The application of remote sensing techniques for air pollution analysis and climate change on Indian subcontinent

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Abstract. India is home to an extraordinary variety of climatic regions, ranging from tropical in the south to temperate and alpine in the Himalayan north, where elevated regions receive sustained winter snowfall. The subcontinent is characterized by high levels of air pollution due to intensively developing industries and mass fuel consumption for domestic purposes. The main tropospheric pollutants (O3, NO2, CO, formaldehyde (HCHO) and SO2) and two major greenhouse gases (tropospheric O3 and methane (CH4)) and important parameters of aerosols, which play a key role in climate change and affecting on the overall well-being of subcontinent residents. In light of considering these facts this paper aims to investigate possible impact of air pollutants over the climate change on Indian subcontinent. Satellite derived column aerosol optical depth (AOD) is a cost effective way to monitor and study aerosols distribution and effects over a long time period. AOD is found to be increasing rapidly since 2000 in summer season that may cause adverse effect to the agricultural crops and also to the human health. Increased aerosol loading may likely affect the rainfall which is responsible for the observed drought conditions over the Indian subcontinent. Carbon monoxide is emitted into the atmosphere by biomass burning activities and India is the second largest contributor of CO emissions in Asia. The MOPITT CO retrievals at 850 hPa show large CO emission from the IG region. The development of convective activity associated with the ASM leads to large scale vertical transport of the boundary layer CO from the Indian region into the upper troposphere. TCO over the Indian subcontinent during 2007 has a systematic and gradual variation, spatial as well as temporal. Higher amount of TCO in the northern latitudes and simultaneous lower TCO at near equatorial latitudes indicates depletion of ozone near the equator and accumulation at higher latitudes within the subcontinent. In addition, changes in stratospheric ozone and atmospheric abundances of aerosols alter the energy balance of the climate system.

1. Introduction

Major sources of energy in India include coal, petroleum, biomass, nuclear power and hydropower. Combustion of these fuels is the main source of pollution in the natural environment. India has a large variation in climate from region to region, due to its Geographical nature. Extremes of climate and weather events are increasingly being recognized as key aspects of climate change and they adversely...
affect humans and ecosystems, with serious socioeconomic consequences [1]. The complexity of the climate system is enormous. The thermal gradient caused by the lower tropospheric warming and corresponding cooling over the upper troposphere largely regulates the atmospheric general circulation patterns. In the changing climatic scenario, the recent sharp rising trend in the surface air temperature over the Indian landmass is attributed to the large-scale declining trend in Indian summer monsoon rainfall [2]. Not only the temperature gradient but also the pressure gradients across the Indian landmass plays a major role in controlling the climate system in and around the Indian subcontinent [3]. Anthropogenic changes in the atmosphere can have a profound impact on the climate and the consequences are assumed to occur at present [4]. Climate change may result in an increase in the frequency of floods in many regions. However, natural changes in the Earth’s climate might have been augmented by the enhanced greenhouse effect, caused by manmade changes in the Earth’s environment. Greenhouse gases and aerosols are the two most important elements that affect the radiation balance of the earth’s atmosphere. It is well established now that the anthropogenic emissions of greenhouse gases (most importantly CO₂) into the atmosphere cause global warming of the troposphere [1].

In this paper we highlighted and put together role of air pollutant on climate change over the Indian subcontinent. Aerosols play a crucial role in the climate of the Earth–atmosphere system by means of their direct and indirect impacts, and are considered to be one of the largest uncertain components of the global climate system [4]. The overall composition of aerosol density is likely to affect the large-scale heating and pressure gradients in the atmosphere, which can amend the circulation pattern, cloud dynamics, precipitation and so on [5]. CO is another important atmospheric pollutant for a number of reasons. The major source of CO emission in India is traditional bio-fuel use, which is almost 50% of the total Indian CO emission [6]. Carbon monoxide can be measured from space and can be used to identify sources of air pollution. The industrialization of eastern Asia has influenced the chemical climate of India through transport processes and thus through the Indian monsoon [7]. The small belt of ozone around the globe filters the ultraviolet radiations reaching the ground and thereby protects the whole biosphere from harmful effect [8].

