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Modeling of tropospheric NO_2 column over different climatic zones and land use/land cover types in South Asia

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ABSTRACT

We have applied regression analyses for the modeling of tropospheric NO_2 (tropo-NO_2) as the function of anthropogenic nitrogen oxides (NO_x) emissions, aerosol optical depth (AOD), and some important meteorological parameters such as temperature (Temp), precipitation (Preci), relative humidity (RH), wind speed (WS), cloud fraction (CLF) and outgoing long-wave radiation (OLR) over different climatic zones and land use/land cover types in South Asia during October 2004–December 2015. Simple linear regression shows that, over South Asia, tropo-NO_2 variability is significantly linked to AOD, WS, NO_x, Preci and CLF. Also zone-5, consisting of tropical monsoon areas of eastern India and Myanmar, is the only study zone over which all the selected parameters show their influence on tropo-NO_2 at statistical significance levels. In stepwise multiple linear modeling, tropo-NO_2 column over landmass of South Asia, is significantly predicted by the combination of RH (standardized regression coefficient, $\beta = -49$), AOD ($\beta = 0.42$) and NO_x ($\beta = 0.25$). The leading predictors of tropo-NO_2 columns over zones 1–5 are OLR, AOD, Temp, OLR, and RH respectively. Overall, as revealed by the higher correlation coefficients (r), the multiple regressions provide reasonable models for tropo-NO_2 over South Asia ($r = 0.82$), zone-4 ($r = 0.90$) and zone-5 ($r = 0.93$). The lowest r (of 0.66) has been found for hot semi-arid region in northwestern Indus-Ganges Basin (zone-2). The highest value of β for urban area AOD (of 0.42) is observed for megacity Lahore, located in warm semi-arid zone-2 with large scale crop-residue burning, indicating strong influence of aerosols on the modeled tropo-NO_2 column. A statistical significant correlation ($r = 0.22$) at the 0.05 level is found between tropo-NO_2 and AOD over Lahore. Also NO_x emissions appear as the highest contributor ($\beta = 0.59$) for modeled tropo-NO_2 column over megacity Dhaka.

1. Introduction

The atmospheric nitrogen oxides ($NO_x = NO + NO_2$), especially NO_2, adversely impacts human health and the natural environment (Case et al., 1979; Barck et al., 2005). NO_x and hydrocarbons are correlated with surface level ozone (Varotsos et al., 1992). The tropospheric NO_2 (tropo-NO_2) pollution is greatly influenced by spatial patterns of socio-economics as well as by the changes in meteorological conditions, and topographic attributes (elevation, land use and land cover) of the area (Parra et al., 2009).

NO_2 largely comes from industrial and vehicle combustion processes, biomass and crop-waste burning, soil emissions, and sky lightning (Richter and Burrows, 2002; Cheng et al., 2012). NO_2 is mainly removed from the atmosphere by its reaction with OH (Kanaya et al., 2007). The changes in meteorological parameters (e.g., air temperature, relative humidity, wind speed, precipitation, solar radiation, and cloud fraction), atmospheric chemistry and surface emissions largely determine seasonally dependent NO_2 concentrations (Ghude et al., 2009; Sheel et al., 2010; ul-Haq et al., 2014).

Several researchers have explained and modeled trace gases variations by employing polynomial, multiplicative and multiple linear regression models (e.g., Varotsos et al., 1992, 2014a,b; Clapp and Jenkin, 2001; Kondratyev and Varotsos, 2001; Ferm et al., 2005; Sheel et al., 2010; Han et al., 2011). The adequate performance of the regression models help to assess the air quality and formulate localized environmental protection policies (Varotsos et al., 1992).

Multiple linear regression (MLR) has become a well-known and effective technique for predicting relationships and modeling the environmental systems (Demuzere and van Lipzig, 2010). This study suggests the relationship of tropo-NO_2 with anthropogenic nitrogen oxides (NO_x) emissions, some important meteorological parameters such as air temperature (Temp), relative humidity (RH), wind speed (WS), precipitation

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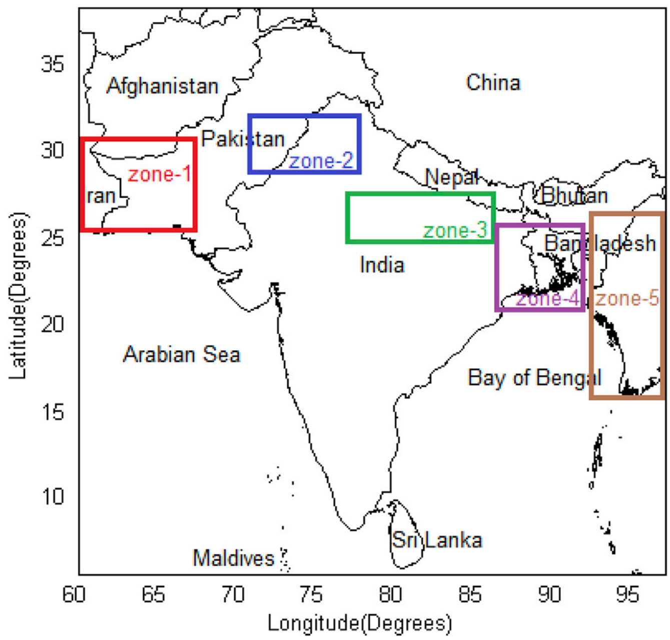

Fig. 1. Geographical map of South Asia and five study zones (1–5).

