Variability of Anthropogenic aerosols and their impact on Indian Summer-Monsoon

MS Thesis

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Certificate

This is to certify that this dissertation entitled **Variability of Anthropogenic Aerosols and their impact on the Indian Summer Monsoon** towards the partial fulfilment of the BS-MS dual degree programme at the Indian Institute of Science Education and Research,Pune represents study/work carried out by **Rakshit Thaware** at **Indian Institute of Tropical Meteorology (IITM Pune)** under the supervision of **Dr Suvarna Fadnavis, Scientist F, Atmospheric Chemistry** during the academic year 2021-2022

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Declaration

I hereby declare that the research work presented in the report entitled **Variability of Anthropogenic Aerosols and their impact on the Indian Summer Monsoon** have been carried out by me at the Department of Earth and Climate Sciences, Indian Institute of Science Education and Research, Pune, under the supervision of Dr.Suvarna Fadnavis and the same has not been submitted elsewhere for any other degree.

Rakshit Thaware

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Abstract

Understanding the variability of aerosols in troposphere over the South Asian region is highly essential since aerosol in this region plays a vital role in the modulating Indian summer monsoon. The rapid increase in the anthropogenic emissions of sulphur aerosols is of serious concern. All around the globe emissions of SO_2 have become two-fold over the century (Baron et al., 2017). Developing countries in Asia, mainly India produces SO_2 emissions at high growth rates. Past study shows increase of SO_2 aerosols of the total Aerosol Optical Depth (AOD) by 4.8% per annum over India).

Large amounts of anthropogenic emissions of sulfur dioxide (SO_2) over India play an important role in radiative forcing, circulation changes and hydrology. Here, using a state of art chemistry-climate model, ECHAM6-HAMMOZ, we investigate impacts of South Asian anthropogenic Sulfate aerosols on the Indian summer monsoon rainfall during three typical years (1) 2010 a La Niña, (2) 2015 an El Niño, and (3) a normal year 2016. Our sensitivity simulations for 48% enhancement in South Asian SO_2 emissions is based on a trend of 4.8% yr^{-1}, estimated from Ozone Monitoring Instrument (OMI) satellite observations during 2006-2017.

The model simulations show Sulfate aerosols reduces summer monsoon precipitation (by 7.85 mm day^{-1}; 7.1 % in 2010 La Niña; 6.88 mm day^{-1}, 10 % in 2015 El Niño and 5.35 mm $^{-1}$, 9.3% in 2016 normal year. The larger reduction in precipitation seen in 2010 La Niña is due to strong radiative cooling at the surface due thicker Sulfate aerosol column over the Indian region than in 2015 El Nino and 2016 a normal year. The Sulfate aerosols loading over the Indian region caused weakening of the Hadley circulation, increases upper tropospheric stability, and reduced moisture transport over the Indian region leading to precipitation reduction.

The South Asian Sulfate aerosols are transported(towards the high latitudes) by the monsoon convection. This transport occurred in the UTLS during 2010 (La Niña), mid troposphere during 2015 (El Nino) and 2016 (a normal year). The strong ascend over the Indian region in 2010 La Niña lifts the aerosols into the UTLS which are then transported to Arctic in the UTLS. While, this transport occurs through mid-troposphere during 2015 El Nino and 2016 a normal year.

This study will mainly focus on the impacts of sulfate aerosols on the Indian Monsoon

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Introduction:

There has been a steady incline in the sulfur dioxide (SO_2) emissions since the,industrial era. It was estimated in past studies, India has experienced a monotonous rise(to be around 50%) since 2006 (Krotkov et al., 2016; Li et al.,2017). The sulfur dioxide and sulfate aerosols were not studied with a serious perspective until it started to show hazardous effect on the health by reducing the quality of air and hydrological cycle.(Li et al., 2017 ; Shawki 2018)

In three studies it was established that the SO_2 gas has been a key factor in the occurence of droughts over the South Asia during the years 1950 and onwards. The sudden rise in droughts and their severity led to massive socio-economic downfall (Kim et al.,2016, Paul et al.,2016, Q.Zhang et al.,2012, Fadnavis et al.,2019)

After numerous hypothesis done by a few groups, on how the sulfate aerosols affect the precipitation, it was found that sulfate aerosols are formed by oxidation of SO_2 that gets released/injected into air. Once formed sulfate aerosols start scattering the solar radiation.The scattering happens due to their structure. This scattering dynamics of sulfate aerosols give us a net cooling effect of the surface, reduced land-ocean temperature gradient, and disturbance in the circulation (explained in sec 2.5)

The Indian Ocean Experiment (INDOEX) conducted during January to March 1999, concluded that Indian emission of sulfate aerosols make up the 29% to the observed total aerosol optical depth (AOD) (Verma et al., 2012). According the data recorded in Northern regions of India the sulfate AOD on an average lied between 0.1 to 0.14 and the corresponding Radiative Forcing at the top of atmosphere was -1.25 W m^{-2} to -2 W m^{-2}.

Furthermore the ARFINET confirmed a consistent rise of 0.004 in the AOD per year. On the global scale, the average Direct Radiative Forcing resulting from sulfate aerosol is -0.4 W m^{-2} (-0.6 W m^{-2} to -0.2 W m^{-2}) (Myhre et al., 2013, Fadnavis et al.,2019).

1.1. Aerosols

The tiny minute particles present in the atmosphere in the form of gases ,liquids and a mixture of both. They are suspended by a number of means. All the types of aerosols are important for certain environmental processes. Aerosols were recently used in tracing the atmospheric movements by NASA, this study is not very well continued to its contingencies.

In the atmosphere, a spectrum of size of aerosols going from very fine particles to visible coarse modes. The areas with heavy industrialisation and dense population are prone to have both the types. The fine mode aerosols are formed mainly when the gas to particle conversion happens.Whereas the sea salt particles, mineral dust getting displaced by air make up the coarse mode particles (Ramachandran et al., 2011)

1.1.1 Why study aerosols?

In 2001 IPCC reported that Earth's climate was heavily influenced by Human activities over the few past decades.In the 1990s it was discovered that sulfate aerosols are responsible in offsetting and counter the effects of the global warming.[IPCC, 2013]. This initiated the exclusive studies on the impacts of aerosols on climate.

Over South asia the anthropogenic aerosols are abundant enough to alter the balance of radiation and the climate on a global scale.(Lau et al., 2008; Ramachandran et al.,2011; Srivastava et al.,2016).

An exclusive study done over India, showed that the number of sources of anthropogenic aerosols differ from region to region, mainly owing to the uneven industrialization that has happened.The geographical factors dictate the transport and the removal of these aerosols.(Habib et al.,2006, Ramachandran and Cherian et al., 2008, Massie et al.,2004)

Evan et al.,2011 in their study deduced that rise in the concentration of anthropogenic aerosols over the oceanic region directly resulted increased intensity of cyclones. Due to a circulation anomaly which occurs over the ocean by the presence of anthropogenic aerosols,there is a reduction in the ocean basin wide vertical wind shear.This phenomenon creates an environment in which cyclones are more sustainable for longer periods of time.(Srivastava et al.,2016)

Aerosols mainly interact with the incoming solar radiation. It was observed that on cloud less conditions (clear skies) aerosols alone have the capacity to control the amount of solar radiation reaching the surface(Nair et al.,2016; Soni et al., 2016). Which is also called as direct effect of aerosol.

Depending upon the type of aerosols; the solar radiation will either be scattered in all directions or reflected back into the atmosphere, or absorbed.The absorbing aerosols create a net heating effect.While the scattering aerosols will produce a net cooling effect.

