

Observations of aerosols from space : An overview

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सार – एरोसॉल प्राकृतिक और मानवोद्भवी (मानव-निर्मित) मूल के होते हैं। एरोसॉल सौर और स्थलीय विकिरण के प्रकीर्णन और अवशोषण द्वारा प्रत्यक्ष रूप से और मेघ संघनन नाभिकीय के रूप में कार्य करके मेघों की परावर्तकता में वृद्धि द्वारा अप्रत्यक्ष रूप से जलवायु को प्रभावित करते हैं। जलवायु पर एरोसॉल के प्रभाव का आकलन करना जटिल कार्य है क्योंकि स्थानिक और कालिक दोनों तरह से उनकी रसायनिक संरचना, अधिकता और आकार के लक्षण बहुत अधिक परिवर्तनशील हैं। एरोसॉलों का मापन स्वस्थाने (प्रत्यक्ष) अथवा परोक्ष हो सकता है। क्षेत्रीय अथवा भूमंडलीय स्केल में एरोसॉल की विशेषताओं का चित्रण करने के लिए केवल उपग्रह पर आधारित सुदूर संवेदन ही विकल्प है। सतह जैसे महासागर अथवा स्थल के दूर संवेदन के लिए उपग्रह से प्राप्त संकेतों के वायुमंडलीय प्रभाव को संशोधित करने के लिए एल्गोरिथ्म में वायुमंडलीय संशोधनों को भी शामिल किया जाना चाहिए। तथापि, एरोसॉल की विशेषताओं जैसे उसकी रसायनिक संरचना के दूर संवेदन का कार्य अभी भी अत्यंत कठिन है। इस शोध-पत्र में, भारतीय क्षेत्र पर विशेष रूप से बल देकर उपग्रह से प्राप्त आँकड़ों का उपयोग करके हमने एरोसॉल की जाँच की समीक्षा की है। एरोसॉल के दूर संवेदन के लिए उपयोग किए गए विभिन्न संस्रों एवं एल्गोरिथ्म पर तथा भविष्य में उनके विस्तार पर भी चर्चा की गई है।

ABSTRACT. Aerosols are of natural and anthropogenic (man-made) origin. Aerosols directly affect the climate by scattering and absorption of solar and terrestrial radiation and indirectly by enhancing the reflectivity of clouds by acting as cloud condensation nuclei. Estimation of effects of aerosols on climate is complicated by the fact that their chemical composition, abundance and size characteristics are highly variable both spatially and temporally. Measurement of aerosols can be *in situ* (direct) or remote. For mapping aerosol properties on a regional or global scale, satellite based remote sensing is the only option. For the remote sensing of surface such as ocean or land, algorithms should include atmospheric corrections to correct for the atmospheric effect to satellite measured signals. However, remote sensing of aerosol properties such as its chemical composition is still extremely difficult. In this paper, we review the investigations of aerosols using satellite data with emphasis to Indian region. Various sensors and algorithms used for the remote sensing of aerosols and future scope are also discussed.

Key words – Aerosols, Remote sensing, Scattering, Climate.

1. Introduction

Atmospheric aerosols are defined as particles of solid or liquid phase dispersed in the atmosphere (Murthy, 1988; Subbaraya *et al.*, 2000). The aerosols are produced mainly by the mechanical disintegration processes occurring over land and ocean and by chemical reactions occurring in the atmosphere. Aerosols directly affect the climate by scattering and absorption of solar (visible) and terrestrial radiation (infrared) and indirectly by enhancing the reflectivity of clouds by acting as cloud condensation nuclei (Charlson *et al.*, 1991, 1992). More aerosols produce more cloud droplets. Estimation of effects of aerosols on climate is complicated by the fact that aerosols and their chemical composition, abundance and size characteristics are highly variable both spatially and temporally. After production aerosols are often carried to

locations far away from their sources (Jaenicke, 1993). For *e.g.*, wind-borne transport of Saharan dust over the Atlantic Ocean (Prospero *et al.*, 1983). Since most of the aerosol sources are located near the Earth's surface, their abundance is larger near the surface, though occasionally there may be layers aloft as well, depending on the atmospheric vertical temperature structure.

In recent years, there has been a substantial increase in interest in the influence of aerosols on the climate through both direct and indirect effects (Subbaraya *et al.*, 2000). In satellite remote sensing applications, the knowledge of aerosol characteristics is essential for correcting the effect of aerosols on satellite imageries. There are two processes of aerosol interaction with radiation; scattering and absorption. The absorption of radiation at any level in the atmosphere will lead to

