Role of aerosols and greenhouse gases in modulating the rainfall characteristics across south Asia in a warming world

Dilip Ganguly

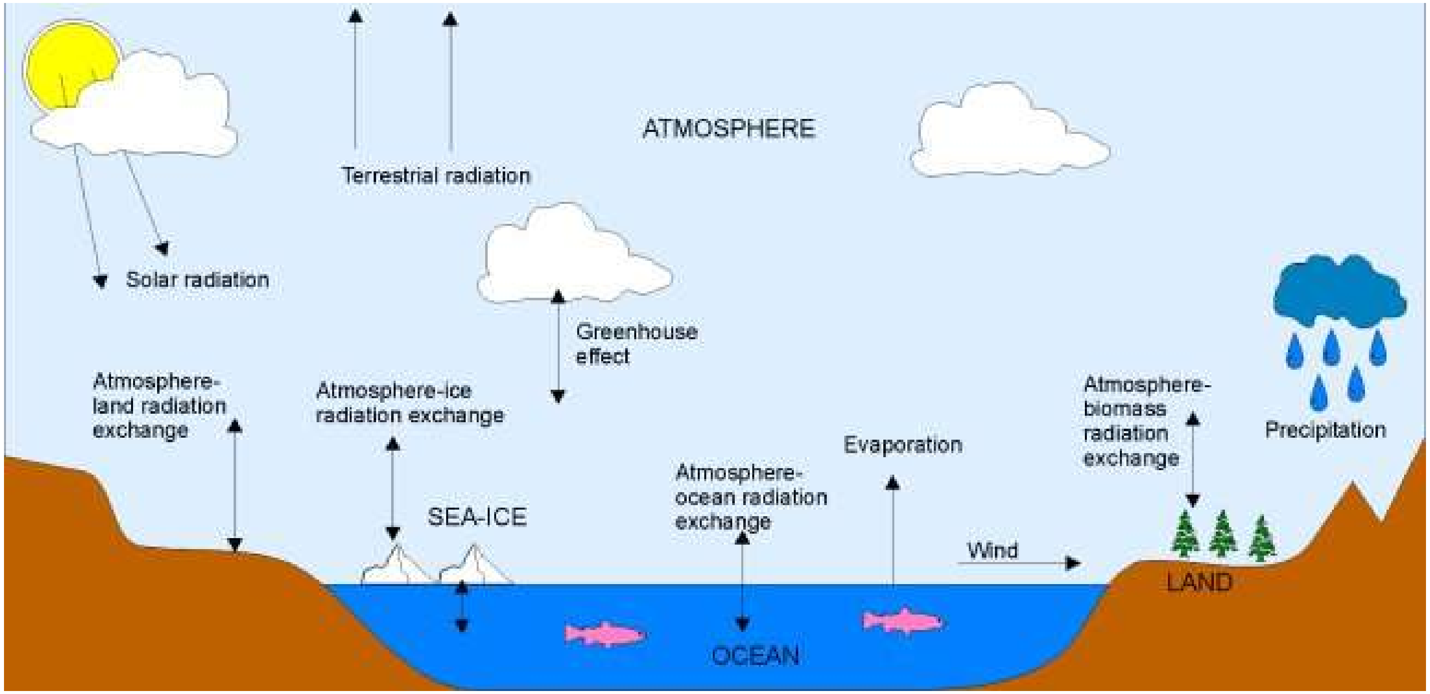
Centre for Atmospheric Sciences

Indian Institute of Technology Delhi

(dilipganguly@cas.iitd.ac.in)

Climate System of our Earth: An overview

It is an interactive system consisting of several components such as the atmosphere, hydrosphere, cryosphere, land surface and the biosphere



Various physical, chemical and biological interactions are continuously occurring among the different components of the climate system on a wide range of space and time scales, making the system extremely complex.

The *atmosphere* is the most unstable and rapidly changing part of this climate system and plays a crucial role in regulating the Earth's climate.

What drives climate

- The main source of energy driving the climate system of the Earth-Atmosphere system is the Solar radiation received from the Sun.

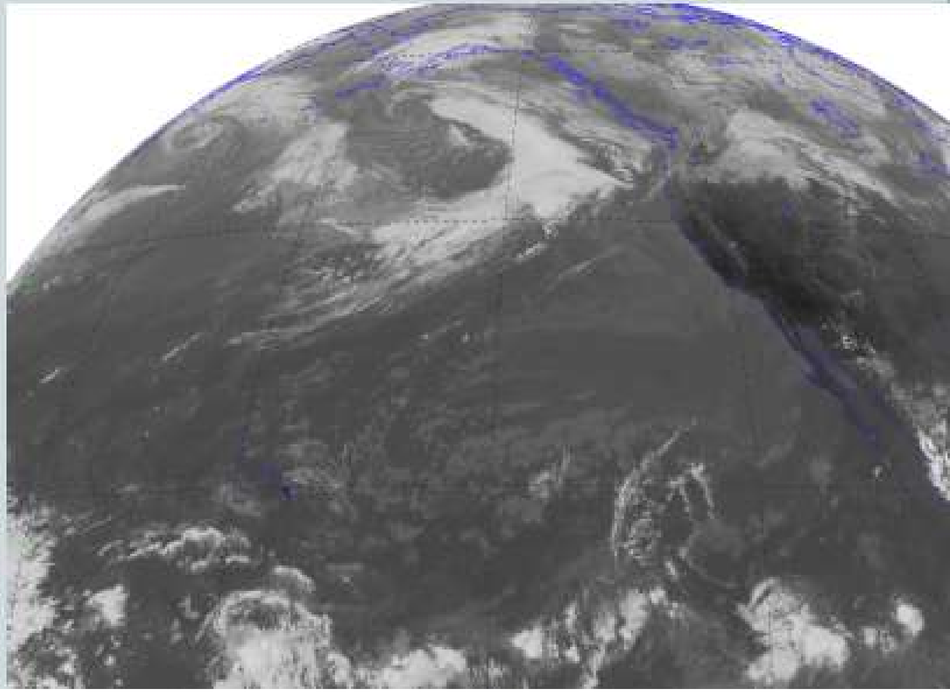
- Transport and transformation of energy within the Earth-Atmosphere system along with the role played by gravity, and the Earth's rotation are responsible for most atmospheric processes/phenomenon.

Solar Radiation and Earth

- When the Sun's radiation reaches the Earth's atmosphere, several things can happen:
  - Scattering/reflection of solar radiation
  - Absorption
  - Transmission
- Most solar radiation makes it straight to the surface
  - **50%** of top-of-atmosphere (TOA) radiation is **absorbed at the surface**
  - 20% is absorbed in atmosphere (17% in troposphere, 3% in stratosphere)
  - **30%** is **reflected** back to space (25% by atmosphere, 5% by surface)

Next Section: Earth Radiation

- In equilibrium, energy in = energy out
  - This is the "energy balance" equation
- The Earth loses energy only through **longwave radiation**
  - The Earth's surface radiates away lots of longwave radiation
  - Is this able to make it out to space easily?



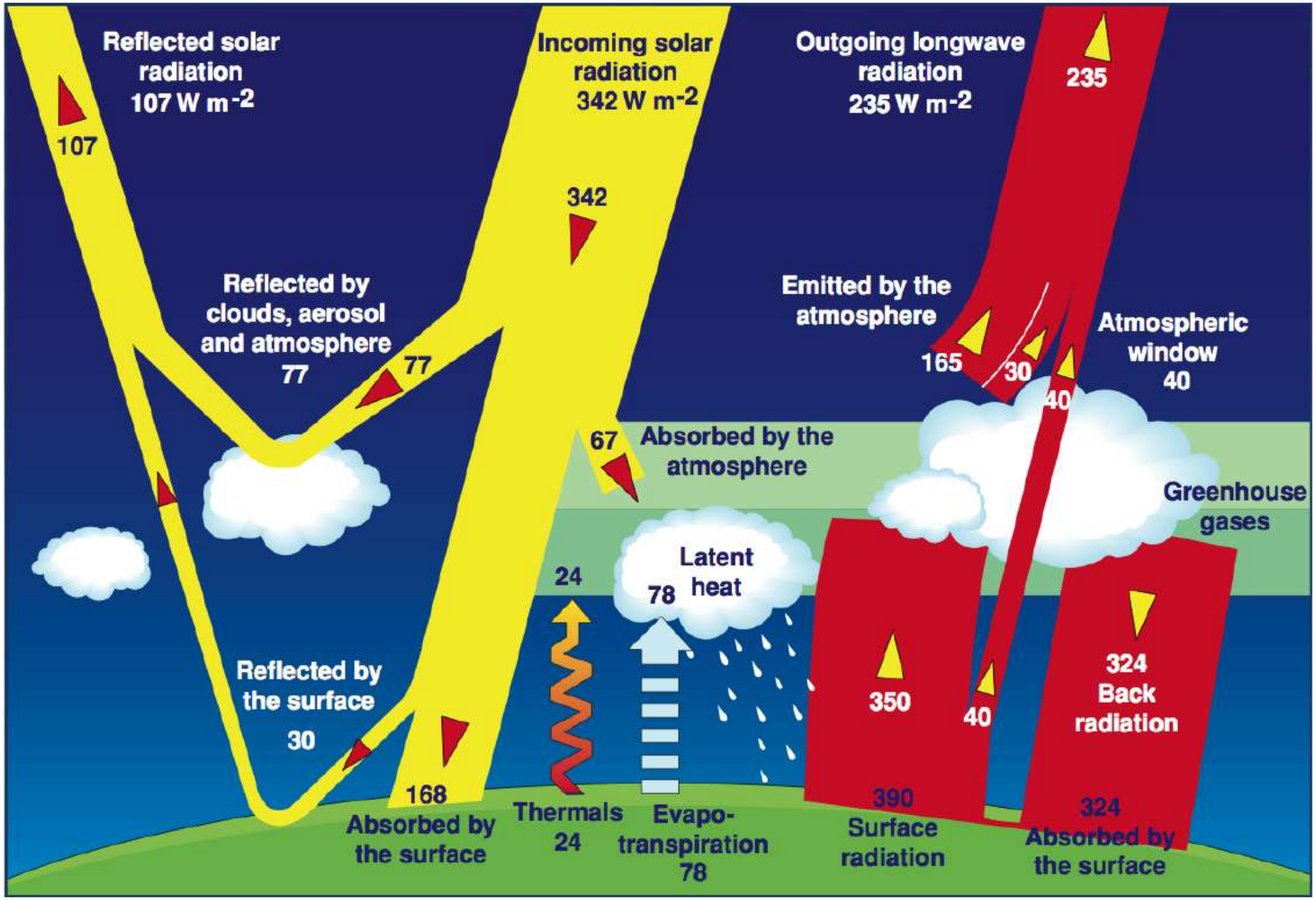
Infrared satellite image →

Greenhouse Effect

- The surface emits **390** W/m^2 of longwave radiation, but only **40** W/m^2 makes it directly out to space

- The rest is trapped by greenhouse gases and clouds!

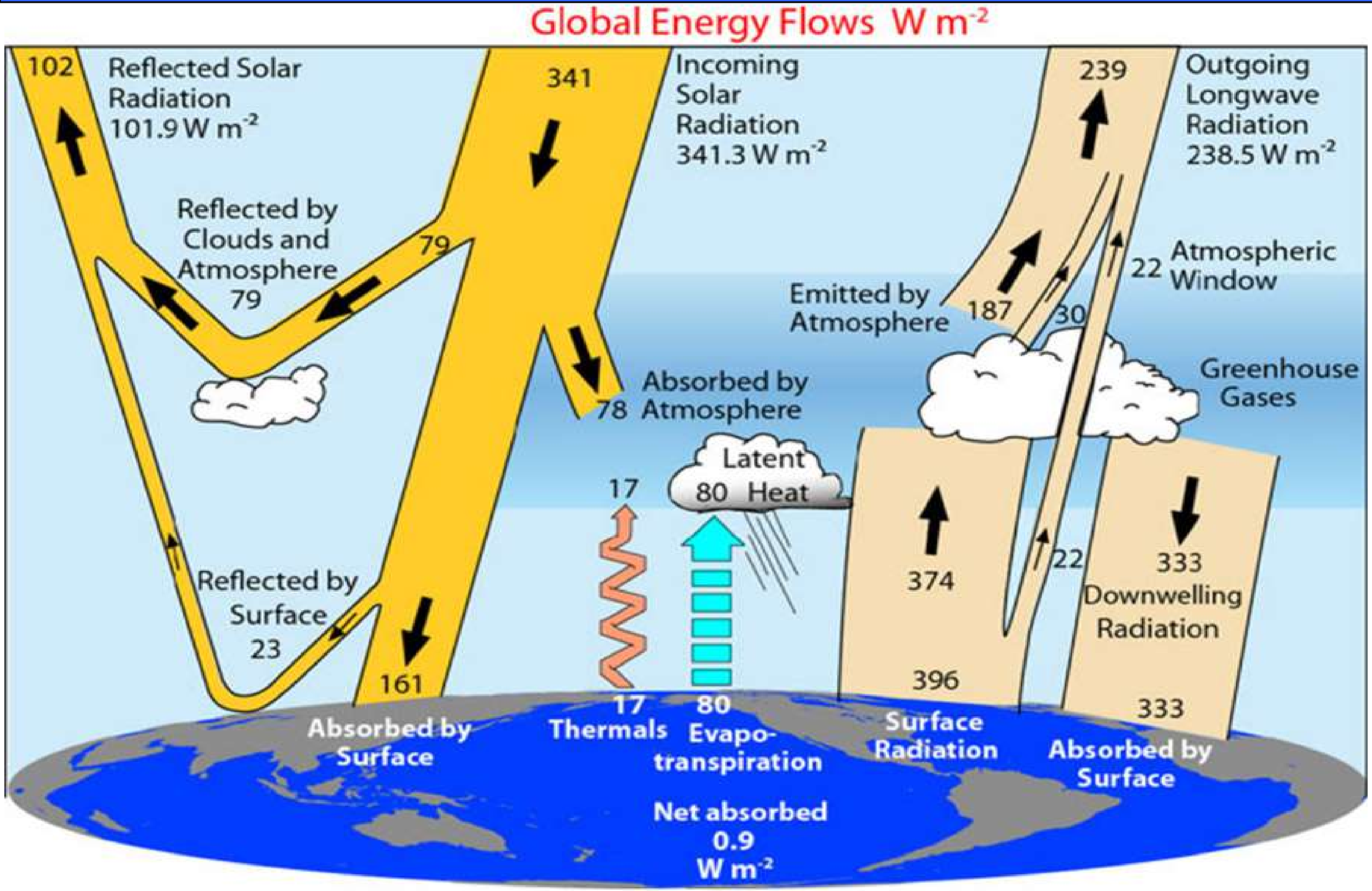
Energy budget of Earth-Atmosphere system



Kiehl and Trenberth, 1997

For the annual mean and for the Earth as a whole, flux of incoming solar radiation is balanced by the outgoing terrestrial radiation at TOA, maintaining the Earth's average surface temperature to be around 288^0 K.

Energy budget of Earth-Atmosphere system



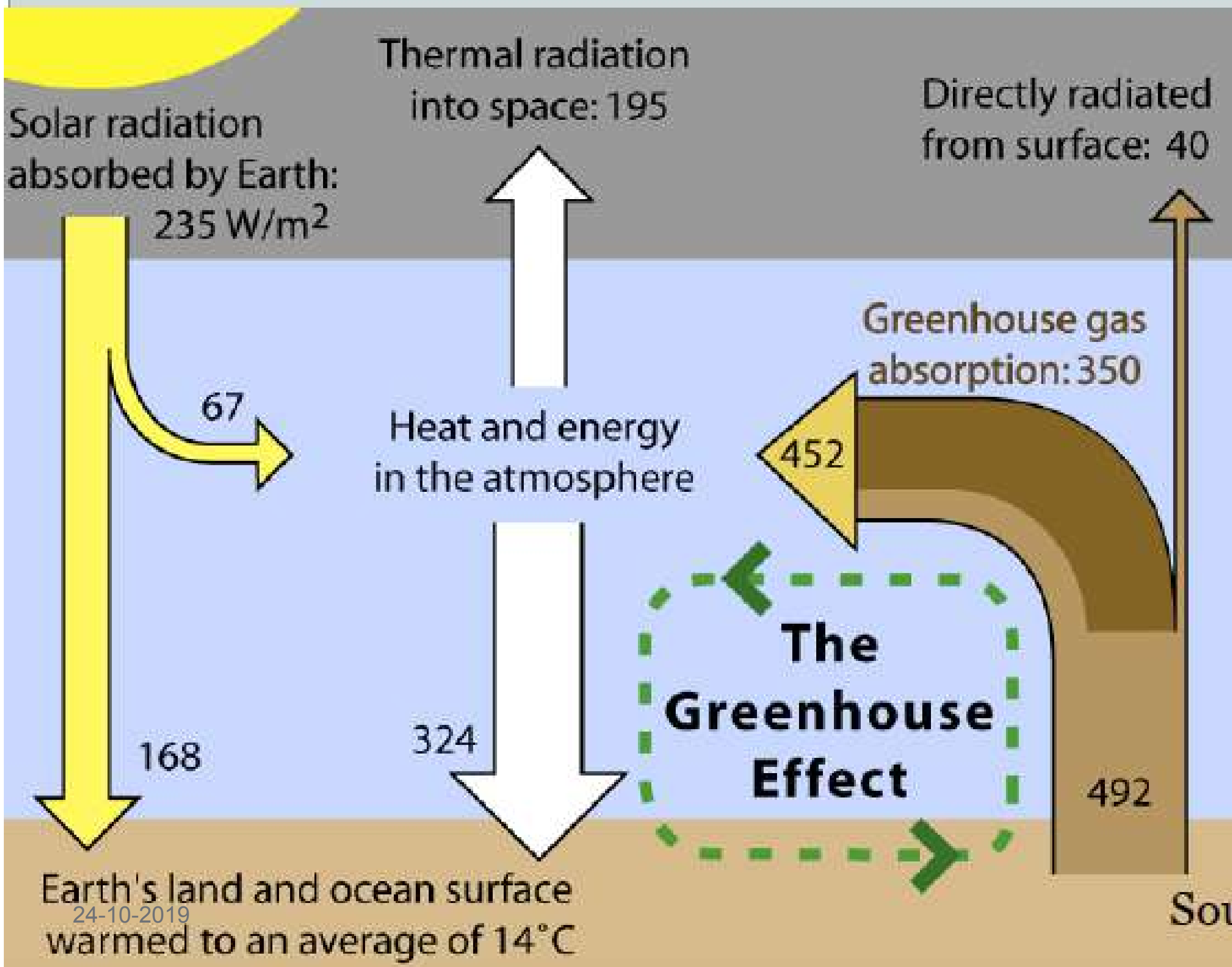
***Trenberth et al.*, 2009**

In the new estimates of global energy flows, some numbers have changed slightly

For the annual mean and for the Earth as a whole, flux of incoming solar radiation is balanced by the outgoing terrestrial radiation at TOA, maintaining the Earth's average surface temperature to be around 288^0 K.

Atmospheric Energy Budget

- Surface is heated more by **longwave** than shortwave!

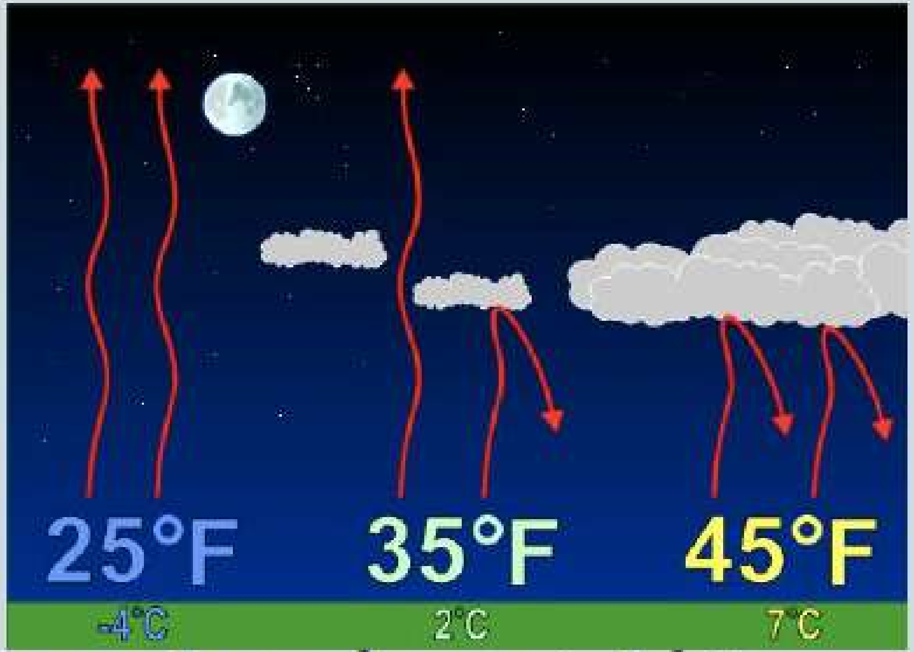


total heat trapped (available) by the atmosphere = 350(LW) + 67(SW) +24(SH) +78(LH) = 519
Heat energy available with atmosphere = 519 = 324 (re-emitted LW absorbed by the surface) + 195 (LW Thermal radiation emitted to space)
324+168=492
492-40=452
452+67=519
324+195=519

Source: Global Warming Art

The Greenhouse Effect

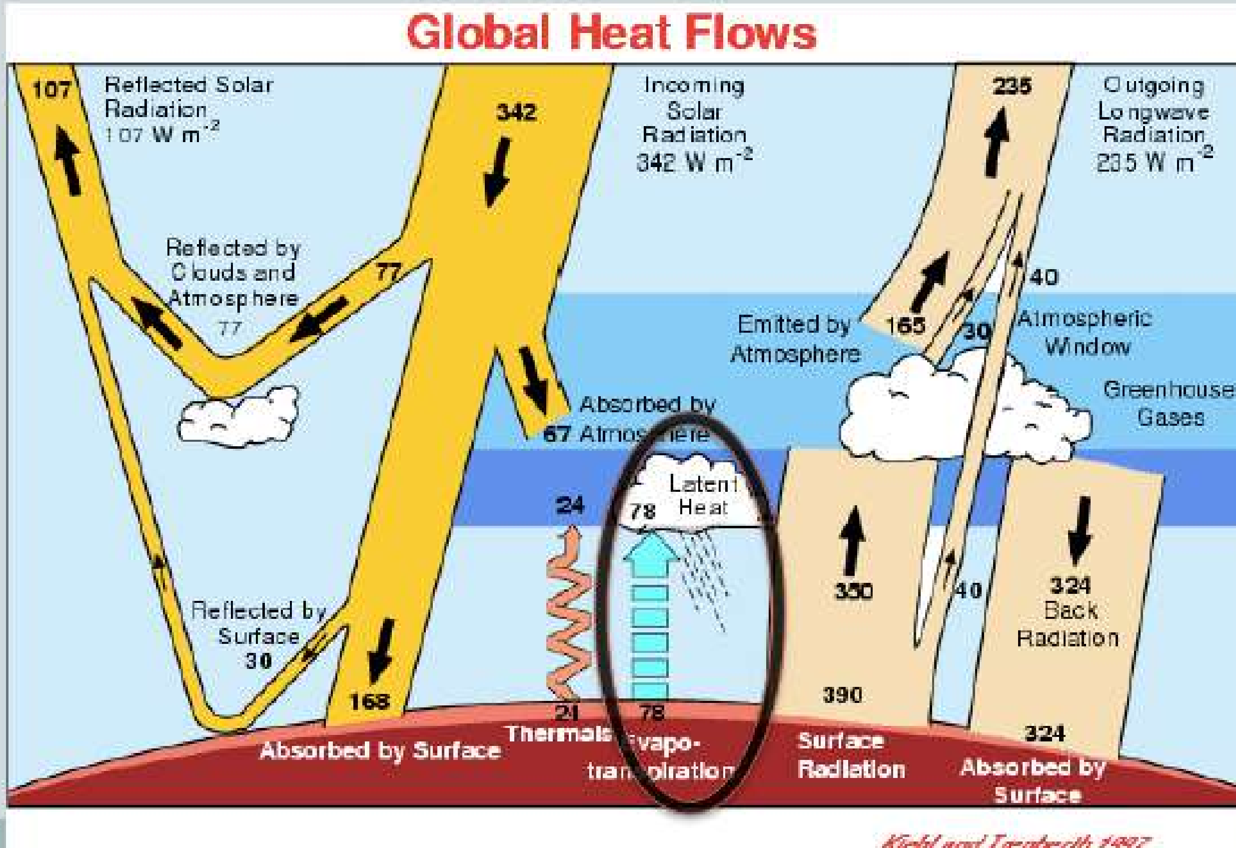
- Greenhouse effect is intuitive if you pay attention to the weather!
  - **Cloudy nights** cool less quickly



  - In the **desert**, temperatures plunge at night!
    - No clouds & little water vapor in the desert: little greenhouse effect

Latent Heating in Energy Budget

- Evaporation/condensation is primary way that energy is transferred from surface to atmosphere:



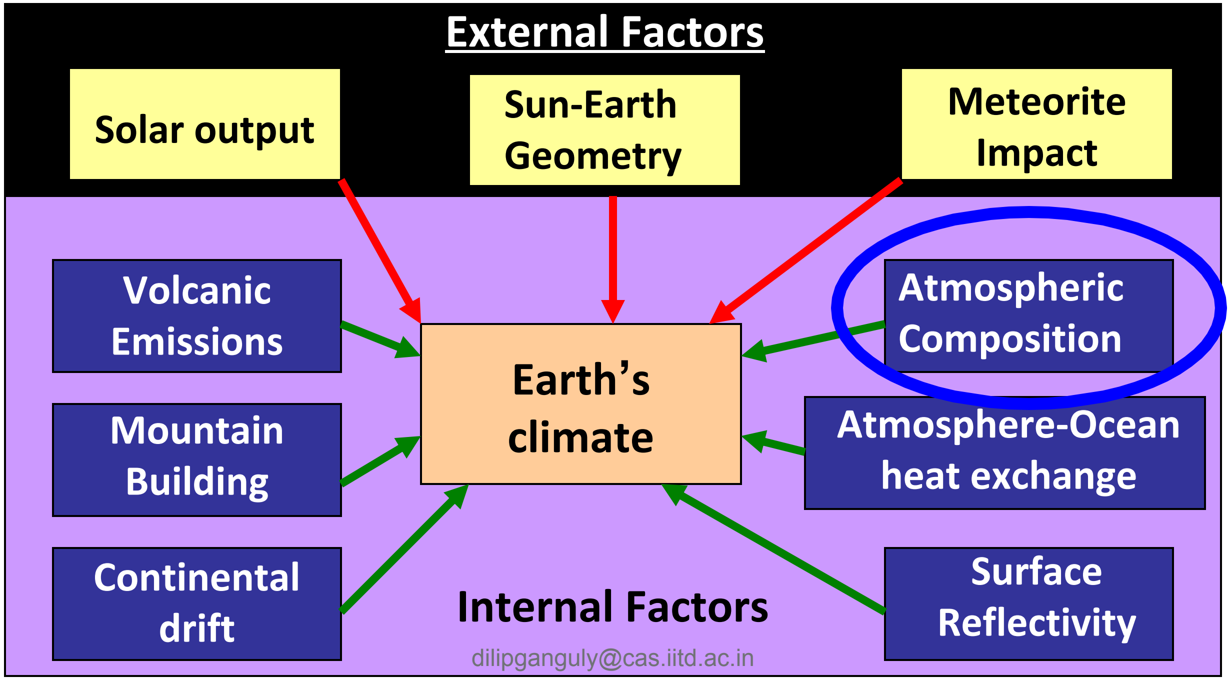
Latent heat flux = 78
Sensible (thermal) heat flux = 24
Net radiative flux from surface to atmos = 350-324 = 26

Over 60% of heat is transferred off of surface by moisture!