The scattering aerosol particles have an inherently cooling effect on climate. When these type of aerosols retain in the atmosphere for longer periods of time, a huge radiative cooling (upto 30 W m^{-2}) is exerted at the surface(Sateesh and Ramanathan et al.,2000)

The indirect effect of aerosols, in which they aggregate to form cloud condensation nuclei (CCN), is a starting point for the formation of clouds.(more in sec 2.6) These clouds will either precipitate rain in a comparatively less intensity.(Lu et al., 2015).

1.2. Types of Aerosols :

The aerosols are mainly categorised into two types. Which are either primary aerosols, secondary aerosols and organic aerosols.

- Primary Aerosols : The particles that are directly emitted into the atmosphere without any compound reaction. These primary aerosols have a short life-time. For example : Sea Spray, Mineral Dust,Volcanic aerosols, Black Carbon Mostly natural aerosols make up this category.
- Secondary Aerosols : Formed due to aggregation of one or more Primary aerosols. This includes most of the anthropogenic aerosols like Sulfate SO_x, Nitrate NO_x

1.3. AOD :

Aerosols scatter light in all the directions due to their extremely small size. This also implies that; from the incoming solar radiation, some amount of energy(heat and light) is always lost due to presence of aerosols.The AOD is a measure of the reduction of solar radiation (light), by aerosol.

Several studies have focused on aerosol's optical properties at both regional and global scales. The seasonal and annual mean trends in AOD and changes in those trends were observed.(Ramachandran et al., 2011). These changes were significant enough to be observed all over parts of world(Paniceker et al., 2013, Raman et al., 2016; Panicker et al., 2022)

The increased urbanisation in the past decades had a increased effect on AOD.This was studied recently(Chelani et al., 2015). Some studies have shown a direct relation between population and AOD levels.The constant change in the population is one of the great factors that significantly control the AOD over most parts of India.

In India the AOD in the last decade has increased by $>$40%. Annual mean increase in the AODs during 2000-2009 in Jaipur, Hyderabad and Bengaluru was also 40%(Ramachandran et al., 2011).

There are variations in trends of AOD.Over the entire Indian region here is a strong variability of aerosols both seasonally and inter-annually.The differences in regional atmospheric dynamics and monsoon systems are a result of these drastic variations. (Kaskaoutis et al.,2011, Cherian et al., 2008)

In their study Patra et al., 2005 established an inverse relationship between the AOD and its corresponding rainfall over India. The high AOD caused less rainfall in India.

2

Influence of aerosols

As the aersosols rise up to the troposhpere (and stratosphere through tropopause); they interact with sunlight and alter the amount of energy to be receipted at the Earth's surface.In this section we will see how the aerosols create alterations in the processes an variables that ultimately affect the Indian Monsoon.

2.1. Radiative Forcing

Radiative Forcing (RF) through an environment variable is an alteration in the earth's stability proportion between entering energy of the sun's radiation and departing energy of the thermal Infrared radiation. During the alteration of the variable; other additional components are kept constant. They happen because of fluctuations in the input of the sun's energy and transitions among the atmospheric concentrations of global warming gas. The radiative effects are also a result of changing atmospheric composition. Every effect induces a different change in climate system.(Dorand et al., 1997)

According to IPCC aerosol's optical properties determines the changes in produced in the RF.

The radiative forcing is direclty influenced by the amount and the type of aerosols.(Dorland et al., 1997) The solar radiation absorbing aerosols cause Positive RF and others cause Negative RF . Sulfate aerosols give a Negative RF effect. However the effect is regional.

Organic aerosols scatter as well as absorb the incoming solar radiation. This phenomenon is caused by 'Brown Carbon'(BrC) (Lu et al.,2015).Overall they have a positive RF effect.

Black Carbon(BC) aerosols have a tendency to absorb a large amount solar radiation and have a positive RF.BC has a warming effect on both ice and snow, however it produces a cooling effect at the surface (Menon et al., 2002; Ramanathan and Carmichael et al., 2008)

The increase in tropospheric ozone over the past two deacades caused a serious Negative RF which is comparable to the Negative RF magnitude due to increase in the troposhperic sulfate(Dorland et al.,1997)

Nitrate aerosols scatter the radiation (Dorland et al., 2015), which leads to a cooling effect in the respective regions . They cause a negative radiative forcing from 0.17 W m^{-2} to 0.36 W m^{-2} (Bellounin et al., 2011)

2.2. Heating Rates :

The climate and life on Earth majorly depends on the solar energy(IPCC, 2013). The surface energy balance which is required for diverse processes is also dependant on the solar radiation received at the surface.(Pan et al., 2017)

Due to difference in heating rates of land and ocean,there is always a thermal gradient between them.The summer and Winter Monsoon is a consequence of this thermal contrast between the land and ocean. The Sea Surface Temperature (SST) influences the exchange of heat in the air-sea, land-sea dynamics. This further dictates the speed and amount of convection over the associated regions. (Borgaonkar et al., 2010)

High Aerosol loadings that modify the cloud properties generally increase the planetary albedo (Charlson et al., 1992).In a study it was found that a cooling effect is produced with the increase in the planetary albedo (Choi and Son et al., 2018)

In a study conducted by Soden and Chung,they witnessed a world-wide reduction in the absorption of solar radiation. They also reported westerly winds carry from their source to the Northern Hemisphere and towrads the oceans (Chung and Soden et al., 2017)

There is a massive reduction of moisture and heat and this results in reduction and uneven distribution of precipitation over the India(Pandey et al., 2019).

There is an increase in the planetary albedo, which is an effect of sulfate aerosols' direct scattering of shortwave radiation and modification of clouds' shortwave reflective properties. As a consequence there a cooling effect is exerted.(Charlson and Shwartz et al., 1992)

2.3. Long range transport of Asian aerosols :

The aerosols due to their extremely light weight are transported to both upper levels of atmosphere and also to other continents, by strong gusty winds.

The winds go at an extremely high-speed, carrying away and circulating the aerosols in the upper layers of atmosphere and also around the globe. It is crucial to understand the importance of role of meteorology in air pollution studies.

The long range transport (LRT) of aerosols cause an effect on the climate locally regionally and globally, which causes certain and anomalous weather patterns.(Fadnavis et al., 2019)

2.4. Transport to UTLS :

The layer of pollutants at the extremes of Asian regions may be transported to the upper troposphere and lower stratosphere (UTLS) by deep convections occuring over South China Sea and Malay Peninsula, and Bay of Bengal during the monsoon season.(Randel et al., 2010; Murugavel et al.,2012; Fadnavis et al.,2013,Chavan et al., 2021).

The aerosol burden gets altered on large extent by the LRT of sulfate aeros from the Asian boundary layers to the UTLS and to the high latitudes region(Fadnavis et al., 2019).

The Asian Tropopause Aerosols Layer (ATAL) is formed due to the transport of sulfate aerosols from the monsoon convections (SPARC-ASAP, 2006; Fadnavis et al., 2013; Vernier et al.,2015, 2018; Yu et al., 2017).The ATAL majorly is composed of aerosols from India and China(Lau et al., 2018)

An Instrument Container suggested the composition of aerosols in ATAL. According to that, sulfate aerosols and BC dominate the ATAL, a large amount of dust particles,then there are organics and nitrates in small amounts.(Höpfner et al.,2019)

The influx of aerosols to uppper levels of troposphere causes its local heating. There is an amplification in the vertical circulation in the troposphere which is induced by this heating of upper troposphere. This result was shown by Fadnavis et al., 2019.

