

# **India-Skynet: New Skyradiometer network of India Meteorological Department to measure aerosol optical properties over Indian region**

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## **Abstract**

Study of the optical and physical properties of aerosol particles is important for assessment of their effect on climate and for development of more accurate remote sensing procedures of aerosols from satellite sensors. Tropospheric aerosols have a short lifetime; as a result their properties vary from one region to another and vary with time. For a full assessment of aerosol characteristics such measurements have to be performed frequently in locations with different aerosol types and in varying meteorological conditions in automatic mode including communication to Central Data Processing Centre. In order to examine aerosol impact on the local and global climate in addition to understanding and modeling the impact of aerosol on radiation budget and precipitation efficiency, India Meteorological Department has established a network of sun-skyradiometer consisting of twelve stations located in different geographic regions and named as IMD's India-Skynet. This network is supplement to aerosol network being maintained using multichannel sunphotometer for the last three decades in the country and research skyradiometer since 2006. The sun-skyradiometer acquires direct solar spectral irradiance and circum-solar radiance distribution within a  $1^\circ$  full field-of-view at eleven bands of 315, 340, 380, 400, 500, 670, 870, 940, 1225, 1600, and 2200 nm at every 10 minute. The instrument is based on the aureolemeter and is composed of a sun- and sky-scanning spectral radiometer, a sun sensor, a sun tracker, a control unit, a rain sensor, and a personal computer. The sky radiance is measured at 24 pre-defined scattering angles at regular time intervals. The main properties of the aerosols which are being monitored from this network and important for climate studies are; Aerosol Optical Depth, Angstrom Exponent, Size Distribution of the aerosols, Scattering Phase Function, Single Scattering Albedo and Refractive Indices etc. The data are analysed using Version 4.2 of the Skyrad.Pack radiative transfer model.

## 1. Introduction

There has been a growing interest to observe atmospheric aerosol properties over Asian region which contain approximately 60% of world's population, and have recently been experiencing a period of unprecedented economic and industrial growth that is expected to be continued into the foreseeable future. This has been accompanied by a large increase in pollutant emissions, particularly from China and India, which still have much lower per-capita emissions than most of the developed world. The coincidence of natural and anthropogenic aerosol sources in Asia leads to high aerosol concentrations throughout the southern part of the continent (Chung et al., 2005). Another important aspect to study the aerosol properties over Asian region is the effect of aerosol on the rainfall during Monsoon season. General circulation model studies have suggested that anthropogenic aerosol forcing could influence the seasonal rainfall distribution in the monsoon regions over South (Ramanathan et al. 2001, 2005; Chung et al. 2005) and East Asia (Menon et al. 2002).

Atmospheric aerosols have significant local, regional and global impacts. Aerosols impact the global and regional climate through two processes, one is by directly interacting with solar radiation (scattering and absorption), and other is by indirectly modifying cloud microphysics (e.g., Russell et al., 1999; Nakajima et al., 2001). Aerosols consist of many kinds of chemical compounds which have different optical properties. The quantification of aerosol radiative forcing is highly complex because aerosol mass and particle number concentrations are highly variable in space and time. This variability is largely due to the much shorter atmospheric lifetime of aerosols (few hours to a week) and the numerous ways they interact with other elements of the climate system (Kaufman et al., 2002). The radiative effects of aerosols have the largest uncertainties in global climate predictions to quantify climate forcing due to man-made changes in the composition of the atmosphere. A better understanding of the formation, composition and transformation of aerosols in the atmosphere is of critical importance in order to better quantify these effects. Consequently, quantification of this variability requires comprehensive observations. Reliable data as well as, systematic study is needed to understand the complex processes between aerosols and hydrological cycle.

Studies during the Indian Ocean Experiment (INDOEX) have shown that approximately 70% of aerosol load over the oceanic regions surrounding India during winter is of anthropogenic origin (Ramanathan et al., 2001). Eck et al. (2001) have studied the effect

of the monsoon on aerosol optical properties over the Indian Ocean using ground-based Sun-sky radiometer. Concentration of aerosols over the Indian region is found to be increasing, and studies report that the aerosol optical depth (AOD) over the northern part of India is higher as compared to the southern part (Singh et al., 2004; Sarkar et al., 2006; Gautam et al., 2007). The AOD in the northern part of India shows an annual variability with higher aerosol loading during the dry season due to dust events.

Because of short life time of aerosols and variability of the meteorological parameters over Indian subcontinent, a wide network of aerosol monitoring stations is required. Considering this and with the objective to improve our knowledge of the aerosol effects on the Earth's climate, India Meteorological Department has established a network skyradiometer named as India-SkyNet consisting of twelve stations in different geographical stations of India. The network will be expanded further in near future. The long-term research goal is to characterize means, variability, and trends of climate-forcing properties of different types of aerosols, and to understand the factors that control these properties. This paper presents details of the India Meteorological Department's newly established network of sun-skyradiometer "India-SkyNet" consisting of twelve stations located in different geographic regions of India.

## **2. Methodology**

### **2.1 Description of the Skyradiometer System**

Skyradiometer Model POM-02 manufactured by Prede Co. Ltd, Japan is used in IMD-SkyNet. Sky radiometers make measurements in eleven narrow wavebands in the ultraviolet, visible and infrared parts of the solar spectrum (315, 340, 380, 400, 500, 675, 870, 1020, 1627, 2200 nm). The sky radiometer includes a sun- and sky-scanning spectral radiometer, sun sensor, sun tracker, control unit, rain sensor, and a personal computer. The skyradiometer is also equipped with dust protection system. This equipment blows air on the lens surface of Skyradiometer to prevent dust or small insect invading. Detector sensitivity is strongly dependent on temperature, so the detector temperature is kept constant at 20 °C. For this a cooling system is attached with the skyradiometer. During winter season, skyradiometer can be operated without this cooling system.

