APCC
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# TECHNICAL REPORT

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# PREFACE

It is our pleasure to present to you the APEC Climate Center (APCC)'s Technical Report 2012, which reports the core outcomes of our research activities from the past year.

Since 2005, APCC, as a hub of climate information in the Asia-Pacific region, has strived to share our analysis and prediction of abnormal climate and to apply this information to regional development. The Center has established the most extensive Multi-Model Ensemble (MME) system for seasonal prediction in the world through its international science network and has provided value-added products to various stakeholders. Recently, APCC has expanded its mandate to include enhancing the capacity of APEC member economies to respond effectively to climate change and variability through better application of climate information.

In 2012, APCC continued to make an effort to improve the quality and quantity of our short-term climate forecasts and our online climate information systems, as information dissemination tools. Additionally, APCC began its endeavor to produce more applicable climate information through interdisciplinary research among various sectors, such as agriculture and hydrology. The following technical report provides more information about our research outcomes from 2012.

In 2013, following APCC's goal to enhance socioeconomic well-being through better utilization of climate information, APCC will continue to improve the quality and accuracy of its climate information, recognizing that the utility of this information is only as good as its quality. We would like to make the best use of our research outcomes in various scientific and application areas. We welcome any feedback on this report or on our services.

My best and warmest regards to all of you.

Dr. Chin-Seung Chung
Director/APEC Climate Center

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Aerosol Variability on Global and Regional Scales Using Multi-satellite Observations

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# Aerosol Variability on Global and Regional Scales Using Multi-satellite Observations

Dr. Rohini Lakshman Bhawar

## ABSTRACT

The non-uniform distribution of aerosol sources and sinks, their differing sizes, short atmospheric lifetimes and intermittent removal processes means that the spatial distribution of aerosols is also non-uniform. The amount of aerosols varies substantially between locations and from year to year, and also exhibits a strong seasonal cycle. Evaluation of the effects of aerosols on climate requires high-resolution measurement of the spatial and temporal variation of aerosol amounts and their properties. An effort is made in the present study to understand global and regional aerosol columnar and vertical variability. In the mid-latitudes in the southern hemisphere, aerosol optical depths (AOD) are better represented by data from the MODIS (Moderate resolution Imaging Spectro-radiometer) sensor whilst in the northern hemisphere, because of the presence of a desert in the tropical latitudes, CALIPSO (Cloud-Aerosol Lidar and Infrared Pathfinder Satellite Observations) observes higher AODs compared to MODIS. The natural dust and burning biomass aerosols seem to dominate the total AOD, and show a strong seasonal cycle with increased dust aerosols during the spring and summer, and burning biomass aerosols dominating during September-November. South East Asia and East Asia shows a small aerosol occurrence at higher altitudes, mainly attributed to convective activities.

To better understand the impact of aerosols on climate, the regional aerosol variability must be understood and quantified, rather than simply using a global average. Hence, this study also focuses on the variability of aerosols over East Asia. The annual variation from different sensors shows the same variability: maximum AOD during the spring season (due to dust transport and smoke aerosols), and a minimum during the summer monsoon period (due to the wash out effect or aerosols acting as cloud condensation nuclei). However, the sensors used also differ considerably from one another and therefore it is necessary to establish a combined approach using all the different sensors to obtain a better perspective. The maximum dust loading over East Asia occurs in March-May, and the maximum smoke aerosol loading occurs during June-August, mainly as a result of wind transport from Southern China. The vertical aerosol distribution of aerosols is very important in understanding aerosol-cloud interaction processes. Across East Asia we observe that dust aerosols in spring show a broad distribution from the surface to 10 km altitude, while in June-August, a lower dust loading is seen. While the smoke aerosols show similar concentrations in both March–May and June–August, the altitude at which they are dominant differs; in March–May, the smoke layer is present at higher altitude than that observed in June–August. This may prove an important observation to help explain in detail the differing radiative effects and aerosol-cloud interaction phenomena over East Asia.

# 1. INTRODUCTION

## 1.1 Purpose of this research

Aerosols are tiny particles suspended in the air. Although tiny in size, their effects on the weather and climate are enormous. Aerosols are now recognized as potentially acting as the "Atmospheric switches" of our planet's climate. They play a crucial role in affecting the present climate, creating unpredictable and chaotic weather patterns around the world. The presence of particulate aerosols in the atmosphere has become a peculiar signature of the unusual weather changes that are currently being witnessed globally. This study focuses on columnar and vertical aerosol variability to better understand the role of aerosols on a global scale, using aerosol information from the A-Train platform, which spans the Earth with data from UV to microwave wavelengths and provides composite information about a variety of climate parameters. In addition, a detailed study of aerosol variability over East Asia has been carried out. Using these data, the key science question addressed in this report is: what types of aerosols dominate in which seasons over different parts of the globe?

## 1.2 Background

Aerosols are becoming a central theme in climate research, following the discovery of their significant direct and indirect effects on climate (e.g., by altering temperature, cloud cover, radiation, and precipitation) and the large uncertainties remaining in our estimates of aerosol forcing on climate. Investigations of a wide range of aerosol effects have ensued and many breakthrough findings were reported in the following years, referred to as the "exploratory phase" of aerosol research [Kaufman *et al.*, 2002a]. Major findings include: the contribution of aerosols to the suppression of precipitation and the slowdown of hydrological cycles by dust storms [Rosenfeld *et al.*, 2001; *Ramanathan et al.*, 2001]; and their contribution to air pollution [*Rosenfeld,*

2000; *Rosenfeld and Woodley*, 2001], and to fire smoke plumes [*Kaufman and Fraser*, 1997; *Rosenfeld*, 2000]. Other important findings include a larger reduction of the solar radiation budget at the surface than at the top of the atmosphere due to absorbing aerosols [*Li*, 1998; *Satheesh and Ramanathan*, 2000; *Li and Trishchenko*, 2001] and strong radiative heating in the atmosphere as a result of the mixing state of black carbon [*Jacobson*, 2001].

