TEMPORAL AND SPATIAL VARIATIONS OF NO_2 OVER SAUDI ARABIA AND IDENTIFICATION OF MAJOR HOTSPOT AREAS DURING 2005-2014 BY USING SATELLITE DATA

UL-HAQ, Z.[1*] – BATOOL, S. A.[1] – TARIQ, S.[1] – RANA, A. D.[1] – MAHMOOD, K.[1] – CHAUDHARY, M. N.[2] – NAEEM, M. A.[3]

[1]*Remote Sensing and GIS Group, Department of Space Science, University of the Punjab Lahore, Pakistan*

[2]*College of Earth and Environmental Sciences, University of the Punjab, Lahore, Pakistan*

[3]*Department of Electrical Engineering, University of the Punjab, Lahore, Pakistan*

**Corresponding author*
e-mail: zia.spsc@yahoo.com

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Abstract. The present study was designed to analyze the concentration of tropospheric NO_2 over Saudi Arabia for a decade from 2005-2014 based on observations from satellite borne Ozone Monitoring Instrument (OMI). The spatial analysis has identified two hotspots: Jeddah and Riyadh. The result of temporal analysis shows increase of 1.45%, 3.15% and 3.10% per year over Saudi Arabia, Jeddah and Riyadh respectively. The Linear Regression analysis and Analysis of Variance (ANOVA) have been performed to analyze the relationship between meteorological parameters, seasons, years and concentration of NO_2. The results show that temperature and NO_2 are moderately correlated whereas wind and humidity give negative correlation. The major causes of elevated NO_2 over the hotspots are road traffic and the fossil fuel combustion for electrical power generation.
Keywords: *tropospheric NO_2, OMI, spatiotemporal analysis, Saudi Arabia, hotspots*

Introduction

Anthropogenic activities play a very important role in changing the atmospheric composition. It would be very disastrous for the whole ecosystem. Nitrogen dioxide (NO_2) is a very harmful for human beings and their environment. Nitrogen dioxide is an eminent air pollutant due to its strong influence on the chemistry and quality of atmosphere. It helps to normalize the ozone concentration in troposphere and also affects the amount of hydroxyl (OH) ions. The increase in anthropogenic activities especially fossil fuel burning, vehicular traffic and industrial production has enhanced the amount of NO_x in the atmosphere. Identification of the areas rich in this and other pollutants may be the first step to clean the environment. Satellite Remote Sensing (SRS) has now become a useful technique for air pollution monitoring by measuring the pollutants concentration within the study area. This technique helps to assess large scale coverage with uniformity of averaged measurements.

The main objective of the present work was to identify the NO_2 hotspots and analyze their spatial and temporal patterns over Saudi Arabia by using SRS technique. Saudi Arabia is the biggest Arab state in Arabian Peninsula, Western Asia with an area of 2.1 million km^2.

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Review of literature

Satellite data is more appropriate and recent for different emissions. Hence it could be compared with in situ measurements (Zohary and Spiegel-Roy, 1975; Hayn et al., 2009; Kgosiesele, 2010; Lamsal et al., 2010; Sheel et al., 2010; Kloog et al., 2012; Khan, 2012; Khanum et al., 2013a). Satellites provide a high-coverage alternative to ground-based measurements. Many studies (Lennon et al., 2000; Hayn et al., 2009; Kumar and Stohlgren, 2009; Khan et al., 2010) provide useful assessment trends for air pollution especially for NO_2. It is observed that human activities produce approximately 75% NO_x, whereas combustion of fossil fuel contributes about 50% (Leyequien et al., 2007; Jeschke and Strayer, 2008). The tropospheric NO_2 columns derived from satellite have been used to evaluate chemical transport models (Zyrichidou et al., 2013), to study long term changes in anthropogenic emissions of NO_x over developing areas (Khanum et al., 2013b; Yang et al., 2013) and to examine the spatio-temporal patterns of NO_x emissions on global and regional scales (Yuan et al., 2015). In some recent studies these measurements have already been used to provide top down estimates of land surface NO_x emissions via inverse modeling on the global scale (Martin et al., 2003; Jaegle et al., 2005; Lin et al., 2010; Miyazaki et al., 2012). Due to rapid urbanization and industrialization air quality degradation is a serious threat to Saudi Arabia. (Yost et al., 2008; Taheri, 2010; Joly et al., 2004) have provided the temporal and spatial distribution of air pollutants specially NO_x and O_3 for Jeddah using ground based data.

Methodology

Study area and its meteorology

The research has been carried out in Saudi Arabia (16.5 to 32 °N and 35 to 55.6 °E) with population 26.9 million. Its geography is mostly dominated by BSh and BWh (Koppen climate classification types for dry climate, BSh for steppe hot desert and BWh for true hot deserts) There are no water bodies like rivers, ponds or lakes. The central plateau is the major topography from Red Sea to Persian Gulf. Meteorological data have been collected from www.wunderground.com. In general desert climate is dominated in Saudi Arabia with major difference of day and night. The summer temperature is usually found to be >45 °C and winter temperatures do not fall below 0 °C. The precipitation is negligible. The detailed meteorological parameters like maximum and minimum temperature, wind speed and pressure have been taken in account during the analysis of hotspots regarding NO_2.