The sky radiometer observes simultaneously direct and solar aureole radiance at various scattering angles from the Sun which enables estimation of optical parameters of aerosols such as single scattering albedo (SSA), Angstrom coefficient, phase function and

complex refractive index as well as aerosol optical thickness (AOT) for each wavelength and columnar size distribution of aerosols. The wavelength of 940 nm is used for determining water vapor amount and the two wavelengths of 1600 and 2200 nm are used for cloud analysis (cloud optical thickness and effective radius). The measured sky radiometer data have been analysed using SKYRAD.PACK (version 4.2) software [Nakajima et al., 1996] for deriving aerosol optical properties. The instrument is advantageous for sensor calibration as it can estimate aerosol parameters without any calibration constant, using ratios of aureole radiance to direct radiance supposing the known field of view of the sensor [Tanaka et al., 1986]. The sun/sky radiometer can be also calibrated onsite for solid view angle and for absolute sensitivity ( $V_o$ ). This is possible because of the speed of the tracking system. The sun/sky radiometers are operated at least once a month in the disc scan mode on a clear sky day to estimate the solid view angles at different wavelengths as part of a recommended calibration procedure. Disk scan is performed by scanning the area of  $2^\circ \times 2^\circ$  around the solar disk from up to down and from left to right, with an angular resolution of  $0.1^\circ$ . The Normal Langley method of calibration is based on measurements of direct radiation under the hypothesis that optical depth is constant during the calibration. Under most situations, such an assumption is not valid. It was demonstrated by Shaw [1976] that for a typical urban station,  $V_o$  deduced from the Langley method can have an error of approximately 10%. Hence, an improved method of calibration based on both direct and diffuse radiation data [Nakajima et al., 1996] is used here.

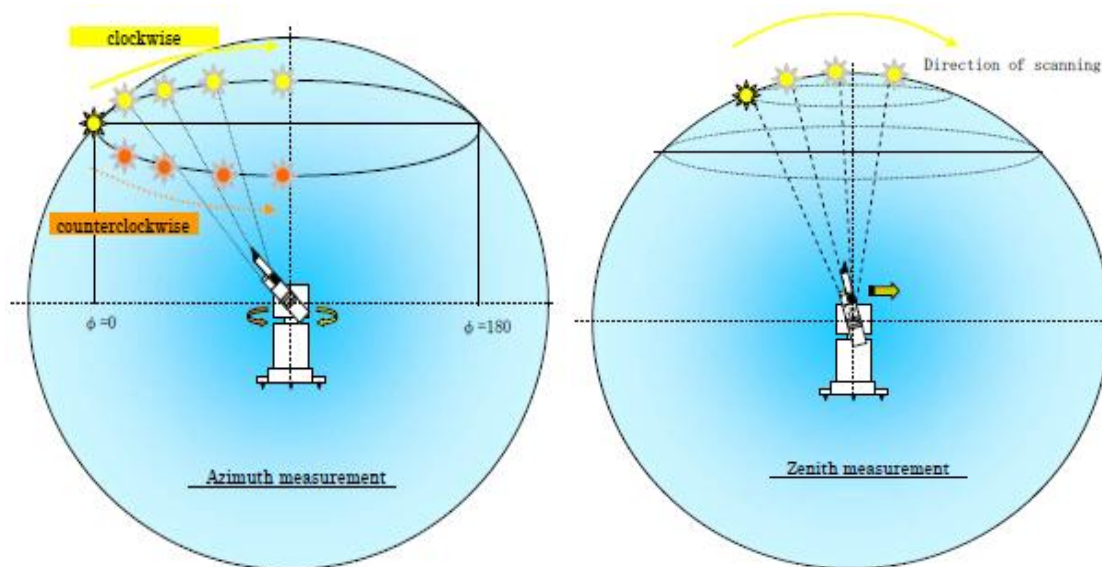


Figure-1: Geometry of the ground-based sky radiometer system. Diffuse solar radiation is measured by two different scanning methods depending on the solar zenith angle.