2. Aerosols mechanism and its influence on climate

In the monsoonal countries like India and China, aerosol problem is ever becoming acute due to increased loading of atmospheric pollutants from anthropogenic as well as natural sources [9]. They interact with various monsoon activities, for example, energy balance, cloud formation processes and so on [10] and perturb their normal occurrences. The magnitude and sign of aerosol radiative impact depend on physical, chemical and radiative properties of these aerosols. Aerosols are classified into natural and anthropogenic, according to their origin. Sea salt, dust, natural sulphates, etc., are naturally occurring aerosols, whereas soot, industrial sulphates, black carbon, etc., are of anthropogenic origin. Soot is an absorbing aerosol whereas dust and organic matter are partly absorbing. Interactions between dust aerosols and clouds in the upper troposphere and lower stratosphere can produce a significant impact on atmospheric radiation budget, and hence on global and regional climates.

Carbonaceous aerosols have received much attention recently because of their potential role in regional climate change [11]. Black carbon is a light-absorbing aerosol, that is, the by-product of incomplete combustion of carbonaceous fuel. Because of its absorptive nature, Black Carbon accounts directly for the reduction in incoming short-wave solar radiation at the Earth’s surface, leading to heating of the atmosphere and thus possibly changing the temperature structure in the troposphere, which in turn affects the cloud microphysical properties and thereby rainfall mechanisms [11]. Global warming produced by greenhouse gases is partly suppressed by aerosols; they therefore have a substantial role in the radiation budget and climate. The radiative effects of aerosols on the Earth’s atmospheric system are governed by the quantity of aerosols in the atmosphere, their vertical distribution, size distribution and single scattering albedo, and the reflectivity of the underlying surface. Climate change is one of the most burning issues globally; aerosols have great potential to bring out changes in climatic conditions at regional and global scales [12].
2.1 MODIS AOD data

Moderate Resolution Imaging Spectroradiometer (MODIS), one of the first passive satellite spectroradiometer designed to observe aerosols from an altitude of about 700 km. MODIS measures reflected solar radiance and terrestrial emissions in 36 wavelength bands between 0.405 and 14.385 μm, with resolutions between 250 and 1 km. It was launched onboard the Terra satellite in late 1999 and onboard the AQUA satellite in May 2002. The data obtained from MODIS Aura has a spatial resolution of 1.0° (latitude) × 1.0° (longitude). Collection 5 (MOD08_M3-005) of MODIS-Terra level-3 monthly aerosol data was used. The MODIS AOD available from Giovanni (http://disc.sci.gsfc.nasa.gov/giovanni) is used in order to analyze spatial variations of aerosol loading. MODIS with its 2330 km viewing swath provides almost daily global coverage. The MODIS AOT uncertainty is ±0.05 ± 0.15 × (AOT) over the land [13].

2.2 AOD profile over Subcontinent

The dominance of the monsoon climate over the Indian subcontinent controls the seasonal highs and lows of aerosol concentration. Due to the climatic characteristics, during the winter and summer dry seasons (prior to the onset of the monsoon season), the concentration of aerosol particles remains high in the atmosphere. Hence the aerosol properties and their effects on weather and the climate of Indian Subcontinent are certainly different from rest of the world. AOD distribution during pre-monsoon affects cloud formation and hence rainfall distribution which is found to be prominent in last 4 years. Complex interaction between aerosols, clouds, climate and vegetation needs to be addressed in the light of harmful effects observed in several studies by different workers [14]. Organizations (WMO) recognize dust as a major component of atmospheric aerosol, which is an essential climatic variable to study. Mineral dust emitted from arid and semi-arid regions plays an important role in climate and also cause changes in cloud properties, such as the number, concentration, and size of cloud droplets, which can alter both cloud albedo and cloud lifetime. The phenomenon termed the ‘indirect aerosol effect’. [10], using aerosol forcing derived from atmospheric brown clouds field experiments, suggested that aerosol induced cooling decreases surface evaporation and reduces the north south surface temperature gradient over the Indian Ocean, leading to a weakened monsoon circulation. [5] Found that an abundant amount of dust aerosols from the Thar Desert and the Middle East deserts are transported into northern India, during the summer season (April through early June). Forced by the prevailing wind against the steep topography of the Himalayas, the dust aerosols pile up against the foothills and spread over the Indo-Gangetic Plain (IGP). The airborne dust particles become even more absorbing when transported over megacities of the IGP and coated by fine black carbon aerosols from local emissions [15].