Satellite data

Tropospheric NO_2 data have been collected from Ozone monitoring instrument (OMI) onboard NASA's satellite Aura. OMI uses spectral range of 270–500 nm (Levelt et al., 2006a, b). Its spectral resolution is about 0.5 nm (Zyrichidou et al., 2013). The data collected is for the past decade (2005-2014). Differential optical absorption spectroscopy (DOAS) analysis has been used to obtain tropospheric NO_2 column with spectral range 405–465 nm spectral range (Yu et al., 2014; Ellis, 2015). NASA's online user's manual for OMI products (Giovanni, 2014) has been consulted for further data analysis and filtering. The collected data of NO_2 column (OMNO2d.003, level–3) is screened for 0–30% cloud cover and binned spatially at 0.25 × 0.25 degrees (Slee and Feliciano, 2015). There is an uncertainty of 0.1×10^{15} molecules/cm^2 in dataset for

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tropospheric NO_2. The tropospheric NO_2 data is compared with in situ data and bottom up emission inventories.

The satellite sensor data is compared with Global Ozone Monitoring Experiment (GOME-2) sensor data from January to December 2013. Both these sensors operate in sun-synchronous orbits, with 13:30 and 10:00 local time crossing at equator, respectively (van Noije et al., 2006). GOME-2 located on board MetOp-A satellite is the first of a series of three identical instruments which will provide more than 15 years of space-borne UV/visible observations of the atmosphere (Munro et al., 2000). The GOME-like nadir viewing spectrometer covers the spectral range between 240 and 790 nm at 0.2–0.4 nm resolution, has a ground pixel size of 80 × 40 km^2 and overpasses the Equator at 09:30 LT in the descending node (Callies et al., 2004). With its large swath of 1920 km, GOME-2 provides near global coverage every day. For this purpose Doha, capital city of Qatar, is considered due to limited data availability over Saudi Arabia. Doha has been considered due to its similarity with Saudi Arabia regarding climate and industrial activities. Both places have hot desert climate with long summers. *Figure 1* shows the time series of both sensors datasets. The time series shows good consistency between mean values of OMI (4.0×10^{15} molecules/cm^2) and GOME-2 (5.04×10^{15} molecules/cm^2) data. It is observed that the both datasets are positively correlated ($r = 0.534$).

Anthropogenic NO_x emissions have been obtained from Emissions of atmospheric Compounds & Compilation of Ancillary Data (ECCAD) web site available at http://eccad.sedoo.fr. These NO_x emissions have been estimated by Monitoring Atmospheric Composition and Climate (MACC) and megaCITY-Zoom for the Environment, CityZEN (Granier et al., 2011; ul-Haq et al., 2017). MACCity anthropogenic NO_x estimates are largely based on emissions from residential, transportation, agricultural, industrial, energy, waste and shipping sectors. Atmospheric Infrared Sounder (AIRS) instrument suite aboard the NASA Earth Observing System satellite Aqua provides the distribution of atmospheric trace gas constituents including ozone (Pagano et al., 2010). We have used monthly averaged and gridded AIRS O_3 product.

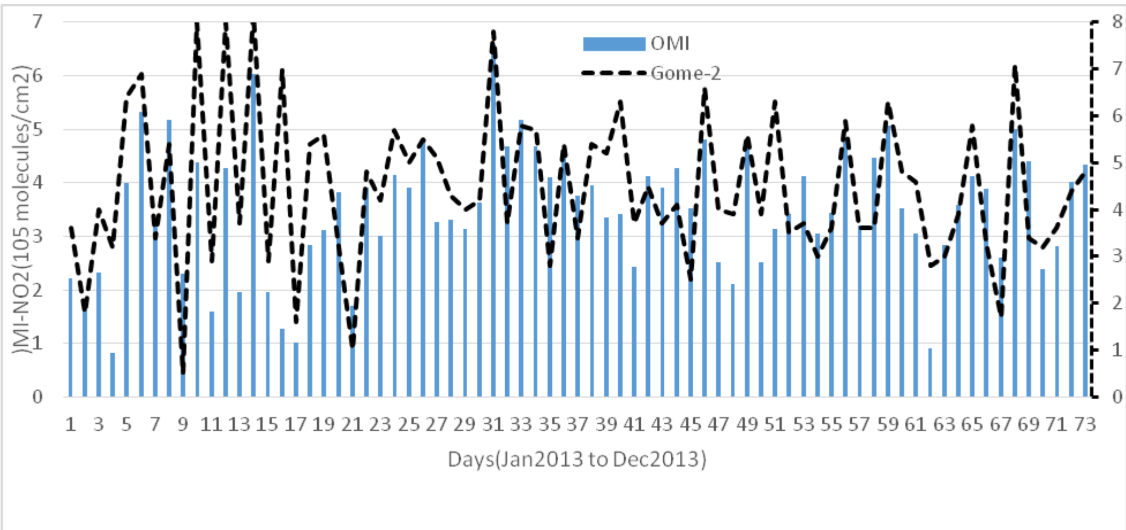

Figure 1. *Time series of OMI-NO_2 ($\times 10^{15}$ molecules/cm^2) and GOME2-NO_2 ($\times 10^{15}$ molecules/cm^2) over Doha during January 2013 to December 2013. Dotted line corresponds to secondary vertical axis*

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Analysis of data

Time series plotting techniques have been used for Data analyses, especially for determining the seasonal and monthly trend of NO_2. These trends over two cities were further explored with Pearson's correlational analysis. Analysis of significant factors associated with concentration of NO_2 was carried out through General Linear Model (ANOVA.). The concentration of NO_2 for two sites has been compared between years, months and seasons. SPSS 20.0 version has been used for this purpose.