Aerosols are produced either by mechanical disintegration processes occurring over land (e.g., release and elevation of dust) and ocean (sea spray) or by chemical reactions occurring in the atmosphere (e.g., conversion of sulfur dioxide to sulfuric acid droplets) [*Junge*, 1963; Prospero *et al.*, 1981]. The variable concentrations and compositions of these particles have a strong influence on altering local climate and, to some extent, the regional climate too. After production at a particular location, aerosols are often carried by wind to locations far away from their source. Large-scale major transport of dust occurs from Africa to the South Indian Ocean, from West Asia to the Arabian Sea, from China across the Pacific, and from Australia over to the Indian Ocean [Prospero *et al.*, 1981; Uematsu *et al.*, 1983; Tyson *et al.*, 1996]. Owing to these long-range continental origins and associated transport mechanisms, the atmospheric aerosols have potential impacts on a global scale. The removal time of aerosols depends on their composition, and ranges from a few hours to a week. In general, aerosols originate mostly from the surface and travel and settle in the lower tropospheric levels. However, following some explosive volcanic eruptions, aerosols can rise up to stratospheric levels. Owing to their varied composition, most processes involving or initiated by aerosols are not well understood. As a result, it is important to understand the variability of atmospheric aerosols with respect to their physical and chemical characteristics as well as their composition.

As the aerosol sources are located mostly near the Earth's surface, their concentration is higher near the surface. Depending on the source and production mechanism, the sizes of aerosols vary from $10^{-3}$ to $10^{2}$ μm and are classified into three major categories according to size:

1) Nucleation mode or Aitken mode (radius ~0.001 to 0.1 μm)
2) Accumulation mode (radius ~0.1 to 1 μm) and
3) Coarse mode (radius ~>1 μm)

The nucleation mode aerosols are produced mainly by gas-to-particle conversion in the atmosphere, the accumulation mode particles form through coagulation and growth of nucleation mode aerosols by condensation of water vapor [*Seinfeld and Pandis*, 1986], and coarse mode aerosols are derived directly from mechanical processes. Aerosols of different sizes give rise to different atmospheric processes. For example, the nucleation mode aerosols are important in atmospheric electricity, accumulation mode aerosols significantly influence solar radiation, and coarse mode aerosols act as cloud condensation nuclei [*Seinfeld and Pandis*, 1998]. For particles with the radius ranging from 0.01 to 0.1 μm, the average lifetime is typically a few days, while larger particles, greater than 10 μm in radius, cannot remain suspended in the air for long periods and settle rapidly under gravity.

## 1.3 Distribution of Aerosols in the Atmosphere

Aerosols are most numerous in the lower atmosphere, that is, in the troposphere and near their primary source on the Earth's surface. Their concentration decreases as the altitude increases. Nevertheless, the upper atmosphere is not free of them, as some dust particles are carried to great heights by rising currents of air, and other particles are delivered by meteoroids that disintegrate as they pass into the atmosphere. Explosive volcanic emissions can directly inject aerosols into the stratosphere thus increasing their concentration there. The lifetime of aerosols in the troposphere is a few days to less than a week, while in the stratosphere it can be one or two years or more. Because of their short lifetime in the troposphere, aerosols are distributed unevenly over the globe [Frederick *et al.*, 2004]. On a global scale, the natural sources of aerosols are three to four times larger than anthropogenic ones, however anthropogenic emissions can be significant on a regional scale [Charlson *et al.*, 1991; 1992].

## 1.4 Types of Aerosols

### 1.4.1 Volcanic Aerosol

Three types of aerosols significantly affect the Earth's climate. The first is the volcanic aerosol layer, which forms in the stratosphere after major volcanic eruptions (e.g., Mt. Pinatubo in 1991). The dominant aerosol layer is actually formed by sulfur dioxide gas, which is converted to droplets of sulfuric acid in the stratosphere over a week to several months following the eruption. Winds in the stratosphere spread the aerosols until they cover the globe. Once formed, these aerosols stay in the stratosphere for around two years. They reflect sunlight, reducing the amount of energy reaching the lower atmosphere and hence cooling the Earth's surface. The relative coolness of 1993 is thought to have been a response to the stratospheric aerosol layer that was produced by the 1991 Mt. Pinatubo eruption. In 1995, although several years had passed since the Mt. Pinatubo eruption, remnants of the layer remained in the atmosphere. Data from satellites have enabled scientists to better understand the effects of volcanic aerosols on our atmosphere.

### 1.4.2 Desert Dust

The second type of aerosol that may have a significant effect on climate is desert dust. Images from weather satellites often reveal dust veils streaming out over the Atlantic Ocean from the deserts of North Africa. Fallout from these layers has been observed at various locations on the American continent. Similar veils of dust stream off deserts on the Asian continent. The particles in these dust plumes are minute grains of sediment blown from the desert surface. They are relatively large for atmospheric aerosols and would normally fall out of the atmosphere after a short flight if they were not blown to relatively high altitudes (15,000 ft. and higher) by intense dust storms.

### 1.4.3 Human-made Aerosol

The third type of aerosol originates from human activities. While a large fraction of these human-made aerosols consist of smoke particles from the burning of tropical forests, the major component comes in the form of sulfate aerosols created by the burning of coal and oil. The concentration of human-made sulfate aerosols in the atmosphere has grown rapidly since the beginning of the industrial revolution. At current production levels, human-made sulfate aerosols are thought to outweigh the naturally produced sulfate aerosols. The concentration of aerosols is highest in the northern hemisphere where industrial activity is centered. The sulfate aerosols absorb no sunlight but they reflect it, thereby reducing the amount of sunlight reaching the Earth's surface. Sulfate aerosols are believed to survive in the lower atmosphere for about 3-5 days. The highest concentrations are usually found in urban areas, reaching up to $10^8$ and $10^9$ particles per cubic centimeter [*Seinfeld and Pandis*, 1998].

## 1.5 Climatic Effects of Aerosols

The additional reflection of incoming solar radiation caused by pollution aerosols is expected to have an effect on the climate comparable in magnitude to that of increasing concentrations of atmospheric greenhouse gases. The effect of these aerosols, however, will be opposite to the effect of the increasing atmospheric gases—cooling instead of warming the atmosphere. The warming effect of the greenhouse gases is expected to take place worldwide, but the cooling effect of the pollution aerosols will be regionally dependent, close to and downwind of industrial areas. As yet, it is not known what the outcome will be of atmospheric warming in some regions and cooling in others, and climate models are still too primitive to provide reliable insight into the possible outcomes. Current observations of the build-up are available only for a few locations around the globe and these observations are fragmentary.

### 1.5.1 Impact of Aerosols on Global Climate

Aerosols are produced both by natural and anthropogenic processes. Over the ocean, they (mostly natural sea-salt and sulfate) reduce the surface-reaching solar radiation whereas over land they heat the lower atmosphere (due to the presence of absorbing aerosols) in addition to reducing the surface-reaching solar radiation. Over land, the reduction in surface solar radiation occurring concurrently with lower atmospheric heating may influence boundary layer properties.

