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Satellite remote sensing of fine particulate air pollutants over Indian mega cities

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Abstract

In the backdrop of the need for high spatio-temporal resolution data on $PM_{2.5}$ mass concentrations for health and epidemiological studies over India, empirical relations between Aerosol Optical Depth (AOD) and $PM_{2.5}$ mass concentrations are established over five Indian mega cities. These relations are sought to predict the surface $PM_{2.5}$ mass concentrations from high resolution columnar AOD datasets. Current study utilizes multi-city public domain $PM_{2.5}$ data (from US Consulate and Embassy's air monitoring program) and MODIS AOD, spanning for almost four years. $PM_{2.5}$ is found to be positively correlated with AOD. Station-wise linear regression analysis has shown spatially varying regression coefficients. Similar analysis has been repeated by eliminating data from the elevated aerosol prone seasons, which has improved the correlation coefficient. The impact of the day to day variability in the local meteorological conditions on the AOD-$PM_{2.5}$ relationship has been explored by performing a multiple regression analysis. A cross-validation approach for the multiple regression analysis considering three years of data as training dataset and one-year data as validation dataset yielded an R value of ~0.63. The study was concluded by discussing the factors which can improve the relationship.

Keywords: MODIS; Regression; Boundary layer height; $PM_{2.5}$

1. Introduction

Air pollution is widely recognised as one of the major environmental risk factors to health. $PM_{2.5}$ (particulate matter with aerodynamic diameter less than 2.5 μm) is a potential air pollutant linked with several health hazards such as heart diseases, respiratory infections, altered lung functions and lung cancers (Pope, 2000). Over India, approximately 1.04 and 0.627 million deaths were attributed to household and ambient $PM_{2.5}$ concentrations, respectively (Balakrishnan et al., 2014). These facts in conjunction with diverse emission source strengths, land use patterns, rapid urbanisation, varied geographical and meteorological conditions over India underscore the need for high resolution (in space and time) $PM_{2.5}$ measurements to address its impact on public health. Monitoring of air quality by government agencies is highly limited to cities/urban areas whereas, rural India was also characterised with comparable (to urban) concentrations (e.g. Massey et al., 2009) potentially due to the emissions from solid household cooking fuels, agricultural crop burning residue (slash and burn agriculture) and fugitive road dust (unpaved roads). Infrastructural challenges and lack of local expertise are some of the major barriers for systematic long-term air quality monitoring over rural India, which comprises of 70% of the India population in 69% of the geographical area (according to 2011 census). These circumstances emphasize the importance of alternate and indirect methods for estimating $PM_{2.5}$ concentrations.

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Estimation of $PM_{2.5}$ concentrations based on (1) remotely sensed aerosol properties by satellite sensors and (2) simulating aerosol characteristics using Chemical Transport Models (CTMs) are the likely solutions to achieve high resolution and long term $PM_{2.5}$ data base. Aerosol Optical Depth (AOD, which can be retrieved from satellite measurements) is the most common and appropriate product for approximating the surface $PM_{2.5}$ concentrations. AOD products from several satellite sensors like MODIS (Moderate Resolution Imaging Spectroradiometer), MISR (Multi-angle Imaging SpectroRadiometer), GOES (Geostationary Operational Environmental Satellite), POLDER (POLarization and Directionality of the Earth's Reflectances) etc. are utilized for estimating surface $PM_{2.5}$ (e.g. van Donkelaar et al., 2015). Some of these satellite sensors have near global coverage on a daily basis and their measurements are spatially much denser and can fill gaps between $PM_{2.5}$ monitors. $PM_{2.5}$ estimations from AOD products make use of various statistical approaches (single/multivariate linear/non-linear/power-law regressions, Geographical Weighted Regressions), some of which use meteorological/land use parameters as ancillary data. AOD being an optical property of columnar aerosols, the theoretical relation between AOD and $PM_{2.5}$ incorporates parameters corresponding to vertical distribution of aerosols, aerosol extinction efficiency and size. Various proxies are also used to account the above parameters in establishing multi-variate empirical relationships. For example, Angstrom wavelength exponent (a qualitative parameter on the relative dominance of the fine particles in the size spectrum) was used as proxy for aerosol size by Li et al. (2016). The limitations on satellite AOD as a surrogate for $PM_{2.5}$ such as pixel size, spatial and temporal autocorrelations in AOD, AOD and $PM_{2.5}$ collocations, retrieval uncertainties and noise levels in the retrieved AOD are also well-documented (Paciorek and Liu, 2010).