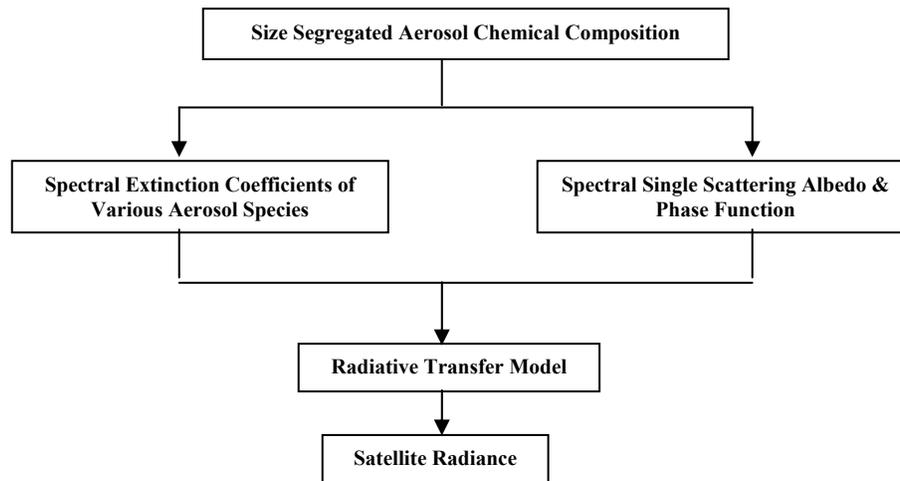


Fig. 1. Block diagram showing the simulation of satellite radiance

heating of the atmosphere and scattering leads to increase in reflectance of earth (albedo) and thereby cooling the climate system (Hansen *et al.*, 1998; Haywood *et al.*, 1999). Increase or decrease of aerosol may also lead to change in cloud properties like size of cloud droplets (larger number of aerosols would imply smaller cloud droplets and smaller number of aerosols would imply larger cloud droplet for the same amount of water vapour present), which also affect the cloud lifetime (Ramanathan *et al.*, 2001).

The top of the atmosphere radiation budget influences the climate (Murthy, 1988). Top of the atmosphere (TOA) radiation budget data can be most efficiently obtained (regionally and globally) based on the satellite-borne measurements. Several past and present satellite missions have significantly contributed to the present understanding of the Earth's radiation budget (King *et al.*, 1999). In addition to the radiation budget, satellites are useful for observing the synoptic regional and global distribution of aerosol properties (such as aerosol optical depth).

2. Basics of aerosol remote sensing

Ground based measurements basically involve measurement of extinction of direct solar light from the sun (Shaw *et al.*, 1973). The same technique is utilized in satellite occultation measurements but is restricted to the stratosphere and upper troposphere (McCormick *et al.*, 1979). The most basic aerosol characteristic retrieved from any single wavelength measurement is the extinction or aerosol optical depth. This is done once we know the influence of air molecules and an idea of the surface reflectance. There are many methods employed for the quantification of aerosol characteristics; they are measurements involving single wavelength, multiple wavelength, multiple angle and also polarization methods.

The simplest case of remote sensing is that over black surface (*e.g.* ocean for near infrared) where the satellite observed radiance at the top of the atmosphere is only due to photons back scattered by the atmosphere (Kaufman *et al.*, 1997; King *et al.*, 1999).

Atmospheric Reflectance,

$$R_{\text{atmos}} = \frac{\pi L^{\text{TOA}}(\mu, \phi, \mu_0, \phi_0)}{\mu_0 F} \quad (1)$$

Where μ_0 is the solar zenith angle, ϕ_0 is the solar azimuth angle, μ is the satellite view angle, ϕ is the satellite azimuth angle, F is the solar constant, and L^{TOA} is the satellite observed radiance.

In case of black surface, $L_S=0$ and $L^{\text{TOA}} = L_P$.

Top of the atmosphere radiance is due to both molecules and aerosols.

$$L^{\text{TOA}} = L_{\text{molecules}} + L_{\text{aerosols}} \quad (2)$$

The boundary conditions in this case are (i) incoming solar radiation at the top of the atmosphere and (ii) black surface (no illumination at the bottom of the atmosphere).

The molecular composition of the atmosphere is known with reasonable accuracy. Thus if the aerosol characteristics are also known, then we can estimate the top of the atmosphere radiance, $L^{\text{TOA}}(\mu_0, \phi_0, \mu, \phi)$ for any Sun-satellite geometry. This is the forward problem (Fig. 1). In satellite remote sensing of aerosols, the observed quantity is top of the atmosphere radiance, L^{TOA} measured using satellites. In this case, the signal received by satellite is a function of the target (in this case,

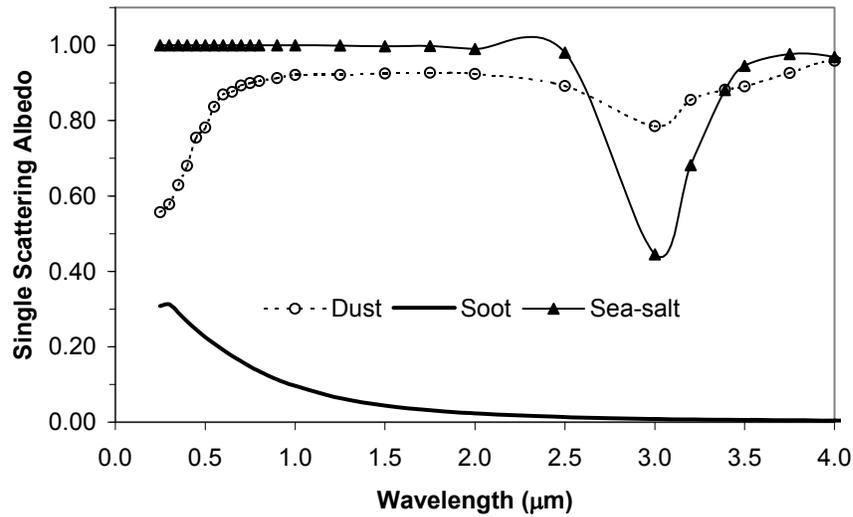


Fig. 2. Spectral single scattering albedo for various aerosol types

aerosols). The parameter to be retrieved is the aerosol characteristics. This is more complex inverse problem and the solution is not unique (Kaufman *et al.*, 1997). There can be a large number of combinations of aerosol properties, which can reproduce the same TOA radiance. The single scattering albedo of three major aerosol components are given in Fig. 2 (Hess *et al.*, 1998). However, if direct measurements are available at carefully selected points within the observation region, that can provide some broad information about the aerosols in that region. Moreover, once aerosol parameters (such as aerosol optical depth) are retrieved, it can be validated using ground based or aircraft based aerosol measurements at selected points within the region of observation.