### 1.5.2 Aerosol Forcing

Aerosols modify the incoming solar and outgoing infrared (IR) radiation. The change in radiative flux caused by aerosols is referred to as "aerosol radiative forcing." The effect of aerosols on radiative fluxes at the top of the atmosphere (TOA) is called "TOA radiative forcing" and that on surface radiative fluxes is called the "surface radiative forcing." The difference between these two effects is the "atmospheric radiative forcing." Aerosol forcing can be estimated from both models and observations. Estimation of the effect of aerosols on radiation is more uncertain than the effects of well-mixed greenhouse gases, because of the former's short lifetimes, highly inhomogeneous spatial distribution, and the complex nature of their interaction with radiation [Hansen *et al.*, 1997, 1998; Haywood *et al.*, 1999; IPCC, 2001].

The report of the Intergovernmental Panel on Climate Change (IPCC) concluded that emissions of greenhouse gases and aerosols due to human activities continue to alter the atmosphere in ways that are expected to affect the climate [*IPCC*, 2001]. Previously, the relationship seemed to be simple: greenhouse gases warm the Earth and aerosols, especially sulfate, cool it down [Charlson *et al.*, 1992]. This effect was mainly because of the direct action of aerosols that scatter the sunlight back into space and hence reduce the amount of sunlight reaching the Earth's surface. However, the radiative effects of other types of aerosols, such as elemental carbon and mineral dust, can lead to heating of the lower troposphere [*Andreae*, 2004]. It has even been

proposed that the warming effect of black carbon aerosols may balance the cooling effect of sulfate aerosols [*Jacobson,* 2001]. Aerosols scatter and absorb sunlight [*McCormick and Ludwig*, 1967; *Charlson and Pilat*, 1969; *Atwater*, 1970; Mitchell, Jr., 1971; Coakley *et al.*, 1983]; these are defined as "direct effects" on shortwave (solar) radiation. Secondarily, aerosols act as sites at which water vapor can accumulate during cloud droplet formation, serving as cloud condensation nuclei (CCN). Any change in the concentration or hygroscopic properties of such particles has the potential to modify the physical and radiative properties of clouds, altering cloud brightness [*Twomey*, 1977], and the likelihood and intensity with which a cloud will precipitate (e.g., *Gunn and Phillips*, 1957; *Liou and Ou* 1989; *Albrecht*, 1989]. Collectively, changes in cloud processes due to anthropogenic aerosols are referred to as "aerosol indirect effects." Finally, absorption of solar radiation by particles is thought to contribute to a reduction in cloudiness, a phenomenon referred to as the "semi-direct effect." This occurs because absorbing aerosols warm the atmosphere, which alters the atmospheric stability and reduces surface flux by reducing radiation reaching the surface.

Keeping these direct and indirect effects in mind, it is still necessary to conduct a detailed study into precisely how aerosols affect the regional and global climate. It is important to separate and quantify the relative impacts on climate due to natural and anthropogenic aerosols. Moreover, the regions in which the amounts of atmospheric aerosols are increasing, decreasing, or remaining roughly constant are as yet unknown. Thus, it is essential to establish the variability of aerosols concentration and type dominating globally or regionally. Hence, the purpose of the analysis reported herein is to understand the variability of aerosols over the globe and in different regions through columnar and vertical aerosol distribution.

## 2. DATA AND METHODOLOGY

Recently, there has been an enormous increase in scientists' and the layman's concern for the weather. This has been facilitated by major advances in our understanding of the Earth's atmospheric systems. The advent of remote sensing and satellite analysis has provided a new tool for observing the Earth's weather systems and environment, by providing valuable data over remote areas and oceans. Use of satellite observations is the most efficient way to determine the physical properties of aerosols on temporal and spatial scales, required to understand and monitor their impact on the Earth–atmosphere system. Traditional aerosol satellite-based retrievals have been limited to ocean areas that are dark in the visible and near IR wavelengths [Stowe *et al.*, 1997; Mishchenko *et al.*, 1999]. For land areas, the surface contribution to the reflected visible and near-IR is significantly larger than that contributed by aerosols. Therefore, aerosol analysis over land through visible and near-IR observations is very difficult without a precise characterization of the surface radiative properties. In the last decade, an additional remote sensing tool for aerosol detection and characterization has been developed [Herman *et al.*, 1997; Torres *et al.*, 1998]. The realization that aerosols can affect surface temperature and precipitation patterns creates a demand for more informative space-borne observations.

Here, we use level 2 version 3.01 aerosol profile (APro) data from Cloud-Aerosol Lidar and Infrared Pathfinder Satellite Observations (CALIPSO). Aqua Moderate resolution Imaging Spectro-radiometer (MODIS) daily level 3 data for aerosol optical depth (AOD) are used for the aerosol columnar variability. CALIPSO and Aqua MODIS both fly in the A-Train constellation [*L'Ecuyer and Jiang* 2010]. Aqua leads the constellation followed by CALIPSO around 2 minutes later, and cross the equator at approximately 01:30 local time. In addition, Total Ozone Mapping Spectrometer (TOMS) Aerosol Index data have been used in this study. TOMS has flown since 1978, and has two channels sensitive to ultraviolet light that were discovered to be excellent for observations of elevated smoke or dust layers above the scattering atmosphere; it is now followed by the Ozone Monitoring Instrument (OMI). Daily

precipitation during the monsoon months is derived from the Tropical Rainfall Measuring Mission (TRMM).

There are two terms used in the present study: Aerosol Optical Depth (AOD) and Aerosol Occurrence Frequency (AOF). Aerosol Optical Depth (AOD) (also known as aerosol optical thickness, AOT, in the literature) is a measure of the amount of incident light either scattered or absorbed by airborne particles. AOD is a dimensionless quantity, the integral of the product of particle number concentration and particle extinction cross-section. The AOF is calculated from CALIPSO in the presence of aerosols and/or thin clouds, as observed by lidar. AOF is derived from the observed aerosol extinction profiles and defined as the frequency of occurrence of aerosol pixels divided by the total number of aerosol and clear sky pixels at a particular level. CALIPSO also has retrieval algorithms to detect different types of aerosols. Hence, information on different types of aerosols is presented here, to assist in understanding and identifying the different sources, sinks, and transport of aerosols.