In the process of deep convection, the UTLS aerosol layer is extremely important. The aerosols in the upper troposphere are transported as a result of this deep convection(Borgaonkar). As it extends vertically from 13 to 18 km and horizontally from the east Mediterrana to west parts of China.

A decrease in temperature of surface was observed in the years 1975–2000.This effect initiated and continued trend of 0.02 K decade^{-1}. This effect was produced by the sulfate aerosols over the globe (Yang et al., 2018). It has been projected that the recent changes in SO_2 emissions in Asia can potentially the atmospheric balance of sulfate aerosols. Thus the Sulfate emissions from Asian parts are going to impact on RF, clouds, average temperature on both regional as well as global scale.(Fadnavis et al., 2019)

2.5. Circulation and Stability :

The atmospheric mass circulation between 30ºS and 30ºN is termed as Hadley Cell (HC) . The direction is zone dependant. In lower troposphere the trade wind flow towards equator, and in the upper troposphere it moves pole-ward (Quan, Diaz, Hoerling et al., 2004)

A long time ago Halley (1686) and Hadley (1735) described the dynamics of HC involving function of the meridional cells and associated physical processes.(Webster, The Hadley Circulation : Past, Present and Future)

HC plays a critical role in the hydrological cycle, and atmospheric circulation. It is well known that the ascending and descending motions are the drivers of the seasonal shift. The ascend involves convection of warm-moist air in the equatorial region leading to formation of clouds, and ultimately rain. The descend involves the subsidence of cool-dry air. (Hur, Kim and Yoo et al., 2021)

There are two HCs running in opposite directions; on the either side of equator.Both control and govern the seasonal climatic shifts in their respective hemisphere.The strength of each HC is more than Polar cells and Ferrel cells (Quan, Diaz, Hoerling et al., 2004)

The changes in circulation induced by aerosol are likely to disturb the vertical transport and circulation to the UTLS (from the surface) (Borgaonkar et al., 1997)

As already described in sec 2.2, there is reduction in heating rates caused by scattering aerosols, this further extends to slow evaporation of water surfaces, and thus there is also decrease in the strength of HC. In a few past studies, it has been confirmed that the strength of HC , SSTs and the Monsoon are inter-dependant.The weaker the HC, the weaker the SSTs and thus weaker the Monsoon. An environment scarce rainfall will drive even more weaker circulations and sustain the positive feedback. (Bindof et al. 2013; Zhou et al. 2020)(Hur, Kim and Yoo et al., 2021)

Another study proposed that due to presence of excessive aerosols the cross-equatorial and lateral circulation of the monsoon clouds is globally affected (Webster et al., 1998)

2.6. Impacts on Clouds and Rainfall :

The Clouds play a vital role to sustain life on Earth. After the formation they begin to intercept the incoming solar radiation and thus affect the net energy budget of the Earth(Lee et al., 2014; Houze et al., 1993). Once clouds become heavy enough they precipitate

At the top of the atmosphere, clouds regulate the flow of radiation and affect the energy balance in the atmosphere. In a study it was reported that cloud microphysics drastically affects the regulation process. There are numerous processes involving among different types of entities namely rain,ice crystals,snow, and hail.(Lee, Donner and Phillips et al.)

According to the some reports of observations and model conducted in a study, it was concluded that cloud formation is affected by aerosols. The formation and distribution of cirrus clouds and precipitation cloud get strongly affected by the presence of aerosols near the tropopause.(Li et al., 2005; Yin et al., 2005; Su et al., 2011).

In a different study it was found that cloud and aerosols interacting will have a non-linear relation. This dependency is in reference with size,concentration and composition of the aerosol.(Charlson et al., 1992)

A separate study aimed to determine the dependence of rainfall on high CCN; it was concluded from model experimentation that the cooling in the lower troposphere induced by evaporation alters the dependency of rainfall on high CCN (Tao, Li, Khain, Matsui, Lang and Simpson et al., 2007)

The dependence and feedbacks between aerosol and precipitation can be determined by Convective clouds.The most of global precipitation is received through the convective clouds(Lee et al., 2014; Houze et al., 1993)

Recent studies have been done to highlight the impacts on clouds and precipitation by increasing aerosol concentration. Some of these studies have been focusing the impacts since the industrialization period. Over the decades the effects have been compounded and the hydrological cycles have been severly affected, due to delay in the formation of convective clouds. The aerosols can potentially disturb the Indian Summer Monsoon Rainfall (ISMR).(Krishnamurthy and Goswami et al., 1987)

Khain, D. ROSENFELD and A. POKROVSKY et al., 2004, concluded the dependency of cloud condensation nuclei (CCN) on the rate of precipitation from their study. Any small increase in CCN results in the decrease of size and increase in the quantity of small droplets. This causes a slow collision rate between the molecules. Ultimately there is a delay in raindrop formation. Even after the raindrops are formed there is an increase in the vertical velocity, and thus there is a delay in Rainfall.

The growth of cloud droplets is deterred by the different types of aerosols and also of their continental origin.(Rosen-feld et al., 2001; Andreae et al., 2004, Patra et al., 2005).Overall there is a decrease in the intensity of rainfall.

Another study demonstrated that when large-scale spatial co-variation between cloud cover and aerosols is also considered then regional-mean warming effect of aerosols increases three-fold . Thus it is important to develop and study cloud prediction to quantify direct effects produced by aerosols. (Chand et al., 2009)

In a seperate study the effect of dust and biomass burning on Clouds was demonstrated. These aerosols first cause a heating effect and thereby slow the formation of cloud droplets.After the drops are formed they do not aggregate in a proper setting, this causes an increased residence time. As a result, rainfall is delayed.(Rosenfeld et al. (2001) and Andreae et al. (2004)

Indian monsoon season (June–September, JJAS) gives more than 75% of total precipitation. (Borgaonkar et al., 2010) The overall precipitation is a consequence of formation of low-pressure zones. When the surface is heated by solar radiation. The wind flows and pushes the clouds from the high-pressure zones towards these low pressure zones.

The first and second indirect effects of Sulfate aerosols which are namely scattering of solar radiation and acting as CCN, result in low reception of solar radiation at the surface. As a result the evaporation is delayed and reduced.(Henrikson et al.,).

The weakened pressure gradients caused by the decrease in heating rates between the high and low monsoon component, ultimately prevents the growth of cloud droplets.(Patra et al., 2005) Based on ensemble simulations, it was reported that polluted layer of BC, OC ,Sulfate cause a weakening of the ISMR(Ramanathan et al.,2005)

The North Hemisphere experienced a southward precipitation shift during 1931-1950 to 1971–1990; one of the potential cause for this was the cooling effect induced by the scattering caused by aerosols.(Hwang and Freirson et al.,2013)

2.7. ENSO :

El Nino-Southern Oscillation (ENSO) is a massive interaction occuring between the winds and the ocean. It is characterised and dependant on anomalies in by sea surface temperature over the equatorial centre to eastern Pacific(Fang and Sie et al., 2019; Rasmusson and Carpenter, 1982)

Numerous studies have investigated and found out that ENSO begins and expands from the equatorial Pacific regions, but it affects climate and ecosystems all over the world through its influence on the Hadley and Walker Cells.(Borgaonkar et al.,2009)

El-Nino and La-nina are the climate patterns which repeat after a frequency of 2-3 years, and they affect the zones(countries) differently(FANG and XIE et al., 2019).The statistics done in a study a few years ago showed that the mean rainfall in India during La Niña and normal years is more than during the El Niño years .(Rishma and Katpatal et al.,2016)

