The Impact of Megacities on the emission of NO2 using GOME and SCIAMACHY data

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ABSTRACT

Continuous satellite measurements now offer the opportunity to compare NO2 concentrations to variables such as anthropogenic sources. Decadal population and NO2 trends were analyzed for 14 regions by use of population data records from Columbia University and NO2 column data from the Global Ozone Monitoring Experiment (GOME) and the Scanning Imaging Absorption Spectrometer for Atmospheric CHartography (SCIAMACHY) instruments. A number of noteworthy trends are present in the time series the most important being that despite population increases in many regions around the world, NO2 decreases were present in all regions of study except for Beijing and a selected Pacific Ocean region. An increase in NO2 of 14.9% was present over the selected Pacific Ocean region. This may have been due to influences from surrounding regions. However, further research of this region is essential to determine a definite cause. NO2 increased 72% per decade over China and this is likely related to increases in energy consumption of 149% per decade and other industrial activities in China, while the population increased at 9.5% per decade. These trends indicate that population growth and increasing energy consumption and industrial activity are correlated and without effective limitations on energy consumption and industrial activity pollutants in the atmosphere will continue to increase.
1. Introduction

In recent years, scientists have studied anthropogenic sources of atmospheric aerosol, including emissions of pollutants from motor vehicles, burning of fields for agricultural control, emissions from power plants, fumes from aerosol sprays and other solvents, etc. An increase in the production of pollutants seems to be present in heavily populated areas, due to the effects of economic growth and industrialization. Cities in developed and developing countries are experiencing mass migrations from rural areas to industrial cities. Therefore, activities performed by humans on a daily basis are contributing to high levels of pollutants emitted into the atmosphere.

Mexico City is a typical example of a megacity with an air quality problem. Emissions of pollutants in Mexico City, hourly ozone levels of 600 gm$^{-3}$, SO$_2$ levels 80-200 gm$^{-3}$, and suspended particulate matter 100-500 gm$^{-3}$ all exceed the World Health Organization (WHO) recommended levels (WHO, 1994). Exposure to these pollutants can cause respiratory problems, headaches, coughs, and eye irritations. Also, humans run the risk of suffering alterations in cells of the nose and throat, causing cancer later in life.

Satellite measurements allow a new and independent approach to the determination of trace gas emissions (Beirle et. al, 2003). The first retrievals of tropospheric nitrogen dioxide (NO$_2$) column data was achieved by use of a relatively new instrument called the Global Ozone Monitoring Experiment (GOME). The main scientific objective of the GOME mission was to determine the global distribution of ozone and several other trace gases, which play an important role in the ozone chemistry of the earth’s stratosphere and troposphere (Burrows et. al, 1999). GOME was a forerunner to the Scanning Imaging Absorption Spectrometer for Atmospheric Chartography (SCIAMACHY) instrument. The SCIAMACHY mission objective is similar to that of GOME. The solar radiation transmitted, backscattered, and reflected from the atmosphere is recorded at relatively high resolution (0.2 nm to 1.5 nm) over the range of 240 nm to 1700 nm, and in selected regions between 2.0 µm and 2.4 µm (SCIAMACHY homepage, 2006). Another instrument used for detecting gases in the troposphere is the Measurements Of Pollution In The Troposphere (MOPITT) instrument. The MOPITT instrument is a nadir sounding instrument that uses correlation radiometry for the detection of carbon monoxide (CO) and methane (CH$_4$) (MOPPIT Homepage, 2006). Finally, the Total Ozone Mapping Spectrometer (TOMS) and the Moderate Resolution Imaging Spectroradiometer (MODIS) both measure tropospheric aerosol. The TOMS aerosol record is unique in its capability to detect all aerosol types over land. The MODIS instrument has trouble performing this task due to high surface refractivity (Massie et. al, 2004).

Based upon analyses of the data obtained by the experiments discussed above, many different approaches have been taken to study atmospheric pollution. Research conducted by Irie et al (2005) compared GOME data to similar observations of NO$_2$ by ground-based data. The comparisons show a slight linear drift in GOME data. However, it is much smaller than the standard deviation of the differences between GOME and ground-based data and much smaller than the increasing trends in NO$_2$ seen by GOME over industrial areas of China, demonstrating the validity of the GOME data (Irie et. al, 2005). McPeters et al (1996) determined a trend in tropospheric ozone by analyzing TOMS data. Data from November of 1978 through May of
1993 were examined. Annual-average trends derived from the Nimbus 7 Version 7 data are 0-2.5% per decade less than those derived over the same time period using Version 6 data (McPeters et. al, 1996).