# 3. RESULTS AND DISCUSSION

## 3.1 Global perspective

### 3.1.1 Dust AOD

Figure 1 shows the column-integrated AOD for dust aerosols during different seasons. There is a large difference between dust AOD over North Africa and other regions. As North Africa is a desert region, a greater AOD is observed over the North African region, compared to other areas. In addition, there is a broad maximum from March to October over this region indicating the presence of dust aerosols. Although the dust AOD is reduced in other regions, the seasonal cycle within South East Asia and East Asia is of note. East Asia always shows a peak in dust aerosols

1–2 months before the peak in Southeast Asia. In South East Asia, dust AOD peaks in summer as a result of the transport of dust from the Saharan region. For East Asia, the peak is in spring, and the dust here is derived from the Gobi desert. South America has a broad dust AOD peak in spring through summer, while South Africa shows a small peak in spring. The lowest dust AODs observed are over the South African region.

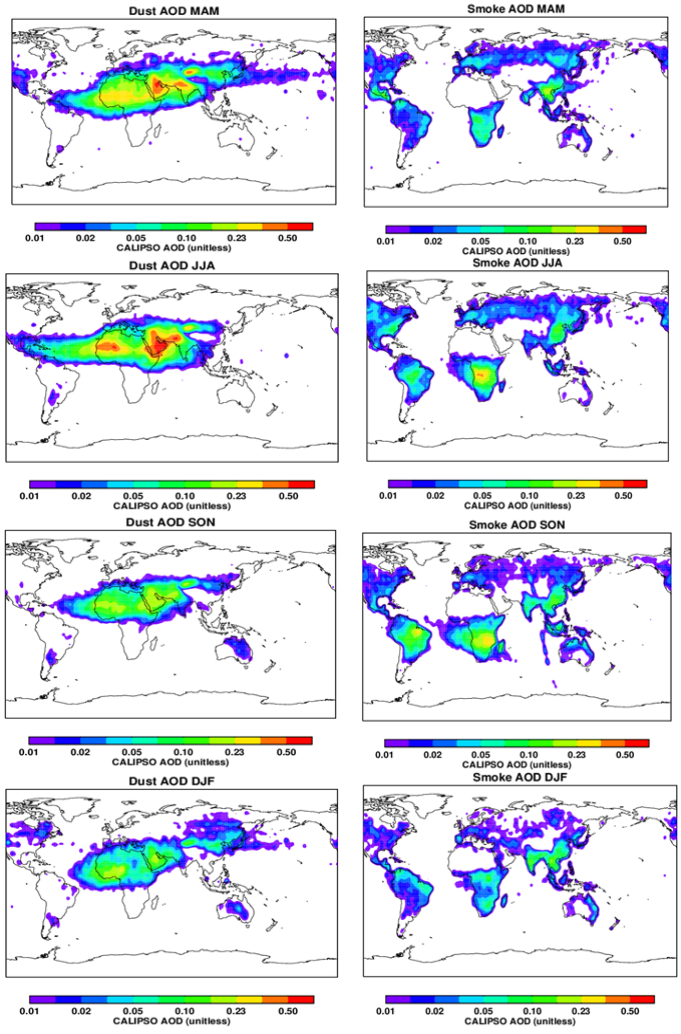


**Figure 1** Spatial distribution of two types of aerosols, derived from CALIPSO; dust and smoke for March–May (MAM), June–August (JJA), Sept–Oct (SON), and Dec–Feb (DJF).

### 3.1.2 Smoke AOD

Figure 1 illustrates the smoke AOD over the globe for different seasons. The dominant smoke AODs are found over South Africa. The AOD begins to increase in the summer months and peaks sharply in September, then decreases rapidly until November. South America also shows a peak in September but the period here is narrower than for South Africa, peaking mostly in autumn over South America.

### 1.1.1 Latitudinal variation in AOD

Figure 2 shows the latitudinal variation of AOD. The southern hemisphere mid-latitudes (especially the biomass-burning region) show higher AODs from MODIS. Due to presence of desert dust in the tropical northern hemisphere, CALIPSO observed higher AODs compared to MODIS. This is because MODIS is not able to observe over desert and snow regions due to sun-glint effects. The northern hemisphere mid-latitude AODs are represented very well in combined CALIPSO and MODIS data.

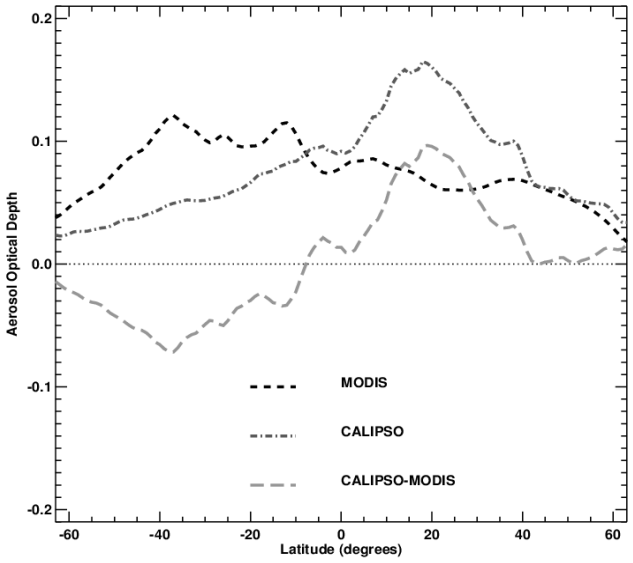


**Figure 2** Latitudinal variation of Aerosol Optical Depths (AODs) from CALIPSO and MODIS.

## 3.2 Region-wise aerosol profile characteristics

Figure 3 shows the global total AOD distribution from the CALIPSO satellite, from June 2006 to December 2010. We observe different specific hot spots, such as desert dust, transported dust, burning biomass, and pollution aerosols. The five boxes highlighted in the figure are the five different regions considered in the study: East Asia (90E–190E and 20N–45N), South East Asia (70E–120E and 10S–20N), North Africa (19W–45E and 0S–25N), South Africa (15W–50E and 30S–0N) and South America (90W–25W and 40S–15N). Jiang *et al.*, [2008] used Microwave Limb sounder observed carbon monoxide (MLS CO) as a proxy to understand the distribution of clean and polluted clouds. As such, the purpose of this study was to use the aerosol information within the same regions considered by Jiang *et al.*, [2008] to understand the role of aerosols in the polluted cloud scenario, a case study of aerosol-cloud interactions (indirect effect). To further investigate the aerosol-cloud interaction phenomenon, the aerosol variability in these regions must be understood and documented.