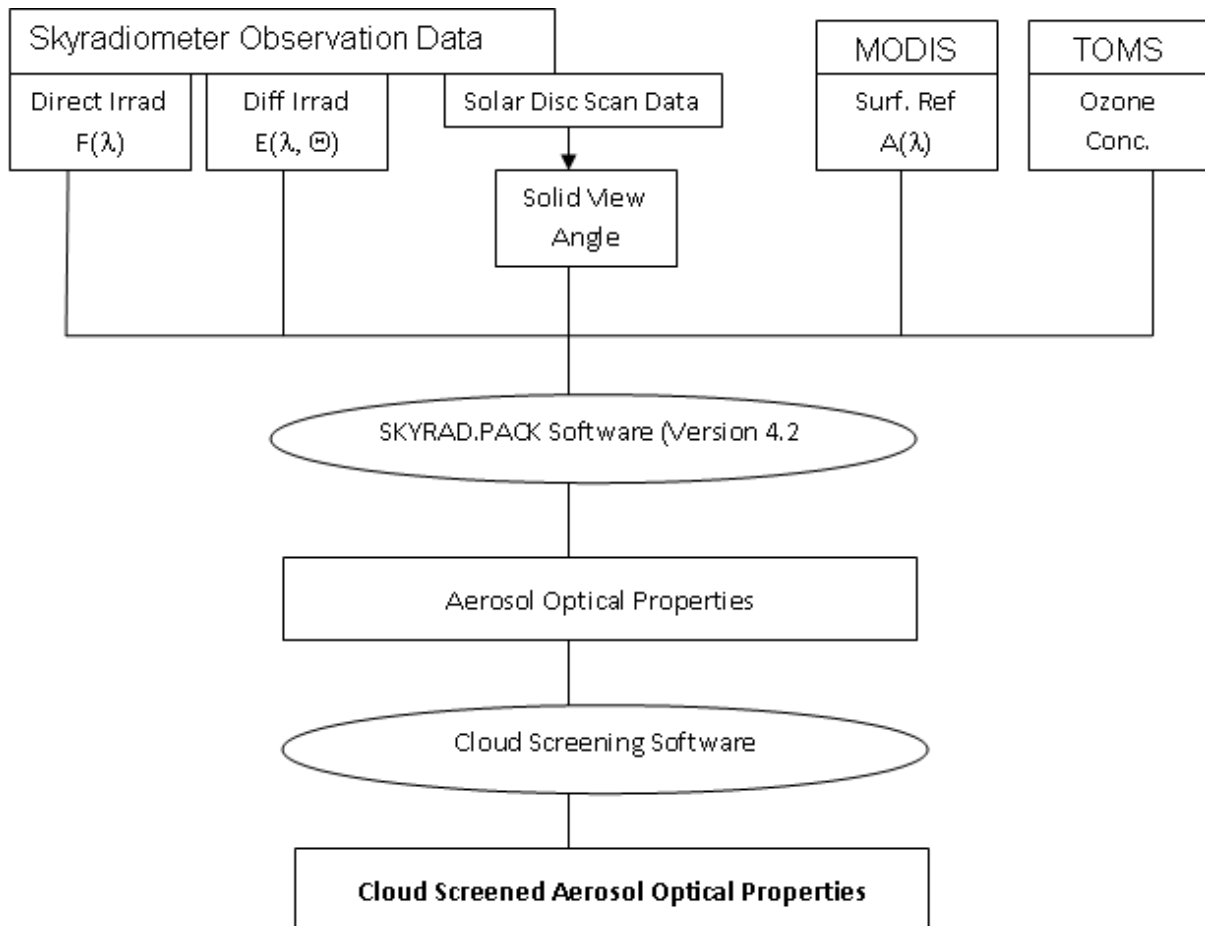
### **Specifications of Skyradiometer POM-02**

Half view angle	0.5°
Min scattering angle	3°
Half Band width	10nm
Channel Wavelength	315 340 380 400 500 675 870 940 1020 1627 2200
Detector	Short wave 315nm - 1020nm: Si photodiode Long Wave 1627nm - 2200nm: InGaAs photodiode
Temperature control	20°C
Tracking control	Stepping Motor: 2 way, Azimuth and Zenith, Stepping angle 0.0036°/pulse
Sun sensor	Si photodiode
Potential tracking area	Azimuth $\pm 300^\circ$ Zenith -60 - 170°
Communication	RS422
Power consumption	200W, 100V/2A
Precipitation sensor to prevent collimating tubes filling with water or snow	

### **2.2 A brief description of SKYRAD.PACK software**

SKYRAD.PACK software can be used with various options (Nakajima et al., 1996). One option is to simulate aerosol optical (spectral aerosol optical thickness ( $\tau$ ), single scattering albedo ( $\omega$ ), normalized phase function or asymmetry parameter ( $g$ ) and physical volume size distribution ( $dV/d\ln r$ )) using the ratio of measured spectral direct and diffuse radiations. This procedure does not require any information of calibration constant for direct radiation ( $F_0$ ), which can be generally obtained using Normal Langley (NL) calibration procedure. To simulate aerosol optical and physical parameters using this technique, one needs only calibration constants for diffuse radiations for each wavelength. Such calibration constants for diffuse radiations i.e., solid view angles (DE), can be obtained using disk scan data of very clear sky days (Nakajima et al., 1996) measured by sky radiometer. Disk scan data are measured by setting an instrument in disk scan mode. This data analysis technique is termed as “level 0” analysis in the manual of SKYRAD.PACK software. Another option is to use  $F_0$  as well as the ratios of measured spectral direct and diffuse radiations and DE to

simulate above mentioned optical and physical parameters and spectral real ( $m_r$ ) and imaginary ( $m_i$ ) refractive indices.  $F_o$  can be estimated using an improved Langley (IL) calibration method (Nakajima et al., 1996). IL is an onsite calibration technique using field observation data. This technique doesn't require strict criteria like NL. This data analysis technique is termed as "level 1" analysis in SKYRAD.PACK software. For detail, see Nakajima et al. (1996) and Campanelli et al. (2002; 2004).



**Schematic diagram of Level 1.0 data analysis method of SKYNET sky radiometers**

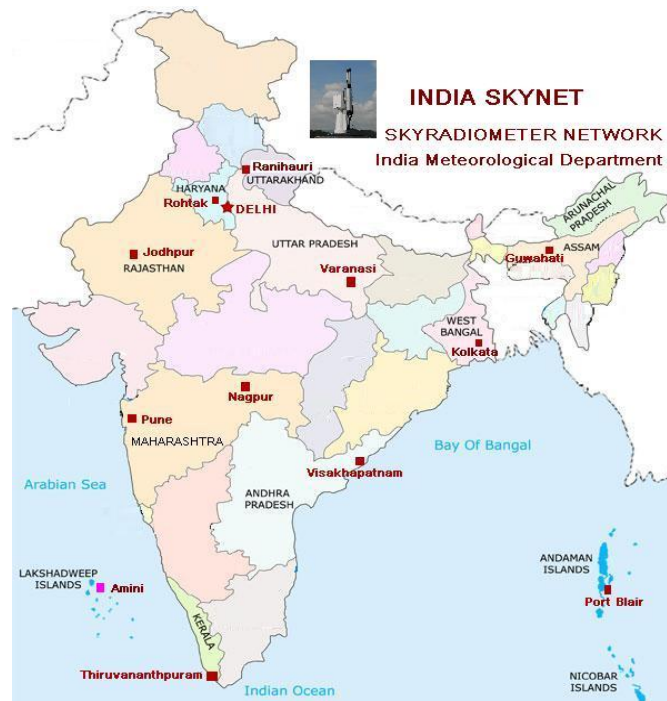
### 3. Details of IMD's India-SkyNet Network

