

Role of Aerosol in Precipitation: Key Issue in Climate Research and Predication

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ABSTRACT

Aerosols are the crucial element that influence water cycle and radiation budget. They are responsible for cloud formation to take place and they also absorb solar radiation coming towards earth surface and by these processes aerosols also effect climate on earth. As the aerosols are responsible for cloud formation, research is being performed how these aerosol results can be extended towards precipitation and to generate an aerosol cloud precipitation relationship. However, the problem faced is lack of understanding of the different mechanism responsible for precipitation. Research work is being performed by atmospheric and climatic communities in order to understand mechanism and to remove uncertainties related to the prediction of climate. In this article, past efforts are reviewed and current understanding on the effect of aerosols on precipitation are summarized. Aerosols effect on precipitation can be analyzed by (a) theoretical approaches that helps in understanding cloud micro physics, (b) observation data and (c) numerical models simulations. There are few differences between results obtained by ground based observational data (the data obtained through satellites) and numerical data (obtained through cloud models) that are also discussed.

The article discusses the following topics: theories explaining the effect of aerosol over cloud micro physics and precipitation, evidence of aerosols effecting the precipitation obtained from observations, aerosols effecting cloud formation and cloud dynamics through large scale analysis, cloud resolving models and simulations, results from numerical models over global scale. Lastly future research areas for understanding aerosol cloud precipitation relationship has also suggested.

Keywords: Condensation nuclei, Cloud droplets, Cloud droplet effective radius, aerosol optical depth (AOD), Liquid water path, Cloud resolving models

INTRODUCTION

Cloud Physics involve the processes that results in the formation, growth and precipitation of clouds. It is important for understanding the formation of precipitation, climate change, weather prediction and methods for weather modification. The process of cloud formation is complicated which leads to difficulty in understanding the mechanism how a cloud forms and evolve. A wide variety of topics has been explored previously such as cloud modelling and field experiment, relation between cloud physics and precipitation, hail, thunder storm and aerosol cloud precipitation relationship due to high demand in weather forecast, changing climate and weather modification activities.

Earth climate and water cycle are significantly being affected by aerosols as they are the key factors

for cloud formation and precipitation. Being such an important factor, their effect is still not known clearly. The reason for this unclear understanding is the indirect effect of aerosols. The aerosols effect clouds not directly but they actually effect some features of clouds and hence better termed as aerosol indirect effect. These indirect effect can be traditional in nature and termed as “Twomey,” effect. By traditional here means effecting the basic features of cloud such as droplet size, liquid water path and there is another indirect effect called “second indirect” effect. This effect is complex in nature and mainly considered for mixed phase clouds. It effects cloud extent and lifetime. Due to first indirect effect, large number of aerosols can decrease the warm rain process by diminishing particle size and resulting in a small droplet spectrum that hinders interaction and attachment process.

Aerosols also affects solar radiations by either absorbing or scattering them which is often said to be aerosol-radiation interaction the effect of this interaction is visible in changing ambient conditions such as change in temperature, stability and large scale circulation.

Recent advancement of techniques due to a large number of simulation models resulted in more insight concerning the relation between aerosol cloud and precipitation. For example cloud top temperature and droplet size data obtained from high resolution radiometer can be used to predict the effect of aerosol particles in the form of smoke and dust. The data obtained from TRMM (Tropical Rainfall Measuring Mission) satellite suggest that super cooled liquid droplets are present at the top of cloud. Here TRMM satellites are the part of Tropical Rainfall Measuring Mission coordinated jointly by space agency NASA and Japan Aerospace Exploration Agency (JAXA). These super cooled liquid droplets may be due to high seeding or pollution. These findings from different sources such as aircraft and TRMM have suggested that increase in aerosols loading due to pollution or seeding results in decreasing the mean size of cloud water droplets which can further decrease merging of droplets and hence ultimately leads to warm rain suppression. As there is less precipitation, hence freezing of cloud droplet occurs and release of latent heat which enhance cold rain processes. Andreae et al. (2004) analyzed during an experiment on Amazonia the relation between smoke, aerosols, cloud, climate and rainfall. It was found that an increase in smoke due to burning of fossil fuel results in higher clouds heights and more freezing of water particles which results in an increase in enhancement of cold rain process over amazon basin. Lin et al. (2006) also obtained the same results by analysis satellite data over amazon basin that high biomass burning leads to high cloud height and increase in cold rain process. Koren et al. (2005) analyzed data using Moderate Resolution Imaging Spectro radiometer satellite (MODIS) over Atlantic ocean and found that aerosols from biomass burning produce invigoration effect. Bell et al. (2008) observed with the help of TRMM satellite data that increase in thunderstorm over south east region of U.S due to increased aerosol loading. Li et al. (2011) and Niu and Li (2011) analyzed past ten year data

obtained through satellites TRMM and MODIS and also through observations in order to find the conditions responsible for cloud formation and precipitation suppressed or enhanced by aerosols.

In urban areas, due to human activities large quantities of aerosol particles are generated. These particles act as a source of cloud condensation nuclei and hence affect precipitation. The observation made in the above paragraph that aerosol produce invigoration effect and they enhance cold rain processes and also suppress warm rain process are due to the fact that aerosol affect cloud micro physics and cloud dynamics. They also vary the electrification properties of cloud and hence some thunderstorms are observed in summer monsoons due to biomass burning. Table 1 gives the effect of high and low aerosol concentration over environment. Aerosols effect cloud drop size, cloud height, warm and cold rain processes and also the frequency of thunderstorm and lightning. The cloud formation process has different steps and it follows from the warming of the ground, rising of warm air to cooling of air and also the meeting of this cold air with the water vapor present followed by condensation and clouds form. This complete process is affected by aerosols at different steps and it ultimately leads to effect precipitation.

Table 1 summarized the various cloud features such as cloud drop size, warm-rain and cold-rain process, mixed phase regions present in cloud and lightning. As discussed earlier, large aerosol particles creates more condensation nuclei that results in formation of small cloud droplet size due to less collision and coalescence results in suppression of warm rain process. As warm rain process decreases, hence more number of droplets are formed in the top portion of the cloud that leads to enhancement of cold rain process. Mixed phase clouds are the clouds which contain liquid particles as well as ice crystals. They show a deeper penetration in case of high cloud condensation nuclei. Large aerosol loading causes high lightening as observed in U.S south sea experiment given previously.

Warm clouds are present at lower level in the atmosphere. It act as an air conditioner as they reflect the solar radiation falling over them back into space. Temperature is mainly above zero degree Celsius, hence no mixed phase and ice phase regions and

Table 1. Summary of various cloud feature

Properties	High CCN(Dirty)CCN (Cloud Condensation Nuclei)	Low CCN (Clean)
Cloud droplet size and distribution	Smaller and narrower	Larger and broader
Warm-rain process	Suppressed	Enhanced
Cold-rain process	Enhanced	Suppressed
Mixed-phase region	Deeper	Shallower
Lightning	Enhanced (downwind side)/ higher maximum flash	Less and lower maximum flash

hence these clouds are studied deeply in comparison to deep convective clouds. Warm clouds are affected by aerosols and they don't present any significant improvement in precipitation, elongate cloud lifetime, and increase cloud cover.

The objective of this article is to gain deep insight into the process that results in the interaction between aerosols cloud which leads to enhanced precipitation. The paper discusses the impact of aerosol particles over precipitation in seven sections. The first section contains the introductory part of the aerosol clouds. Theories that are related to aerosol effect over precipitation are discussed in Section 2. The third section describes impact of aerosol on the formation of condensation nuclei and warm rain processes and also effect of aerosol on ice nuclei formation and mixed phase clouds. Later on, aerosol generated by urbanization effecting thunderstorm and lightning is also discussed. In section 4, observational data obtained from different satellites are used to predict the aerosol impact over different regions. Section 5 deals with cloud resolving models used for simulating convective moist phenomenon. Formation of complete life cycle of cloud or part of it over a limited area. Cloud resolving models (CRM) helps in understanding complicated micro physics. In section 6, large scale or global scale models for understanding aerosol impact are discussed. In section 7, challenges in aerosol precipitation interactive process, cloud microphysical sensitivity to aerosol effects and future research directions are discussed. The areas that are currently under progress and have a potential to be further explored are also discussed in this section.

Theories behind effects of aerosol in cloud formation and precipitation

Aerosol conversion into cloud condensation nuclei

Aerosols can act as condensation nuclei (CN) on which water vapor condenses. The condensation nuclei is key to cloud droplet formation. The capability depends on the mass of hygroscopic components present in condensation nuclei. The above mechanism was explained by Kohler's theory with the help of Kohler curve. Kohler's theory describes the process related to condensation of water vapor and the formation of liquid drops and the above process follows equilibrium thermodynamics. It describes the equilibrium saturation for each drop and varies as a function of the drop size. The solution drop surface attains a maximum value at a critical radius r^* and saturation ratio corresponding to that critical radius is critical saturation ratio S^* . In the atmosphere, if ambient saturation ratio is greater than critical saturation ratio, drop forms otherwise it remains as haze.

In Figure 3, if $s > s_c$ that is ambient super saturation is greater than critical saturation ratio then the particle grows and it becomes critical nucleus and then by continuous addition of water it becomes a cloud drop. The particle can be of any size and it keeps on growing until the condition of $s > s_c$ is satisfied. In Figure 4, if $s < s_c$ that is ambient super saturation is less than critical saturation ratio and also if drop radius is small then drop grows until it reaches the condition $s = s_c$. These drops are called haze drops often observed in summer time. They are incapable of nucleation and stays in smaller size. Kohler theory combines the Kelvin effect, also known as curvature

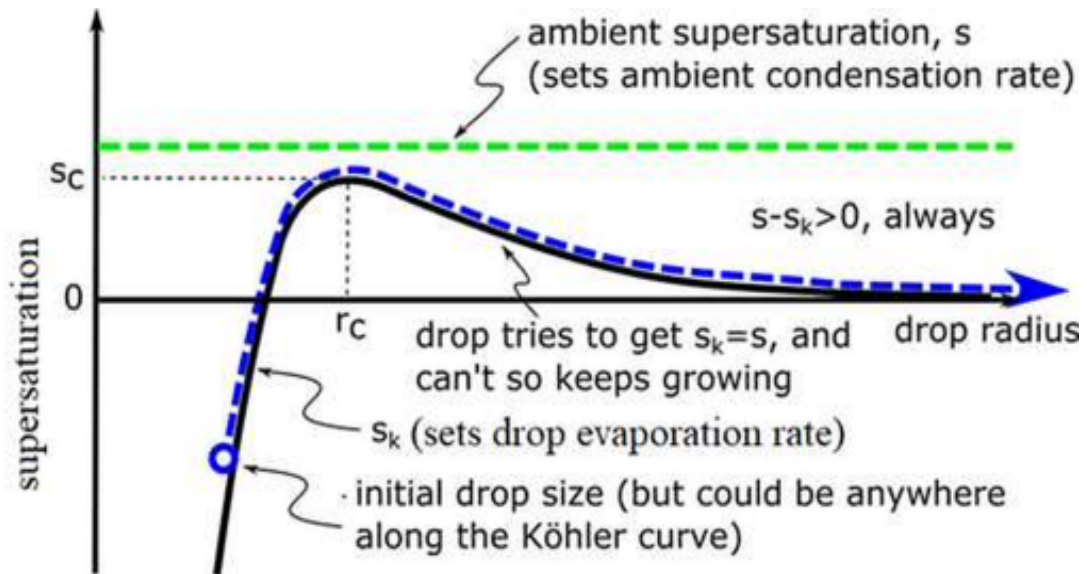


Figure 1. Ambient super saturation variation on Kohler curve (Brune 2006)

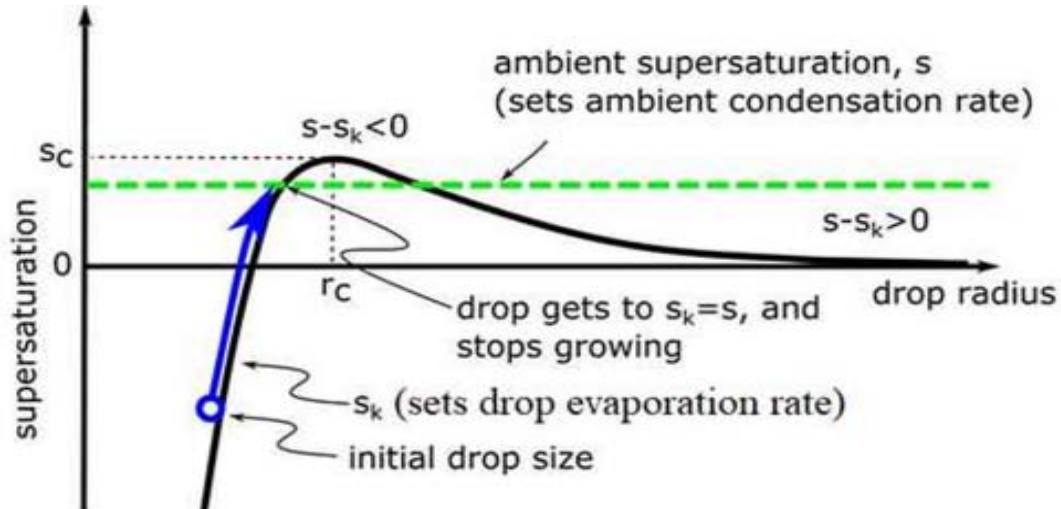


Figure 2. Ambient super saturation variation on Kohler curve (Brune 2006)

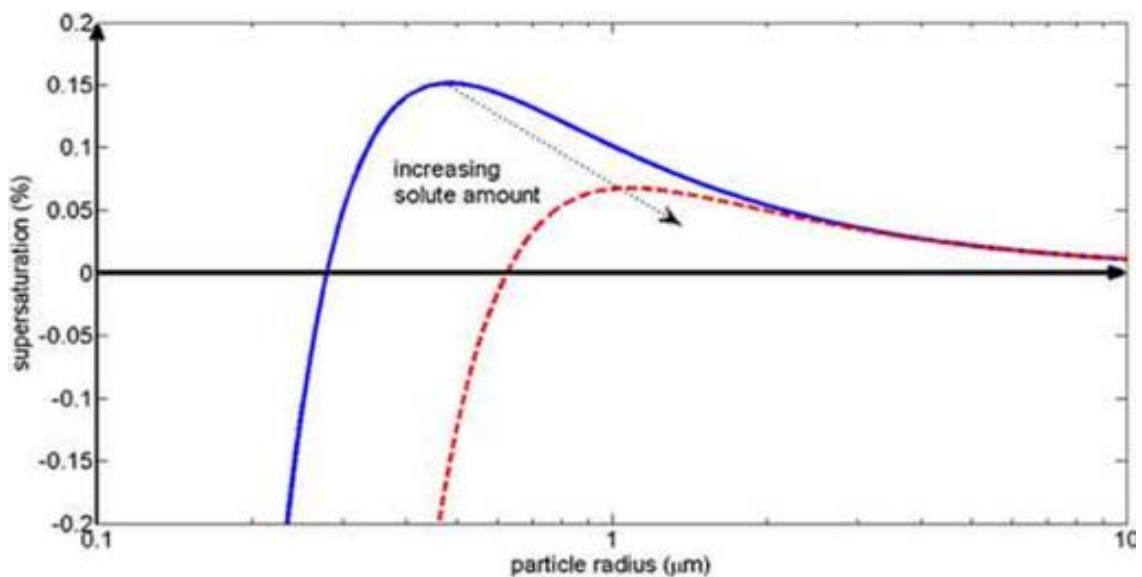


Figure 3. shows variation of S^* with aerosol mass (Brune 2006)

effect which explains the change in saturation vapor pressure due to a curved surface, and Raoult's Law, which describes the saturation vapor pressure to the solute. It is an important process in the field of cloud micro physics. Condensation nuclei becomes a cloud condensation nuclei while the conversion process depends on many factors such as aerosols mass, chemical composition, temperature, insoluble portion present in condensation nuclei. Besides the conversion is affected by above factors ambient properties also influence conversion process.

From Figure 3 it is evident that large aerosols have lower S^* , hence they can easily activated besides aerosols mass its chemical composition have effects on surface tension and water activity also temperature can affect aerosols activity. An increase in temperature have effect on saturation vapour pressure, surface tension and molecule activity. Beside this the insoluble portion present may also effect particle size by affecting surface tension.

Particle concentration at cloud base is related to aerosol concentration and study of this relationship is important to understand as aerosols effect cloud micro physics and also the radiation coming over landscape are also scattered by aerosols. Understanding aerosols through Kohler curve is the first step towards this study. Kohler curve only tells whether a condensation nuclei can be converted into cloud condensation nuclei on the basis of super saturation. The maximum value of ambient super saturation must be known in order to determine the number of particles activated near cloud base.