Numerous studies have focused on the correlation between the Indian Summer Monsoon (ISMR) and ENSO indices. To establish a direct connection the study was conducted during and after the monsoon season (Borgaonkar et al., 2010)

The variations of Sea Surface Temperatures (SST) over the Indian Ocean directly create the inter-annual variations in ISMR.(Sikka et al., 1980; Shukla and Mooley et al., 1987;Pandey et al.,2019)

The years which were ISMR deficit also had stronger El-Nino events(positive SST anomaly) this was concluded from a study focused on a ISMR variability pattern.(Patra et al.,2005)

2.7.1 El-Nino :

When the SST on the equatorial Pacific is anomalously warm, it heats up the regional atmosphere, which results in the subduction of the Walker circulation. The weakened Walker circulation lead to weakening of westward trade winds(Bjerkens et al., 1969)

The trade winds weaken and the warm pool of the Ocean which is moving west slows down and moves east instead and as a result there is a reduction in the upwelling of cold water near to the landmass(South America). The impacts build up slowly and are mostly visible in the winter. The jet streams shift towards the South due to warmer ocean. A positive feedback is generated for El Nino and it intensifies the original positive SST; i.e. (Fang and Xie et al.,2019) Consequentially, there are floods in South America and dry conditions in the North America.

2.7.2 La-Nina :

When trade winds become much more stronger than normal, warm pool of ocean is pushed to the western pacific. This in turn causes an upwelling of cold water in the eastern pacific. In la-nina, there are unusually cold conditions in the tropical regions. La Nina is also known as the cold phase of ENSO. La-nina can lead to drought in southern US, whereas Pacific Northwest experiences heavy rains and floods.

It is very well known that countries lying in the zones of India recieve a heavy amount of rainfall in the La-Nina years.

3

Objectives

We aimed to study the impacts of Sulfate aerosol on the Indian Monsoon.

In this study, we will address the following research questions :

(1) What is the seasonal contribution of SO_2 emissions from India to the AOD?

(2) What is the associated radiative forcing?

(3)What is the aerosol-climate effects on the seasonal rainfall for JJA cycle over India?

For this purpose, we plot simulations based on data recorded by satellites. We increase the SO_2 emissions over India (48% increase) for the year 2010,2015, and 2016 using the state-of-the-art aerosol–chemistry–climate model ECHAM6–HAMMOZ.

4

Methodology:

We are implementing the ECHAM6–HAMMOZ aerosol–chemistry–climate model. It is composed of two models. The ECHAM6 is a global climate model coupled to the HAMMOZ.

Now HAMMOZ itself is composed of two sub-models : HAM which is a two-moment aerosol and cloud microphysics module and the sub-model MOZ (Kinnison et al., 2007).(Fadnavis et al., 2019)

The HAM module is used to predict the initiating, evolving and terminating processes of certain aerosols like Sea salt, Mineral dust, Particulate Organic Matter, BC and Sulfates. Starting with the nucleation, it monitors the aggregation and formation. Then afterwards it checks for growth and evolution of the aerosols into clusters. Finally it checks for sinks.The HAM sub-model also carries out the simulations of changes in the cloud droplets and ice crystal particles induced by aerosols.

In the atmosphere there is an enormous amount of trace-gas chemistry. In our experiment the MOZ sub-model monitors such reactions ranging from troposphere to lower thermosphere. There are certain oxide families which are contained in these chemical mechanisms, which are O_x, NO_x, HOX, ClOX and BrOX(Fadnavis et al., 2019)

There are 108 chemical entities interacting in 71 photolytic processes that make upto 218 gas-phase reactions. Exclusively there also 18 heterogeneous reactions on aerosols (Kinnison et al., 2007).

The dimensions of at which our model perform simulations are given by $1.875° \times 1.875°$ (horizontal resolution) and 47 hybrid p levels from the surface up to 0.01 hPa(vertical resolution). This overall corresponds to T-63 spectral resolution. (Taylor et al., 2000) The seven log-normal modes (M7 aerosol module) describe size distribution of the aerosol population (Stier et al., 2005; K. Zhang et al., 2012).

For further detailed working mechanism of the model refer to Fadnavis et al., 2019

In control simulation (CTRL),the experiment was carried out by fixing the initial conditions for the years 2010, 2015 and 2016. According Ozone Monitoring Index (OMI), there has been a rising trend of 4.8% per year over India since 2001. The Ind48 simulations was designed based on this report of OMI. We enhanced anthropogenic SO_2 emissions over India by 48%.

We initially quantified the total AOD, followed by Sulfate AOD, mean Direct radiative forcing(at surface) of anthropogenic Sulfate aerosols.

Further we took the same approach of this experiment on Hadley circulation, atmospheric stability and the cloud cover to see their response and their relative contributions to the Precipitation.

All the plots were required to be made on the average of JJA season.For this we first had to check the time-steps(termed as 'T size' in the program).This T size helps the user to understand if the file is averaged hourly/daily/weekly/monthly. The T size is 12 by default for most of the files. This indicates that file of the selected year contains a compiled data on a monthly basis. We can plot the rainfall for any given year by selecting the corresponding data file. The rainfall for a specific season or for certain months can be plotted by putting upper and lower limits. For ex : January to April then the value of limits will be *t=1,4* where each number corresponds to a respective month of the year. We proceeded to isolate the monthly data from the files, and compiled only the required months' data (June July and August). The averaged files were termed as **'JJA_mean'**.

In plots of AOD, Sulfate AOD and HC the wind vectors are plotted using the parameters 'var131' and 'var135' from the echam files. The length of the arrow is standardised to correspond the wind-speed of 10 km hr^{-1} at 850 hPa. Now different parameters were executed from different types of data files. The plots of Hadley Circulation (HC),Cloud Cover,Rainfall were made from using echam files as input.However the parameters used were quite different for each plot. For rainfall we used large scale precipitation, convective precipitation and snowfall.To plot HC we used mean orography and wind vectors parameter. The Cloud Cover displayed in the plots are displayed by the lower cloud parameter.

To construct plots of AOD, radm files were used and the total AOD was computed through optical thickness (tau_2d) at 865 nm. This parameter tau2d is a resultant of optical thickness caused by individual aerosols. To get the sulfate AOD plots we just used the sulfate component(tau_comp_so4_55) of this parameter.This component corresponds to the optical thickness of sulfate AOD at 550 nm.

In RF plots we used the forcing data file and implemented the forcings caused by longwaves and shortwaves at the surface in a clear sky.There are three boxes in the plots to highlight the RF in the respective regions. The choices of boxes was made on the distinct differences in the RF values and to minimize the areas external to India .The regions marked in boxes (i),(ii) and (iii) that correspond to the North-West, North-East and South parts of India.

Using a .ncl script for a year separately,a parameter of Brunt-Vaisalla (BV) frequency for each year was computed, which was used to determine the atmospheric stability.

All the outputs displayed are a difference between the Ind48 simulation and CTRL simulations. The plots are averaged through 75°N to 95°N

The simulations explicitly projects and computes the impact of Asian Sulfate aerosols. The RF due aerosols other than sulfate aerosols is neglected. Further more a complex system known as the Quasi-biennial Oscillation (QBO) is not an integral part of the model. The underestimation of model AOD over India compared to Multi-angle Image

Spectro Radiometer (MISR) is an agreement with ECHAM6–HAMMOZ simulations in Kokkola et al. (2018) and Tegen et al. (2019). (Fadnavis et al., 2019)

The calculations however are accurate enough to provide an authentic insight into the impact of sulfate aerosol on Indian Monsoon.