The aerosol parameters of general interest to be retrieved from satellite data are (i) aerosol columnar concentration (ii) optical depth as a function of wavelength (iii) phase function as a function of wavelength (iv) single scattering albedo as a function of wavelength (v) aerosol size distribution and (vi) chemical composition.

Examples of different sensors using different measurement techniques are given below.

(i) Single measurement: Advanced Very High Resolution Radiometer (AVHRR).

(ii) Multi-spectral Measurement: Moderate Resolution Imaging Spectroradiometer (MODIS).

(iii) Multi-angle measurement: Multi-angle Imaging Spectroradiometer (MISR).

(iv) Polarisation Measurement: Polarisation and Directionality of Earth's Reflectance (POLDER).

(v) Various combinations of the above measurements can be efficiently used for the retrieval of aerosol information.

2.1. Single scattering

Over a black background, satellite observed radiance in the visible and near infra red wavelengths can be written as,

$$L^{\text{TOA}} = L_0 T_0 + L_{\text{molecules}} + L_{\text{aerosols}} \quad (3)$$

Where L_0 is the radiance leaving the surface, T_0 is the transmittance of the atmospheric column from surface to satellite, $L_{\text{molecules}}$ is the radiance due to Rayleigh scattering, and L_{aerosol} is the radiance scattered by aerosols.

Assuming single scattering (*i.e.* $\tau_a < 0.4$), the radiative transfer equation can be solved to get,

$$L_{\text{aerosol}} = \frac{\omega}{4\pi} E_{\text{sun}} P(\psi) \frac{\tau_a}{\mu} \quad (4)$$

Where $\mu = \cos \theta_z$, ω is the aerosol single scattering albedo, E_{sun} is the solar constant, $P(\psi)$ is the phase function, $\psi = \theta_z + \theta_0$, τ_a is the aerosol optical depth, θ_z is the solar zenith angle and θ_0 is the satellite view angle.

If the aerosol load is relatively less, then single scattering assumption can be safely used especially over remote marine locations.

2.2. Multiple scattering

When aerosol load is relatively high, (*i.e.*, $\tau_a > 0.4$), then radiation scattered once by aerosols may get scattered again by other scatterers (Coakley and Cess, 1983, 1985). This is called multiple scattering. When multiple scattering is present in the atmosphere a simple equation (4) (as in the case of single scattering) is not sufficient describe the TOA radiance. In this case, radiative transfer model that includes multiple scattering effects has to be run to estimate radiance (Fig. 1).

In the case of multiple scattering, instead of simple equation, simple look up tables of radiance *versus* aerosol optical depth has to be used (Kaufman *et al.*, 1997; King *et al.*, 1999). Radiative transfer equation has to be solved for different aerosol models and tables can be generated for radiance for different aerosol optical depths. For a given aerosol model, for given solar zenith angle, θ_z

$$L^{\text{TOA}} = L^{\text{TOA}}(\tau_a) \quad (5)$$

For each aerosol model,

$$L^{\text{TOA}} = L^{\text{TOA}}(\tau_a, \theta_z) \quad (6)$$

This means that a basic knowledge of the aerosol properties over a region is essential (at least for selected points) mapping that region.

King *et al.* (1999) has provided an overview of the past, present and future satellites and its applications to aerosol remote sensing.

3. Various space-borne sensors

Global and continuous coverage are the two main advantages of space-based platforms (Stowe *et al.*, 1997). Their low accuracy and poor spatial resolution are their main shortcomings. Since these measurements are taken from several hundreds of kilometers above the ground their intelligent retrieval is very important for these measurements to be accurate (King *et al.*, 1999). These signals that reach the sensors after traveling through the atmosphere would have undergone attenuation due to absorption and scattering as well as polarization. Aerosols are present both in troposphere and stratosphere. Stratospheric concentrations are generally quite small, except following major volcanic eruptions, such as Mount Pinatubo (McCormick *et al.*, 1995; Moorthy *et al.*, 1996).

The stratospheric aerosol optical depth is typically an order of magnitude smaller than the tropospheric optical thickness. It can be inferred by using satellite occultation measurements (*e.g.*, Stratospheric Aerosol and Gas Experiment, SAGE) (Kent *et al.*, 1995). Satellite like Upper Atmospheric Research Satellite (UARS) also primarily focuses on observation of stratosphere.

