

PDO and local climate

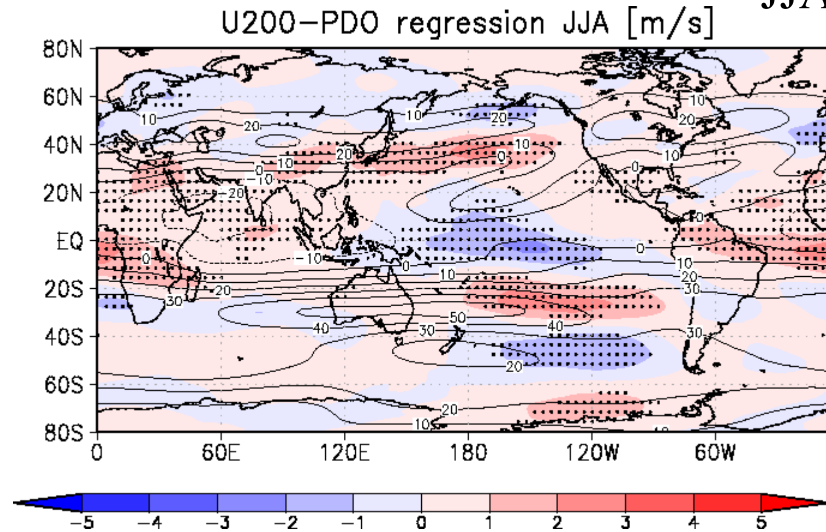
(from JMA website)