Climate change

- The general state of the Earth's climate is dependent upon the amount of energy stored by the climate system, and in particular the balance between the amount of energy the Earth receives from the Sun and the amount which it releases back to space.

- Any factor that alters the radiation received from the Sun or lost to space, or anything that alters redistribution of energy within the atmosphere or between the atmosphere, land, and ocean, can affect climate.



Radiative Forcing

- It is an index of the importance of any factor responsible for a potential climate change mechanism.

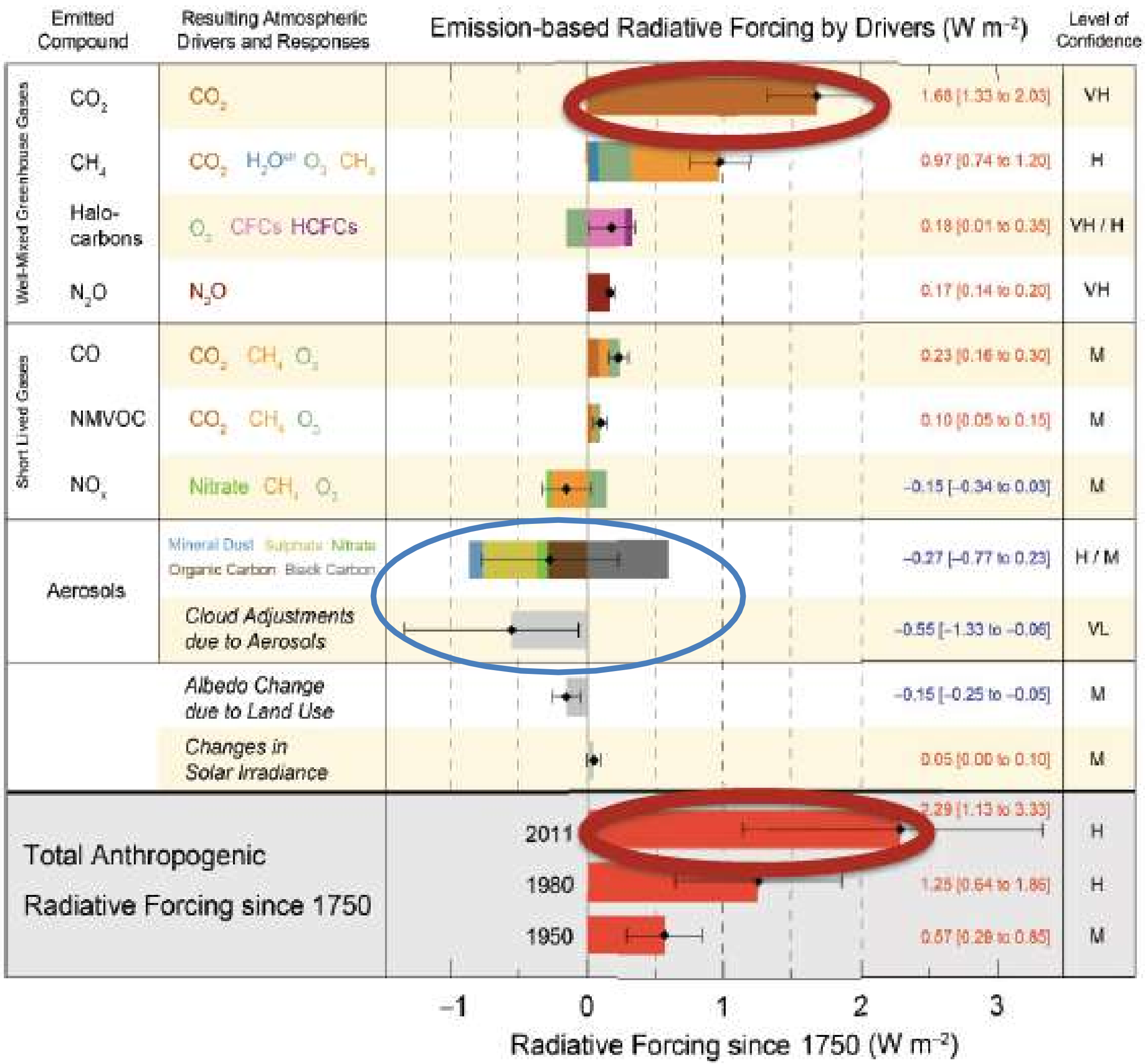
- It is a change in the net radiative energy available to the Earth-Atmosphere system.

- Radiative forcing due to a given component is a measure of its influence in altering the balance of incoming and outgoing energy in the Earth-Atmosphere system.

- It is quantified as the change in net radiance (down minus up, solar plus terrestrial) at a given level in the atmosphere, expressed in units of (W/m^2).

'+'ve forcing warms the atmosphere and '–'ve forcing cools it

Climate drivers and Radiative Forcing



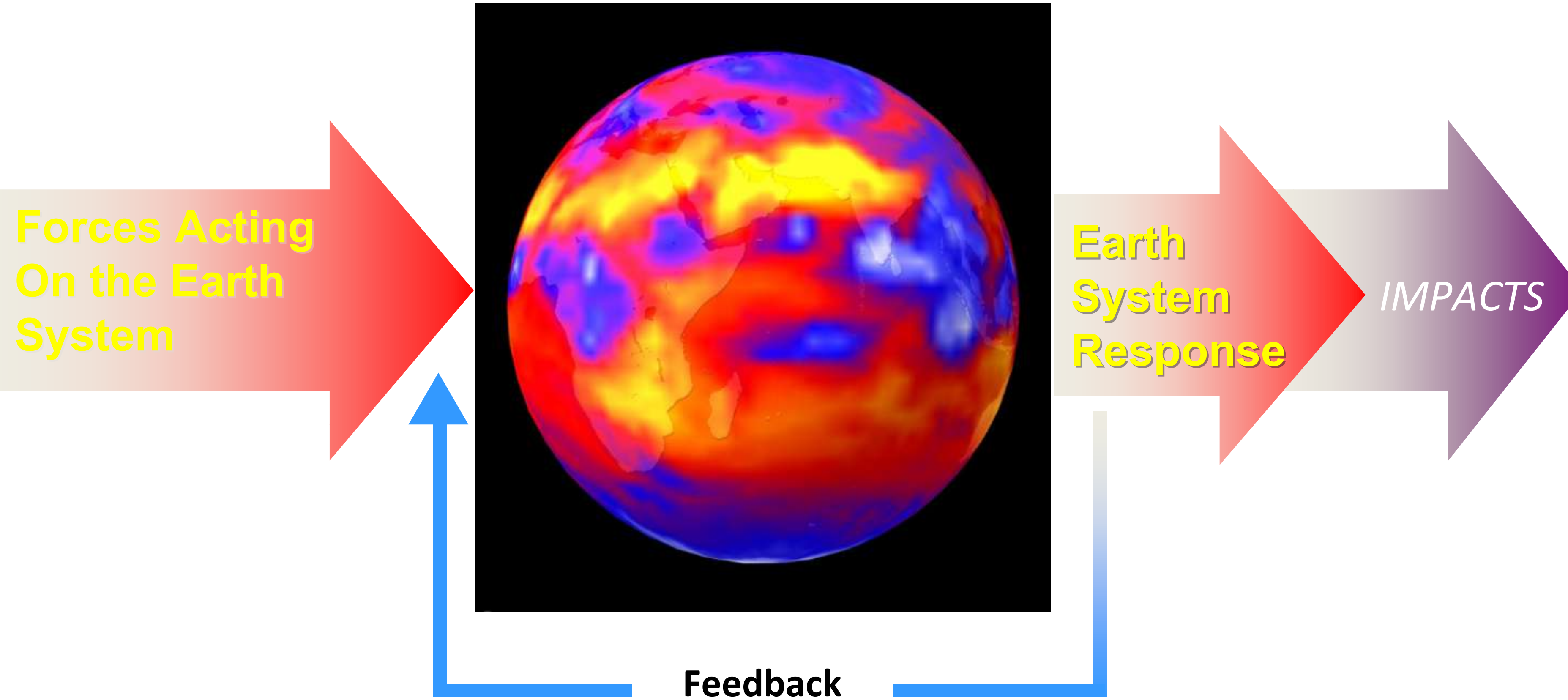
Total radiative forcing is positive, and has led to an uptake of energy by the climate system.

The largest contribution to total radiative forcing is caused by the increase in the atmospheric concentration of CO_2 since 1750.

IPCC AR5

Unlike well-mixed greenhouse gases in the troposphere which always produces '+'ve radiative forcing, there can be '+'ve or '–'ve radiative forcing due to aerosols depending on their composition and geographical location.

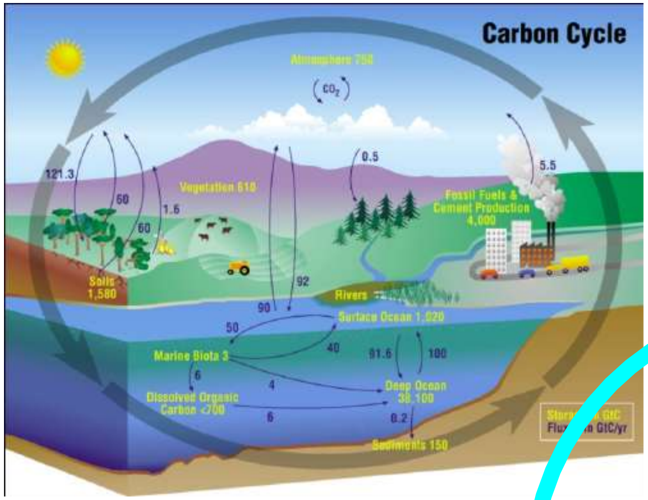
How does the Earth Respond?



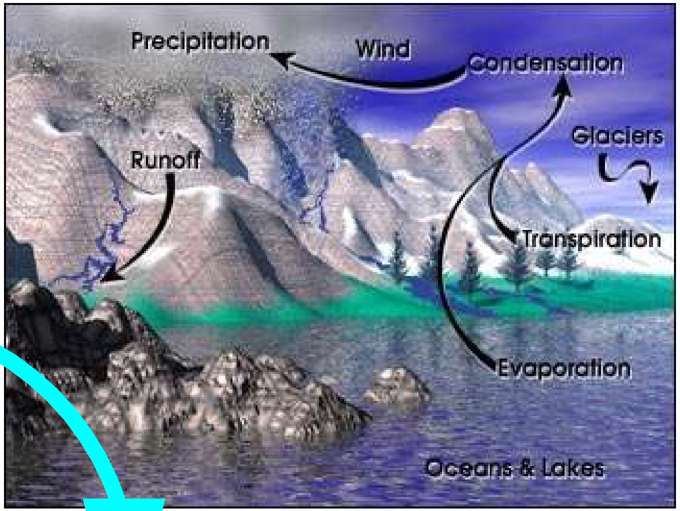
Of the total forcing of the climate system, 40% is due to the direct effect of greenhouse gases and aerosols, and 60% is from feedback effects, such as increasing concentrations of water vapor as temperature rises.

Major Climate System Elements

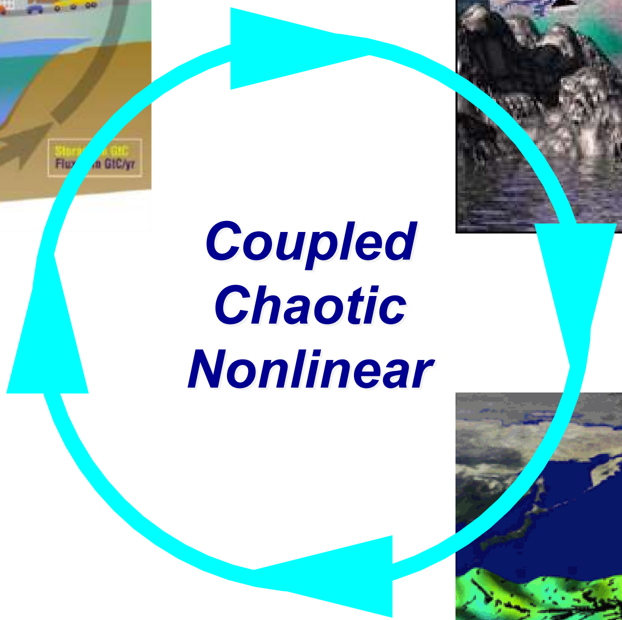
Carbon Cycle



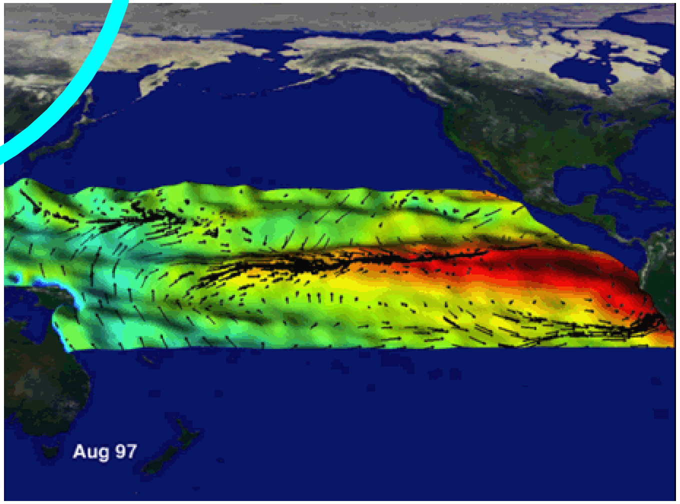
Water & Energy Cycle



Atmospheric Chemistry



Atmosphere and Ocean Dynamics



Atmospheric Aerosols: Air Pollution to Climate Change

•**Atmospheric aerosols (or particulate matter)** are solid or liquid particles or both suspended in the atmosphere, excluding cloud droplets and ice crystals.

Species		**Source (partly anthropogenic)**
Mineral dust	(DU)	windblown, mostly from deserts (also: roads, agriculture)
Sea salt	(SS)	windblown
Sulfate	(SO_4)	combustion, biogeochemistry, volcanos
Soot, Black carbon	(BC)	combustion (fossil fuel, biomass, wildfires)
Organic matter	(OM)	combustion, biogeochemistry
Nitrate	(NH_4)	air chemistry, fertilisers, combustion





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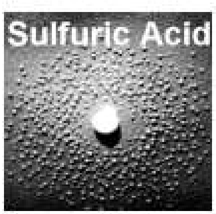
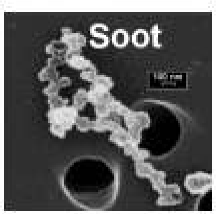
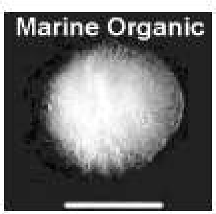
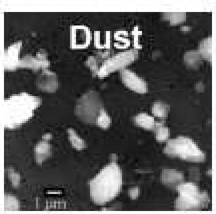






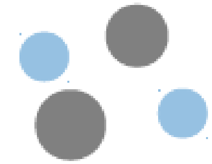


Primary aerosols (emitted in form of particles)

Secondary aerosols (emitted as gas, transformed in the atmosphere to particles)

Mixing state of aerosols

External mixture: Pure chemical composition per particle

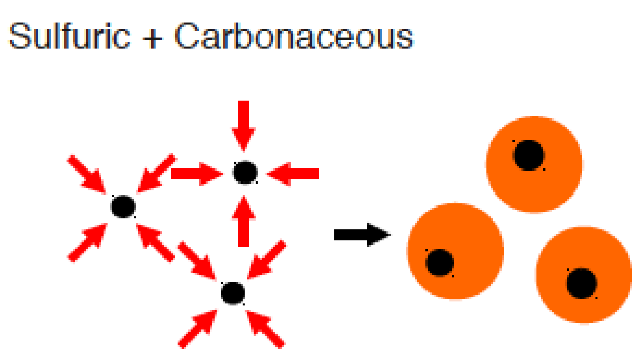


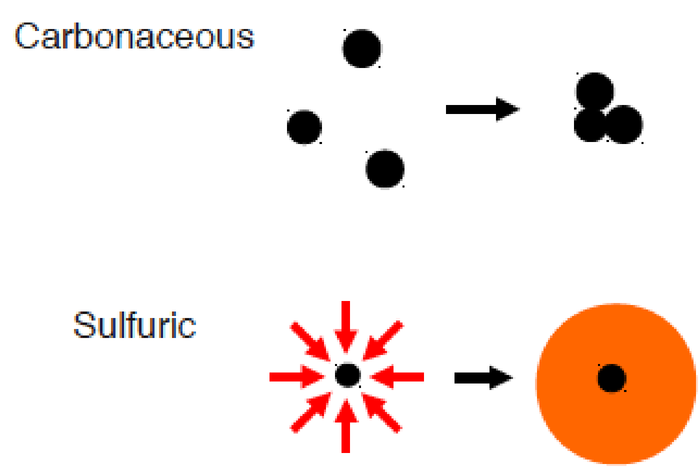
Internal mixture: A particle consists of different chemical components

Interactions of particles:

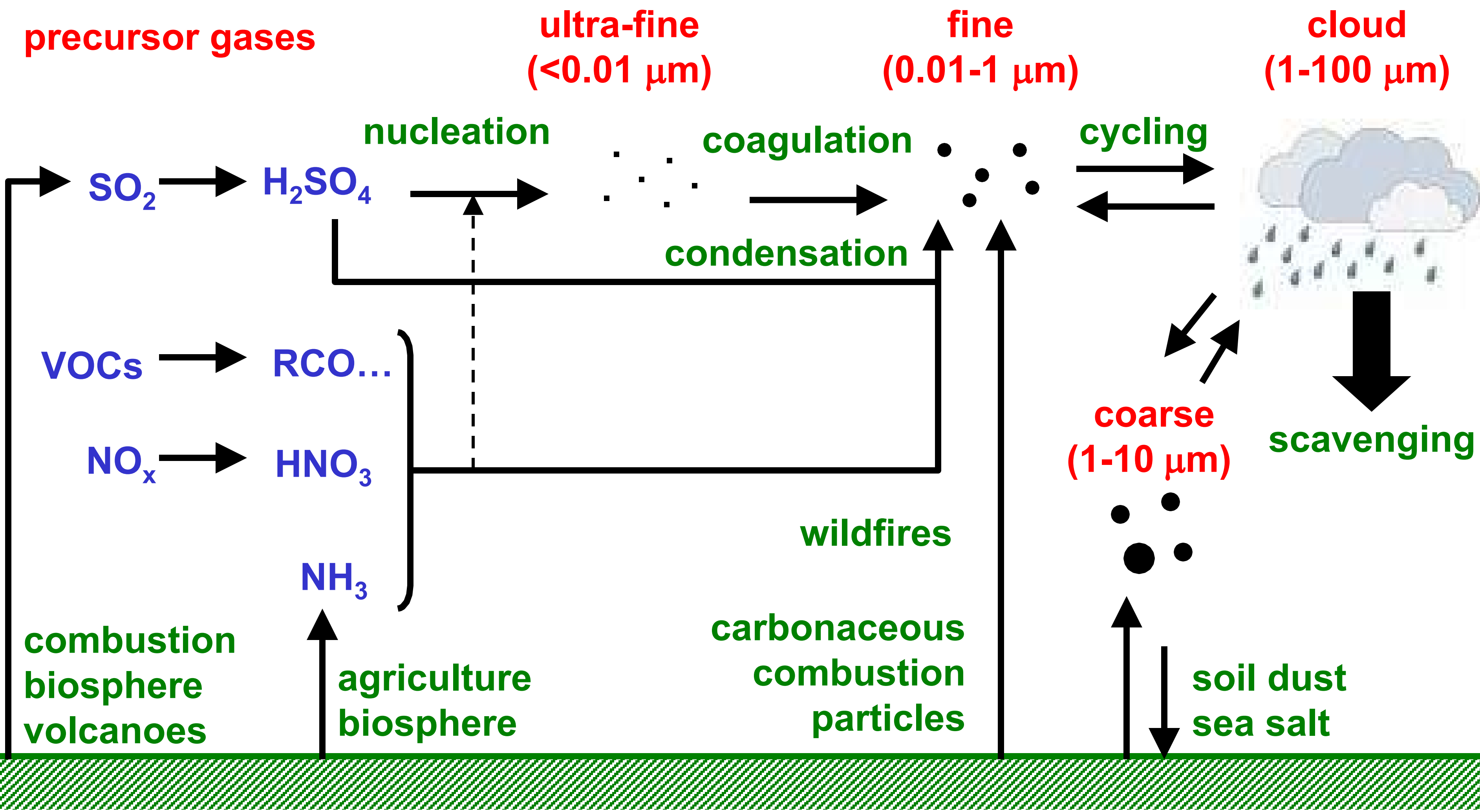
(i) microphysical (by collision and coalescence, as in clouds,
(ii) chemical (e.g., condensation of SO_2 onto dust or black carbon)

processing of aerosols also called "aging"



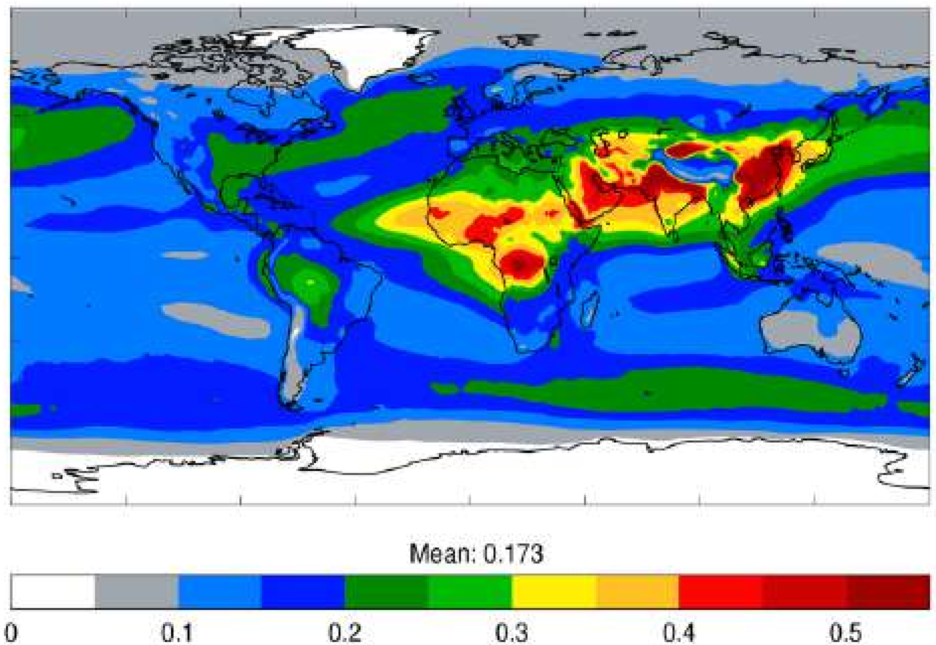


Particulate matter (PM, aerosols) sources and processes

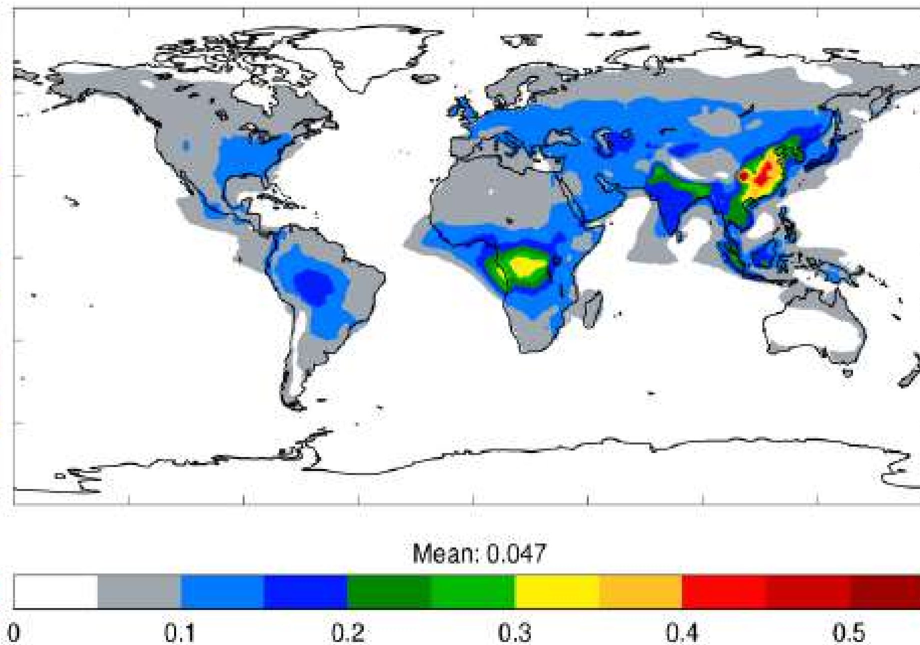


Anthropogenic aerosols

Monitoring Atmospheric Composition and Climate: MACC reanalysis

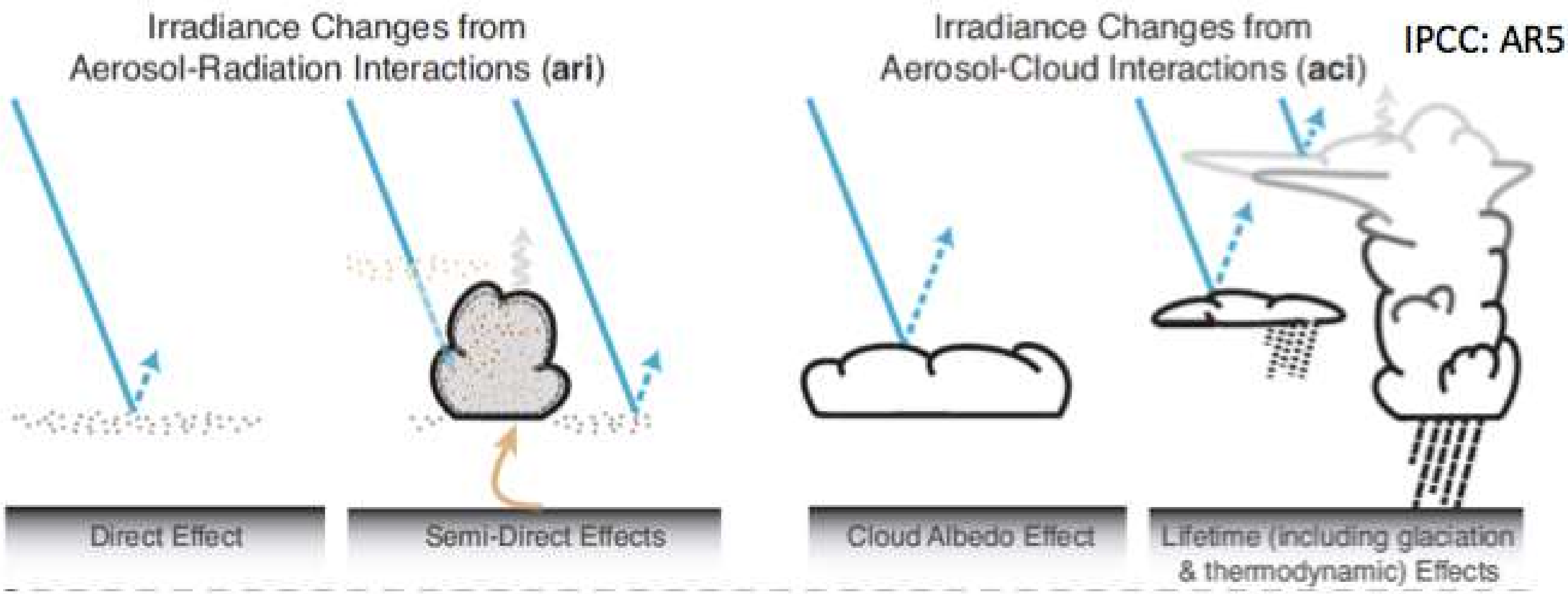


Total Aerosol optical depth (2003-05)
Global annual mean: 0.173



Anthropogenic AOD:
Global annual mean: 0.047
(~ 30%, large regional variability)