The ambient saturation can be effected by two factors (Squires, 1952)

$$\frac{ds}{dt} \propto = A_1 \frac{dz}{dt} - A_2 \frac{dq_w}{dt} \quad (1)$$

where the coefficients A_1 and A_2 are characteristics of atmospheric air, z is the elevation, and q_w is the cloud water content.

In Equation (1), the first term is source term it increases due to expansion cooling the second term is sink term it increases when condensation of water vapour occurs.

The rate of condensation depends upon super saturation, cloud drop size and cloud concentration. Cloud concentration is depend on condensation nuclei size spectrum and variation in super saturation.

As more and more condensation nuclei transformed into drops sink term increases and it surpasses the source term and after sometime super saturation start to decrease. This phenomenon occurs above few meters of cloud base. In following sections, different form of condensation nuclei and its relation with cloud concentration are discussed.

(1) Condensation Nuclei spectra measurement is performed on the basis of Köhler theory. In order to perform the study a diffusion chamber is taken this diffusion chamber is filled with aerosol particles the diffusion chamber is maintained at a controlled super saturation, the number of aerosol particles converting into cloud droplets are counted. These CCN particles can be represented empirically as

$$N_{CCN} = CS_{\text{ccmax}}^k \quad (2)$$

where C and k are temporal and spatial-dependent coefficients of the Condensation Nuclei spectra.

(2) Aerosol measurement can also be performed by a different approach by separating aerosol particles on the basis of aerodynamic sizes and after separation these particles are counted for each size segment and a size spectrum can be formed. This approach was previously used and particles with dry size radius r_a greater than 0.1 μm and represented by a power law relationship by (Junge 1952, 1955):

$$n(r_a) = \frac{dN(r_a)}{dr_a} = c_1 r_a^{-c_2} \quad (3)$$

where c_1 and c_2 are constants and $N(r_a)$ denotes the count of condensation nuclei having dry size greater than r_a . Note that SS_{max} in equation (2) actually shows the super saturation conditions for the smallest Cloud Condensation Nuclei, and this S_{max} can be related to the r_a of that particle by the approximation,

$$s^* \propto H^{1/2} c r_a^{-3/2} \quad (4)$$

where c depends on the chemical composition. As mentioned before, these formulas might not apply to $< 0.1 \mu\text{m}$, yet under some conditions, such as in strong convection, very small Condensation nuclei can also form cloud drops. Characterizing aerosols on the basis of sizes as given in equation (3) has a disadvantage that the chemical composition of particles must be known for calculating the cloud

concentration and this information usually not available.

Some cloud resolving models are capable of resolving SS, and with the help of Kohler theory obtaining cloud concentration for a particular CN spectrum as given in equation (2). These models use sophisticated bin microphysics and bulk micro physics. Cheng et al. [2007] suggested the use of Lagrangian parcel scheme for calculating the super saturation. Alternatively, cloud concentration (N_c) may be derived by using diagnostic formulas introduced.

Apart from using theoretical approaches discussed above empirical relationship can also be used for calculating cloud concentration. In the empirical approach correlation is made between cloud concentration above cloud base and aerosol concentration below cloud base. This method has been applied in various global climate models.

Inorganic constituents of aerosols can mainly serve as condensation nuclei as observed by previous studies. But some organic compounds such as organic carbon can also be an important constituent of aerosols such as sulphate. Organic carbon retard water activity and also lower down surface tension of water. The effect is similar but less weaker in comparison to inorganic solutes on mass basis. The effect of organic solutes has been studied in few studies (e.g., Nenes and Seinfeld 2003). Surfactant kind of organic carbon contains both polar and non-polar segments. These molecules present on drop surface and forms a thick layer. This layer slow down the condensation process by decreasing water accommodation coefficient. This slowdown of condensation process by formation of thick layer has been represented by a one dimensional model. Feingold and Chuang showed that formation of thick layer causes higher ambient super saturation and it results in advancing of condensation nuclei activation. These surface film effects are highly complex and also less information is available regarding behaviour of surface active agents in aerosols and hence not focused in recent cloud models.

Effect of cloud condensation nuclei on rain formation

Rain formation processes can be classified into two

categories (a) warm-rain processes with no presence of ice crystals and (b) cold-rain processes that includes presence of ice crystals. Condensation Nuclei have high influence on rain formation processes of their ability to effect cloud concentration (N_c). The higher cloud concentration (N_c) results into smaller water droplets. These Small droplets are not able to undergo collision because of smaller collision speed and efficiency. As soon as a raindrop is formed it start growing by collecting other cloud drops and this process of rain drop growth proceeds efficiently if drop are of sufficient sizes so it can be said that the process of rain or cloud formation mainly depends on cloud drop sizes.

Cloud drop becomes narrower as the condensation nuclei rises and it can be a potential impact of condensation nuclei over warm rain process. This narrowing of cloud drop results in suppression of warm-rain formation. It is to be noted that the suppression of collision coalescence results in enhancement of narrowing the cloud drop size spectrum.

Very large Cloud Condensation Nuclei often termed as Giant Cloud Condensation Nuclei (GCCN) are used to prevent warm rain suppression. Because of their inbuilt large sizes, Giant Cloud Condensation Nuclei (GCCN) can be directly converted into rain embryos and can promptly initiate the warm-rain process. Giant CCN sized salt particles are inserted into clouds to speed up rain initiation. These Giant nuclei can also compete for water vapor, hence they can lower $SS_{,max}$. It prevents small Condensation Nuclei probability to be activated into cloud drops. The advantage of having fewer cloud drops is that now each cloud drop can grow larger and thus is more efficient at converting into rain by collision coalescence. GCCN counteract both Twomey's first and second indirect effects. However, GCCN are not effective in clean atmospheric conditions as demonstrated by Feingold et al. [1999]. Dust particles can serve as condensation nuclei but their chances of converting into cloud condensation nuclei are very less. Dust particles can serve as CCN in certain conditions and hence they have a broad impact on global climate, ecosystem, human health and also on agriculture and need to be explored.

Large number of CCN particles not always increase water content of cloud or cloud lifetime. As

demonstrated by Ackermann et al. (1977) flow of dry air over stratocumulus cloud results in drying of cloud water and hence water content decreases even though CCN particles increases. Smaller cloud drops increase evaporation in the downdraft region of cloud because of which cloud size, cloud depth and cloud fraction decreases. In upward draft of cloud, effect of CCN particles is more complicated.

Heterogeneous nucleation by ice particles can also be used for initiating cloud ice formation. Water can deposit on these ice nuclei as liquid and then freeze which is called condensation-freezing nucleation or it can also deposit on these ice nuclei as ice called deposition nucleation. This process of water deposition and its conversion is highly dependent on SS. From equation (1) this SS depends on cloud condensation which is further dependent on condensation nuclei hence it can be said that condensation nuclei can effect ice nucleation process. Condensation nuclei helps in nucleation of ice particle apart from this they also helps in growth of ice particles. Initially after formation ice crystals grow by vapour deposition. The vapour required for growth are supplied by continuous lifting of cold air or by evaporation of cloud drops. This evaporation of cloud droplets is called Wegener-Bergeron-Findeisen (WBF) process or cold rain process. After evaporation these droplets are converted into ice and this conversion is dependent on rate of evaporation. If more number of drops are present then evaporation occurs rapidly and growth of ice particles proceed at a faster rate. Growth can also proceed by accumulating of cloud water a process called rimming but this is only possible when particles are of sufficient size. Rimming process is also dependent on condensation nuclei but this relationship is indirect relationship as rimming process is suppressed due to large condensation nuclei.

Effect of Ice nuclei particles on rain formation processes

Ice nuclei particles are important for cloud physical processes for formation of precipitation and in order to balance global radiation as these particles helps in scattering solar rays. Similar to condensation nuclei, Ice nuclei also effect cloud microphysics by effecting cloud ice number concentration N_c and this number concentration is important in mixed (ice and

liquid) phase zone of cloud. There is less information available for particles that are responsible for ice nucleation therefore modelling of mixed phase zone is challenging.

Ice nuclei particles are transferred through strong winds that flow over land such as deserts, semi-arid areas, agricultural uplands and river beds most common among them are dust particles. Mineral particles may reach up-to upper troposphere and helps in the formation of cirrus cloud. The hypothesis that dust particles can modify cloud microphysics and dynamics is well supported by ice particle residual measurement. Anthropogenic sources can also release soot particles that serve as ice nuclei, however their efficiency is lower. Biological particles such as bacteria, pollen, fungi can also be potential source of ice nuclei, these particles are efficient but they are low in number.

Ice nuclei promote ice formation by four different mechanisms among them are deposition nucleation, condensation freezing nucleation, immersion freezing and contact freezing nucleation. Temperature is the controlling factor for ice nuclei to ice conversion. Immersion freezing (IF) takes place when an Ice Nucleating Particle acts as Cloud Condensation Nuclei remains in unfrozen state and later on it gets freezes when the temperature is lowered. In contact freezing, the ice nucleating particle collides with the droplet followed by freezing. Contact freezing (CF) in the original sense is understood as the process in which freezing of a super cooled droplet results from the collision with an aerosol particles. Ice formation by mineral dust was influenced by immersion freezing and for soot particles immersion and contact freezing both influence the process Hoose et al. (2010a). Ice formation by biological tissues is only possible when they have high concentration in atmosphere.

All condensation nuclei could not get converted into cloud drops. Similarly not all ice nuclei form cloud ice and it varies from cloud environment. Two hypothesis are presented in this regard. First is stochastic hypothesis that states that nucleation is probabilistic and time dependent process which results in nucleation of only a fixed quantity of ice nuclei during a fixed length of time and the rate of nucleation varies as per the properties of particle and environmental conditions. Another hypothesis that

is singular hypothesis states that nucleation depends on impurities and on number of active sites present on surface of ice nuclei. Each active site have a particular temperature and super saturation pressure.

Ice nucleation process and cloud model representation need improvement hence research is being done in these areas. Simulation can be performed related to emission and movement of mineral dust and soot particles the atmosphere. Advancement of model generation helps in simulation of biological particles that are present in atmosphere for example bacteria. Ice nucleating particles parameterization based on laboratory data is also getting attention among the researchers.

Observational evidence of processes and mechanisms behind the aerosol indirect effect

Different mechanism are used to study the impact of aerosol over precipitation. Aerosols can modify water cycles and energy through the scattering and absorption of solar radiation. These aerosols serve as cloud condensation nuclei and ice nuclei and most of the processes studied involved the methods responsible for aerosol conversion into CCN.

All the mechanisms shown in Figure 4 (IPCC Fourth Assessment Report: Climate Change 2007) except the seventh one has its origin from the Twomey effect. The effect states that increase in aerosol concentration results in cloud droplet concentration that results in cloud particles of smaller

size and hence suppression of rainfall with an extended cloud life time for the fixed liquid water path. Invigoration effect results in development of convective clouds and also increases cloud height. This invigoration effect is caused by aerosol and hence it can be said that aerosol can effects precipitation, cloud height, amount/liquid water path (LWP). These aerosol effect can be grouped into a common term known as second aerosol indirect effect (Albrecht, 1989) and it is more complicated than the first aerosol indirect effect. Initially only atmospheric dynamics and thermo behaviour are sufficient for determining cloud precipitation relationship. Later on, different mechanism for producing aerosol invigoration are continuously evolved and more aerosol indirect effect can be obtained by adding or removing constraints. However, finding these mechanism is a difficult task as these mechanism are not alone they are coupled to one another.

In atmosphere different processes occurs because of the presence of atmospheric variables such as aerosol, cloud, precipitation and a relationship need to be made between them for measuring aerosol invigoration effect. These processes are studied in a column over a large domain and effects such as advection, convection, vertical motion due to convection all are taken into consideration in order to isolate aerosol effect over precipitation. Aerosol invigoration effect are studied to establish a relationship between newly generated clouds and the local aerosols.

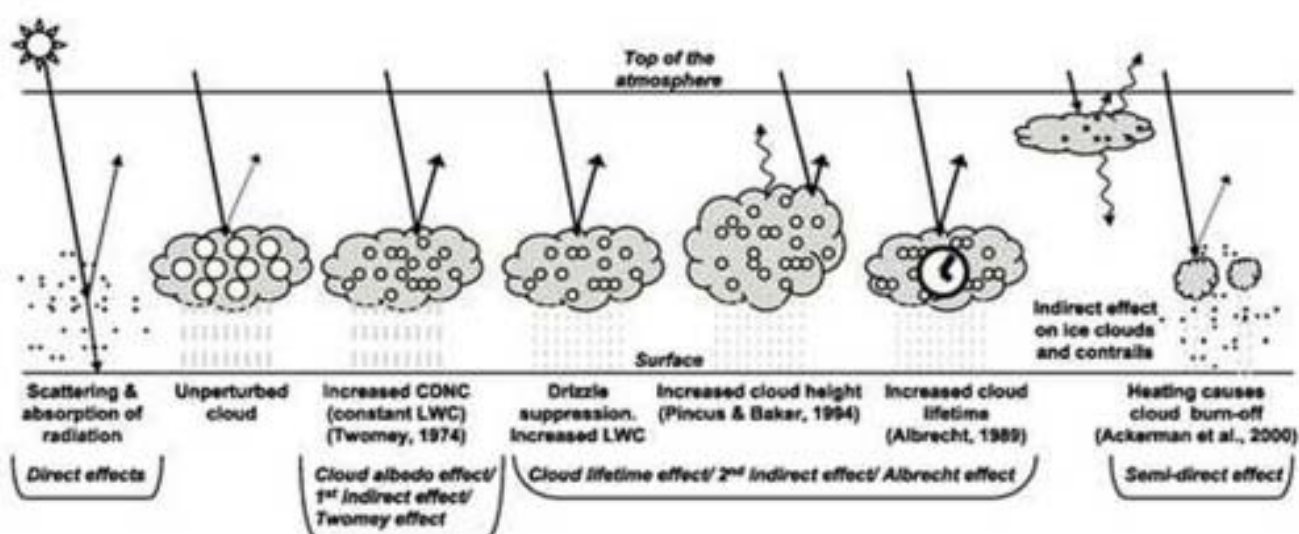


Figure 4 Mechanism through which aerosol effect precipitation (IPCC 2007)

Impact of aerosol loading on cloud droplet size distributions and warm-rain processes

As the cloud droplet size decrease with an increase in aerosol concentration for a fixed liquid water path a phenomenon termed as cloud albedo is observed. As per this phenomenon, smaller cloud size particles those are large in number reflect more radiation than large particle size but fewer in number. The above phenomenon has been supported by different satellite data. Satellite covers a wide area and collect multiple data than ground based measurement. However, it suffers from the problem of data separation and distinguishing between real to false data. Also, satellites cannot determine cloud and aerosol properties at a same time and at a same location. The above problem is solved by large scale observation as discussed later. The problem associated with large scale data collection is variation in aerosols size and data mismatch also there are changes in cloud properties which also seen as a limitation of large scale data collection.

The above limitation can be lowered by ground based observations but there also large variation occurs due to sensitivity of cloud micro physics towards aerosols. These variations are because of the use of different analysis used for data collection and also due to natural variation. Data obtained from ground based measurement is plotted as a graph between cloud droplet size and aerosol extinction coefficient and found out that ground based measurement data is valid for small variation in liquid water path (LWP) and a large variation aerosol loading but the data is invalid for opposite effect. Large range variation of liquid water path and small range variation of aerosol loading

As discussed in previous portion cloud particle size and aerosol loading has an inverse relationship. Yuan et al. (2008) has conducted a study using MODIS (Moderate Resolution Imaging Spectro-radiometer) satellite and found a positive relationship on two portions of the world Gulf of Mexico and south China coast during summer season. These regions are influenced by monsoon wind that blows from the sea towards the polluted areas. The curve between cloud droplet size and aerosol optical depth shows a positive relationship due to the presence of moist air as now water vapor need not to compete in order to

grow.

The effect of aerosol loading on warm rain processes has been studied and it is found that aerosol loading suppress warm rain process because large aerosol loading provides significant number of condensation nuclei. Hence, large number of small cloud drops form these large number of droplets inhibits the collision and coalescence process.

Aerosol loading in form of smoke and dust can affect the cloud properties such as cloud water particle size, optical depth and liquid water path. These factors are then responsible for suppression of warm rain processes. Aerosols particles in form of dust, warm the clouds and hence rate of evaporation increases. This leads to reduction in liquid water path and as the liquid water path and aerosol loading are inversely correlated it leads to increase in aerosol loading and suppression of warm rain process. Decrease in liquid water path can also termed as semi direct effect which is responsible for drought in many areas of northeast china.