Results

The yearly averaged column value of NO_2 is found to be 1.1680×10^{15} molecules/cm^2 with increasing trend of 1.45% per year over Saudi Arabia (*Table 1*).

Table 1. *Descriptive analysis of OMI-NO_2 column ($\times 10^{15}$ molecules/cm^2) over the study area and hotspots during 2005-2014*

	N	Range	Minimum	Maximum	Mean	Std. deviation
Saudi Arabia	3637	2.09	0.28	2.37	1.1680	0.29215
Jeddah	3344	9.99	-0.55	9.43	3.0616	1.18307
Riyadh	3230	11.49	-0.06	11.44	3.0828	1.41565

Two NO_2 hotspots have been identified within the study area as shown in *Figure 2*.

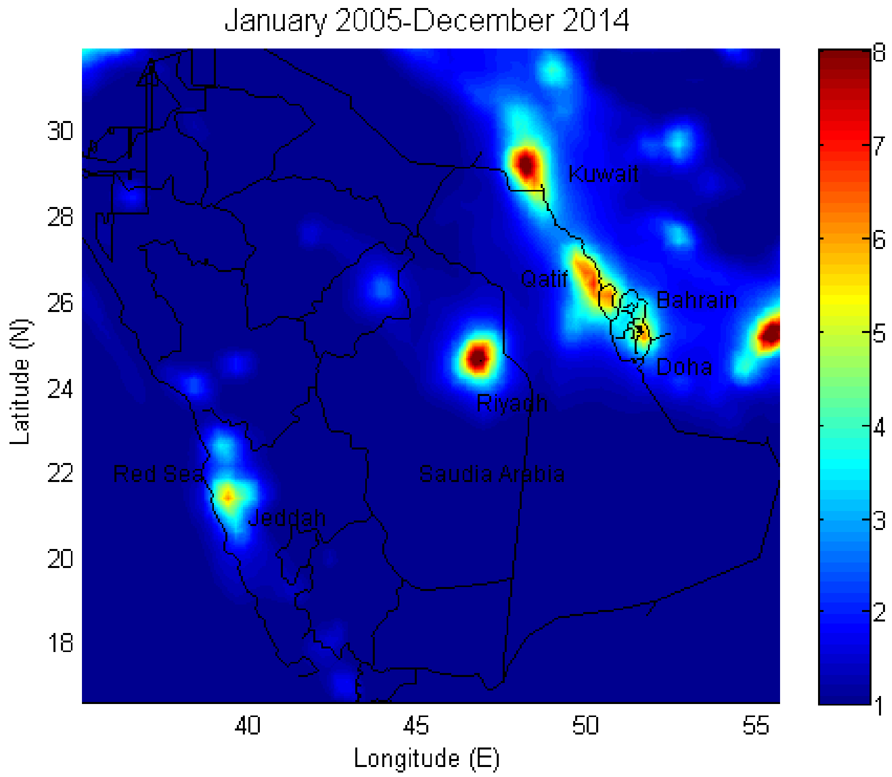

Figure 2. *OMI-NO_2 mean concentration ($\times 10^{15}$ molecules/cm^2) over the study area and two hotspots from 2005 to 2014*