We demonstrate the changes in RF and Circulation induced by sulfate aerosol which lead to disturbance in atmospheric stability and formation of clouds, and response of Precipitation.

5

Results and Discussion

In this section we will analyse our result from the experiment and verify if they are agreeable with previously done studies. The impacts of increasing SO_2 emissions by 48% on the variables are as follows :

5.1. AOD:

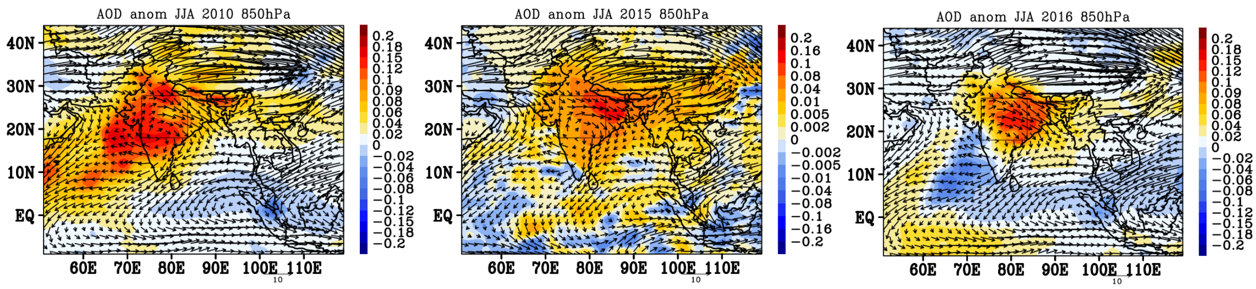

Figure 5.1: The spatial distribution of anomalies in seasonal total AOD (a) JJA 2010, (b) JJA 2015, (c) JJA 2016, from ECHAM-HAMMOZ simulation(at 850 hPa). The arrows point in the direction of flowing wind ; the length of the arrow is proportional to its speed.

In a study; S Ramachandran, Sumita Kedia and Rohit Srivastava examined the variations in the trends of AOD for past 10 years.The results were given by MODerate resolution Imaging Spectroradiometer (MODIS) on an annual and as well as seasonal scale.

The fig 5.1 shows the enhancement of AOD over the Indian region during JJA for 2010, 2015 and 2016. The model reproduces large AOD over central India in JJA 2010 , over IGP region in JJA 2015, and over Indo-tabetian Plateau in JJA 2016. As illustrated in the figures 5.1a and 5.1b, the values of AOD range from +0.0273 to +0.159 for 2010 extending form landmass to Arabian Sea (fig 5.1a) .However in 2015 anomalies in AOD (+0.0118 to +0.135) extend towards Bay of Bengal, Indochina and Eastern China region (fig 5.1b); and from +0.0345 to +0.1427 in 2016(fig 5.1c).

The range of concentration of aerosols corresponding to the total AOD anomalies over the Central India for the three years are displayed in Table 1.

We see that in the Fig 5.1 ; the IGP region in all the three years has around the maximum concentration of AOD. In few past studies done by Dey and Girolamo et al., 2011, Kumar et al., 2018 and a recent study done by Mhawish et al., 2020 ; they made an observation which confirms our results.(Gautam et al., 2011; Jethva et al., 2005; Mhawish et al., 2017, 2019)

The enhancement of AOD during the year 2010 is larger than in 2015 and in 2016.This could only suggest one thing that 2010 naturally had more AOD (without any enhancement). In 2010, the AOD is strongly transported to the (South-West)Arabian Sea and as a consequence we see a high aerosol loading over the Arabian Sea. and moderately in the east. The wind-pattern is the main reason that we observe the positive anomalies in AOD over the Arabian sea.

In 2015 anomalies in AOD extended towards the (South-East)Bay of Bengal, Indochina and Eastern China region.During El Nino the trade winds coming from Southern America weaken during Southwest Monsoon(Pandey et al., 2019) and as a consequence the winds travel to east more in 2015

The year 2016 a Normal year, the AOD distributed towards the Bay of Bengal with much less concentration as compared to AOD in 2010 and 2015.With no influence from El-Nino and La-Nina.

The presence of sulphate aerosols over the ocean(Arabian sea in 2010 and Bay of Bengal in 2015) does not cause a significant difference in the rainfall of central India(Goswami et al.,2006)

Table 5.1: Total AOD Anomalies

Years	**AOD over Central India**
2010	+0.0273 to +0.159
2015	+0.0018 to +0.135
2016	+0.0345 to +0.1427

In the Fig 5.1a we see that in 2010 there is strong transport of AOD from landmass to the ocean. This AOD extending from the South East Asian region to Arabian Sea; with the values around +0.06 to +0.13. This is due to strong trade winds as a result of La-Nina

Similar to 2010, the 2015 has the maximum AOD enhancement over Central India.The values going from +0.0362 to +0.108 However we see very moderate transport of AOD from landmass to the Arabian Sea,thus the AOD is scarcely scattered in that region.Intrestingly we see a strong transport of AOD into the Bay of Bengal, and also to the North-East regions.

Finally in 2016 we again see maximum AOD enhancement over central India with a value of +0.1427. Further compared to 2010 and 2015, we see in 2016 there is relatively less transport to the Bay of Bengal, and negligible transport to the Arabian Sea and North-East parts.

5.2. Sulfate AOD:

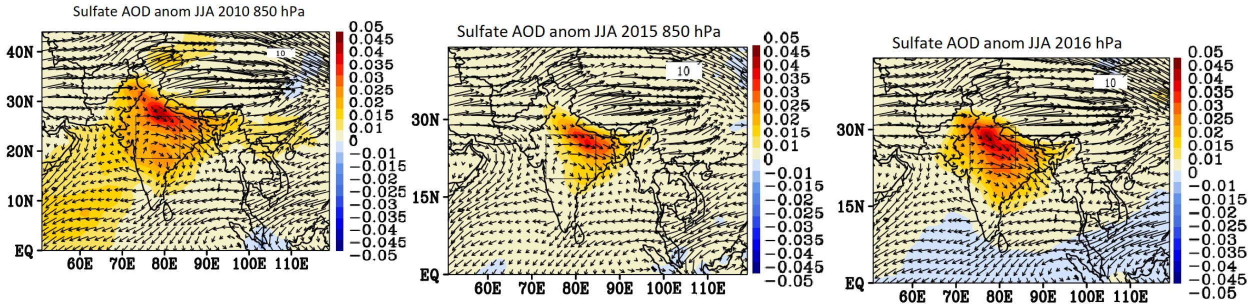

Figure 5.2: The distribution and transport of Sulfate AOD for the years; (a) 2010, (b) 2015, (c) 2016 from ECHAM6-HAMMOZ model simulation.

From the fig 5.2; we see the Sulfate AOD is maximum over the IGP region for all three years.In a previous study conducted by a group of Scientists, it was found out that IGP had most aerosol burden In 2010 the complete IGP is covered; In 2015 only the Eastern IGP and In 2016 the central IGP.

In 2010 the values of AOD range from +0.009 to +0.05. The AOD extends from central India to the western side; it is further transported to the Arabian Sea.

In 2015 the AOD is present in very low concentration; which varies from +0.0041 to +0.04.The majority of the AOD is distributed over the Central-east regions.

And in 2016, the AOD concentration is on a scale of +0.0091 to +0.045, which is comparable to 2015.The difference in the total AOD can be measured by comparing them with Sulfate AOD plots.