Zonal wind

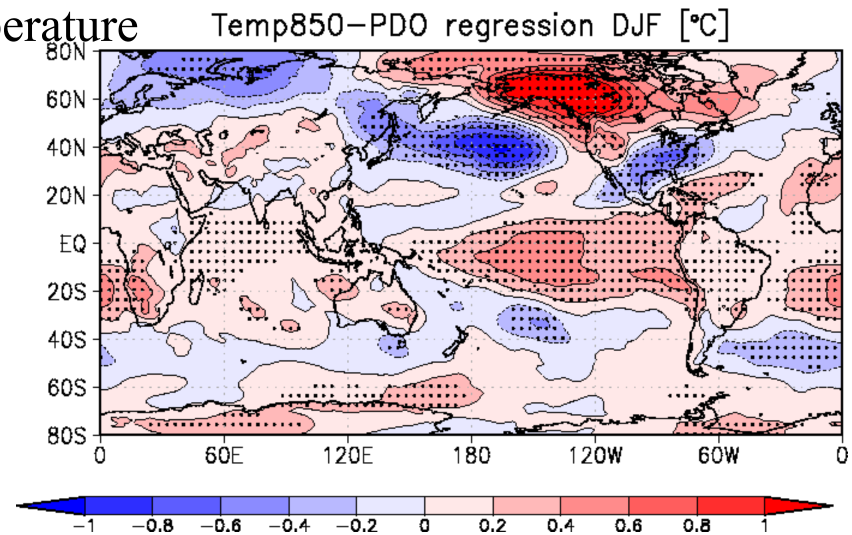
DJF

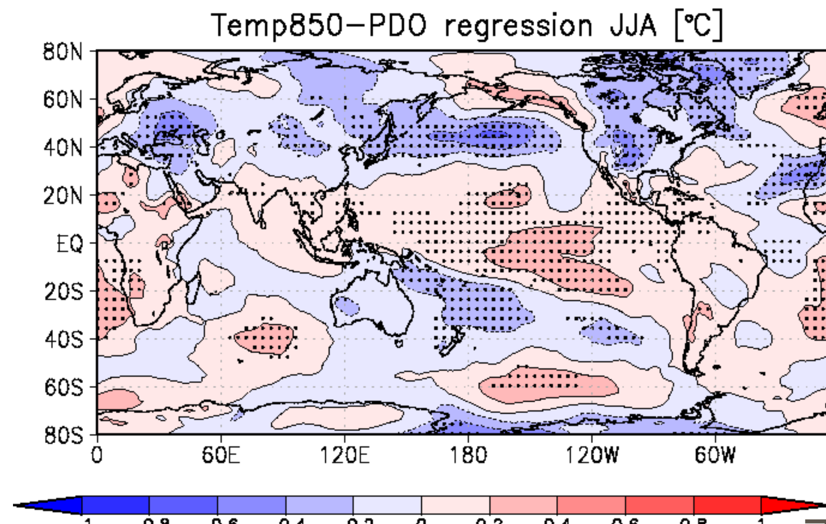


JJA

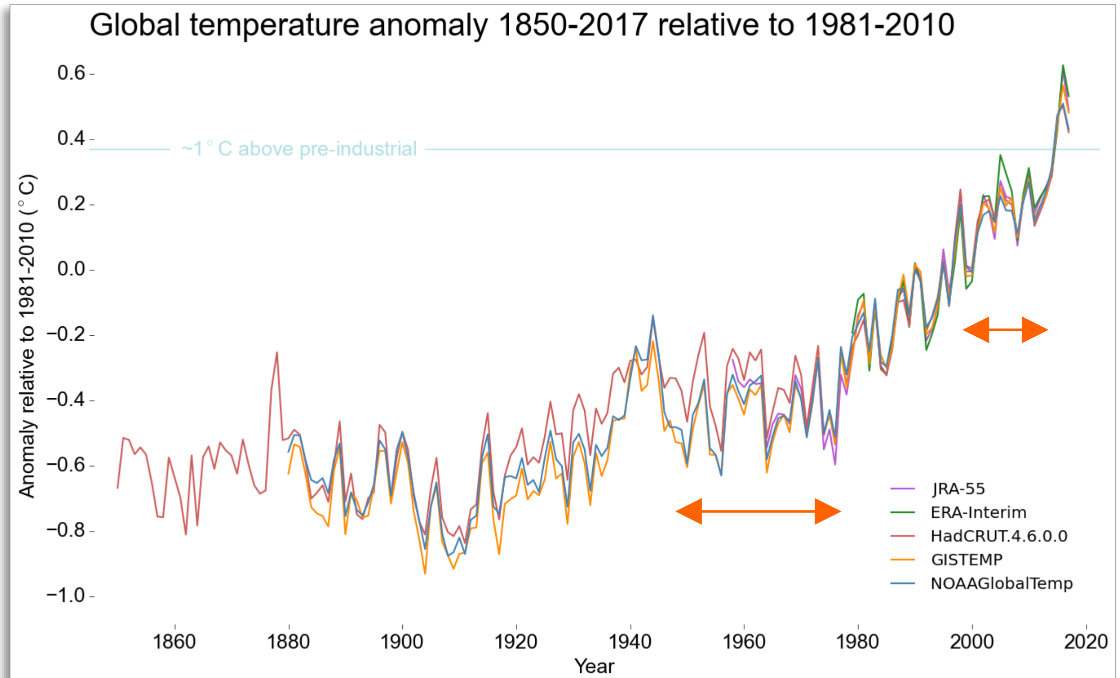


Temperature



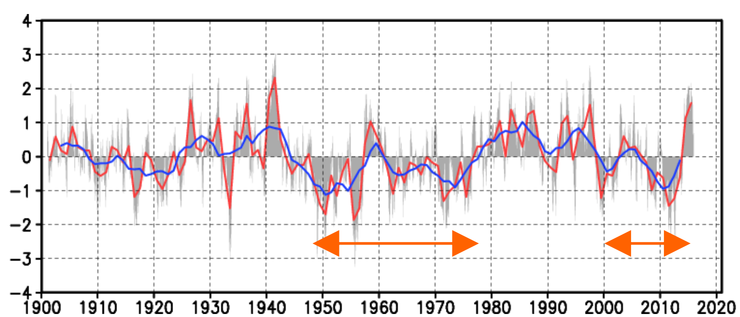


Global Warming Slowdown and PDO

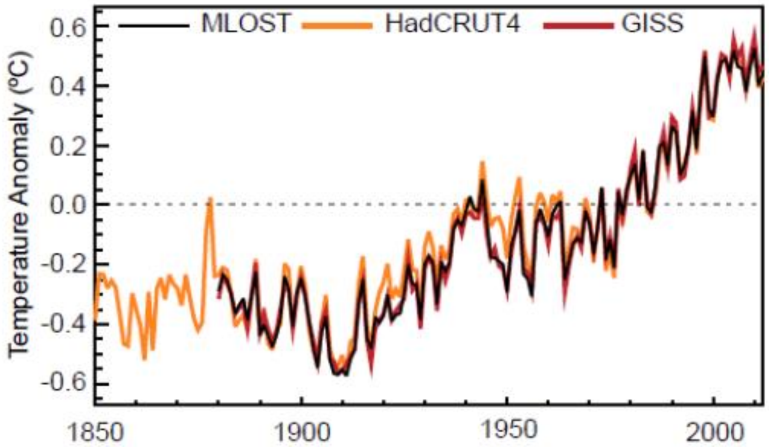


Phases of global warming slowdown ("hiatus") correspond to the negative phase of PDO index