All the previous analysis was performed on cloud too height and it was observed that cloud drop size increases with cloud height. Cloud drop size influenced by many factors such as atmospheric stability, water vapor available, cloud thickness. A curve plotted between liquid water path and cloud optical depth shows a downward slope and hence quantities are negatively correlated. Increase in Cloud droplet size does not always leads to an increase in precipitation as increase in precipitation is determined by many other factors such as cloud micro physics, cloud dynamics, cloud thermodynamics.

Impact on ice and mixed-phase clouds: Aerosol invigoration effect

Ice particle effective radius is negatively related to aerosol index as observed with Total Ozone Mapping Spectrometer. The above observation was done for cumulonimbus cloud. The above relation says that as the aerosol loading increases the ice particle radius decrease. This is not always true and some studies found a minor change in ice particle radius due to aerosol loading. By combining data from different satellite such as MODIS and TRMM (Tropical Rainfall Measuring Mission) it can be concluded that aerosol effect on ice cloud depends on moisture

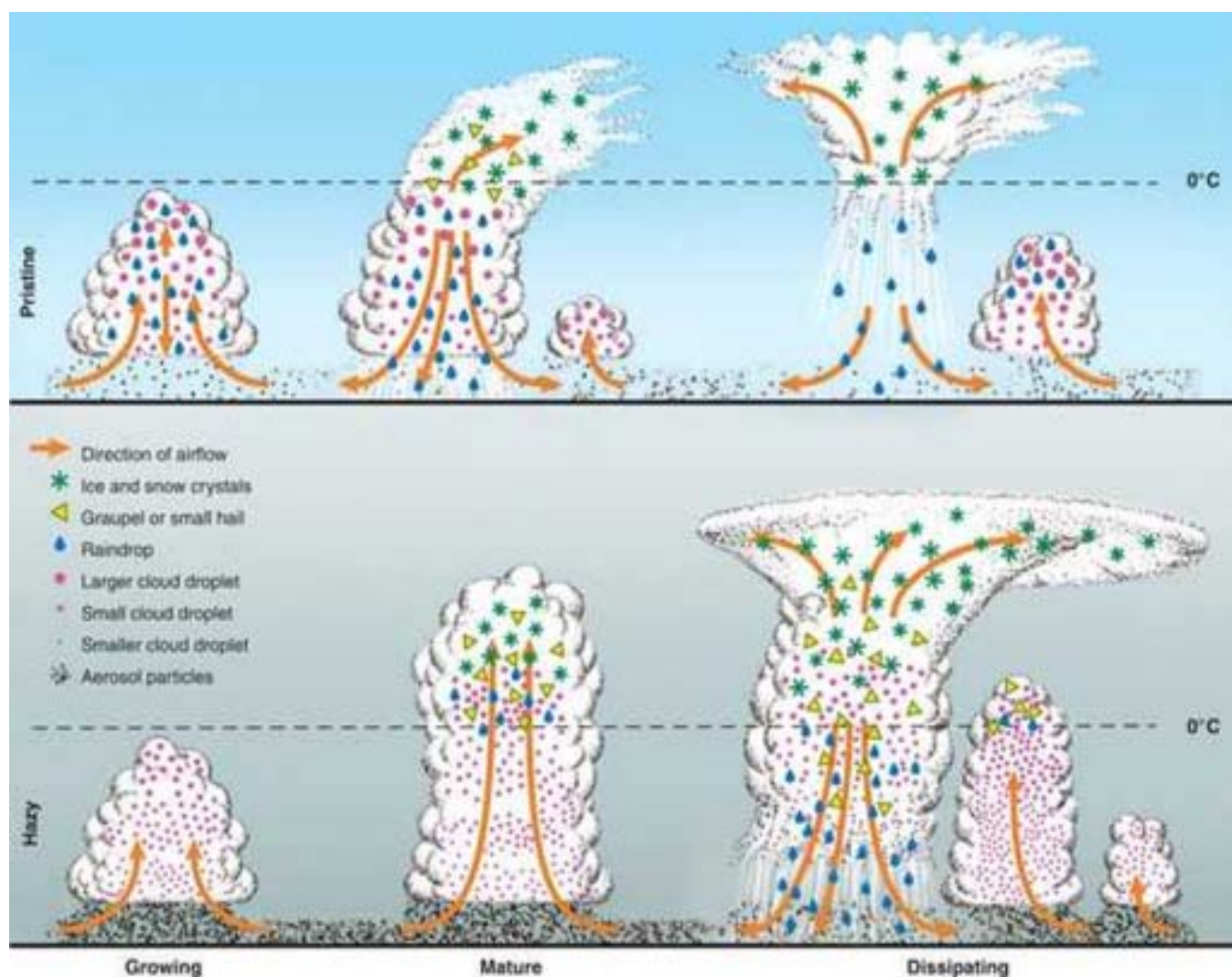


Figure 5. Schematic for aerosol invigoration effect (Rosenfeld et al. 2008)

content. If the environment is dry aerosol reduce ice crystal size and precipitation get decreased. On the basis of above observation, ice particle radius can be parameterized as a function of water content and its different for different regions.

Data obtained from aircraft and TRMM satellite shows the presence of super cooled liquid water near cloud top in convective clouds. These findings are observed in regions with high concentration of aerosols and it suggest that these aerosols can reduce cloud drop size, suppress coalescence and warn rain process. This reduction in cloud drop size leads to more freezing of cloud drops and release of large latent heat which enhance cold rain processes and the above phenomenon is known as aerosol invigoration effect. Figure 5 shows a schematic illustration of aerosol invigoration effect for two deep

convective clouds formed under clean (top) and dirty (bottom) conditions. Due to this effect clouds in dirty atmosphere grow higher and brings strong thunderstorm than the clouds formed in cleaner environment.

As discussed in previous paragraph, high aerosol particles causes high cloud heights. The concentration of aerosols can be enhanced by different factors. For example, high biomass burning produces large number of aerosol particles results in higher cloud heights and increase in cold rain processes also pollutants from the industries also lead to increase in aerosols. These observations indicate that precipitation shifted to higher levels in the regions of polluted environment. High aerosol invigoration effect can bring following changes as observed by Rosenfeld et al. (2008) using a parcel

model (a) suppression of rainfall and holding condensed water without freezing, (b) precipitation without freezing, (c) precipitation with freezing at temperature below -40°C and (d) suppression up to -40°C and then freezing and precipitation above that temperature.

Cloud top height increases with increase in aerosol loading. The above observation is made by the U.S. Department of Atmospheric Radiation Measurement program. As aerosol particles serving as condensation nuclei increases there occurs a decrease in light rain while an increment in heavy rain. These findings suggest that aerosol loading caused by pollution can make moist regions wetter and arid regions drier.

The invigoration effect depends upon latent heat release that depends on cloud height as if cloud base is high. Hence, less number of liquid water particles results in less release of latent heat. The aerosols generated by smoke can alter the thermodynamics of atmosphere as they heat the atmosphere and cool the surface. This heating increase the stability of atmosphere but reduces the moisture content of atmosphere and hence stops the formation of new clouds.

Impact of aerosols due to urbanization on thunderstorms and lightning

Aerosols are generated by urban activities and these aerosol can effect atmospheric environment and modify local climate. There are two major sources of aerosols emissions a) land cover and (b) atmospheric emissions in the form of greenhouse gases. These greenhouse gases emissions have a larger and longer impact.

Different regions were studied for understanding effect of aerosol over precipitation by different authors and found that large concentration of aerosols can enhance precipitation as these aerosols can act as potential source of cloud condensation nuclei. Hypothesis are proposed but still clarity is not present whether this increment in precipitation is due to urban heat island effect or due to aerosol effect or both. During summer season large amount of warm air blows from sea towards land this air carries away large quantity of hygroscopic aerosols with them that are generated due to industries located near lakes. During summer season the land gets heated fastly than lake. This heating causes low pressure over the

land surface and high pressure over the surface of lakes. This difference in pressure causes the flow. These results are supported by the findings of Bell et al. 2008 that says there is large thunderstorm and lightening in summertime near south eastern U.S. region.

Yuan et al. (2011) examined satellite data from TRMM satellite and found that high lightening has been observed in areas with high concentration of aerosols and they further related the frequency of lightening with aerosol loading and found that a 60 percent increase in aerosol loading leads to 150 percent increase in lightening flashes and this increment is due to the ability of aerosols to alter the cloud micro physics. However, with increase in aerosol loading cloud ice particle size decreases.

Large-scale observational diagnostics of the aerosol effect on precipitation

Isolating aerosol effects

This section differs from the previous section as the previous section considers the physical processes that govern the aerosol invigoration effect. On global scale, precipitation is affected by moisture budget that is influenced by surface evaporation. Aerosols can modify the timing and location of precipitation but they cannot alter surface evaporation.

Large observational studies consider data quality, methods used for analysis and correctness of results, and also causality. Aerosols and other meteorological factors affects the precipitation. It has been found that there is no relation between rain and water vapor transport. Hence, light rain can possible due to changing meteorological conditions. A large number of aerosol emissions due to pollution causes heavy rain. Wilcox et al. (2010) found that rainfall shifted towards the north in ITCZ (Intertropical Convergence Zone) over tropical Atlantic ocean. This shift was due to lower tropospheric warming of the Saharan air layer, high subtropical subsidence and heating of dust due to radiation.

Lau and Kim (2006) observed the effect of aerosols over the wind, temperature, and precipitation in the Indian summer monsoon region. They suggested that elevated heat pump theory, high concentration of aerosols before monsoon season is responsible for atmosphere warming that leads to an

increase in rainfall over India. Both the theories of Wilcox and Lau indicate that aerosol has a significant effect but their theory was still not clear although it was consistent with numerical simulations.

Alpert et al. (2008) pointed out that the urban dynamics did not take into consideration it may lead to misinterpretation of data. It could be possible that that decreasing rainfall may not due to increasing urban pollution. Bollasina and Nigam (2009) showed that aerosol generation in May month results in delayed monsoon rainfall as aerosol has a radiative effect. To separate precipitation dependency on other factors, various methods have been used to establish a direct relationship between aerosols and precipitation. While studying the effect of biomass burning over rainfall on amazon basin Jones and Christopher (2010) uses principle component analysis method to find out different parameters affecting rainfall and observed around 23 parameters such as aerosol optical thickness, environmental variables (winds, humidity and temperature) affect the precipitation. These parameters were weighted and found that environmental factors receive a dominant status for rainfall variation. Apart from this aerosol radiative effect is the next most important factor responsible for rainfall. These results shows that smoke has only a suppressing effect and not dominant one.

Huang et al. (2009, 2009a, 2009c) used a multivariable linear regression method to study the relationship between aerosol and precipitation and it was to be linearly dependent. It had been found that during the season of high aerosol emission, there was a decrease in precipitation. Numerical simulations have reproduced these results but only after considering the radiative effect of black carbon aerosol. Hence, the biomass burning results in large aerosol particles and it results in low precipitation. In order to understand aerosol impact completely and separate the results from other factors observation need to be done at different regions. These regions are separated on the basis of environmental conditions, cloud microphysics as illustrated in below examples.

Lin et al. (2006) studied convective characteristics and examined the relationship between aerosol optical depth and precipitation during the months of high biomass burning mainly in august to October.

In this study clouds are stratified into bins and a vertical integration has been performed by buoyancy per unit mass flux and this is termed as cloud working function (CWF). Cloud working function indicate that aerosol optical depth increase with precipitation, cloud top height. Sorooshian et al. (2009) studied cloud micro physics in form of liquid water path LWP and given a concept of precipitation susceptibility. This precipitation susceptibility is defined as:

$$S = -\frac{\partial \ln R}{\partial \ln N_d} \cdot \quad (5)$$

Where R is rate of precipitation and N_d is Cloud droplet number concentration within cloud. Low LWP shows insensitive towards Cloud droplet number concentration within cloud. Intermediate LWP shows precipitation can form by drops interaction and it can be suppressed by Cloud droplet number concentration. High LWP shows precipitation susceptibility to decrease. Later on, Sorooshian et al. (2010) studied the separate precipitation susceptibility into two parts and this separation provide more confidence in results.

Panicker et al. (2010) mainly focused on environmental factors and studied aerosol indirect effect by the help of MODIS satellite data and mainly focused on cloud water radius, cloud ice radius, cloud liquid water path, cloud ice path and found that for a fixed cloud liquid water path and cloud ice path aerosol have a positive indirect effect during years when monsoon was below normal and negative indirect effect when rainfall is normal or above normal. Based on previous discussion separating aerosol effect over precipitation from other factors had its advantages and disadvantages. Large scale observations are incomplete without considering cloud microphysics, cloud dynamics, and environmental factors such as aerosol transport and water budget. So collaboration and coordination must be required among sub-disciplines.

Applications of satellite data in revealing ACPI

Satellite data provides observational evidence and follow different approach than large scale models. Satellite data can be used to understand weather predictability. The generation of multiple advanced earth observation sensors has increased capability of weather prediction. Clouds micro physical

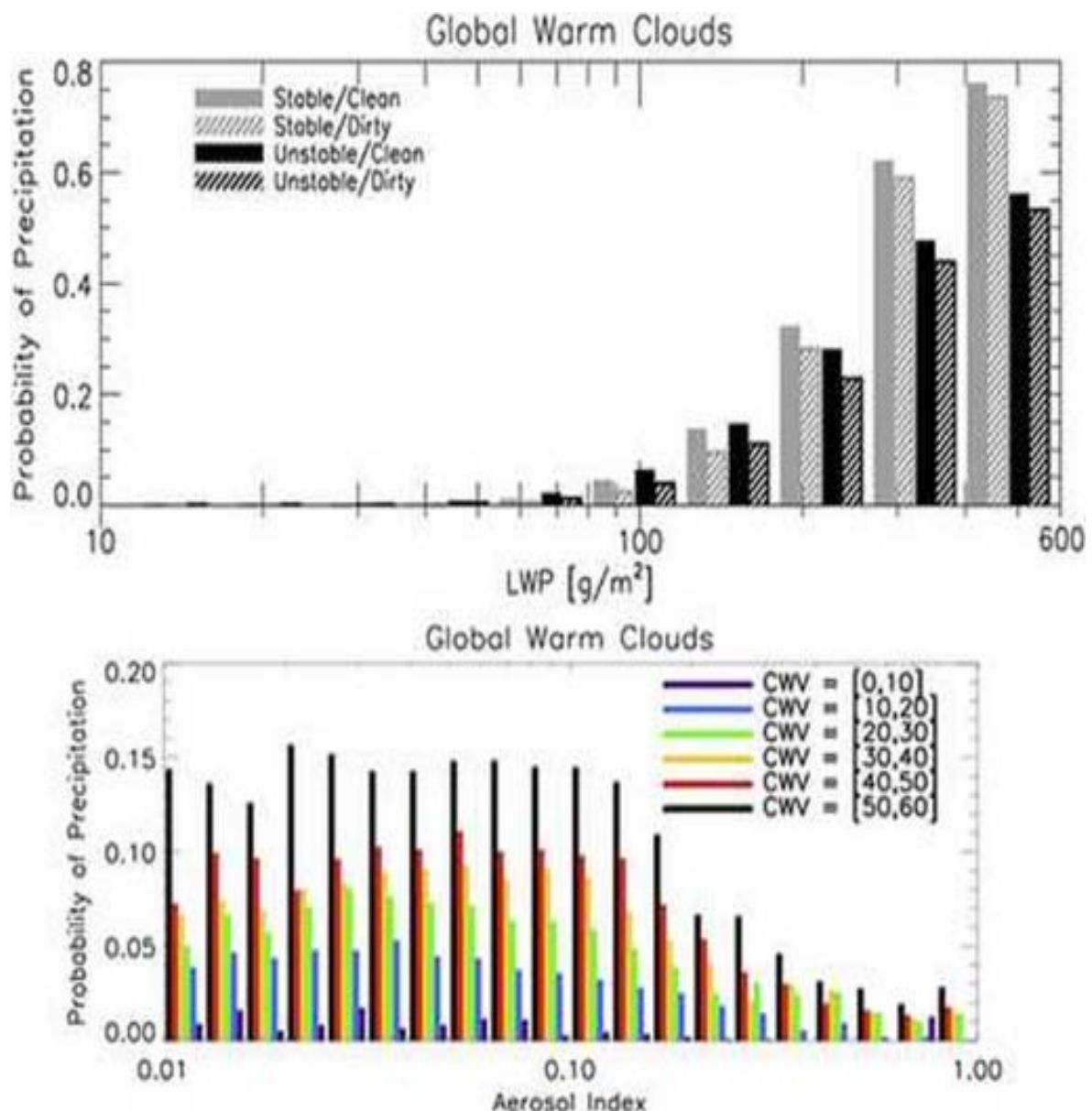


Figure 6 Change in Precipitation rate with Liquid water path and aerosol index (Lebsock et al. 2008).

properties are observed by satellites with limited certainty.