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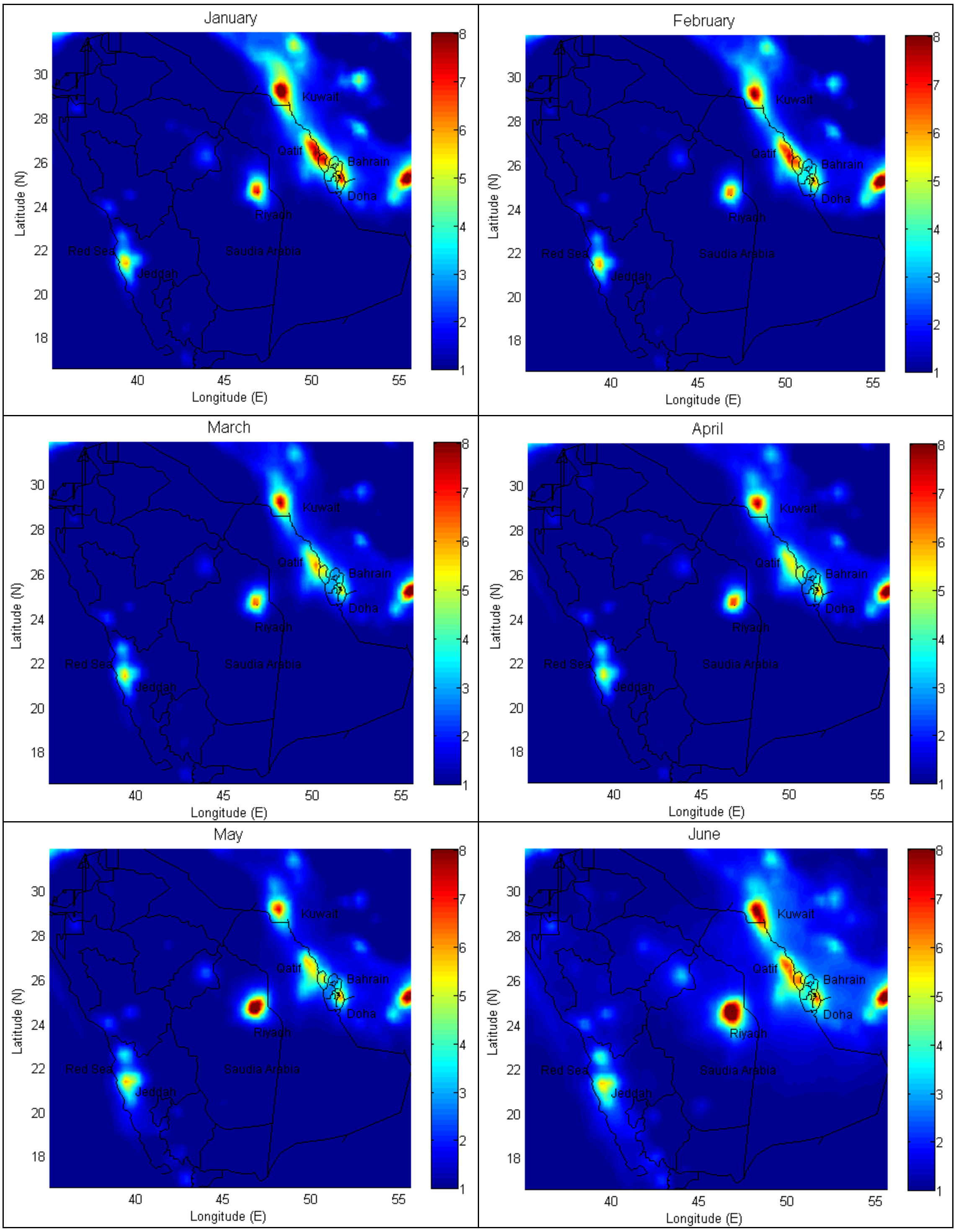
The yearly averaged column value of NO_2 is found 3.06×10^{15} molecules/cm^2 with increasing trend of 3.15% per year over Jeddah and 3.06×10^{15} molecules/cm^2 with increasing trend of 3.10% per year over Riyadh. These elevated values can be seen throughout the year as shown in *Figure 3*.

The overall trend is found higher in higher percentile. An increasing trend also found year after year both in Jeddah and Riyadh (*Table 2*).



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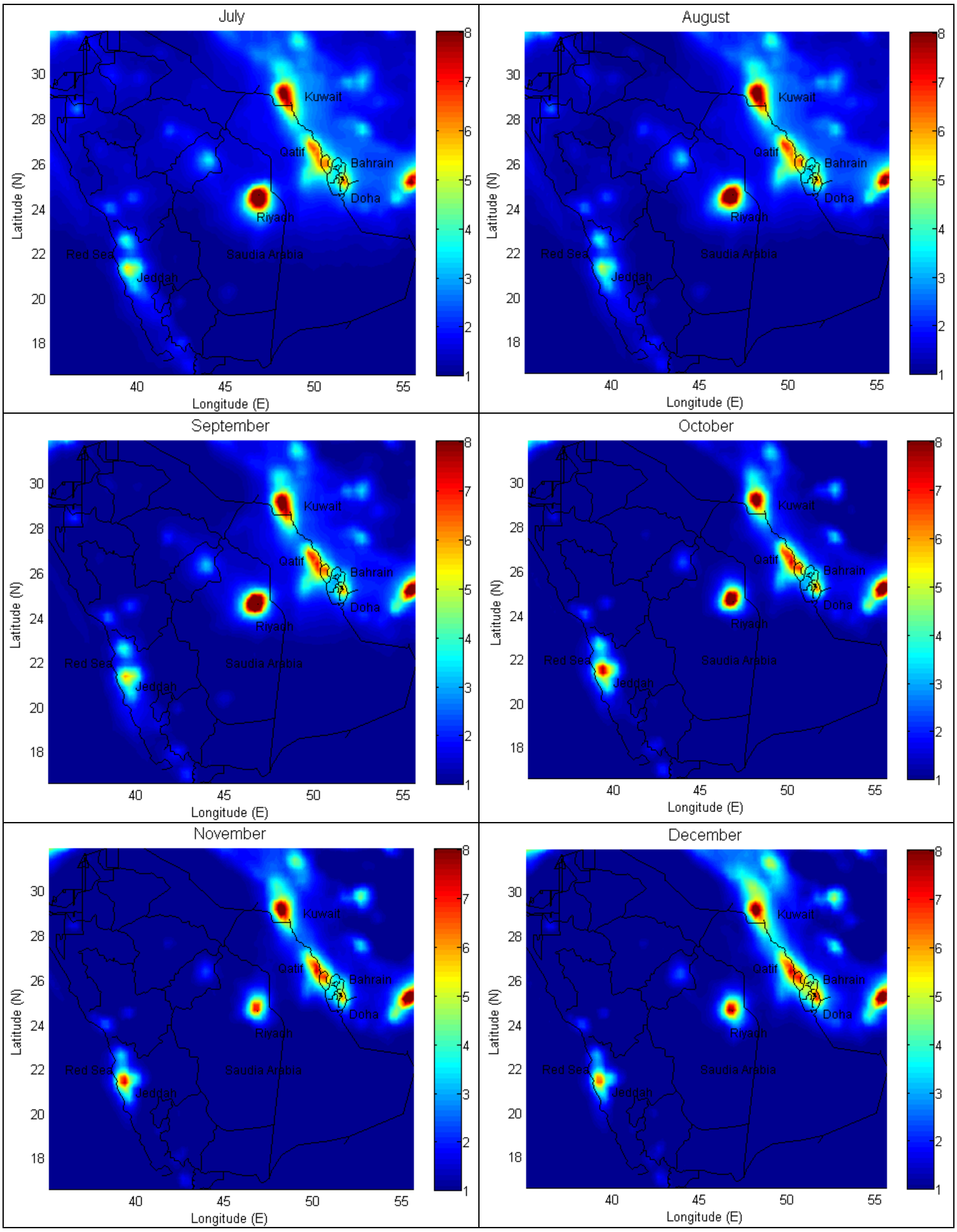