The Indo-Gangetic Plain is an aerosol “super hotspot”, hosting the world’s highest population density and concentration of coal-firing industrial plants. AOD is found to be very high (>6) in Ganga basin with increasing aerosol concentration at an alarming rate in eastern part of basin shown in Figure1. Southern parts of India show a much cleaner environment with AOD less than 0.4. The spatial gradient of AOD is showing increase from southern part of Indian subcontinent to northern part up to Himalaya. The central India shows moderate AOD values. Input of aerosols (mostly coarser fraction) from Thar Desert and dry season during pre-monsoon cause high AOD in the Ganga basin. AOD at eastern part of subcontinent increased during summer 2014 shown in Figure2 indicates high level of concentration over IG region. The concentration of AOD is in variable nature over the subcontinent shown in Figure3, frequency distribution curve of AOD. Indo Gangetic plane and eastern part of continent shows high values of AOD as compared to rest of the world. The impact of increasing aerosol loading over Indian subcontinent during summer season affecting monsoonal rainfall distribution which is responsible for serious drought conditions and adverse effect to the agricultural crop production and also to the human health.
Figure 1. MODIS AOD over the Indian Subcontinent during summer 2000 and 2004.

Figure 2. MODIS AOD over the Indian Subcontinent during summer 2008 and 2014.
3. Carbon monoxide over the tropopause

CO contributes to air pollution, acts as a precursor to tropospheric ozone and is a sink for OH radicals. The photochemical oxidation of CO and hydrocarbon in the presence of NO_x is a major source of tropospheric ozone at both regional and global scales [8]. CO is produced at the Earth’s surface by incomplete combustion processes related to industry, traffic or biomass burning [16]. The main sources of CO are from anthropogenic and natural direct emissions and from the oxidation of methane and other gases. Dominant emissions are from road traffic, fossil fuel and biomass burning together with smaller contributions from vegetation and the oceans. High levels of CO pollution are found around the world, and they result from different types of biomass burning in different locations [17].

Emissions from biomass burning account for about one-quarter of the CO released to the atmosphere, with an average of around 600 Mt (600×10^6 tonnes) CO per year. CO is an ideal tracer for monitoring the air pollution sources and transports due to its moderately long lifetime (weeks to months) and inhomogeneous distribution in the troposphere [18]. The estimation of CO profiles and total CO
3.1 Retrieval of atmospheric CO profile from MOPITT

The MOPITT instrument [19] is onboard the Terra platform and measures tropospheric CO with nadir sounding. MOPITT is a correlation radiometer for estimating vertical profiles of atmospheric CO through the thermal radiance received in the 4.7 \mu m spectral region. The horizontal resolution of MOPITT CO data (version 3) is 22 km×22 km. The super-observations give around 8000 daily vertical profiles that are retrieved on seven pressure levels (surface, 850, 700, 500, 350, 250 and 150 hPa). This sensor was initially designed to carry out measurements of both CO and CH\(_4\), but, currently, there are no plans for dissemination of CH\(_4\) data.

