Possible Influences of External Factors on the Indian Summer Monsoon

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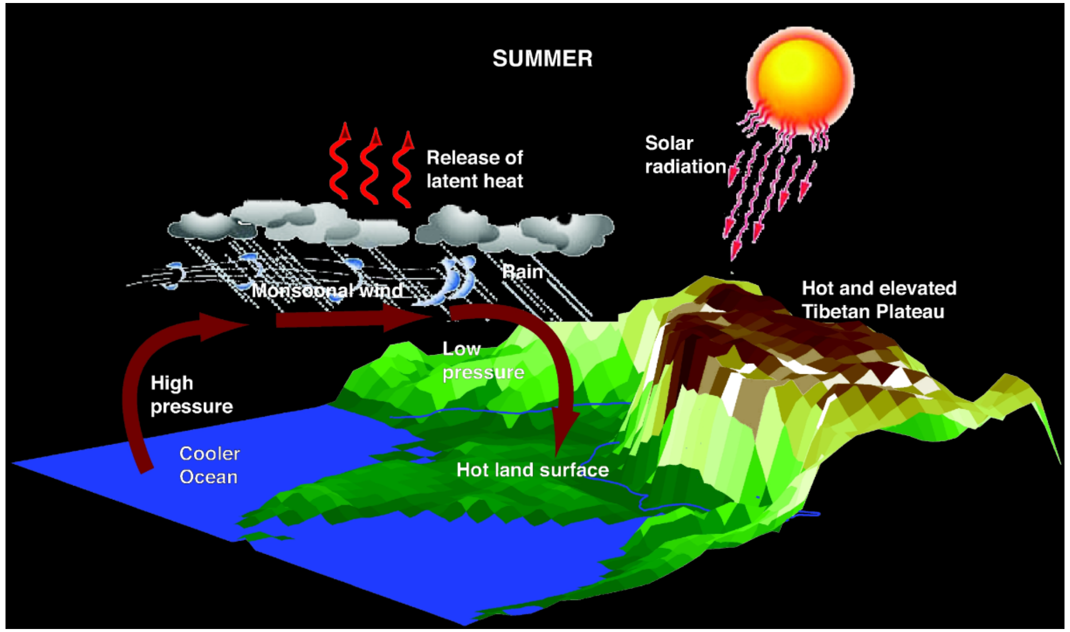
Indian Summer Monsoon



Definition: Seasonal reversal of winds which blow from the Arabian Sea and the Indian Ocean to the Land and associated thermal contrast between Ocean and land is required to bring rainfall.

Monsoon season: June to September.

Impacts: The Indian summer monsoon plays a significant role in shaping the socioeconomic and ecological aspects of the region. Adequate monsoon rainfall contributes to agricultural productivity, while deficient rainfall can lead to droughts, crop failures, and water scarcity.

Factors influencing the monsoon: The monsoon is influenced by several factors, including the differential heating of land and water, heating over the Tibetan Plateau, interaction with aerosol, global warming due to GHG, the El Niño-Southern Oscillation (ENSO) phenomenon, etc.

Precipitation changes over the Indian region

The Indian summer monsoon rainfall is vital for the livelihood of millions of people in the Indian region. Droughts caused by monsoon failures often resulted in famines

Declining trend in Indian summer monsoon since last 100 yrs.

There are complex unexplored linkages of the Indian monsoon weakening and associated droughts with

(1) El Niño
(2) El Niño induced circulation which is linked to volcanic eruptions.
(3) Aerosols causing solar diming

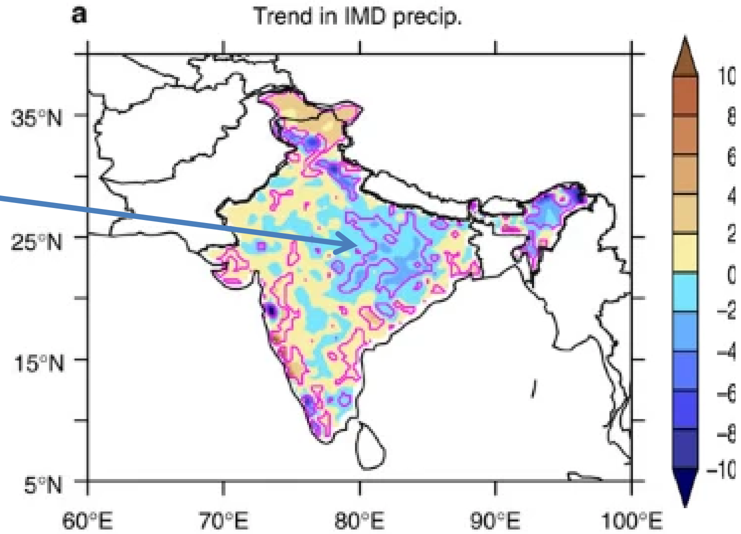


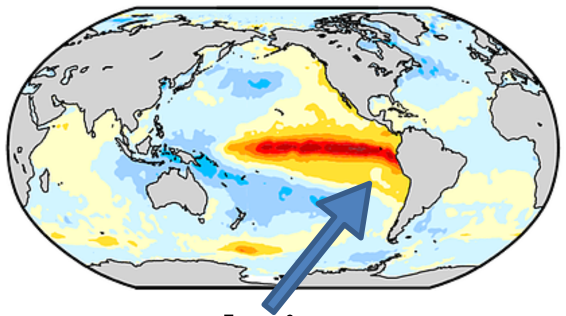
Fig.: Trend in precipitation (mm day^{-1}) in IMD data (1901-2012).

Roxy et al., 2015

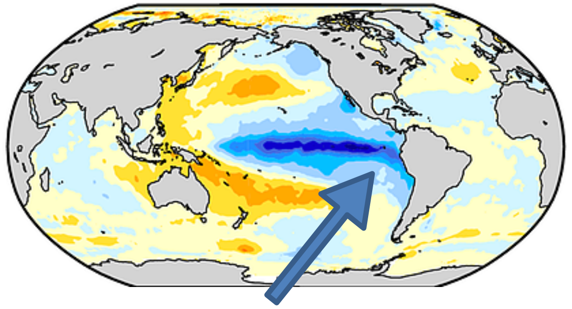
El Niño and La El Nina

El Nino	La Nina
Temperature at Sea Surface: Warm sea surface temperatures in the central and eastern equatorial Pacific Ocean.	**Temperature at Sea Surface:** It involves colder-than-normal sea surface temperatures in the central and eastern equatorial Pacific Ocean.
Pressure: It is laden with high air surface pressure in the western Pacific.	**Pressure:** It contain low air surface pressure in the eastern Pacific
Trade winds: It originated when tropical Pacific Ocean trade winds die out and ocean temperatures become unusually warm.	**Trade winds:** It occurs when the trade winds blow unusually hard and the sea temperature become colder than normal.
Effects: Heavy rains near equator and Peru; Heavy rains in southern Brazil but drought in north East Brazil; Drought in Zimbabwe, Mozambique, South Africa, Ethiopia; Warm winter in the northern half of the United States and southern Canada. Drought, **Scant rains off Asia including India**, Indonesia, and Philippines ;Coral bleaching worldwide; Drought in eastern Australia	**Effects:** Causes drought in equator and Peru. Created low temperature, high Pressure in Eastern Pacific. Heavy floods in Australia; High Temperature in Western Pacific, Indian Ocean, Off coast Somalia and good rains in India.

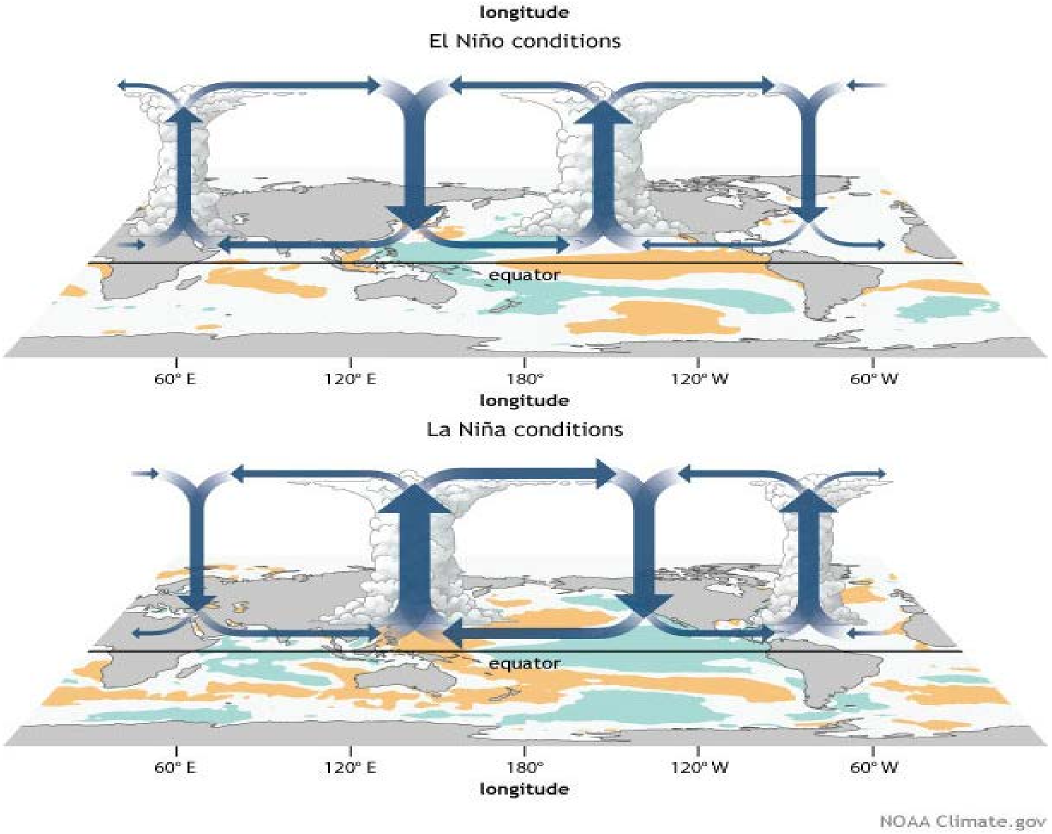
Aerosols and GHG also plays important role in monsoon variability



El Nino

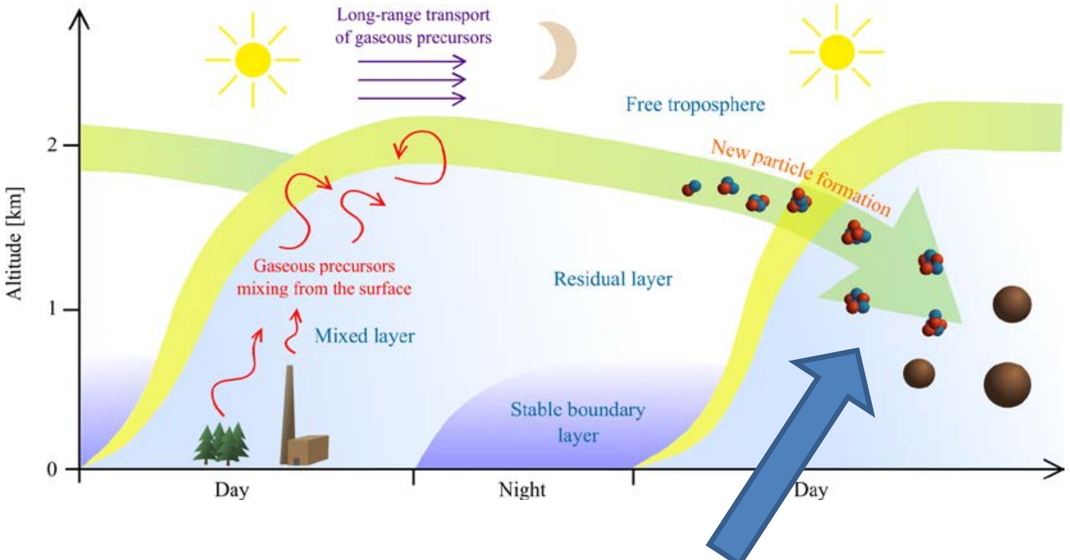


La Nina

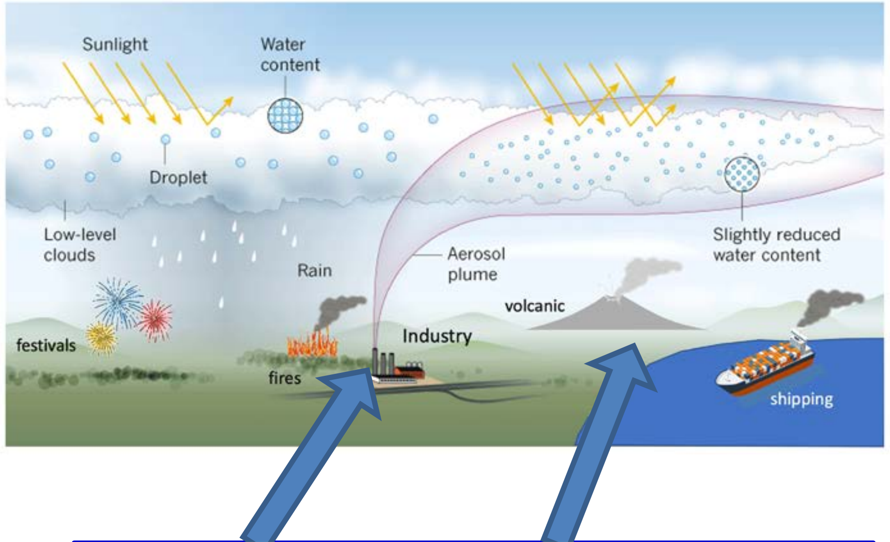


Atmospheric Aerosols

- Atmospheric aerosols are tiny solid or liquid particles suspended in the Earth's atmosphere.
- They can vary in size, composition, and origin.
- These particles can be natural, such as dust, sea salt, pollen, or volcanic ash, or they can be generated through human activities, such as industrial emissions, vehicle exhaust, or the burning of fossil fuels.



New aerosol formation



Anthropogenic and Natural aerosol

Atmospheric Aerosols

- Aerosols can be emitted directly (such as dust, sea salt, black carbon (BC)) –Primary aerosols.

- Aerosols are also formed indirectly through chemical reactions (including sulfate, nitrate, ammonium, and secondary organic aerosols). –Secondary aerosols.

- Aerosols exhibit complicated compositions and vary substantially in shape and size.

- Particles with a diameter of 10 microns or less (PM10) are inhalable into the lungs and can induce adverse health effects.
- Fine particulate matter is defined as particles that are 2.5 microns or less in diameter (PM2.5).

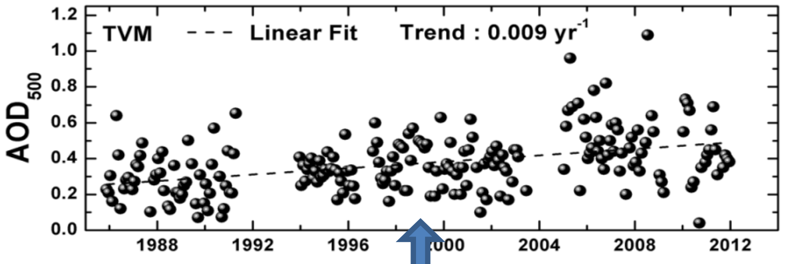
- Depending on these structural and compositional characteristics, aerosols can scatter and/or absorb shortwave radiation.
- Purely scattering aerosols include sulfates, nitrates, ammonium, and sea-salt particles.

- whereas absorbing aerosols are primarily BC, with dust and organic carbon.

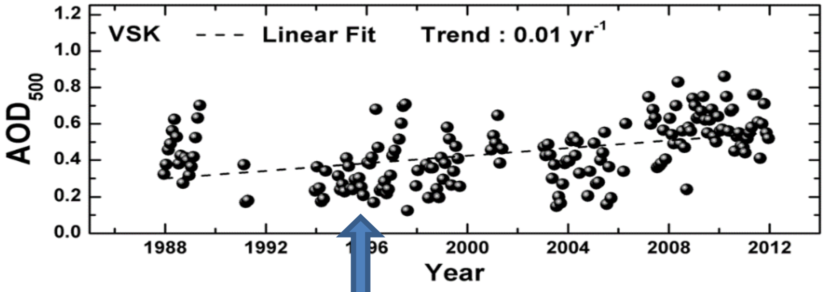
- Aerosols can further serve as cloud condensation nuclei (CCN) or ice-nucleating particles (INPs), which modify the reflectivity and lifetime of clouds through microphysical processes.

- **Aerosols affect clouds and precipitation. They are one of the key components of the climate system and the hydrological cycle.**

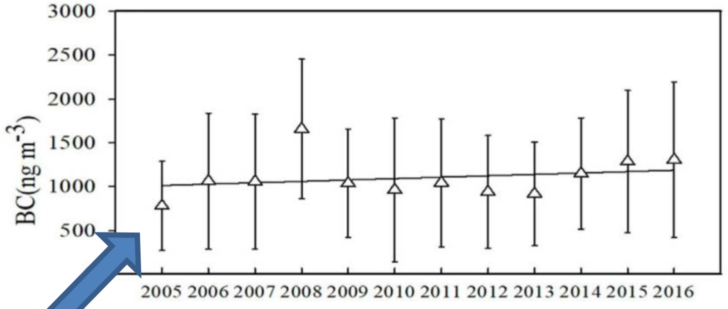
Trends in aerosol over Indian region



Trivandrum



Visakhapatnam



Black carbon increasing trend over the Himalayan region

- ➢ Statistically significant and consistent increasing trends in AOD are seen over the stations in India.