Different micro physical properties such as droplet effective radius (DER), liquid water path (LWP), cloud optical depth (COD) are observed by satellites. Among these properties LWP plays an important role in precipitation. Chen et al. (2011) studied the probability of rainfall in warm clouds and found that LWP is important factor which is followed by DER and COD. Chen et al. (2011) showed that LWP is an important micro physical property and the aerosol effect on LWP need to be

studied. By different observations, it was found that relationship followed a mix behavior. Large amount of evaporation reduces LWP whereas decrease in coalescence stops precipitation but increases LWP. As shown in Figure 6, an precipitation probability increases with increase in Liquid water path (LWP) and Cloud water path (CWP). It can also be observed that aerosols can inhibit precipitation and result in less rainfall from dirty clouds than clean clouds but not all aerosols inhibit precipitation like sea salt aerosols as they are of giant size range and can act as rain embryos. The data shown in Figure 6 obtained

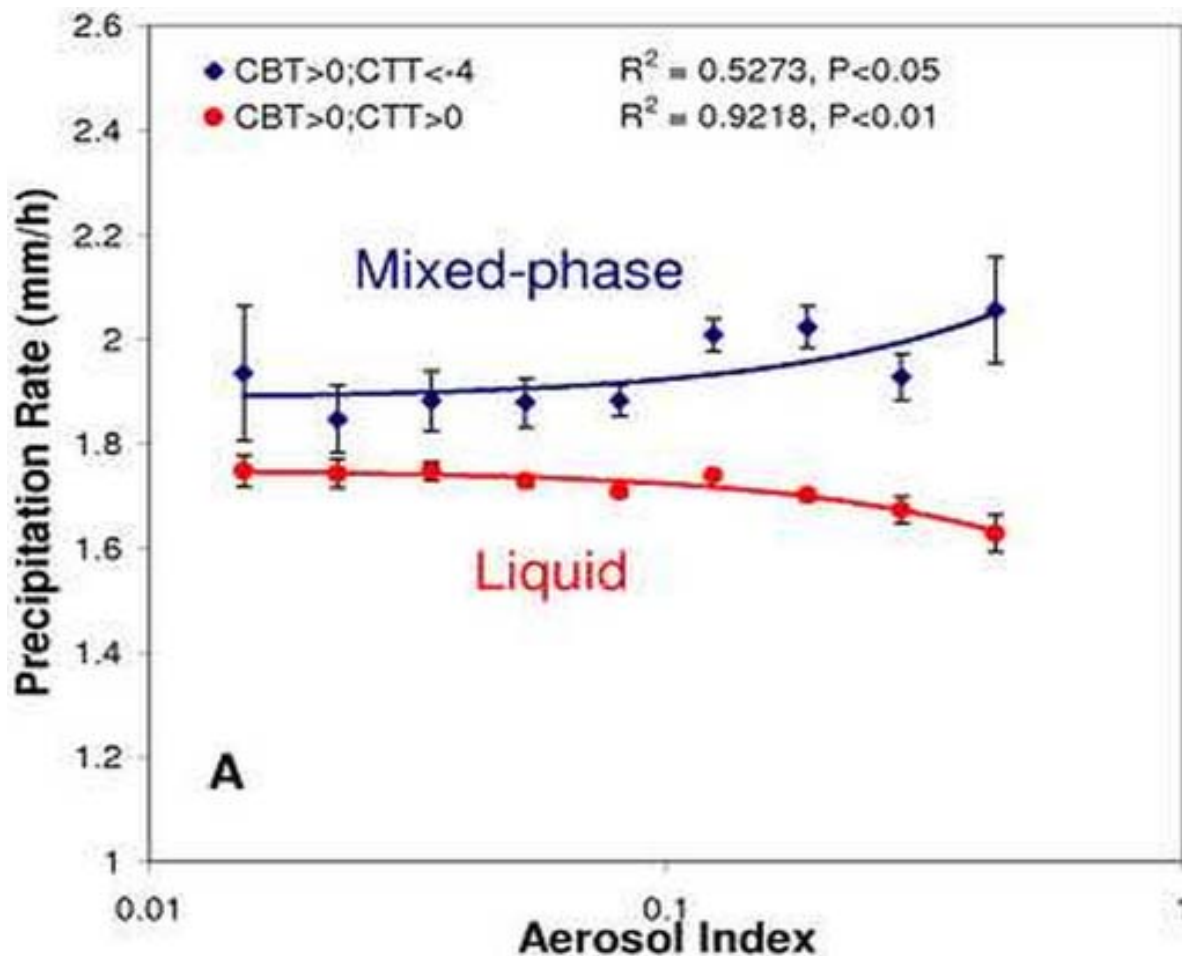


Figure 7. Variation of precipitation rate with aerosol index (Niu and Li 2011)

from multiple A-train sensors. A-train is an acronym for Afternoon Constellation which comprise of set of coordinated satellites such as Auro (2004), Aqua (2002) PARASOL (2004).

Rate of precipitation is different for warm and mixed phase clouds and it depends on aerosol index. In Figure 7, red line shows warm liquid cloud and blue shows mixed phase clouds data obtained using CloudSat and MODIS satellite. CBT is cloud base temperature and CTT is cloud top temperature. For warm clouds light rain occurs with increasing aerosol index while for mixed phase clouds rain increase with increase in aerosol index Li et al. [2011a]. These results show that aerosol have both invigoration effect and they also play a significant role in precipitation. Local emissions from different sources are by far the largest emitter of aerosol as measured by aerosol optical, physical and chemical properties.

CLOUD RESOLVING MODELS

Cloud Resolving models are used for numerical simulation of different types of clouds such as shallow cumulus stratocumulus different features of these clouds are simulated with a high resolution varying from few meters to several kilometers. The simulated features include micro physical processes, their dynamic behavior and parameterization. The data obtained from the model was compared with observational data. CRM found applications in understanding cloud phenomenology and for the development of algorithm for weather prediction and also they used for parameterization of large scale models. In this session, few results based on above applications are presented. With the increase in computational power largely effect growth and application of CRM models. There are some questions that also discussed in this session which

Methodology

Cloud resolving model

In order to understand cloud processes, observation data and CRM models data should be taken together. Flow into CRM models can be either incompressible or compressible. Usually incompressible flow analysis is used so that density variation can be neglected in continuity equation. However, in order to solve equations containing surface terrain data compressible analysis can be used as it does not complicate solution procedures.

Cloud processes represented by CRM models are more realistic than those represented by other models. Solar radiations coming from the sun interact with the cloud, land surface and ocean surface. These interactions are well represented by CRM models but these models require initial conditions and data for their validation. In large models CRM data can be used for parameterization. Also, cloud structure

and life cycle can also be represented by CRM models. Aerosol movement can be better studied by using CRM models and it is termed as cloud dynamics. Atmospheric layers are usually mixture and it is difficult to separate them into either completely cloudy or clear. High space resolution helps in understanding atmospheric layers by distinguishing them separately.

Micro physics in CRM models

Aerosols are used for precipitation as discussed earlier. These aerosols are converted into cloud condensation nuclei and ice nuclei. This conversion can be represented by two schemes bulk micro physics and bin micro physics. The major difference between the two schemes is on the basis of cloud particle size spectrum as shown in Figure 8. Bulk micro physics scheme also termed as two moment scheme that combines the feature of single moment scheme and variables related to number concentration of particles. Ice free clouds also known

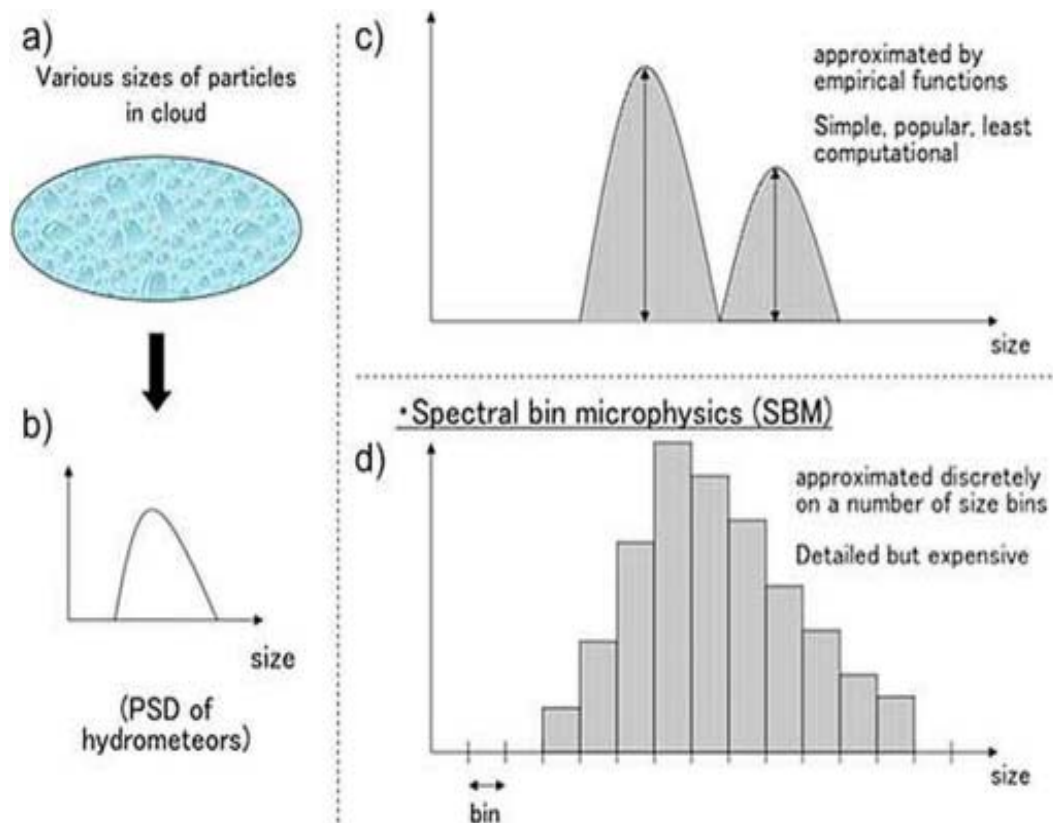


Figure 8. (a) Different size of particles in clouds, b) Representation of these particles using particle size distribution (c) and (d) shows representation of these particle size distribution using bulk microphysics scheme and bin microphysics (Tao et al. 2012)

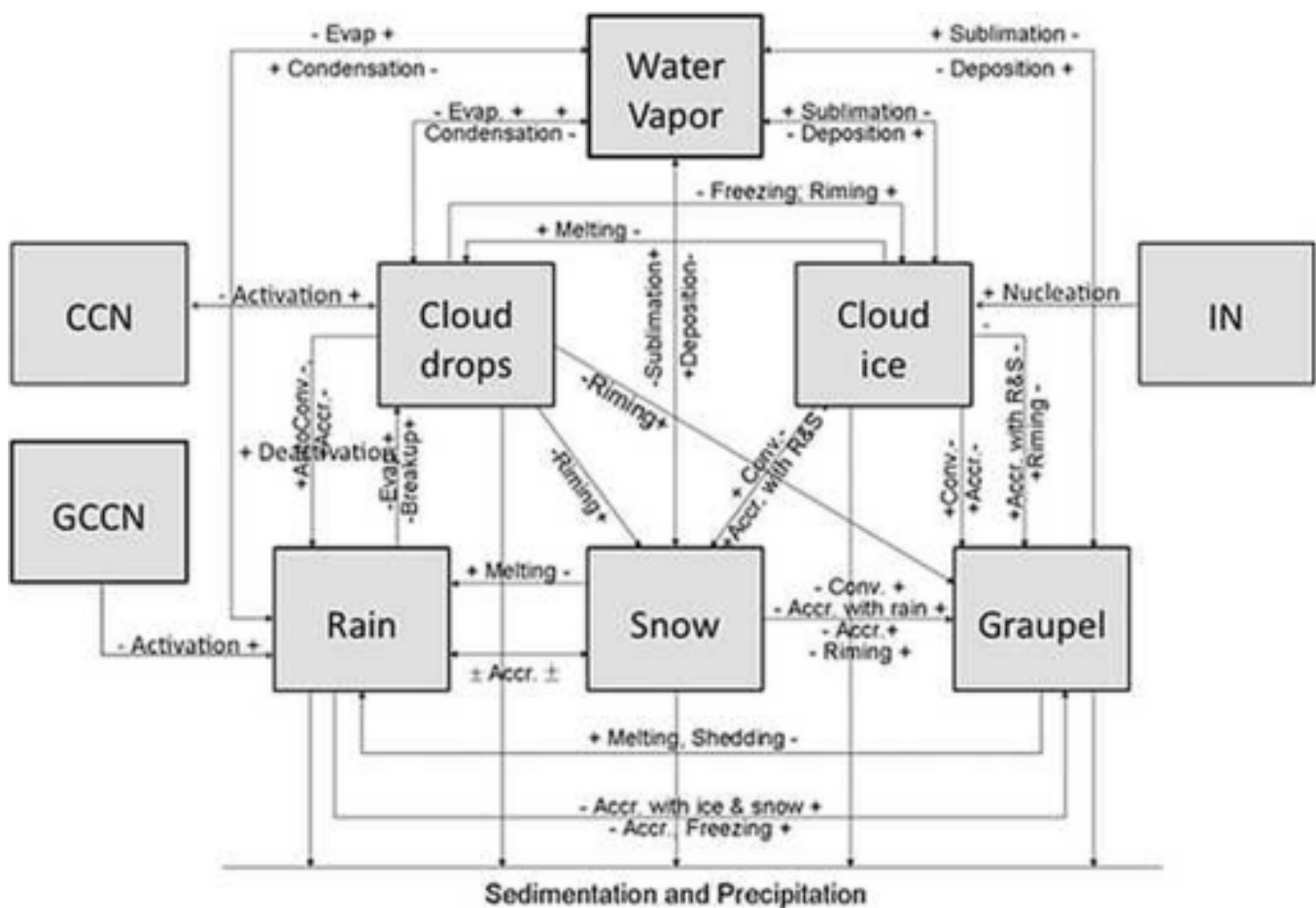


Figure 9. Different transformation takes of water, ice and liquid particles plus and minus sign shows path of transformation

as warm clouds have water particles in two forms one having small size with low velocity and other large size with high velocity. Ice containing clouds have three types of water particles with negligible velocity termed as small cloud ice, particles with low velocity that is snow and finally large graupel that have high velocity. Recent CRM models also define frozen drops or hail as fourth particle. There are many transformations occurs while water particles undergo changes among water vapour, liquid particles and ice particles.

As shown in Figure 9, ice nuclei (IN) went on nucleation to form cloud ice which on melting form cloud drops. These cloud drops aggregate to form graupel. Their size are determined by different mathematical formulations such as for cloud drop the distribution function used is Khrigian-Mazin distribution function while for snow and hail Marshall-Palmer distribution function. These

different distribution functions are used because different transformations occur between water vapour, liquid and ice particles.

The bulk microphysics scheme require less computational power but as the time progresses and computational speed increases more attention is drawn towards bin micro physics scheme for studying aerosol precipitation interaction. This scheme was used because of the involvement of ice particles for studying atmospheric layers as ice particles are more complicated because of their different shapes.

Spectral bin micro physics involves the following different processes:

§ Triggering or nucleating of cloud droplets.

§ Nucleation of ice particle by different processes such as homogeneous freezing, deposition nucleation, condensation-freezing nucleation, immersion freezing and contact freezing;

- § Ice multiplication (Hallett and Mossop 1974, Mossop and Hallett 1974);
- § Detailed melting (Khain et al. 2004);
- § Condensation or evaporation of liquid droplets (Pruppacher and Klett 1997, Khain et al. 2000);
- § Deposition or sublimation of ice particles (Pruppacher and Klett 1997, Khain et al. 2000);
- § Drop-Drop, Drop-Ice, and Ice-Ice collision/coalescence (Pruppacher and Klett 1997, Pinsky et al. 2001);
- § Turbulence effects over liquid drop collisions (Pinsky et al. 2000, 2008); and
- § Collisional breakup (Low and List 1982, Seifert et al. 2005).