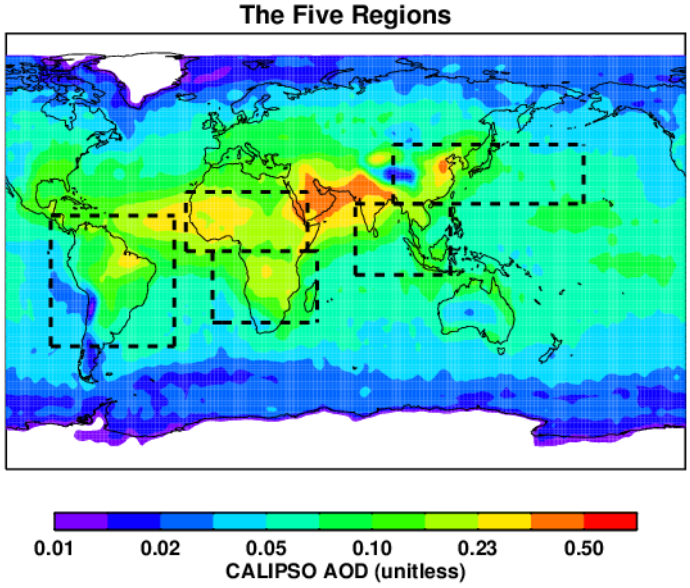


**Figure 3** Distribution of global total AOD derived from CALIPSO. The boxes represent the five study regions: East Asia, South East Asia, North Africa, South Africa, and South America.

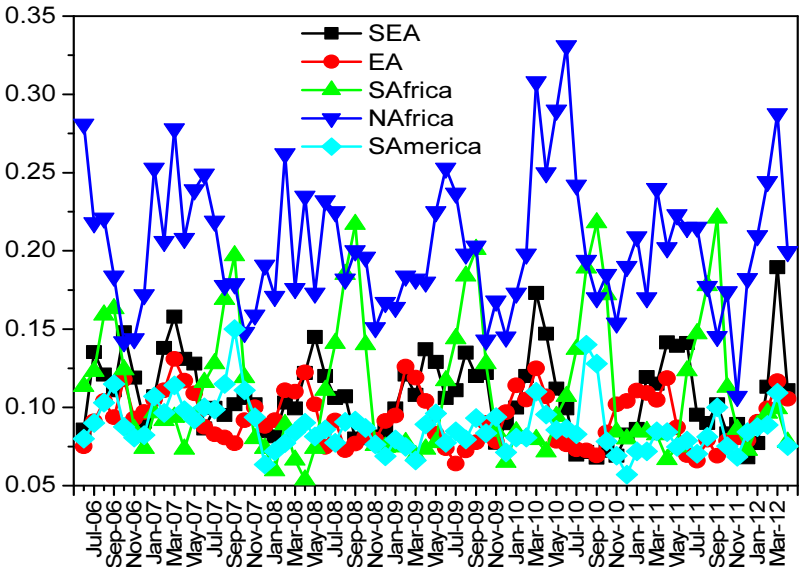


**Figure 4** Monthly AOD variability for the five different study regions.

Figure 4 shows the column-integrated AOD for all aerosols present over the 5 regions from June 2006 to April 2012. The dominance and large values of AOD are observed over the North African region, due to the presence of dust aerosols that are of coarse mode and therefore integrate to higher AOD values. The AOD in North Africa shows a broad maximum from winter to summer seasons. There is considerable interannual variability observed, with maximum AOD during 2010 in this CALIPSO record. The South Africa region shows a prominent increase in AOD in summer and autumn, peaking in September-October. This increase is strictly tied to the burning biomass aerosols. The South American region shows two peaks: one in spring, and the other in autumn. While in South East Asia we see an increase in AOD from March, which peaks around May (due to dust transport) and low values in the summer due to the Southwest monsoon. A similar type of variation is observed in the East Asia region, except that the peak is shifted to earlier months, resulting from a combination of smoke and transported dust. In order to study the variability of different types of aerosol over these regions, we have presently plotted two types of aerosols, derived from CALIPSO: dust and smoke (Figure 8). It will be interesting to see the variability of these two types, which are contributed through natural and

human processes, respectively. In addition, this will help in characterizing aerosols and their role in climate change.

Figure 4 shows two prominent peaks in 2007 and 2010, which are related to strong biomass burning events in South America. In addition, a 2-peak pattern is also seen over the South East Asia region: one is spring, peaking in April, with another in autumn, peaking in October. The first peak is related mostly to agricultural burning in the spring season, while the autumn peak is due to biomass burning over the Indonesian region. Over East Asia, two peaks are also seen: one in spring and the other in summer. In addition to local emissions, the emissions from biomass burnings in South East Asia in the spring may be transported to East Asia. The second peak in summer is low compared to the spring peak. It is possible that there may be aerosol emissions from heavily industrialized areas. In the North African region, there is a strong broad maximum from summer to autumn, as seen in South Africa. However, there is some transport of aerosols from Southern Africa by the southeasterly winds in summer and autumn, which blows off some of the burning biomass aerosols over the North Africa region.

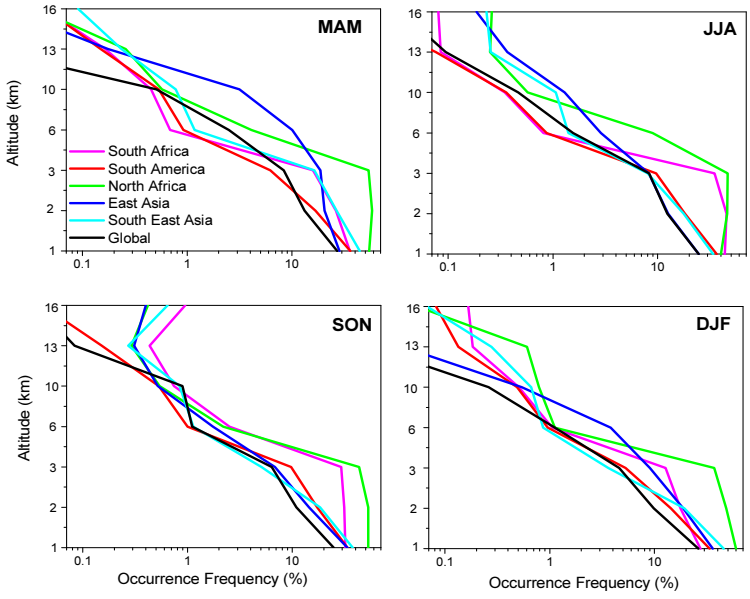


**Figure 5** Vertical distribution of aerosols derived from CALIPSO for different seasons and regions.

### 3.2.1 Vertical distribution of aerosols

Figure 5 shows the vertical distribution of Aerosol Occurrence Frequency (AOF) from 2006-2010 for the five regions considered in this study, in addition to a global average. The altitudes considered represent the boundary layer aerosols, the middle layer aerosols mostly contributed by long-range transport, and also aerosols reaching the upper levels as a result of vertical transport. The figures also illustrate in-depth analysis showing seasonal variations in aerosol patterns, for the four seasons; March-April-May (Spring-MAM), June-July-August (Summer-JJA), September-October-November (Autumn-SON) and December-January-February (Winter-DJF).