It is important to conduct research with data over several years time to detect time trends. Massie et al (2004) analyzed TOMS observations of aerosols in Asia over a 20-year time period. By doing this, they were able to recognize a trend and determine specific percentages of the increases of aerosol and relate trends to SO\textsubscript{2} emissions. They also took a step forward on categorizing anthropogenic sources of aerosols by focusing upon data observed during the winter months. Work done by Beirle et al (2003) serves as another example of the importance of the study of yearly data. They based their work on the assumption that combustion processes are reduced during weekends. Regions around the world were studied to determine the “weekend effects” of the weekly cycle of NO\textsubscript{2}.

A frequent common denominator in recent studies deals with analysis of observations of NO\textsubscript{2}, one of the tropospheric NO\textsubscript{X} species (NO\textsubscript{X} = NO + NO\textsubscript{2}). Nitrogen oxides form in high temperature fossil fuel combustion. NO reacts rapidly with ozone (O\textsubscript{3}) to produce NO\textsubscript{2}. This cycling between NO and NO\textsubscript{2} takes place on a time scale of about one minute during the daytime (Jacob, 1999). Nitrogen dioxide is a reddish-brown gas that reacts in air to form nitric acid (HNO\textsubscript{3}). NO is emitted from soils and natural fires and is formed in situ in the troposphere from lightning (National Research Council, 1991; World Meteorological Organization, 1995), and is emitted from combustion processes such as vehicle emissions and fossil-fueled power plants (National Research Council, 1991). The dominant sink for NO\textsubscript{X} in the stratosphere is transport to the surface by deposition (Jacob, 1999).

The outline of this paper is as follows. In section 2, we will describe the population and satellite data sets used in this paper. In section 3, we will discuss the geographical regions of interest for which we determine trend analysis. In section 4, we will determine population and NO\textsubscript{2} concentrations for our selected set of regions. In section 5, we compare trends for different parts of the world. Finally in section 6, we state our conclusions.

### 2. Population and Satellite data sets

This research was conducted to enable us to analyze NO\textsubscript{2} and population decadal trends on a global and regional basis. We will compare the trends in the different regions, and comment later in this paper on why different regions have different trends. As for visualization, Interactive Data Language (IDL) was used to generate graphs that tell the relationship between NO\textsubscript{2}, population, and change in time. The linear least square method (best fit line on a graph) was used to determine approximate percent changes in population and NO\textsubscript{2} versus time.

The geographical distribution of population was analyzed from 1995 to 2005. The population data sets are generated by Columbia University and grouped into five year increments for regions across the globe. Table 1 shows the specific regions selected and their latitude and longitude ranges. An Interactive Data Language (IDL) program was modified to determine the decadal trends in population for specific regions of the world (see section 3).
NO₂ column data from the GOME and SCIAMACHY instruments was also analyzed. GOME measures ozone and other trace gases within the troposphere and has a resolution of 320 x 40 km². SCIAMACHY is well-known for its wavelength range and high horizontal resolution (30 x 60 km²). The SCIAMACHY instrument is able to detect many trace gases such as nitrogen dioxide (NO₂), ozone (O₃), sulfur dioxide (SO₂), etc. A three degree range in the latitudes and longitudes for each region was set in the population and NO₂ programs to account for the different resolutions of the GOME and SCIAMACHY instruments. The GOME and SCIAMACHY instruments measure NO₂ columns in units of quadrillion molecules of NO₂ per squared centimeter (10^{15} molecules/cm²). This measurement can be depicted in terms of a cylinder that stretches from the surface to the tropopause, with a cylinder base of 1 cm². GOME data for years 2003-2005 were unavailable due to malfunctions in the instrument so data from the SCIAMACHY instrument was used for 2003-2005. An IDL program was used to determine the decadal trends of NO₂ for the same regions of the world as per our analyses of the population.