Aerosols affect the climate of our Earth in a variety of ways



- **Direct:** Scattering & Absorbing the Solar & IR radiation
- **Semi-direct:** Altering the cloud liquid water by absorbing radiation
- **Indirect:** Influencing the microphysics and life time of clouds

All of these processes ultimately influences the **atmospheric heating pattern** and its temperature structure & hence influence climate

Aerosols affect the climate of our Earth in a variety of ways

Light scattering and absorption: direct and semi-direct effects

→ aerosol particles scatter sunlight
(appear white from above)

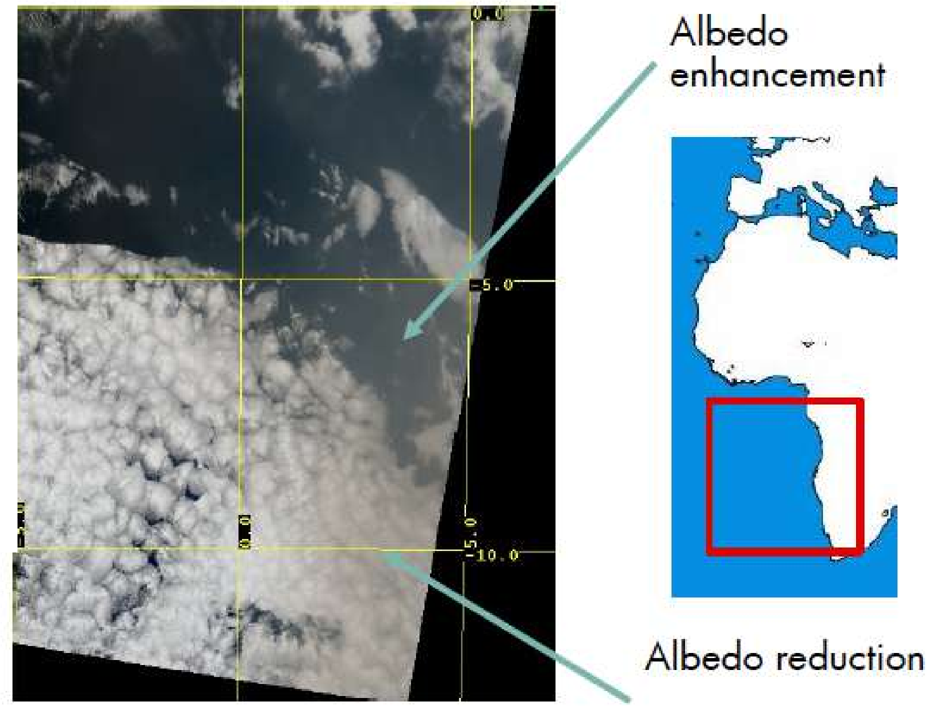
→ some also absorb sunlight
(appear black)

Aerosols affect the climate of our Earth in a variety of ways

Light scattering and absorption: direct and semi-direct effects

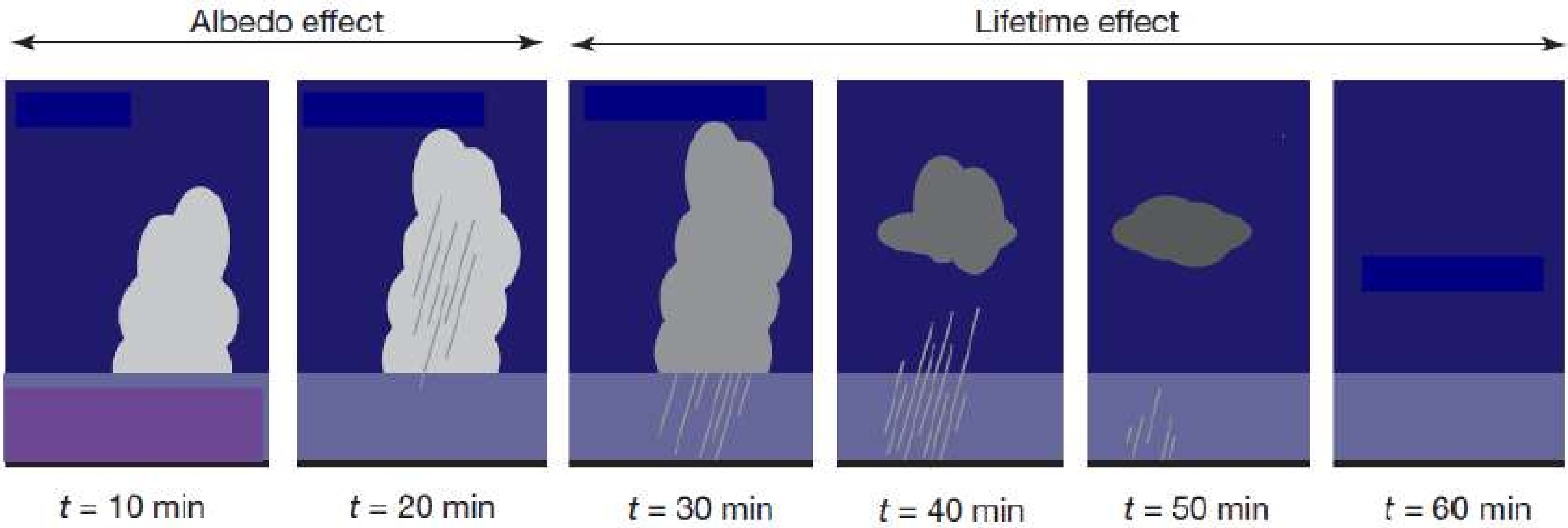
→ Scattering acts to cool system (top-of-atmosphere) and surface
no effect within the atmosphere

→ Absorption acts to warm the system
cools the surface
warms the atmosphere

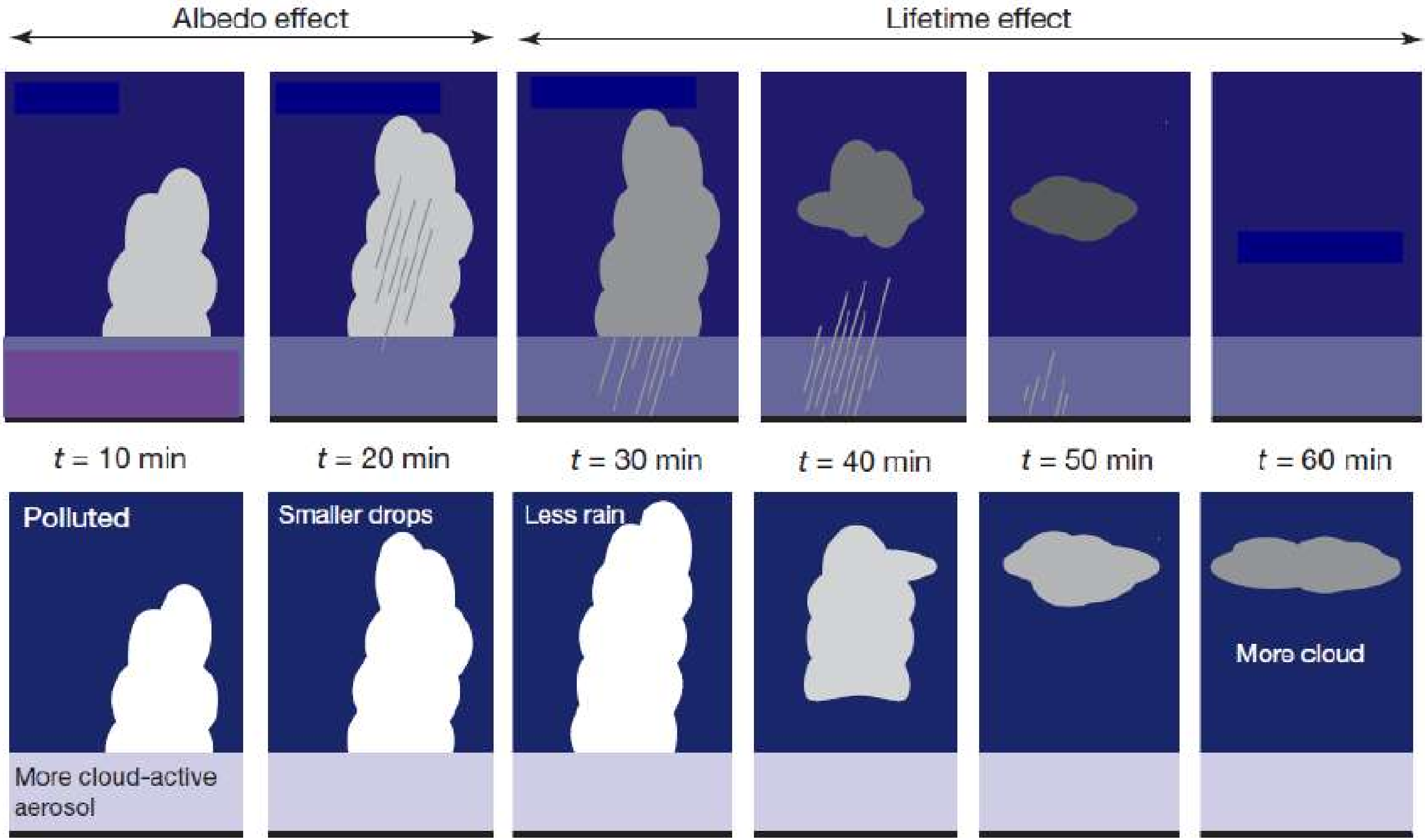


MODIS 13 August 2006

Aerosol-cloud interactions



Aerosol-cloud interactions

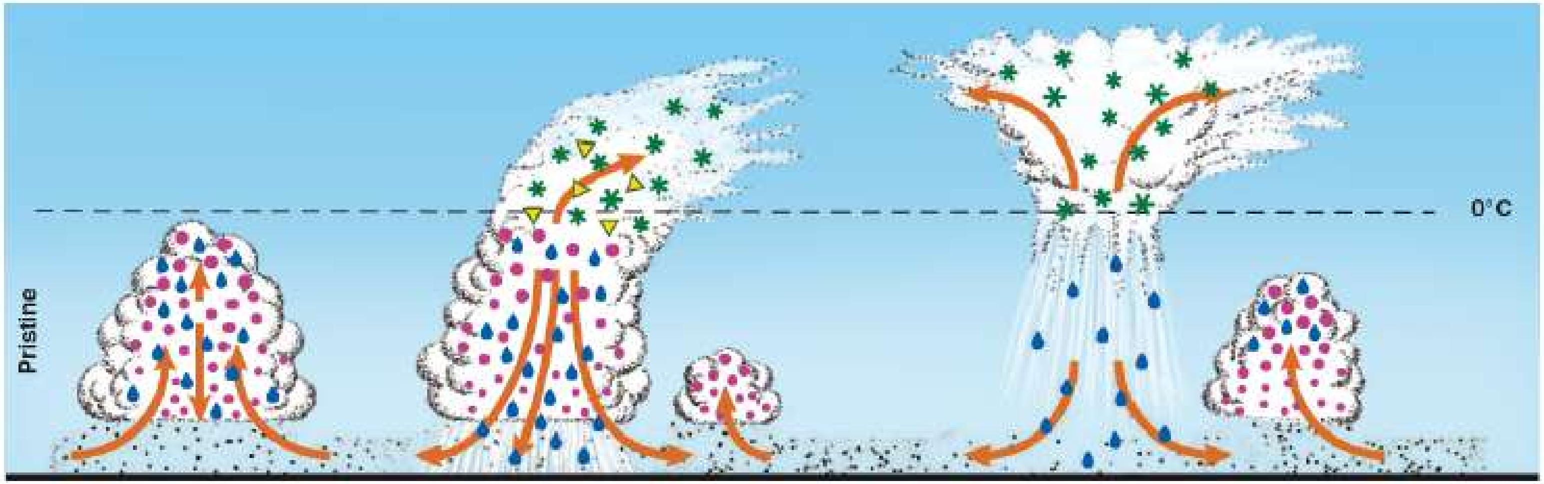


→ **larger cloud liquid water path**

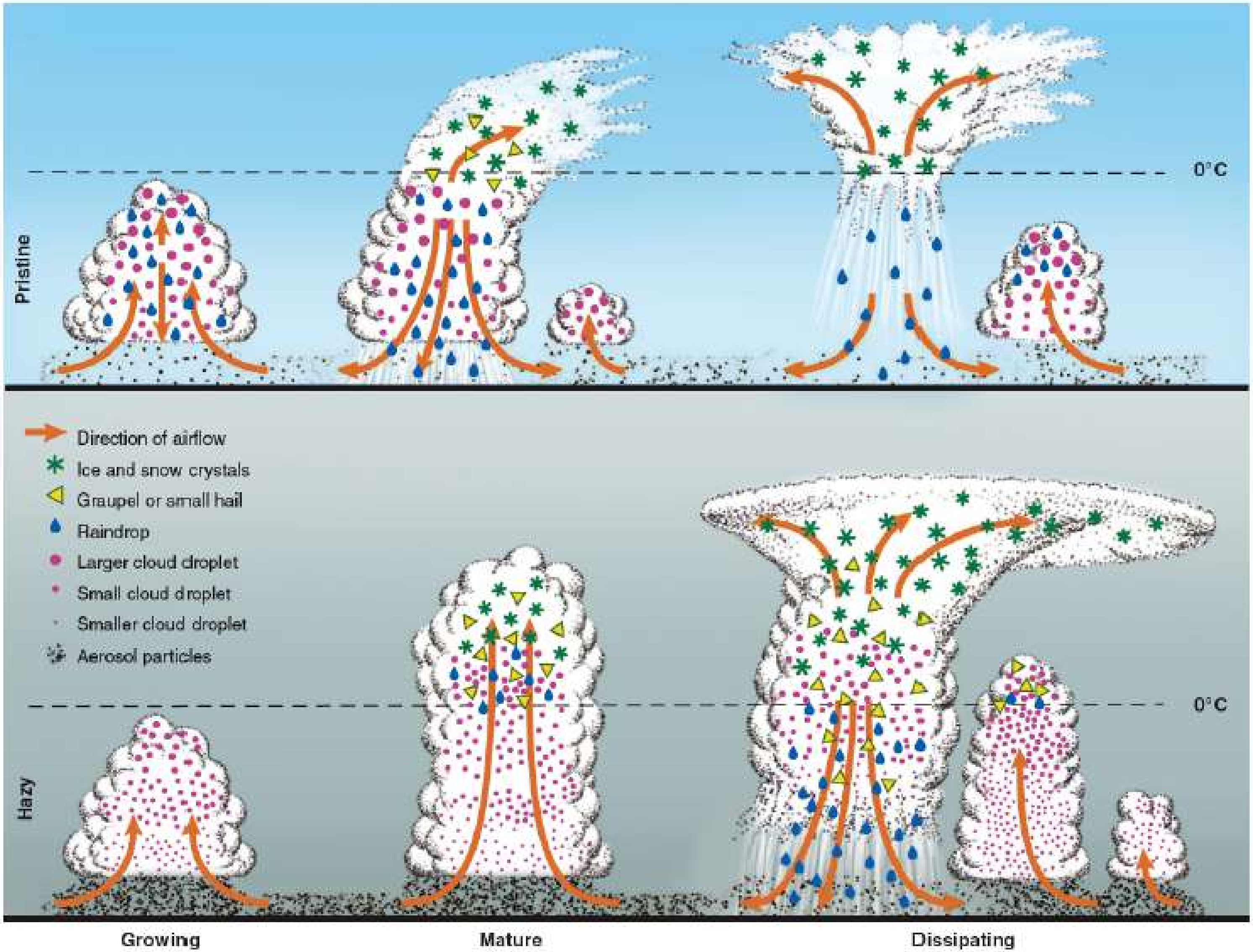
→ **larger cloud fraction**

Albrecht, Science 1989; Stevens and Feingold, Nature 2009

Aerosol-cloud interactions: Cloud Invigoration effect



Aerosol-cloud interactions: Cloud Invigoration effect



(i) delayed precipitation → more liquid water brought to freezing level

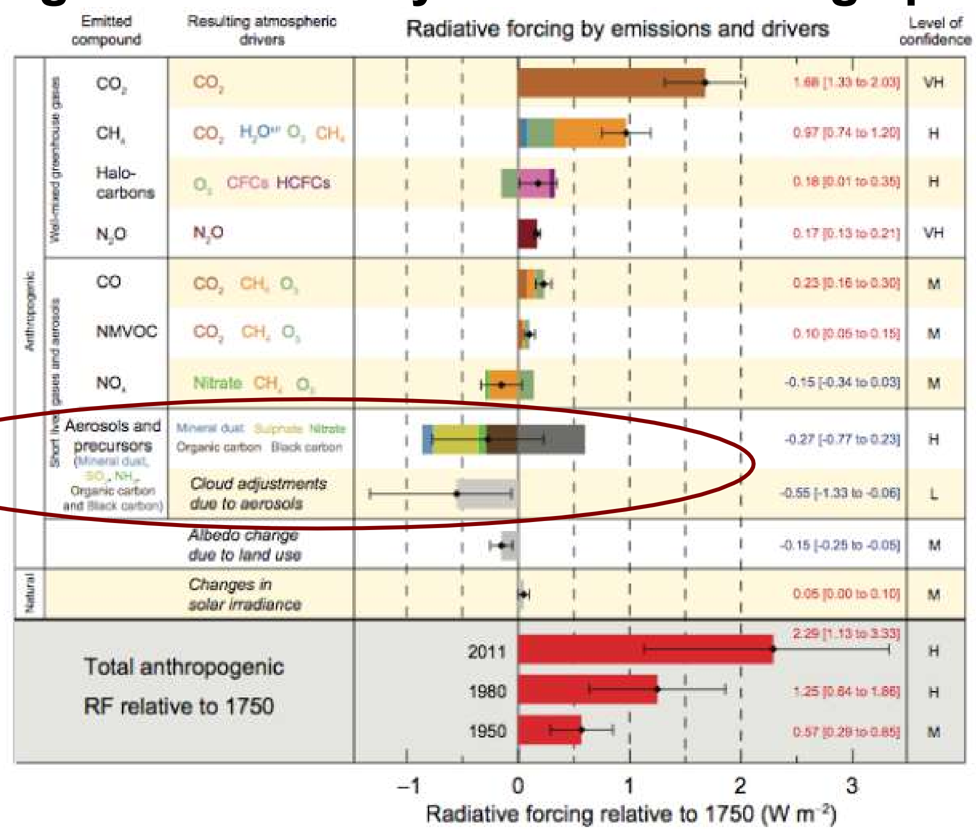
(ii) smaller droplets freeze later (higher) → grow more → more liquid water freezes

→. more latent heat release

Rosenfeld et al., Science 2008

Aerosol-cloud-climate interactions continues to be uncertain

- According to IPCC-AR5, both direct and indirect effect of aerosols produce an **overall cooling effect on the global mean climate**.
- **<u>Large</u>** uncertainty in aerosol effects through direct radiative forcing, associated with large uncertainty in emissions of aerosols.
- **<u>Larger</u>** uncertainty in aerosol effects through cloud radiative forcing.
- **Cloud response to both changing emissions of aerosol as well as greenhouse gases is the largest uncertainty in climate change predictions.**



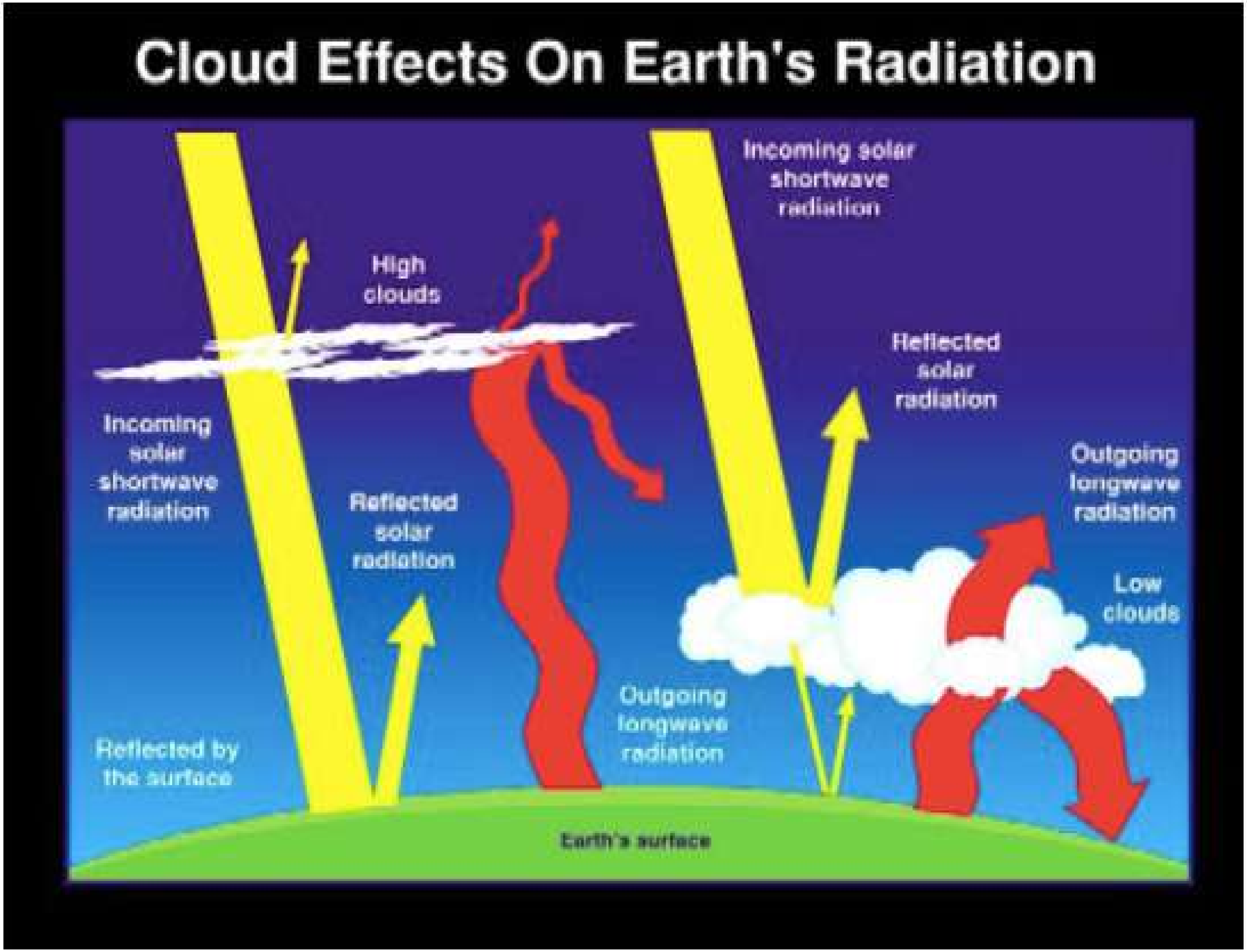
IPCC: AR5

Ingredients for Cloud Formation: Dynamics vs. Microphysics

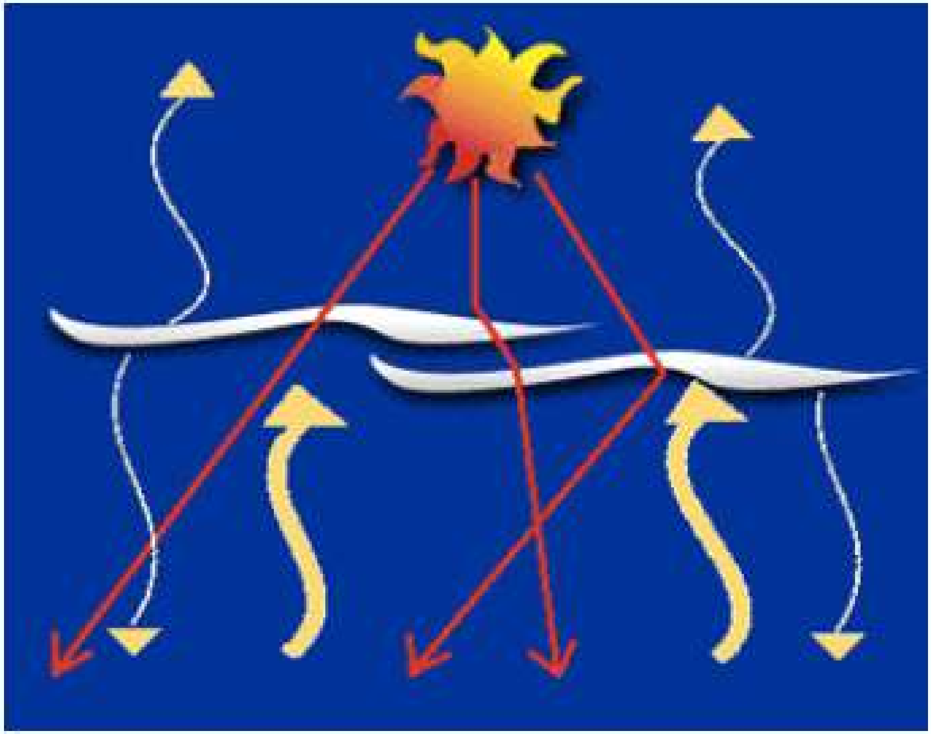
- Cloud formation is mainly decided by atmospheric dynamics
  - Updrafts due to moist convection, orographic uplift, etc.
  - Expansion, cooling, generation of supersaturation, etc.