The global MOPITT retrieved CO data have been utilized for estimating CO distributions, atmospheric transport, sources, and sinks. MOPITT is a correlation radiometer, which means that the CO profiles are retrieved using an optimal estimate of the maximum likelihood solution. With this technique, the retrieved CO profiles depend not only on MOPITT radiance measurements, but also on the a priori CO profile and the averaging kernels which are also averaged and are taken into account in the assimilation system.

CO mixing ratios over the Indo Gangetic region for the month of May, averaged for the 8-year period 2000–2007 shown in Figure 4. It is clearly observed that CO mixing ratios over the northern part of India is much higher compared to other part of India. CO mixing ratio higher values of 185 ppb to 220 ppb are observed over the Indo Gangetic region due to rapid growth of Industrialisation, urbanisation and growing population. Besides strong seasonal variations as shown by previous studies [20], CO has also been shown to have large interannual variability in the troposphere [21]. Despite of these higher values, CO mixing ratios over the central part of India observed by MOPITT at 850 hPa level is low due to less industrial activities and low biomass burning.

![Figure 4. MOPITT carbon monoxide (CO) mixing ratios (ppb) at 850 hPa over the Indian subcontinent (a) averaged during May 2000–2007, (b) averaged for 2000–2007.](image-url)
4. Atmospheric ozone and climate

Atmospheric ozone is a strong oxidizing agent. Together with water vapor, as a precursor of the hydroxyl radical, ozone has a strong influence on the oxidizing power of the atmosphere and hence on the rate at which many natural and anthropogenic compounds are eliminated from the atmosphere [22]. Tropospheric ozone impacts air quality and human health, atmospheric radiative forcing and ecosystem productivity with resulting impacts on food and climate. It also modifies the “oxidizing capacity” of the troposphere, impacting the lifetime and radiative forcing of methane. The small belt of ozone around the globe filters the ultraviolet radiations reaching the ground and thereby protects the whole biosphere from harmful effect [8]. The ozone located in the vicinity of tropopause where temperature is considerably lower than near the surface is the largest contributor to the ‘greenhouse’ warming [23]. The presence of ozone in the Earth’s atmosphere protects the human biological life system from harmful solar UV-B radiation and also plays a pivotal role in controlling the thermal structure of the stratosphere [24]. Changes in UV irradiance can influence the structure of the middle atmosphere through modification of photochemical dissociation rates; with associated effects on ozone [22]. Solar UV radiation, apart from its dependence on stratospheric ozone, is closely associated with tropospheric ozone abundance [8]. The Indian region has indicated a possible rise in tropospheric ozone, which could be related to increasing industrialization, transportation growth, and urbanization.

4.1 Measurement of Total Column Ozone (TCO) by using TOMS

TCO values were measured by Total Ozone Mapping Spectrometer (TOMS) carried on board NASA Earth Observing System, Aura Ozone Monitoring Instrument (OMI). OMI is a nadir-viewing spectrometer that measures the solar irradiance and Earth backscattered radiance from 270 to 500 nm with a spectral resolution of approximately 0.5 nm [25]. It provides near global coverage with a nadir pixel size of 13 km×24 km in the UV-2 channel used to retrieve TCO. Monthly average TCO data were retrieved from NASA’s website ftp://toms.gsfc.nasa.gov/pub/. It is observed that TCO over the Indian subcontinent remains nearly equal to 260 ± 20 DU during the winter 2007 and 2008 shown in Figure 5. Spatial gradients in TCO observed during this period, gradually increases from a low value near the equator to a maximum at high latitude. This observed latitudinal variation pattern of TCO over the Indian subcontinent may be due to the geographical and meteorological characteristics of the region which strongly influence the transportation as well as the production and loss of TCO shown in Figure 6 during monsoon period.