- ➢ Aerosols modulate the cloud formation process which impacts precipitation

Babu et al., 2013

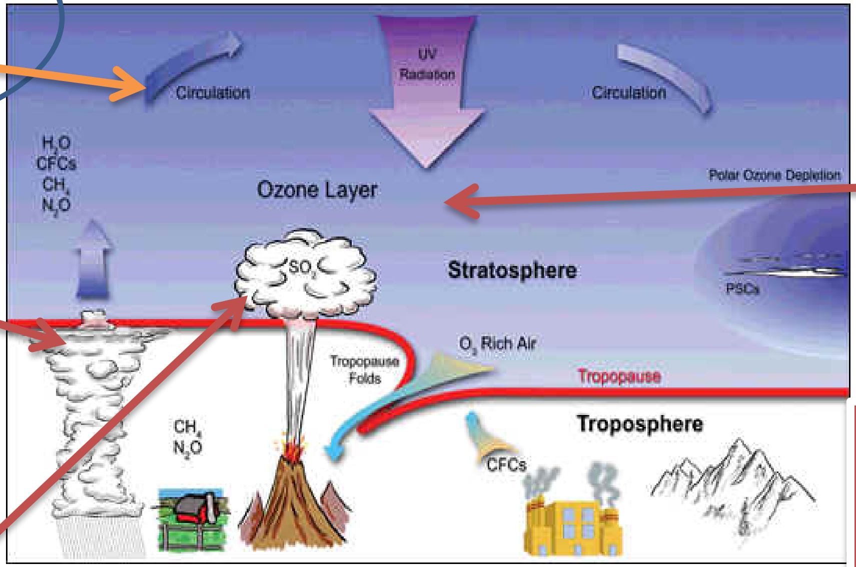
Joshi et al., 2022

Processes caucusing interaction between Troposphere and Stratosphere: Linkages with the Indian monsoon

Brewer-Dopson circulation in Global warming scenario

Troposphere to stratosphere transport

Impact of volcanic eruption during the monsoon Season

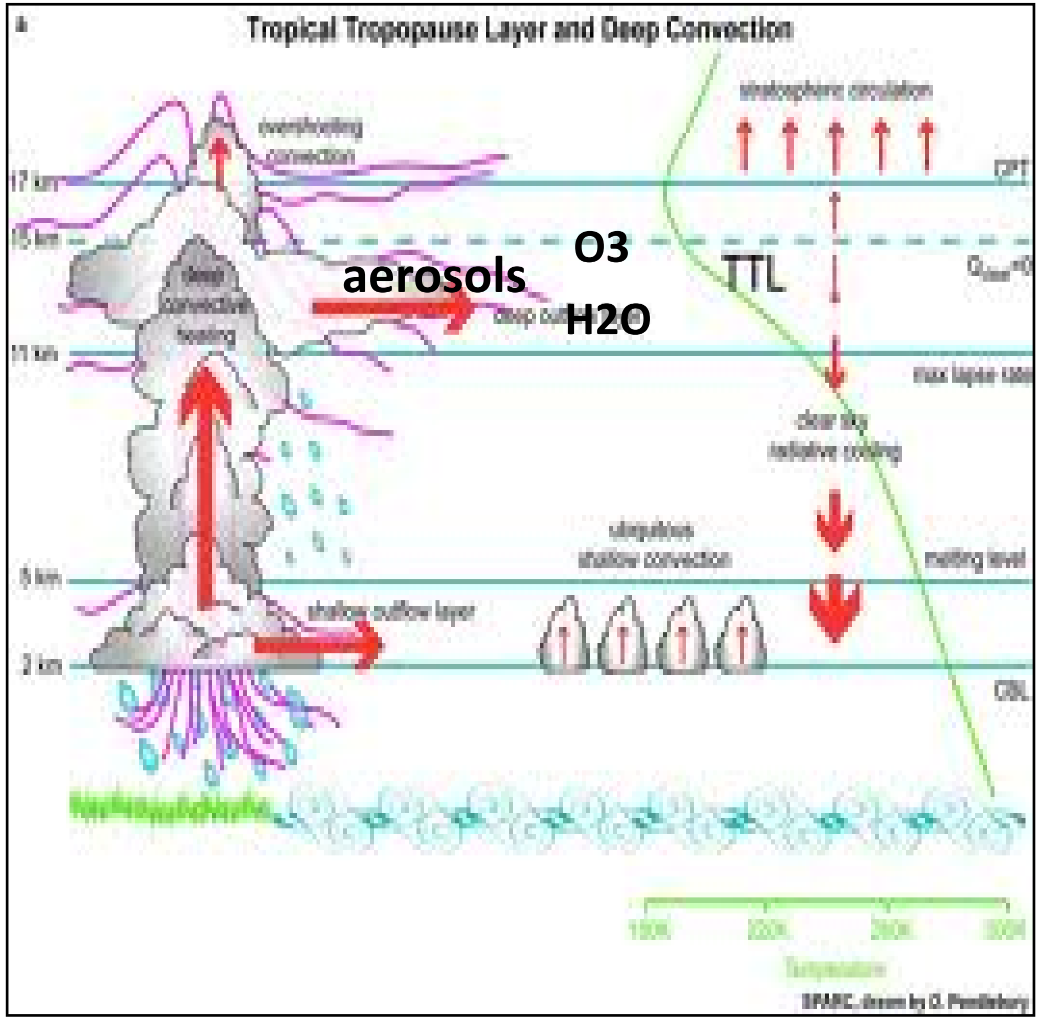


Variation of ozone

Variation of tropopause temperature and stratospheric hydration/dehydration --- Climate change

Tropopause fold and variability of anticyclone and linkages with Monsoon break

Transport of aerosols by the monsoon convection



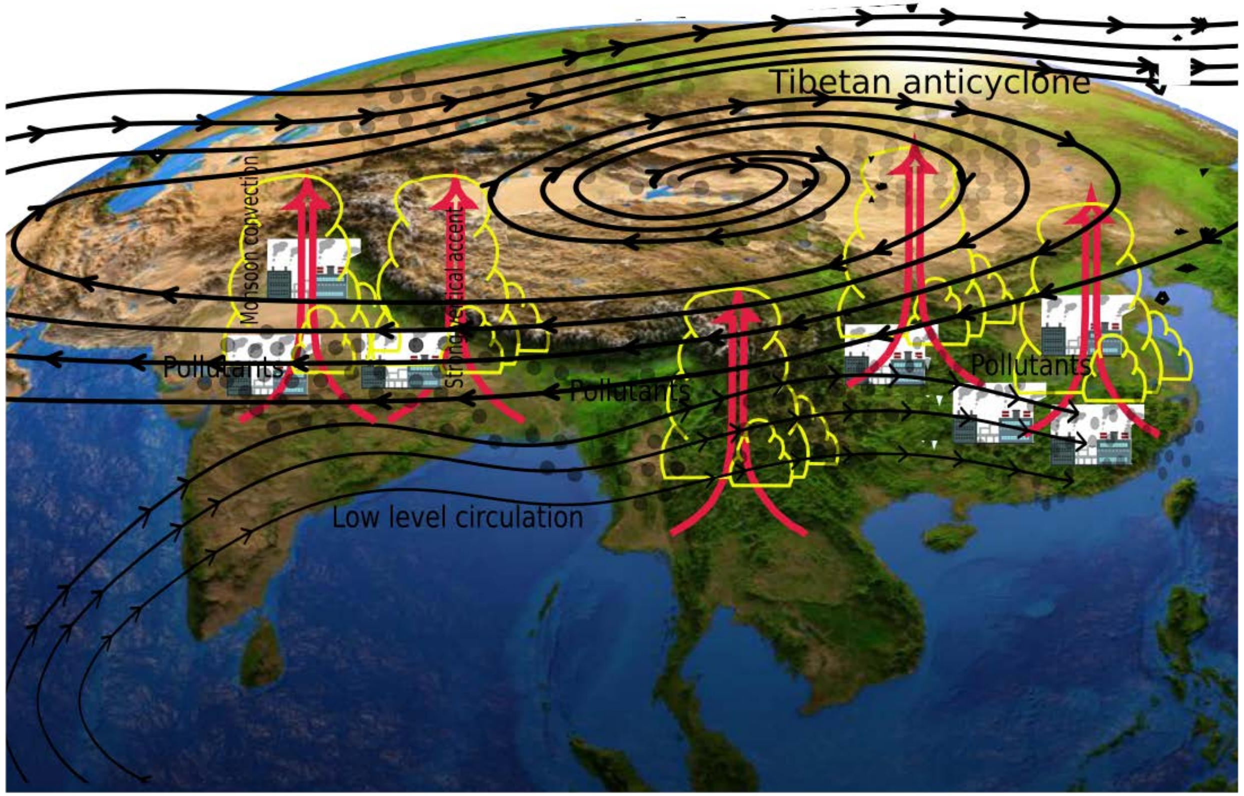
Satellite observations shows that increasing influence of aerosols warm the TTL, increase cloud radiate heating and H_2O. (Su et al. 2011, J. Clim)

Observations show that higher water vapor enter into the stratosphere. (Soloman et al 2010, Science).

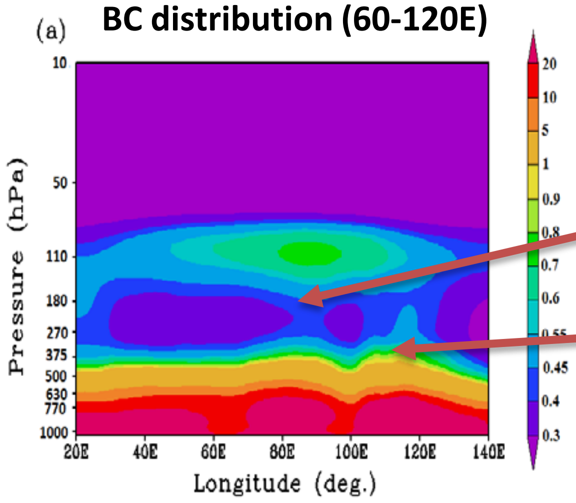
This may lead to cooling of stratosphere and warming of the surface, which may affect Hydrological cycle.

Asian Summer Monsoon Anticyclone

Pollution transport into the monsoon anticyclone



The ECHAM-HAMMOZ chemistry-climate model simulations

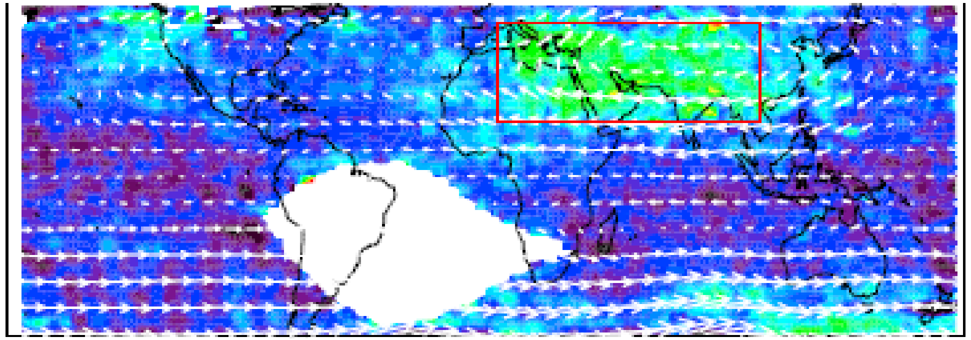


- Transport into the ASMA occurs via two branches:
- (1) over South Asia
- (2) over East Asia

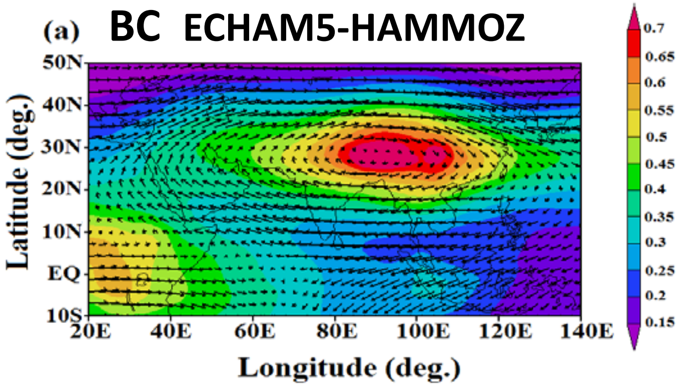
- **Asian summer monsoon convection plays an important role in transporting boundary layer pollutants from Asia to the ASMA.**

Aerosols into the monsoon anticyclone

CALIPSO 15 - 17 km (Jul-Aug 2006)



adopted from Vernier et al., 2015

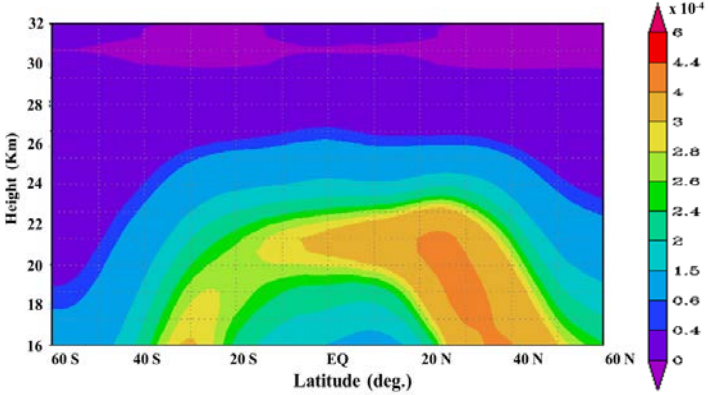


- ➢ Aerosol maxima in the UTLS.
- ➢ Transport by the convection over the BOB and China Sea.

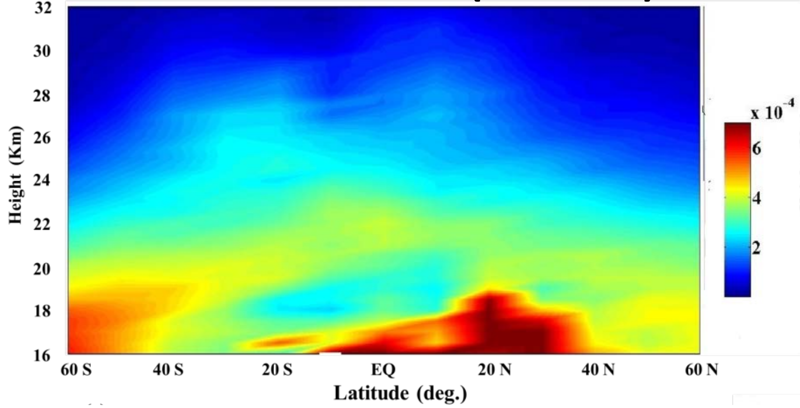
Fadnavis et al., 2013, ACP

monsoon 2003

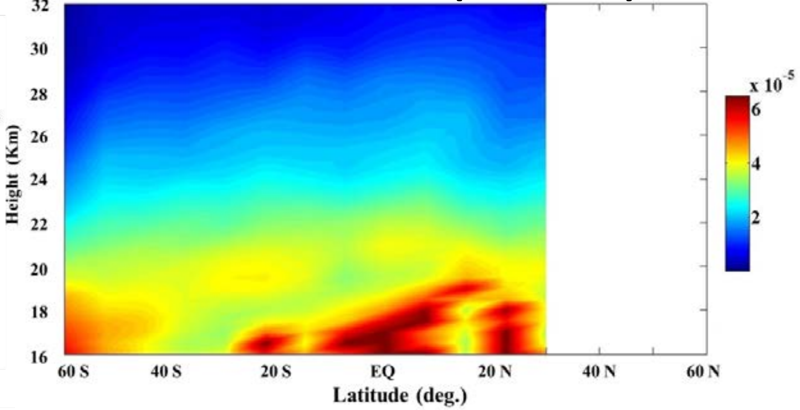
ECHAM Extinction (60-120E)



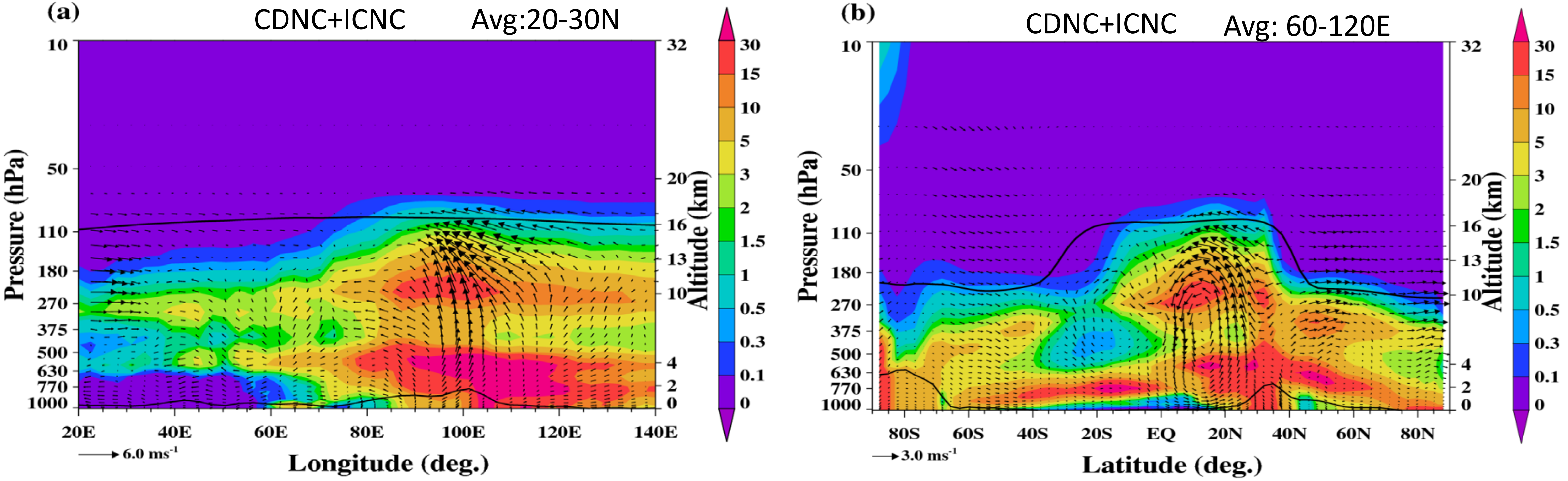
SAGEII Extinction (60-120E)



HALOE Extinction (60-120E)



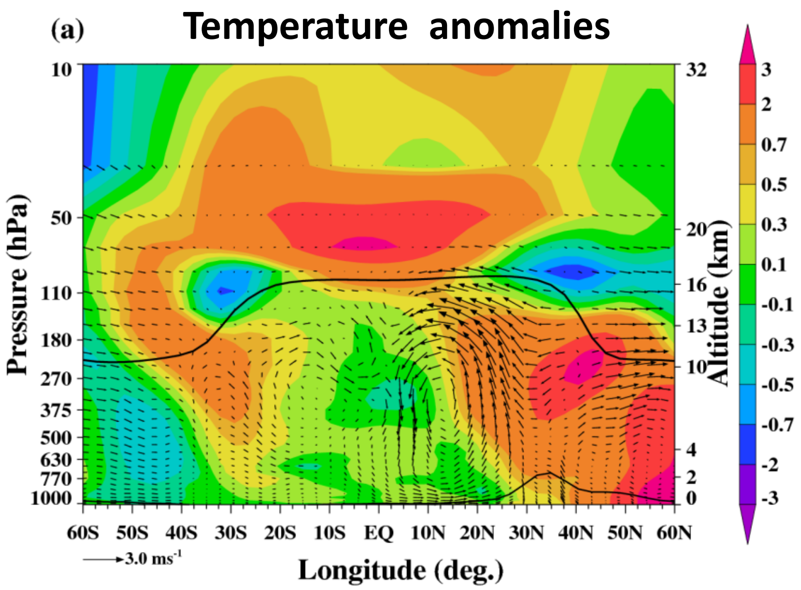
Convective transport during the summer monsoon season



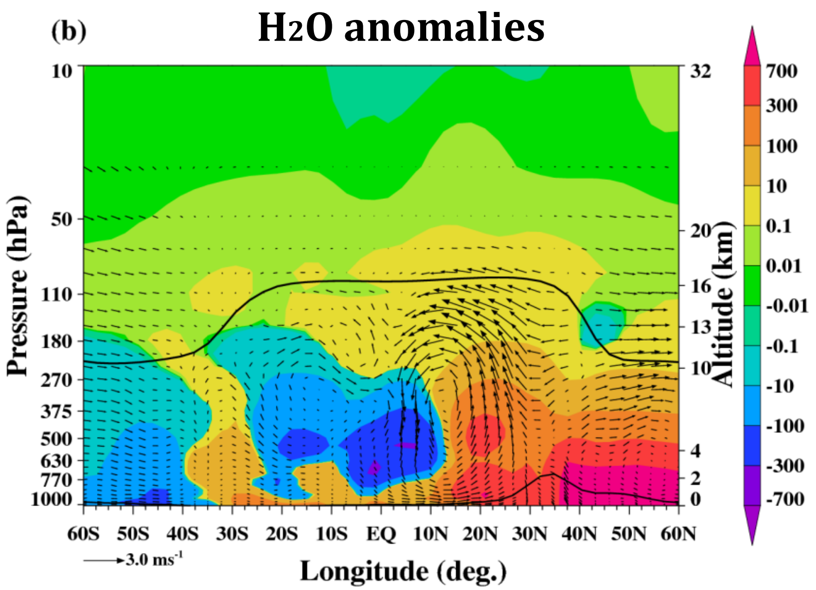
Simulations show that deep convection and heat-driven circulation over the southern flanks of the Himalayas dominate the transport pathway of aerosols and gases into the UTLS.