Network of skyradiometer consists of twelve stations locate in different geographical locations. Ranichauri is a high altitude station with background environment. Portblai is an island station in the Bay of Bengal and Vishakapatnam and Thiruvananthapuram are located on east coast of India. New Delhi and Kolkata are Metropolitan cities. Rohtak is close to New Delhi. Jodhpur is located in desert area. Nagpur represents central India. Guwahati is located

in the northeast India. Pune is located on leeward side of Deccan plateau. The raw skyradiomete data are collected at all the twelve stations. These stations are linked to the Central Data Processing System (CDPS) at New Delhi. The data are transferred daily to CDPS through broadband internet automatically. The data are processed and quality controlled to get the useful products.

**Table-1: Details of India-SkyNet stations**

S.No.	WMO Index	Station	Latitude °N (deg min)	Longitude °E (deg min)	Altitude (m)
1.	43063	Pune	18 32	73 51	559
2.		Ranichauri	30 15	78 05	1800
3.	42410	Guwahati	26 06	91 35	54
4.	42339	Jodhpur	26 18	73 01	224
5.	42867	Nagpur	21 06	79 03	310
6.	43333	Port Blair	11 40	92 43	79
7.	43371	Thiruvananthapuram	08 29	76 57	60
8.	43150	Vishakapatnam	17 43	83 14	18
9.	42483	Varanasi	25 18	83 01	90
10.	42809	Kolkata	22 39	88 27	88
11.	42176	Rohtak	28 50	76 35	214
12.	42182	New Delhi	28 35	77 12	216



**Figure-2: Map showing location of the India-SkyNet stations**

#### **4. Dust plume over India: An observational study using Skyradiometer data**

On March 20, 2012, a giant dust plume stretched across the Arabian Sea, from the coast of Oman in the west to the coast of India in the east. This extensive plume followed days of dust-storm activity over the Arabian Peninsula and Southwest Asia. The dust storm resulted from two different storms converging. The first front carried dust from Iraq and Kuwait, and the second front stirred dust in southeastern Iran. The storm causing low pressure moved eastward, reaching over southeastern Iran and kicking up dust and sand that engulfed the northern region of UAE, parts of Oman, and the western coastal areas of Pakistan up to Karachi.

On 17.03.2012, a low pressure formed over northern Iraq, and winds quickly accelerated towards the centre of the low, blowing from eastern Syria to Iraq which led to the formation of a sandstorm, covering the entire land of Iraq. A high pressure with cold air formed behind the low, ensuring all the dust will move southeastward into Arabia. The sandstorm quickly engulfed Kuwait and Saudi Arabia. Later, sandy conditions made their way to Bahrain and Qatar with gusty winds. On Sunday March 18, dusty conditions reached the UAE but with much less intensity as the high pressure caused the major sandy air to turn clockwise into central Saudi Arabia and then reach Yemen. Mar 19, 2012: As the low and high pressure travelled eastward in close proximity, large pressure gradients set over SE Iran and SW Pakistan on 19<sup>th</sup> March, resulting in another, yet rare, massive sandstorm there. The sand and dust got pushed southward over the Gulf of Oman, into the northeastern coastlines of UAE and northern coastlines of Oman. This is incredibly rare as it is not a typical area for such large scale sandstorms. Large part of Oman, got hit by sandy conditions worse than other parts of the country, with visibility going down to 500m. These cities are usually the least dusty as they are much more protected from the sand of the Empty Quarter (The Rub' al Khali; one of the largest sand deserts in the world). But this time all the dust came from the north, from Iran and Pakistan and the mountains of the east coast trapped the dust.

The winds that brought the dust over Indian region were blowing 5.8 km above sea level. The large scale dust plume caused visibility to fall from 11.30 AM in Delhi when it suddenly fell from 3,000m to 1,000m. Cities like Jaipur, Jodhpur, Ahmedabad and Ludhiana had visibility of 500-800 m in the morning hours.

#### **4.1 Changes in Aerosol Optical Characteristics due to Dust Events**

##### **4.1.1 Volume Size Distribution**

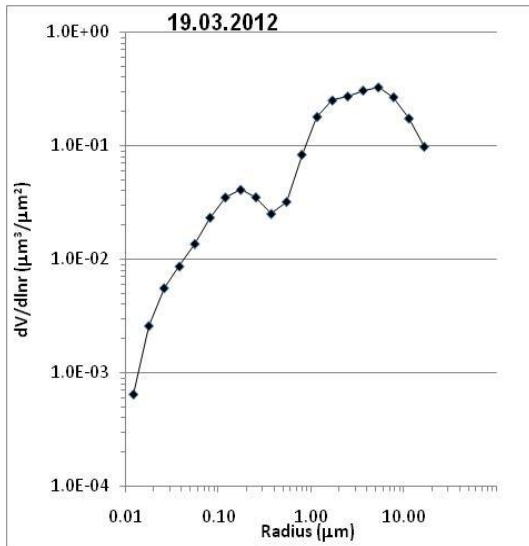


Radiative impact of aerosols depends not only on aerosol concentration in space and time but also on their size and chemical composition. Compared to anthropogenic sulfate, desert dust is generally larger in size and more absorbing at solar and infrared wavelengths. This results in increased atmospheric heating along with decreased incident solar radiation at the ground and some greenhouse trapping of outgoing thermal radiation [Lubin et al., 2002]. The volume size distribution was retrieved from the direct solar and diffuse sky radiance measurements as discussed by Nakajima et al. [1996]. An improved version of the Skyrad.Pack radiative-transfer model is used (Version 4.2) in the present study. In the retrieval algorithm, it is assumed that the aerosols are composed of spherical and homogeneous particles. Scattering is simulated using Mie formulation, and multiple scattering effects are also taken into account. Figure-3(a) and 4(a) shows the ensemble of daily average aerosol volume size distribution retrieved from the sun/sky radiance data for clear sky day of 19<sup>th</sup> March, 2012 at New Delhi and Jodhpur. It can be seen that the aerosol distribution is bimodal with fine-particle mode around 0.1–0.2  $\mu\text{m}$  and coarse particle mode around 3–4  $\mu\text{m}$  as represented in