Figure 3. *Monthly spatial distribution of OMI-NO_2 ($\times 10^{15}$ molecules/cm^2) column over the study region during 2005-2014*

The relation between meteorological parameters and tropospheric NO_2 has been found through bivariate correlation analysis and the trends have been found by linear regression (*Table 3*). The mean value of meteorological factors, temperature, wind

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speed, humidity, cloud cover, visibility and sea level pressures has been considered. The meteorological data was collected from www.wunderground.com.

Table 2. *Summary OMI-NO_2 ($\times 10^{15}$ molecules/cm^2) trends statistics over hotspot cities during 2005 to 2014*

	NO2 concentration over Jiddah									
Percentiles	2005	2006	2007	2008	2009	2010	2011	2012	2013	2014
5	1.631	1.468	1.485	1.502	1.510	1.224	0.975	1.138	0.970	1.107
10	1.910	1.734	1.820	1.887	1.811	1.612	1.461	1.677	1.695	1.729
25	2.238	2.114	2.254	2.336	2.321	2.387	2.233	2.335	2.470	2.600
50	2.702	2.552	2.706	2.959	2.889	3.065	2.845	3.154	3.224	3.329
75	3.285	3.149	3.530	3.780	3.668	3.879	3.550	3.950	4.148	4.146
90	4.006	3.848	4.083	4.617	4.437	5.003	4.412	4.979	5.486	5.178
95	4.506	4.367	4.657	5.072	5.113	5.309	5.532	5.739	6.450	5.960
NO2 concentration over Riyadh										
5	1.180	1.058	1.256	1.203	1.216	1.353	1.155	1.114	1.109	1.186
10	1.429	1.284	1.632	1.633	1.583	1.688	1.532	1.478	1.639	1.638
25	1.981	1.906	2.132	2.128	2.249	2.430	2.293	2.110	2.130	2.192
50	2.562	2.442	2.725	2.957	3.026	3.286	3.193	3.008	2.790	2.832
75	3.447	3.189	3.420	3.773	4.225	4.359	4.212	4.107	3.843	3.859
90	4.154	4.075	4.083	4.700	5.376	5.456	5.635	5.688	5.284	4.918
95	4.626	4.632	4.784	5.425	6.118	6.519	6.693	6.588	6.122	5.653

Table 3. *Correlation between concentration of NO_2 over Jeddah, Riyadh and meteorological factors*

		NO_2	**Temperature (°C)**	**Pressure (hPa)**	**Visibility (km)**	**Humidity (%)**	**Wind speed (km/hr)**	**Cloud cover**
Riyadh	Pearson correlation	1	0.347**	-0.288**	-0.038	-0.342**	-0.319**	-0.166**
	Sig. (1-tailed)		0.000	0.000	0.057	0.000	0.000	0.001
Jeddah	Pearson correlation	1	0.131**	-0.010	-0.123**	-0.004	-0.305**	-0.274**
	Sig. (1-tailed)		0.000	0.278	0.000	0.418	0.000	0.000

**Correlation is significant at the 0.01 level (1-tailed)

Table 4 highlights the effect size of NO_2 concentration for seasons and years over two hotspots Riyadh and Jeddah. Eta square η^2 for both one-way and multiway ANOVA from General Linear Model and then Univariate analysis has been calculated.

Figure 4 shows that Range of NO_2 concentration is higher over Riyadh whereas it found lower for Jeddah for the same reason. The NO_2 Range is high for Riyadh with 7.79×10^{15} molecules/cm^2 than Jeddah with 4.69×10^{15} molecules/cm^2. The seasonal temperature difference of 8 °C and 20 °C has been found for Jeddah and Riyadh respectively. The regression analysis shows that for every one degree increase in temperature tropospheric concentration of NO_2 over Riyadh increased by 0.15, which represent 0.36 standard deviation. $F (1, 2388) = 327$ had an associated probability level of $p < 0.001$, while for Jeddah increase in one degree in temperature will increase the value of NO_2 by 0.06.