- Aerosols are an essential ingredient for droplet formation
- Aerosols modify cloud microphysical and optical properties
- **However, in the absence of favorable dynamics, aerosol particles can not form clouds!**

High and low cloud LW radiative forcings

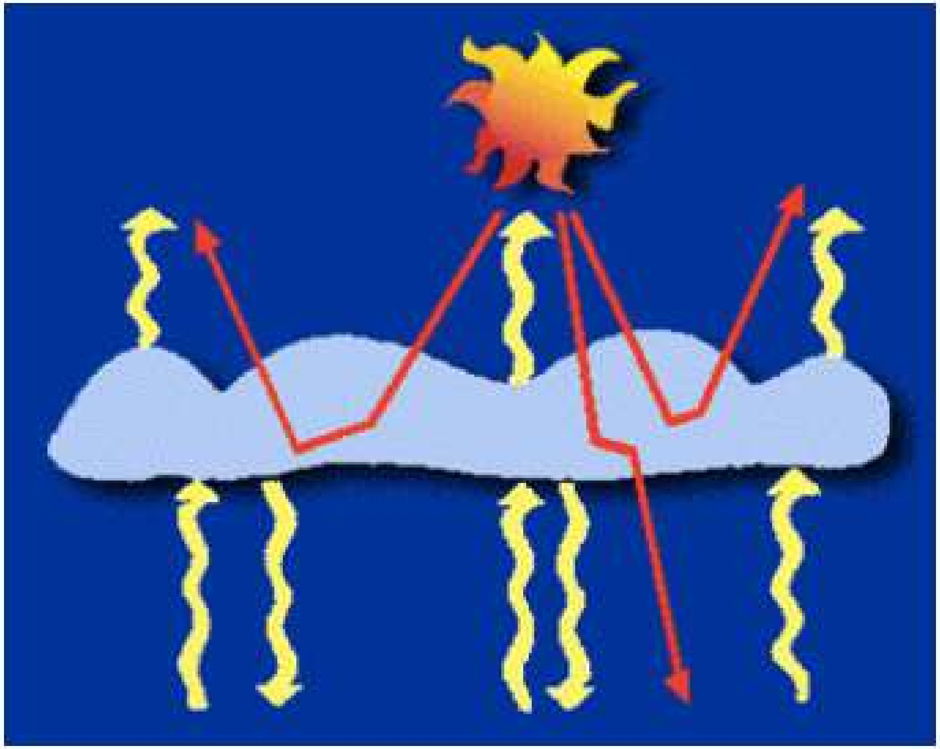


High Clouds



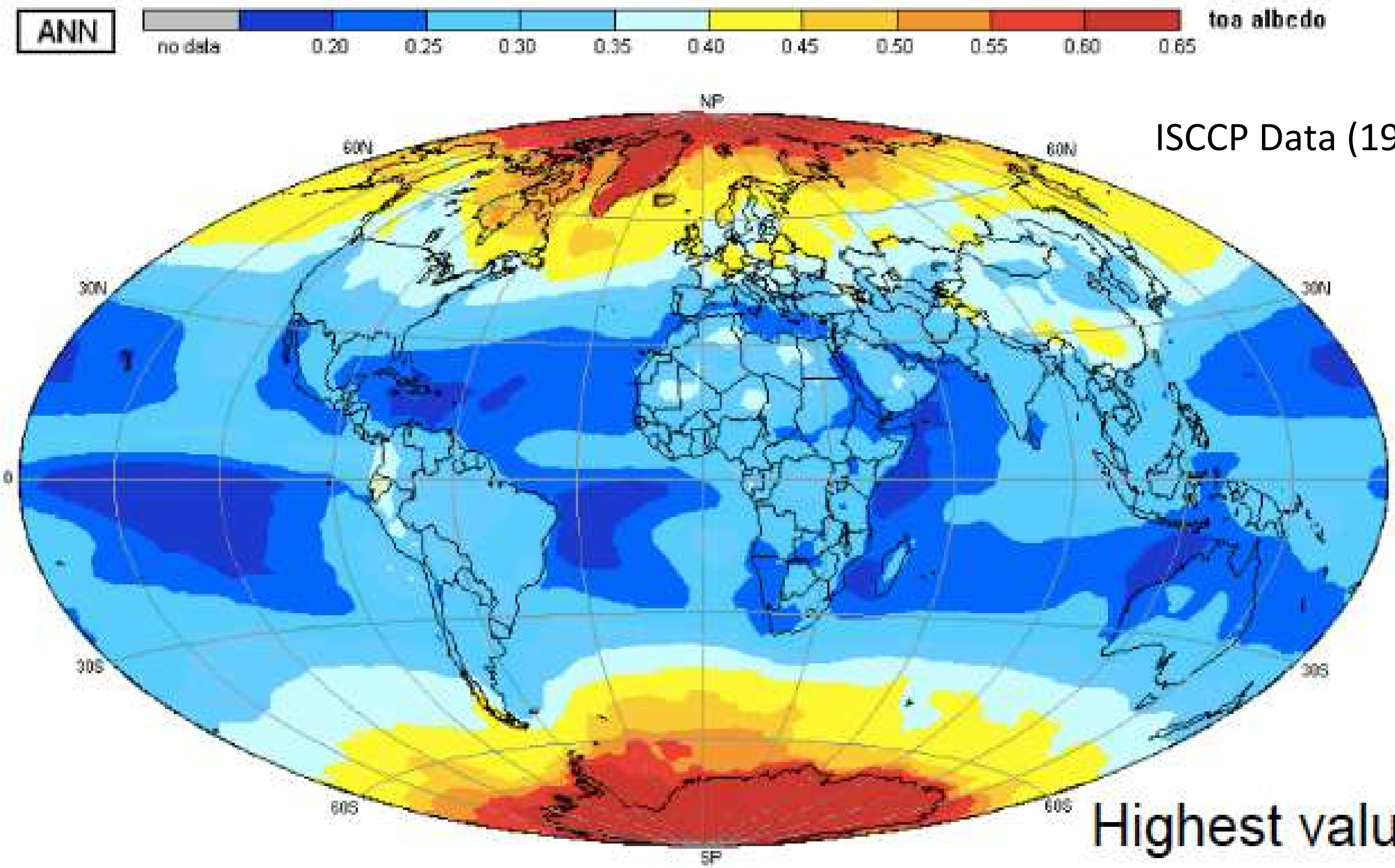
- High, thin cirrus clouds are highly transparent to shortwave radiation
- Albedo approx. 0.2

Low clouds



- lower clouds are much thicker than high cirrus clouds and therefore more reflective.
- Albedo on the order of 0.6 - 0.7

Planetary albedo



ISCCP Data (1991-1995)

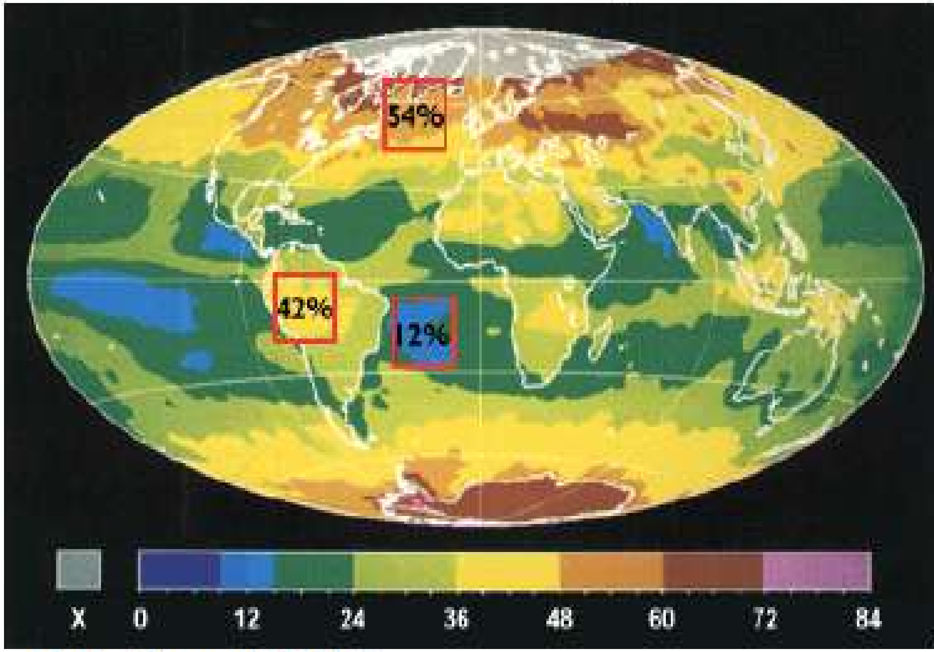
Highest value 0.68

Lowest value 0.16

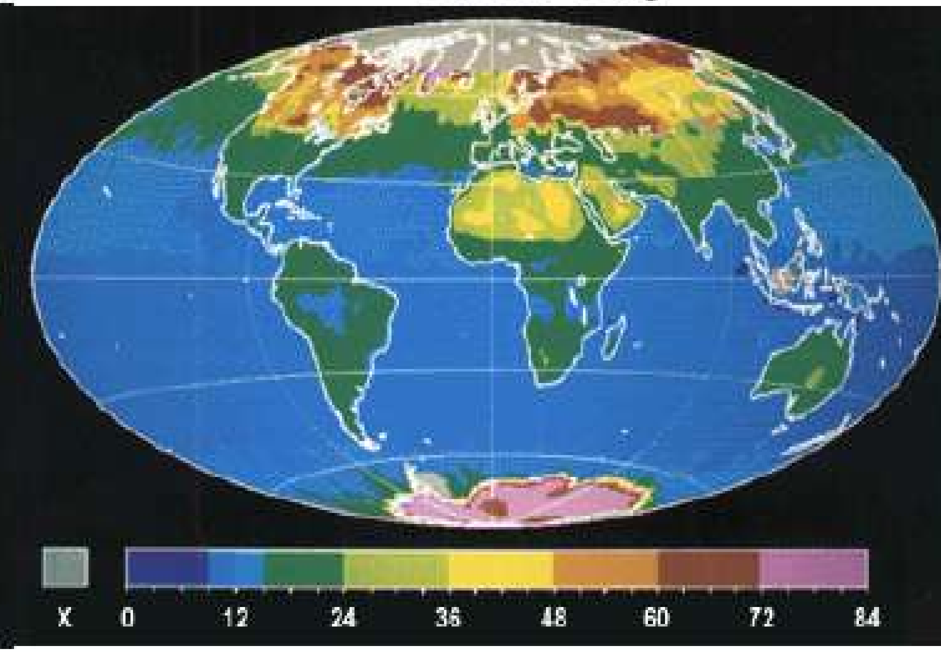
Global mean 0.30

Clear and all sky albedo

All sky



Clear sky



Data from ERBE
Jan. 1986

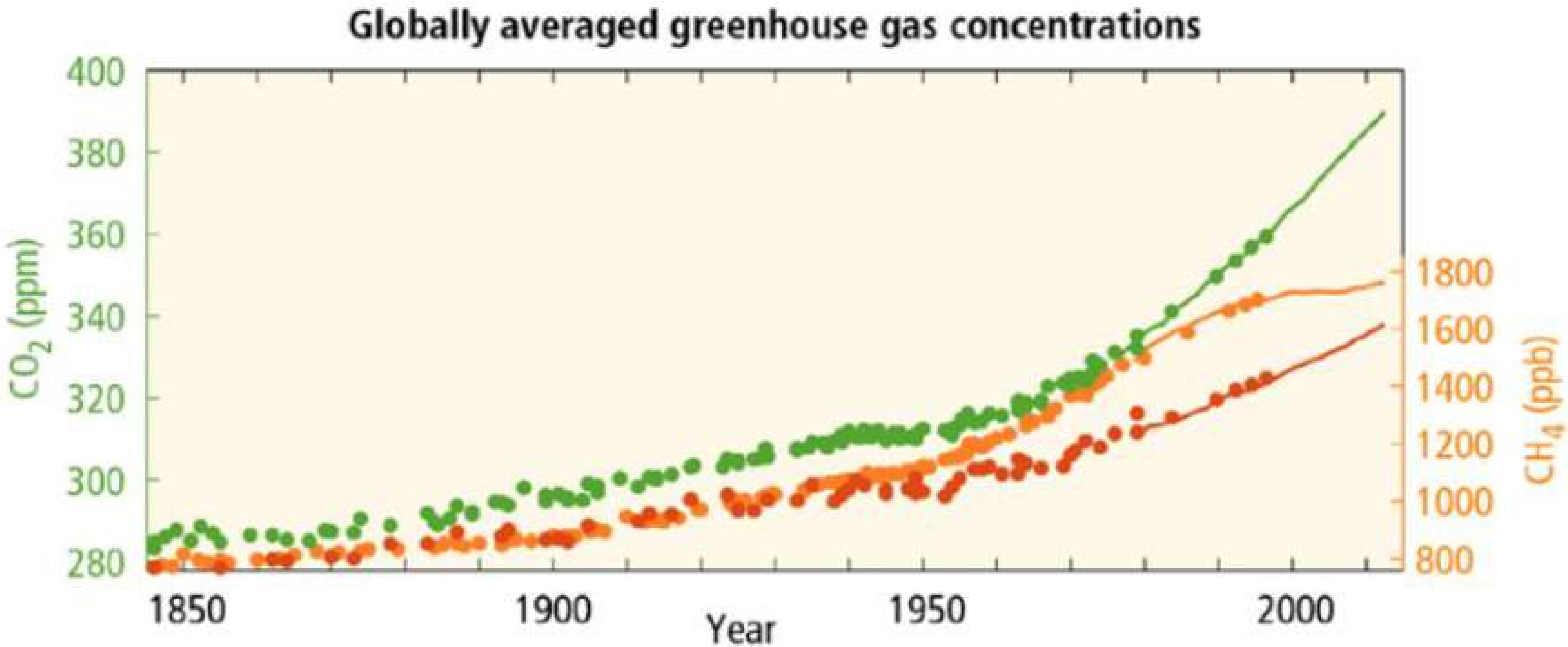
30 %

15 %

Clouds enhance planetary albedo by 15 %

(cf. 1%=3.4 Wm-2, 15 % = 51 Wm-2)

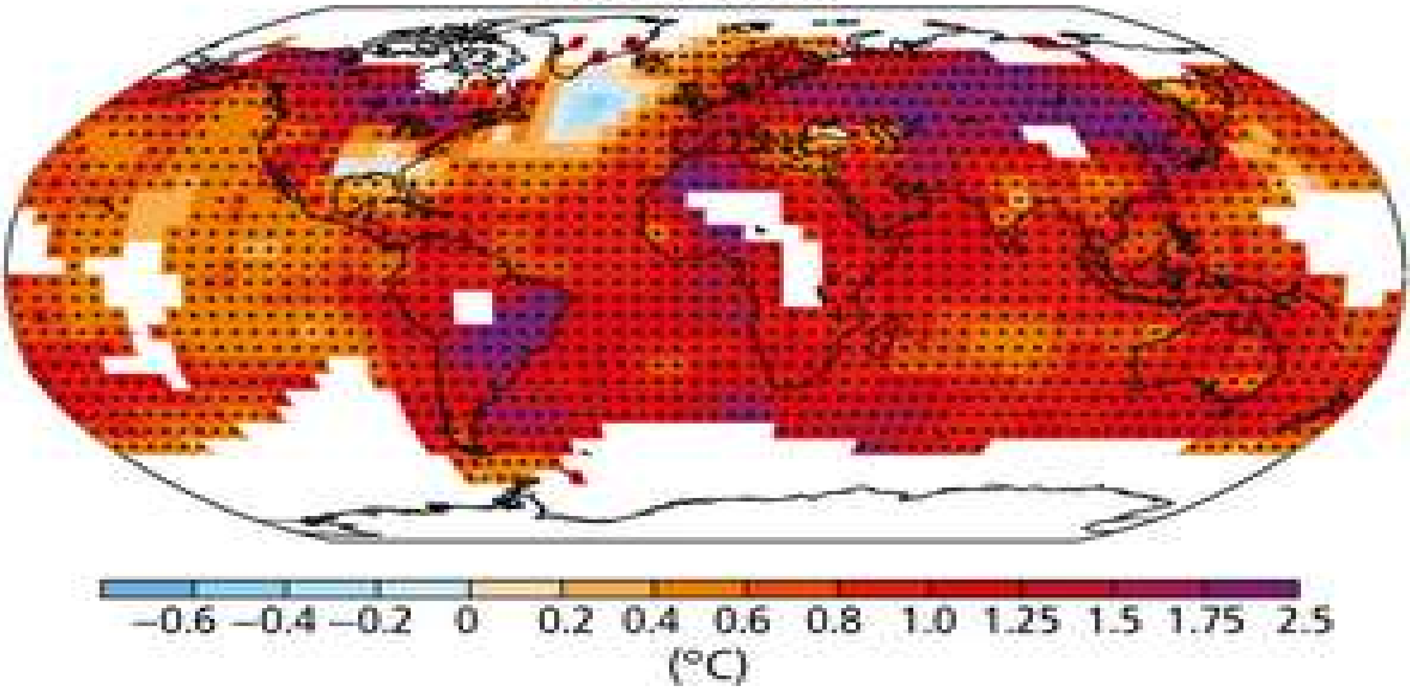
Historical GHG Emission



The atmospheric concentrations of carbon dioxide (CO_2), methane (CH_4), and nitrous oxide (N_2O) have increased to levels unprecedented in at least the last 800,000 years.

Trend of Surface Temperature Increase

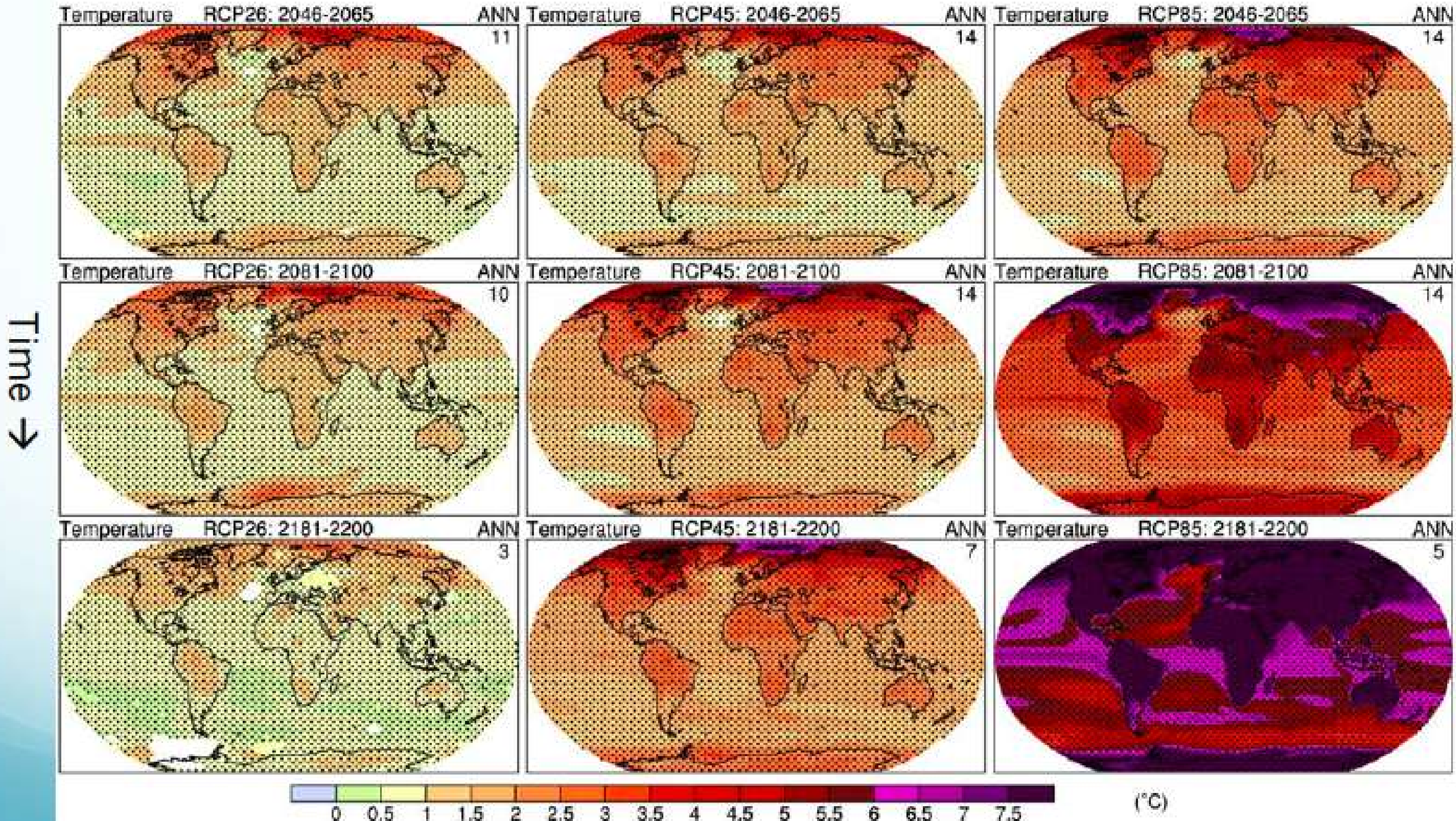
(b) **Observed change in surface temperature 1901–2012**



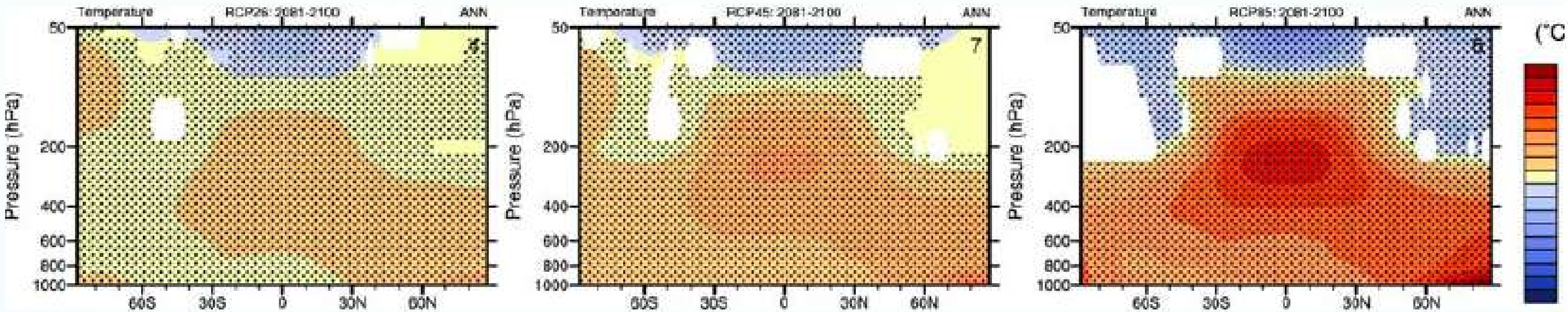
Warming of the climate system is unequivocal