Sedimentation of liquid and ice particles should also be considered, and for the ice particle, crystal shape is an important factor. Spectral bin microphysics is specially designed to take into account the effect of atmospheric aerosols on cloud development and precipitation formation by calculating the activation of aerosols explicitly according to the Köhler theory. Section 2 describes in more detail processes associated with the initialization of CCN, GCCN, and IN. A detailed comparison between spectral bin and bulk parameterization has been made by Khain et al. (2015). The following equations can be used in a Cloud Resolving Models. For example density is assumed inelastic and z is used as vertical coordinate also the variables used to define equations of momentum, heat and water conservation. The set ODE (ordinary differential equation) consists of (Guichard et al 2017):

The equation of state:

$$\frac{T}{\theta} = \left(\frac{P}{P_0}\right)^{\frac{R_d}{C_p}} \tag{6}$$

Where P = pressure (N/m²), T = temperature (°C), P₀ = reference pressure (N/m²), R_d = universal gas constant for dry air (J K⁻¹ mol⁻¹) and C_p = specific heat coefficient (J kg⁻¹ K⁻¹).

The continuity equation (mass conservation)

$$\rho_r \frac{\partial u_j}{\partial x_j} + w \frac{\partial \rho_r}{\partial z} = 0 \tag{7}$$

The dynamic equation (momentum conservation)

$$\frac{\partial \bar{u}_i}{\partial t} = -\frac{1}{\rho_r} \frac{\partial(\rho_r \bar{u}_i \bar{u}_j)}{\partial x_j} - \frac{1}{\rho_r} \frac{\partial P}{\partial x_i} + \frac{g}{\theta_r} (\theta_i - \theta_r) \delta_{i3} - \frac{1}{\rho_r} \frac{\partial(\rho_r \bar{u}'_i \bar{u}'_j)}{\partial x_j} - 2\varepsilon_{ijk} \Omega_j \bar{u}_k \tag{8}$$

The thermodynamic equation (heat conservation)

$$\frac{\partial \bar{\alpha}}{\partial t} = -\frac{1}{\rho_r} \frac{\partial(\rho_r \bar{u}_j \bar{\alpha})}{\partial x_j} - \frac{1}{\rho_r} \frac{\partial(\rho_r \bar{u}'_j \bar{\alpha}')}{\partial x_j} + Q_{rad} + Q_{mp} + \left(\frac{\partial \bar{\alpha}}{\partial t}\right)_{LS} \tag{9}$$

The prognostic equation of water vapor or hydrometer species (Conservation of water)

$$\frac{\partial \bar{r}_x}{\partial t} = -\frac{1}{\rho_r} \frac{\partial(\rho_r \bar{u}_j \bar{r}_x)}{\partial x_j} - \frac{1}{\rho_r} \frac{\partial(\rho_r \bar{u}'_j \bar{r}'_x)}{\partial x_j} + S_x + \left(\frac{\partial \bar{r}_x}{\partial t}\right)_{LS} \tag{10}$$

Here, any variable \acute{a} can be expressed as $\acute{a} = \bar{\alpha} +$ where $\bar{\alpha}$ is denoted as the mean value of \acute{a} on the grid mesh and can be sub-grid fluctuation, and $u'_j \acute{a}'$ is the turbulent flux of \acute{a} .

$\dot{\Omega}_j$ is the J_{in} component of the earth's angular velocity and g = gravitational acceleration; θ_r = reference potential temperature.

Q_{rad} = radiative heating rate and $Q_{m\ddot{o}}$ = heating rate associated with the microphysical processes such as condensation, evaporation, precipitation, freezing, while S_x = sum of the microphysical processes affecting r_x . The last term, indexed as LS, corresponds to the large-scale temperature change. The virtual potential temperature, which is used in the buoyancy term of the momentum equation is expressed as $\theta_{v,i} = \theta(1 + 0.61q_v - q_i)$

Condensation nuclei effect on cloud

In an environment with less number of cloud condensation nuclei that is clean environment less number of drops with wider spectrum are formed. On the other side in dirty environment that is presence of more number of condensation nuclei results in large number of drop formation. These drops are of smaller size and smaller drops results in narrow spectrum. Width of droplets have an impact on precipitation process. Small cloud drops results in low precipitation. A cloud with high condensation nuclei produce large number of smaller droplets.

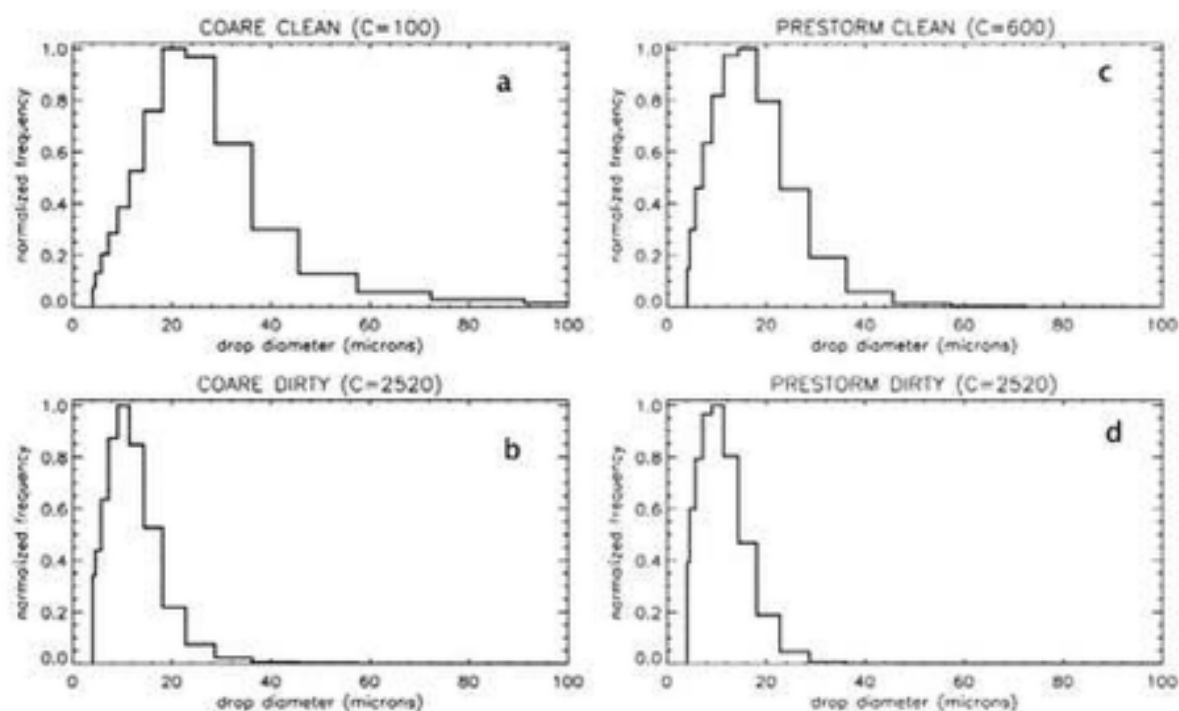


Figure 10. Simulated cloud drop size distributions for two mesoscale convective systems a) tropical oceanic squall system b) mid-latitude continental squall system (Tao et al. 2007)

These droplets are results in low precipitation, however lifetime of cloud increases. In some cases, it is also found a decrement in both cloud lifetime and precipitation with increasing aerosol concentration. Figure 10 shows that in a clean environment drops of bigger diameter are formed while in dirty environment drops of smaller diameter are only formed.

Cloud condensation nuclei effect on precipitation

In order to understand cloud condensation nuclei effect on precipitation different models are designed. These models are differentiated on the basis of configuration, size of domain, spacing provided in grid and also microphysics scheme used. Some researchers such as Phillips et al. (2002), Khain et al. (2004, 2005), Khain and Pokrovsky (2004), and Teller and Levin (2006) found that there is a decrease in precipitation with increasing CCN while few observations made by Wang (2005), Khain et al. (2005), Lee et al. (2009a), and Fan et al. (2007) found increase in precipitation with CCN. Hence, on the basis of above observation it can be concluded that high CCN can increase or decrease precipitation for cumulative clouds. In a simulation study, it was

found that during the initial stage of cloud formation cloud drop size is an important factor as the clouds with large drop size results in high precipitation. However, high condensation nuclei leading to small droplet formation results in both high low and no effect on precipitation on the basis of location. Hence, complete life cycle of cloud formation need to be simulated for understanding cloud precipitation interaction.

Figure 11 shows that if relative humidity is large then condensation, gain is large and condensation loss is less which results in large precipitation. Seifert and Beheng (2006), Khain et al. (2008), and van den Heever et al. (2011) also observed that effect of aerosol on precipitation and cloud depends upon the type of cloud. Cloud types such as cumulus clouds, cloud forming in dry environment with low relative humidity and in the presence of strong wind shear there occurs low precipitation when concentration of cloud condensation nuclei increases. Shallow clouds also show the previous results and deep convective clouds shows mixed results with increasing CCN concentration. However, in wet environment, high CCN concentration results in high precipitation. These studied are verified using CRM

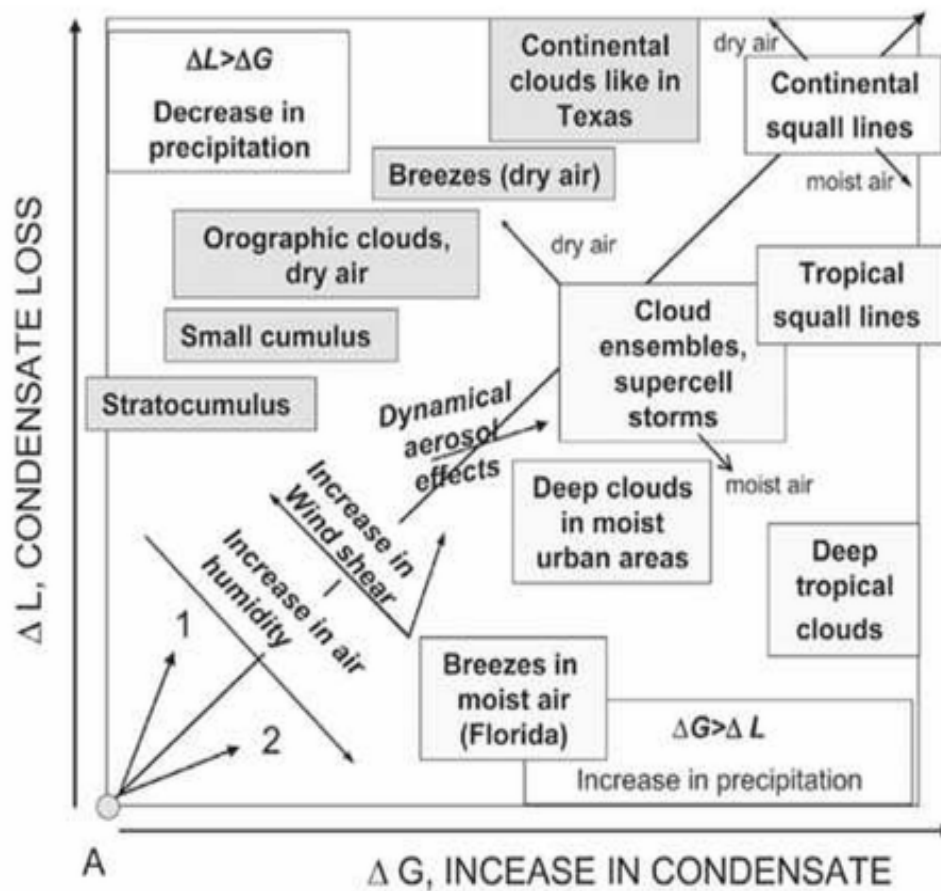


Figure 11. Effect of cloud type and precipitation (Khain et al. 2008)

models and large eddy simulations.

Results obtained from CRM models and observations are in good comparison with clouds having less CCN concentration at lower level of cloud, however at upper levels due to mixed phase formation results may vary. This variation shows the lack of understanding of different ice phase mechanisms.

Physical Processes behind CCN Effect of Precipitation

High CCN particles results in large number of small drop formation. These small droplets are not effective in precipitation as they form narrow droplet spectrum and results in suppression of warm rain process. However, in some cases while studying isolated convective systems opposite effects are also observed. High CCN particles result in increase or decrease of precipitation and it can be explained by three different mechanism: (a) high CCN particles results in frozen particles at the upper level of cloud

and it is called latent heat dynamic effect. Due to this effect an increase in precipitation has been observed in deep convective cloud system. (b) High precipitation due to high CCN is related to evaporative cooling. Evaporative cooling generates a pool of cool air that interacts with wind and high convection results which ultimately leads to heavy precipitation and it is called cool pool effect. Figure 12 shows cool pool effect for oceanic convective case (c) Impact of CCN particles on cloud microphysics. High CCN particles results in small droplet formation in large numbers. These small droplets results in cold rain formation hence large rain production is observed in tropical deep convective region due to more cloud condensation nuclei in the form of ice particles. High CCN effect is different for surface precipitation as observed by Cheng et al (2010). In case of surface precipitation low CCN results in suppression of warm rain processes and enhancement of rimming operation while high CCN results in decrease in snow rimming resulting in suppressed

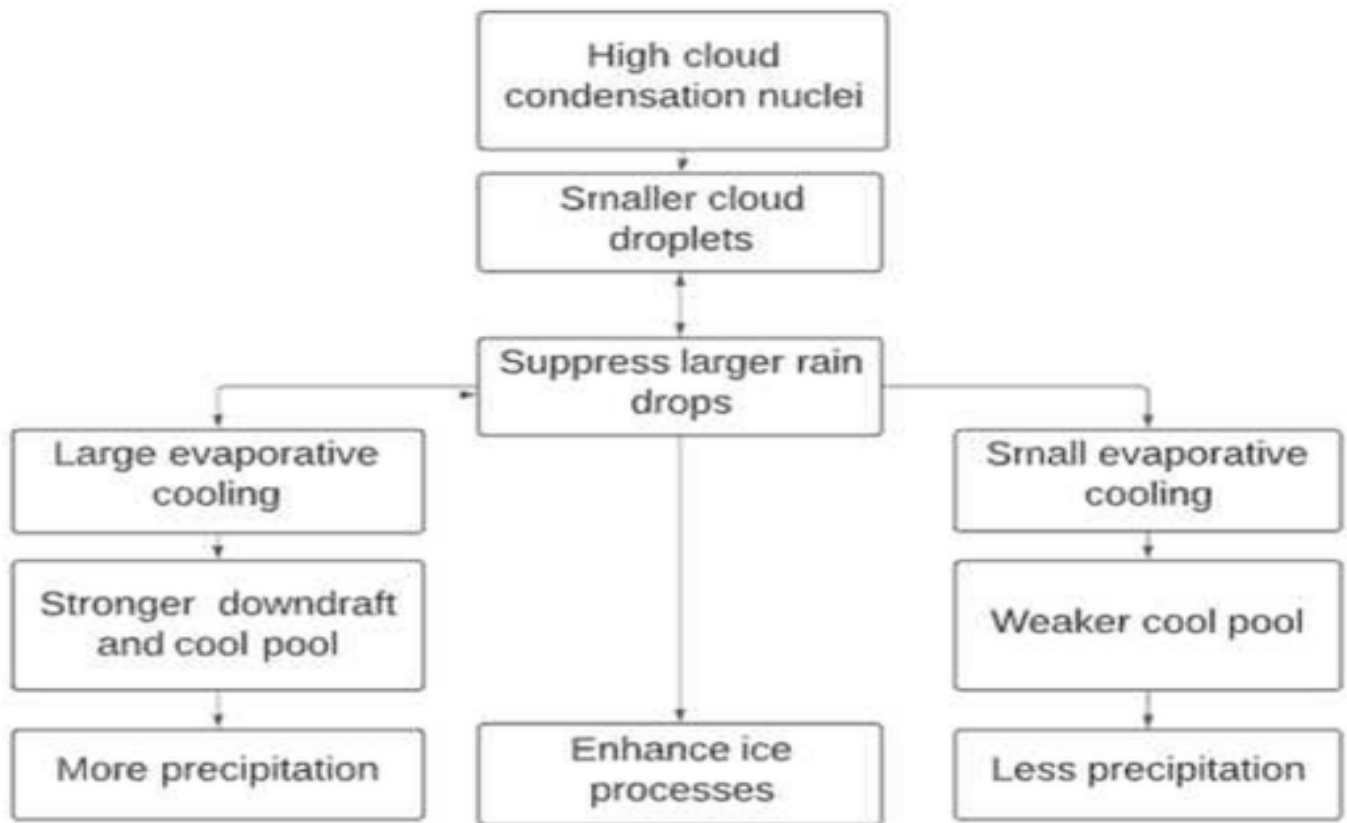


Figure 12. Effect of CCN particles over wet and dry environment (Adapted from Tao et al. 2007)