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Table 4. *Comparison between the measured NO_2 values of the sites and years and seasons through ANOVA*

Source	df	Mean square	F	Sig.	Partial eta squared
Season and NO_2_Jeddah	3	60.873	45.217	.000	.039
Year and NO_2_Jeddah	9	19.028	14.073	.000	.037
Season and NO_2_Riyadh	3	191.015	104.477	.000	.089
Year and NO_2_Riyadh	9	29.484	15.298	.000	.041

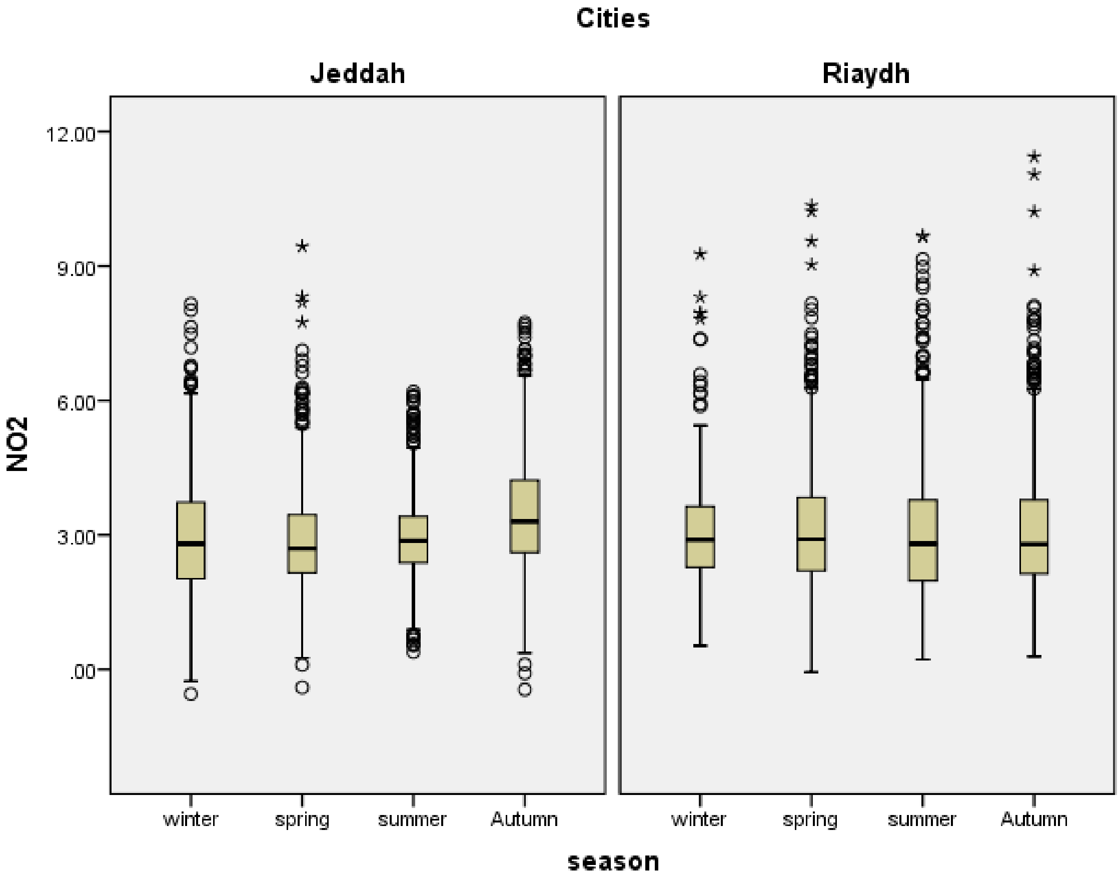

Figure 4. *Concentration of NO_2 ($\times 10^{15}$ molecules/cm^2) in different seasons over hotspots during 2005-2014*

The activities regarding electricity consumption, fossil fuel burning in automobiles and electrical power generators have been noticed at the peak during summer months. Therefore, high concentration of NO_2 has been found both in summer and autumn. The highest value found in Riyadh, i.e. mean 3.41×10^{15} molecules/cm^2 (Std. Dev = 1.25 whereas in Jeddah highest value found in autumn, i.e. mean = 3.39×10^{15} molecules/cm^2 (Std Dev = 1.19) (*Figure 5*).