There is a similarity in the pattern of distribution of the total AOD and the Sulfate AOD. Examining the plots for the year 2010; we see that there is a strong outflow of the AOD from the landmass towards the Arabian Sea, which is further carried over to the South by the winds.

There is no transport from the landmass to the ocean in the year 2015. From the figure we see that in 2016 there is AOD transported from landmass to the sea, however it is carried towards the east(Bay of Bengal) more as compared to the west(Arabian Sea). Quantitatively the AOD outflow in 2016 is very less than in 2010.

In their study Dorand et al.,2005 computed distribution of RF due to Sulfate AOD for a single month January in 1999. They showed increasing sulfate AOD results into large negative radiative forcing.

There has been a serious increase in sulfate composition in the atmosphere due to emission of anthropogenic SO_x.(Dorand et al.,)

When SO_2 is emitted, it translates into particulate Sulfate(SO_4^{2-}) compunds. As these aerosols rise upto the troposphere, they might get oxidised or reduced by certain chemical entities. Regardless of that, it has been studied that in the troposphere sulfate aerosols on an average live up to six days(Dorand et al) The tropospheric sulfate aerosol layer is accumulation of these particulate sulfate compounds.Due to extensively uneven industrialisation, the strongest increase in the concentration of SO_2 has been found in the vicinity of industrial areas. As a consequence there are certain parts and areas of the world are relatively more polluted by sulfate aerosols. This has caused a non-uniform distribution of sulfate aerosols over the globe.(Langner and Rhode)

These sulfate compounds are inherently effective in scattering the shortwave radiation. As a consequence, there are two ways in which energy budget of Earth is altered by Anthropogenic sulfate aerosols.

The first is a direct effect, which includes the sulfate aerosols scattering the radiation back into the atmosphere.

The sulfate aerosols altering the distribution and concentration of cloud condensation nuclei (CCN)(Jones et al., 1994) (For more details refer to sec 2.6)

There are evidence from a few studies, which highlight the increase in the local and regional planetary albedo (for more details refer 2.6)

5.3. Radiative forcing:

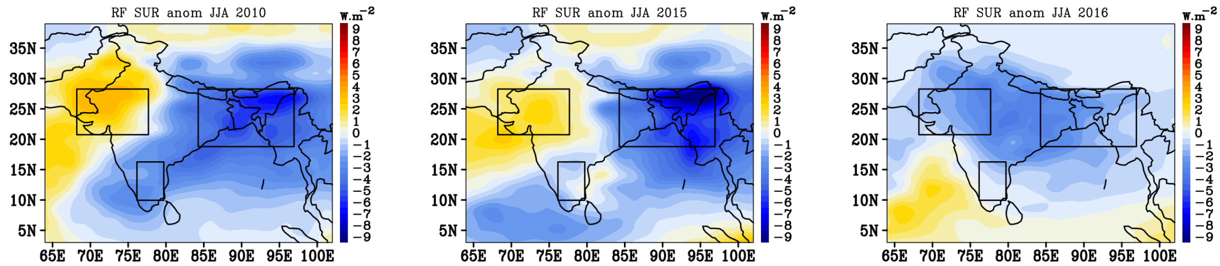

Figure 5.3: The distribution of seasonal mean radiative forcing at surface in the JJA season for (a)2010; (b)2015 and (c)2016 ECHAM6-HAMMOZ model simulation.

The Fig 5.3 illustrates the JJA mean anomalies in the RF at the surface due to sulfate aerosols from the IND48 simulations.Clearly from the Fig 5.3, we see that an overall negative radiative forcing anomaly over most of the Indian region, the neighbouring countries and the ocean

As already mentioned in section 1, the INDOEX experiment conducted during Jan-March 1999 produced values about (-1.25 to -2.0 W m^{-2})(Verma et al., 2012)(Fadnavis et al., 2019) and In a very recent and similar study, Fadnavis et al., 2019 obtained the results for RF at surface from Ind48 simulation, which were -2.0 W m^{-2} over the Arabian Sea. The values in resulted in our experiment are fairly agreeable with both the previous works.

In a very recent work, Fadnavis et al., 2019 showed a local cooling effect(at surface) induced by the excessive heating of scattering (sulfate) aerosol particles that are transported to the UTLS(mostly to upper troposphere).Our results agree with their study

Table 5.2: Radiative Forcing Anomalies(W m^{-2})

Years	**North-West(i)**	**North-East(ii)**	**South(iii)**
2010	0.5443 to 3.345	-6.7843 to -1.8026	-3.67 to -0.9538
2015	0.4715 to 2.6197	-10.601 to -0.4265	-2.026 to 0.4166
2016	-3.745 to 0.0376	-3.3683 to -0.244	-2.532 to 0.9595

Fig 5.2 shows that Sulfate aerosols are carried south-west to Arabian Sea (strongly in 2010) and scarcely to the Bay of Bengal (towards East),. These areas correspond to negative radiative forcing for Ind48 simulations as shown in Figs 5.3

A study conducted in Poland by Markowicz et al., 2021 aimed at the dependence of radiative fluxes on a clear sky condition reaching the surface on the aerosols. Their study proved a reduction in incoming solar radiation in the presence of a huge aerosol concentration.

A.Jones, L.Roberts and A.Slingo estimated in their experiment; the effect of aerosols at the top of atmosphere to be approx -1.3 W m^{-2} in the global annual mean This value might be subjected to high levels of uncertainty despite the effect being only half as large.(Jones et al., 1994)

In a study done by Yu et al. (2016), focused on the forcings induced by sulfate AOD since pre-industrial period. They reported that the increase from 0.06 to 0.15 in sulfate AOD over the tropics (30° S–30° N) and corresponding forcing of -0.6 to -1.3 Wm^{-2}

The North-west part or region (i) of India has Positive Radiative Forcing in both the years. Contrast to 2010, in 2015 the anomaly is comparatively less intense. However, in 2010 and 2015 the Sulfate aerosols are transported south-west over the Arabian Sea and partially to the east (towards Myanmar and China). In 2016 we see a net negative radiative forcing all over India.Implying the amount of the Sulfate AOD was enough to out-impact the other aerosols.

Focusing on the positive anomalies in region(i) in 2010 and 2015; there can be a few possible explanations. As described in a previous study the Northern parts of India and the IGP region contains the aerosols mainly dust particles flowing from the Middle east and the Desert from the Rajasthan. The Anthropogenic activities add a fine layer of BC in the same areas. (Pandithurai 2015 a,b)

The positive radiative forcing in region(i) for 2010 and 2015, implies presence of other aerosols (in a concentration higher than Sulfate aerosols) dominating and out-affecting the sulphate aerosols over the region (i); and thus the positive RF anomaly.Another reason might be the transport of Black Carbon aerosols (by the westerly winds) from the neighbouring countries.

However these are just the possibilities we considered, the exact reason was not investigated.