Projections of Future Warming

Scenario: Greenworld → Business as Usual

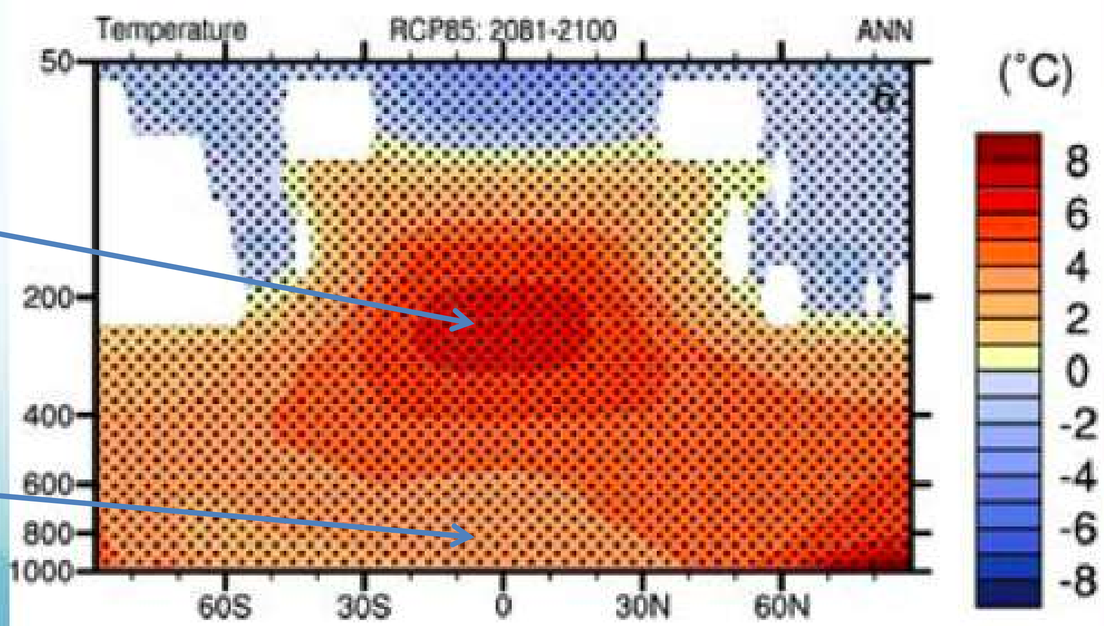


Zonal Structure of Change



More Warming

More Water Vapor



dilipganguly@cas.iitd.ac.in

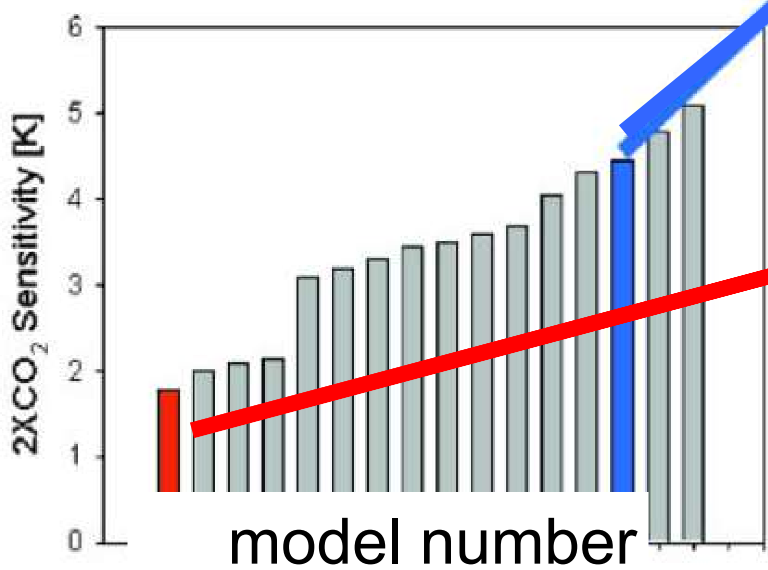
Changing Clouds in Changing Climate

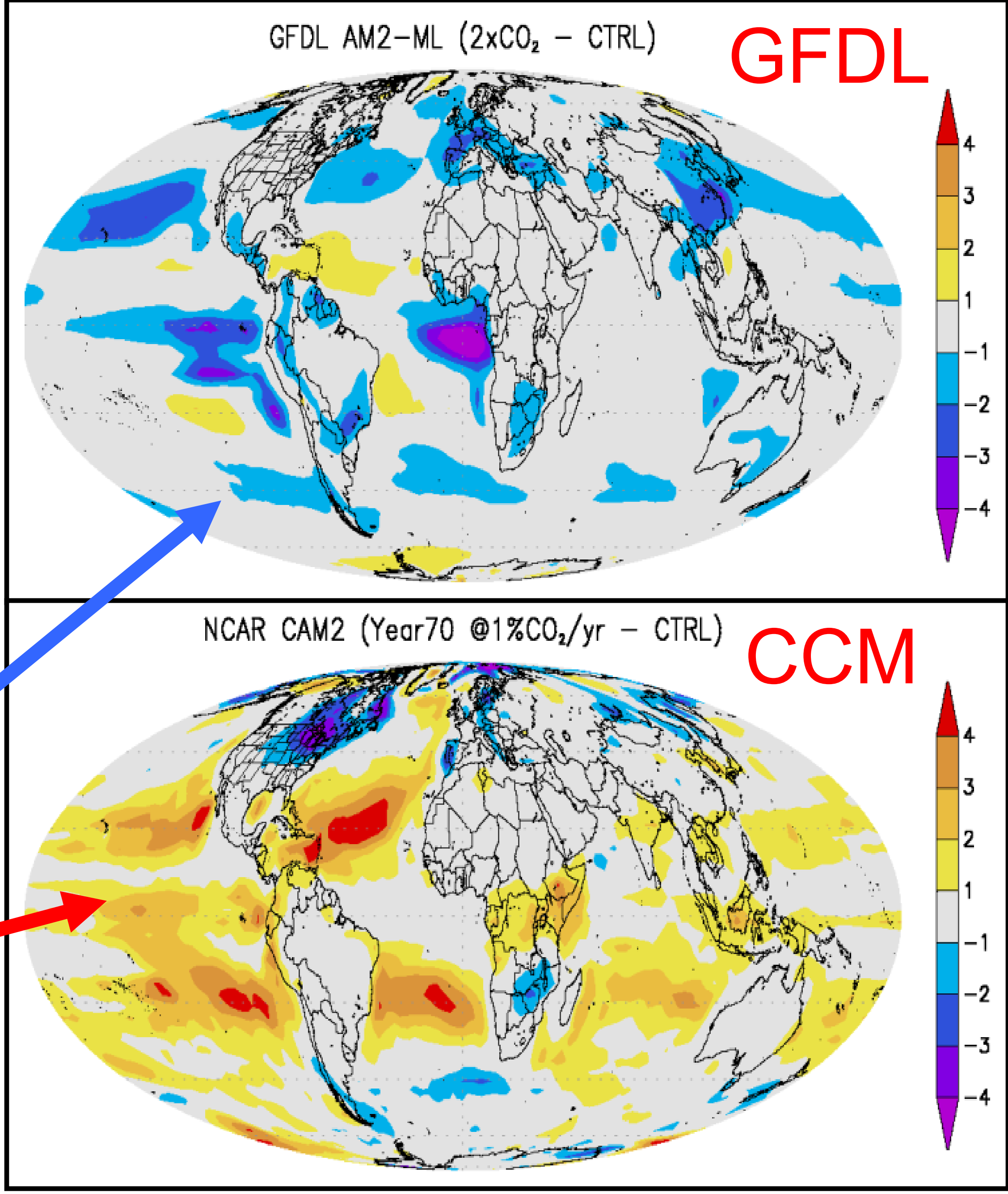
- **Cloud response to global warming (increase in GHG) is also highly uncertain**
  - Increasing CO_2 can change the cloud characteristics by changing the atmospheric temperature structure (eg. by making it more stable).
  - Global warming also increases the atmospheric water vapor.
  - Increase in CO_2 levels is known to cause Global warming, but how the clouds will respond to this global warming is highly uncertain due to our poor knowledge about cloud formation in general and specifically the low cloud response to global warming.

Earth's Climate ⇄ **depends on** Planetary albedo / Absorption of LW ⇄ **influenced by** Clouds ← Aerosols, GHG

Cloud feedbacks in climate models

- change in low cloud amount for $2\times CO_2$



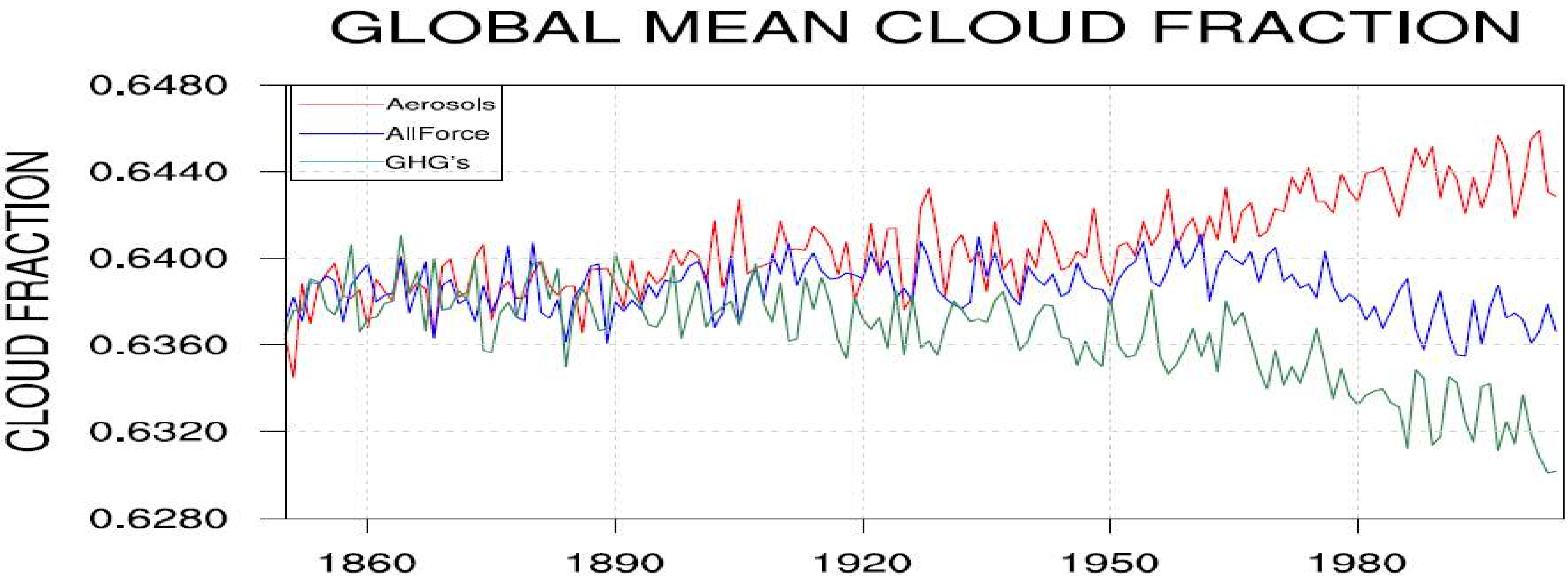


from Stephens (2005)

Which clouds matter most ?

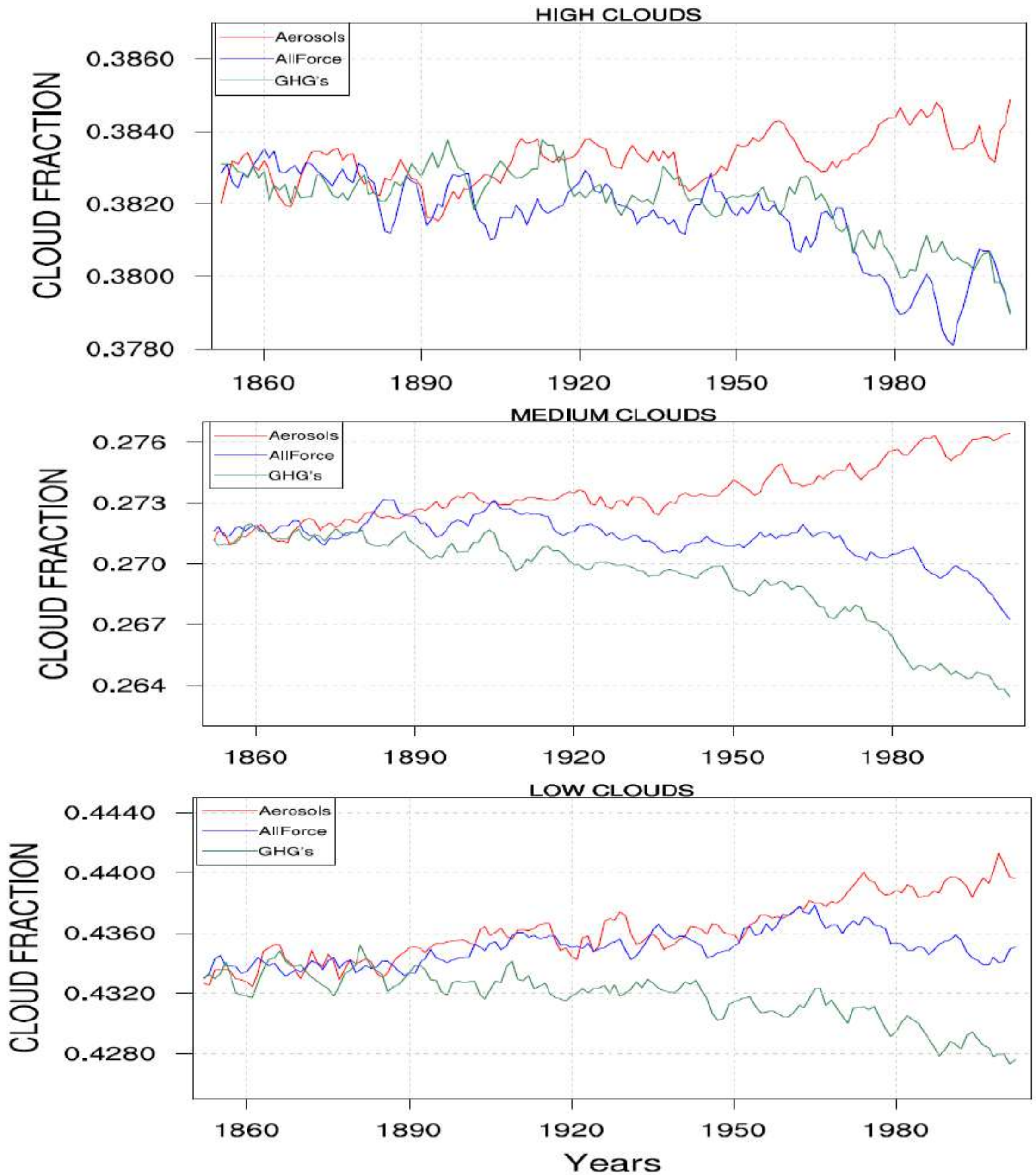
- Low clouds provide strong shortwave (SW) forcing
  - Strong contrast with underlying dark ocean
  - Radiate at ~ same T° as ocean therefore no longwave effect
- High clouds (cirrus) provide longwave (LW) forcing by trapping outgoing longwave radiation
- Persistent and frequently occurring clouds

Global Annual Mean Cloud Fraction from CESM1 simulations



- Changing aerosol emissions alone are resulting in increase in cloud fraction from 1950 onwards
- Changing GHG emissions alone are resulting in decrease in cloud fraction from early part of 20^{th} century.
- When aerosols and GHG emissions are both allowed to change, global mean cloud fraction also shows a weakly decreasing trend over last few decades.

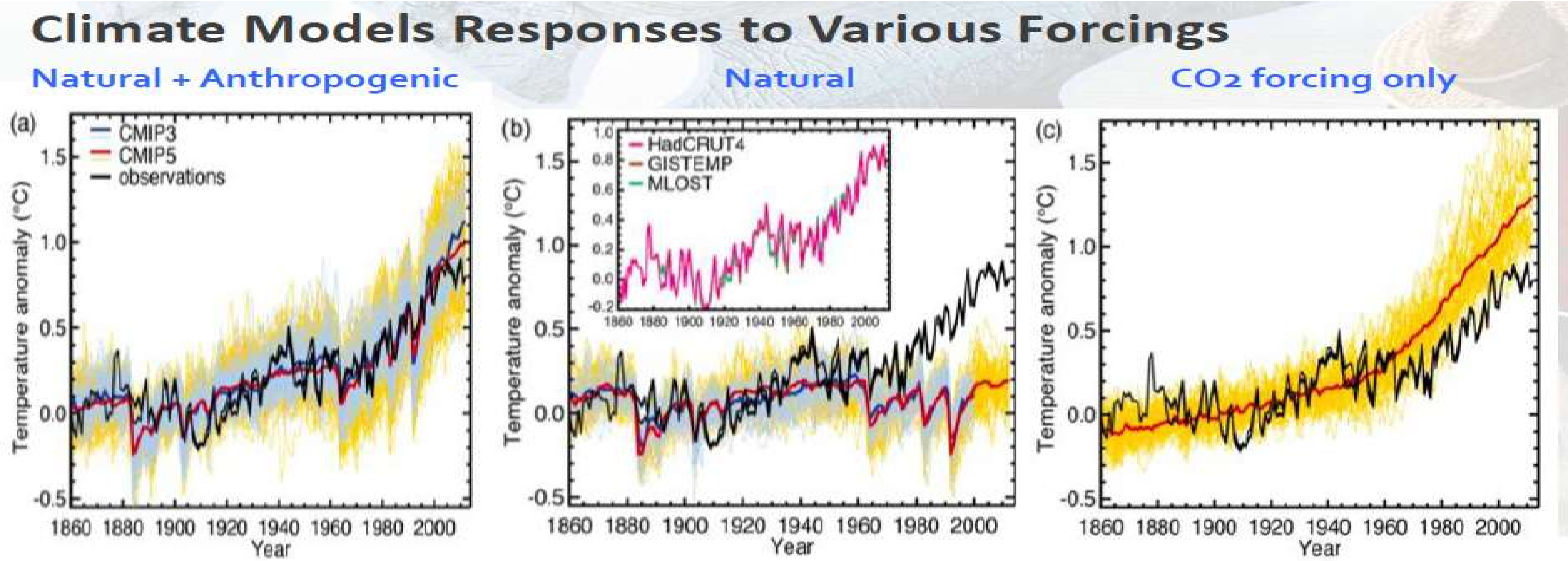
Global Annual Mean Cloud Fraction from CESM1



- Global mean MID and HIGH level clouds show trends similar to TOTAL cloud fraction for all three experiments.
- However, the global mean LOW clouds for All-forcing experiment does not show any significant trend over the entire period from 1850 to 2005.

Climate Models as tool to Quantify Climate System Responses to Aerosol and GHG Forcing

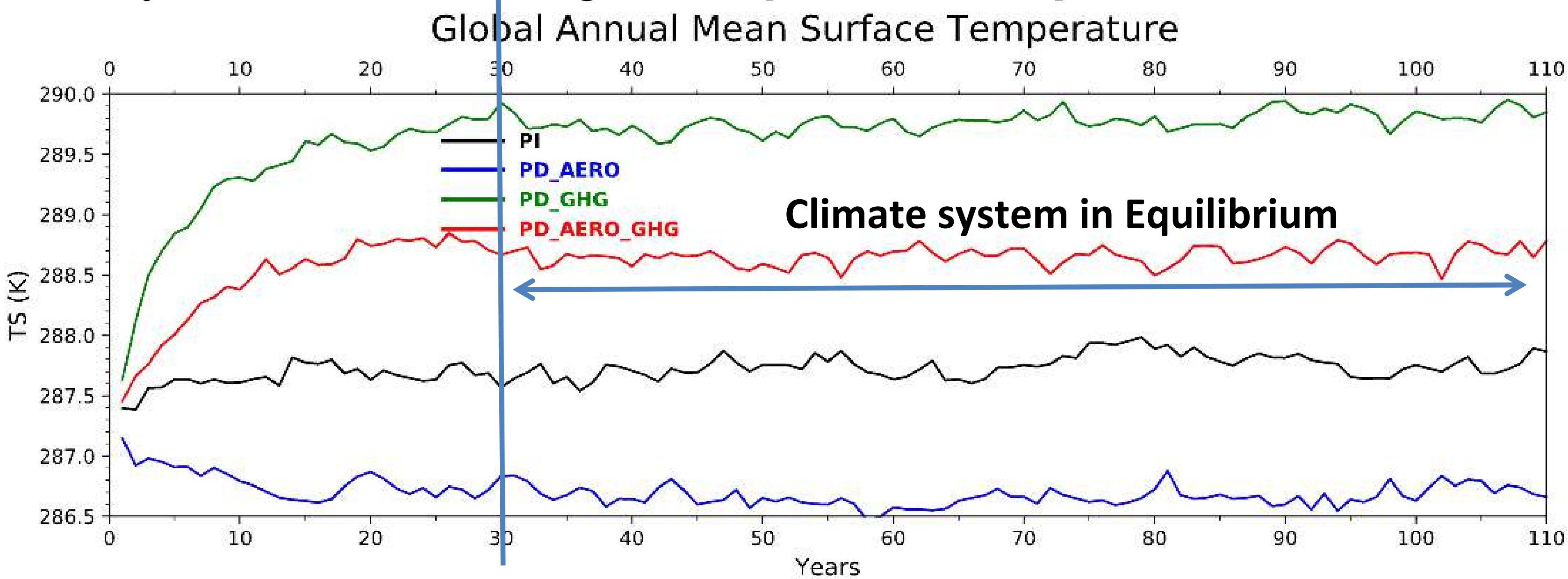
- **Transient climate response:** It quantifies the response of the climate system to a continuously **changing radiative forcing** on a decadal to century timescale using a **fully coupled AOGCM**.



- **Advantage:** It can be directly compared with observations & hence useful for detection and attribution of climate change.
- **Disadvantage:** Models exhibit a slow response time with lot of variability, so they require multicentury control (computationally very expensive).

Quantification of Climate System Responses to Aerosol Forcing

- **Equilibrium climate response:** It quantifies the response of the climate system to **constant radiative forcing** on a decadal to multi-century time scales using a **coupled atmosphere-slab ocean model**.



- **Advantage:** Possible to identify the climate responses to individual forcing agents separately. Useful for understanding processes. Computationally less expensive compared to full AOGCM.
- **Disadvantage:** Results may not be directly compared with observations. Limitations due to lack of full ocean dynamics.

Multi-scale response of climate to radiative forcing

- **Equilibrium Climate response** to any forcing agent such as aerosols can be conceptualized as a combination of a **fast and a slow** component

Fast Response: These include responses of the climate system that are induced through the direct impact of aerosols on radiation, clouds and land surface, **before the global surface temperature can change**.

- ✓ Mostly works on **shorter time scale (hours to weeks)**
- ✓ Can be significant up to ~ 1000s of km away from the location of forcing (in case it is localized as for aerosols).
- ✓ Only **rapid adjustments are included** as part of the response.
- ✓ Can be estimated using atmospheric GCMs with prescribed SST.

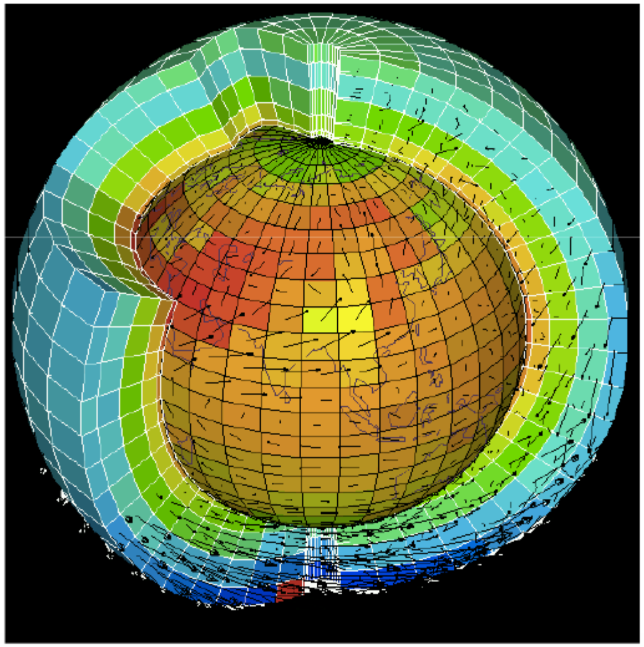
Multi-scale response of climate to aerosol forcing

Slow Response: These include responses of the climate system to global surface temperature change (mainly SST change) induced by changes in aerosol emissions.

- ✓ Works over **longer time (months - years)** and almost **global scale**.
- ✓ Can be **significant globally** depending upon the magnitude of forcing
- ✓ **Feedbacks** are part of the Slow response.
- ✓ Positive feedback to initial forcing makes Slow response stronger than the Fast response.
- ✓ On a global scale, Slow response is usually stronger than the Fast response.
- ✓ However, locally or regionally, relative strength of the Fast and Slow response depends on both the sign and magnitude of the forcing as well as feedbacks.
- ✓ Can be estimated only using atmosphere-ocean coupled GCMs with SST responding to changes in forcing.

Multi-scale nature of aerosol-climate interactions

How to reconcile the *spatial* and *temporal* gaps between General Circulation Models (GCM) and aerosol/cloud microphysics?



A typical GCM gridbox (~300 km ´ ~300 km)

<u>The size of</u> <u>any state in India such as Bihar</u>

Aerosols (~1 nm to ~1 μm)

<u>A continuous size distribution spanning 3 orders of magnitude</u>

Cloud droplets (10 μm to 30 μm)

A difference of 10 orders of magnitude!

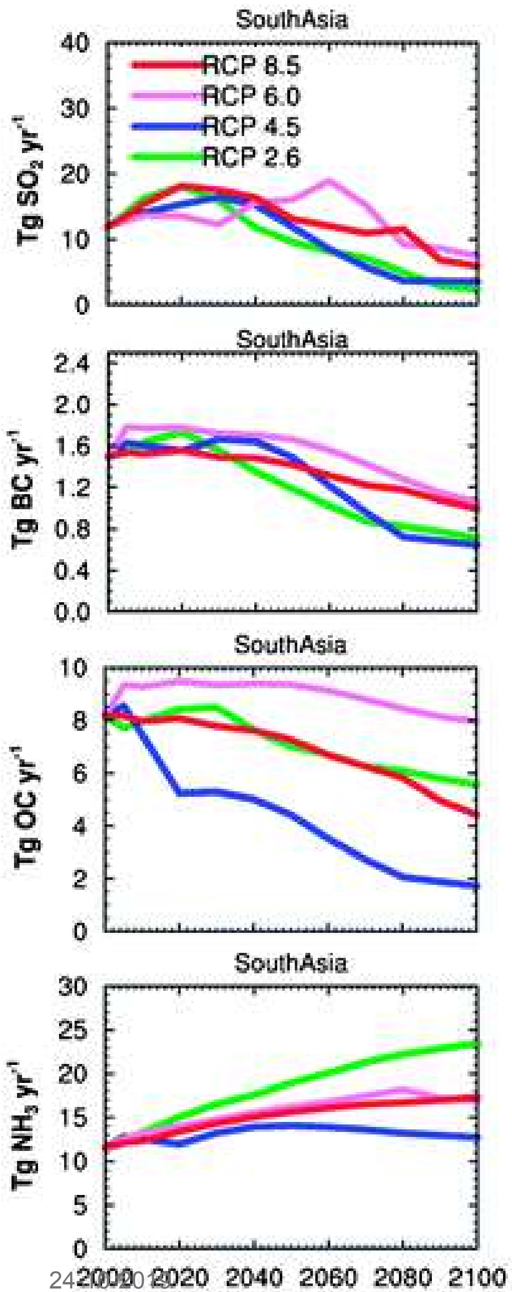
A typical GCM timestep (30 min.)

A typical microphysics timestep (1 sec.)

A difference of 3 orders of magnitude!

This Scale Problem is tackled through parameterization

How aerosols can modulate the Indian summer monsoon



Fiore et al., [2012]

- South Asia is a region where aerosol sources are expected to change in the future due to rapid growth in industrialization as well as changes in land use land cover patterns.