Several satellites have been launched in to the space with different types of sensors to obtain data on several parameters. But sensors designed to obtain specifically aerosol properties have always been less in number. Data from geo-stationary meteorological satellites (*e.g.*, METEOSAT) and polar orbiting instruments as National Oceanic and Atmospheric Administration (NOAA) Advanced Very High Resolution Radiometer (AVHRR) have been widely used for the studies of aerosols over the oceans (Husar *et al.*, 1997; Moulin *et al.*, 1997). However, for understanding of the impact of aerosols on climate requires a correct determination of the aerosol spectral optical properties. This limits the use of broadband sensors for accurate aerosol quantification due to their wide spectral channels. On one hand, they do not allow for aerosol type characterization, constraining the algorithms to the use of standard aerosol models available in the literature and thus introducing significant errors in the optical depth retrievals. Now due to the greater understanding of the importance of aerosols, sensors like POLDER are designed specifically to obtain aerosol information (Mishchenko and Travis, 1997). To obtain the vertical profile of aerosols, advanced sensors like LIDAR become essential and experiments like LITE (Lidar in space Technology Experiment) by NASA are under way to develop an active sensor to probe vertical variation of aerosols.

A few important sensors used in the retrieval of aerosol information are discussed in brief below.

3.1. NOAA-AVHRR

The first retrieval of aerosol information was made from the data from Advanced Very High Resolution Radiometer (AVHRR) sensors in the NOAA series of satellites. AVHRR is a five-band cross track scanning radiometer. NOAA has retrieved aerosol thickness over the oceans since 1981 using the NOAA polar orbiting satellite series. The single-band (0.63 μm) algorithm was applied to the backscattering half of the scan swath avoiding the sun glint. The first maps of aerosol optical depth were produced operationally above the oceans by using the 0.63 μm channel (Stowe *et al.*, 1990). Improvements have been made in the retrieval algorithms thereafter. Nakajima and Higurashi (1997) have retrieved the aerosol optical depth and the size parameter of Junge

TABLE 1

NOAA AVHRR sensor characteristics

Band	NOAA-6, 8,10	NOAA-7, 9,11,12,14	IFOV
1	0.58 - 0.68	0.58 - 0.68	1.39
2	0.725 - 1.10	0.725 - 1.10	1.41
3	3.55 - 3.93	3.55 - 3.93	1.51
4	10.50 - 11.50	10.50 - 11.50	1.41

distribution using channel 1 and 2 of NOAA AVHRR-11. The characteristics of AVHRR sensor are given in Table 1.

3.2. TOMS

Total Ozone Mapping Spectrometer (TOMS), launched in 1978 on Nimbus-7 space platform. The field of view (FOV) of TOMS is 3×3 degrees (swath width: 42×42 km) and its scanning angle is ± 55.5 degrees (approx. 2,800 km of the ground surface) along the track. This wide swath width can cover the entire earth surface in a day. Its main objective is the retrieval of ozone information. But using its 0.340 and 0.380 μm channels outside ozone absorption band, it was possible to sense the presence of absorbing aerosols. The ultraviolet scanning monochromator onboard has a large FOV (50 kms). It is sensitive to absorbing aerosol particles, both over land and ocean. But its large footprint makes sub pixel cloud contamination by far its largest problem, and uncertainties in the height of the aerosol layer. TOMS has been instrumental in monitoring biomass burning and in following its large-scale transport in earlier periods.

3.3. POLDER

Polarization and Directionality of the Earth's Reflectance (POLDER), developed by French Space Agency, CNES (Centre National d'Etudes Spatiales). POLDER is an optical sensor for observing the surface reflectance in visible and near infrared bands (Mishchenko and Travis, 1997). The major advantages are that POLDER can observe an area from 14 different directions in 16 different wavelengths of the reflected solar light. This observation helps to understand angular characteristics of the earth's reflectance. In addition, POLDER can observe multi-polarization in multi-bands by rotating 16 types of interference filters and polarisers (King *et al.*, 1999). It is expected that the dependence of polarization on shape and chemical composition would allow this information to be retrieved from POLDER data (Kaufman *et al.*, 1997). Similar to TOMS, the wide FOV of POLDER enables the entire earth surface to be scanned four times in 5 days, its swath width is 2,200 km, and its spatial resolution is 7×6 km. POLDER can improve

TABLE 2

MODIS and MISR sensors

Sensor	Wavelength	Resolution	Application
MODIS	0.4-14.4 μm	250-1000 m	Ocean colour, vegetation, clouds, aerosol concentration and properties, temperature and moisture soundings, snow cover and ocean currents.
MISR	0.446, 0.558, 0.672, 0.886 μm	250-275 m	Types of aerosols and scattering properties, clouds, land surface cover

understanding the dynamics of the aerosols in the troposphere and the potential effects of clouds on the radiative balance of the Earth. This sensor is being used to obtain aerosol characteristics both over land and oceans. The information retrievable from POLDER measurements are aerosol optical depth, aerosol refractive index (and in turn single scattering albedo), and size distribution and phase function. POLDER is flown in ADEOS, ADEOS II satellites of NASDA (National Space Development Agency of Japan).