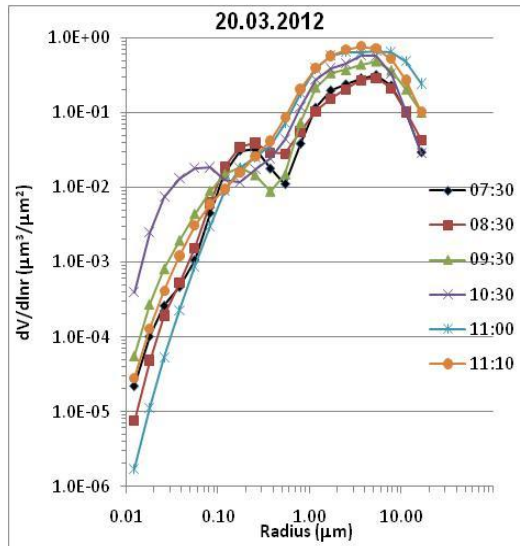
$$\frac{dV}{d\ln r} = \frac{V_o}{\sigma(2\pi)} \exp\left(-\frac{\ln[r/r_m]^2}{2\sigma^2}\right)$$

where  $dV/d\ln r$  is the volume size distribution,  $V_o$  is the column volume of particles per cross section of atmospheric column,  $r$  is the radius,  $r_m$  is the modal radius, and  $\sigma$  is the standard deviation of the natural logarithm of the radii.

On 19.03.2012, the volume of coarse-particle fraction is lower than on 20<sup>th</sup>, 21<sup>st</sup>, 22<sup>nd</sup> March, 2012. In strong contrast to aerosols from biomass burning and urban aerosols (dominated by fine mode accumulation particles) dust (dominated by coarse mode particles) is composed of airborne desert soil material.

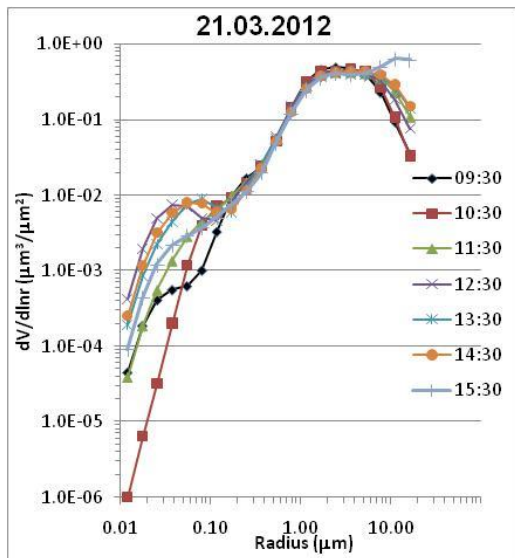


(a)

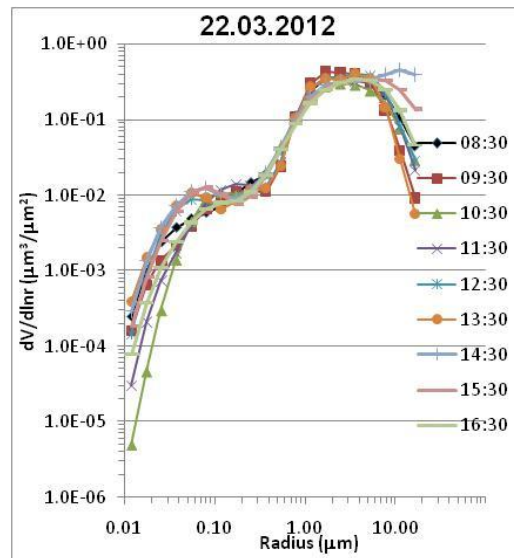


(b)

**Figures-3: (a) Mean Sun-skyradiometer derived aerosol volume size distribution on clear sky day of 19.03.2012 at New Delhi (b) Sun-skyradiometer derived hourly aerosol volume size distribution during the dust event on 20.03.2012 at New Delhi. The skyradiometer observations are not available after 11:10 AM IST as the sun obscured completely.**

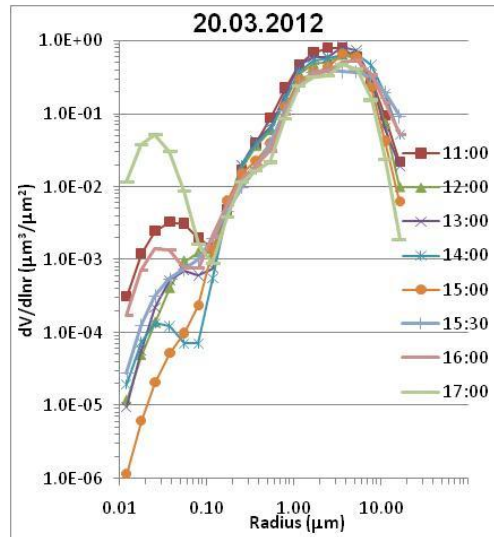
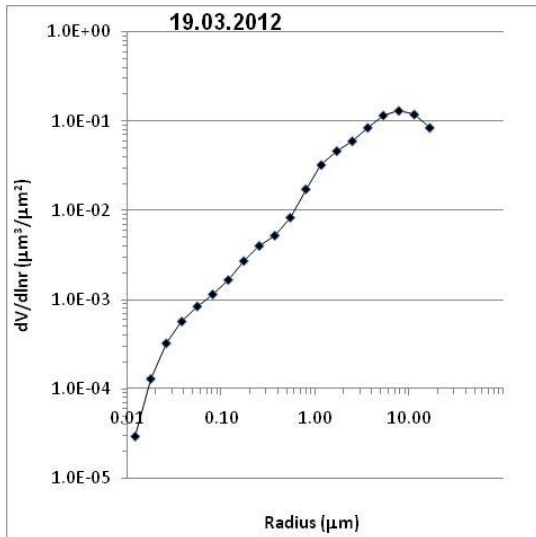