Fadnavis et al., 2013, ACP

Impacts of aerosols on temperature and water vapour



(a) Temperature anomalies



(b) H_2O anomalies

Experiment Setup: Using ECHAMHAM-MOZ model

- ➢ CTRL with aerosol on
- ➢ Aerosols off over the Asian region
- ➢ Time period: June – September 2003
- ➢ Horizontal resolution: 1.875°×1.875°
- ➢ Horizontal resolution: 1000hPa to 0.01hPa.

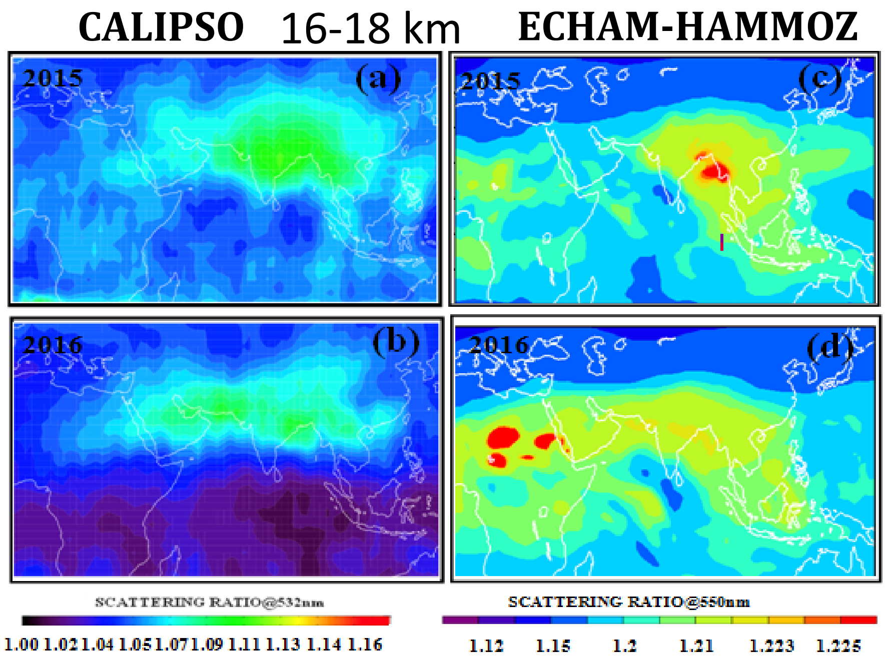
❖ Increase in temperature along the transport path of aerosols by 1–3K. Aerosols enhance warming (>3K) over the Tibetan Plateau.

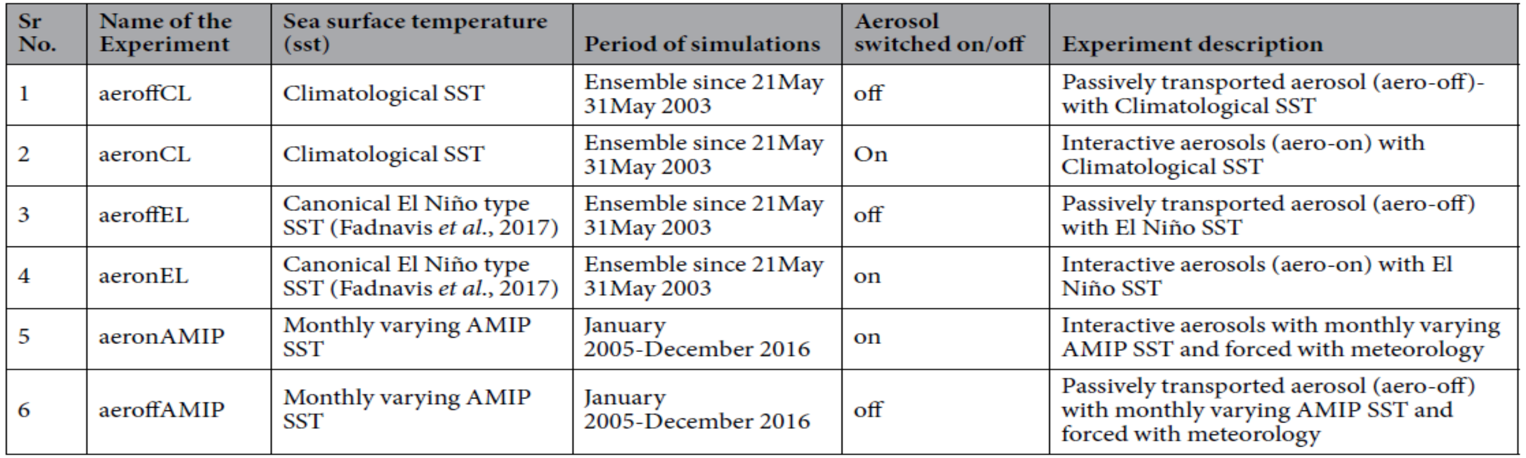
❖Increase in vertical transport of water vapour from the southern flanks of the Himalayas to the UTLS.

❖ It may affect stratospheric ozone.

Fadnavis et al., 2013, ACP

Elevated aerosol layer over South Asia: Indian droughts during El Niño

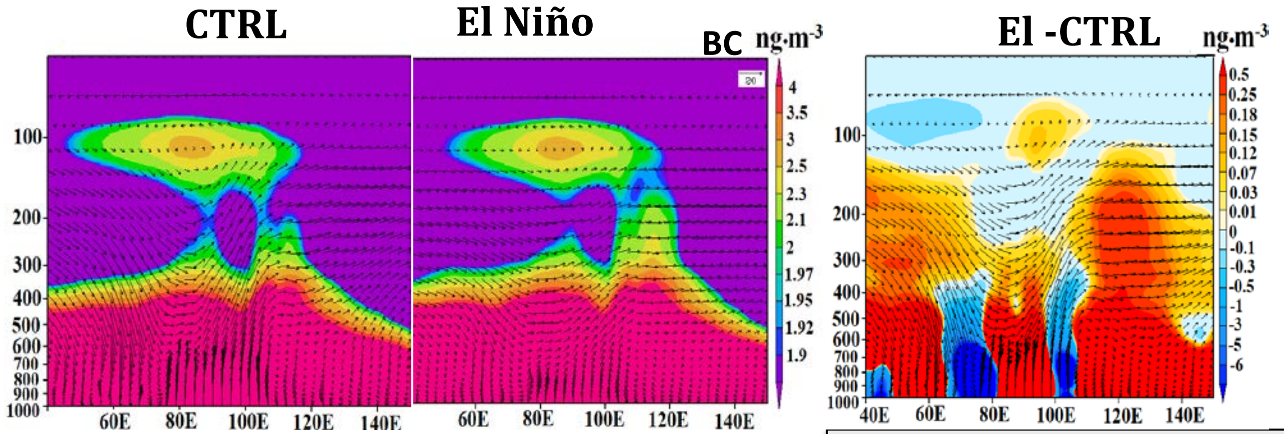




Sr No.	Name of the Experiment	Sea surface temperature (sst)	Period of simulations	Aerosol switched on/off	Experiment description
1	aeroffCL	Climatological SST	Ensemble since 21May 31May 2003	off	Passively transported aerosol (aero-off)-with Climatological SST
2	aeronCL	Climatological SST	Ensemble since 21May 31May 2003	On	Interactive aerosols (aero-on) with Climatological SST
3	aeroffEL	Canonical El Niño type SST (Fadnavis *et al.*, 2017)	Ensemble since 21May 31May 2003	off	Passively transported aerosol (aero-off) with El Niño SST
4	aeronEL	Canonical El Niño type SST (Fadnavis *et al.*, 2017)	Ensemble since 21May 31May 2003	on	Interactive aerosols (aero-on) with El Niño SST
5	aeronAMIP	Monthly varying AMIP SST	January 2005-December 2016	on	Interactive aerosols with monthly varying AMIP SST and forced with meteorology
6	aeroffAMIP	Monthly varying AMIP SST	January 2005-December 2016	off	Passively transported aerosol (aero-off) with monthly varying AMIP SST and forced with meteorology

- ❖ **During El Niño the ATAL is thicker and centered over the Indian region.**
- ❖ **The ATAL is wide spread and thinner during a normal year.**

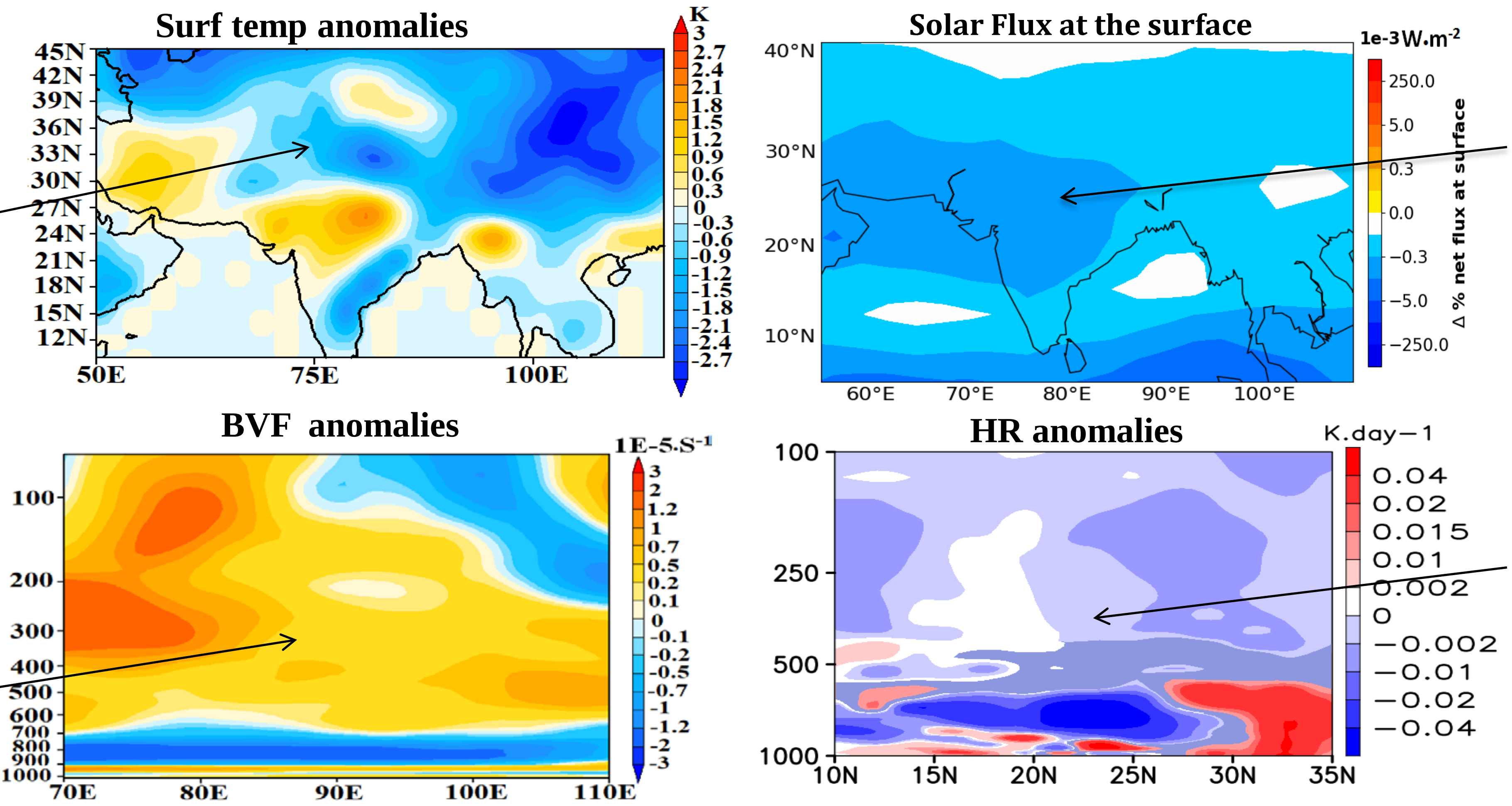
- ➢ **Aerosols in the ATAL are transported from: (1) South Asia and (2) East-Asia.**
- ➢ **During El Niño aerosols in the ATAL are mostly from East Asia.**



Fadnavis et al., Sci. Reports, 2019

Impact of aerosol layer during El Niño

Aero-on EL-CL



Surface cooling over the IGP

Reduction in solar radiations at the surface.

Stability in the troposphere over the Indian region

Tropospheric cooling

Aerosol Layer over South Asia over caused surface cooling, reduction in solar radiations, increased stability of the troposphere and cooling of the troposphere.

Fadnavis et al., Sci. Reports, 2019

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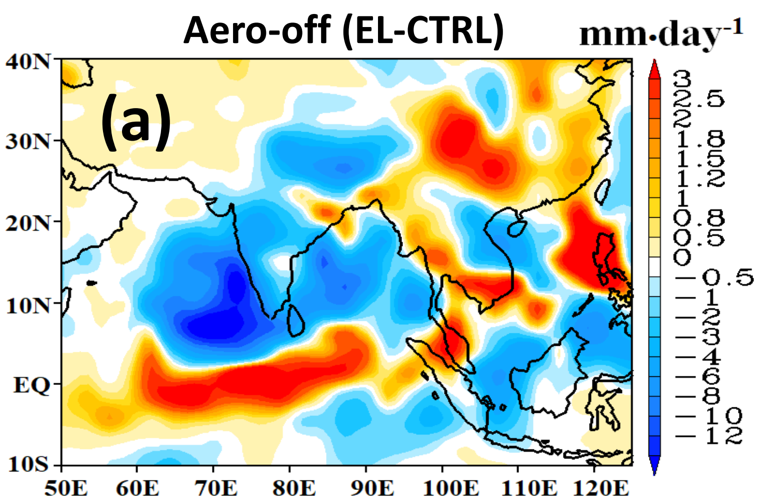
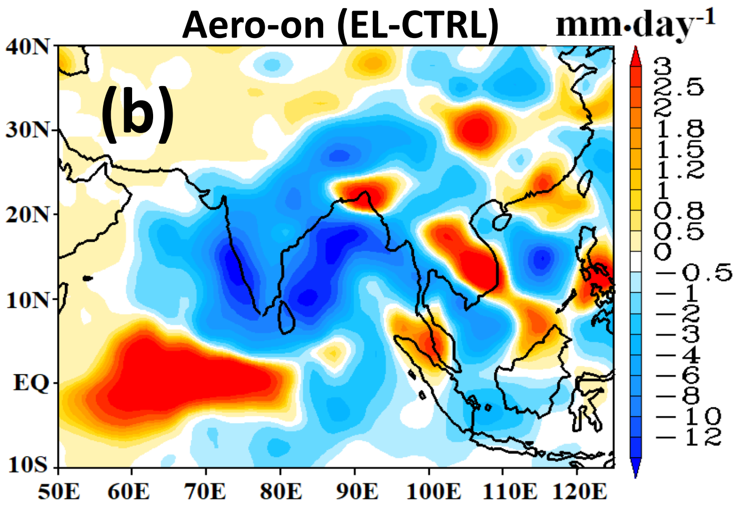
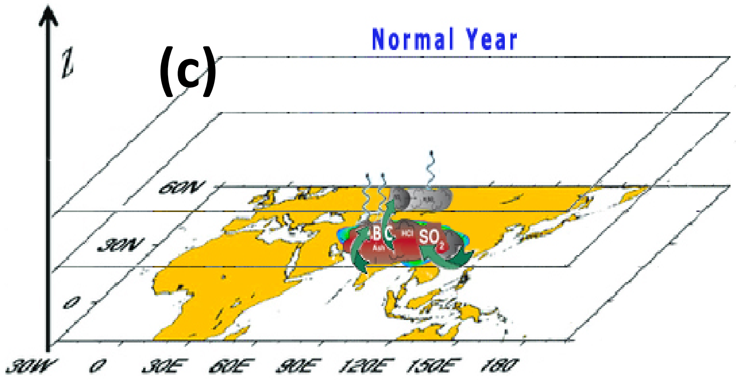
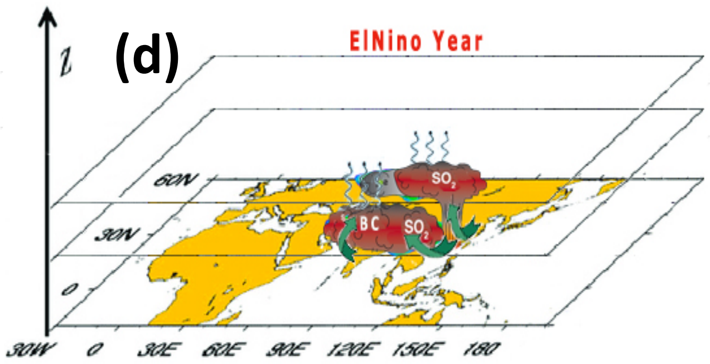
Impact on precipitation during El Niño





The changes in aerosols exacerbated severity of droughts during El Niño (rainfall reduction by 17%).