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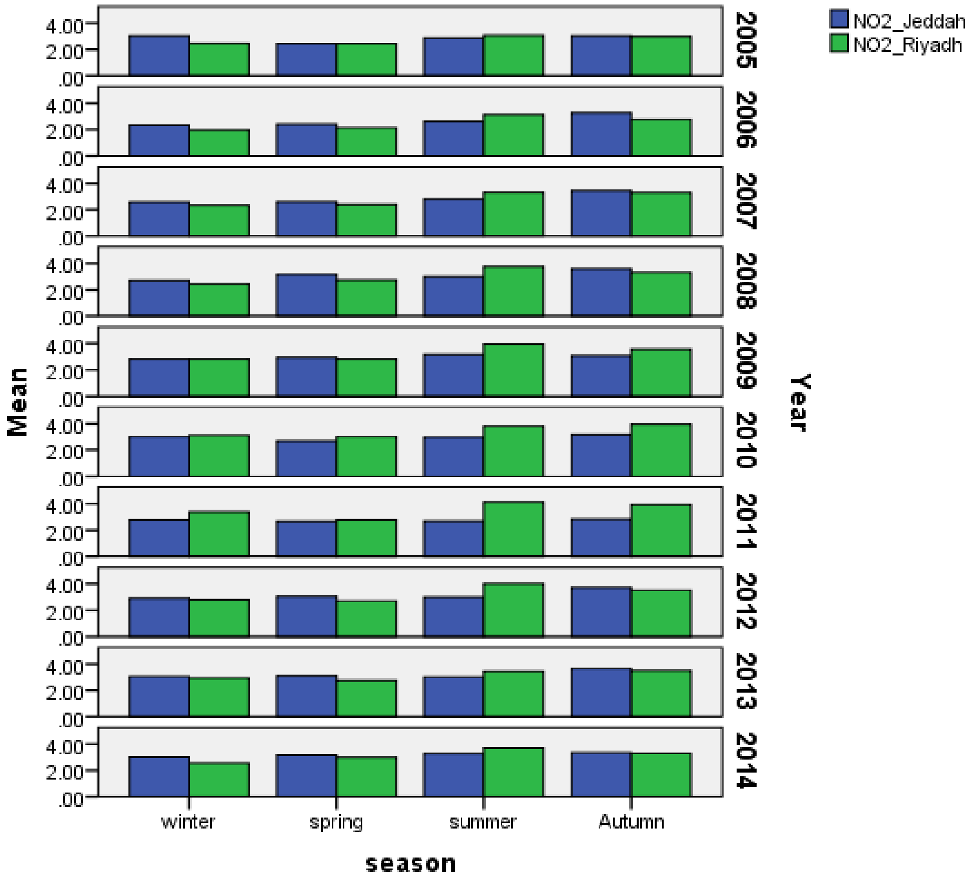

Figure 5. *Seasonal mean variations of NO_2 ($\times 10^{15}$ molecules/cm^2) over hotspots during 2005-2014*

An overall correlation between OMI tropospheric NO_2 and AIRS tropospheric ozone is found $r = 0.21$ during 2005-2014. Also spatial mapping of correlations between OMI tropospheric NO_2 and AIRS tropospheric ozone has been presented in *Figure 6* during 2005-2014. The correlations have been observed to be ranging from $r = 0.6$ to $r = -0.8$. Most of the northern parts of Saudi Arabia are found with higher positive correlations compared to southern parts largely due to more population and economic activities.

Discussion

The results show yearly averaged column value of NO_2 has been increased annually by 1.45%. This increasing trend is in close agreement with previous regional study by (Zohary and Spiegel-Roy, 1975). In Saudi Arabia the consumption of oil (million barrels per day) has increased 60.9% from 1996 to 2006 (EIA, 2008). This increase has contributed to increased levels of NO_2 in the atmosphere. The increase in Saudis' manmade activities contribute significantly to this trend. The most prominent sources of pollution are motor cars, factories and oil refineries. The number of private vehicles was found large because of weak public transportation system in Saudi Arabia (Kaba et al., 2007). According to Arab News (2014) an increase of 6% in motor vehicles from 2012 has been recorded.

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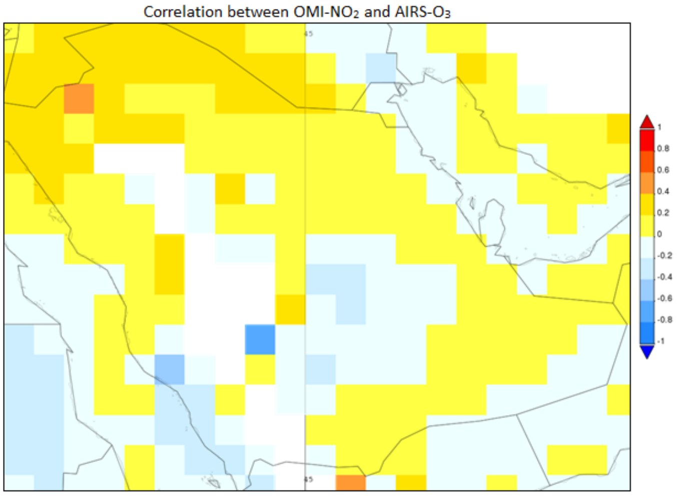

***Figure 6.** Spatial map of correlation between OMI observed NO_2 and AIRS retrieved tropospheric ozone over Saudi Arabia during 2005-2014*

EDGAR (Emission Database for Global Atmospheric Research) data has shown 9.4% increase in NO_x emissions in Saudi Arabia (EDGAR, 2010) during 2005–2008 and has identified major sources with significant annual increase in various emission categories, i.e. public electricity and heat production (18.3%), manufacturing industries and construction (15.03%), manure man- agreement (6.93%), direct soil emissions (1.78%). Average oil industrial production growth rate was found 20% from 2010 to 2015 (Arab News, 2014).