PDO index

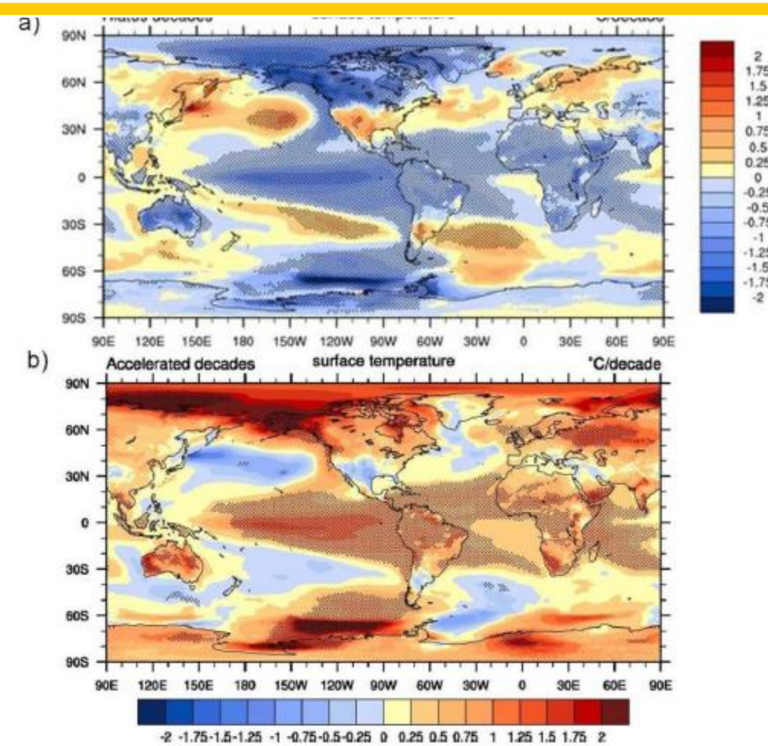


Global warming slowdown and PDO/IPO



Annual Global Mean Surface Temperature (GMST) anomalies relative to a 1961–1990 climatology from the latest version of the three combined Land-Surface Air Temperature (LSAT) and Sea Surface Temperature (SST)
datasets (HadCRUT4, GISS and NCDC MLOST).

IPCC AR5 (2014)

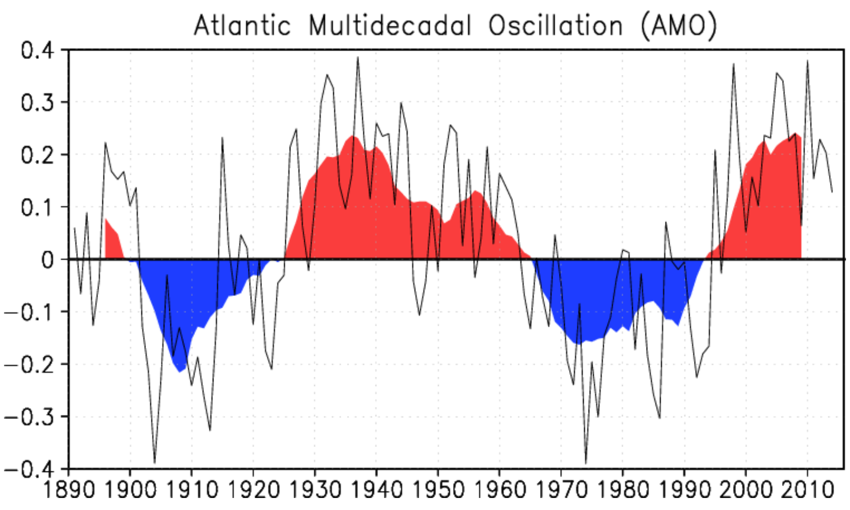


Five CCSM4 21st century simulations with RCP4.5
(uniform increase in GHGs, no volcanoes):
Composites of decades with near-zero warming trend (hiatus decades) and decades with rapid global warming (accelerated warming decades) show opposite phases of the IPO in the Pacific
(hiatus=linear trend of global T <-0.10K/decade; 8 hiatus decades
Accelerated=linear trend of global T>+0.41K/decade; 7 accelerated warming decades)