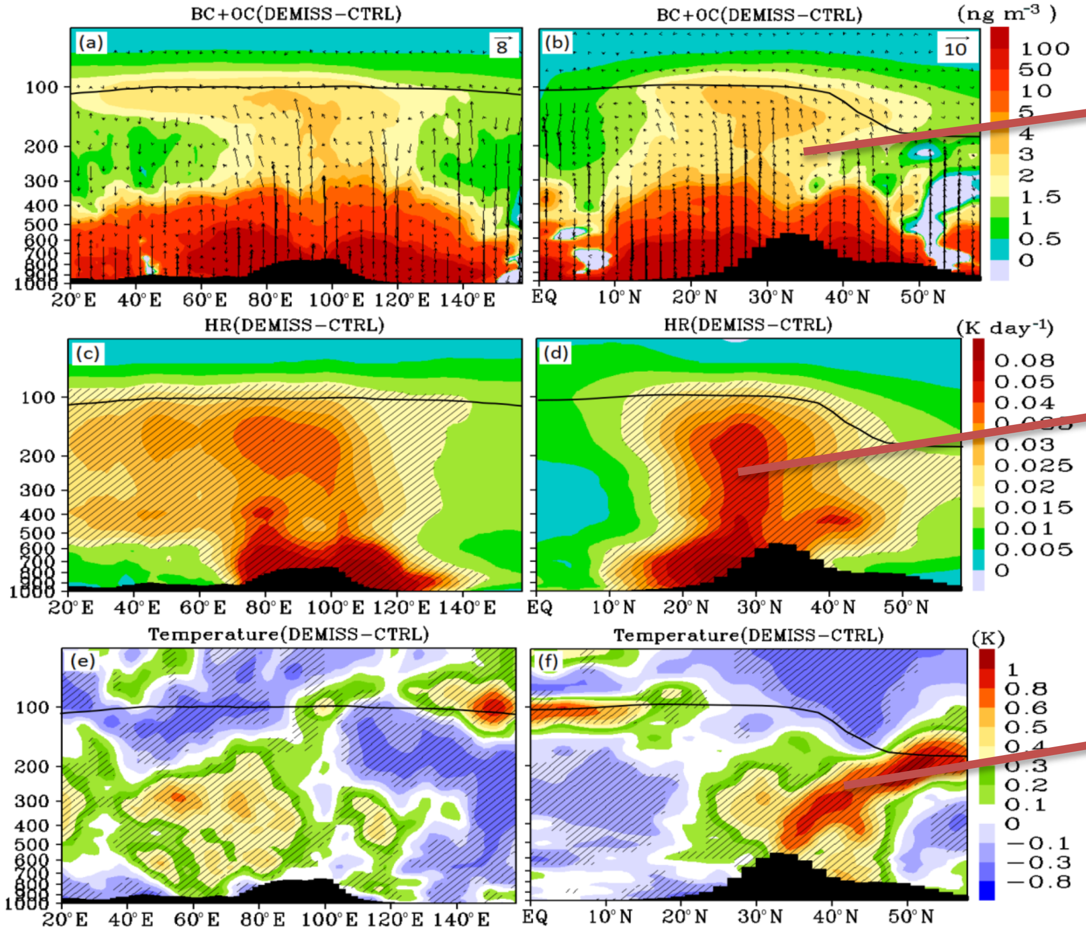




- ❖ The added blanket of aerosol layer leads to a weakening of the monsoon Hadley circulation.
- ❖ The anomalous large-scale subsidence results in amplifying the severity of monsoon droughts.

Fadnavis et al., 2019

Transport of carbonaceous aerosol by the monsoon circulation into the UTLS



Plume of BC and OC aerosols during the monsoon season

Increased heating rates

Increased Temperature

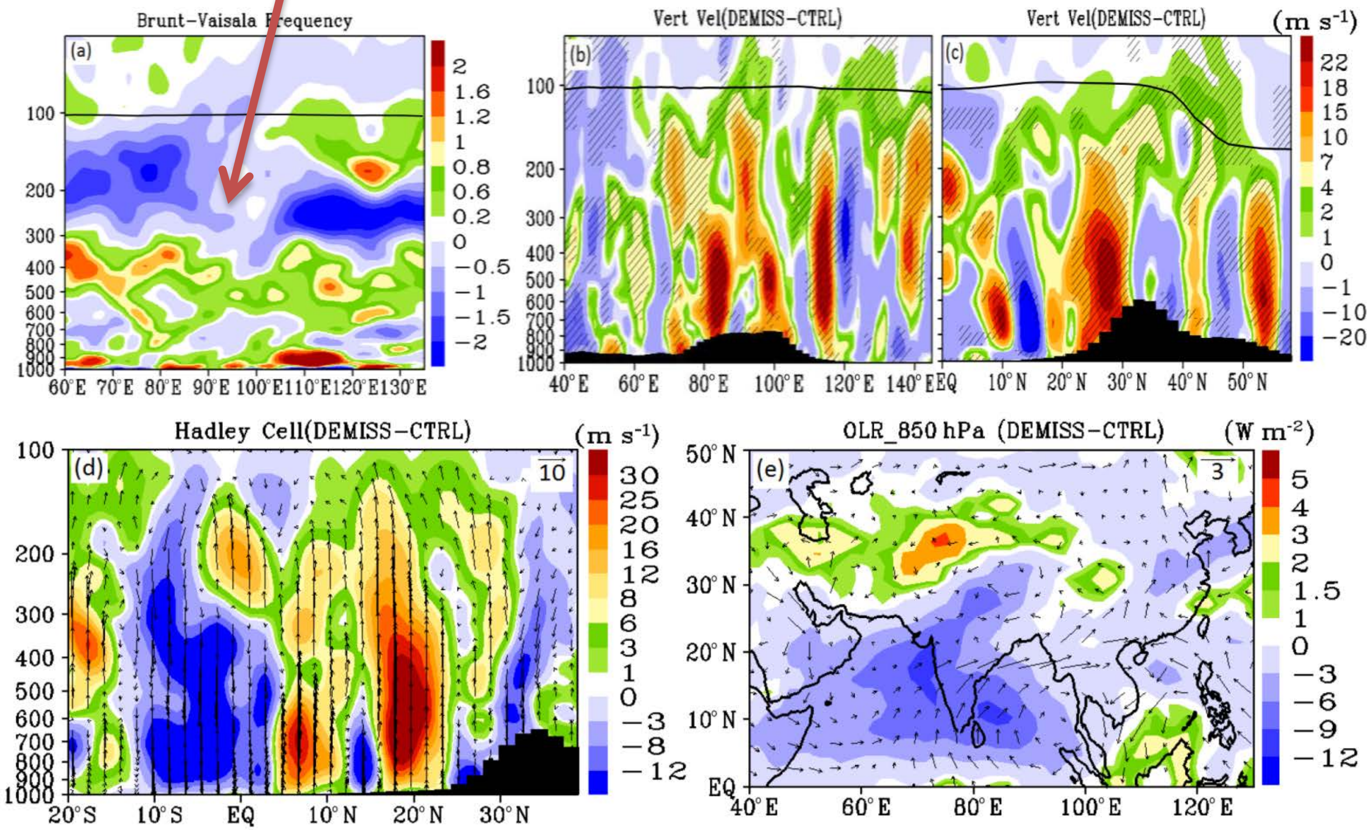
Experiment Setup: Using ECHAMHAM-MOZ model

- **CTRL with baseline**
- **sensitivity simulations for doubling of carbonaceous aerosols over the Asian region**
- **Time period: June-Sept 1997-2016**
- **Horizontal resolution: 1.875°×1.875°**
- **Horizontal resolution: 1000hPa to 0.01hPa.**

Impacts of carbonaceous aerosols on the monsoon circulation and rainfall

Upper atmosphere is less stable

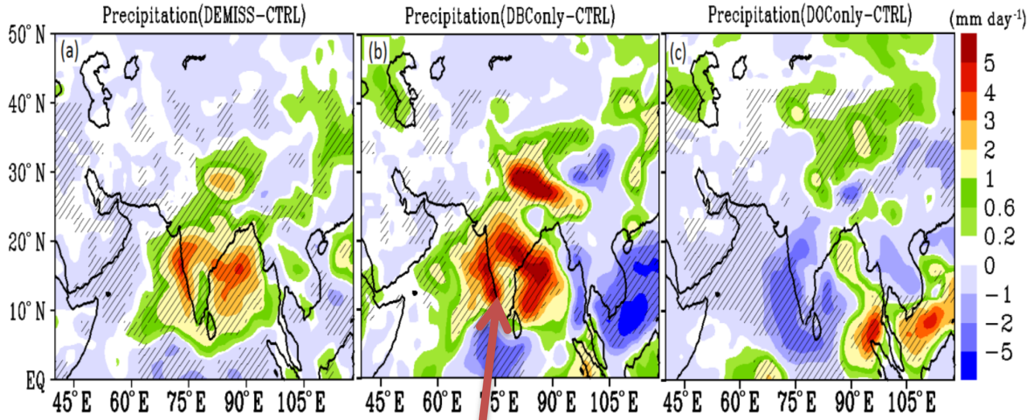
Vertical velocity increases



Strengthen the Hadley Circulation

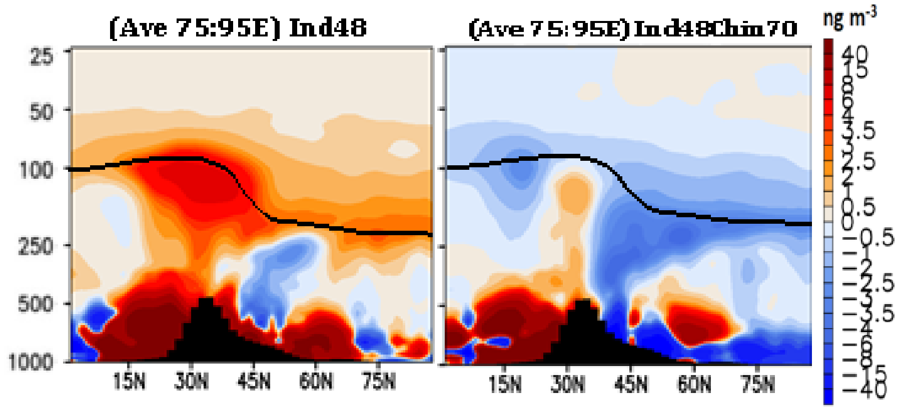
Deepening of OLR

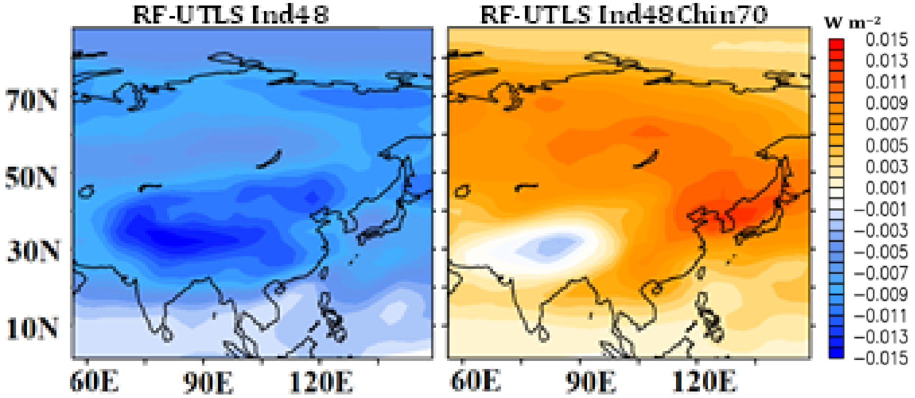
The enhanced carbonaceous aerosols strengthen the monsoon Hadley circulation by intensifying warming over the TP.



Increased precipitation by 1 to 4mm day^{-1}

Sulfate aerosols in the UTLS: Radiative changes



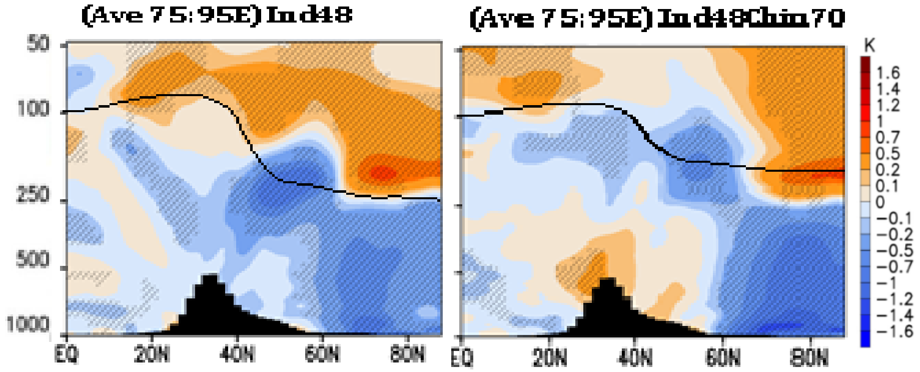


IND48-> Increased SO2 emission by 48% over India.
Chin70-> Decrease SO2 emission over India by 70% following OMI observations during 2006-2017.

Sulfate aerosols from BL over India are transported to the UTLS by the monsoon convection.

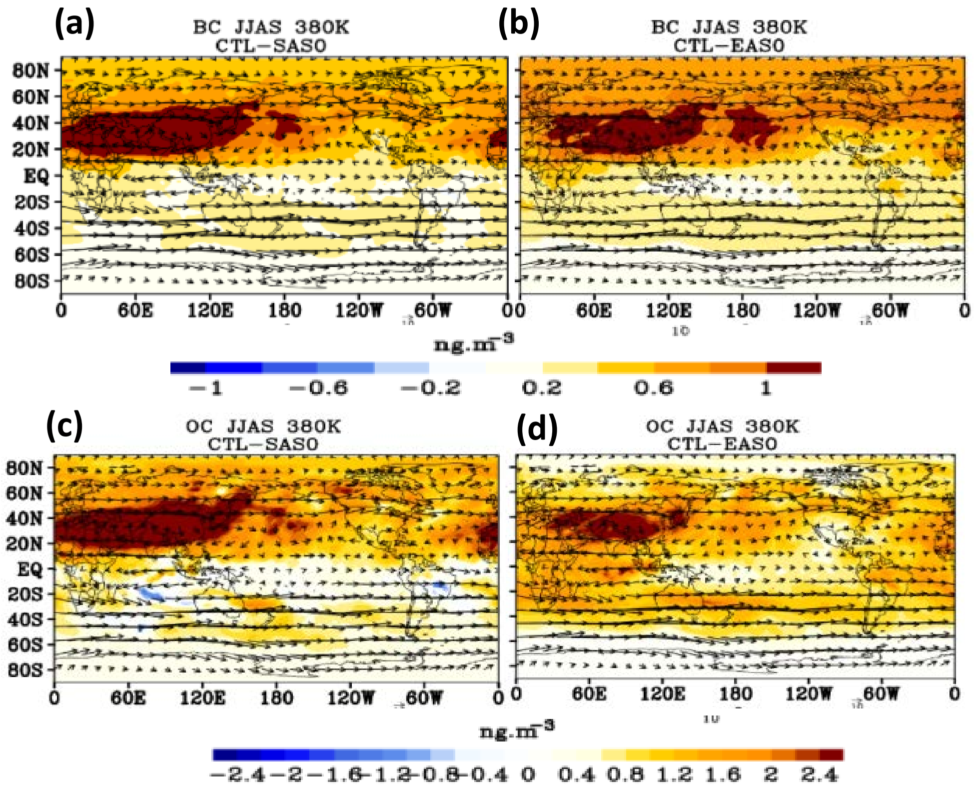
RF (TOA) by Indian SO_2 emission -0.2 to $-1.5\ \mathrm{W\,m^{-2}}$ over northern India. (UTLS: $\sim -0.025\ \mathrm{W\,m^{-2}}$)

This leads to a warming 0.8±0.72 K in the UTLS and to a cooling below it in the troposphere (-0.6 ± 0.4 K)



Fadnavis et al., ACP. 2019.

Transport of South Asian and East Asian aerosols into the monsoon anticyclone



Experiment Setup: Using ECHAMHAM-MOZ model

- CTRL (where all aerosol were kept on)
- SAS0 (Where all South Asian aerosol kept off)
- EAS0 (where all East Asian aerosol kept off)
- Time period: June-Sept 2001-2018
- Horizontal resolution: 1.875°×1.875°
- Horizontal resolution: 1000hPa to 0.01hPa.

- Higher contribution of BC and OC aerosols from South Asia into the ASMA than East Asia.

- It indicates that heat-driven circulation over the southern flanks of the Himalayas dominates the vertical transport from South Asia.

Transport of Asian aerosols to the Arctic region and its impacts

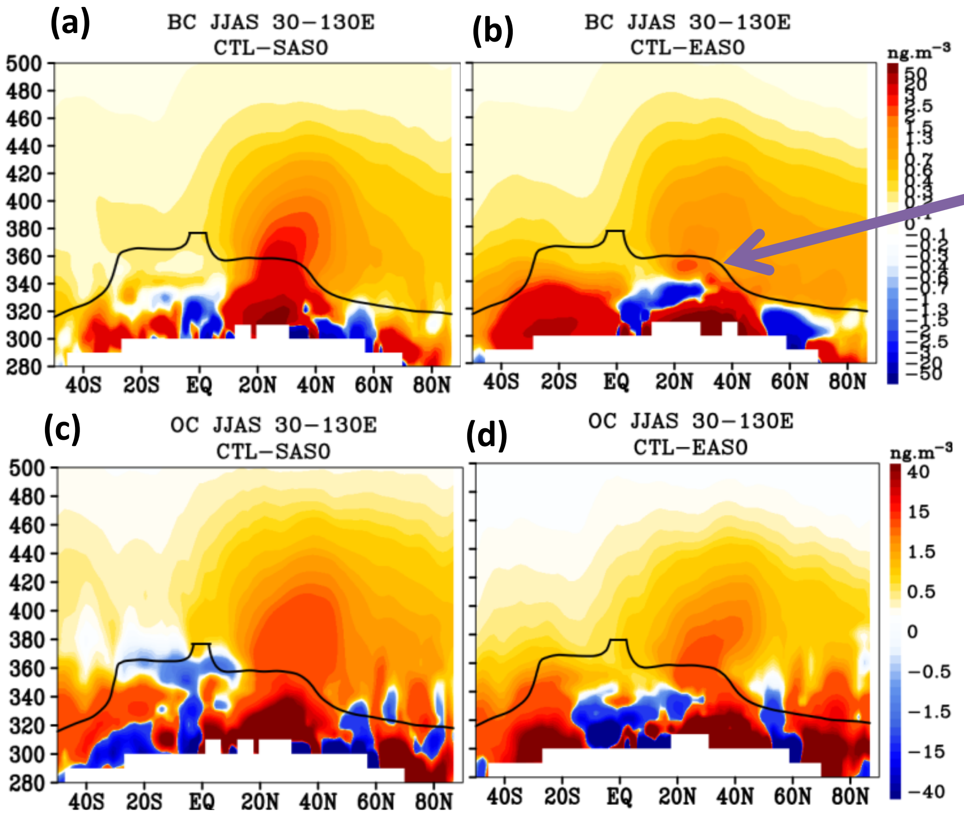


Fig: Distribution of anomalies of BC (ng.m-3) averaged over the ASMA (30-130E) from (a)CTL-SAS0 (b)CTL-EAS0. (c-d) same as (a-b) but for OC aerosols.

- The transported into the anticyclone are further transported to the Arctic in the UTLS (340-420K).

- The convection over the South Asia extends to a higher altitudes than over East Asia, likely influenced by the high elevation of the Himalayas. As a consequence, the outflow of South Asian aerosol occurs at higher levels than for East Asian aerosols.