3.4. MODIS and MISR

The Moderate Resolution Imaging Spectrometer (MODIS) on board the Earth Observation Satellite (EOS) series, Terra is capable of observing aerosol properties over ocean and land (Kaufman *et al.*, 1997; Tanre *et al.*, 1997; King *et al.*, 1999, 2002). Terra is part of the Earth Observing System (EOS) of NASA. It has five sensors of which MODIS and MISR (Multiangle Imaging Spectroradiometer) can be used to retrieve aerosol information (Tanre *et al.*, 1997; Martonchik, 1997) (Table 2). MODIS is a scanning imaging radiometer that contains a cross-track scanning mirror, collecting optics, and a set of linear arrays with spectral interference filters. The cross-track scan rate of the continuously rotating double-sided scan mirror is 20.3 rpm. The swath of the scan is 2330 km cross track by 10 km along track. One of the main objectives of MODIS was to observe aerosol concentration and properties (Kaufman and Tanre, 1996). The MODIS algorithm has several constraints over land retrieval of aerosol optical depth. First is that aerosol optical depth can only be retrieved over moist or semi arid surfaces. This immediately excludes the Saharan desert, Tibetan plateau, and parts of southwestern USA. Aerosol optical depth cannot be retrieved over snow and ice because of the high background reflectance that would mask the aerosol signature.

TABLE 3

Reflectance of different types surfaces and their combinations

Surface Type	0.4 - 0.7 μm	0.7 - 1.5 μm	1.5 - 3.0 μm
Soil	0.178	0.386	0.492
Vegetation	0.089	0.367	0.170
70% soil; 30% vegetation	0.151	0.380	0.395
50% soil; 50% vegetation	0.133	0.376	0.331
30% soil; 70% vegetation	0.115	0.373	0.267

3.5. Indian Remote Sensing Satellite, IRS-P4 (OCEANSAT)

Indian Remote Sensing Satellite (IRS-P4) is the first satellite of its kind exclusively designed for Ocean applications. It carries primarily two sensors OCM (Ocean Colour Monitor) and MSMR (Multi-frequency Scanning Microwave Radiometer). OCM with its wavelength range extending from 400 nm to 885 nm in 8 bands is capable of collecting data on chlorophyll concentration, detect and monitor phytoplankton blooms and obtain data on atmospheric aerosols and suspended sediments in the water. MSMR, which operates in four microwave frequencies of 6.6, 10.65, 18 and 21 GHz both in vertical and horizontal polarization is used to collect data on sea surface temperature, wind speed, cloud water content and water vapour content in the atmosphere above the ocean.

3.6. CERES

The Clouds and Earth's Radiant Energy System (CERES) radiometer is a broad band radiometer flown in space [onboard Tropical Rainfall Measuring Mission (TRMM)]. CERES was launched in December 1997. CERES is calibrated during pre-launch and routinely during orbit using in-flight calibration sources. Calibration of the instrument (instrument gain) has changed by less than 0.1% in 9 months of space flight. The CERES measures the radiance and then converted to irradiances (fluxes), using empirical algorithms (Ramanathan *et al.*, 2001). This sensor provides the TOA reflected flux, which is due to back-scattering by air molecules and aerosols (over a black surface such as ocean). As the back-scattering by air molecules are known with sufficient accuracy, aerosol effect on radiative fluxes (also called "aerosol radiative forcing") can be inferred (Satheesh *et al.*, 1999; Satheesh and Ramanathan, 2000).

4. Aerosol remote sensing algorithms

4.1. Single wavelength algorithms

Single channel algorithms were the most common method in the past. The diffused reflected radiation at the top of the atmosphere is represented in terms of reflection function, which in turn is dependant on optical depth, single scattering albedo, angle of scattering, solar zenith angle with respect to the observation and many other parameters. In single channel algorithms, the difference between reflection function and surface reflectance is plotted as a function of surface reflectance at different values of optical depth and single scattering albedo. The reflectance of various types of surfaces are given in Table 3. The maximum sensitivity to aerosol optical depth occurs over dark surfaces. For surfaces with surface reflectance brighter than 0.1, the sensitivity is much reduced and depends on aerosol absorption. Therefore measurements over ocean surfaces or dark targets over land are most frequently used to detect aerosol optical depth from space borne sensors (Griggs, 1979) and a combination of dark and bright surfaces are used to detect aerosol single scattering albedo (Kaufman and Joseph, 1982). The effect of surface reflection is clearly seen in Fig. 3 where the TOA radiance simulated for NOAA AVHRR sensor is shown for different aerosol types and surfaces. It can be seen that the percent contribution of aerosol signal is most significant over dark background. The filter function for satellite sensor used is shown in Fig. 4.

Different methods are employed to determine aerosol characteristics, one channel method is one of the widely used methods used to determine aerosol optical depth. The total reflection function is due to surface reflectance plus the reflectance due to atmosphere. An increase in earth