![Figure 5. Latitudinal variation of total column ozone (TCO) over the Indian subcontinent for winter 2007 and 2008.](image-url)
5. Conclusions
These study summaries the following aspects which influence the climate change over the subcontinent due to increased level of air pollution. AOD is found to be very high in the Indo-Gangetic region with increasing aerosol concentration in eastern part India. AOD is increasing from southern part of Indian subcontinent to northern part up to Himalaya. The increasing aerosol loading over the Indian subcontinent affects the rainfall distribution which is responsible for agricultural production and human health. MOPITT CO daytime retrievals provide sufficient information about the vertical and horizontal transport of CO and the deep convective activities during the monsoon period. Higher values of CO mixing ratios over the central part of India are observed low due to less industrial activities and low biomass burning. Spatial gradients in TCO during winter period, gradually increases from a low value near the equator to a maximum at high latitude. The variation pattern of TCO over the Indian subcontinent may be due to the geographical and meteorological characteristics of the region which strongly influence the transportation as well as the production and loss of TCO. The geographical diversity of the Indian Peninsula may be one of the major causes of spatial variability of total ozone concentration.

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Note: Following abbreviations have been used in this paper.

| Abbreviation | Meaning                  |
|--------------|--------------------------|
| O₃           | Ozone                    |
| NO₂          | Nitrogen Dioxide         |
| CO           | Carbon Monoxide          |
| HCHO         | Formaldehyde             |
| SO₂          | Sulphur Dioxide          |
| CH₄          | Methane                  |
| AOD          | Aerosol Optical Depth    |
| AOT          | Aerosol Optical Thickness|
| ASM          | Asian Summer Monsoon     |
TCO Total Column Ozone
MODIS Moderate Resolution Imaging Spectroradiometer
MOPITT Measurement of Pollution In the Troposphere
TOMS Total Ozone Mapping Spectrometer
OMI Ozone Monitoring Instrument
WMO World Meteorological Organization
IGP Indo-Gangetic Plain

References
[1] Kondratyev, K.Y. and Varotsos, C.A., 1995, Atmospheric ozone variability in the context of global change. *International Journal of Remote Sensing*, 16, pp. 1851–1881.
[2] Singh, R.P., Prasad, R.K., Chauhan, S.S. and Singh, S., 2005, impact of growing urbanization and air pollution on the regional climate over India. *International Association for Urban Climate Newsletter*, 14, pp. 5–10.
[3] Patil, S.D. and Revadekar, J.V., 2009, Extremes in total ozone content over northern India. *International Journal of Remote Sensing*, 30, pp. 2389–2397.
[4] Craknell, A.P. and Varotsos, C.A., 2007, The IPCC Fourth Assessment Report and fiftieth anniversary of Sputnik. *Environmental Science and Pollution Research*, 14, pp. 384-387.
[5] Lau, K. M. and Kim, K. M., 2006, Observational relationships between aerosol and Asian monsoon rainfall and circulation. *Geophysical Research Letter*, 33, L21810, Doi: 10.1029/2006GL027546.
[6] Dalvi, M., Beig, G., Patil, U., Kaginalkar, A; Sharma, C. and Mitra, A.P., 2006, A GIS based methodology for gridding large scale emission inventories: application to carbon monoxide emissions over Indian region. *Atmospheric Environment*, 40, pp. 2995-3007.
[7] Krishnamurti, T.N., Chakraborty, A; Martin, A., Lau, W.K; Kim, K.M; Sud, Y. and Walker, G; 2009, Impact of Arabian Sea pollution on Bay of Bengal winter monsoon rains. *Journal of Geophysical Research*, 114, D 06213.
[8] Kondratyev, K.Y. and Varotsos, C.A., 1996, Global total ozone dynamics: impact on surface solar ultraviolet radiation variability and ecosystems. *Environmental Science and Pollution Research*, 3, pp. 205–209.
[9] Lau, K. M., Kim, K. M., Hsu, C.N. and Holben, B.N., 2009, Possible influence of Air Pollution, dust- and sandstorms on the Indian monsoon.*WMO Bulletin* 58 (1), pp.22-30.
[10] Ramanathan, V. and Ramana, M., 2005, persistent widespread and strongly Absorbing haze over the Himalayan foothills and the Indo-Gangetic Plain. *Pure and Applied Physics*, 162, pp. 1609–1626.
[11] Menon, S., Hanse, J., Nazarenko, L. and Luo, Y., 2002, Climate effects of black carbon aerosols in china and India. *Science*, 297, pp. 2250–2253.
[12] Ghude, S.D., Kulkarni, P.S., Kulkarni, S.H., Fadnavis, S. and Van Der, R. J., 2011, Temporal variation of urban NOx concentration in India during the past decade as observed from space. *International Journal of Remote Sensing*, 32, pp. 849–861.
[13] Remer, L., Kaufmen, Y., et al., 2005, The MODIS aerosol algorithm, product and Validation. *Journal of Atmospheric Sciences*, 62, pp. 947-973.
[14] Kaufman, Y.J., Boucher, O., Chin, M., Remer, L.A. and Takemura, T; 2005, Aerosol anthropogenic component estimated from satellite data. *Geophysical Research Letter*, 32, L17804.
[15] Prasad, A.K. and Singh, R.P., 2007, changes in aerosol parameters during major dust
storms events (2001-2005) over the Indo-Gangetic Plain using AERONET and MODIS data. *Journal of Geophysical Research* 112, D 09208.