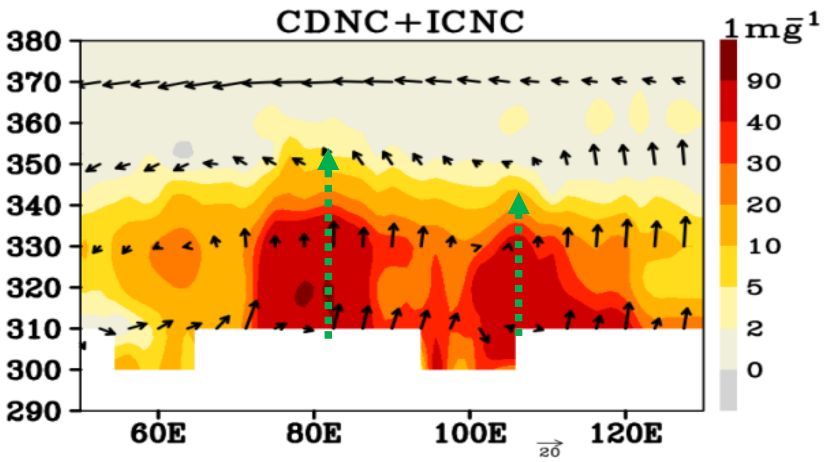
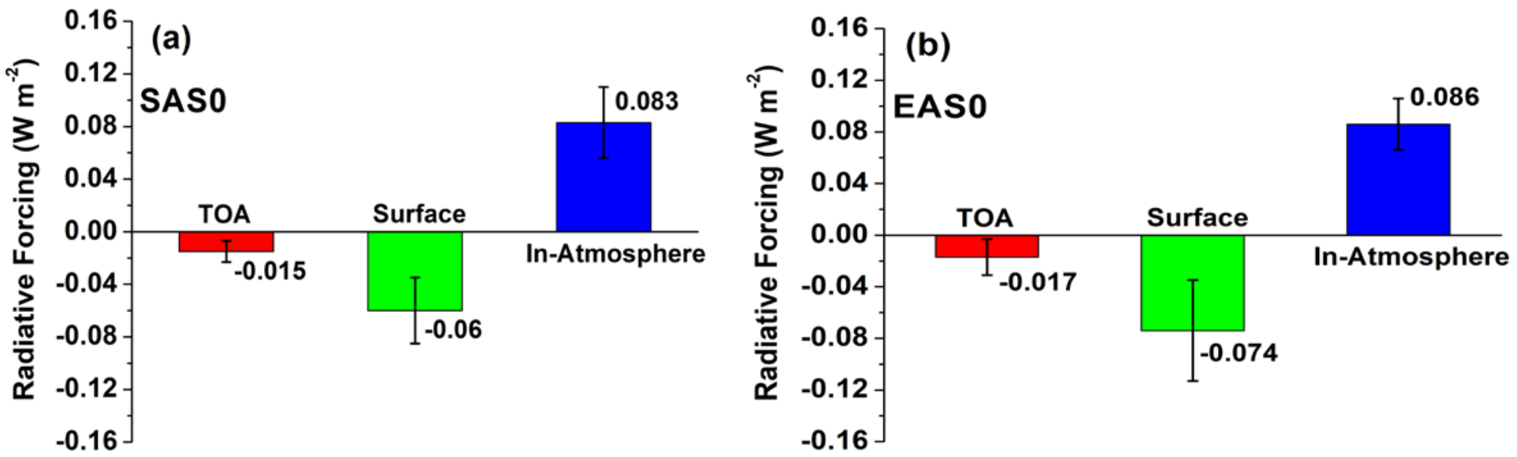


Fig: Vertical distribution of cloud droplet number concentration along with ice crystal number concentration (mg^{-1}) averaged for 10°-30°N and the monsoon season.

Impact on Radiative Forcing in the Arctic during the monsoon season

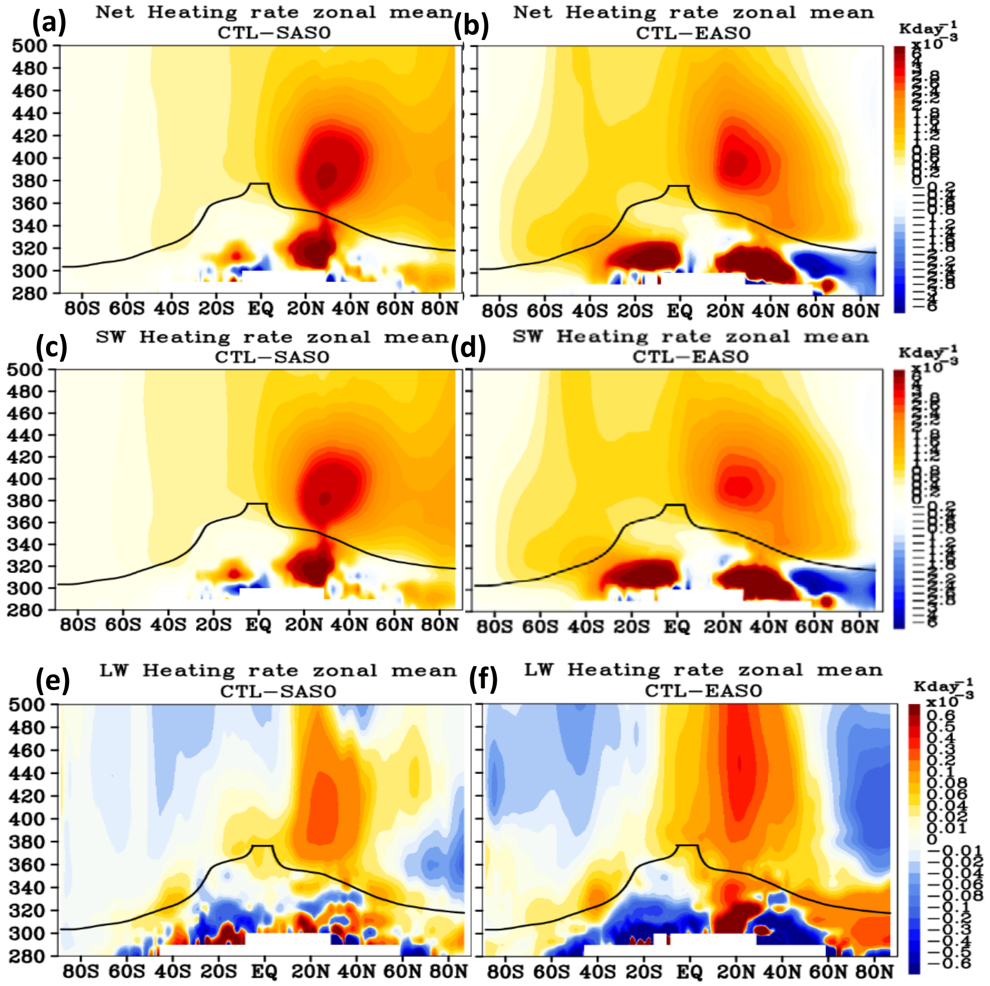


- The aerosol radiative forcing at the Arctic due to aerosol transported from South Asia is -0.06±0.02 Wm^{-2} at the surface and -0.015±0.008 Wm^{-2} at the top-of-the atmosphere (TOA) (with a corresponding in-atmosphere forcing of +0.083±0.02 Wm^{-2}).

- The aerosol transported over the Arctic from East Asia reduces RF by -0.074±0.04 Wm^{-2} at the surface, -0.017±0.01 Wm^{-2} at the TOA (i.e., in-atmosphere RF by +0.086±0.02 Wm^{-2}).

- The South Asian and East Asian anthropogenic aerosols emissions lead to an Arctic near surface temperature change of -0.56 K and -0.43 K, respectively in simulations with fixed sea surface temperature.

Impacts on heating rates

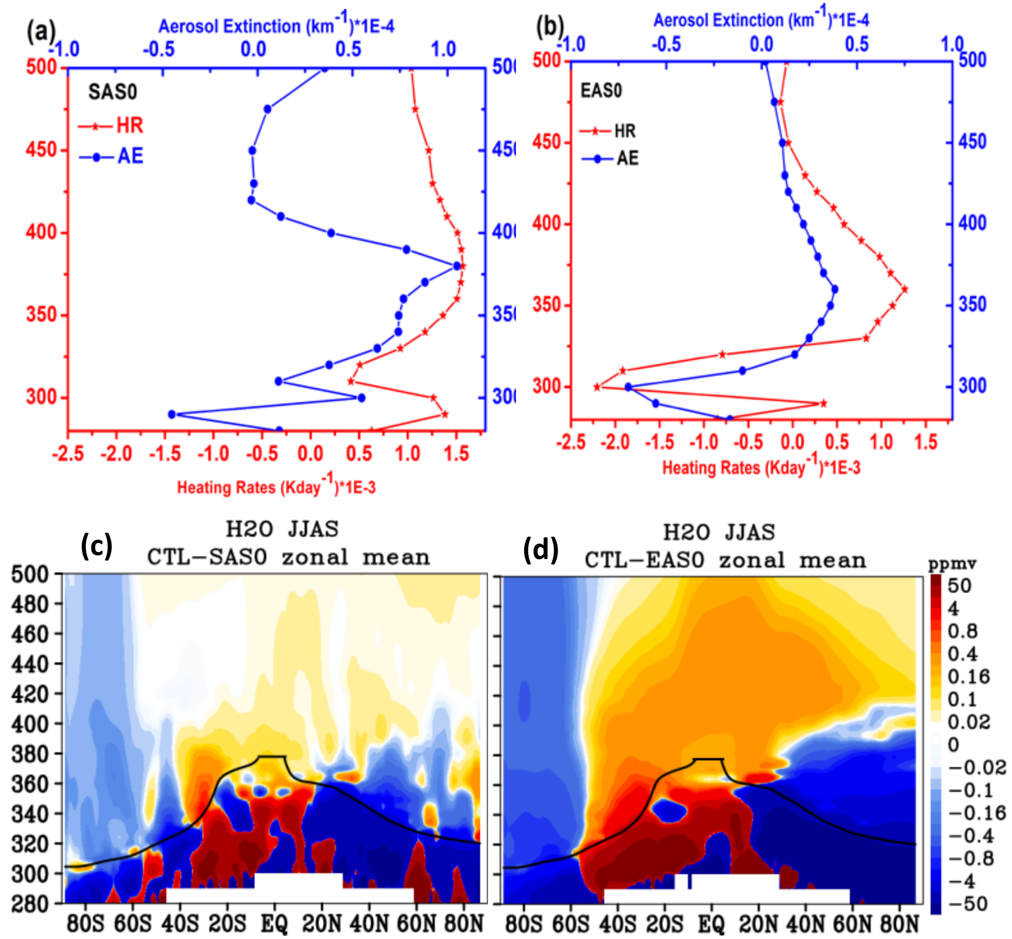


- Figure a-b shows that South Asian emission enhances net heating by 0.0012K da^{-1} to +0.0018K day^{-1} at the Arctic while East Asian emission cause negligible heating 0.0005K day^{-1} at the Arctic UTLS.

- Figure a-f shows that aerosols short wave heating is the dominating factor in the net heating rates while long wave heating rates are negative in the Arctic UTLS (South Asia: -0.0002K day^{-1}, East Asia: -0.0004K day^{-1}).

- The monsoon anticyclone region shows enhancement in shortwave and longwave heating rates for South Asia emission (SW: 0.0042K day^{-1}, LW: 0.00015K day^{-1}) and East Asia (SW: 0.0022K day^{-1}, LW: 0.00018K day^{-1}) the higher amount of short wave and long wave heating in the ASMA region than in the Arctic is due to higher amount of aerosol and gases including water vapor.

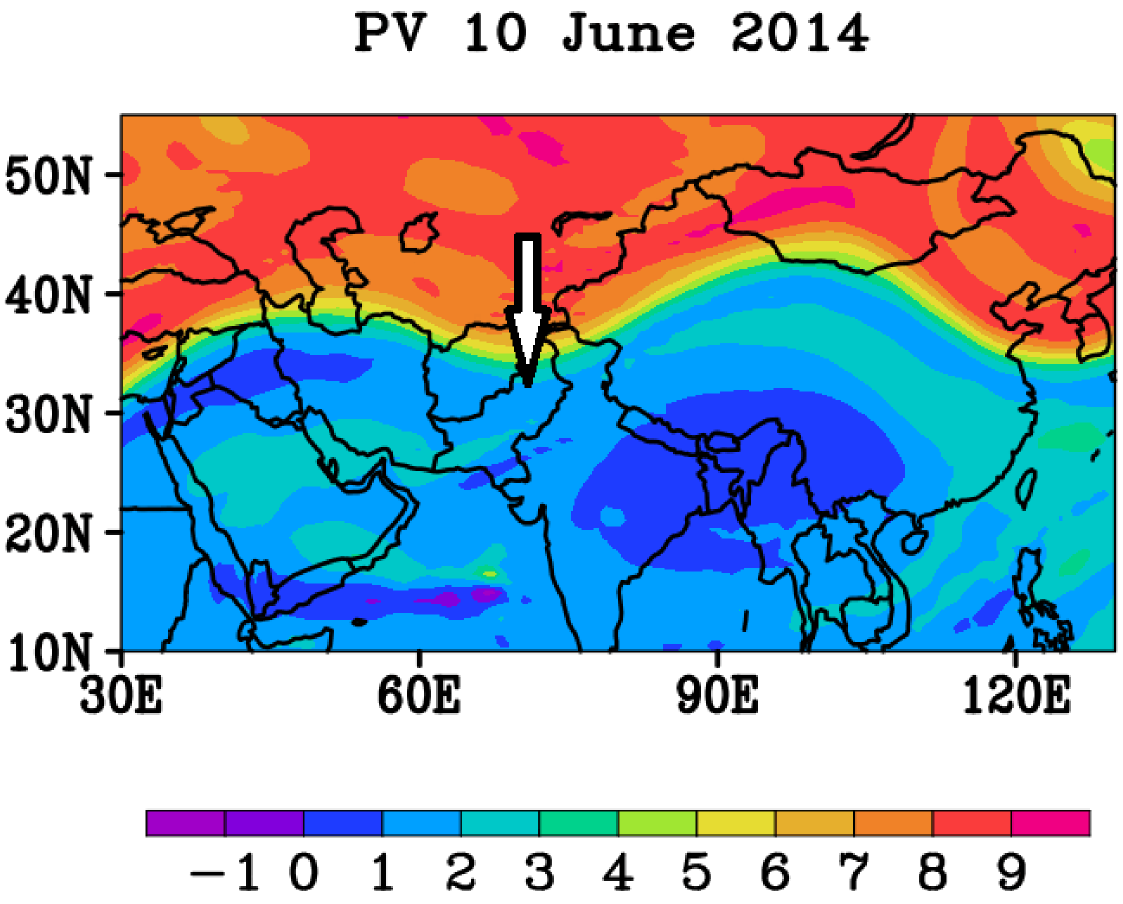
Vertical distribution of aerosol extinction and the heating rate and water vapor anomalies over the Arctic



- ➢ The South Asian aerosols produce maximum heating of 1.57E-3K day^{-1} and extinction (1.05E-4 km^{-1}) at 380K potential temperature level. The East Asian shows lower heating rates 1.26E-3 K day^{-1} and extinction a maximum (0.38E-4 km^{-1}) at 360K level which is below the South Asian extinction maximum.

- ➢ The larger amount of water vapor is transported to the Arctic stratosphere (420-500K) due to East Asian aerosol emission changes than due to South Asian emission (South Asian 0.025ppmv, East Asian ~0.16 ppmv) that cools the Arctic stratosphere, water vapor long-wave cooling partly offsets the aerosol short-wave heating resulting in producing negligible net heating.