3. Regions of Interest

There are 14 regions selected for this study (see table 1) based on current population trends, economic and industrial activity, and overall air quality. Developed cities included places that demonstrated exceptional economic and industrial growth, higher living standards, and higher incomes compared to other regions. Developing cities included places that demonstrated low economic and industrial growth, lower living standards, and lower incomes. Examination of a sparsely populated region was necessary in order to investigate a place with no population or industrial features that may contribute to NO₂ emissions.

4. Results

Among the regions of study, places like Los Angeles, Berlin, Mexico City, Delhi, and Beijing had the highest increase in population. On a global basis, the population has increased by 12.8% from 1995 to 2005. The Pacific Ocean was selected to represent a sparsely populated region. Table 2 lists the regions and the percent change in population for the past decade.

A number of noteworthy trends were observed when the NO₂ column data was analyzed for the past decade, i.e. Beijing. Beijing is located in Northern China and has struggled with air quality issues in past years. This megacity experienced a 9.5% increase in population, rising from 108 million to 118 million. NO₂ concentrations over Beijing rose by 72% since 1995. Beijing was the only populated region under study that had an increase in NO₂ concentrations for the past decade. Figure 1 is a graph generated by the IDL program that shows NO₂ concentrations versus time. Although it has experienced minor increases and decreases throughout the year, it is very obvious that the NO₂ over the area has increased significantly during this time period. However, Beijing is not the only region under study that has increased in NO₂ concentrations over the years.

The exact location of the region of the Pacific Ocean that was studied is a couple hundred miles west of Los Angeles (Refer back to Table 1 of section 3 for specific latitude and longitude ranges). There was a 0.0% increase in population for this region (because no one lives there).
However, NO\textsubscript{2} over that region increased by 14.9\% in the past decade. Figure 2 is a graph of the NO\textsubscript{2} over this region for the past 10 years. One may observe the steady decrease in NO\textsubscript{2} from mid 2001-2004 and its sudden increase in NO\textsubscript{2} from 2004-2006. Compared to the other regions of study, the NO\textsubscript{2} concentrations over the Pacific Ocean are significantly lower and could make one question the statistical significance of the result.

The last noteworthy trend observed deals with the remaining regions studied. Scientists have assumed that population increases are associated with anthropogenic sources of NO\textsubscript{2} and other pollutants. In this study, every region experienced increases in population except Thailand. However, decreases in NO\textsubscript{2} concentrations were present for these same regions. Table 3 shows a detailed listing of regions and NO\textsubscript{2} percentage changes. The remaining sections of this paper will explore some probable causes of the trends discovered in the results.

5. Discussions

A. Beijing, China trends

China has experienced an incredible increase in industrial activity since 1990. Both heavy industrial activity (i.e. mining, smelting) and light industrial activity (i.e. consumer goods) percentages have increased in the past 8 years according to Donald and Benewick, authors of the book “The State of China Atlas”. As mentioned in the introduction, sources of NO\textsubscript{2} are mainly industrial. Hence, places that experience increases in industrial production will struggle with regulating NO\textsubscript{2} levels.

It is well known that there is a correlation between in population growth and industrialization. Therefore, as Beijing experiences industrial growth, people from rural areas migrate to the urbanize area in search of jobs and a better living. Upon Beijing’s urbanized expansion, more energy sources will be consumed, more motor vehicles will be used as means of transportation, and hence there will be an increase in NO\textsubscript{2} levels.

There has also been a tremendous growth spur in the production of motor vehicles and changes in travel in China. The production of motor vehicles has increased by 537\% since 1990 and the percentage of the population that uses the roads for transportation has increased from 65\% in 1980 to 92\% in 2002. In Beijing, Donald and Benewick note that Beijing’s private transportation and truck ownership has also increased. There have also been changes in energy consumption in China. The total amount of energy consumed (i.e. coal, oil, etc.) increased from 987 million tons (1990) to 1,480 million tons (2002), a change of 149\% per decade. These changes in industrial activity and transportation give insight as to why the NO\textsubscript{2} levels over Beijing have increased over the past 10 years. Figure 3 shows the NO\textsubscript{2} column data and the population for 2005.