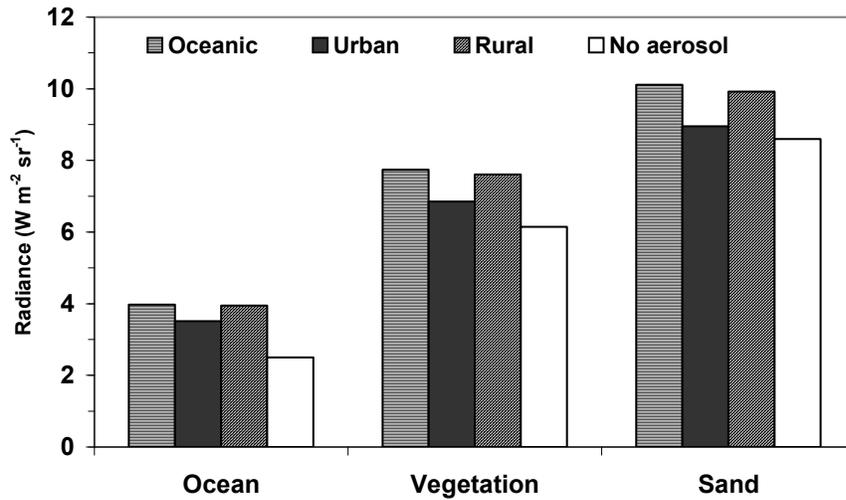


Fig. 3. Effect of surface reflection on satellite radiance

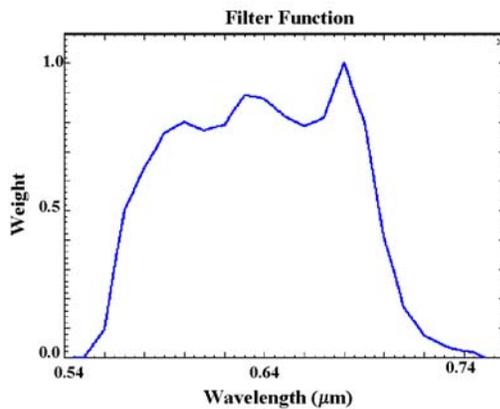


Fig. 4. Filter function of NOAA-AVHRR sensor used to simulate radiance in Fig. 7

reflectance is the most distinctive feature in any satellite imagery for detecting particulate matter. These can be easily observed from an enhanced brightness observed in the visible imagery. NOAA has been using this one channel algorithm for quite a long time since, to determine the global distribution of aerosol optical thickness over the ocean.

When the surface reflectance is small then the reflectance from atmosphere dominates, this atmospheric reflectance is due to different components, aerosol and molecules. This aerosol component can be determined by simply subtracting the surface and molecular component from the measured reflectance and assuming an aerosol

model. This aerosol component on the other hand is primarily a function of aerosol optical depth and to a little extent on single scattering albedo.

4.2. Multi-spectral algorithms

This method is an improvement to the single channel approach discussed earlier. It can be used to determine not only the optical thickness but also aerosol characteristics like aerosol size distribution and single scattering albedo. Here as the name suggests more than one wavelength band is used to determine aerosol characteristics. The colour ratio is the primary information used to determine aerosol characteristics. Colour ratio is the ratio between the reflection functions at two different wavelengths measured by the satellite. This ratio can be related to the single scattering albedo, phase function and optical thickness. It is given by,

$$\epsilon_{1,2} = \frac{R_1}{R_2} \tag{7}$$

Where R_1 and R_2 are measured reflectance functions at wavelengths λ_1 and λ_2 respectively. In the single scattering approximations,

$$\epsilon_{1,2} \approx \frac{\omega_1 \tau_1 P_1(\theta)}{\omega_2 \tau_2 P_2(\theta)} \tag{8}$$

Where ω is the single scattering albedo, τ is the optical thickness, $P(\theta)$ is the phase function. Durkee *et al.*

(1991) has estimated the colour ratio as well as the aerosol optical thickness from AVHRR measurements in channels with wavelengths 0.63 μm and 0.83 μm . Angstrom wavelength exponent can be calculated using the relation,

$$\tau_{\lambda} = \tau_{\lambda_0} \left[\frac{\lambda}{\lambda_0} \right]^{-\alpha} \quad (9)$$

Where λ_0 , is the reference wavelength (0.5 to 1.0 μm) depending on the sensor. Different aerosol models can be used while determining the optical thickness. It has been found that the assumption of log-normal distribution is more accurate in representing the aerosol size distribution. AVHRR channels 1 and 2 were used by Nakajima and Higurashi (1997) to determine optical thickness and Angstrom coefficient. Fukushima and Toratani (1997) assumed single scattering albedo to be one, *i.e.* non-absorbing aerosol, for channel-4 (0.55 μm) of CZCS sensor to determine single scattering albedo at shorter wavelengths for Asian dust particles which have a strong absorption in the blue channel.

4.3. Retrieval over dark surfaces over land

Aerosol retrieval is easier over dark regions due to small surface reflectance. Green vegetation and some soils are dark in the red (0.6-0.7 μm) and blue (0.4-0.5 μm) spectral regions. These dark regions can be utilized to obtain aerosol optical depth over land region, but for this we need to first calculate surface reflectance. We need to find the surface reflectance through a layer of unknown optical depth. Therefore to overcome this difficulty, a spectral region such that aerosol effect is negligible can be used to determine surface reflectance. When we look at Optical Depth dependence upon wavelength, optical depth is larger for shorter wavelength and smaller for longer wavelengths. It is around 3 to 30 times smaller in SWIR (2 to 4 μm) than visible (0.47 and 0.66 μm) region. Soils on the other hand have reflectance increasing with wavelength (Kaufman *et al.*, 1997) (Table 3). Vegetation decreases the reflectivity in the visible region due to chlorophyll absorption and in the SWIR region due to absorption by liquid water (Table 3).

5. Recent investigations

Remote sensing of aerosols over Indian region is mostly carried out using IRS satellite series. Recent studies have shown the transport of industrial plumes from Bombay coast to Arabian Sea (Das *et al.*, 2002). They observed that aerosol optical depths are as high as 0.4 over Arabian Sea.