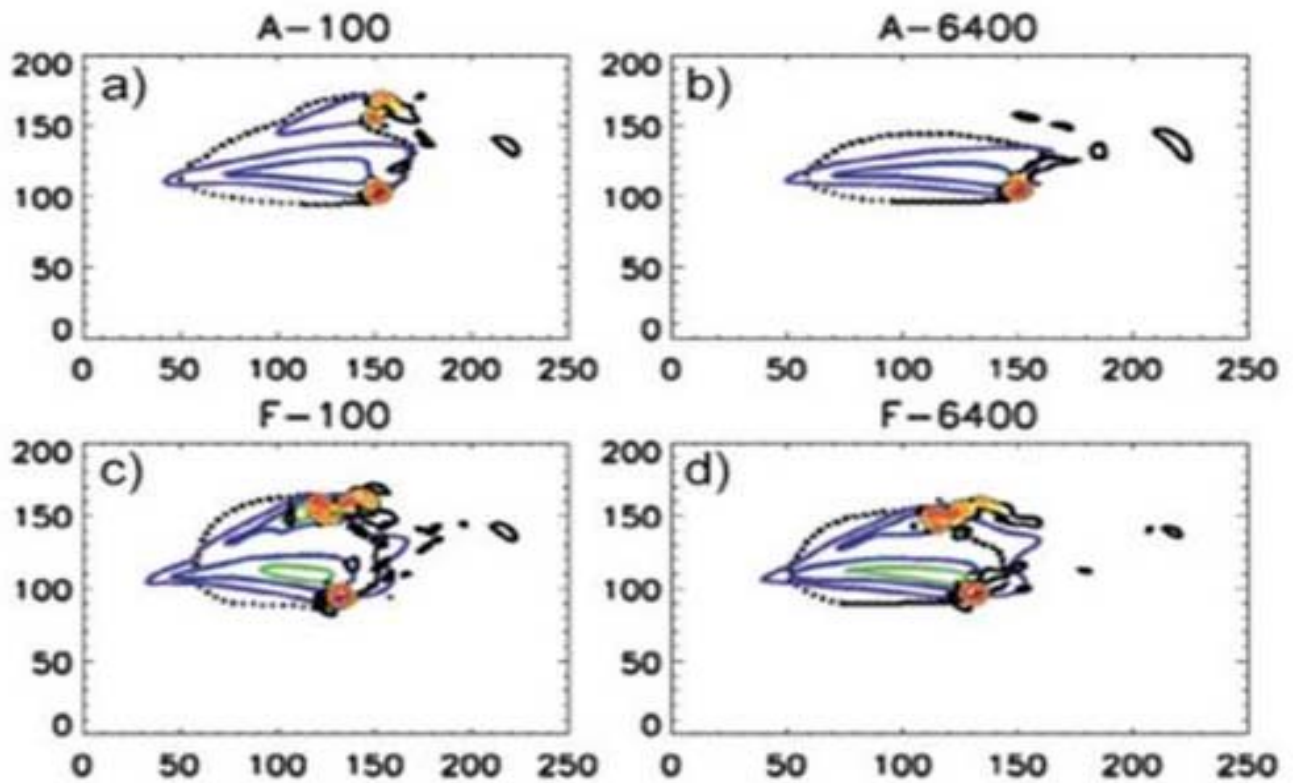


Figure 13. Variation of aerosol density and convective available potential energies (Storer et al. 2010)

surface rainfall.

The above three mechanism are interrelated and difficult to get separated. For example, high CCN particles results in large number of small drop formation these small droplets converted into ice particles due to latent heat release effect. These ice particles generate high evaporative cooling when cooled due to cool pool effect. This high cooling generates more ice nucleation formation.

Convective precipitation influenced by CCN particles analysis by regional scale models

Different regional scale models are used to study the influence of aerosol particles on convective precipitation over different regions of world. Apart from precipitation other climatic conditions are also studied such as cyclones, super cells, tornadoes by many researchers. The advantage of regional scale models are more realistic surface terrain and land surface presentation. The results of regional scale models are similar to CRM models and states that precipitation can be enhanced or suppressed due to increase in aerosol concentration.

The study of tornadoes and super cell formation shows that an environment with large number of particles result in better formation of supercell then an environment with low CCN concentration particles. Further, results also show suppression of precipitation due to large number of CCN particles and also the life of supercell increases. Some researchers also studied that the supercell structure using RAMS model. The purpose of their study was to understand the effect of aerosol concentration and convective available potential energy (CAPE) over the supercell. The four cases analyzed (Fig. 13) such as: Yellow orange and red shows vertical velocity (5, 10 and 20 m/s, respectively). This vertical velocity is completely diminished in high aerosol concentration case. Purple, green cool and blue shows precipitation (1, 10 and 20 mm, respectively). The dotted line shows cool pool region; low aerosol concentration and low CAPE, high aerosol concentration and low CAPE, low aerosol concentration and high CAPE, high aerosol concentration and high CAPE. High aerosol concentration results in low precipitation. Cloud water path, rain drop diameter is effected more by aerosol concentration then by CAPE, however ice

water path is equally sensitive to both CAPE and aerosol concentration.

The study of storms and cyclone was also performed using regional scale models. The presence of aerosols can effect tropical cyclone intensity. High CCN concentration liquid particles results in ice particle formation these ice particle on conversion to water results in latent heat release and leads to weakening of tropical cyclone. These ice particles also results in formation of ice pool and evaporative cooling. The weakening of cyclone intensity can be explained by three processes: due to high aerosol concentration there is increase in updraft velocity that results in flow of mass in vertical direction and less penetration to the core of cyclone. Also excessive heating at the surface of cyclone leads to decrease and results in negative pressure gradient in horizontal direction. There is also competition between two convection zones.

The structure of hurricanes are also studied using Regional scale models. The hurricane Katrina which was a large category 5 Atlantic hurricane that caused over 1800 deaths in august 2005 obtained particularly in the city of New Orleans, Gulf of Mexico was studied. This study was performed using spectral bin microphysics scheme. Later on bulk micro physics scheme was used to study the effect of aerosol concentration over precipitation on cumulus cloud. The precipitation increases with aerosol particles but this increase in precipitation suddenly decreased when concentration of aerosol particles increased to a significant amount. Large aerosol concentration results in suppression of warm rain process but enhancement of mixed phase regions. At very high aerosol concentration precipitation decreases as large number of small droplets forms and these small droplets are not able to convert into ice particles. Hence, less release of latent heat and less evaporative cooling. Bulk micro physics scheme can also be used for the study of thunderstorms.

Ice nuclei effect on precipitation process

Ice formation in clouds is not studied very well because large number of aerosol particles which are transported to the middle and upper layer of troposphere. It also serve as ice nuclei which make it is difficult to separate ice nuclei particles and aerosol particles present in upper layer. Hence, ice

nuclei effect on precipitation is not well understood.

High concentration of ice nuclei particles results in enhanced surface precipitation while high concentration of CCN (Cloud Condensation Nuclei) particles results in suppression of precipitation as high number of Ice nuclei particles produce cool pool effect. While large CCN particles produce large number of small droplets that results in narrow drop spectrum and hence rainfall suppression. Also, high CCN concentration produce large number of droplets these droplets can be converted into ice nuclei and hence ice mixing ratio increases. On the other hand, Giant CCN particles results in enhanced surface precipitation.

Ekman et al. (2007) studied heterogeneous nucleation and found that with high Ice nuclei concentration results in enhanced up draught due to large release of latent heat. This high ice nuclei concentration results in high anvil coverage and hence large precipitation. The findings of Ekman et al. (2007) suggest a link between high IN (Ice Nuclei) concentration and stronger updraft strength. Fan et al. [2010] uses different parameterization schemes for studying homogeneous and heterogeneous nucleation and observed that large nucleation rate results in strong convection, large anvil lifetime and large anvil coverage.

Aerosol precipitation relationship using large scale modelling

Aerosols effect precipitation globally by following microphysical and dynamical path. The microphysical path causes change in precipitation which is mainly fixed in aerosol laden regions while dynamical path changes precipitation in remote areas of these regions. The microphysical path consist of micro physical processes and dynamic feed backs which are started by the conversion of aerosol into Cloud Condensation Nuclei or Ice Nuclei. The final conversion of aerosol into CCN or IN is termed as indirect radiative forcing as microphysical path follows indirect aerosol forcing, dynamical path take place through both by aerosol direct or indirect forcing. During the aerosol scattering and absorption of solar radiation it is known as Aerosol Direct forcing while when the aerosols bring change in cloud formation processes by altering drop size it is

termed as aerosol indirect forcing. Aerosol also causes decrease in precipitation efficiency due to indirect forcing.

In order to numerically simulate the effect of aerosols over precipitation, feedback of dynamical processes to aerosol forcing must be required. Aerosol distribution in clouds can be derived by atmospheric transport model or chemical transport model. Chemical transport models are a kind of numerical models used for simulating atmospheric chemistry and also for estimating pollution levels. However, the above methods do not provide necessary feedback hence not discussed in detail. Recent development in computational technology helps cloud resolving models to simulate effectively over a continent level scale. This section mainly focuses over global climatic models.

Methodology

Precipitation involves a large number of complicated processes that involve feedback from aerosol chemistry and physical behavior, also cloud microphysics and cloud dynamics are to be considered at large scale. The data obtained from the feedback forms the bottom of the research and also act as the largest sink of ambient aerosols. Above processes take place at a small scale so in order to study effects of aerosols over precipitation at a global scale, it requires a reasonable representation of above processes. To understand climatic response obtained by aerosol forcing, it need a good linkage between aerosol model having detailed aerosol processes on one hand and an effective computational speed at a low computational cost. Currently, many research activities performed with models having fixed aerosol profiles.

Atmospheric aerosols can be distinguished on the basis of different characteristics such as size distribution of particles, complex mixing state and composition of chemical species. The optical and microphysical properties of aerosol can be determined, if the chemical composition of the aerosol particle is known. In earlier climatic models, aerosol's mass mixing ratio could be detected. On the basis of detected mass mixing ratio, size of aerosols along with radiative properties can be determined. Field experiments performed recently

shows the coexistence of both internal and external mixing in atmospheric aerosols and it is found that internal mixtures are not always dominant. Field experiments shows that internal mixtures consist of absorbing core which is coated by a scattering material and that material is responsible for enhancing the bulk absorption as compared to external mixtures. The observations of above experiments are different from well mixed condition of organic carbon and sulfate mixtures.

Currently, all the present models comprise only internal or external mixtures. Efforts are being made currently to refine the resolution of aerosols in Global cloud models Figure 14. In a coarsely defined grids, computational cost was very high as absorbed when some aerosol models with coarse grid structure are used for mass concentration of aerosols. In order to solve above problem, multi moment approach have been adopted. This approach can be used for predicting aerosol properties including number, mass

and size variation. In comparison to previously used single moment scheme current approach, if designed properly helps in improving the presentation of aerosol size while remaining computationally effective and able to perform longer simulations.

Aerosols impact on precipitation through microphysical processes

Aerosols effects cloud micro physics and this effect can be implemented in a highly parameterized fashion for global cloud models because of their coarse space resolution. Such parameterization can be done in two steps. Firstly activation of cloud droplets, Secondly conversion of small cloud droplets to precipitation agents that is rain or snow. Second conversion involves a set of micro physical processes that involve a random collection of tiny cloud drops under the influence of updrafts or downdrafts and mixing at a small grid scale.

Most of the global aerosol cloud modelling that

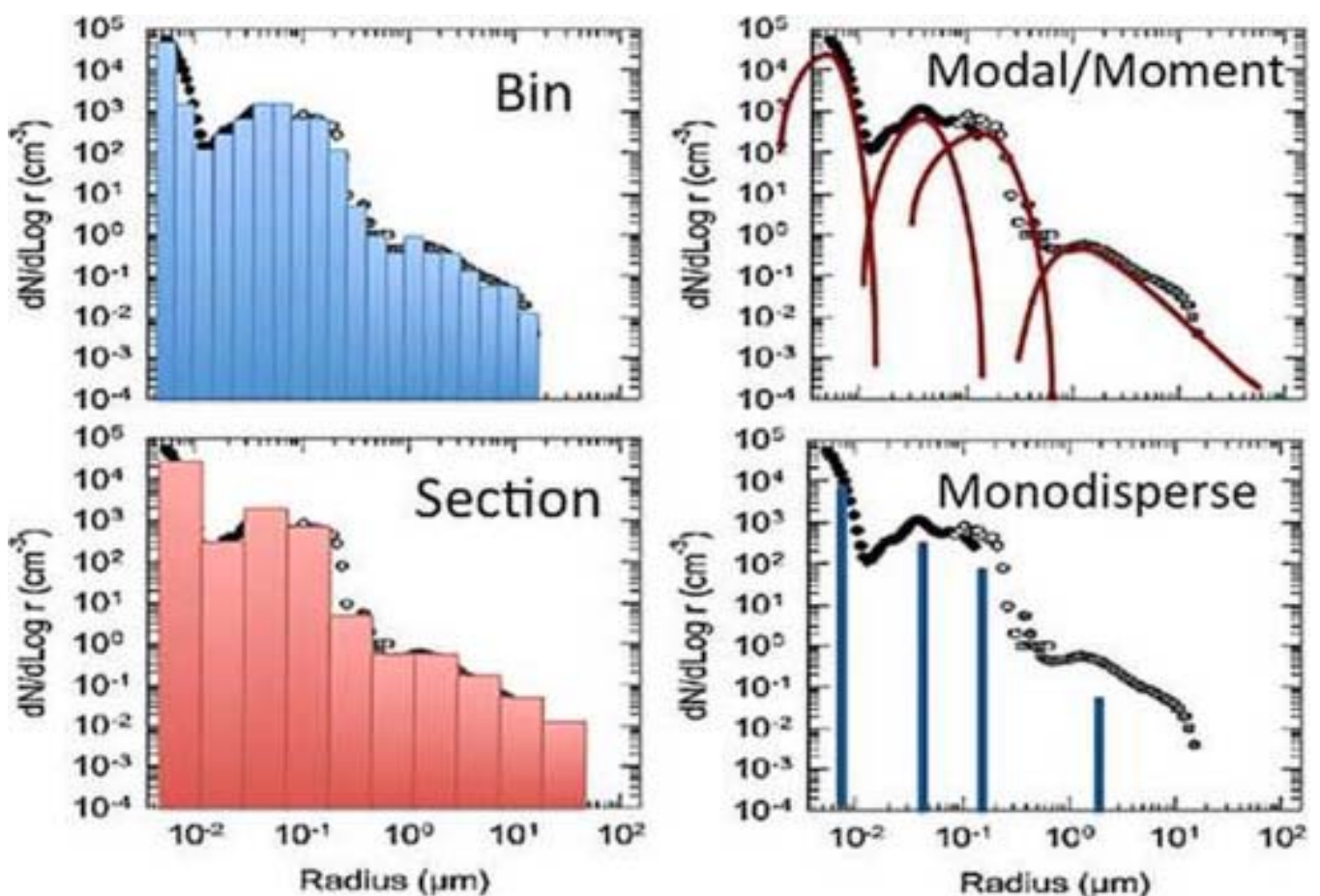


Figure 14. Aerosol size distributions in global models (O'Dowd et al. 2001)

deals with studying microphysical impact usually focused on deriving indirect forcing of aerosols rather than precipitation effect. Aerosols have a direct forcing as they scatter and absorb atmospheric solar and infrared radiations. Simultaneously they also change warm, ice and mixed phase cloud generation process by increasing concentration of droplets and ice particles. They can also decrease precipitation efficiency and hence causes an indirect forcing. The task of aerosol forcing can be performed by an empirical method in which aerosol mass are connected with CDNC, auto conversion rate and precipitation efficiency that simulate various aerosols impact. Aerosol Cloud Droplet Number Concentration (CDNC) relationship provide a close relationship between qualitative data and satellite data. However, the results came after modelling that deals with aerosol albedo effect, cloud optical response differ from satellite based results. The models also fails to show satisfactory outcomes while dealing with sophisticated tasks such as calculating cloud height, lifetime and radiation involving dynamical feedback. Indirect forcing of aerosols and its effect and responses are still not able to be identified clearly and seems to be biggest uncertainties in climatic modelling.