B. Pacific Ocean trends

Since the region of the Pacific Ocean under study is located a couple hundred miles west of Los Angeles, increases and decreases in NO\textsubscript{2} may have been influenced by the transport of pollutants from surrounding regions. Given the fact that this region has no significant sources of
NO$_2$, the most likely answer of why this region experienced this trend is due to its location, its surrounding regions, and the fact that pollutants are able to travel long distances around the world. It was determined that the Pacific Ocean region under study needs further study on topics such as an error analysis of data due to the fact that the NO$_2$ column values are small.

C. NO$_2$ decreases in other regions under study

The remaining regions under study experienced decreases in NO$_2$ even though the population and industrial activity increased. Through further research, it was found that these regions enacted air quality laws and regulations on anthropogenic emissions of pollutants such as NO$_x$, SO$_2$, PM, and CO$_2$. With the values being -64% and -73% respectively, Berlin, Germany and Capetown, South Africa were the two regions that experienced the greatest decrease in NO$_2$. Contrarily, Mexico City, Mexico and Bangkok, Thailand experienced the least amount of decrease in NO$_2$, both with values of -10%.

According to the German Federal Environmental Agency, major sources of pollutants are required to have fully inspected emission monitoring systems. There are numerous monitoring sites scattered throughout Germany, assuring the major emitters of pollutants aren’t exceeding emissions standards. As for air quality monitoring in urbanized areas, trends that are investigated include general air pollution, traffic-related air pollution, and projections of measurements of pollutants of future industrial activity. Generally, regulation standards and air quality laws are strict and regularly followed, hence significant decreases in NO$_2$ are present.

Similar to Germany, England’s significant decrease in NO$_2$ is due to structured and strict air quality policies. The Air Quality Strategy was enacted in 1995 with goals of reducing emissions of pollutants by requiring vehicles to go through emissions checks, traffic management, and building regulations among other things (DEFRA, 2006). A unique factor in the success of this strategy is the fact that the general public is encouraged to send comments and suggestions on how to improve air quality as well. This suggests that the citizens have a strong interest in air quality which also contributes to the effort in improving air quality.

Countries in Africa have greatly succeeded in reducing NO$_2$ levels. Along with Egypt and South Africa, many countries such as Algeria and Tunisia have put forth the effort to advocate and fund the use of cleaner fuels and environment-friendly vehicles (UNEP:GEO, 2002). Also, the appetite for the knowledge of anthropogenic air pollution sources has encouraged National Environment Action Plan that address these issues. Additionally, most African countries have approved the United Nations Framework Convention on Climate Change (UNFCCC) and are in favor of the Kyoto Protocol, which also depicts Africa’s concern for air quality management.

Megacities in the USA have been noted for significant decreases in pollutants except for NO$_x$ emissions. Just recently in October of 2000, the US joined the global movement in attempting to reduce NO$_x$ emissions by signing an annex to the Canada/US Air Quality Agreement that sets goals for reducing emissions from fossil fuel power (UNEP:GEO, 2002). Figure 4 shows NO$_2$ graphs for both Los Angeles and New York. The decrease in NO$_2$ from years 2001-2005 may be a result of recent attempts to lower NO$_2$ levels in the US.
Due to its increased industrial activity and continuous air quality issues, the Asian continent has been the main focus in studies of air pollution. Air quality has been an issue in India mainly due to increases in private transportation and the haze problem due to the Asian Brown Cloud (ABC) (UNEP:GEO, 2002). However, NO$_2$ levels over India have decreased by 31%. To combat these air quality issues, numerous amounts of improved cooking stoves and biogas plants have been placed in India to reduce firewood burning. Also, electric and natural gas vehicles are being introduced.

Tokyo, Japan has also experienced a considerable decrease in NO$_2$ levels. There have been numerous attempts to regulate NO$_2$ levels in Japan. In 1993, the Basic Environment Law was enacted to produce laws and policies that could better the environment (Japan Fact Sheet, 2006). Also, the Automotive NO$_x$ and PM law was enforced to regulate the production and use of diesel vehicles. However, delays in this regulation allowed continued use of diesel vehicles from 2003 to early 2005.

A probable cause of the slow decrease in NO$_2$ over Bangkok may be partially due to the ABC problem. Forest fires in Southeast Asia in 1997 contributed heavily to haze problems over Thailand (UNEP:GEO, 2002). The Regional Haze Action Plan was approved in 1997 and since this plan is relatively new, it may take longer to make a difference in NO$_2$ levels.