5.4. Impacts on Hadley Circulation :

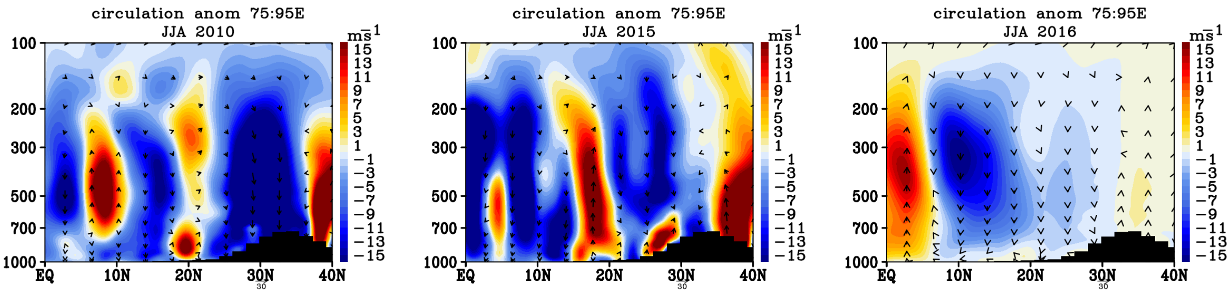

Figure 5.4: The effect on the circulation in the JJA season by enhancement in sulfate aerosols; (a)2010, (b)2015, (c)2016 from ECHAM6-HAMMOZ model simulation

The impact on strength of Hadley Circulation (HC) by the increase in sulfate aerosols is plotted using vertical velocities and has been illustrated in Fig 5.4. We can understand the large scale changes induced by aerosols on monsoon circulation by interpreting these plots. The plots are averaged from 75°N to 95°N. After a trying a few permutations of the longitudes, this selected interval showed the least background interference from the other regions.

As we can see there is high subsidence throughout the latitudes (8°N to 39°N) encompassing the Indian region. Although there are some bands of convection present in some levels in the years 2010 and 2015.The negative anomalies indicate a suppressed convection phenomenon.

Over the IGP region we see strong descending motion of winds from 20°N–30°N indicating a suppressed monsoon convection (subsidence) over the regions that have a high aerosol loading.The ascending branch of the HC is observed over the oceanic tropical convergence zone (TCZ).

In Fig 5.3 (a), from the plots RF for 2010 JJA, we see the region(i) and certain neighbouring areas showing a positive RF. This implies, that these areas do not experience a strong cooling effect (produced by sulfate aerosol) as compared to the areas with negative RF.

By assessing the Fig 5.3 (b), a similar argument can be made for the result of 2015 HC plot. The RF plot for 2015 also displays a lot of positive RF, however it slightly extends to Central-Western region of India.

In both the plots Fig 5.3 (a) and (b), the intensity of the positive RF is not very strong. And the positive RF lies between the region 20°N to 35°N for 2010 and 16°N to 35°N in 2015.

This explains the anomaly of uprising convection in the HC plots for 2010 and 2015.The regions experiencing these uprising motions will not have a sharp temperature gradient.(explained in 5.5) This in-turn will cause a relatively faster formation of clouds and there will not be a strong decrease in the precipitation in such regions in both the years.

The HC plot for 2016 JJA shows a neat subsidence over the entirety of the regions.The reason why we do not see any uprising wind motion is because the effect of other aerosols is not prominent and furthermore 2016 is a Normal year, so the westerly winds remain non-anomalous.

Studies in the past decade have gathered evidence of weakening the low level westerly and HC((Rao et al. 2004; Joseph and Simon 2005; Krishnan et al. 2013).)

From our analysis we can say that aerosols weaken the HC and consequently the Monsoon.Also the forcing induced by Sulfate aerosols play a negative feedback, which decrease the intensity of precipitation.

5.5. Impact on stability :

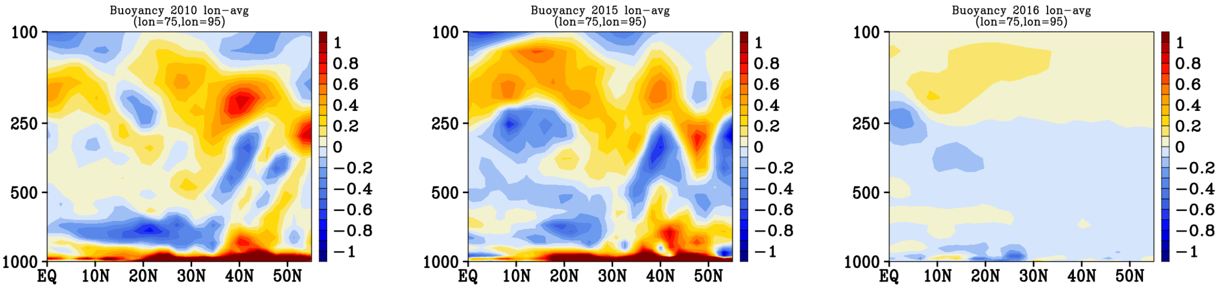

Figure 5.5: The impacts on the atmospheric stability caused by the increase in the AOD by 48% for JJA season by enhancement in sulfate aerosols;(a) 2010, (b)2015, (c)2016 from ECHAM6-HAMMOZ model simulation

In this section we report the impact of sulfate aerosols on Stability parameter of the troposphere. For this purpose we analyze the Brunt-Vaisala frequency (BV frequency) which is the stability parameter . In fig 5.5 we plot the BV frequency all panels show that, there is enhancement in the stability of the upper troposphere at pressure levels 100 hPa.

There is an increase in the temperature of the upper layers of troposphere and subsequently a cooling effect is induced by the sulfate aerosols in the layers below them. The stability increases as this temperature gradient increases.(Chavan et al., 2017; Fadnavis et al., 2019)

The extent of cooling effect is directly dependant on the amount of Sulfate loading. Thus higher the sulfate AOD, higher the stability

The CAPE parameter is widely used in the recent studies conducted on the effects of aerosol on the instability. These studies have been performed bys using a convective cloud isolated in an air column. Studies over the last few years have shown that when aerosols start acting as CCN, they can warm the air-parcel by decreasing their surface pressure, and thus decreasing the amount of rainfall(Seoung-Soo Lee, Wei-Kuo Tao,and Chang-Hoon Jung, et al.,2014)indicating high atmospheric stability both at the upper levels(upto 100 hPa) and closer to surface.

Focusing on the Fig 5.5 (a) and (b), we see that from 8°N to 40°N there is a high BV frequency. As described in the sec 2.5 the stability of the atmospheric system is inversely dependant on the BV frequency.

It is well known that high Stability will cause a decrease in the convection. The atmospheric stability is dependant on subsidence.

In their study Seosung lee showed that the basic dynamic intensities of cloud systems is determined by instability. Consequentially, the cloud dynamics will get affected any changes in the atmospheric stability.(Tao and Jung, et al., 2014, Fadnavis et al., 2019). Furthermore the increased stablity hinders the formation of the clouds. The droplet formation is slowed down and they do not aggregate because of the decreased pressure.

Our analysis indicates that the enhancement of sulphate aerosol caused an increase in the stability during La-Nina year (2010) and El-Nino year (2015); however during the neutral year (2016) there is less enhancement of stability.

5.6. Effect on Cloud Cover :

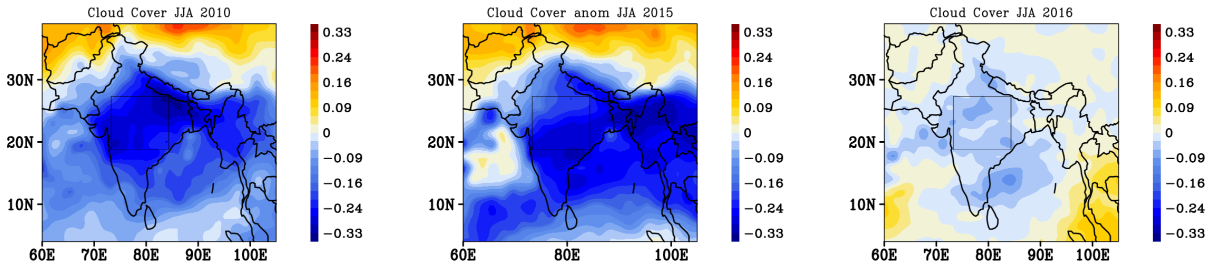

Figure 5.6: The effective Cloud cover on India caused by the increase in the AOD by 48% for JJA season by enhancement in sulfate aerosols; (a) 2010, (b) 2015, (c) 2016 from ECHAM6-HAMMOZ model simulation.