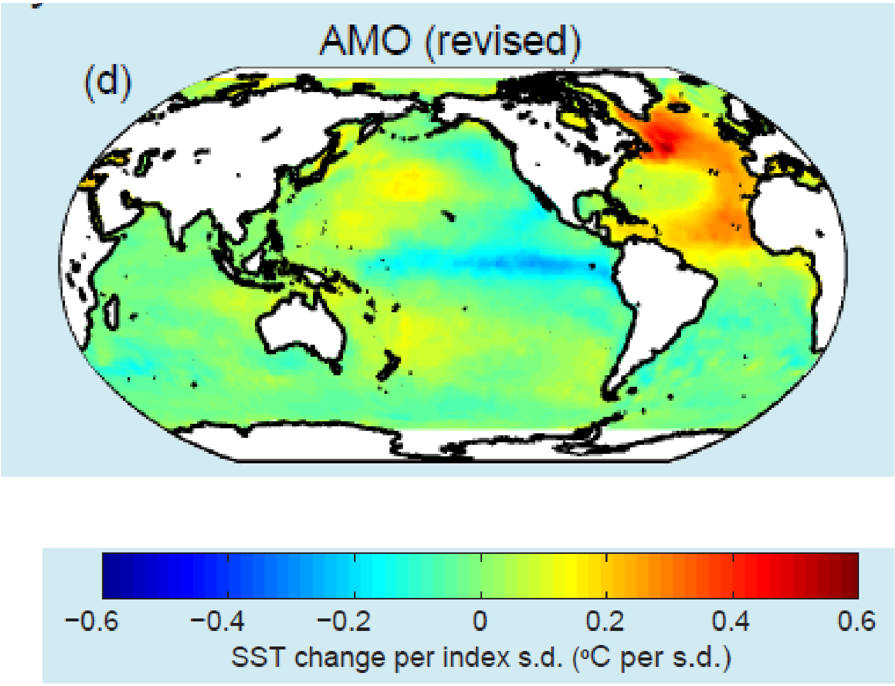
Meehl et al. (2013)

- IPO in positive phase → Accelerated warming decades
- IPO in negative phase → Hiatus decades

Atlantic Multidecadal Oscillation (AMO)