### 3.2.2 South East Asia region

AOF below about 3 km dominates the entire vertical profile of aerosols during all the four seasons, which indicates a dominance of boundary layer aerosols tied to local sources. The middle layer aerosols at 6 km play an important role in climate dynamics. Most of these aerosols over South East Asia are derived from long range transport from the Saharan region [Pandithurai *et al.*, 2004, *Bhawar and Devara*, 2010] The AOF present at higher levels (i.e.,10 km, 13 km, and 16 km), although representing just a small percentage, are of great importance. The aerosols that reach these levels do so through vertical transport, which occurs during the monsoon season mostly in deep convective clouds. The AOF continues to decrease as height increases during all four seasons and for all five years considered (2006-2010). The presence of aerosols at upper levels in the summer monsoon season of South East Asia hints at the deep convective activities responsible for transporting the aerosols vertically [Jiang *et al.*, 2008]. Overall, the spring and winter seasons show higher AOF as compared to the summer and autumn seasons at altitudes from 1 to 3 km. The spring values are high as a result of dust aerosols transported from the Saharan region while in winter the abundance is mainly due to a temperature inversion that traps the agricultural burnings and biomass burnings in the low altitudes, forming a thick hazy layer and also affecting visibility. Reduced AOFs at 1-2 km altitudes

in the summer months is due to the presence of cloud cover, resulting in cloud scavenging and the wash-out effects of rain, which are combined features of the Southwest Monsoon.

### 3.2.3 East Asia region

The increase of AOF seen in autumn, compared to spring and summer, is due to aerosol emissions from heavily industrialized areas, and retreating monsoon winds giving rise to biomass burning activities. In comparison, the increase of AOF in winter occurs due to agricultural burnings and local emissions trapped by temperature inversions at lower altitudes. The air near the ground is much cooler than the air above it, which probably assists in trapping aerosols in winter [*Di Girolamo et. al.*, 2004]. The increase in AOD during autumn and winter over the East Asia region is clearly reflected in the increase in AOF at lower altitudes, as observed by CALIPSO vertical profiles. At altitudes from 2 km to 10 km there is a dominance of AOF in spring, which is a result of the dust aerosols transported from desert regions as well as from the South East Asia region. The summer shows reduced AOF due to cloud scavenging and rain wash-out effects, and also probably because of reduced aerosol retrievals due to cloud cover during the Southwest monsoon season, as also observed over the South East Asia region.

### 3.2.4 South America region

The AOF for spring and summer show the same pattern, and the AOF for autumn and winter also show the same behavior. There is no clear noticeable difference between the four seasons over South America. The spring and summer seasons are dominated by dust aerosols transported over the Atlantic to South America, while autumn and winter seasons are dominated by the burning biomass aerosols over South America. There is a very small proportion of aerosols (0.01%) reaching the higher altitudes 13 and 16 km, as shown in Figure 4. The small percentage of aerosols

observed at higher altitudes is a result of vertical transport in presence of deep convection, mostly occurring in the autumn, which is the biomass-burning season in South America. At altitudes of 2–3 km there is an increase in AOF during the autumn, which is indicated by the elevated smoke layer.

### 3.2.5 North Africa region

At the lower altitudes, 1–2 km, the AOF is larger during the spring, autumn and winter seasons, while at altitudes 3 and 6 km the AOF is larger in spring and summer respectively. Spring and summer are the seasons with more dust in the atmosphere. There are frequent dust storms at this time due to dry weather and high temperatures, and dust is lifted to higher altitudes and also transported by winds to the Asian continent and across the Atlantic Ocean to South America. The increase of AOF in autumn and winter is mostly a combination of dust and the burning biomass aerosols blown by winds from the South African region. The AOF is very high at lower altitudes over the desert region compared to higher altitudes, dominated coarse mode dust aerosols in the boundary layer.

### 3.1.6 South Africa region

The highest AOF over South Africa occurs in the summer months, which is the biomass-burning season. The lower altitudes (1–3 km) are dominated by the AOF in the summer months while the AOFs in the autumn months do not vary much with the increase in altitude from 1 to 3 km. The spring and winter AOFs show a decrease as the altitude increases, which possibly suggests the presence of low level dust aerosols over the South Africa region. It is interesting to note that there is a higher AOF in the autumn season at higher altitudes, which suggests elevated levels of burning biomass aerosols in addition to vertical transport in deep convective clouds, as in South America.

### 3.3 East Asia regional perspective

East Asia is an important source region for many major aerosol types. Chin *et al.*, [2003] estimated that the fast economic development of a large area of desert and the intensive forest and agricultural fires in the region contribute to around $^1/_4$ - $^1/_3$ of the global emission of $SO_2$, organic matter, soot, and dust. Figure 6 shows annual variation from different sensors over East Asia: MODIS, TOMS, and CALIPSO. CALIPSO underestimates AOD compared to MODIS. The annual cycle in aerosol is similar all these sensors. The maximum AOD was observed during the spring, while the minimum occurred during the summer season. CALIPSO shows two peaks in the annual variation: first during March-April, and secondly between July–October. In contrast, the TOMS aerosol index shows a maximum during the spring season and a minimum during the summer months.

