論 文 の 内 容 の 要 旨

論文題目　　Analyzing impact of socio-economic development and land-use change on urban air quality in India
（インド大都市の大気質に及ぼす社会経済成長と土地利用変化の影響分析）

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Currently more than 50% of the global population lives in urban areas. As per estimates of United Nations, developing countries are expected to further raise this figure to 70% by 2070 on account of socio-economic development in the form population rise and economic growth. Since 1990, particulate pollution in the form of PM2.5 has risen by at least 20% in densely populated cities across rapidly developing countries e.g. Bangladesh, China and India. This is in contrast with cities of developed countries where air quality improved during the same period. Research has shown that in a business as usual scenario, premature mortality attributable to outdoor air pollution is slated to rise from 2.0 million in 2010 to 4.3 million in 2050, led by Asian countries. In light of this fact it is important to understand the factors responsible for rise in air pollution so that effective policies can be designed. Several studies have established linkages between socio-economic development and emissions at country scale. For example, as per IPCC AR5 report although improvements in technology have taken place, these however have not been enough to compensate the effect of GDP and population growth, thus increasing energy consumption and emissions over time. At an urban level such studies could inform successful current policy measures to control air quality deterioration. e.g. in Beijing in China prevention and control policy interventions in 2013 are finally resulting in lowering of PM2.5 levels.

However, the proportion of studies for urban regions that analyze how socio-economic development impacts urban air quality is low specially for cities in developing countries other than China. Lack of relevant monitoring datasets is one of the major challenges in understand long-term impact of socio-economic development impacts urban air quality. The requisite datasets are : a) absence of long-running historical and spatially continuous ground PM2.5 monitoring, b) spatial datasets outlining growth of contributing factors (e.g. factories, residential biomass burning, diesel electricity generator in commercial areas, roads dust, etc.).

In this research we focused on Indian cities where half of the world’s 20 most polluted cities are present. We chose all 5 megacities (New Delhi, Mumbai, Kolkata, Bangalore and Chennai) as well as other cities reported to have high PM2.5 levels. Association of socio-economic drivers with urban air quality has not been extensively understood in many Indian cities in contrast to Chinese cities, which also face similar issues. Environmental Kuznets curve hypothesis states that environmental impact and per capita income are related in an inverted U-shaped relationship. Our hypothesis is that urban air quality in India is related with socio- economic development. Based on IPCC AR5(2014), we consider population and per capita gross domestic product (GDP) as immediate drivers and land-use change in the form of industrialization and urbanization as underlying drivers. In light of this our research question is to use remote sensing to answer: How does the growth in socio-economic drivers and land-use change affect urban air quality?

To test support for the hypothesis and answer the research question we set 4 objectives: i) characterize trend of anthropogenic aerosols in urban areas from 2001 to 2016 using MODIS sensor, ii) correlate aerosol, SO2 and NO2 levels with population, GDP, built-up area and calibrated nighttime light in Indian cities, iii) estimate location-wise expansion of urban land-use (residential, commercial and industrial regions) from 2001 to 2015 driven by per capita GDP and population, iv) model anthropogenic aerosol concentration based on growth of emission sources and technology development.

We used several remote sensing datasets in the course of this research to achieve our objectives. These were aerosol optical depth (AOD) and angstrom exponent(α) retrievals from MODIS, SO2 and NO2 vertical column densities using OMI, night- time light datasets from DMSP OLS and VIIRS DNB, digital surface models from AW3D30 and ASTER GDEM, backscatter dataset from PALSAR2 as well as Landsat 7 and 8 for NDVI and built-up class classification.

We developed a new method to decompose daily level (since year 2001) aerosol optical depth (AOD) and angstrom exponent(α) retrievals from MODIS sensor into 3 components. The three component R, G, and B represent proximity of aerosols to three cases a) R-high AOD and high α ,b) G-low AOD and high α and c) B-low AOD and high α on a scale of 0 to 100. We are interested in the R component as it depicts fine mode aerosols which are mostly a result of anthropogenic emissions activities like combustion, burning. We noticed a positive R trend (slope 0.04) in most Indian cities after 2009. We found that the anthropogenic component of aerosol, R is rapidly increasing in most Indian cities (17 out of 20 considered). On the other hand, Chinese cities show a decreasing trend in R after 2011.

Recent literature supports that changes in emission trends are reflected in satellite retrievals. To understand the rise of urban PM2.5 emissions in India, I investigated correlation of AirRGB R, SO2 and NO2 with population, GDP, built-up area and calibrated nighttime light. Nighttime light, which indicates human economic activities, showed rising anthropogenic aerosol loading in high economic areas over 2001 to 2014. A reverse trend was seen for SO2 and NO2 i.e. increasing number of high nighttime light regions with low pollution levels. It is suspected that this maybe due to increasing contribution from construction activities in relatively economically developed regions and while an increasing contribution of vehicular emissions was also inferred. Further AirRGB R showed unidirectional or bidirectional 'Granger causations' from construction and industries GDP in 6 out 8 polluted administrative states.

I identified residential, commercial and industrial areas and modeled their expansion since previous studies have indicated their differing and significant contribution to urban PM2.5. Land-use maps were prepared at 30m resolution by using built structure heights and nighttime lights as distinguishing features in support vector machine classification. Due to limited availability of open digital surface models to extract building heights, I prepared these maps for two years: 2001, using ASTER GDEM and 2011, using AW3D30. Currently, the accuracy of this approach is sensitive to presence of complex structures such as tall residential apartments, bridges and mixed land-use buildings and results in Kappa greater than 57% depending on the city. By exploring the role of per capita GDP and population in modeling urban expansion of land-use classes, expansion of land-use types in megacities depended mostly on per capita GDP while expansion of land-use types in medium sized cities depended on population size as well.

Emission contributions of urban land-use types (and vehicles) were identified by modelling their impact on changing fine aerosol, AirRGB R, in Indian urban areas using a hierarchical Bayesian framework between 2001 and 2015. The random effect was whether a location is a mega-city. For this, IPCC recommended emission framework was employed for three built-up urban land-use types (residential, commercial and industrial area), biomass burning, brick kilns and vehicle population. The framework was modified to represent satellite observed concentration as a function of land-use unit count, simulated seasonal emission coefficients from a single land-use unit and technological changes represented by emission intensity. The model performed well (correlation 0.52) when observed seasonal variation can be well simulated. Thus emission coefficients could estimate long term AiRGB R concentration based on land-use types which were dependent on GDP per capita and population. The results suggest that emissions from residential areas contributed the most to AiRGB R concentrations (mean 28.12%) followed by brick kilns (mean 6%) and vehicles (4.5%) over central part in each city. This suggests need for policies focusing emissions from residential regions. Although, these results were consistent with recent studies, about 51% of concentration was not explained by the considered emission sources. Exploratory analysis suggested that this could be decreased by around 30% by counting emission sources beyond city administration boundary up to 100km.