Bangkok, Thailand and Mexico City, Mexico both experienced a 10% decrease in NO$_2$ over the past decade. There have been many significant attempts to control emissions of NO$_2$ in Mexico City in recent decades. According to United Nations Environment Programme, programs that promote fuel quality improvements, public transportation, and reduction of emissions form industrial activities have been taking place since 1990. Also, a trust fund was established to cover expenses of environmental improvement programs such as the “Day without a Car Program”. However, since Mexico City is so densely populated and air quality programs are relatively new, it may take longer to see a significant decrease in NO$_2$.

In contrast, Rio de Janeiro has experienced a considerable decrease in NO$_2$ over the past decade. The Brazilian Ministry of Environment and Natural Resources has been taking an active role in protecting the country’s environment through regulation and enforcement (EIA, 2003). Fines increased by 4000% in 1999. Also, Brazil partnered with the Carbon Sequestration Leadership Forum whose main goal is to reduce greenhouse gas emissions. These events show Brazil’s awareness and willingness to work toward a cleaner environment.

The decrease in NO$_2$ on a global basis is mainly due to the combined efforts of air quality laws and activities such as converting to the usage of cleaner fuels and catalytic converters that clean vehicle emissions. This implies that efforts to improve air quality are succeeding and further implies that reduction in air pollution is possible. Figure 5 shows global NO$_2$ trends and population for 2005. Figure 6a-i shows NO$_2$ trends for the remaining regions of study.

6. Conclusions

Population increases and emissions of NO$_2$ have been assumed to be correlated due to economic and industrial advancing. Conducting this study for the past decade serves as a
progress report on megacities across the globe. Investigation of the results through further research determined that megacities of the world are addressing and slowly solving the problems associated with NO₂ emissions by enacting laws and policies. These findings suggest that future research should concentrate on megacities with slow progress such as Mexico City, Bangkok, and Beijing. The results can also be used in atmospheric chemistry models to predict the effects of pollutants from one region of the world on other regions of the world.
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Figure 1: Yearly NO$_2$ averages vs. Time: Beijing, China (1996-2005). 
**Diamonds**: data from GOME instrument  
**Squares**: data from SCIAMACHY
Figure 2: Yearly NO$_2$ averages vs. Time: Selected Pacific Ocean region (1996-2005)
Figure 3: Beijing China: NO₂ column data and population for 2005.
Figure 4: Yearly NO₂ averages vs. Time: Los Angeles, California (1996-2005)
Figure 4 cont: Yearly NO$_2$ averages vs. Time: New York City (1996-2005)

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Figure 6b: Yearly NO$_2$ averages vs. Time: London, England (1996-2005)

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Figure 6g: Yearly NO$_2$ averages vs. Time: Rio de Janeiro, Brazil (1996-2005)
Figure 6h: Yearly NO$_2$ averages vs. Time: Capetown, South Africa (1996-2005)
Figure 6i: Yearly NO$_2$ averages vs. Time: Bangkok, Thailand (1996-2005)
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<th>Developed</th>
<th>Latitude Ranges</th>
<th>Longitude Ranges</th>
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<th>Latitude Ranges</th>
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<td>Delhi, India</td>
<td>32°-38° N</td>
<td>9°-15° E</td>
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<td>Tokyo, Japan</td>
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<td>136°-142° E</td>
<td>Bangkok, Thailand</td>
<td>42°-48° N</td>
<td>27°-33° E</td>
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<td>Rio de Janeiro, Brazil</td>
<td>20°-26° S</td>
<td>40°-46° W</td>
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<td>Mexico City, Mexico</td>
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<td>137°-143° E</td>
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**Table 1:** Regions under study and latitude longitude ranges
### Table 2: Regions and change in population for the decade.

Every region’s population increased by at least 4% during the past decade, except for Thailand and the Pacific Ocean region.

<table>
<thead>
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<th>Regions</th>
<th>Population 2005 (millions)</th>
<th>% Change in population/ Decade</th>
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<td>India</td>
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Table 3: Change in NO$_2$ for regions of study. Every region decreased in NO$_2$ except for Beijing and Pacific

<table>
<thead>
<tr>
<th>Regions</th>
<th>NO$_2$ 2005 (10**15 molecules/cm$^2$)</th>
<th>% Change in NO$_2$/ Decade</th>
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