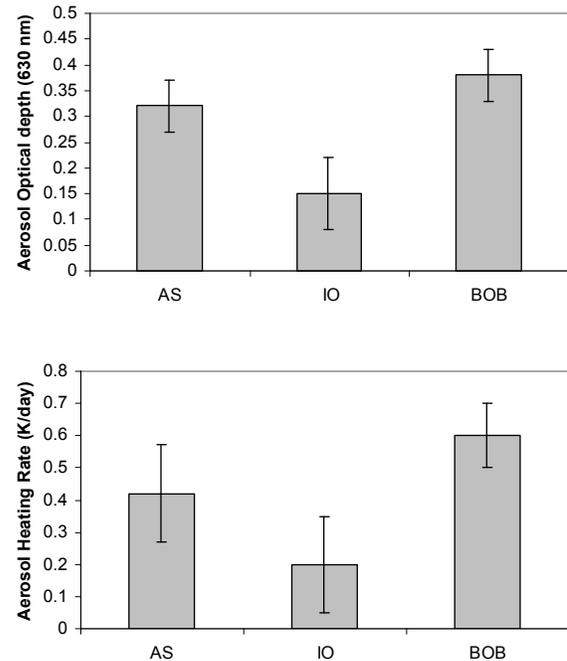


Fig. 5. Average aerosol optical depth and aerosol heating rate over Arabian Sea (AS), Indian Ocean (IO) and Bay of Bengal (BOB)

As part of Indian Ocean experiment (INDOEX), extensive studies of aerosols were carried out using data from various satellite sensors such as AVHRR, METEOSAT, TRMM etc. Aerosol optical depths were retrieved using single channel AVHRR data. In retrieving aerosol parameters from satellite data, a major problem is the presence of clouds. To detect cloudy pixels and clear sky pixels, applying threshold radiance has been the common technique. However, this threshold is not unique for ocean and land. It also depends on various factors such as time of the day (angle of the sun), season etc. Thus, multi-sensor satellites are of great use. Otherwise simultaneous observations using different sensors (such as visible and IR) is essential for identifying clear and cloudy sky pixels. During INDOEX, the data from AVHRR was extensively used for retrieving aerosol optical depth and METEOSAT data (IR channel) for identifying cloudy pixels. The surface and aircraft observations of aerosol properties were incorporated into satellite retrieval algorithms (Satheesh *et al.*, 1999; Satheesh and Ramanathan, 2000; Ramanathan *et al.*, 2001). The combined data along with aircraft data was used for assessing the indirect effect of aerosols also. The aerosol optical depth retrieved from AVHRR have shown that aerosol optical depths are as high as 0.5 near Indian coast and gradually decreases as the distance from the coast increases (Rajeev *et al.*, 2000). Over the Indian Ocean, the

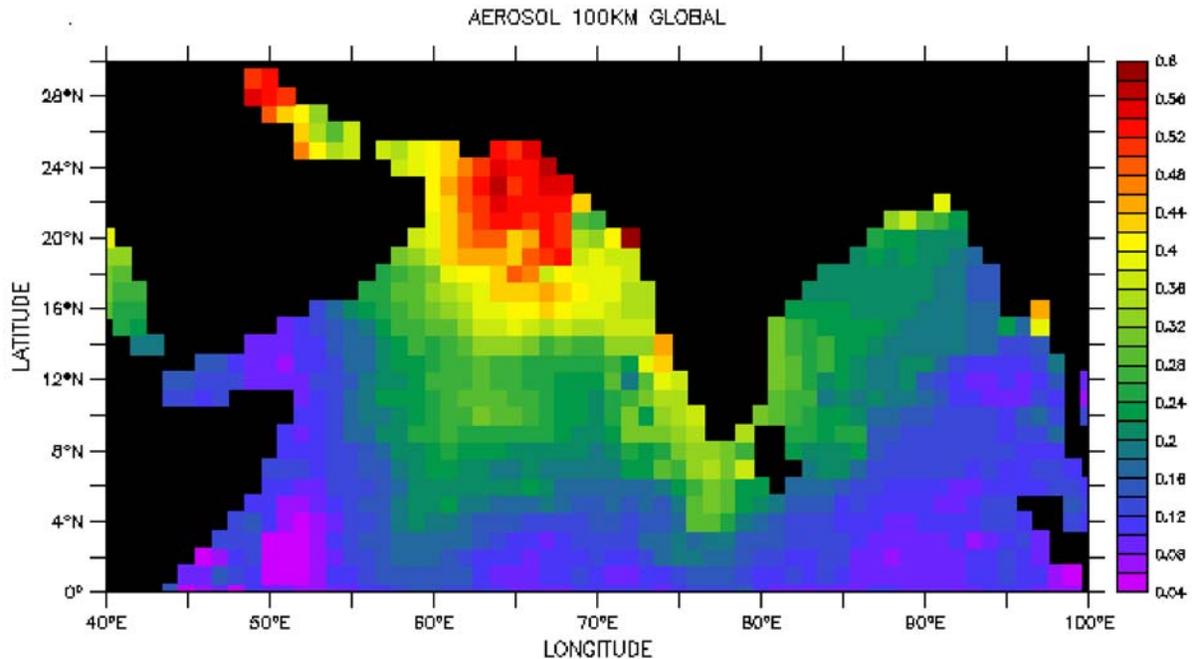


Fig. 6. Aerosol optical depth at 630 nm distribution over oceanic regions adjacent to India. The values are obtained from NOAA AVHRR operation product. The map shows the distribution during the first half of May, 2000

optical depths were in the range 0.1 to 0.15 and over Bay of Bengal in the range 0.2 to 0.4. These results provided a confirmation to the previous reported results over this region (Satheesh and Moorthy, 1997; Moorthy *et al.*, 1997; Satheesh *et al.*, 1998; Jayaraman *et al.*, 1998).