In order to simulate activation of liquid or ice particles, different parameterization based on cloud physics have been developed for global cloud models. Researchers also put efforts to incorporate more descriptions based on cloud physics and the study is not kept limited to aerosol activation to rain drop generation only. For instance incorporated parameterization of micro physics processes into Community Climate Model version 3 (CCM3) of the National Center of Atmospheric Research (NCAR) that include automatic conversion of cloud water into rain and ice to snow. With the help of above implementation, it is possible to simulate certain effects of aerosols on cloud drop size cloud drop concentration and on precipitation and its quantity. Recently a two moment microphysical scheme has been developed for global climate model. This two point scheme is based on simultaneous prediction of both mass and number concentration of a condensation nuclei. The two point moment scheme has just introduced for convective clouds Ming et al. (2007). The common example of double moment

scheme are WDM6 scheme and the Thompson scheme. The double moment scheme prove to be beneficial for estimating aerosol effect as the scheme is more physics based and involves more parameters for evaluation of precipitation in comparison to earlier schemes, where only mass mixing ratios were predicted. Simultaneously, a subgrade scale variability has also been incorporated into two moment scheme which helps in improving the microphysical features of clouds. In the above scheme, cloud drops are represented by a Probability Density Function which is obtained from observations and then it is extended to microphysical conversions.

Theoretical studies show that data generated by models based on two moment scheme shows closer resemblance with the observational data. On the other hand during representation of the process that involves collection of small droplets and formation of a raindrop through two moment scheme parameterization of auto conversion and gradual growth of aerosols particles must be included. Hence parameterization always remains an important for simulating the impact of aerosol over precipitation. If raindrops are allowed to form directly by incorporating giant cloud condensation nuclei, it has been observed in a recent study that faster rainfall and low atmospheric water content be present although the total precipitation remains unaffected Figure 15. Previous efforts to incorporate two moment scheme into parameterization of global cloud models have shown the impact of aerosols over modeled precipitation. Incorporation improves the geographical distribution of change in precipitation from past to current climate as compared to observational data. Results obtained by using parameterization and two moment scheme shows a suppression of precipitation as the concentration of aerosols increases in convective clouds. Convective clouds are the clouds formed by warming the air. Even though wide advancement in understanding physics of aerosol and two moment scheme into global cloud model, verification of precipitation due to aerosol microphysics is still a challenging task. This is due to introduction of several new parameters due to advancement of schemes which add difficulty in estimating whether cloud aerosol micro physics can explain variability in precipitation.

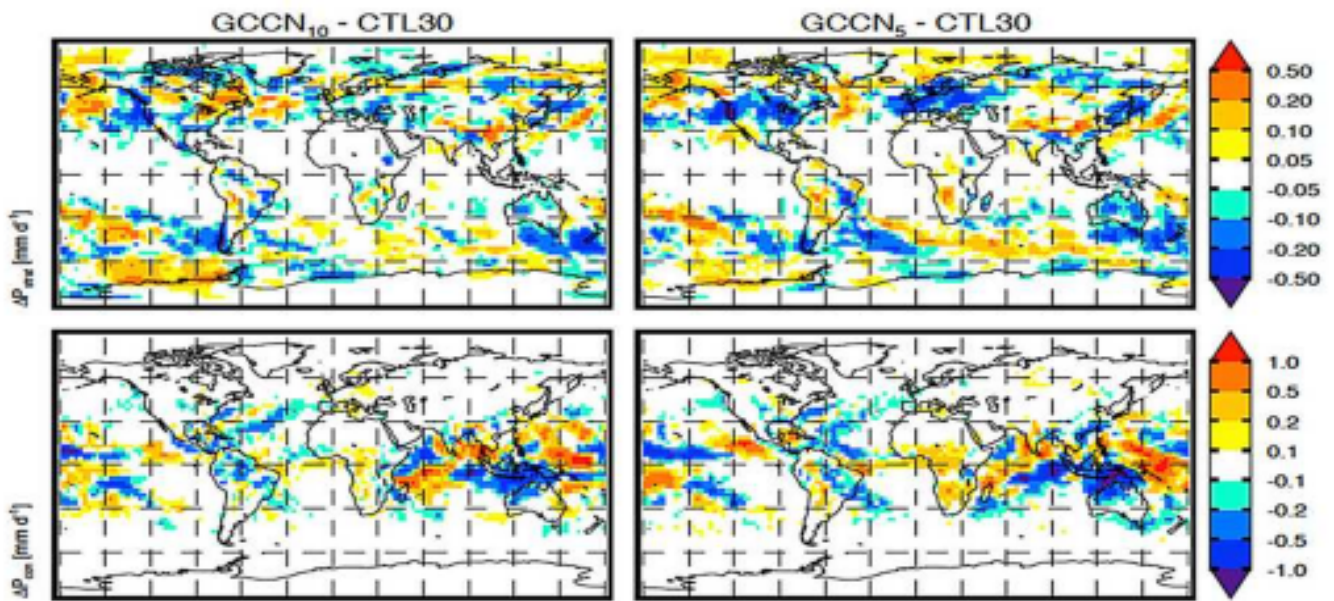


Figure 15. Large Giant condensation nuclei results in faster water cycle (Posselt and Lohmann 2008)

Impact of aerosols on precipitation through coupling with large-scale dynamics

The direct radiative forcing (DRF) of aerosol helps in scattering and absorption of radiation or absorption and emission of long wave radiation. Large particles are responsible for emission of long wave radiation. Aerosols also exerts a cooling effect (negative forcing) on earth surface by scattering and absorption solar radiation and also warming effect (positive forcing) to atmosphere. Aerosols particles have a short life so they only concentrate over generating regions and so applies a constant forcing in these areas. This constant forcing can change atmospheric thermodynamics and cloud dynamics and also affect precipitation producing cloud systems in areas which are away from aerosol laden regions. Let's take an example of shifting of precipitation in ITCZ over Pacific Ocean reported by different global climatic models results due to absorption of black carbon. Current research focused on understanding the impact of aerosols on precipitation obtained by coupling with large scale dynamics and optical properties of aerosols. This coupling is important and can also be related to the aerosol forcing strength.

A large number of studies related to impact of aerosols on monsoon and correlation between precipitation and circulation changes with increasing

aerosols have rapidly grown. These studies are conducted using three dimensional global cloud models which include a prescribed aerosols profile. Simulations allow comparisons to be made for different aerosols forcing assumptions such as direct forcing or indirect forcing. Aerosol forcing has two major component direct and indirect forcing. Direct forcing is related to aerosol influence on planet radiation balance by scattering solar radiations this results in cooling of earth surface. The indirect forcing is related to interaction of aerosol with surrounding clouds. Aerosols effect can be isolated due to the assumption that the effect are not amplifying by using different aerosol profiles.

Aerosols absorbing capacity and its impact on summer monsoon has been extensively studied. Looking at overall analysis, it can be said that aerosol causes decrease in rainfall during summer season and a rainfall enhancement during pre-monsoon and post monsoon seasons. Later studies also suggested an increase in rainfall in certain regions, these studies also conclude that black carbon radiative forcing also disturb the Indian monsoon and change the precipitation pattern and quantity in a noteworthy manner.

Different methods for direct forcing of aerosols for modifying monsoon circulation and rainfall has been suggested in model studies. Absorbing aerosols

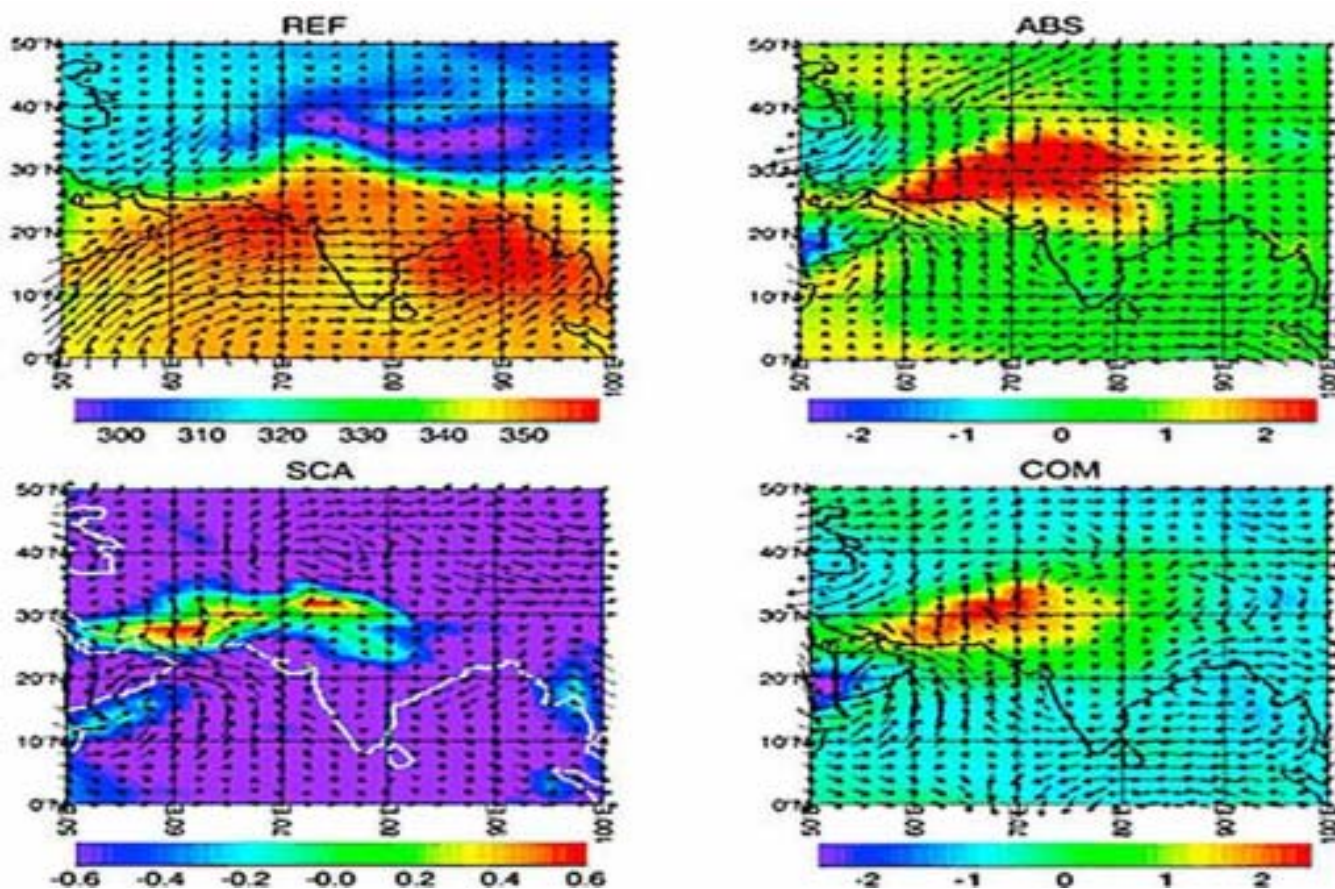


Figure 16. Moist static energy (MSE) observations for reference run (REF) and for only absorbing aerosol (ABS) and only scattering aerosols (SCA) and combined scattering and absorbing aerosol (COM) (Wang et al. 2009b)

in presence with scattering aerosol can change the gradient of moist static energy and thus affect atmosphere stability (Fig.16). Moist static energy is a thermodynamic variable obtained by lifting air to top of atmosphere and then allow all the water vapour present in air to condense and latent heat to be released.

This results in a northward extension of monsoon circulation and convective precipitation which is in close agreement with observed monsoon results during recent decades Figure 17. The absorbing aerosol pattern in COM and ABS shows a northward shifts which is similar to that obtained in CRU data.

Lao and kim (2006) observed that heating of aerosols over Tibet plateau cause the water from oceans and they condensate that further heat the air and is called as elevated heat pump effect (Fig. 18). Ramanathan (2005) suggested that aerosol absorption can also causes a decrease in surface

evaporation and a temperature gradient in sea surface that in turn can effect monsoon circulation and rainfall strength.

Impact of aerosols over East Asian monsoon was studied. In winter monsoon circulation that bring cold air from northwest to southeast China was weekend significantly due to which there is a large increase in humidity and fog also there has been a decrease in wind speed. These results are in accordance with those obtained CAM3 by including and removing radiation effect of aerosols. This provide evidence that aerosols play an important role in development of winter monsoon because they can decrease the surface radiation and also reduce temperature difference between high and low latitude and ocean and land surfaces.

West African monsoon has also been studied in order to understand impact of aerosol. Huang et al. (2009) compared observational results and global

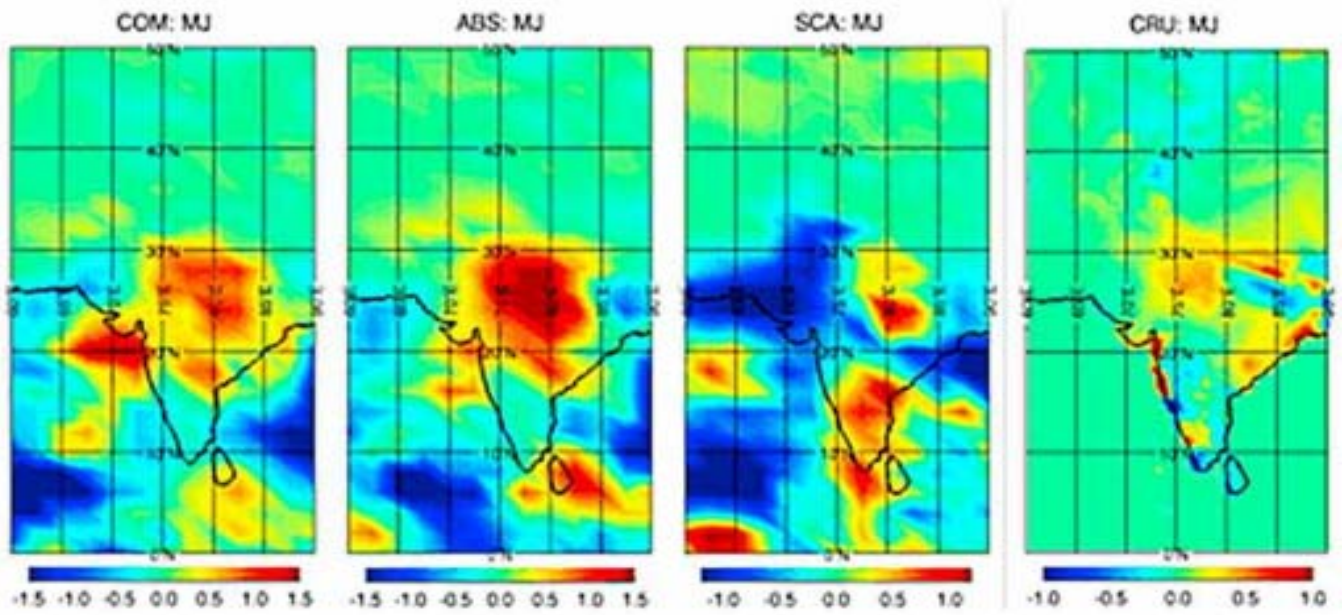


Figure 17. Changes in the convective precipitation COM (absorbing and scattering aerosols), ABS (absorbing aerosols), SCA (scattering aerosols) CRU (climate research unit).