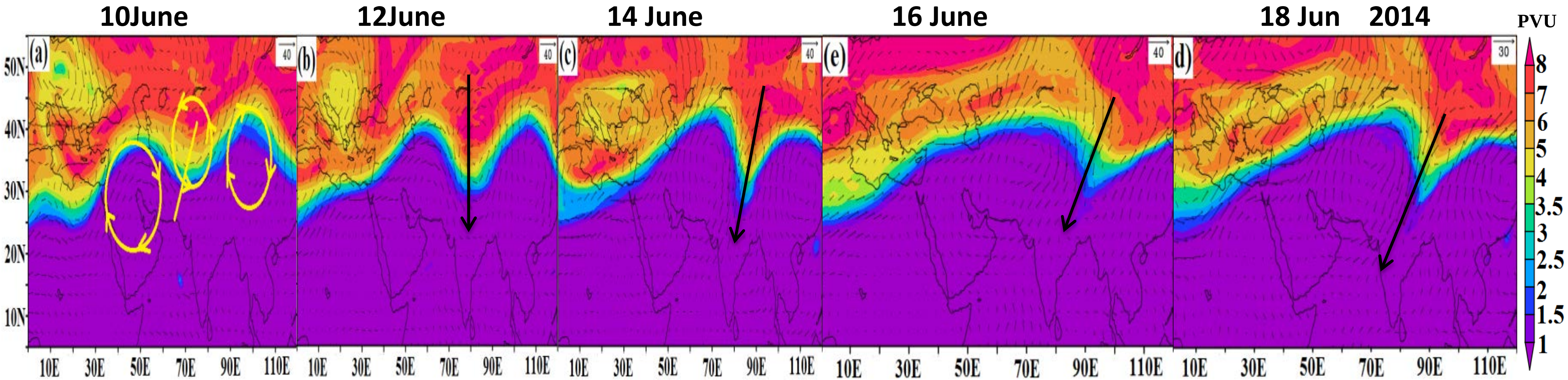
Dynamic monsoon anticyclone



Rossby wave breaking in the subtropical jet

Linkages of stratospheric intra-seasonal intrusions with ISMR deficit

Rossby wave breaking (RWB) in the subtropical westerly jet

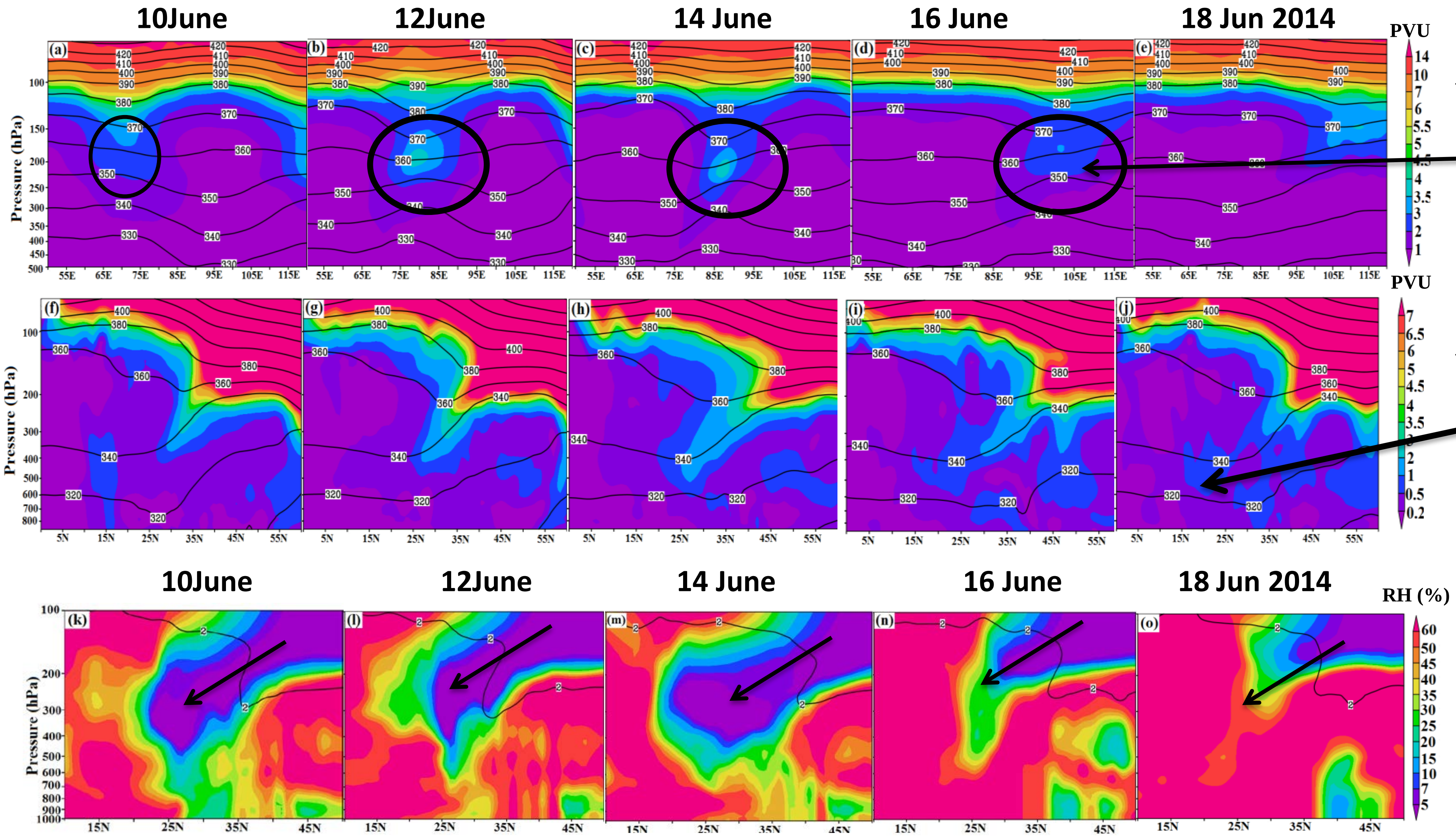


350 K potential surface

- ERA-INTERIM reanalysis data show that deep stratospheric intrusion due to RWB occurred over NI and TP region during 10-18 June 2014.
- RWB in the subtropical westerly jet caused eddy shedding. These eddies propagated downward into the mid-troposphere over NI and TP regions.

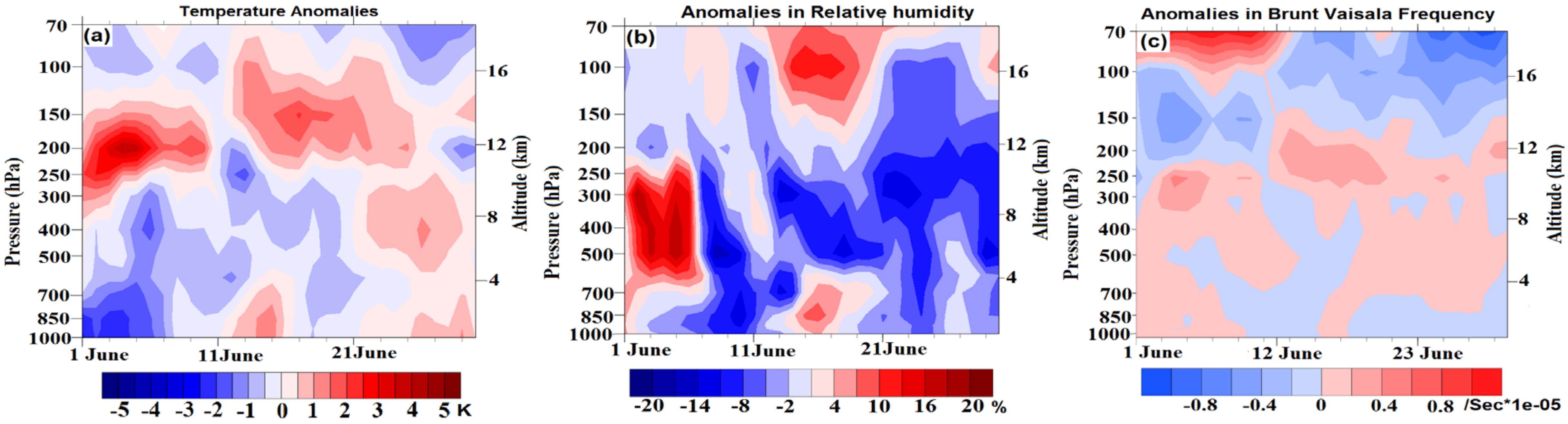
Fadnavis and Chattopadhyay, J. Clim., 2107

Extra-tropical stratospheric intrusions over India



- ❖ Stratospheric intrusions and eddy shedding.
- ❖ Transport from the lower stratosphere to the upper troposphere over North India
- ❖ Intrusion of dry air (RH < 10%).

Impacts on the troposphere



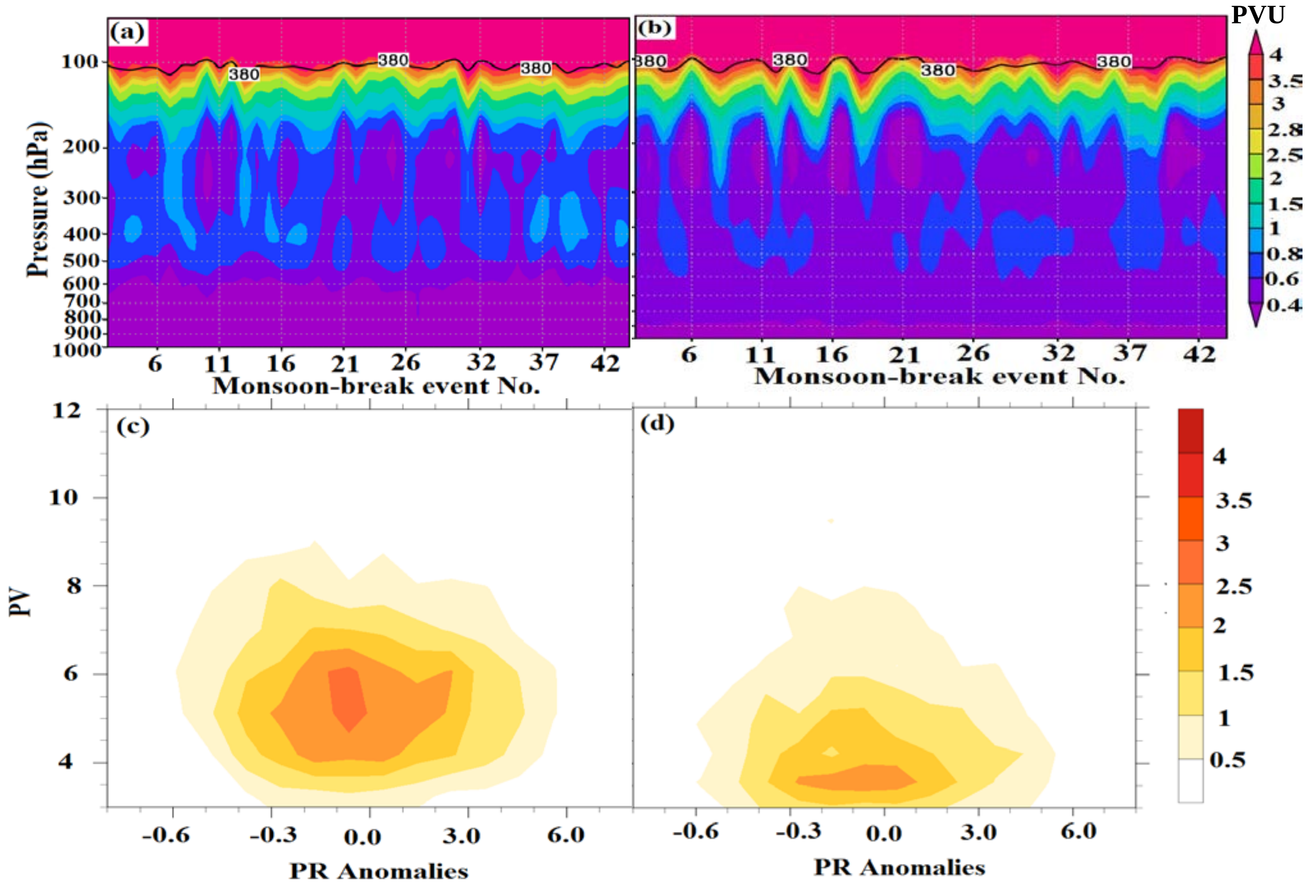
- **The cod and dry intrusion occurred over North India (NI).**
- **The intruded air masses remained until the end of June 2014. They have reduced RH and enhanced the static stability over NI.**

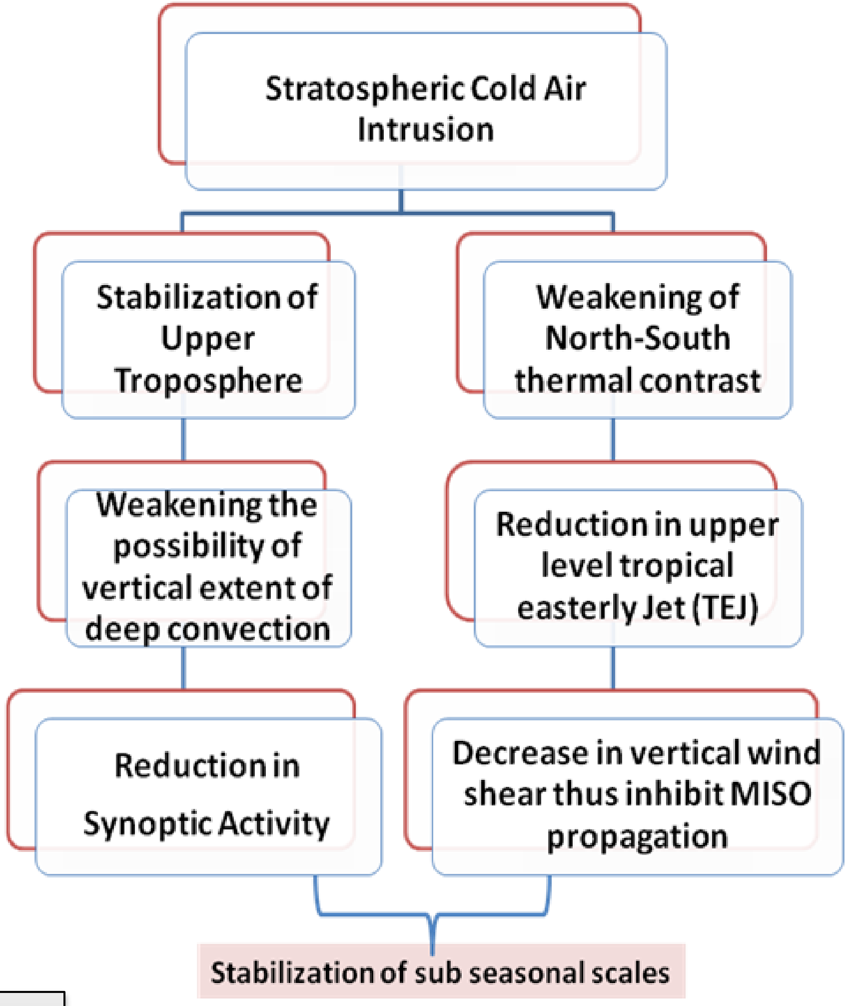
Fadnavis and Chattopadhyay, J.Clim, 2017.

Influence of stratospheric intrusion on ISMR reduction

Monsoon breaks during 1979–2007

(a) Region-1 (27-35°N, 60-78°E), (b) Region-2(27-35°E,78-110°E)





Stratospheric Cold Air Intrusion

Stabilization of Upper Troposphere

Weakening of North-South thermal contrast

Weakening the possibility of vertical extent of deep convection

Reduction in upper level tropical easterly Jet (TEJ)

Reduction in Synoptic Activity

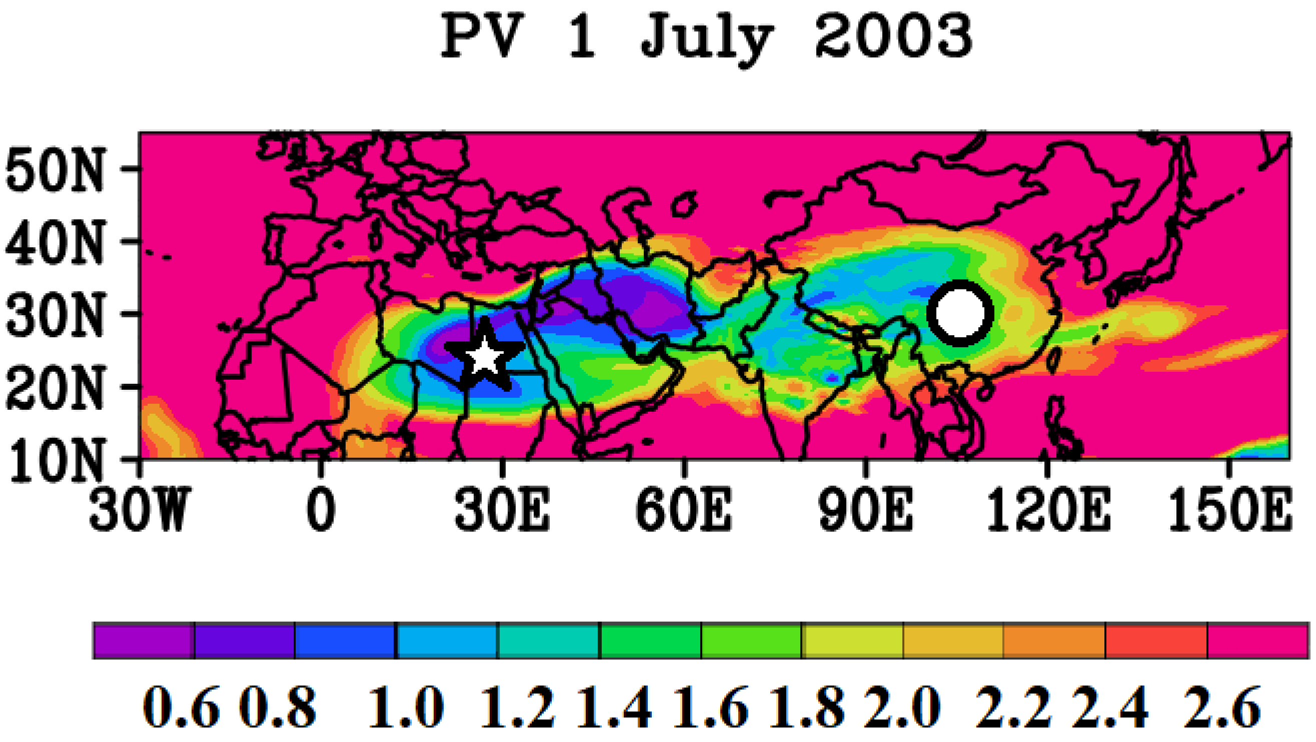
Decrease in vertical wind shear thus inhibit MISO propagation

Stabilization of sub seasonal scales

- **Cold and dry stratospheric intrusions are likely to intensify the development of longer monsoon weak spells during the Indian summer monsoon season.**

Fadnavis and Chattopadhyay, J.Clim, 2017.

Eddy shedding from the monsoon anticyclone

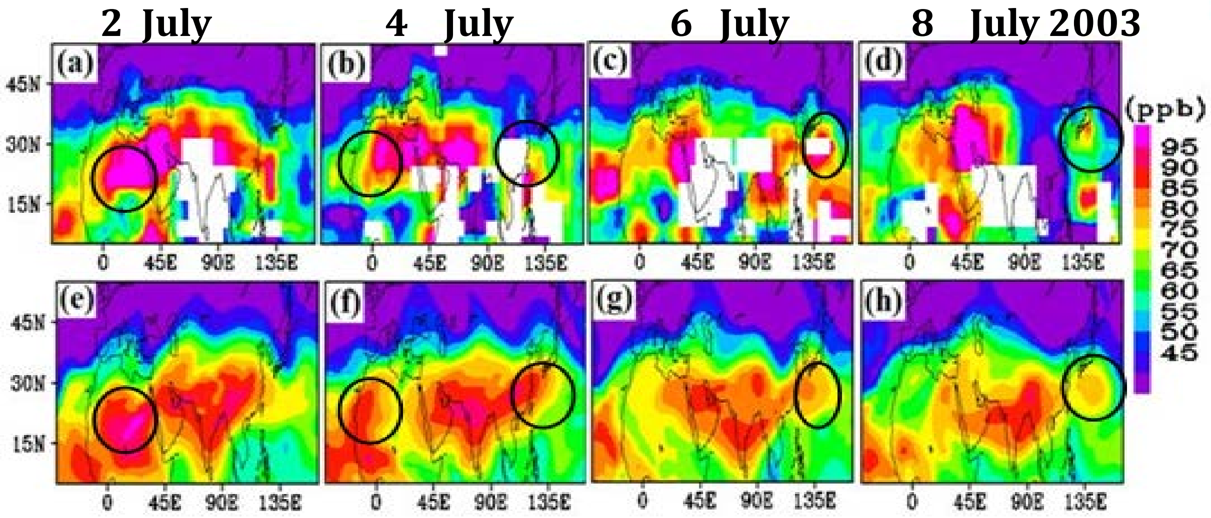


suvarna@tropmet.res.in

Transport of trace gases via eddies

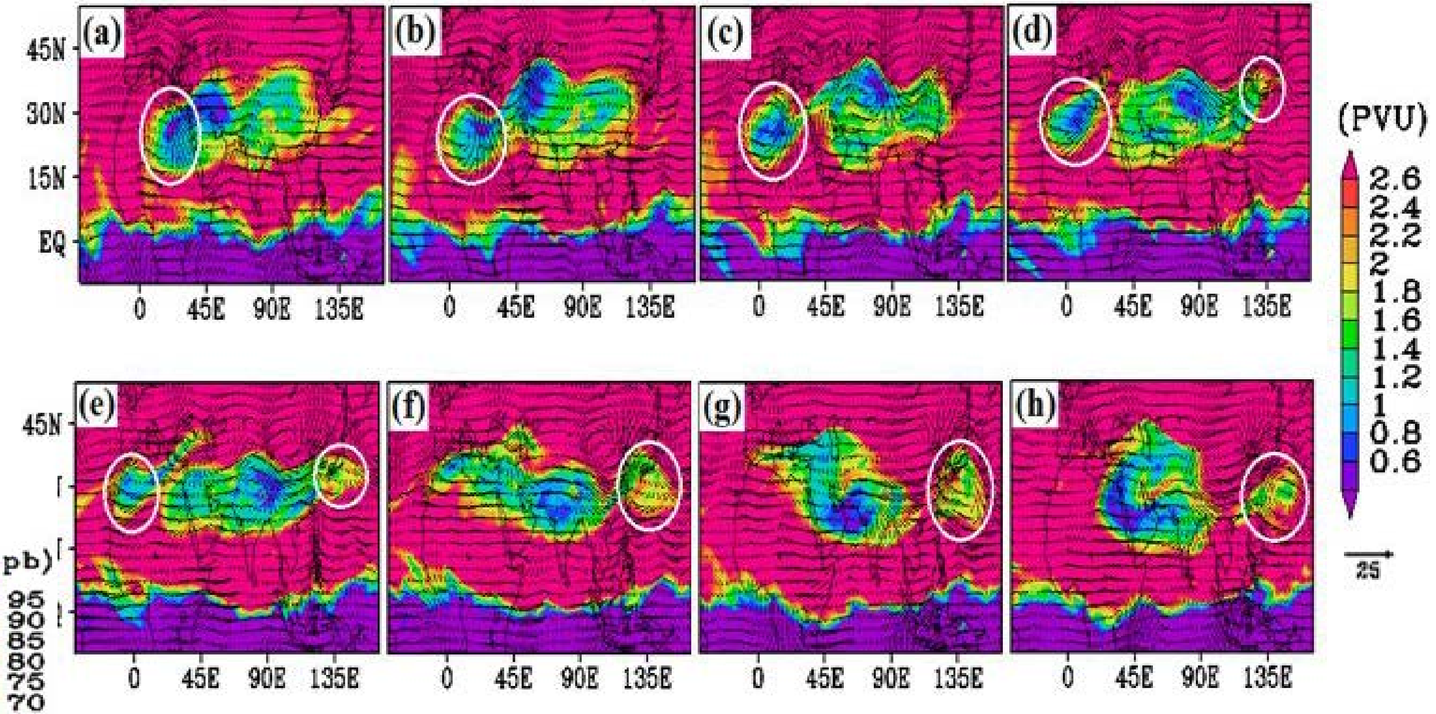
- Wobbling monsoon anticyclone continuously changes shape due to RWB.
- Eddies detached from the ASMA transport pollutants to the west (west Africa) and east (West Pacific).