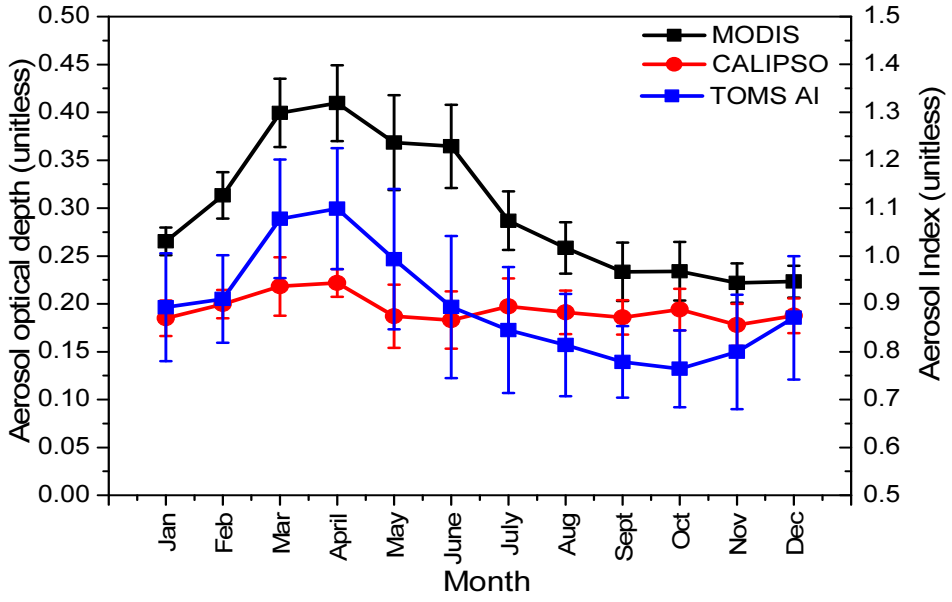


**Figure 6** Annual variation in aerosol optical depth (AOD) from MODIS and CALIPSO and aerosol index (AI) from TOMS over East Asia.

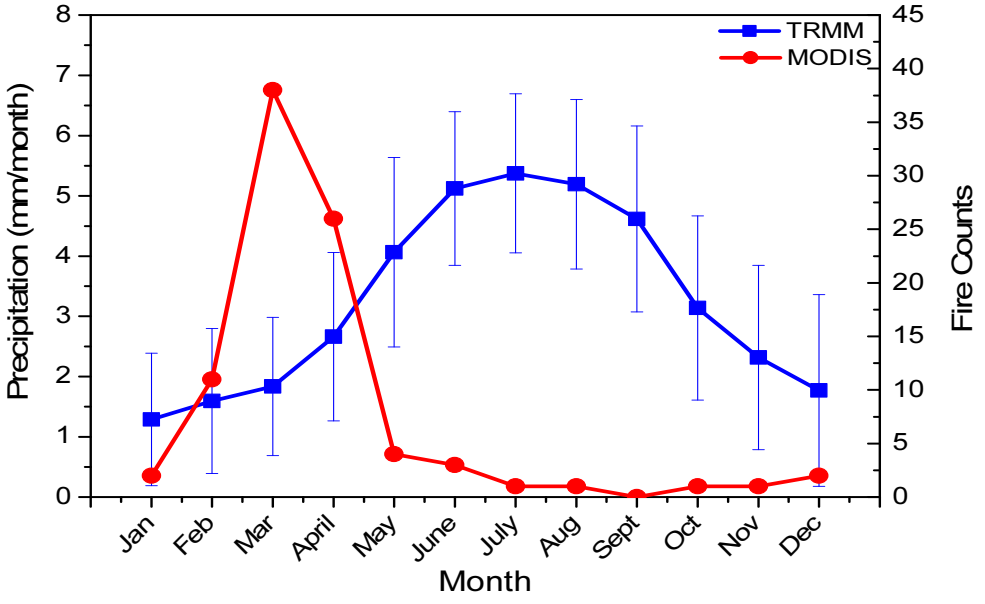


**Figure 7** Annual variation in precipitation from TRMM and fire counts from MODIS over East Asia.

Figure 7 shows the annual variation in precipitation from TRMM and fire count data from MODIS over East Asia. The southwest monsoon winds bring summer monsoon rains over East Asia during June–August. Hence, maximum rainfall is observed over East Asia during this period. In addition, in March and April maximum fires are seen over East Asia, related to agricultural burnings and contributing to the maximum AOD in spring, as seen in Figure 6.

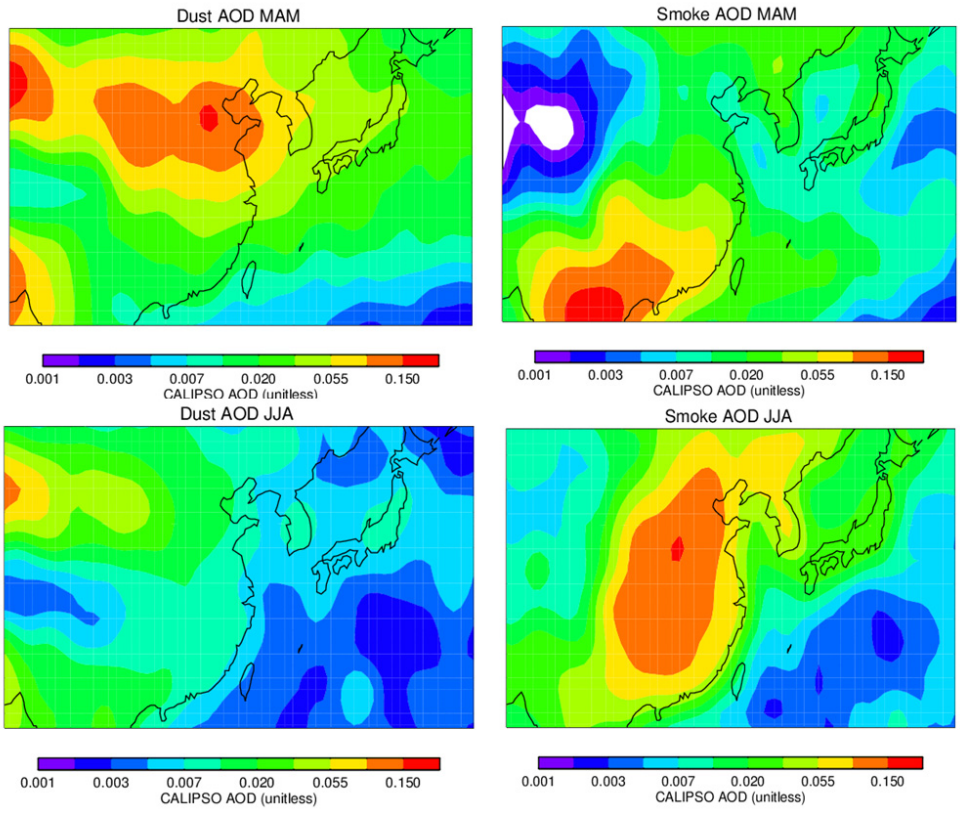


**Figure 8** Spatial variation of dust and smoke type aerosols over East Asia during March–May and June–Aug.

The CALIPSO satellite possesses retrieval algorithms, which use extinction information to derive different types of aerosols. The two main types of aerosols, dust and smoke, derived from CALIPSO data are shown in Figure 8 for two seasons: March-May (MAM) and June-August (JJA). Maximum transport of dust is seen during