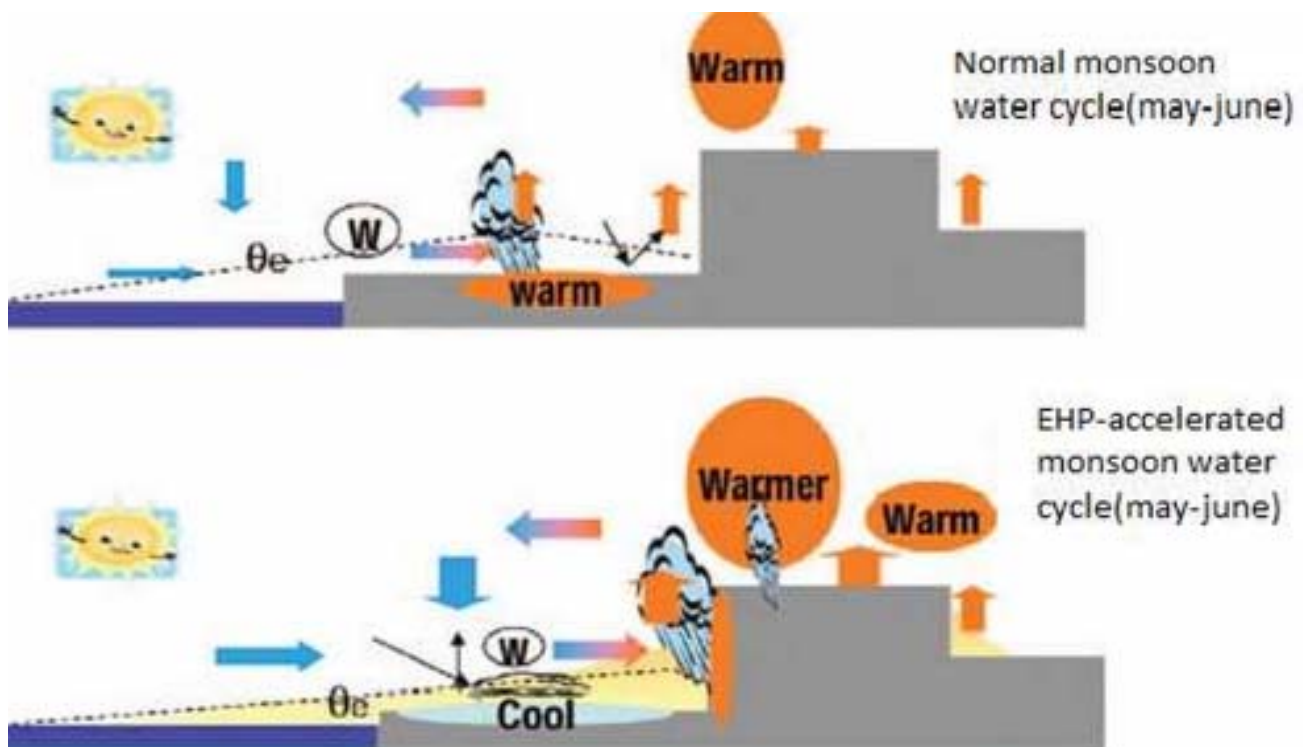


Figure 18. Monsoon water cycle with no aerosol forcing (top) and aerosol induced “elevated heat pump” (bottom) where W denotes Westerlies wind (Lau et al. 2008)

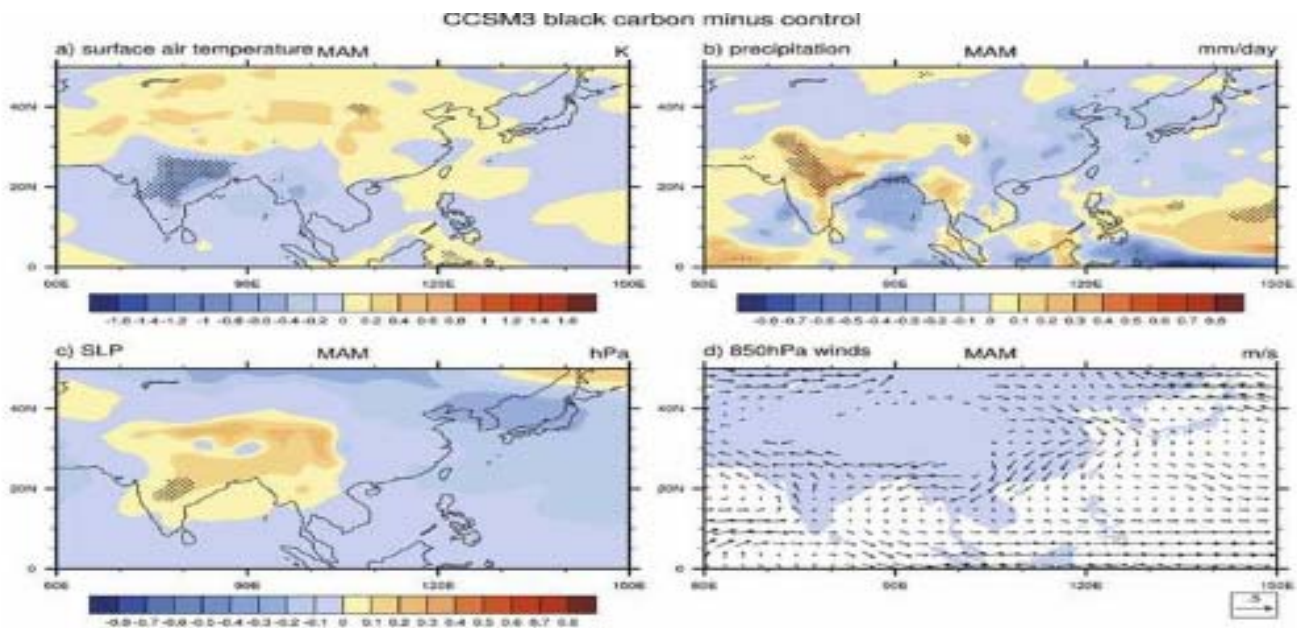


Figure 19 Impact of black carbon on (a) surface air temperature, (b) precipitation, (c) SLP, (d) 850 hPa winds (Meehl et al. 2008)

cloud model with direct forcing of black carbon aerosol. It has been found that high aerosol loading leads to reduction in cloud amount, height gained by cloud and surface precipitation. This reduction in west African monsoon is due to radiative effect of absorbed black carbon (Fig. 19). A study by Lau et al. (2009) found that EHP effect due to dust and black carbon obtained from biomass burning can impact climate and hydro logical cycle of north Atlantic region. During summer absorption of aerosols triggered the atmospheric feedback which results in rising of dust layer which warms the air over west Africa and air rises which results in enhancement of rainfall over western African and suppression over Western Atlantic and Caribbean region.

The level of aerosol generated by human means are lower in southern hemisphere than in northern hemisphere. Australian monsoon system has been less affected by aerosol impact. However, it has been observed that northern hemisphere precipitation can influence southern monsoon system as monsoon system are closely associated with circulation and aerosol may affect it. Rotstayn et al. (2007) observed that Asian aerosol can lead to increase in rainfall in northern western hemisphere of Australia. The above result is in coincidence with data obtained in region since 1950s. This could be due to alteration of

temperature gradient by Asian aerosols. However, the result was not verified by 24 models which participated in coupled model inter comparison project phase 3 (CMIP3) even though indirect or direct aerosol forcing has been performed but it does not produce the hypothesized results.

Scope for future research: Aerosol-precipitation interactions

In previous sections, the effect of an aerosols-precipitation interaction are explained using numerical models, micro physical processes and observational data. The differences between results obtained from the simulated models and observational results are also described. Understanding these differences is an important step in order to further explore the effect of aerosol between over cloud micro physics and dynamics. From the studies described under Section 3 to 6, about physical processes, observational data and numerical models it is clear that keeping away aerosols impact on precipitation from all other factors is a challenging task. Aerosols effect precipitation by transforming into Cloud Condensation Nuclei, Giant Cloud Condensation Nuclei and Ice Nuclei. This effect of aerosol over precipitation if studied at

large scale is incomplete if micro physics (cloud, aerosol, precipitation), dynamics of cloud (life cycle of cloud) and also impact of other environment factors such as water cycle, radiative effects is not considered.

No doubt research is being done in understanding cloud micro physics and the potential of CCN, GCCN and IN to influence precipitation on small scale as well as large scale. Numerical simulations helped in understanding the physics behind the aerosol and precipitation. However, there are a large number of aerosol effect on precipitation that still need to be identified and studied. Combination of observations and simulations provide us a deep knowledge of how clouds are responding to aerosol and the feedback enhances the understanding of precipitation. The below paragraph explains the other challenges and current issues related to aerosol-precipitation interaction processes.

Microphysics

The condensation nuclei transforms into cloud droplets and Ice Nuclei convert into cloud ice. These transformations show the basic impact of aerosols on precipitation. Condensation Nuclei transforming into cloud droplets can be explained by Kohler curves by having an assumption regarding the values of chemical and size coefficient. But above study is only suitable for case analysis and cannot be considered for simulations having longer durations above few days. For such an elaborate study CRM models should be linked with detailed model of aerosols containing information related to particle size, chemical composition and the state of mixing. While combining the CRM models and aerosols models care must be taken so that simultaneous simulations can be done considering the aerosols scavenging and aerosol recycling and also aerosol chemistry.

Ice Nucleation is less studied than Condensation nucleation because of not clear definition of properties of ice nuclei such as their concentration, variation and ice nucleating capacity. Clouds micro physics is sensitive towards aerosols effects and this area is still less explored. Large number of water schemes only give a brief about collision efficiency between cloud droplets and particle of precipitation so the impact of aerosols on size of cloud drop and their process of growth is still unresolved.

Cloud-scale modelling

Previous cloud simulations in cloud resolving models conditions considered are ideal and the space distribution of CCN particles is uniform horizontally. In order to understand aerosols precipitation regionally, non-homogeneous CCN distribution is considered with non-homogeneous environmental conditions. Aerosols chemical composition need to be considered along with Ice nuclei and Giant cloud condensation nuclei as aerosol chemistry can also change precipitation over a region.

No Cloud resolving model studies compare simulation result with observed cloud characteristics such as cloud height, radar reflection, rainfall, cloud dynamics and micro physics as it requires more data to be gathered. Also no doubt that CRM models provide important results of indirect impact of aerosols over precipitation. However, results are limited for short time period and they also consider smaller domain for smaller time period. Such smaller domain cannot resolve whole cloud. Efforts need to be made to establish a close link between global communities so that CRM results can be extended to a regional and global level.

Large scale modelling

Research on climate and prediction of precipitation is heavily influenced by aerosols. Aerosols cloud interaction should be improved in order to understand impact globally. Aerosols model should be designed in a way that they provide high resolution data which helps in better process representation and helps in advancing model. Presently available models are not satisfying this need. Study should also be performed to develop conditions required by high resolution global environmental models.

As the current growth in computational availability, climatic models are developing rapidly. To better represent the consequences of aerosols on clouds and precipitation, size-dependent cloud microphysics schemes along with size- and mixing-dependent aerosol schemes should be adopted in additional models and utilized in long-term climatic linked projects. Parameterization of atmospheric convection has remained a global issue since early days. As it is not possible to resolve large kilometer resolution for global models convection processes

and aerosols precipitation interaction processes are developed using parameters that are resolved at small grid scale. Still the methods adopted today are computationally expensive but it is expected that soon they are explored and it is possible to do long term integrations in a computationally less expensive way as compared earlier. Parameterization of cloud has been replaced by multi-scale modeling framework using a CRM in each column. The multi-scale modelling framework can be used for simulating deep convection clouds, interaction between cloud and radiation, overlap between clouds and also surface hydrology at CRM resolution. The MMF can act as an extended version of present cloud resolving modelling methods. It can also act as a bridge between old CRM models and non-hydrostatic an elastic models. One other less computationally expensive way is using a MMF approach for linking large scale aerosol climate model with a cloud resolving model and obtaining an interaction among aerosols, clouds and precipitation.

Some non-linear aerosol chemical and physical processes occurs on very small scale and should be treated carefully in CRM models. Few air quality models are developed recently for processing aerosol at different environmental conditions which results in much advanced and numerically effective representation of aerosol non-linear processes.

Even the large progress has been made in model development and new computational techniques have been found still there are uncertainties in modelling aerosol precipitation process. Hence, identifying and reducing those uncertainties has been a challenging task. Inverse modelling skills have been used to optimize aerosols emissions but the above development has been at an early stage. As an alternate solution reduced format model has also been derived using a less number of simulation. The reduced format model minimizes computational time, hence, it can be used to replicate the effects of large scale aerosol climate interaction.

The effects of aerosol on precipitation at large scale for fixed weather regions are studied by linking long term quality measurements and CRM models. Aerosols have a large number of effects over precipitation but examining all the effects is a difficult task. In order to examine all the effects a

global modelling framework approach must be needed. One such approach is detection and attribution technique but that is still in early stage and mainly considers aerosol temperature changes.

Observations

Observations are used to provide initial stage and data used for validation of models. The present cloud models can be used for simulating life cycle of cloud involving different steps such as cloud micro physics, dynamic and chemical evolution. They can be used to evaluate the interaction among clouds, aerosols and precipitation. Due to large number of scales present in modern cloud modelling, remote sensing from space has been proved as a necessary part of model validation.

From the last twenty years improved data has been obtained due to satellite retrievals and rain gauge measurement along with surface precipitation data but the collected data is still fall short. Efforts must be made in order to allocate the signal to understand the micro physics of aerosols.

Climatological effects of aerosols on precipitation is now possible because a large series of data has been assailable from satellite sensors and also advanced ground based observations. If reproduction of results can be done by numerical models it can be proved to be solid evidence of net ACPI effect that is currently not possible but of extremely climatic significant.

Understanding the character of absorbing aerosols presented in recent studies, measurements of the absorption capability and space distribution of absorbed aerosols are still not available and efforts must be done for model validation. Vertical Profile of aerosol absorption over highly polluted regions must be specified as they play a role of key indicator in changing atmosphere stability and also govern the interaction and feedback between aerosol and atmosphere dynamics. Apart from this measurement of concentration of aerosol and cloud particle must be performed by satellites such as CALISPO and CloudSat. These satellites give important information but failed to provide information regarding concentration of number of aerosols, size distribution and chemical properties which are important for understanding CCN effect.

If an appropriate composition and ample super

saturation has been provided then smaller size aerosol can also provide better Cloud Condensation Nuclei. Currently data attain from MODIS satellite are used to estimate the cloud droplet number concentration.. Efforts must be made in order to obtain better insight in aerosols optical properties.

Even though large number of efforts are being done to understand aerosol, cloud and precipitation relationship and also there has high increase in published studies but still researchers are puzzled due to disagreement over findings as also discussed in previous sections. No doubt there are clear evidence related to complexity of problem it is difficult to separate meteorological and aerosol effects. A collective approach that combines the strength and minimize the limitations of all individual approaches should be used to solve the problem although individual endeavour have improved our level of understanding at a global scale. Both observation and cloud resolving models doing their work as former provides new evidence of ACPI and later that is cloud resolving models help us in understanding basic processes and also to develop new parameterization schemes for large scale models. Large scale models are developed with the help of clear experiments and for comparison of data relationship should be made between models and observations. In case any mismatch found, it is important to find out the factor that affecting various direct and indirect terms.

CONCLUSIONS

In this article, status of interaction between aerosols and cloud is reviewed and results obtained from observation and modelling is compared. Cloud formation takes place through different steps which involve evaporation of water vapor into air followed by condensation of this water vapor and germination of cloud drop. This water vapor condensation is easier if particle is present upon which water vapour can condense. These particles are termed as condensation nuclei or aerosols. Aerosol concentration can effect cloud droplet size, warm rain processes, cold rain processes cloud top height, mixed phase region and occurrence of lightning. Large aerosol concentration can suppress warm rain processes by reducing particle size and resulting in

narrow droplet formation. However, it results in more freezing of cloud drop and which results in cold rain processes. Warm rain suppression can be avoided by the use of giant cloud condensation nuclei. Hence, there exist an inverse relationship between cloud particle size and aerosol loading over most of the world. However, there are positive relationship observed in two regions, i.e. first gulf of Mexico and the second in South China sea where during summer when atmospheric environment it is influenced by monsoon circulation that blow moist air from the oceans to polluted inland areas. The above observation can also be verified using cloud resolving models and results showed that cloud in clean environment produces few drops of larger size and broader size distribution while in dirty environment small drops of of narrow spectrum are formed. However this result is only valid for initial first hour of simulation when the initial process of cloud development takes place. Hence, it can be said that whole life cycle of a convective system is needed to assess the complete effect of cloud precipitation interaction and in this direction future development of more advanced cloud resolving models will be helpful.

ACKNOWLEDGEMENTS

We would like to thank summer faculty research fellow programme 2020 of Indian Institute of Technology Delhi for giving the opportunity to do research.

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Nomenclature

S	ambient super saturation
S_c	Critical super saturation
Z	elevation
	cloud water content
N_{CCN}	Cloud condensation Nuclei
C	temporal dependent coefficients
k	spatial-dependent coefficient
R	rate of precipitation and
N_d	Cloud droplet number concentration
P	pressure (N/m ²)
T	temperature (°C)
P_0	reference pressure (N m ⁻²)
R_d	universal gas constant for dry air (J K ⁻¹ mol ⁻¹)
C_p	specific heat coefficient (J kg ⁻¹ K ⁻¹)
U_j^p	component of the earth's angular velocity (rad/s)
g	gravitational acceleration (m/s ²)
	reference potential temperature (K)
	virtual potential temperature (K)
Q_{rad}	radiative heating rate
$Q_{m\ddot{O}}$	heating rate associated with the microphysical processes
S_x	sum of the microphysical processes affecting r_x
R_x	mixing ratio hydrometeor species
LS	large-scale temperature change

Received: 6th July 2021

Accepted: 15th September 2021