SST anomalies averaged in North Atalntic after removed linear trend. From JMA-HP



Decadal variability of ENSO/ Monsoon and their relationship

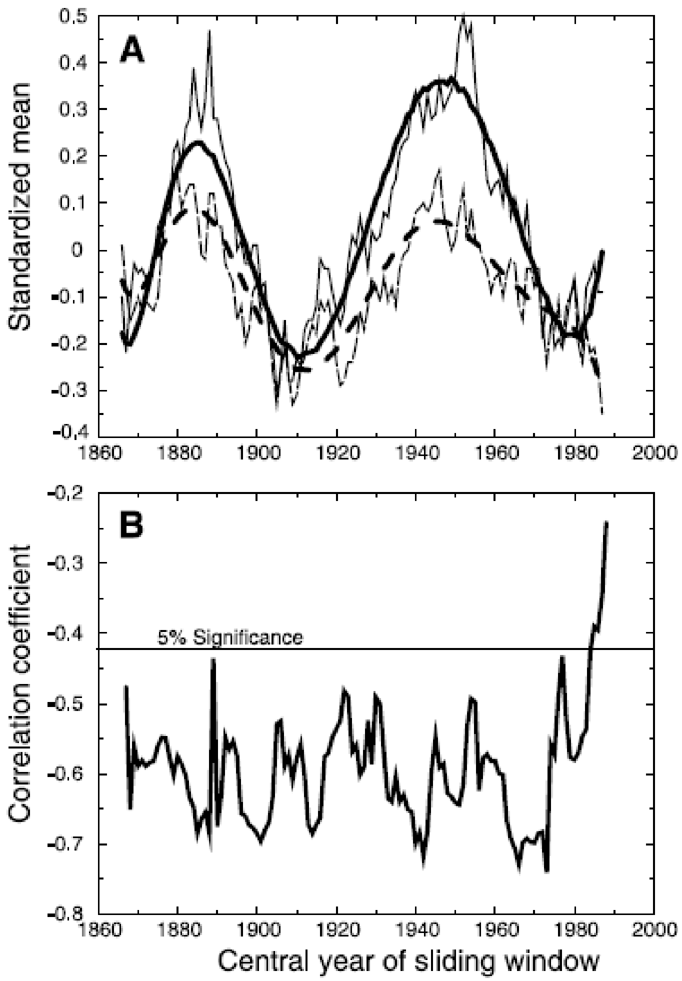


Fig. 1. (**A**) Shown are 21-year sliding standardized means of Indian summer monsoon rainfall (thin line) and June to August (JJA) NINO3 SST anomalies (thin dashed line) during 1856–1997. The corresponding solid lines represent the smoothed values (smoothing is done by fitting a polynomial). The sign of NINO3 SST is reversed to facilitate direct comparison. (**B**) Shown are 21-year sliding correlations between Indian summer monsoon rainfall and NINO3 SST anomalies (JJA) during 1856–1997. The horizontal line shows the 5% significance level.

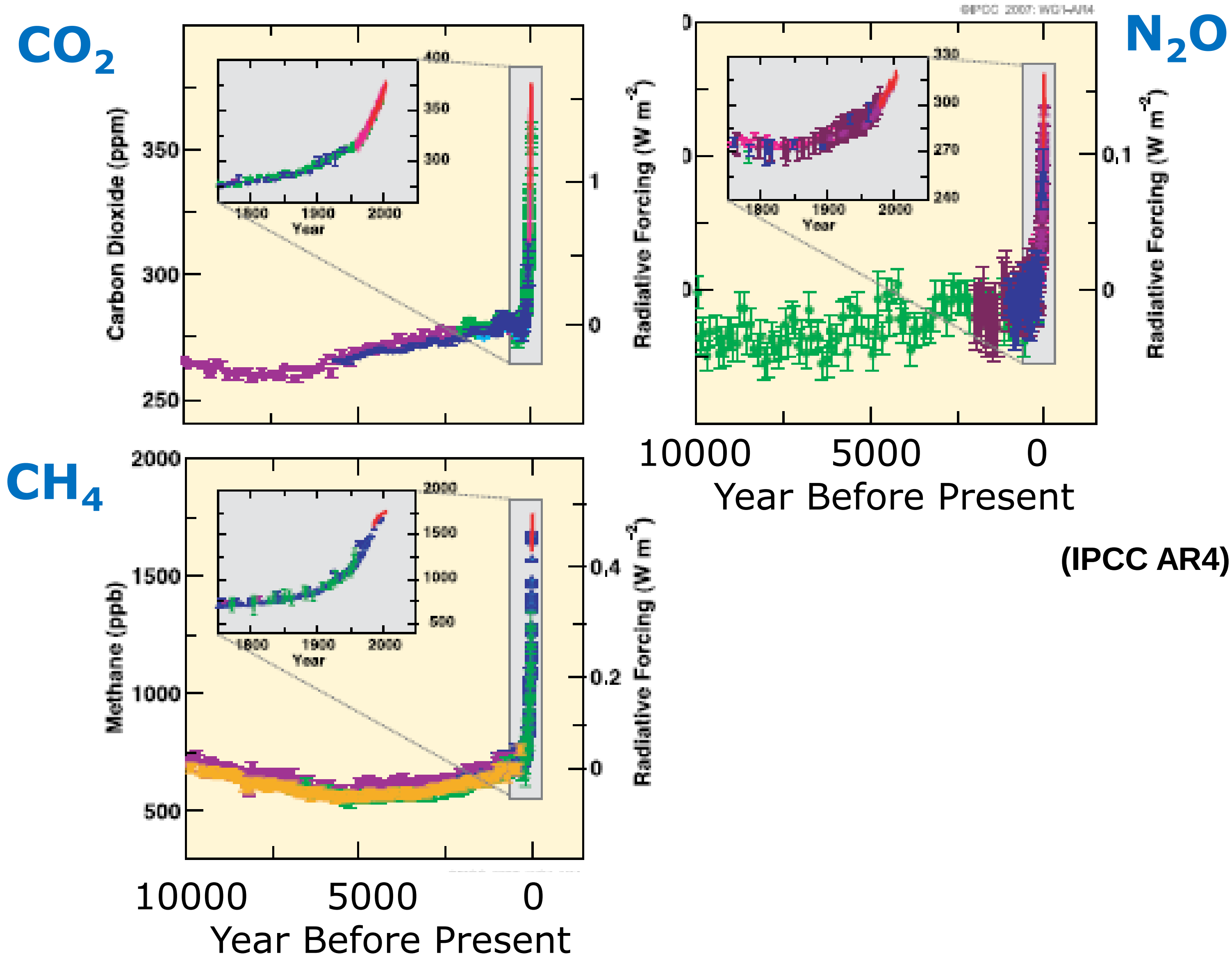
On the Weakening Relationship Between the Indian Monsoon and ENSO