Studies on empirical relations between observational AOD and $PM_{2.5}$ are mostly confined to United States and China (e.g. Wang and Christopher, 2003; Ma et al., 2016; Zhang et al., 2016) and with a limited number over European sector (e.g. Schaap et al., 2009). Very few studies were carried out over India (Kumar et al., 2007). Using two months of MODIS (Moderate Resolution Imaging Spectroradiometer) data, they have shown a positive association between AOD and $PM_{2.5}$ over Delhi. Chitranshi et al. (2015a, 2015b) studied the relationship between PM_{10} and MODIS AOD over urban areas of central Indo-Gangetic Plain using various statistical approaches (linear, log-linear and multi-linear regression analyses), their city-wise seasonal models exhibited better results with correlation coefficients in range of 0.49–0.88. In the present study, we tried establishing empirical relationship between MODIS retrieved AOD (at 550 nm) and publicly available hourly $PM_{2.5}$ concentrations over five Indian cities: Chennai (CHN), Hyderabad (HYD), Mumbai (MUM), Kolkata (KOL) and Delhi (DEL) using single and multi-variate (using meteorological parameters as ancillary variables) regression analysis. Section 2 of the manuscript deals with the materials and methods used for the current study, Section 3 presents the results obtained and discussion drawn out of the results, while we concluded the study in Section 4.

2. Materials and methods

The twin MODIS sensors on-board Terra and Aqua satellites provide daily near global coverage of monitoring Earth's atmosphere. MODIS with its 2330 km swath width observes reflected radiation from Earth's surface over a wide spectral range with a relatively fine resolution (Remer et al., 2008). Terra and Aqua being polar and sun-synchronous satellites with equator crossing times 1030 and 1330 local time (LT), provide single AOD data point per day per satellite. Various aerosol properties are retrieved using a set of algorithms and look-up tables (LUT) specific for land and ocean. Dart Target (DT) algorithm was developed for vegetated land surfaces (Kaufman et al., 1997; Levy et al., 2010) and remote oceanic regions (Tanré et al., 1997), while Deep Blue (DB) algorithm (Hsu et al., 2004) retrieves aerosol parameters over bright surfaces. Collection 6 (C6) daily 3 km DT AOD from Aqua-MODIS and Terra MODIS acquired from LAADS (Level 1 and Atmosphere Archive and Distribution System) Web has been used in the present study. C6 retrieves AOD and size parameters from the observed surface reflectance using a much-sophisticated set of algorithms with improvements (compared to earlier collections) in cloud mask, aerosol type selection as a function of season /location, quality assurance (QA) logic and added diagnostic parameters. QA flags are an indicator of the quality of the data, values range from 0 to 3, where 0 is the lowest quality. More details on the C6 MODIS aerosol products can be found in Levy et al. (2013).

Real time (hourly) $PM_{2.5}$ observations from US diplomatic missions are available over Indian cities (listed above) since early 2013. Finer details on the instrumentation and data collection procedure are extensively discussed in San Martini et al. (2015), Mukherjee and Toohey (2016) and Chung et al. (2001) and are not repeated here. The monitoring program utilizes beta attenuation monitor (BAM-1020, MetOne) for real time $PM_{2.5}$ measurements, whose measurement technique is an US EPA (United States Environmental Protection Agency) equivalent reference method. Daily mean (24-h average) $PM_{2.5}$ values are computed from the hourly data for all the stations only if at least 75% (18 hourly data points) of the data is present in a day. DEL is having more number of data points with 1360 acceptable daily means out of 1400 days. Data from CHN, HYD and MUM stations is available from the second quarter of 2013, while KOL data from the third quarter of 2013.

Meteorological parameters (air temperature, relative humidity, wind speed) for the all stations are acquired from Automated Surface Observing System (ASOS) network, which supports aviation community (measurements carried

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