(c)

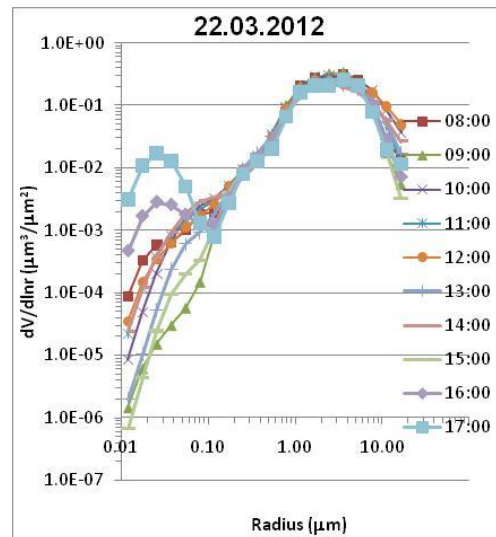
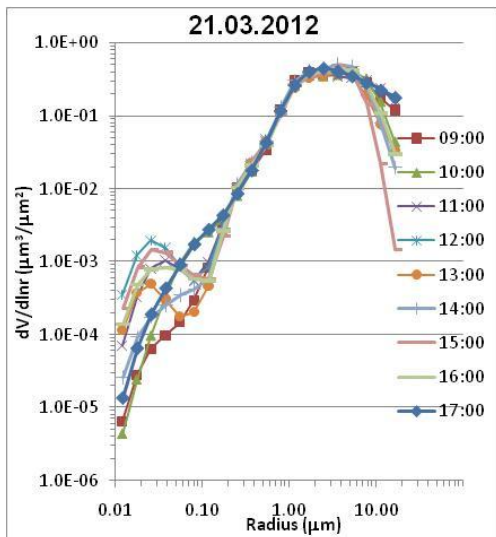


(d)

**Figures-3: (c) and (d) Sun-skyradiometer derived hourly aerosol volume size distribution during the dust event on 21.03.2012. The dust haze was prevailing over Delhi on 21.03.2012.**



**Figures-4: (a) Mean Sun-skyradiator derived aerosol volume size distribution on clear sky day of 19.03.2012 at Jodhpur (b) Sun-skyradiator derived hourly aerosol volume size distribution during the dust event on 20.03.2012 at Jodhpur**



**Figures-4: (c) and (d) Sun-skyradiator derived hourly aerosol volume size distribution during the dust event on 21.03.2012 and 22.03.2012.**

#### 4.1.2 Aerosol Optical Depth, Angstrom Exponent and Single Scattering Albedo

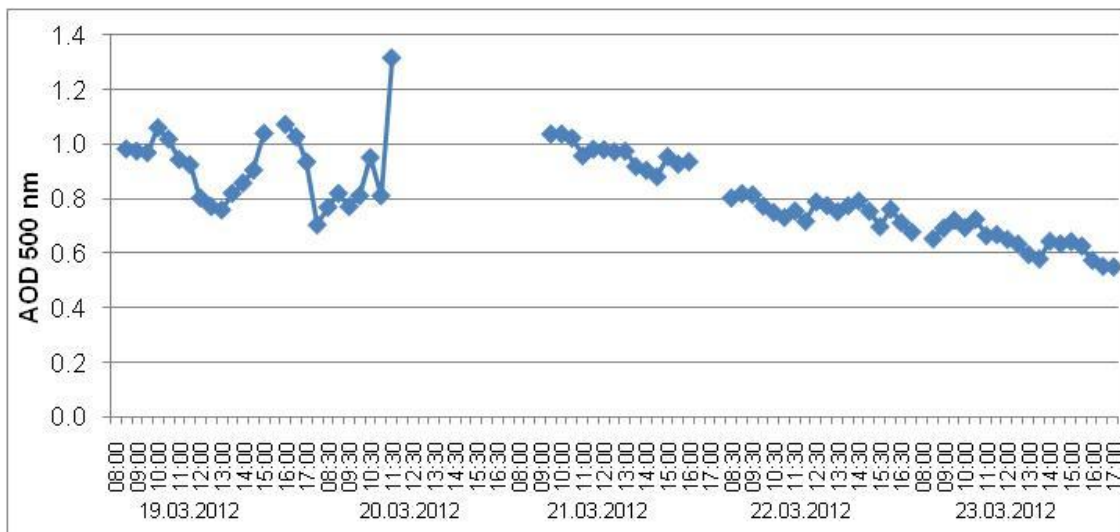
The indication of dust plume at Jodhpur and New Delhi sites is clearly seen; as indicated by high AOT and low alpha values. The Aerosol Optical Depth (AOD) is representative of the airborne aerosol loading in the atmospheric column and is important for the identification of aerosol source regions and their evolution. The Ångström exponent is inversely related to the average size of the particles in the aerosol: the smaller the particles, the larger the exponent. Higher Ångström exponents indicate smaller aerosol particles, and vice versa. Ångström exponent values generally range from greater than 2.0 for particles near combustion sources to values close to zero for coarse-mode-dominated desert dust aerosols.