K. Krishna Kumar,[1*†] Balaji Rajagopalan,[2] Mark A. Cane[2] 1999

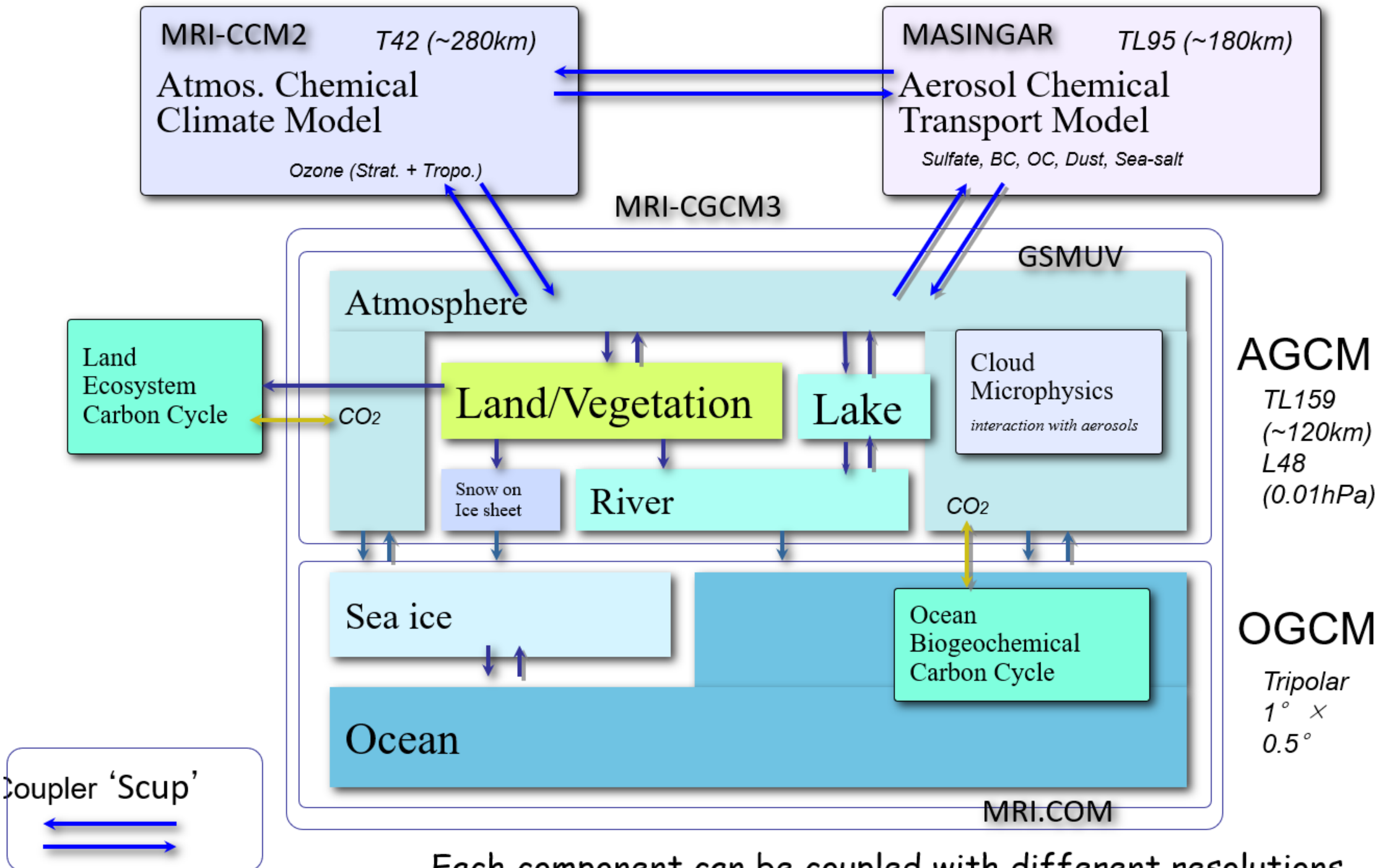
Global Warming

- Boundary Condition Problem
  - ✓ External Anthropogenic Forcing

Changes in greenhouse gases



Example: MRI Earth System Model



Each component can be coupled with different resolutions

Historical Global Warming Experiments

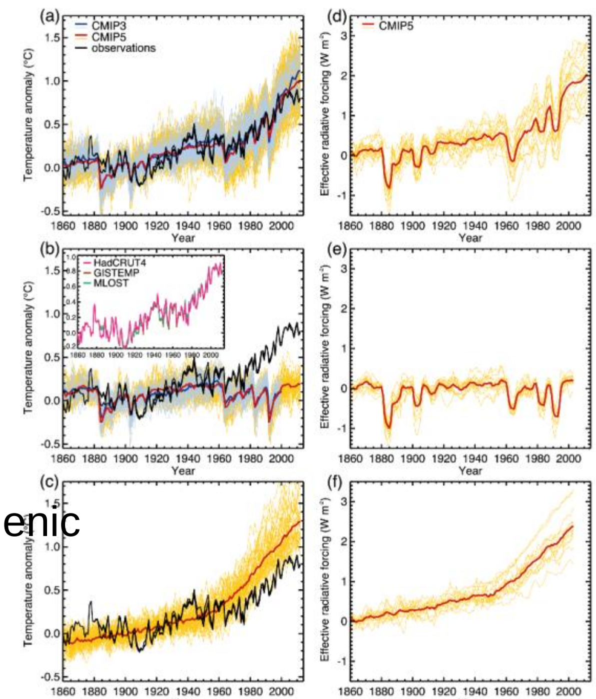
Radiative forcing is the difference between insolation (sunlight) absorbed by the Earth and energy radiated back to space.