- The regional climate of India and the monsoon is expected to change in response to changes in aerosol emissions because **aerosols can change the atmospheric heating pattern associated with monsoon.**

Selected modeling (GCMs with different complexities) studies that address aerosol impacts on the Indian summer monsoon

S. No.	Study	Model Used	SST	Aerosol Treatment	Aerosol Effects	Effect on monsoon
1.	Ramanathan et al. (2005) *PNAS*	NCAR PCM Coupled AOGCM	Prognostic	Prescribed forcing based on INDOEX	Direct	Reduction in rainfall over India ↓
2	Lau et al. (2006) *Clm.Dyn.*	NASA FvGCM	Prescribed climatology from observation	Prescribed aerosol distribution	Direct	Advancement, Intensification of monsoon ↑
3.	Chung and Ramanathan (2006) *J.Clim*	NCAR CCM3	Prescribed trends in meridional SST gradients	Prescribed forcing based on INDOEX	Direct	Decrease in Rainfall during summer ↓
4.	Randles & Ramaswamy (2008) *J.G.R.*	GFDL AM2	Prescribed	Prescribed from offline calculation	Direct, Semi-direct	Increase over northwest India, decrease elsewhere ↓
5.	Meehl et al. (2008) *J.Clim.*	NCAR CCSM3	Prognostic	Prescribed BC from offline CTM	Direct, Semi-direct	↑ Increase during pre-monsoon, decrease during monsoon ↓
6.	Wang et al. (2009) *G.R.L.*	Modified NCAR CAM3-SOM	Prognostic	Prognostic	Direct	Northwest shift in monsoon rainfall ↑

Selected modeling (GCMs with different complexities) studies that address aerosol impacts on the Indian summer monsoon

S. No.	Study	Model Used	SST	Aerosol Treatment	Aerosol Effects	Effect on monsoon
7.	Kuhlmann and Quass (2010) *A.C.P.*	RTM used in ECHAM5	–	Prescribed based on CALIPSO	Direct	EHP is too weak to influence monsoon circulation
8.	Cowan and Cai (2011) *G.R.L.*	Coarse resolution CSIRO-AOGCM	Prognostic	Prognostic	Direct, Semi-direct, Indirect	Decrease in monsoon (Non-Asian aerosols also contribute)
9.	Bollasina et al. (2011) *Science*	GFDL-CM3	Prognostic	Prognostic	Direct, Semi-direct, Indirect	Summertime drying over central India
10.	Ganguly et al. (2012a) *J.G.R.*	NCAR CAM5-SOM	Prognostic	Prognostic	Direct, Semi-direct, Indirect	Decrease in rainfall over most parts of India, increases over northwest
11.	Ganguly et al. (2012b) *G.R.L.*	NCAR CAM5	Prescribed based on Ganguly et al. (2012a)	Prognostic	Direct, Semi-direct, Indirect	Most of the reduction in rainfall is due to slow response
12	Vinoj et al. (2014) Nat. Geoscience	NCAR CAM5	Prescribed	Prognostic	Direct, Semi-direct, Indirect	Positively correlated with rainfall ~7 days

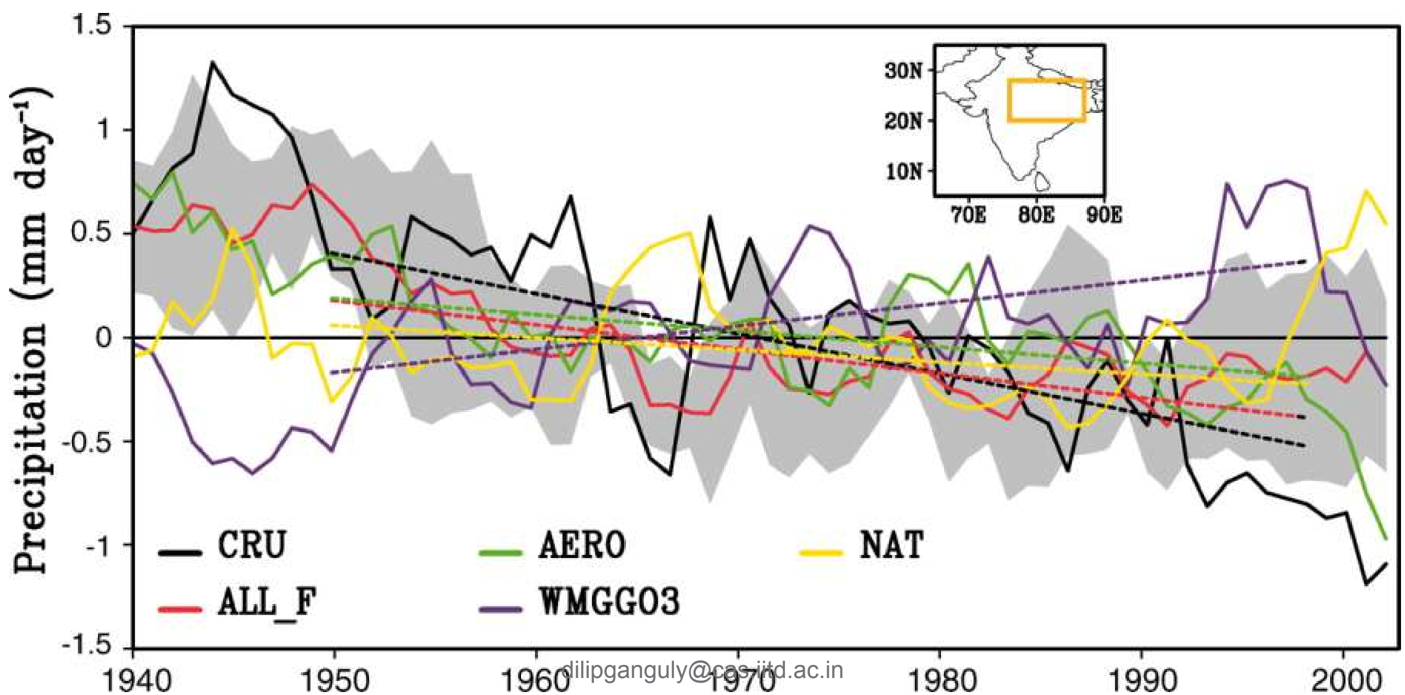
Selected modeling (GCMs with different complexities) studies that address aerosol impacts on the Indian summer monsoon

Study	Model used	SST	Aerosol Tratment	Aerosol effects	Effects on monsoon
Kovilakam and Mahajan (2016)	CAM4_SOM	Prognostic	Prescribed	Direct	100xBC results in increase in JJAS monsoon
Krishnan et al. (2016)	LMDZ4	Evolving SST Prescribed from previously conducted Coarse resolution AOGCM with same forcing	Prescribed	Direct + Semi-direct	Decrease in seasonal mean rainfall due to aerosols alone

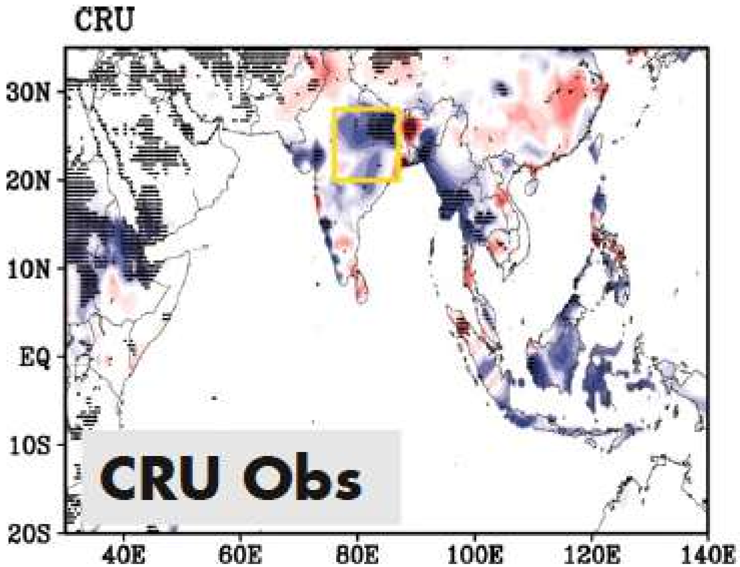
❖ Transient climate response of the south Asian summer monsoon to aerosols and GHGs:

Bollasina et al., [2011]

Conducted a series of fully coupled-climate model experiments to investigate the South Asian monsoon response to natural and anthropogenic forcings and concluded that the observed drying trend over the central Indian region during the second half of 20th century is an outcome of human-influenced aerosol emissions through a slowdown of the tropical meridional overturning circulation

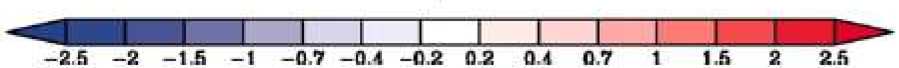


Aerosol impact on the Indian summer monsoon



Linear trends 1950-1999 in June-September precipitation

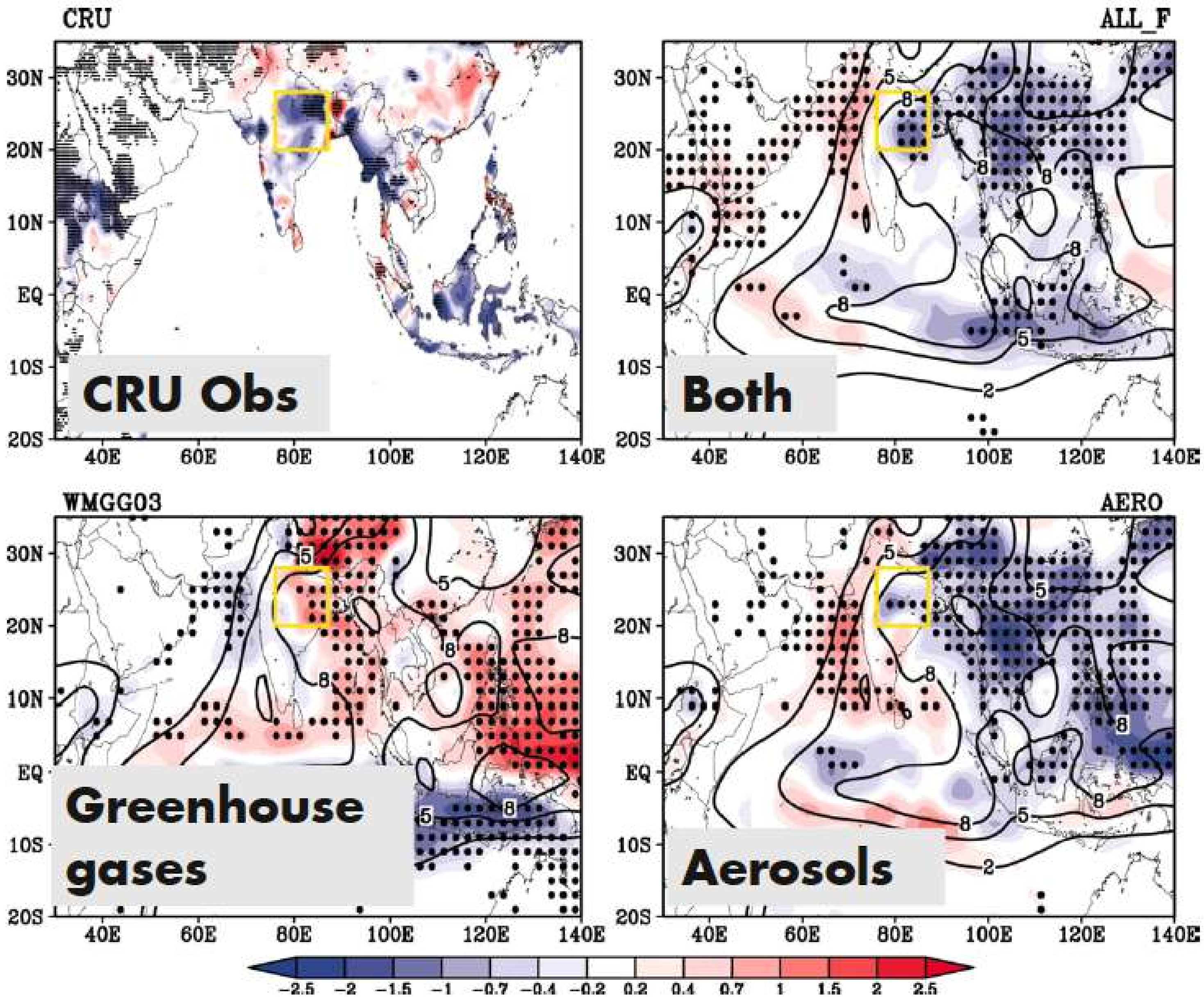
[mm day^{-1} (50 yr)$^{-1}$]



dilipganguly@cas.iitd.ac.in

Bollasina et al., Science 2011

Aerosol impact on the Indian summer monsoon



Linear trends 1950-1999 in June-September precipitation

[mm day^{-1} (50 yr)$^{-1}$]

Slowdown of meridional overturning compensates hemispherical energy imbalance

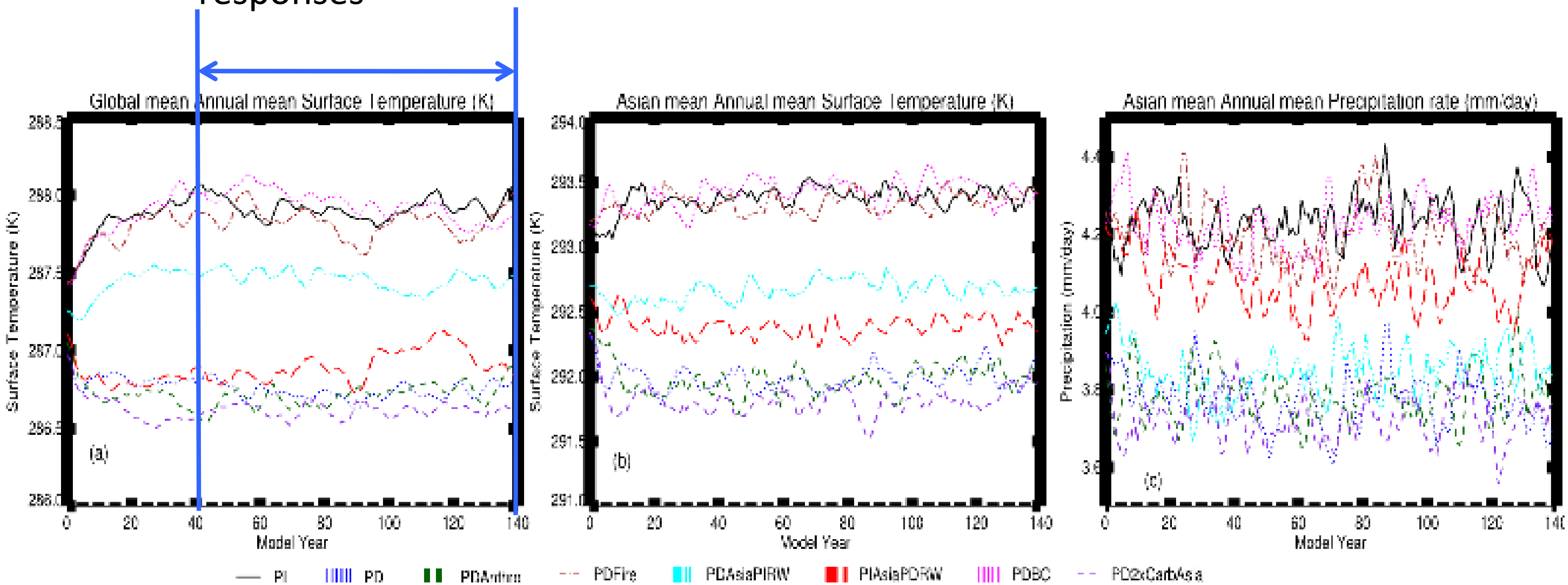
Bollasina et al., Science 2011

❖ Equilibrium climate response of the south Asian summer monsoon to aerosol forcings:

Global mean Annual mean Surface air temperature and precipitation

This data was analyzed for climate responses

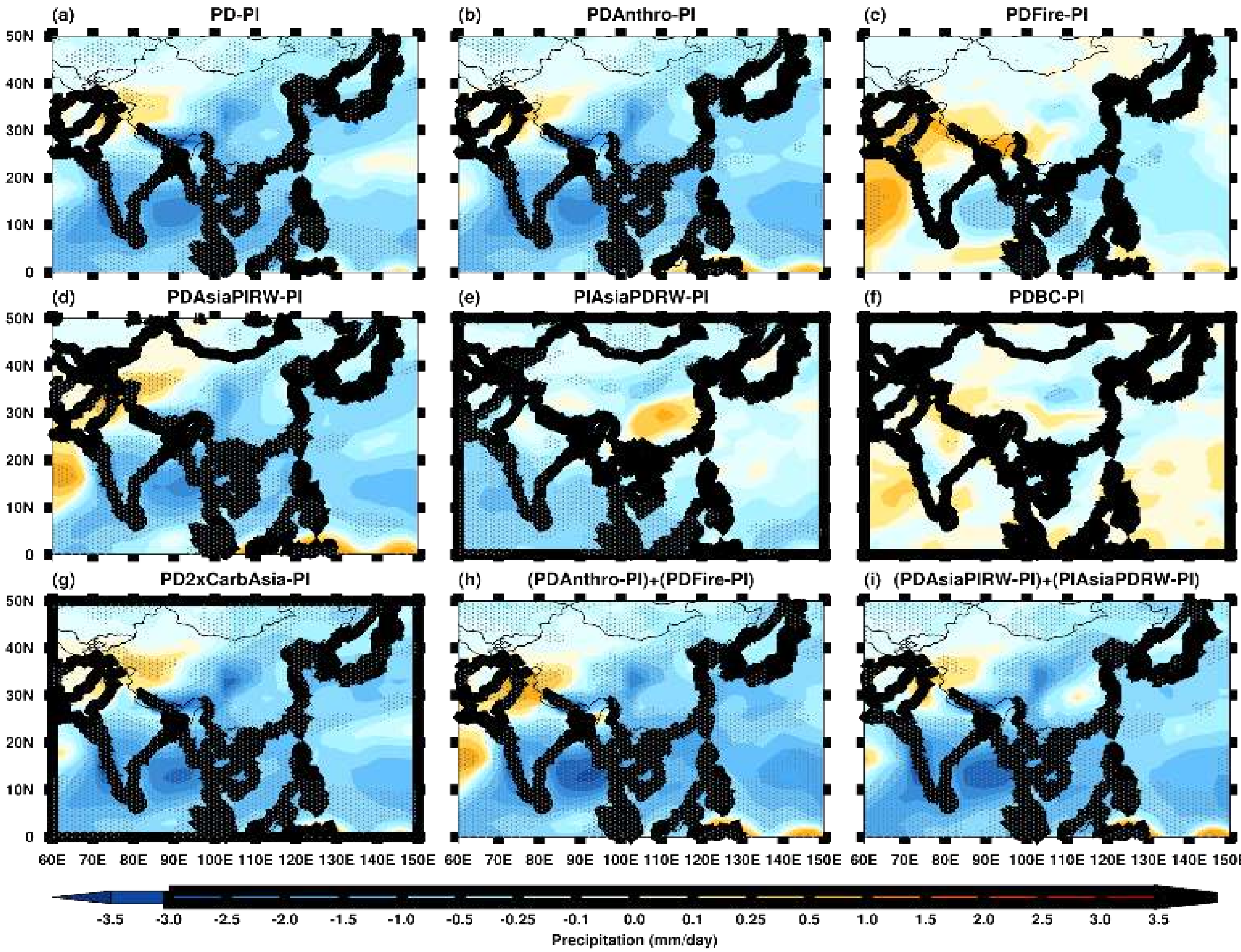
Ganguly et al., [2012]



Increases in anthropogenic aerosol emission from local and remote sources cause a reduction in mean summer monsoon precipitation over most parts of South Asia.

While precipitation responses are primarily driven by local aerosol forcing, regional surface temperature changes over Asia is strongly influenced by anthropogenic aerosols from sources further away (non-local changes).

JJAS mean response in precipitation rate (mm/day)



Increases in anthropogenic aerosol emission from local and remote sources cause a reduction in summer monsoon precipitation over most parts of South Asia

Doubling anthropogenic OC/BC emissions produces the same basic signatures in precipitation responses

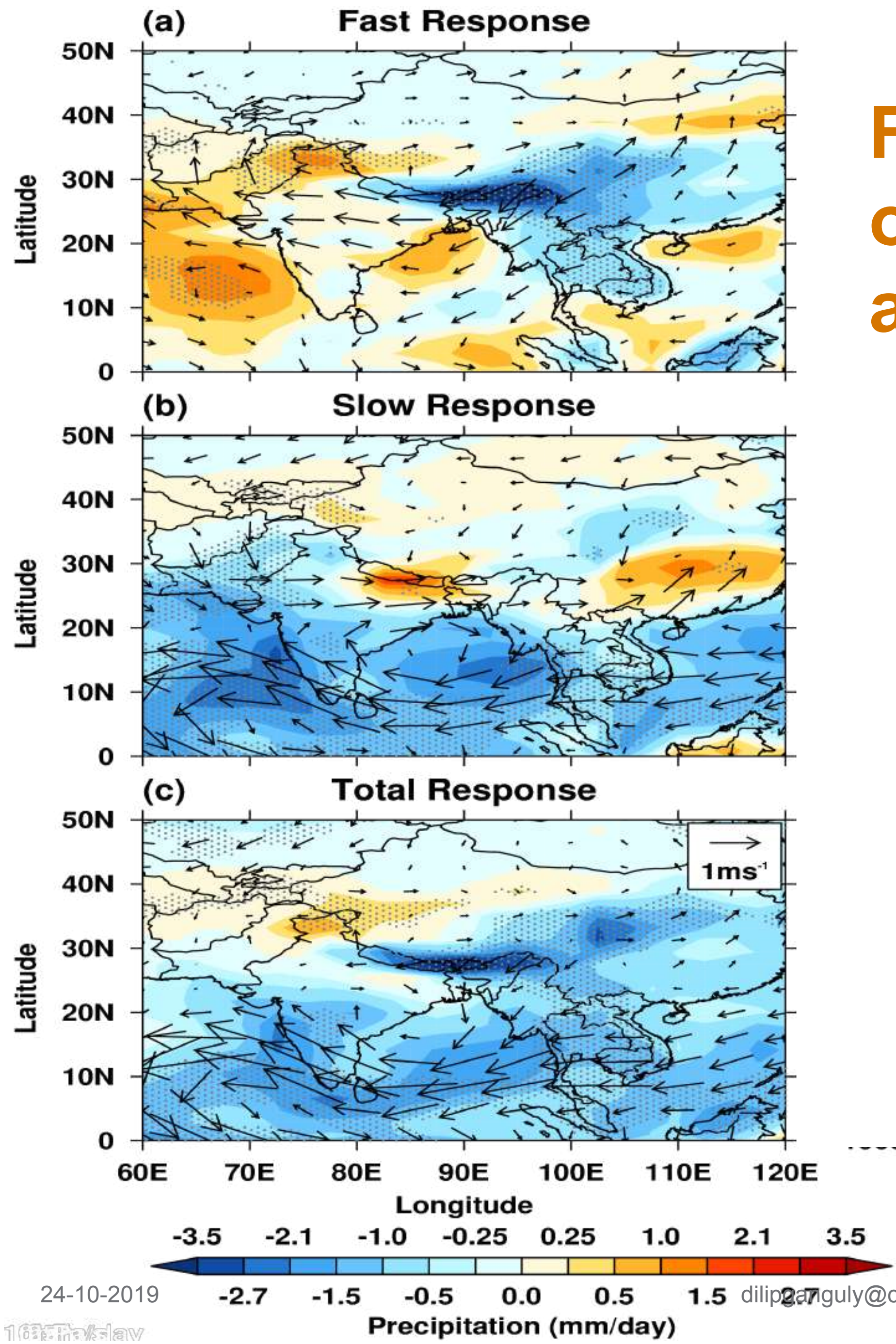
Ganguly et al., 2012, JGR

Question: How much and which of the precipitation responses to increases in anthropogenic aerosols are due to direct impact of aerosols on radiation, clouds and land surface (rapid adjustments) versus those due to SST change caused by changes in aerosol emissions and clouds

Fast Response: These include responses that are induced through the direct impact of aerosols on radiation, clouds and land surface (rapid adjustments)

Slow Response: These include responses to global surface temperature change (or SST change) induced by changes in aerosol emissions

Ganguly et al., 2012, GRL



Fast and slow responses of the monsoon system to anthropogenic aerosols

- SST changes caused by aerosols play a more important role than the aerosol's direct impact on radiation, clouds and land surface (rapid adjustments) in shaping the overall equilibrium response of the monsoon system to aerosol forcing

Ganguly et al., 2012, GRL

ARTICLE

DOI: 10.1038/s41467-018-06015-5 OPEN

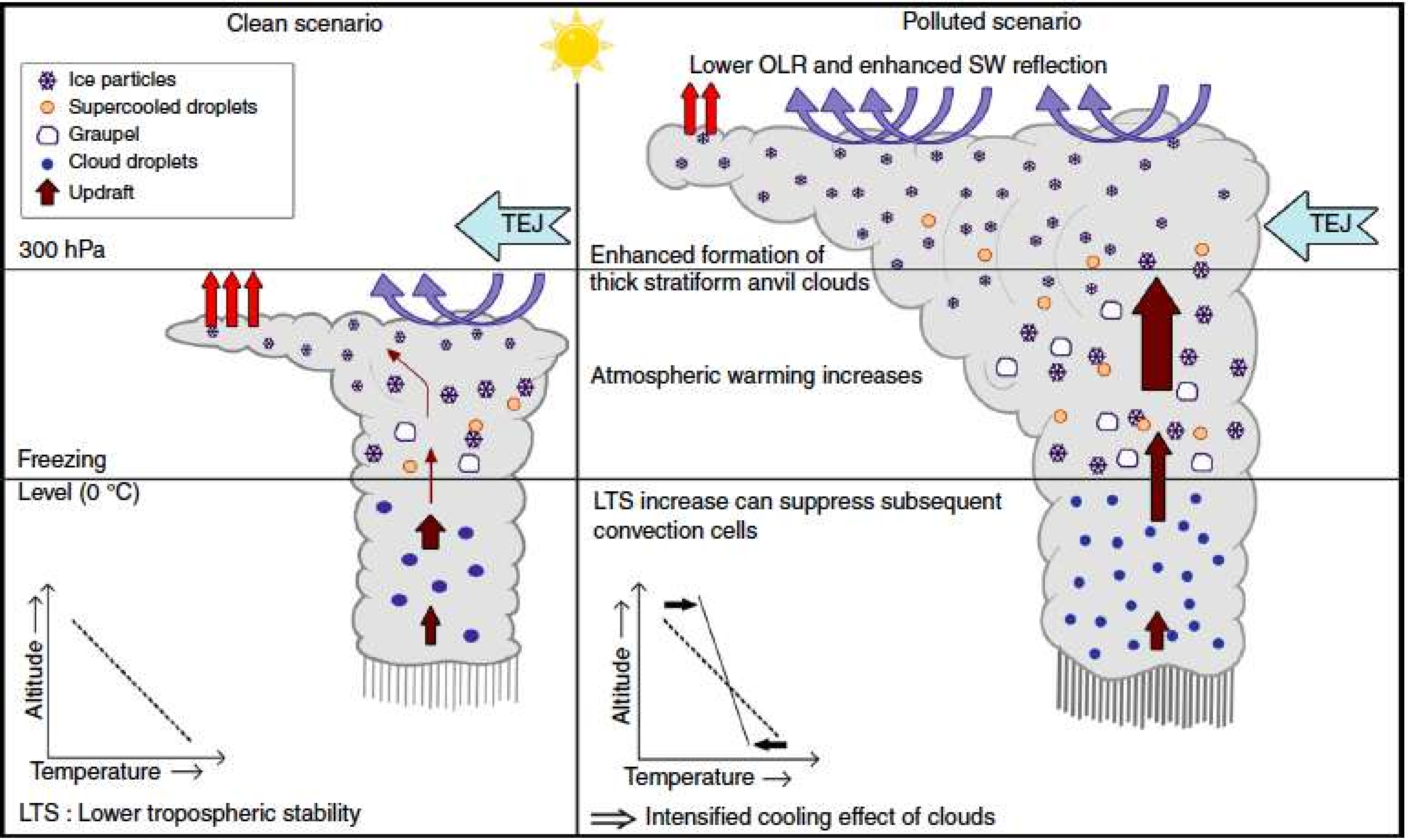
Sarangi et al., Nature Communications 2018

Aerosol-induced intensification of cooling effect of clouds during Indian summer monsoon

Chandan Sarangi[1,2], Vijay P. Kanawade[3], Sachchida N. Tripathi[1], Abin Thomas[3] & Dilip Ganguly[4]

Measurements and models show that enhanced aerosol concentrations can modify macro- and micro-physical properties of clouds. Here, we examine the effect of aerosols on continental mesoscale convective cloud systems during the Indian summer monsoon and find that these aerosol–cloud interactions have a net cooling effect at the surface and the top-of-atmosphere. Long-term (2002–2016) satellite data provide evidence of aerosol-induced cloud invigoration effect (AIvE) during the Indian summer monsoon. The AIvE leads to enhanced formation of thicker stratiform anvil clouds at higher altitudes. These AIvE-induced stratiform anvil clouds are also relatively brighter because of the presence of smaller sized ice particles. As a result, AIvE-induced increase in shortwave cloud radiative forcing is much larger than longwave cloud radiative forcing leading to the intensified net cooling effect of clouds over the Indian summer monsoon region. Such aerosol-induced cooling could subsequently decrease the surface diurnal temperature range and have significant feedbacks on lower tropospheric turbulence in a warmer and polluted future scenario.