Table 1
The spatial bounding of the zones along with important anthropogenic sources of NO_2. Köppen-Geiger climate classification based on native vegetation, temperature, precipitation and their seasonality (Kottek et al., 2006) is also included.

Zones	Spatial bounding	Climate classification and population density	Notable sources of NO_2
Zone-1	25.5–31.5°N,60.5–69.5°E	Warm desert (BWh), very low density	Gawadar and Chahbhar Ports activities, fossil fuel burning
Zone-2	28.5–32.5°N,72.5–76.5°E	Hot semi arid (BSh), High density	Crop residue burning (post and pre monsoon), megacities (Lahore, Delhi, Faisalabad), industries, winter time home heating, brick kilns, power plants
Zone-3	24.5–26.5°N,76.5–85.5°E	Subtropical humid summer, dry winter (Cwa), High density	Crop residue burning (post and pre monsoon), industries, winter time home heating, brick kilns, power plants
Zone-4	20.5–25.5°N,85.5–92.5°E	Tropical savanna, wet & dry (Aw), very High density	Crop residue burning (pre-monsoon), mining activities, power plants, industries, brick kilns, urban
Zone-5	15.5–25.5°N,92.5–97.5°E	Tropical monsoon (Am), low density	Crop residue burning (pre monsoon), megacity Dhaka, power plants

(Preci), outgoing long wave radiation (OLR), cloud fraction (CLF) and aerosol optical depth (AOD) by using bi-variate and multivariate linear regression methods over different climatic zones and land use/land cover (LULC) types in landmass of South Asia.

2. Material and methods

2.1. Location and description of the study area

South Asia is home to one-fourth of the global population with population over 1.667 billion (Joshi, 2015; Li et al., 2015). Eight countries form South Asia namely Afghanistan, Bangladesh, Bhutan, India, Maldives, Pakistan, Nepal and Sri Lanka covering total surface area of 5, 134,613 km^2 (Fig. 1). Its climatic conditions fluctuate from arctic temperatures in the northern Himalayan areas to a temperate climate in the foothills and northern Indus-Ganges Basin (IGB). The tropical conditions are observed in central Indian Deccan plateau. The meteorological conditions of South Asia are heavily affected by wet (summer) and dry (winter) monsoon systems causing alternating periods of wet and dry weather (UNEP, 2008; Joshi, 2015). To perform in-depth analysis, we have formed five study zones (1–5) based on different climatic conditions and LULC types in South Asia (Fig. 1). The details of these zones are given in Table 1 along with important sources of anthropogenic NO_2.

Seasonal mean maps have been generated for some important meteorological parameters such as relative humidity, surface air temperature, wind speed and precipitation rate in South Asia for a period of December 1999 to November 2012 (Fig. 2). These maps are based on the data generated using NCEP-NCAR Reanalysis facility provided at NOAA Earth System Research Laboratory (NOAA-ESRL), Physical Sciences Division (www.esrl.noaa.gov/psd/).

2.2. Data

Ozone Monitoring Instrument (OMI, Levelt et al., 2006) on board Aura satellite is providing global coverage of tropo-NO_2 measurements since 2004. OMI tropo-NO_2 columns generally show a good agreement with ground-based measurements and are underestimated by 15–30% (Celarier et al., 2008). Differential Optical Absorption Spectroscopy (DOAS) algorithm uses radiance from 405 to 465 nm to retrieve tropo-NO_2. Daily retrievals of tropo-NO_2 (OMNO2d v003, level-3, and version-3) gridded at $0.25° \times 0.25°$ during a time period from October 2004 to December 2015 have been used in the present study. Tropo-NO_2 data are obtained from Giovanni (2016). Details of DOAS analysis and data quality control are provided in OMI data user's guide (OMI, 2012) and in Bucsela et al. (2006, 2008, 2013).

Gridded data of NO_x anthropogenic emissions have been obtained from Monitoring Atmospheric Composition and Climate (MACC) and megaCITY-Zoom for the Environment, CityZEN project (MACCity, Granier et al., 2011; ul-Haq et al., 2017). MACCity inventory is based on anthropogenic NO_x emissions from energy, transportation, industrial, residential and agricultural sectors. MODerate resolution Imaging Spectro-radiometer (MODIS) sensor aboard Aqua satellite was launched in 1999 (Salomonson et al., 1989). It uses 36 spectral bands (0.4–14.4 μm) with high radiometric resolution at 12 bits to monitor global radiation budget, aerosol burden and cloud cover on daily basis (Kaufman et al., 1997). Different algorithms are used for aerosols retrievals over land and oceans employing MODIS radiances (Kaufman et al., 1997; Tanre et al., 1997). In this study, we have adopted MODIS/Aqua deep blue Aerosol Optical Depth (AOD) monthly product (MYD08_M3, level-3, collection-6) with $1° \times 1°$ spatial resolution. The collection-6 of AOD is the latest and significantly improved product based on long-term calibration, improved cloud masking and atmospheric profile algorithms.

Some important meteorological parameters have been obtained from Atmospheric Infrared Sounder (AIRS, Pagano et al., 2003) and The Advanced Microwave Sounding Unit-A (AMSU-A, Aumann et al., 2003) on board NASA's Aqua satellite. The simultaneous use of AIRS and AMSU-A provides both new and improved measurements (Aumann et al., 2003; Susskind et al., 2003). These AIRS/AMSU-A derived meteorological parameters are cloud fraction, atmospheric temperature at 925 hPa, relative humidity at 925 hPa, and top of the atmosphere (TOA)