MIPAS and ECHAM CO



1-8 July 2003

370 K potential surface



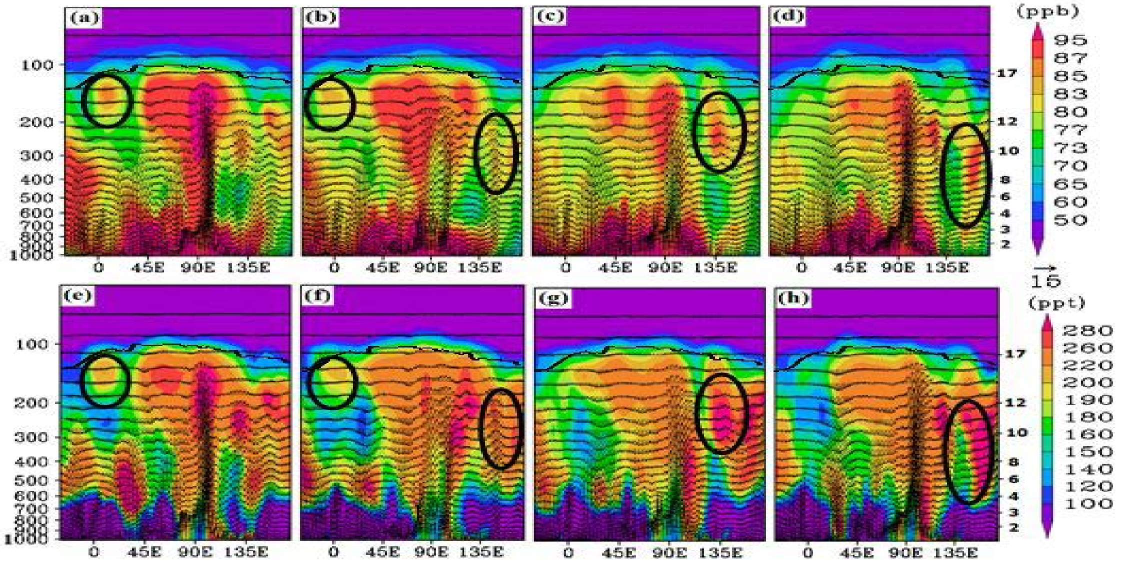
Eddies are the carrier of ozone, water vapor, CO, PAN, and other trace gases.

The transported pollutants change the chemical composition and RF at the receptor region.

Fadnavis et al., ACP, 2018

Transport of PAN via Asian summer monsoon

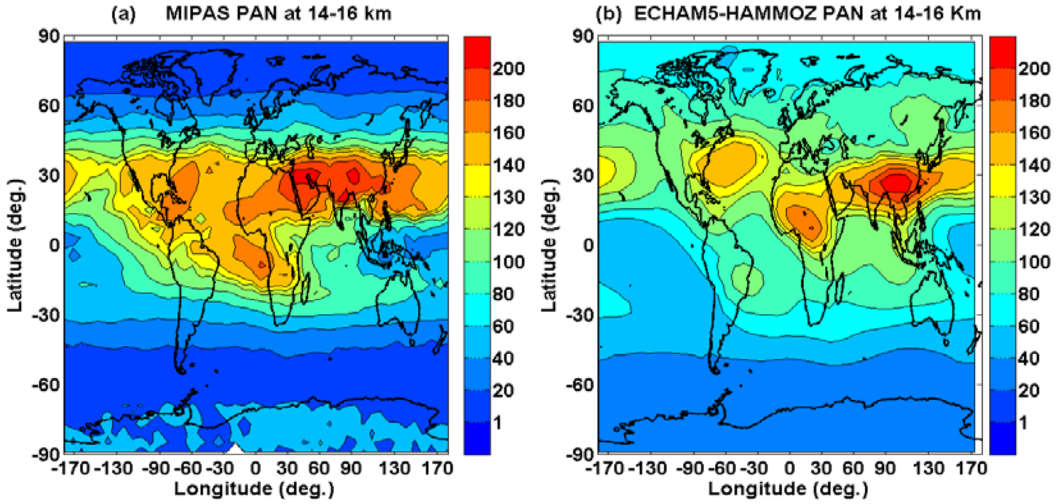
PAN (1-8 July 2003)



- ❖ PAN is lifted into the UTLS by the monsoon convection.
- ❖ It is transported to the east and west of ASAM via eddies.

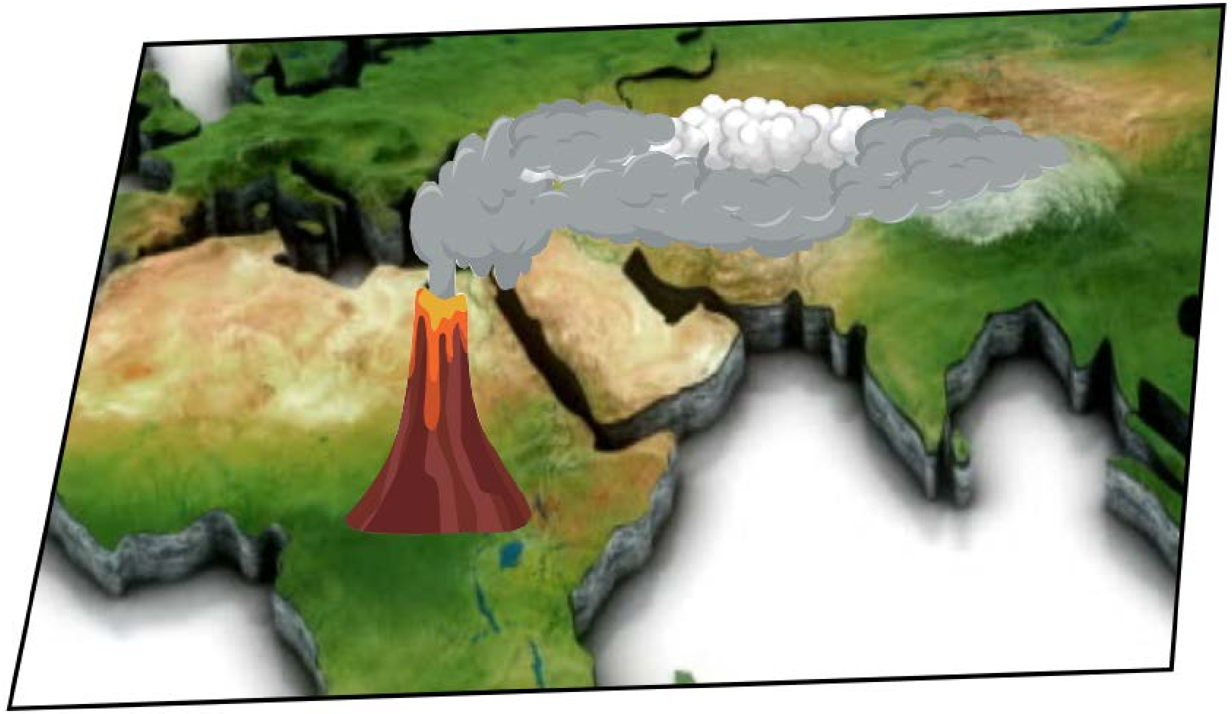
Fadnavis et al., ACP, 2014, 2015

- ❖ The frequency of occurrence of eddy shedding events is higher over the West Pacific (68%) than the West Africa (25%).
- ❖ A 10 % reduction of Asian emissions of NMVOCs and NOx lead to a decrease in ozone (~4.5 %), and ozone heating rates (~0.004 K·day^{-1}) in the UTLS over West Africa and West Pacific.



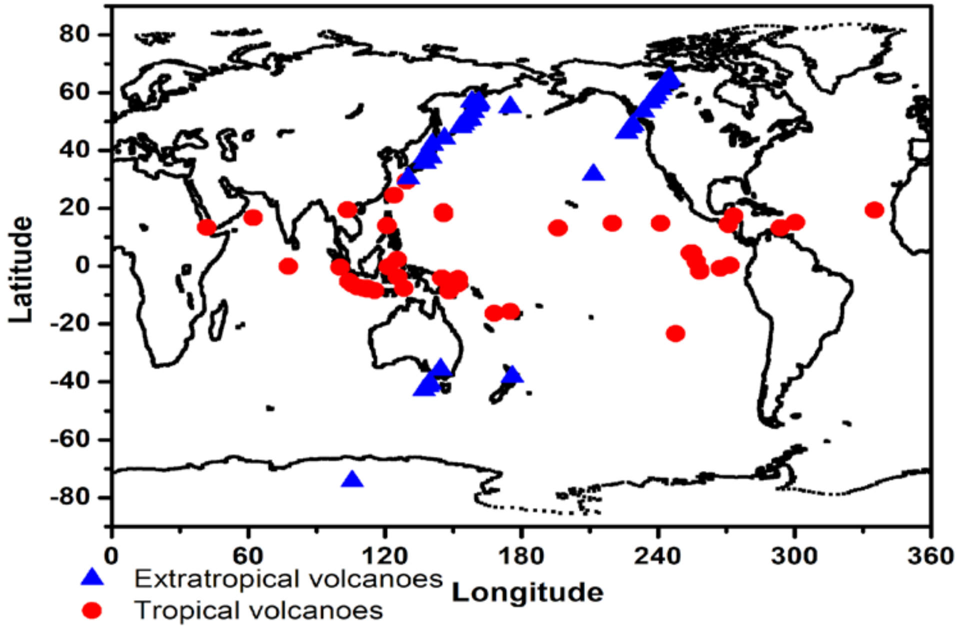
Tropical volcanoes : implications on Indian droughts

Tropical volcanic eruption



Location of tropical/ extra-tropical Volcanoes

1871 –2016



Impact of volcanoes on precipitation

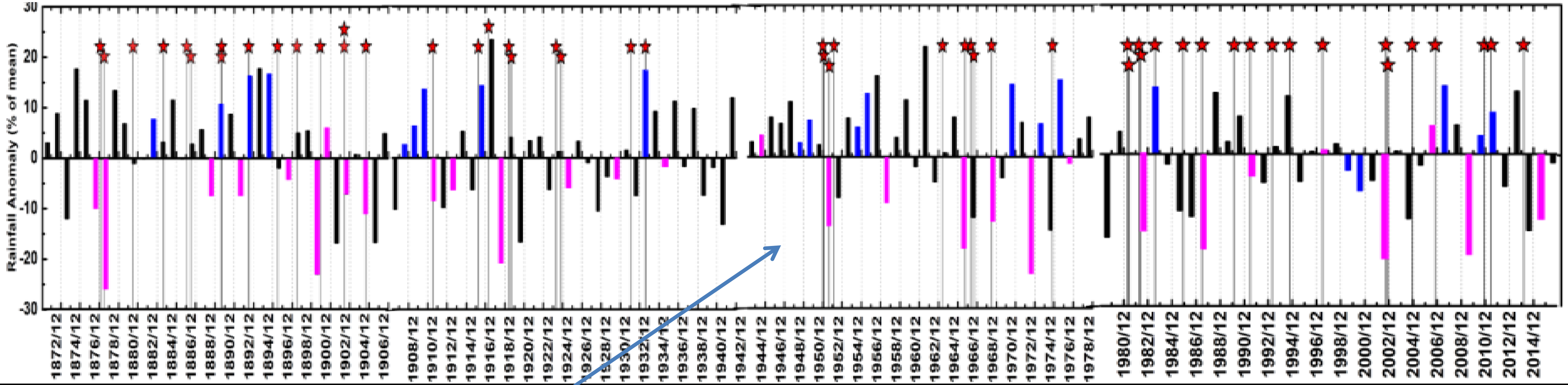
Volcanic eruptions and Global monsoon

- Northern hemisphere (NH) monsoon precipitation is weakened by NH and equatorial volcanic eruptions, but is enhanced by Southern hemisphere (SH) eruptions. (Liu 2010, Zuo 2019).
- CMIP5 models also showed precipitation reductions during the years after tropical volcanic eruptions, mostly in the monsoon regions, for five explosive eruptions (Krakatau, Santa María, Agung, El Chichón, and Pinatubo).

Motivation:

(1) Study linkages of tropical/extra-tropical volcanoes with Indian monsoon.
(2) Quantify the impact of volcanoes on the Indian summer monsoon.
(3) Understand the mechanism for precipitation changes.

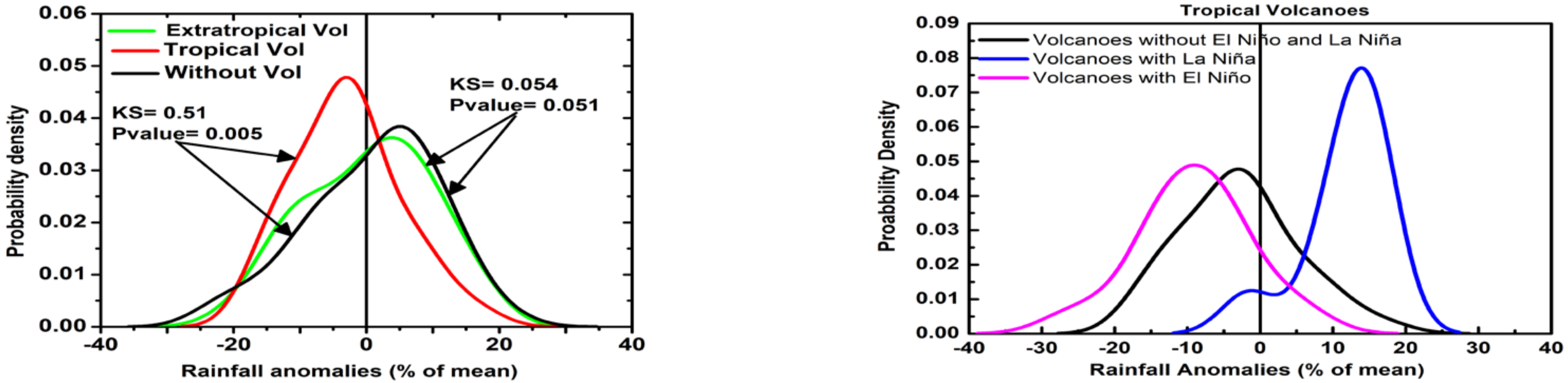
Tropical volcanoes and Indian summer monsoon



VEI>3

India meteorology
rain gauge data

Time series of June–September mean precipitation anomaly (%) during 1871 –2016 along with tropical (30ºS-30N) volcanic eruptions indicated with stars.



Probability distribution of rainfall anomalies within two years of volcanic eruption during El Niño, La Niña, and normal years.