Processes leading to intensified cooling effect of clouds under polluted scenario over the Indian summer monsoon region



Sarangi et al., Nature Communications 2018

Objectives for our new study

- Understand the equilibrium climate response of the south Asian summer monsoon system to increases in anthropogenic emissions of aerosols and greenhouse gases separately and when they are allowed to increase together.

- Does the increases in anthropogenic emissions of aerosols and greenhouse gases also modulate the onset & withdrawal of the South Asian summer monsoon system?

Model description (CESM1.2)

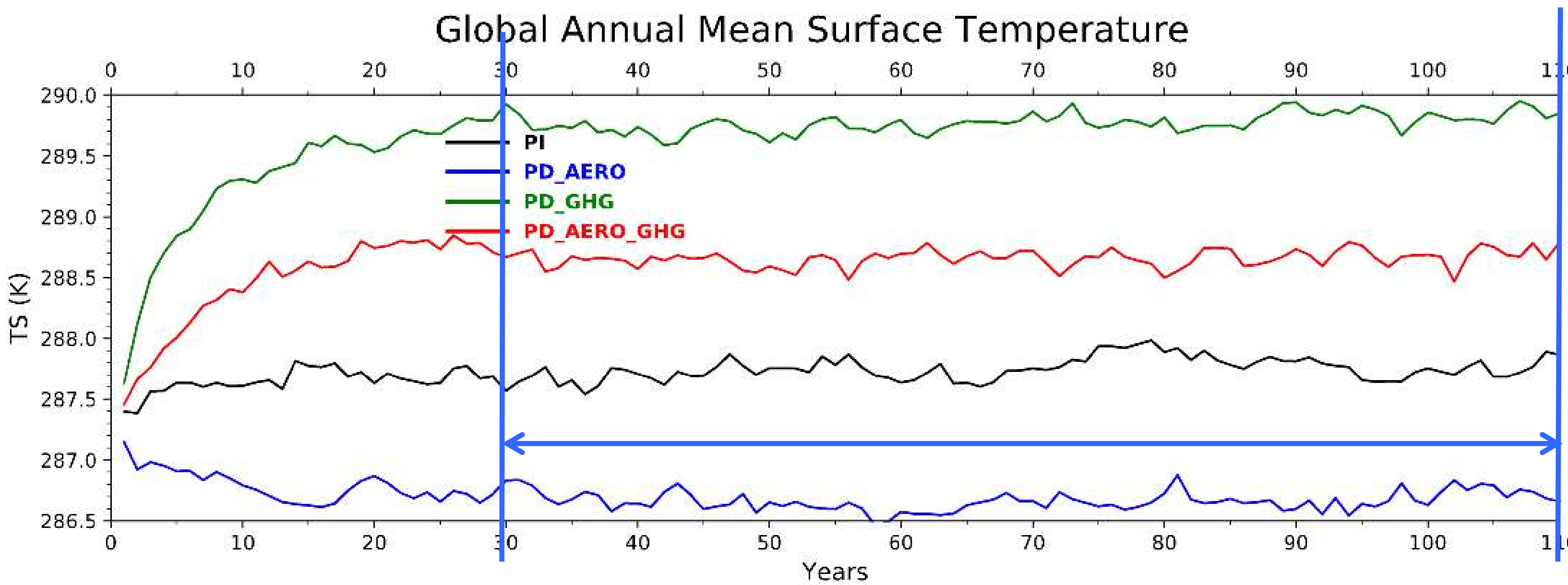
Hurrel et al. 2013

It has separate atmosphere (CAM5.3), Slab Ocean model (SOM or POP), Sea Ice (CICE4), and land model (CLM4.5 with SNICAR model) components, which exchange fluxes through a central coupler component

Some Features of CAM5 model

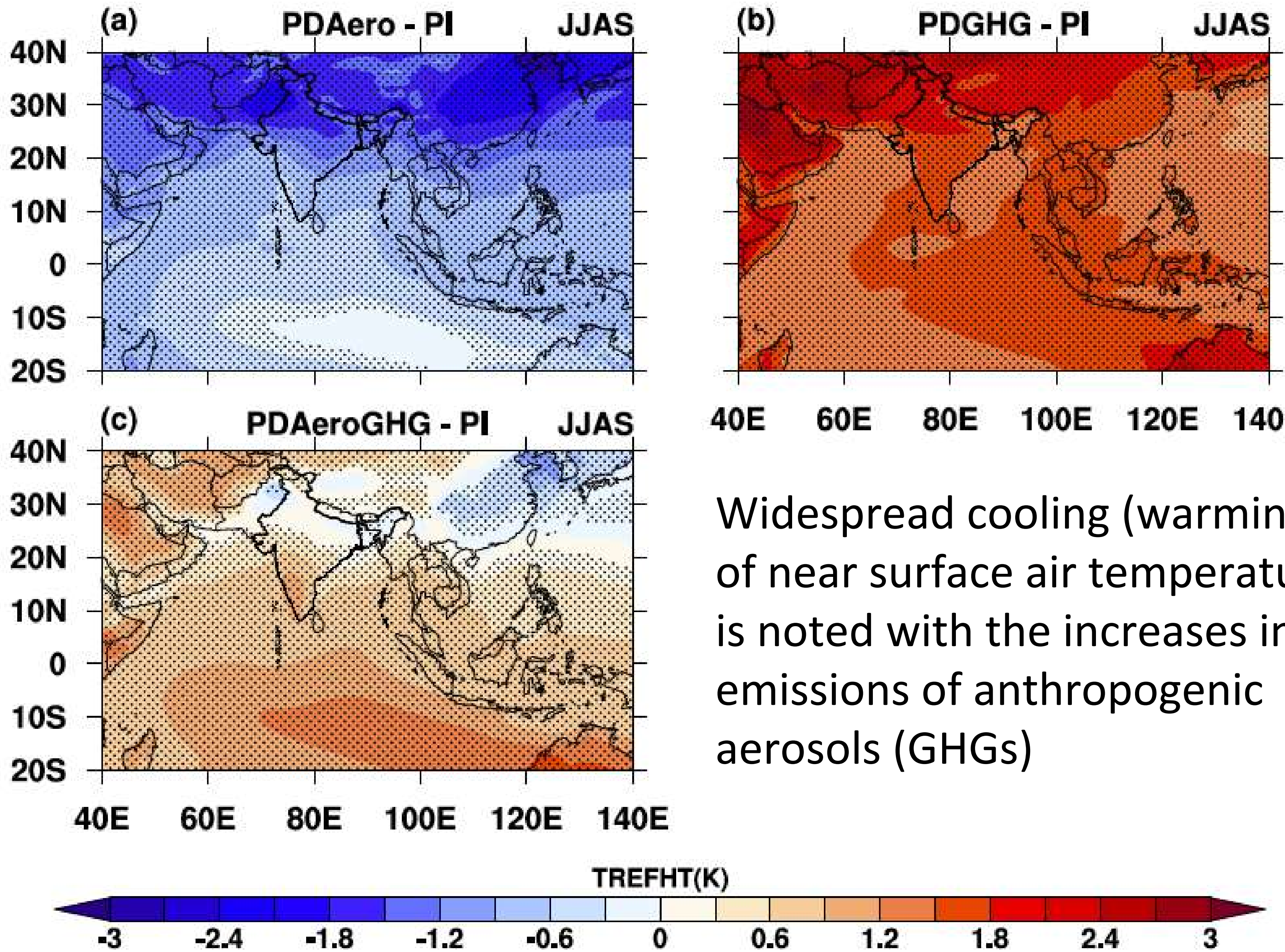
- ~3 mb model top pressure
- 0.9 x 1.25 degree, 30 layers
- 30-minute time step
- Finite volume (Fv) dynamical core
- Community Land Model (CLM4)
- IPCC AR5 emissions for aerosols and radiatively active species
- UW moist turbulence
- UW shallow convection
- UW macrophysics
- Zhang-McFarlane deep convection
- *Morrison-Gettelman* 2-moment stratiform microphysics
- RRTMG radiation
- Mode Modal Aerosol Model (MAM3 / MAM7)

Coupled (CAM5+SOM) climate model simulations have been conducted to understand the equilibrium response of the monsoon system to changes in aerosols and GHG emissions



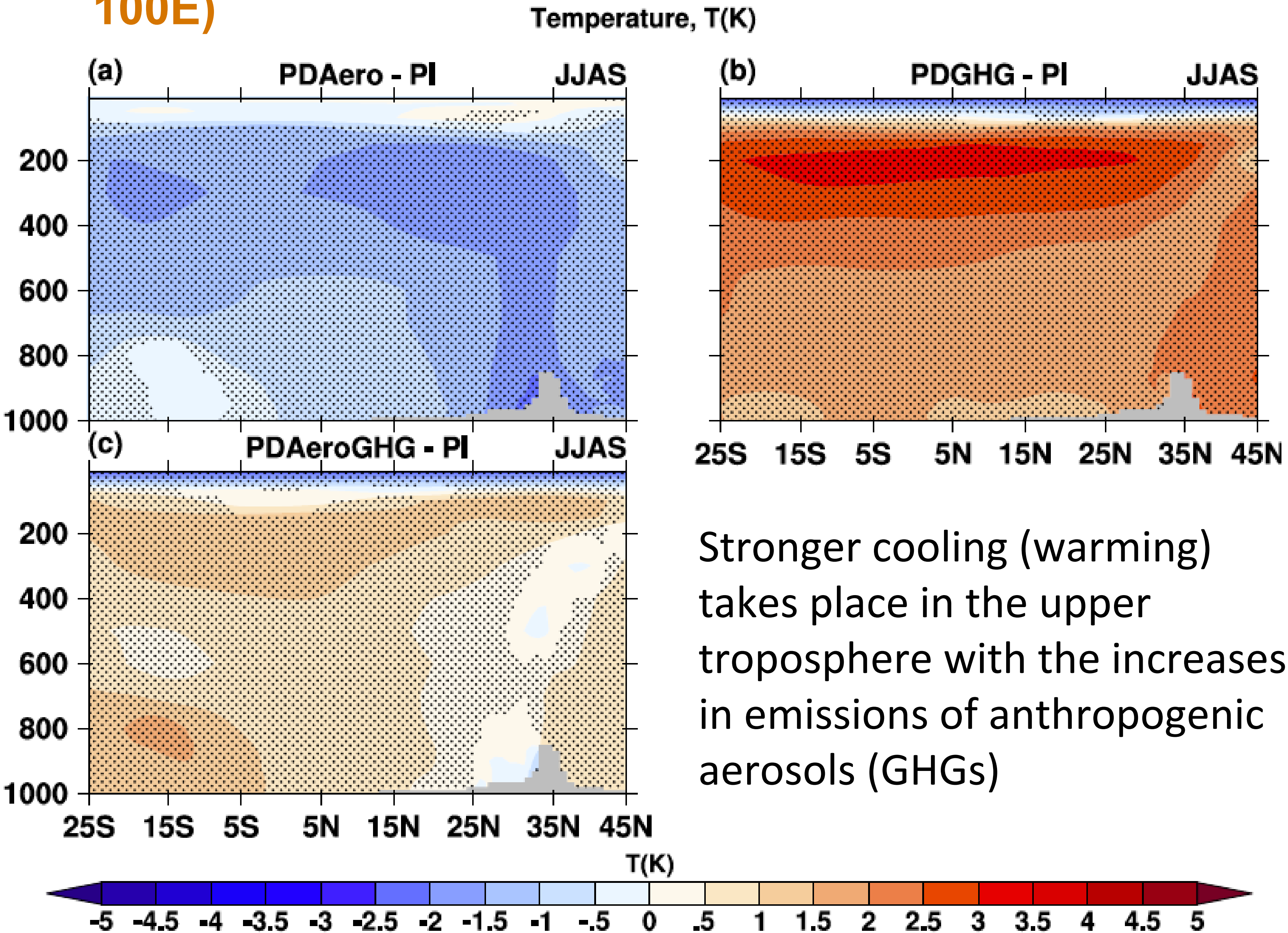
Experiments	Aerosol Forcing	Greenhouse Forcing
PI	PI (1850)	PI
PD_Aero	PD (2000)	PI
PD_GHG	PI	PD
PD_Aero_GHG	PD	PD

JJAS mean changes in Reference height temperature



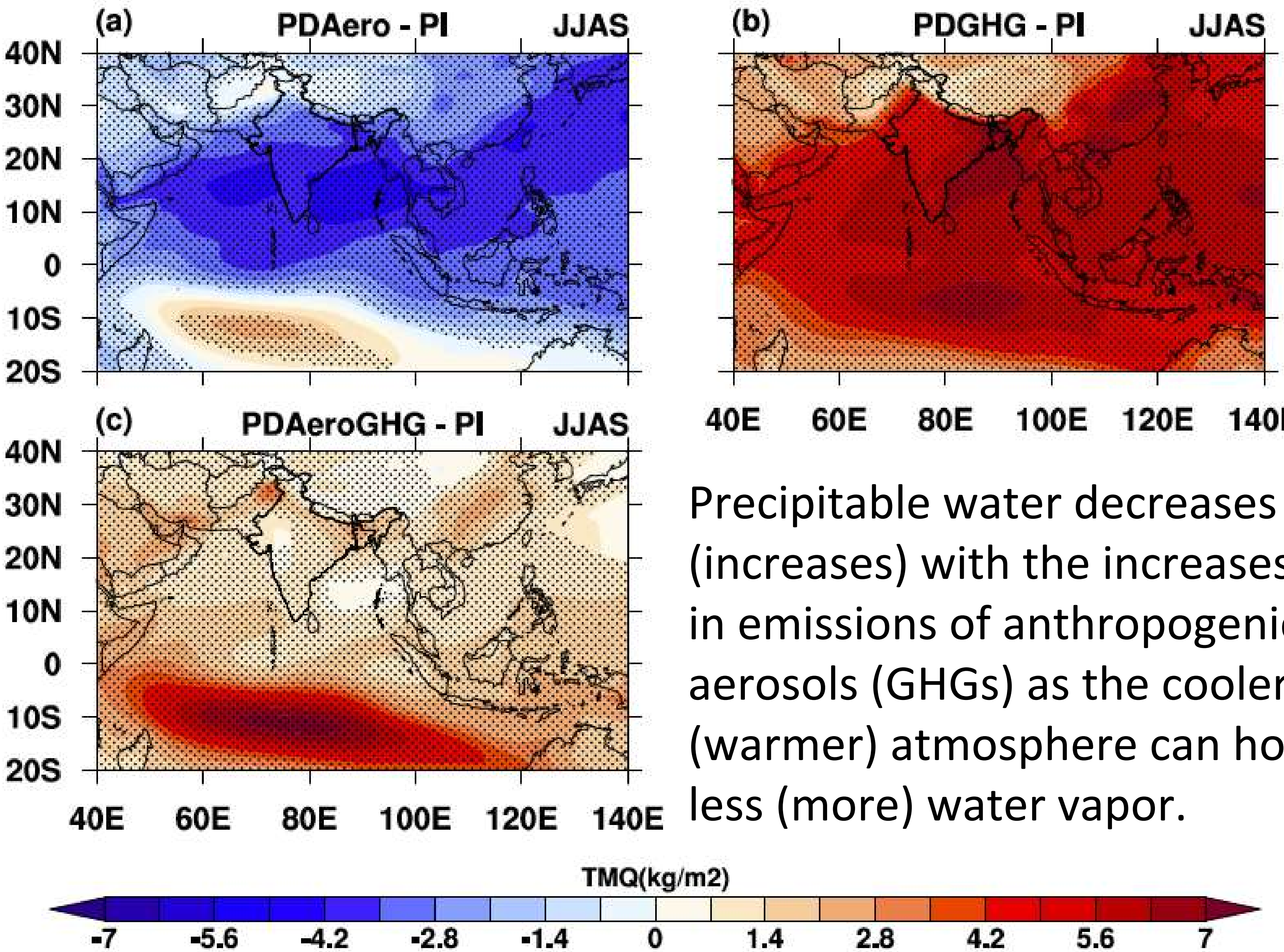
Widespread cooling (warming) of near surface air temperature is noted with the increases in emissions of anthropogenic aerosols (GHGs)

JJAS mean changes in Atmospheric temperature (60-100E)



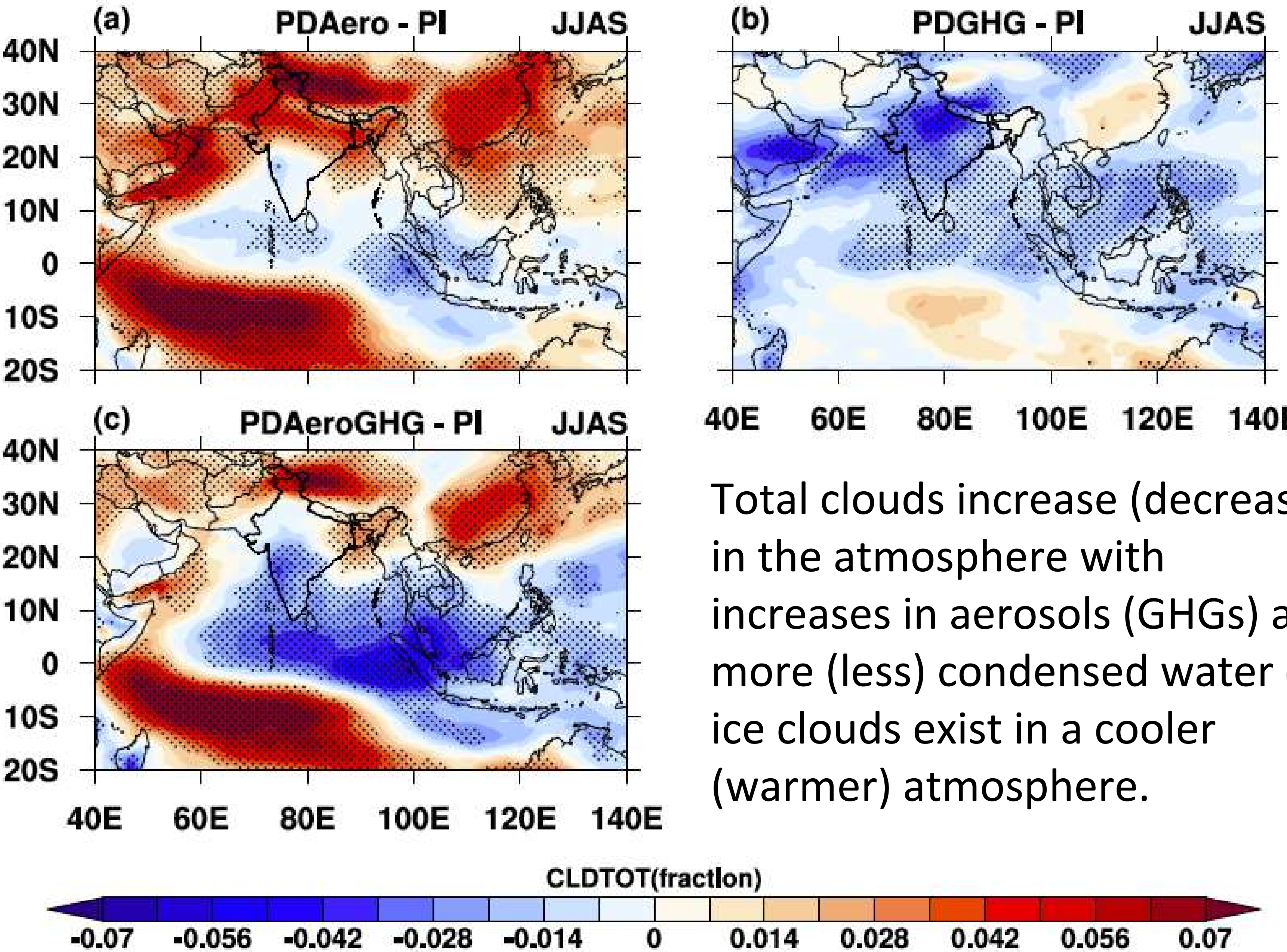
Stronger cooling (warming) takes place in the upper troposphere with the increases in emissions of anthropogenic aerosols (GHGs)

JJAS mean changes in total column vertically integrated percipitable water (Kg/m^2)



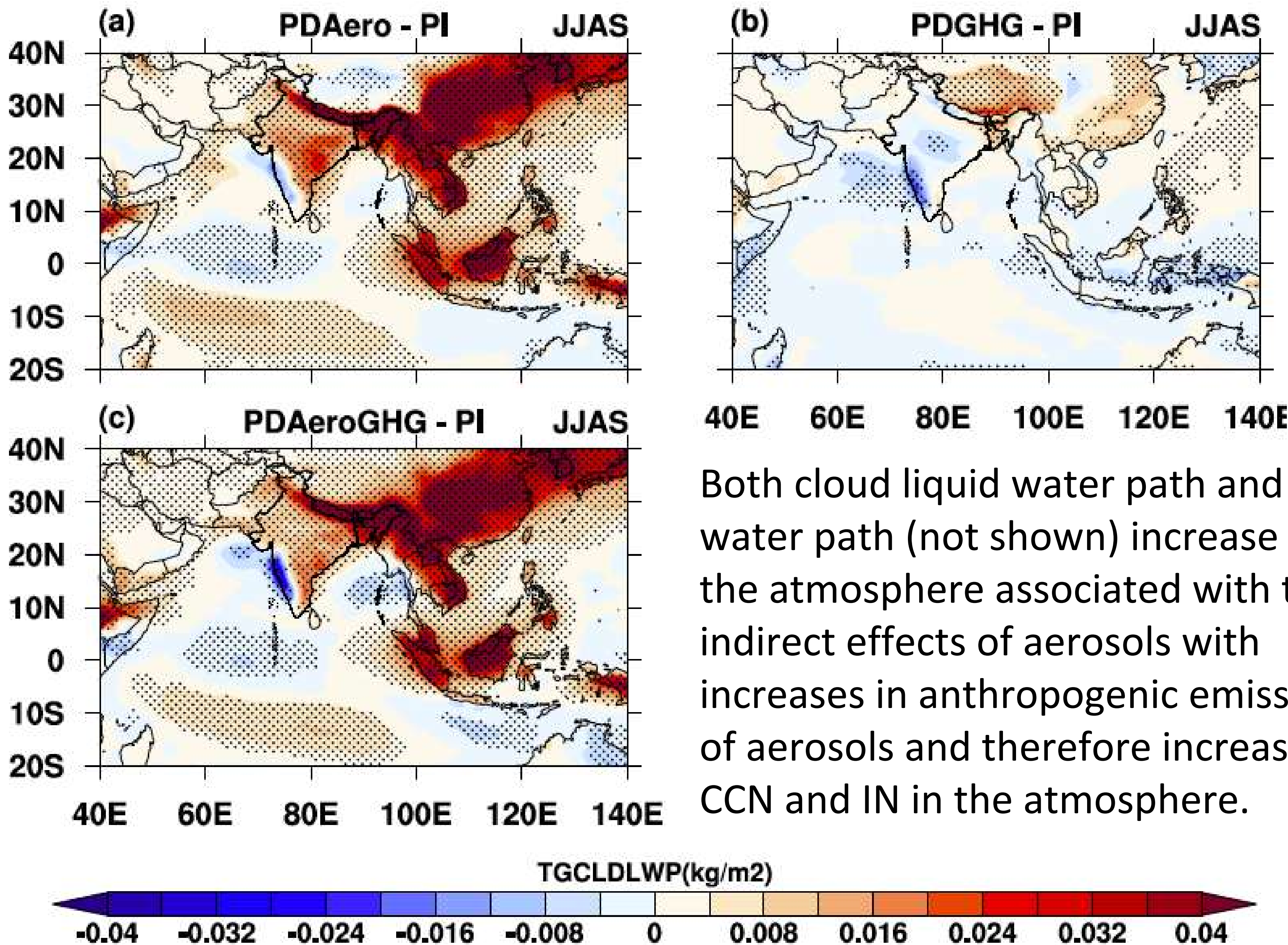
Precipitable water decreases (increases) with the increases in emissions of anthropogenic aerosols (GHGs) as the cooler (warmer) atmosphere can hold less (more) water vapor.