Two cities, Jeddah and Riyadh, of Saudi Arabia have been identified with remarkable concentration of NO_2. Many studies have already identified these two cities as important source of NO_2 (Boersma et al., 2004, 2007; Bowler, 2014). Jeddah lat (20.6, 22.1 °N) long (38.9, 40 °E) has comparatively warm and humid climate with mean temperature 29 °C, mean humidity 54%, mean sea level pressure 1008 mb, 57% humidity and 10.9 km/hour wind speed. Precipitation is negligible. Winds blow in north east direction. The winds mostly come from Red Sea. In summers, dust storms blow from the Arabian Peninsula to Jeddah.

Riyadh lat (24.4, 26 °N) long (46.1, 48 °E) is capital city of Saudi Arabia. It has hot desert climate with increased seasonal range of temperature, i.e. 35 °C (mean temp 27.5 °C). The mean sea-level pressure is 1013 mb, and mean humidity value is 25%.

The reason behind higher concentration of NO_2 over Jeddah and Riyadh can be Industrial and vehicular emissions. Their combined effect gives Jeddah a serious air pollution problem. Many old cars cause serious air pollution in the city due to poor maintenance and improper check of regulations and then the industrial area of the city contribute further to environment (Kadi, 2009). Concentrations of heavy metals, gaseous air pollutants and particulate emissions far exceed internationally acceptable standards (Al-Jeelani, 2008; Hassan et al., 2013). Other important reasons of NO_2 emission in both Jeddah and Riyadh are incinerators, oil refineries, cement and electrical power plants. In Riyadh, sand rock quarries and crushers contribute significantly to NO_2 emission (Salama et al., 2011). The sprawling pattern of the cities, such as Riyadh and Jeddah, also contributes to emissions through long trips to work. Al-

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Ahmadi and Al-Zahrani noted that NO_2 concentrations in Jeddah and Riyadh might be caused by vehicle emissions and urban activities (Kaba et al., 2007).

The correlation between OMI NO_2 and MACCity anthropogenic NO_x from sum sectors including residential, transportation, agricultural, industrial, energy, waste and shipping sectors is (r = 0.78 and slope 0.942) over Saudi Arabia during 2005-2014.

The results show positive correlation between temperature and NO_2 and negative correlation with mean humidity, cloud cover and wind speed for both hotspots (*Table 3*). The literature supports these results as life time of NO_2 is 3-10 hours and may be remain for 5 to 10 days only when humidity level is low (Papes, 2007). The tropospheric NO_2 reacts with OH radical and removed from the atmosphere by converting into nitric acid (HNO_3) in day timings (Oindo et al., 2002). The relationship between NO_2 and temperature is discussed by (Moreno-Amat et al., 2015), that with the increase in temperature a significant increase in HNO_3 has been found. However, no significant correlation has been found between these two variables (NO_2 and Humidity) for Jeddah, a coastal city due to higher and constant level of humidity and less temperature variations over coastal city of Jeddah.

As the results showed, seasonal effects are remarkable for both hotspots. Analysis of variance (*Table 4*) showed a main effect of seasons on NO_2 concentration over Riyadh (p = .000, ηp^2 = 0.08) and Jeddah (p = .000, ηp^2 = 0.03), whereas for years it gives Riyadh (p = .000, ηp^2 = 0.04) and Jeddah ((p = .000, ηp^2 = 0.03). It means seasonal effect is 8% for Riyadh and 3% for Jeddah. The difference in years for NO_2 concentration was found 4% for Riyadh and 3% for Jeddah. Maximum mean values of NO_2 have been found in summer and autumn and comparatively low values are observed in spring and winter. As far as Jeddah is concerned it is one of the major cities of Saudi Arabia and the largest after Mecca. It serves as a major platform for air, road and marine transport. It has also main airport for pilgrims for Hajj (Bowler, 2014). In 2013, 17 million people as tourist enter in Saudi Arabia where its 40.6% approximately 6.9 million were on religious purpose (Ellis, 2015). The highest value of NO_2 found in autumn and early winter reveals the fact that from 2005-2014 the Hajj season came between October and January. *Figure 5* shows a remarkable increase in concentration of NO_2 over Riyadh in summer and autumn 2011. It may be due to heavy transport movement of approximately 1000 Saudi troops (Slee and Feliciano, 2015) to handle the Bahrain uprising and unrest due to the protests in Saudi Arabia especially in Riyadh.

Conclusion

Tropospheric NO_2 has been studied over Saudi Arabia with the help of satellite based OMI data. Two hotspots Jeddah and Riyadh have been identified. The spatiotemporal analysis showed that there was significant increase in NO_2 level from 2005-2014. The NO_2 patterns were also analyzed with the help of meteorological parameters. The results showed positive correlation with temperature and negative correlation with wind speed, humidity and cloud cover. A detailed analysis to assess the relationship of NO_2 with other atmospheric pollutants such as CO, Ozone, SO_2 and aerosols over Saudi Arabia is recommended for future studies with special emphasis on Hajj season.

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