The Angstrom exponent became close to zero and AOD values as high as 1.5 is observed at Jodhpur and Delhi on 20<sup>th</sup> March which indicates the rapid increase of dust in the air column. On the day of the dust event, the AOD values were 2 to 3 fold larger than on non-dusty days. Also, at this time the AOD showed a trend reversal in which AOD increased with wavelength. Figure-5 and 6 show the half-hourly variations of the AOD at 500 nm for the four days of the study period. On 19<sup>th</sup> March, the AOD was around 0.2 at Jodhpur. The AOD value, jumped to 1.5 around 11:00AM, indicating the increased aerosol loading associated with the arrival of the dust storm. AODs remained at high values for the next four hours, and then decreased gradually to reach a value of 0.723 by the end of the day. The increase in average AOD was accompanied by a similar increase in the standard deviation, indicating greater variability in the atmospheric aerosol loading during that day. For example, the standard deviation during the day of the dust event was 0.389 at 500 nm compared with 0.022 on the preceding day. This large variability can be related to the properties of the air mass transporting the aerosols into the study area.

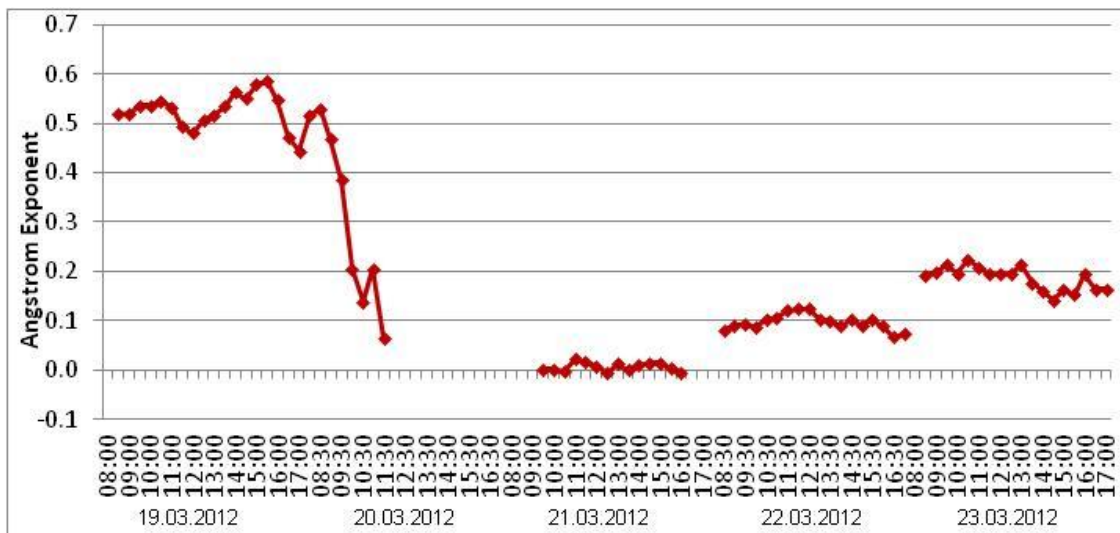
Aerosols can scatter and absorb solar and infrared radiation in the atmosphere. The scattering versus absorption properties of an aerosol are measured by the value of the single-scattering albedo. Single Scattering Albedo (SSA), which is a fraction of scattering in the total extinction and is a key optical characteristic in assessing the radiative effects of aerosols. Single scattering albedo is defined as the ratio of scattering efficiency to total extinction efficiency (a sum of scattering and absorption). The SSA depends on the aerosol size distribution and chemical composition and is wavelength dependent. It is a dimensionless quantity. Values of single scattering albedo range from 1.0 for non-absorbing particles (perfectly white object) to below 0.5 for strongly absorbing particles and zero for a perfectly black object. SSA helps determine whether aerosols have a heating or cooling effect on climate in their interaction with solar radiation.

The sign at the top-of-the atmosphere (TOA) forcing can change depending on the aerosol SSA [Takemura et al., 2002]. Figures-5(c) and 6(c) show the time series of half hourly average SSA at 500nm. In the present study, SSA at 0.5  $\mu\text{m}$  is found to vary between 0.86 and 0.90 with an average value about 0.88 before the dust event. On 20.03.2012 the SSA decreased to 0.82 to 0.84. Also the SSA was found to increase with wavelength mainly owing to abundance of coarse mode particles. Seinfeld et al. [2004] also demonstrate that aerosols in mixed state (adding black carbon and other aerosols to the mineral particles) can change dust aerosol radiative effects in many ways [Chandra et al., 2004]. Previous studies show that dust