Model Experiments

All forcing

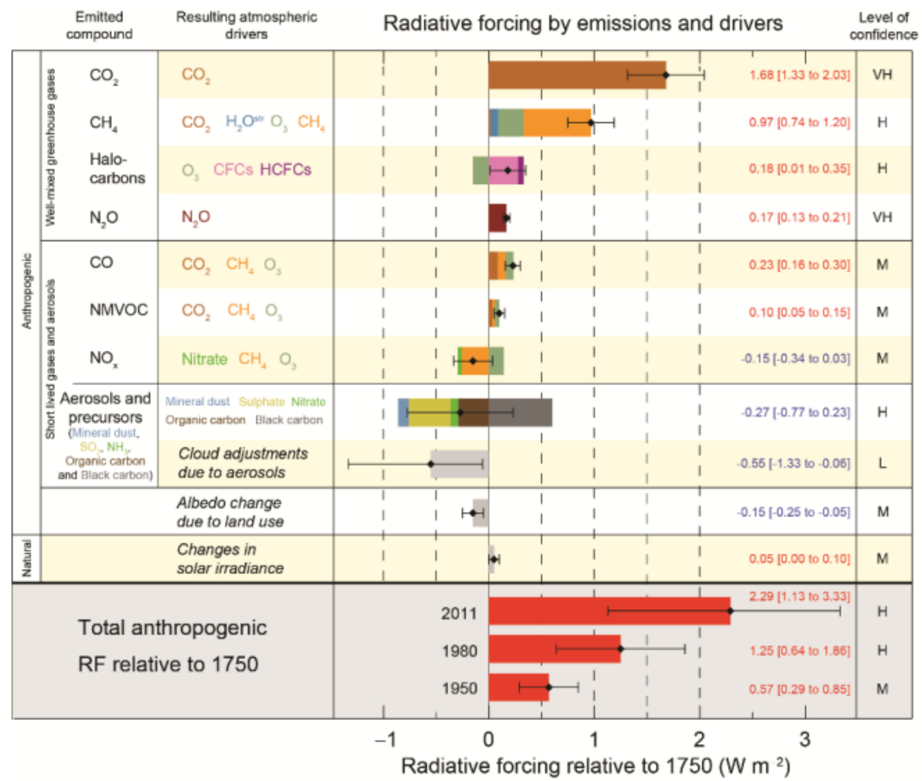
Natural forcing only

Anthropogenic forcing only



WGI_AR5_Fig10-1

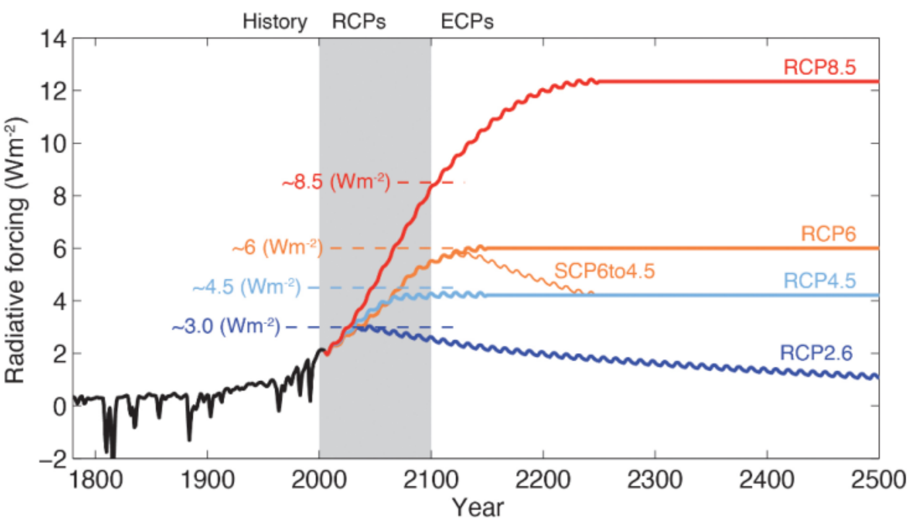
Radiative Forcing



WGI_AR5_FigSPM-5

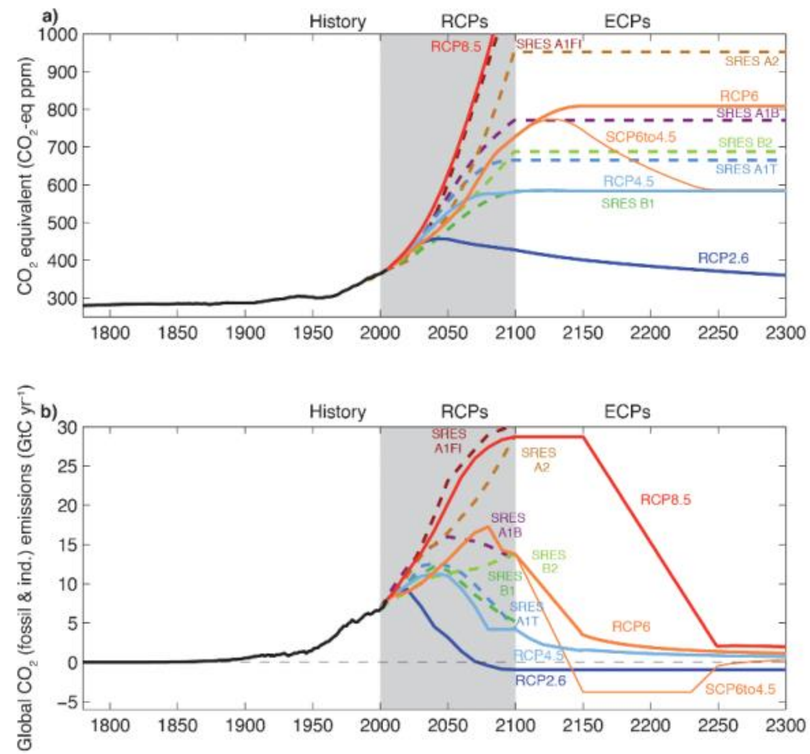
Future Scenarios

Radiative Forcing



WGI_AR5_FigBox11-1

CO2 and Emisson



WGI_AR5_FigBox1_1-3

Summary

- The global climate system consists of atmosphere including its composition and circulation, the ocean, hydrosphere, land surface, biosphere, snow and ice, solar and volcanic activities. These components interact on various spatial and temporal scales through the exchanges of heat, momentum, radiation, water and other materials.
- We have used science, especially physics, to describe the concepts of the climate system and to predict the behavior.
- Climate variability refers to variations in the mean state and other statistics of the climate on all spatial and temporal scales beyond that of individual weather events. Climate variability may be due to natural internal processes within the climate system (internal variability), or to variations in natural or anthropogenic external forcing.
- Experts of climate services must learn climate system, causes, impacts, and predicatbility of climate variability in various spatial and temporal scales.