Simulation of NABRO volcano: ECHAM6-HAMMOZ and MPI-ESM

- **We performed Nabro volcano and control simulations starting from 1 to 10 January 2011 to obtain a 10-member ensemble mean. These simulations ended on 31 December 2013. In all 10 members of simulations, 1.5 Tg of SO_2 was injected at 42 ºE, 13 ºN on 12 June 2011.**

- **Simulations indicate that the Nabro volcanic plume formed a thick aerosol layer in the UTLS over the Indian region lasting up to October 2012.**

- **The volcanic aerosol partially enters the monsoon anticyclone causing a thickening of the ATAL during monsoon 2011 (July-August-September).**

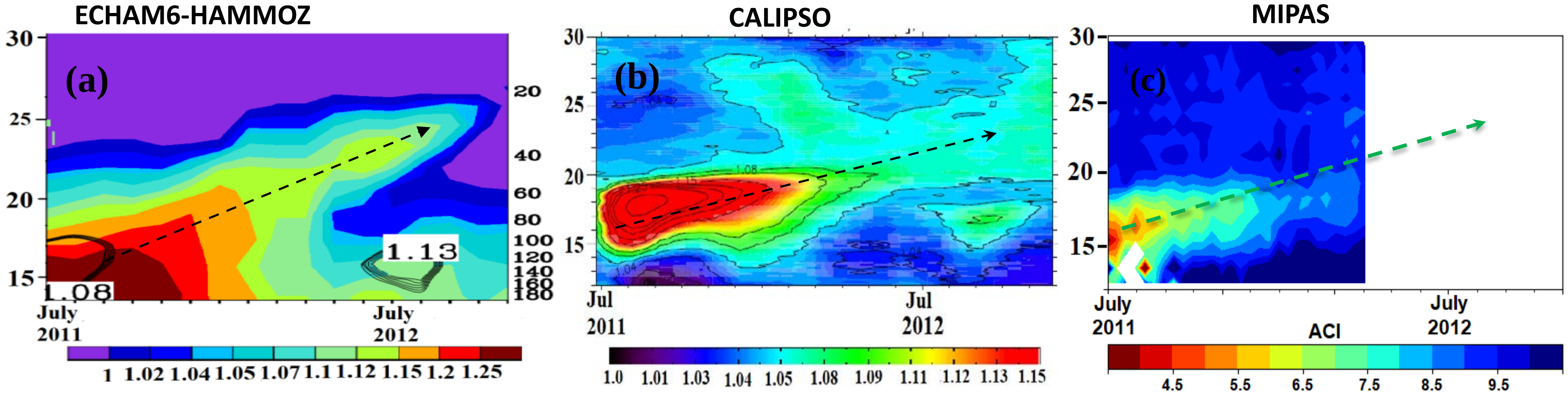
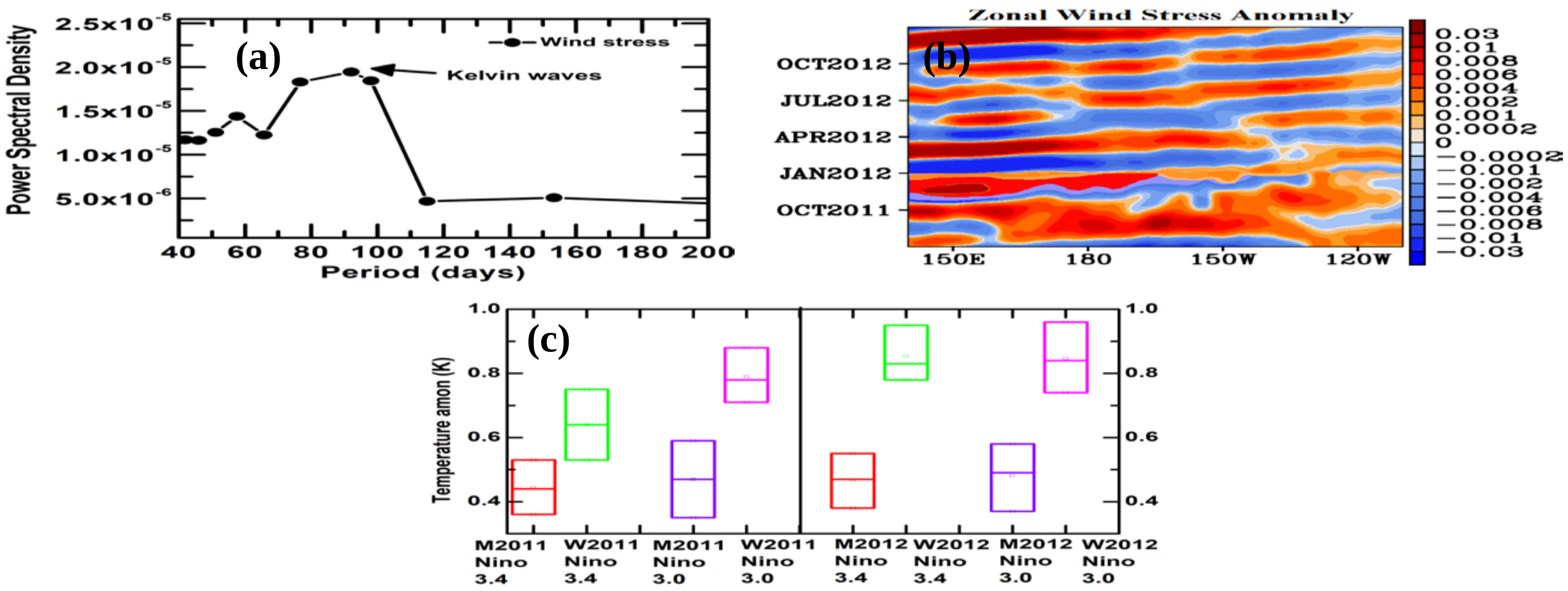


Fig.: Scattering ratio (532nm) vertical distribution during July 2011 – November 2012 averaged over India (70 – 95 ºE; 10 – 30 ºN), (a) ECHAM6-HAMMOZ (b) CALIPSO, and Aerosol cloud index (ACI) estimates from MIPAS (c).

Association of volcanic eruptions with ENSO

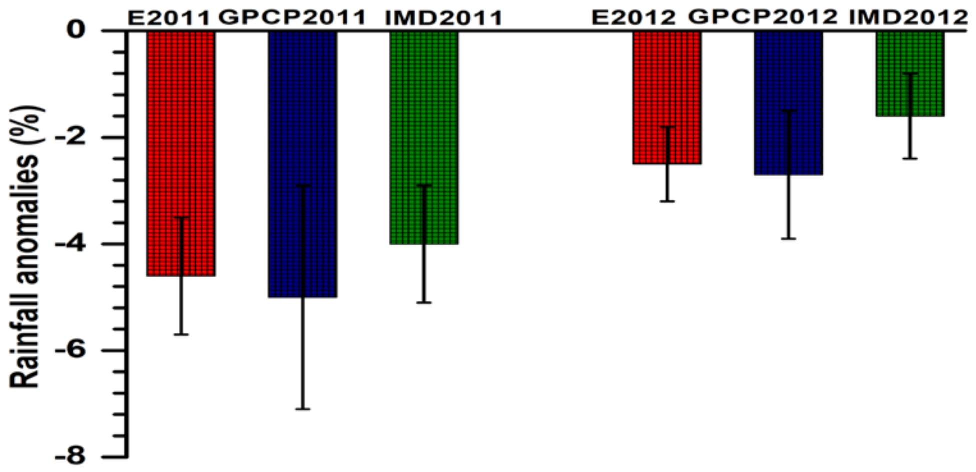


- The surface cooling over the Indian region induced by the aerosol layer from Nabro caused an atmospheric westerly wind anomaly in the central Pacific in July 2011 after the eruption.

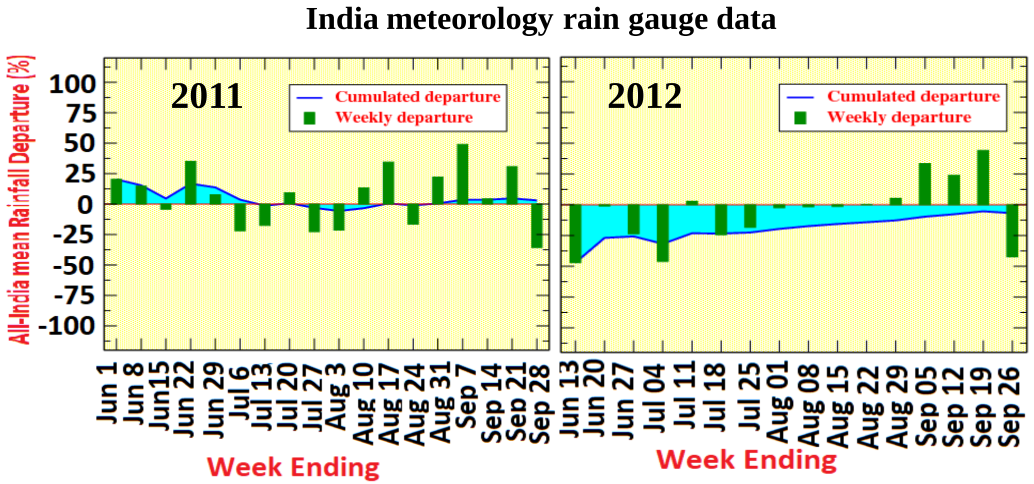
- This wind anomaly resulted in downwelling equatorial oceanic Kelvin waves through air-sea interactions and eventually drove a surface warming in the central Pacific during July 2011 to February 2013.

- The simulations also show warming due to Kelvin wave dissipation is stronger in the following year (monsoon and winter seasons in 2012) than the year of volcanic eruption (monsoon and winter seasons in 2012).

Reduction in Indian summer monsoon precipitation



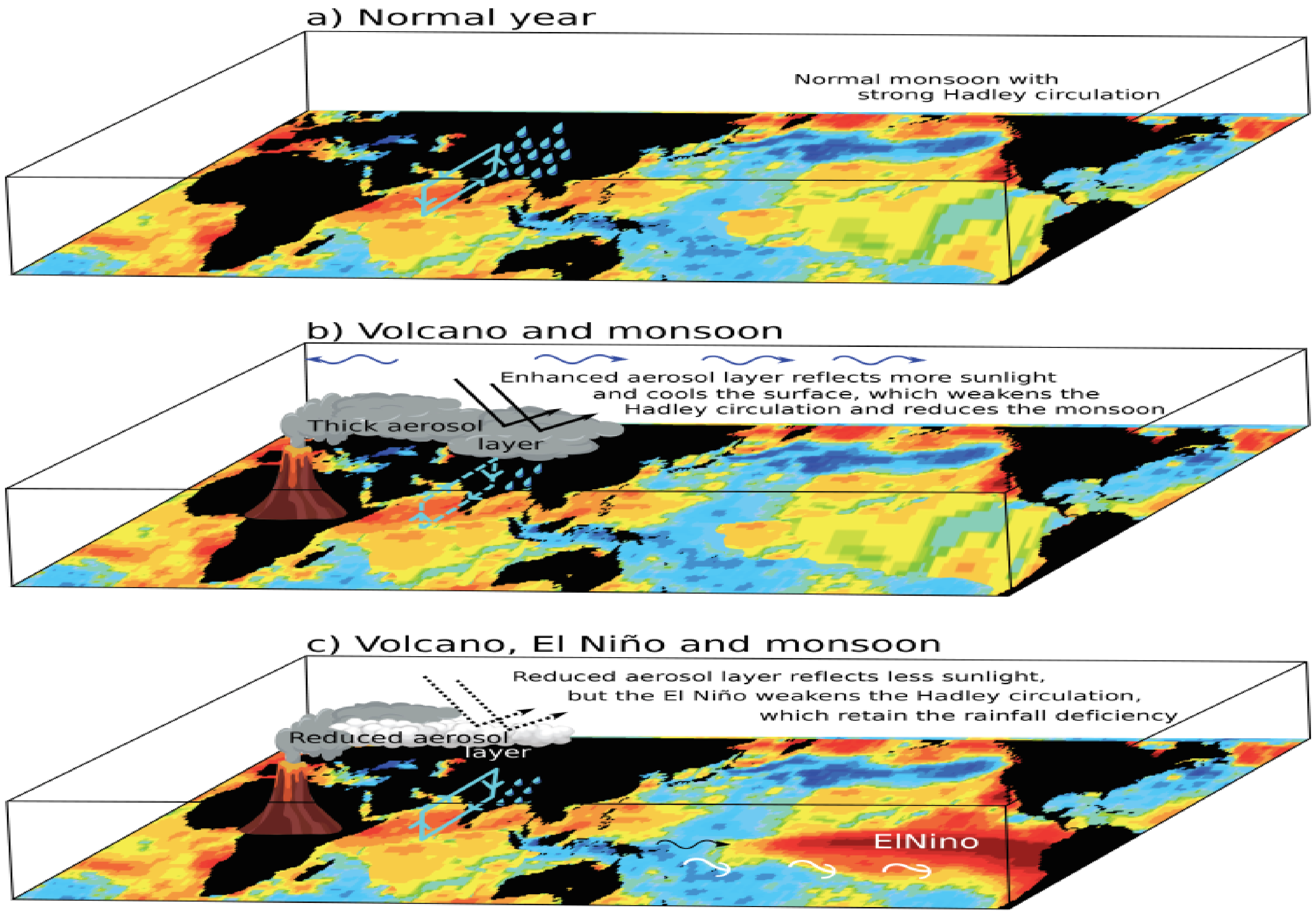
Distribution of anomalies (Vol-CTL) of rainfall (%) (averaged for Indian region and for monsoon 2011 and monsoon 2012 from MPI-ESM, Global Precipitation Climatology Project (GPCP), India Meteorology Department (IMD).


India meteorology rain gauge data

Weekly departure of rainfall for the monsoon in 2011, and 2012 show reduction in Indian summer monsoon rainfall.

- **Nabro volcano has induced a reduction in precipitation over the Indian region by -4.6% (-4.85 mm day-1) in the 2011 monsoon and -2.5% (-3.12 mm day-1) in the 2012 monsoon.**

A schematic of the impact of volcanic eruptions on monsoon precipitation

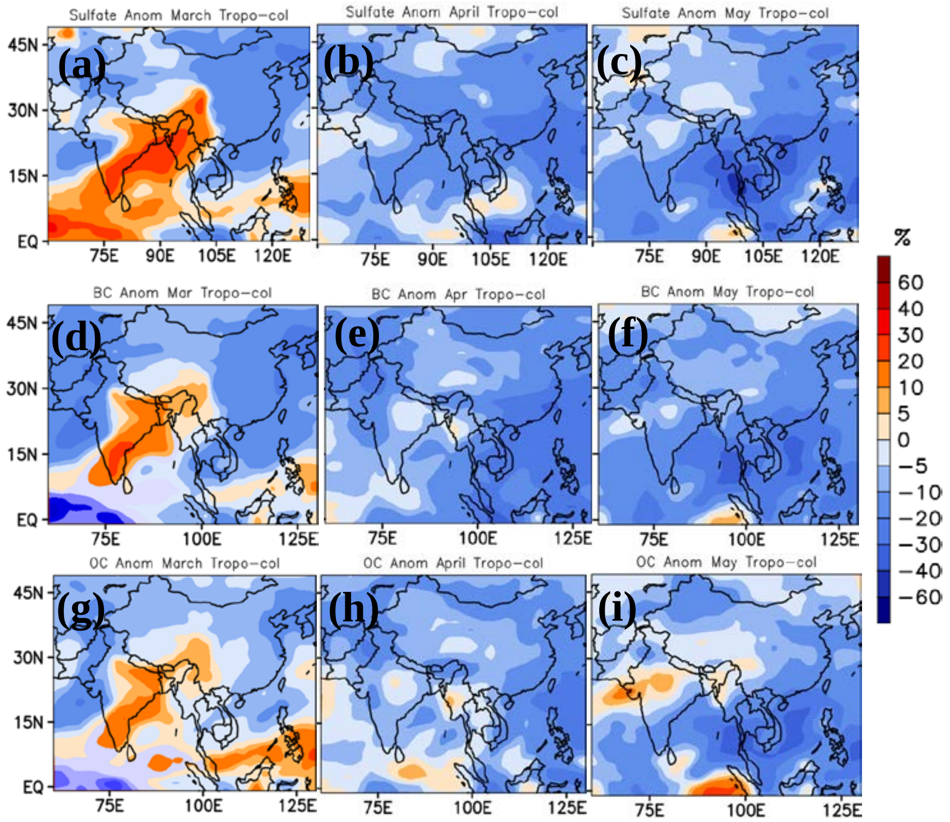


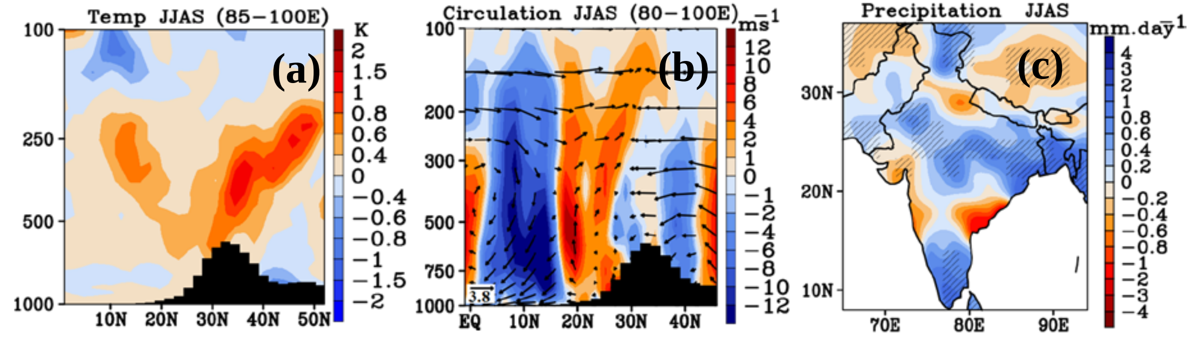
The impact of COVID-19 lockdown measures on the Indian summer monsoon precipitation

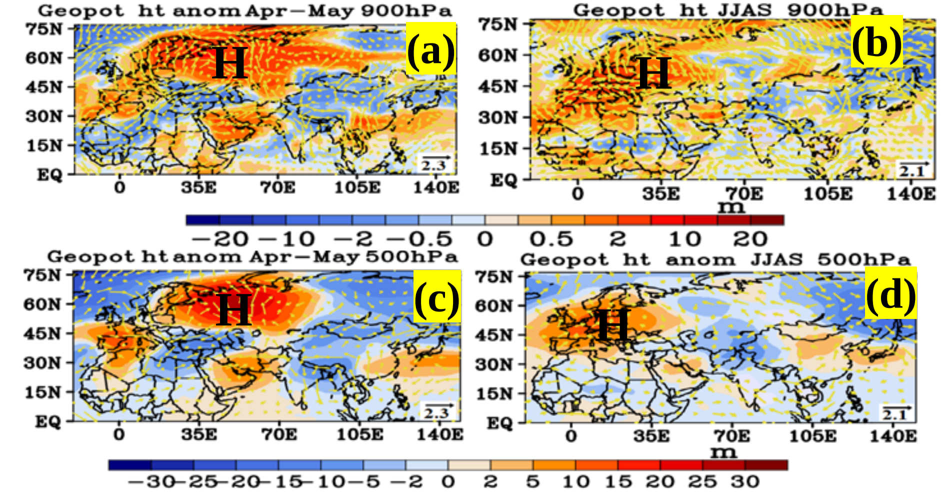
Pollution reduction during COVID-19 lockdown period has enhanced Indian summer monsoon rainfall by 15 % (3 mm·day^{-1})

We used bottom-up estimates of anthropogenic emissions based on national mobility data from Google and Apple along with the ECHAM6-HAMMOZ simulations.

Changes in aerosols during the lockdown period (Apr-May2020)







Fadnavis et al., ERL, 2021

Conclusions

- **Asian pollutants enter the ASMA via two branches: (1) South Asia (2) East Asia.**
- **They are transported to the east and west from the anticyclone to west Africa and the west Pacific via eddies.**
- **Rossby wave breaking in the subtropical jet cause intrusion of cold and dry air from the extra-tropical stratosphere to the troposphere over North India during the monsoon breaks.**
- **The cold and dry air masses remain in the upper troposphere for 10-15 days which slows the northward propagation of the ITCZ.**
- **The aerosol layer in the UTLS over North India during El Nino forms a lid that causes solar insolation and a decrease in precipitation.**

Conclusions

- **Tropical volcanoes form an aerosol layer over India. It causes tropospheric cooling, leading to down welling Kelvin waves (KW). KW dissipation in the central Pacific results in El-Nino like warming.**
- **The aerosol layer causes precipitation reduction in the year of volcanic eruption due to solar inhibition. The precipitation reduction in the next year of volcanic eruption is because of El Nino like warming and associated subsidence over India.**
- **The reduced level of pollutants during COVID-19 lockdown period resulted in an enhancement in precipitation over India.**

Thank You