In another recent study, using data CERES (onboard TRMM) radiation budget data, Satheesh and Ramanathan (2000) reported the aerosol forcing efficiency (forcing per unit optical depth) at the TOA to be in the range -22 to -25 Wm^{-2} . The average aerosol optical depth observed over northern Indian Ocean was ~ 0.4 during 1999, which when multiplied with the forcing efficiency yields the actual aerosol forcing of ~ 10 Wm^{-2} at the TOA. They found that inter-annual variation is significant. The aerosol optical depth over northern Indian Ocean during 1999 was more than two times larger than during 1998 (Satheesh and Ramanathan, 2000). The mean τ_a at 500 nm during 1999 was ~ 0.4 , while during 1998 the value was ~ 0.16 . The aerosol single scattering albedo was in the range of 0.88 to 0.91 during 1998 while during 1999, it was in the range 0.86 to 0.88. Surface forcing was in the range of -12 to -16 Wm^{-2} during 1998 and -27 to -31 Wm^{-2} during 1999. TOA forcing was in the range of -4 to -6 Wm^{-2} during 1998 and -9 to -12 Wm^{-2} during 1999. Aerosol forcing in

each case was two times greater during 1999 than during 1998.

The extensive use of satellite data during INDOEX have revealed important information on aerosols over oceanic regions adjacent to Indian subcontinent. The results are summarised in Fig. 5 where average values of aerosol optical depth, aerosol TOA forcing and aerosol heating rate are shown. The INDOEX, however, concentrated primarily on January to March period.

Recently, Li and Ramanathan (2002) have reported extensive observations of aerosol optical depths over oceanic regions adjacent to Indian subcontinent. The Arabian Sea and Indian Ocean regions during April to August are mostly influenced by air masses from the northwestern regions such as Arabian peninsula and Sahara. This implies that air masses during this season carry dust aerosols from these regions (Takemura *et al.*, 2002; Satheesh and Srinivasan, 2002, Li and Ramanathan, 2002). The optical depth maps reported in Li and Ramanathan (2002) clearly demonstrate that aerosol loading over Arabian Sea is maximum during July/August months. This observations supports the inference made by Satheesh and Srinivasan (2002) that there exists

significant transport of aerosols from Sahara across the Arabian Sea when northwesterly winds prevail. Sathesh and Srinivasan (2002) shows that this transport during May has a greater impact than that transported from Asia by northeasterly winds during January-March period. Aerosol optical depth (630 nm) distribution over oceanic regions adjacent to India (during the first half of May, 2000) obtained from NOAA AVHRR operation product is shown in Fig. 6 which demonstrate the transport of aerosol plumes from regions northwest of India. Li and Ramanathan (2002) also report that, in 1997, the enhanced optical depth over equatorial Indian Ocean was due to aerosol transport from Indonesia. Clearly the above observations show that a major fraction of the aerosol load over Indian region is due to aerosols transported from other continents, which need to be understood. This is possible only by extensive use of satellite data.

6. Future scope

Most of the investigations on aerosols using satellite data over Indian region have been over oceans. This is due to the fact that the satellite sensed radiance is a combination of surface and atmospheric effects and reflection from the ocean is known with reasonable accuracy. However, as the presence of aerosols over land has more climate impacts compared to that over ocean (due to high surface reflectivity over land), the information on aerosols over land is of at most importance to climate change studies. Another aspect is the information on aerosol chemical composition, which is an important information for climate and radiation budget modelers. Even though complete description of aerosol chemistry is not needed, at least information on single scattering albedo is essential. For accurate remote sensing of aerosols requires clear sky. But real aerosol climate effect includes the effect of the presence of clouds too. The presence of aerosol layers relative to the altitude and type of clouds are very important. As such, data from multi-sensor (visible and IR) platforms are essential.

The ocean colour monitor (OCM) in OCEANSAT and instruments such as MODIS and POLDER have multi-wavelength sensors which are needed (as described in previous sections) to estimate aerosol information over land. For the estimation of aerosols over the Indian landmass, use of data from these new sensors are essential.

Another aspect is the validation of satellite derived parameters. As there are many assumptions present in remote sensing of aerosols using satellite data, the validation provides confidence on the results. During the Indian Middle Atmosphere Programme (IMAP), a project was initiated to monitor the aerosol characteristics over

the Indian region by setting up multi-wavelength radiometer stations at a few selected sites. The programme, which became operational in the late eighties has been continued after IMAP as part of Aerosol Climatology and Effects (ACE) project of ISRO's Geosphere Biosphere Programme. As part of this programme, a network of multi-wavelength solar radiometers has been deployed at various parts of India and island stations such as Minicoy and Port Blair. Currently Aerosol Radiation Budget Studies (ARBS) is being implemented to augment the aerosol observations in India. Coordinated observations are being carried out from these stations. The aerosol optical depth measurements are being carried out in these stations regularly. This extensive data set can be utilised to validate the satellite derived aerosol parameters over land.

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