[16] Hollay, T., Levy, H. and Kasibatla, P; 2000, Global distribution of carbon monoxide. *Journal of Geophysical Research*, 105, pp. 12123-12147.

[17] Allen, D. J., Kasibhatla, P., Thompson, A. M., Rood, R.B., Doddridge, B.G., Pickering, K. E., Hudson, R. D., and Lin, S.J., 1996, Transport induced Interannual variability of carbon monoxide using a chemistry and transport model. *Journal of Geophysical Research*, 101, pp. 28655–28670.

[18] Leliveld, J., Crutzen, P.J; Ramanathan, V., Andreae, M.O., et al; 2001, The Indian Ocean experiment: widespread air pollution from South and South-East Asia. *Science*, 291, pp. 1031-1036.

[19] Drummond, J. R., 1992, Measurement of Pollution in the troposphere, in the use of EOS for Studies of *Atmospheric physics*, edited by J.C. Gille and G. Visconti, pp. 77-101.

[20] Liu, J., Drummond, J.R., Li, Q., Gille, J. C. and Ziskin, D. C., 2005, satellite mapping of carbon monoxide emission from forest fires in Northwest America using MOPITT measurement. *Remote Sensing of Environment*, 95, pp. 502–516.

[21] Edward, D. P., Emmons, L.K; Gille, J.C., Chu, A., Attie, J.L., Giglio, L; Wood, S.W; Haywood, J; Deeter, M. N; Massie, S.T; Ziskin, D.C. and Drummond. J.R; 2006, Satellite observed Pollution from southern hemisphere biomass burning. *Journal of Geophysical Research*, 111, p. D 14312.

[22] Braeceeur, G. and Granier. G., 1992, Mount Pinatubo aerosols, chlorofluro carbons and Ozone depletion. *Science*, 257, pp. 1239-1242.

[23] Lacis, A. A., Wuebbles, D. J. and Logan, J.A., 1990, radiative forcing by changes in the Vertical distribution of ozone. *Journal of Geophysical Research* 95, pp. 9971-9981.

[24] Ghude, S.D., Jain, S.L., Arya, B.C., Beig, G., Ahammed, Y.N., Kumar, A. and Tyagi, B., 2009b, Ozone in ambient air at tropical mega city, Delhi: trends and cumulative ozone exposure indices. *Journal of Atmospheric Chemistry*, 60,pp.237–252.

[25] Levelt, P. F., Van, G, H, J; Dobber, M., R., et al; 2006, The Ozone monitoring instrument. *IEEE Transactions on Geosciences and Remote sensing*, 44, pp.1093-1101.