the spring, with high values observed in North China and Korea. Conversely, in MAM the smoke AOD seems to be more concentrated in the South China region. During JJA fewer dust aerosols are observed due to a reversal of winds, while smoke AOD remains elevated with increased transport from South China. The dust and smoke type aerosols play a major role in determining radiative forcing.

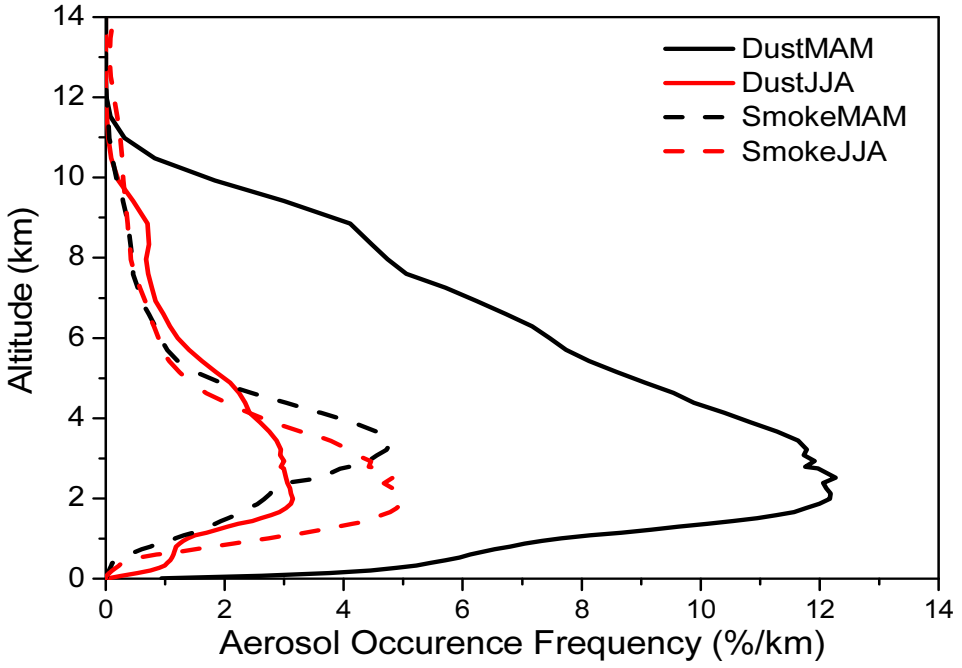


**Figure 9** Vertical aerosol occurrence frequency distribution for dust and smoke type aerosols over East Asia.

The total column AOD content is useful for understanding the aerosol variability as well as aerosol influence on climate, but the vertical aerosol profiles also play a major role. Most importantly, vertical resolution is necessary to assess whether cloud and aerosol layers are intermingled [Avey *et al.*, 2007]. These detailed profiles of aerosols and clouds are needed to quantify the effects of aerosols on clouds and how these in turn influence climate and the hydrological cycle [Kaufman *et al.*, 1997]. Thus, the aerosol layers present at different altitudes affect radiative forcing and therefore climate. Figure 9 illustrates the levels at which dust and smoke aerosols

are present and intermingled with one another, forming polluted dust. It can be seen that during the spring 12% of dust is present, distributed from the surface to about 4 km altitude, while the smoke aerosols comprise around 5% and are present between altitudes of 2.5 to 5 km. In summer, smoke aerosols occur at a lower altitude compared to spring, and dust is also reduced. Both of these changes occur as a result of changes to transport.

## 4. CONCLUSIONS

One of the greatest challenges in studying the impacts of aerosols on climate is the immense diversity, not only of particle size, composition, and origin, but also in spatial and temporal distribution. The main conclusions from the present study are as follows:

1) For most of the aerosols whose primary source is emissions near the surface, concentrations are greatest in the atmospheric boundary layer, decreasing with altitude in the troposphere.

2) Natural aerosols dominate over the globe, and more than 50% of them are desert dust. The second largest contribution is from burning biomass aerosols. These two types of aerosols have pronounced occurrences during different seasons.

3) North Africa shows a broad maximum AOD from the winter to the summer season (desert dust), while South Africa shows a prominent increase in AOD in summer and autumn (biomass burning). The South America region has two peaks: one in spring (transported dust) and another in autumn (biomass burning).

4) South East Asia sees an increase in AOD during spring (transported dust from the Saharan desert) while low values in summer monsoon months are

due to rain wash-out effects. East Asia also shows similar variation to South East Asia, except that the spring peak occurs earlier.

5) High AOF is seen North Africa at 1–3 km altitudes (due to increased desert dust) with a steep decrease higher. East Asia shows dominance of AOF at altitudes 2–10 km in the spring. South East Asia and East Asia show increased AOF at higher altitudes due to enhanced convective activities. South America also shows high altitude aerosols caused by convective activity in the autumn.

6) East Asia shows annual variation in AOD with two peaks in spring and in summer from different sensors. The two peaks in AOD have different causes: the spring peak is due to increased dust transport from the Gobi desert, while the summer high AOD is due to smoke transport from South China. The TRMM shows maximum rainfall during summer months, while March and April months see more fires according to MODIS data.

7) The vertical dust and smoke profiles also show an interesting pattern. Maximum dust occurrence frequency occurs in March-May from the surface to 10 km altitude, with reduced occurrence in the summer months. For smoke aerosols the occurrence frequency is similar in both seasons, with the smoke layer occurring at a higher altitude in March-May compared to June-August.

These observations will be further used to evaluate the CMIP5 (Coupled Model Intercomparison Project Phase 5) models and subsequently the different scenarios will be used for future projections. In addition, using simultaneous aerosol and cloud data, aerosol-cloud interactions will be studied over East Asia.

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