JJAS mean changes in total cloud fraction



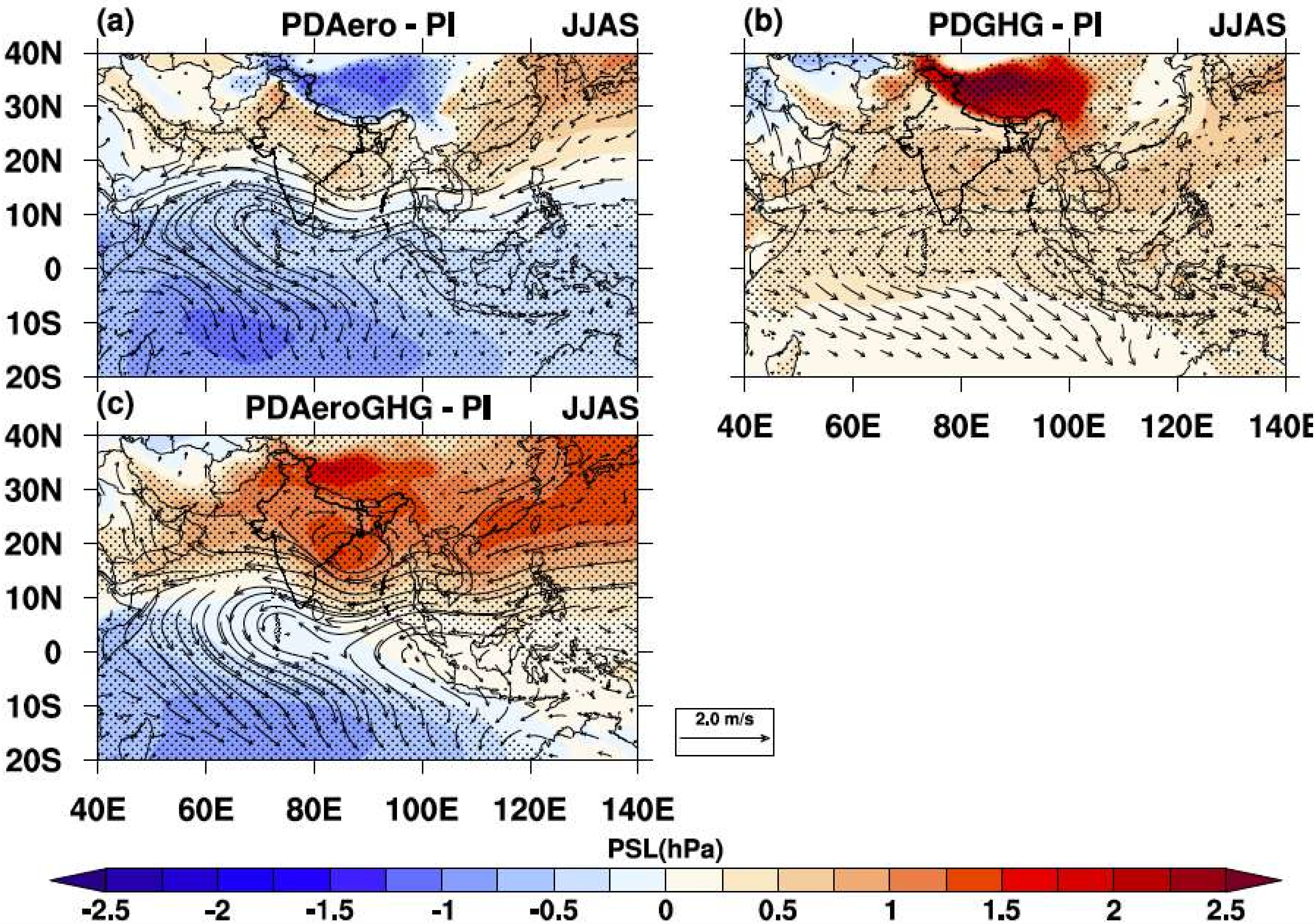
Total clouds increase (decrease) in the atmosphere with increases in aerosols (GHGs) as more (less) condensed water or ice clouds exist in a cooler (warmer) atmosphere.

JJAS mean changes in cloud liquid water path

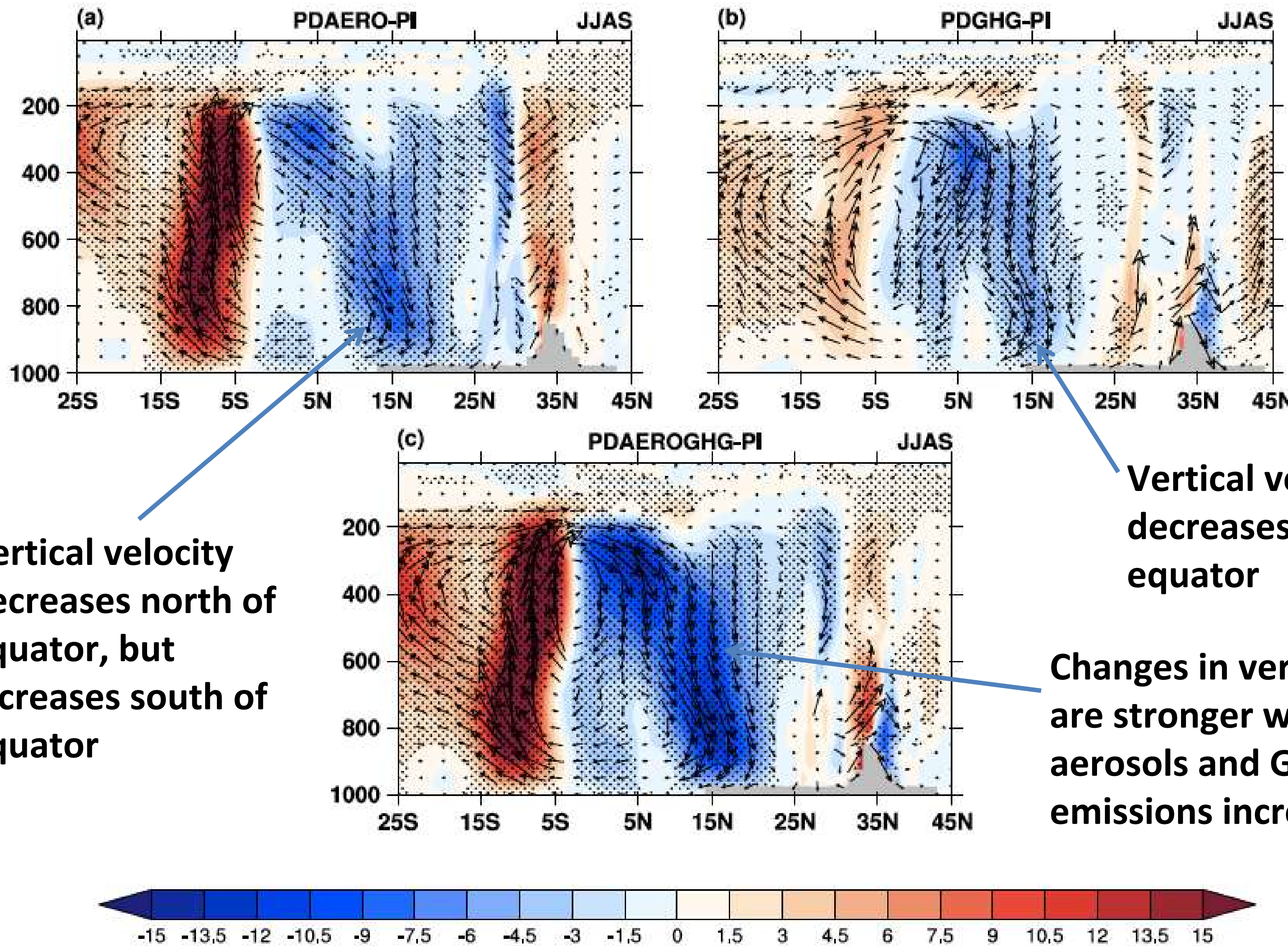


Both cloud liquid water path and Ice water path (not shown) increase in the atmosphere associated with the indirect effects of aerosols with increases in anthropogenic emissions of aerosols and therefore increases in CCN and IN in the atmosphere.

JJAS mean changes in sea level pressure and 850 hPa wind



JJAS mean changes in meridional circulation over 60-100E

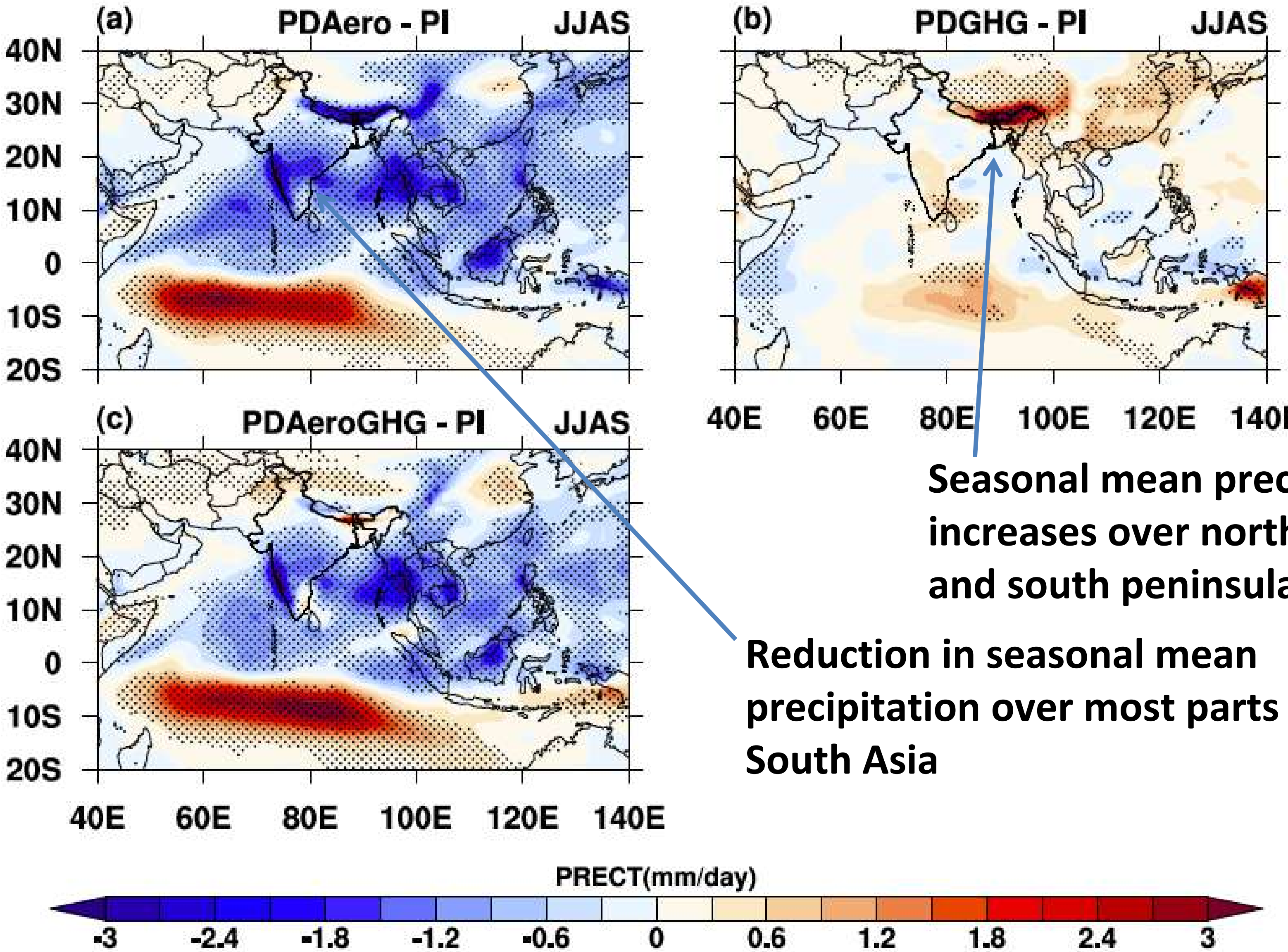


Vertical velocity decreases north of equator, but increases south of equator

Vertical velocity decreases north of equator

Changes in vertical velocity are stronger when both aerosols and GHG emissions increase

JJAS mean response in precipitation rate (mm/day)

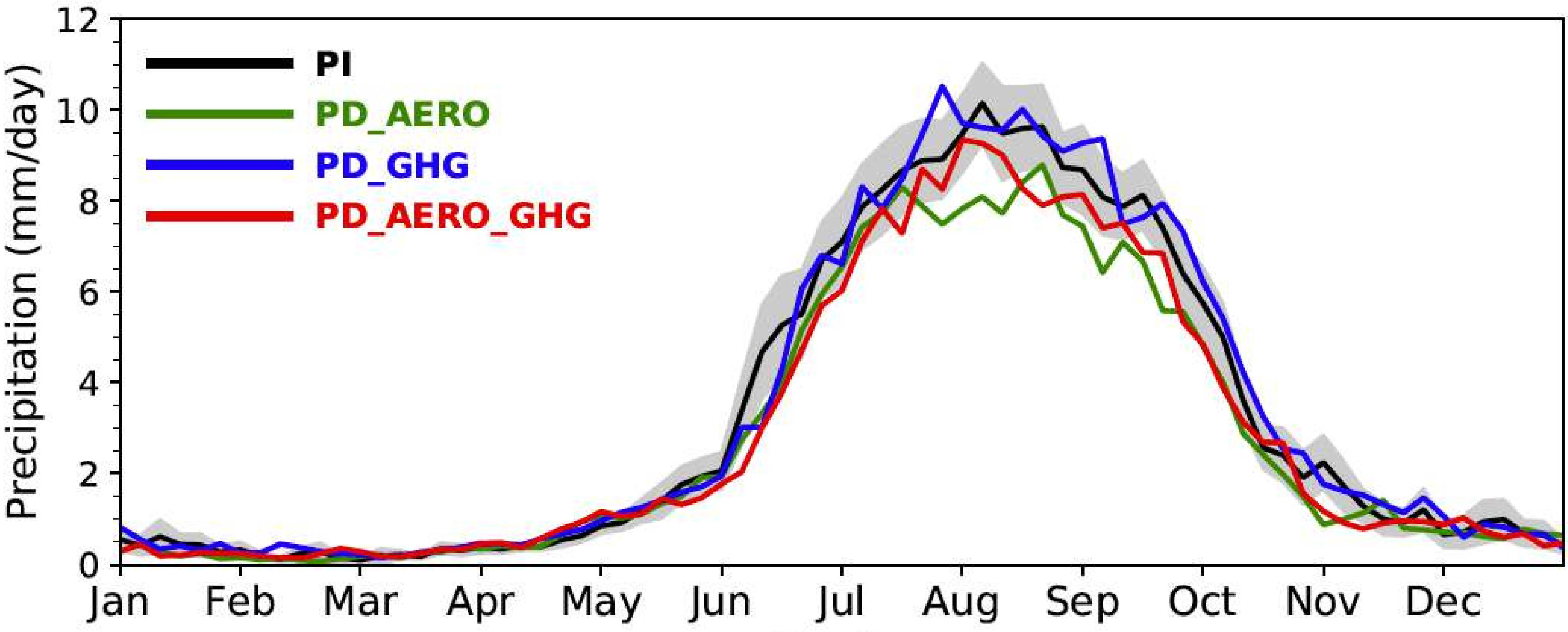


Seasonal mean precipitation increases over north-east and south peninsular India

Reduction in seasonal mean precipitation over most parts of South Asia

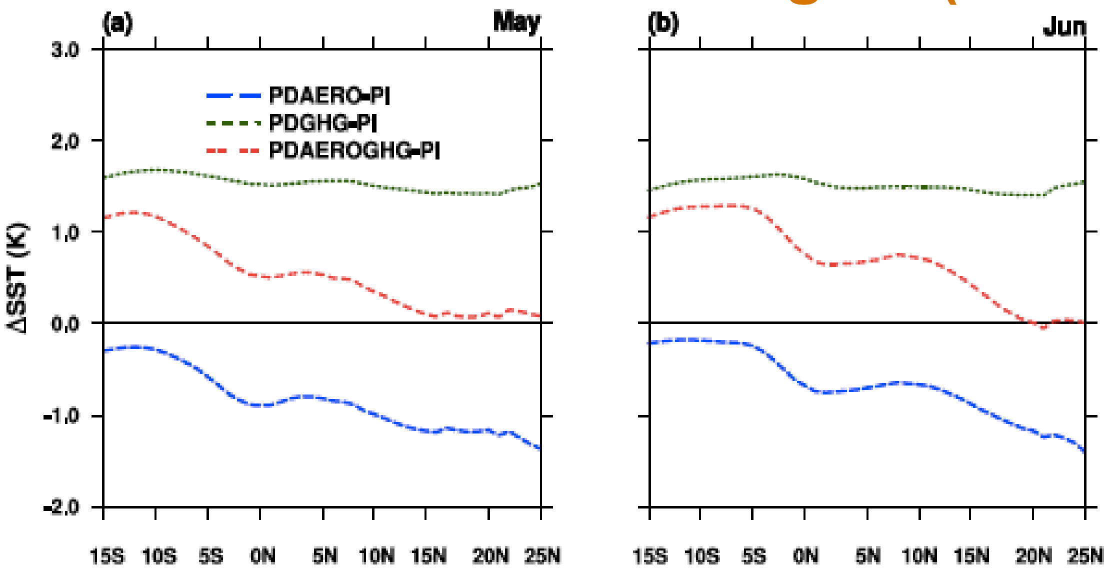
Increased precipitation happens south of the equator while decreases north of it over the south Asian region when the anthropogenic aerosols are increased from PI to PD

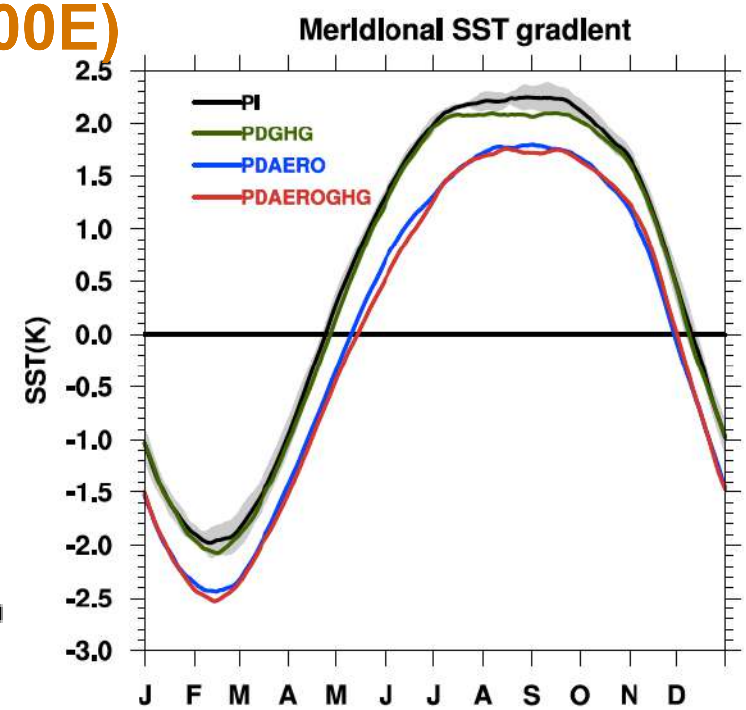
Annual cycle of precipitation rate (mm/day) over Central India



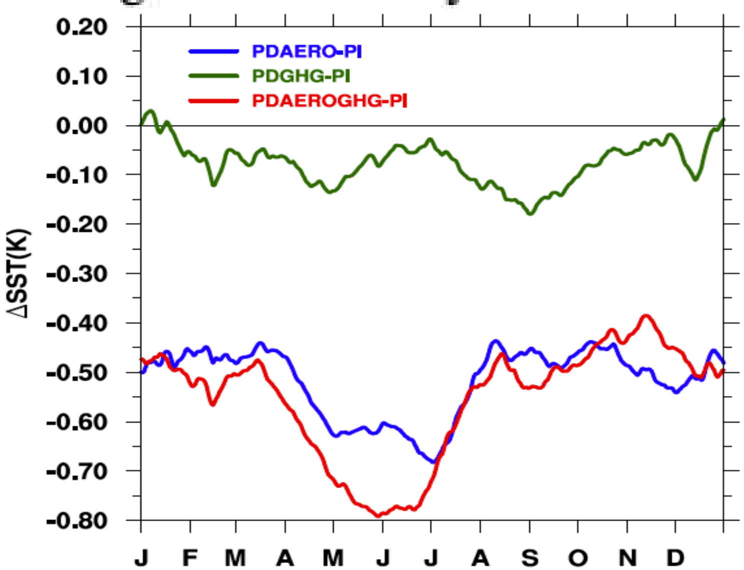
- **Reduction in precipitation is significant over Central India (CI) when only aerosols emissions are increased from PI to PD.**
- **Changes in precipitation over CI is not found significant when GHG alone increase from PI to PD levels.**
- **Significant reduction in precipitation <u>with delayed onset of monsoon</u> is also noted when both aerosols and GHG emissions are increased together.**

Aerosol and GHG induced change in SST and SST gradient over the Indian ocean region (60-100E)



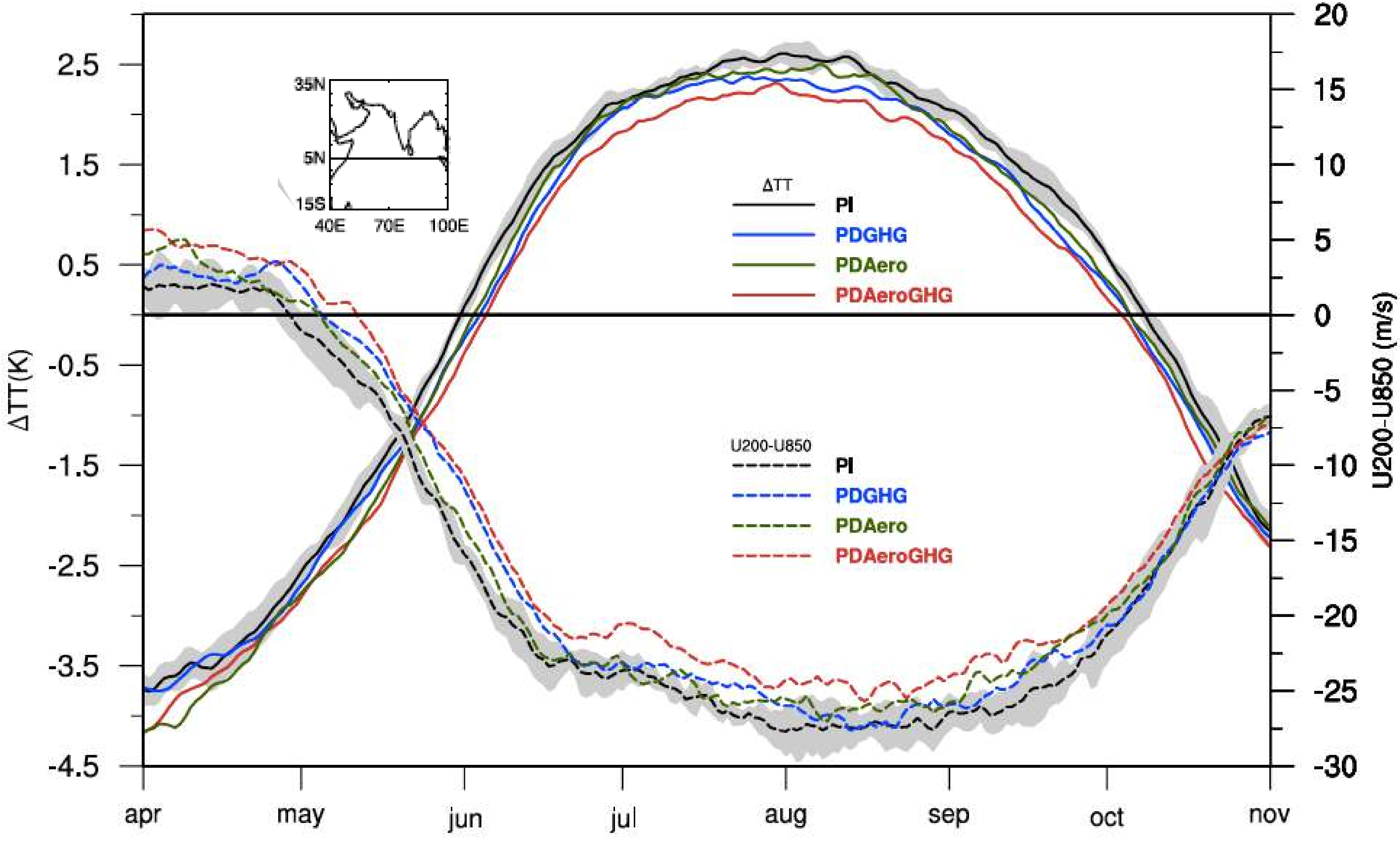


SST gradient anomaly between 5–25°N and 0–20°S



- Increases in GHG (aerosols) alone warms (cools) the Indian Ocean SST.
- Increases in both aerosols and GHG emissions warm the Indian ocean SST.
- North-South gradient is decreased by both aerosols and GHG.
- SST gradient is decreased more strongly when both aerosol and GHG forcings are increased simultaneously.

Tropospheric temperature gradient (ΔTT) and vertical shear of zonal winds)U200- U850(



Conclusions and Future directions

- Climate simulations using GCMs suggest that climate change caused by changing emissions of both GHGs and aerosols can cause significant changes in cloud. What could be the climate implications?
- Increase in CO_2 levels is known to cause global warming whereas climate models seem to suggest that so far the increasing anthropogenic aerosols have produced an overall cooling effect on the global mean climate.
- But how the clouds will respond to this global warming and what will be the ultimate climate response of the microphysical effects of diverse aerosols is highly uncertain due to our poor knowledge about cloud formation and low cloud response to global warming and aerosol indirect effects.
- Need to asses the climatic trends in cloudiness and net cloud forcing over the Indian subcontinent.
- Assess the role of cloud feedback on observed climate change in India.
- Attribution of changing cloud characteristics to changing aerosols and greenhouse gas emissions for reliable prediction of climate change

Thank You