The plots of AOD show that the majority of the Sulfate aerosols are present over the eastern regions. The Sulfate aerosols reflect the sunlight,(Fadnavis et al., 2019) and observing the plots of Heating Rate, it is clear that the incoming solar heat is getting reflected by the sulphate-aerosols we see majority of the aerial space over the eastern parts of India is getting heated.

We see negative anomalies for Cloud cover in all the three years. The Central India receives comparatively less amount of cloud cover than the other regions of country. However, there are strong negative anomalies for the years 2010 and 2015; whereas in the year 2016(Normal year) the anomalies are not intense in any given region of the country.

Over the last decade a number of studies have emphasised on the alteration caused by aerosols on clouds' micro-physical and convective properties.(Lee et al.,)

The impact of sulfate aerosols on clouds was explicitly studied and summarised in seperate studies (Jones et al., 1994) and (Lee et al.,). The sulfate aersols directly affect the Cloud Condensation Nuclei (CCN). The alteration in the distribution of CCN results in change of these two parameters :

(a) the increase in concentration of droplets with increase in concentration of Sulfate aerosol.

(b) the decrease in the droplet size with the increase in the concentration of droplets.

This change in size and number density of droplets severely affect the cloud's albedo and life-time. Which ultimately alters the quantity and the zones of precipitation (Lee) (Ramaswamy et al., 2001)

As we enhanced the sulfate emissions by 48% over India, the clouds experience a drastic amount of decrease in the mass and the size of droplets.Focusing on the years 2010 and 2015, there is a huge reduction in the Cloud cover. Now it is extremely difficult to determine or predict the exact micro-processes, but there is a decrease in density of clouds, as a result of decrease in the size and density of droplet.

Quantitatively the reduction in the cloud cover for 2010 and 2015 appears to be comparable. However, in case of a La-nina year the ratio of precipitating clouds is inherently more than in an El-Nino year. This suggests that in our experiment the effect of enhancement is most intense in (La-Nina)2010.

In 2016, we see negative anomalies over the India entirely except for a few extreme eastern regions,and some south-western parts. The intensity of both negative and positive anomaly is very less, so it is safe to assume that the enhancement of sulfate aerosol emissions did not produce much disturbance in the Cloud dynamics.

5.7. Overall effect on Precipitation :

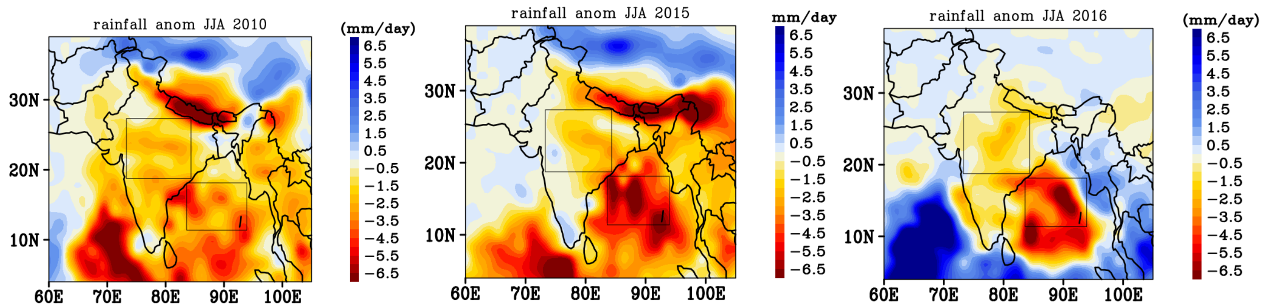

Figure 5.7: The anomalies in the regional distribution in the precipitation for JJA season by enhancement in sulfate aerosols; (a) 2010, (b) 2015, (c) 2016 from ECHAM6-HAMMOZ model simulation

From the Fig 5.7 we can see that in all the years the Central Idina parts experience a moderate and consistent deficit in rainfall. Many studies done by Twomey concluded that an excess of aerosol cause reduction in the droplet size. Furthermore there is a decreased collision between the droplets which increase their residencec time and thus there is a suprresion of rainfall. (Rosenfeld et al., 1999)

The cooling effect induced by Sulfate aerosols increase the surface pressure. This effect is regional and seen mostly over hotspots. This results in a decrease of the land-sea pressure gradient and ultimately weakens the Monsoon.(Henrikson et al.,1999, Fadnavis et al., 2019)

Both scattering and absorbing aerosol types have the potential to influence the precipitation. This occurs through various microphysical and dynamical processes(Yang et al., 2022). In their study, Henriksson et al., 2018 concluded the impact induced by by aerosols on annual variability in rainfall is moderate and negative but consistent.(Chand et al., 2009)

In their experiment, Chung and Soden were estimating the impacts of both greenhouse gases and aerosols separately for the latter half of 20th century.Their models were unable to capture the shift of rain-belt in the absence of aerosols.It was concluded that southward shift of tropical rain belt is primarily driven by anthropogenic aerosols.(Chung and Soden et al., 2017)

We see a negative anomaly(upto -7 mm/day) considering all the years, over the entire landmass of India except for the certain regions of Jammu-Kashmir and Kerela. This inconsistent and small positive anomaly is occurring due to model bias, but largely the model depicts the rainfall by taking only the increased SO_2 emissions into the account. However, the simulated rainfall plots are consistent with the simulated AOD and RF plots. The increase in the SO_2 emissions by 48% over India has shown a significant reduction in the rainfall; which aligns with the expected results.

Table 5.3: Anomalies in Rainfall(mm day^{-1})

Years	**Central(i)**	**Bay Of Bengal(ii)**
2010	-7.84 to -0.126	-5.642 to -1.134
2015	-6.885 to 0.657	-8.056 to -0.956
2016	-2.712 to 0.551	-8.473 to 2.786

6

Conclusions:

The simulated rainfall India showed negative anomalies altogether with the increase in SO_2 aerosols emissions by 48% by ECHAM6-HAMMOZ model.

When the increased SO_2 emissions were simulated, the corresponding RF over India was reduced to a fair quantity. The minimum values of RF were -6.7 W m^{-2} (2010), -10.6 W m^{-2}(2015), and -3.36 W m^{-2}(2016) As we make an increase in the sulfate AOD, there is a decrease in RF at the surface, which induces a cooling effect at the surface.This net cooling effect produced by the enhancement in the increase in the SO_2, which was a result of scattering effect of sulfate aerosols. The cooling effect slows down the convection process.

As the upward transport of warm moist air slows down, there is a disturbance in the circulation and it prevents the shifting of Hadley cell towards the IGP. The plots of Hadley circulation show a large subsidence over the Indian region, when averaged 75°E to 95°E.There is more subsidence than normal caused by the increased stability of the system

As the environment becomes increasingly stable, the formation of clouds slow down. In our plots we saw negative anomaly of the cloud cover over the entire India in all the years. It was strong in 2010 and 2015, and less intense in 2016.

This experiment shows that SO_2 aerosols have serious impacts on Indian Monsoon.We observe an overall negative anomaly in precipitation over India.We have a decrease of 7.84 mm day^{-1}(2010), 6.88 mm day^{-1}(2015) and 2.712 mm day^{-1}(2016).

The continued increase in SO_2 emissions will bring in scarce rainfalls which can potentially lead to droughts.

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