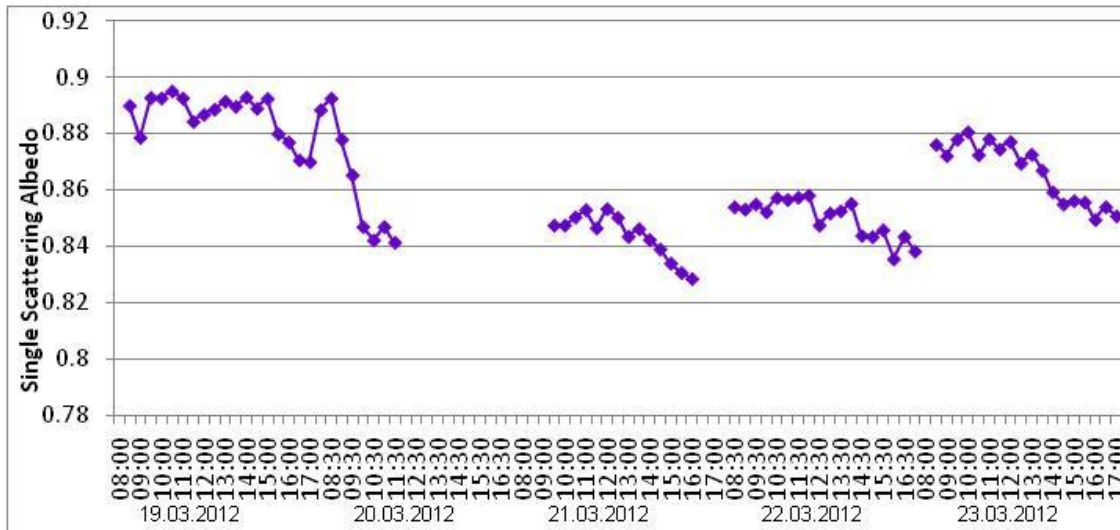
transported from East Asia to the Pacific does not absorb as much light as aerosols from South Asia or from the Sahara Desert [Seinfeld et al., 2004]. The Delhi region is known as one of the world's most polluted urbanized areas. Vehicular emissions, thermal power plants and other industrial units are the major polluting sources. Biomass burning is another important source, as wood is the most widely used fuel in this region. Dust particles internally mixed with soot, sulfates, nitrates, or aqueous solutions can have drastically different properties from those that are evident at the dust source. The ability of dust particles to scatter and absorb solar and terrestrial radiation can be altered in different ways depending on the species that aggregate with dust particles.



(a)

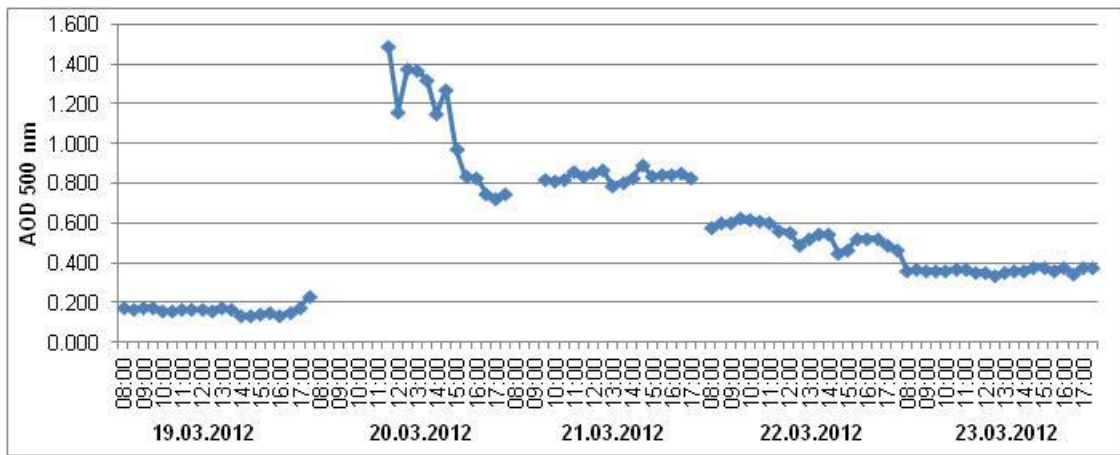


(b)



(c)

Figure-5: Half hourly values of aerosol parameters at New Delhi from 19.03.2012 to 23.03.2012 (a) aerosol optical depth at 500 nm (b) Angstrom Exponent (c) Single Scattering Albedo at 500 nm.

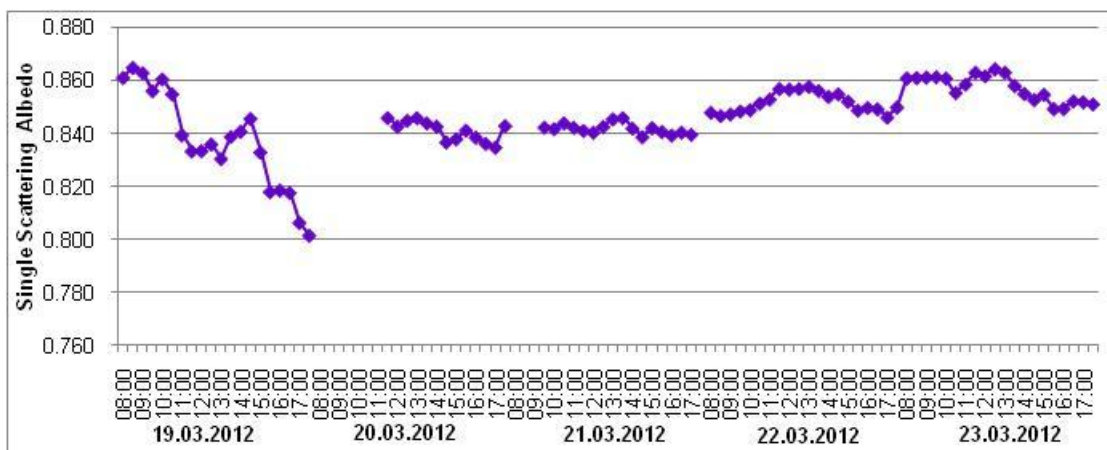


(a)



(b)





(c)

Figure-6: Half hourly values of aerosol parameters at Jodhpur from 19.03.2012 to 23.03.2012 (a) aerosol optical depth at 500 nm (b) Angstrom Exponent (c) Single Scattering Albedo at 500 nm.

## 5. Concluding Remarks

Indian region was lacking a dense ground-based atmospheric network that will provide long term in-situ observations of aerosol properties. The network “India-SkyNet” will characterize means, variability, and trends of climate-forcing properties of different types of aerosols, and help in understanding the factors that control these properties. The overall objective of establishing this network is to improve the observations of the in-situ aerosol properties and ensure quality assured and quality controlled data on aerosols.

## 6. Acknowledgement

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