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# Analysis of tropospheric $NO_2$ over Iraq using OMI satellite measurements

**Key words:** nitrogen dioxide, air pollution, remote sensing, Baghdad, Iraq

## Introduction

There is an agreement, since the onset of the industrial revolution, the continuous emissions of the anthropogenic and pollutions in the atmospheric have increased due to the human activity, industrialization, and deforestation. This increase has redounded significantly to economic dullah, 2012; Rao, Hutyra, Radevelopment and the birth of the anthropogenic reached over 50% (Rajab, Jafri, Lim & Abciti & Templer, 2014; Al-Salihi, 2018). Also, it is a massive source of many air pollutants because of growing anthropogenic emissions related with growth rates of megacities, large urban agglomerations and rapid traffic growth (Molina & Molina, 2004). The significant external variables controlling the climate contains aerosols, solar irradiance and greenhouse gases (GHGs), e.g.: carbon dioxide ($CO_2$), water vapour ($H_2O_{vapor}$), methane ($CH_4$), nitric acid ($N_2O$) and ozone ($O_3$). As a result of human vitalities since 1750, the global atmospheric densities of $CO_2$, $CH_4$ and $N_2O$ have increased perceptibly and beat pre-industrial measurements specified by ice cores for many thousands years (Rajab, MatJafri & Lim, 2014; Al-Salihi, Rajab & Salih, 2019).

Nitrogen dioxide is one of the most important air pollutants trace gases in the atmosphere with important impact on tropospheric and stratospheric chemical processes and human health. It plays a major role for production of ground level $O_3$. Moreover, $NO_2$ contributes to the formation of secondary aerosols and acid rain (Zyrichidou et al., 2013; Yang, Carn, Ge, Wang & Dickerson, 2014; Chan et al., 2015; Al-Salihi, 2017). There are still several disputes about the exact amount of the diverse influx and sources for $NO_x$. The $NO_2$ creating by both natural and anthropogenic activities: biofuel combustion and fossil fuel, thermal power plants, transportation, industries, biomass burning, residential use, aircrafts and microbiological processes in soil. Natural sources of $NO_2$ are lightning and microbial activity in soil by the oxidation of ammonium nitrate (Constantin, Voiculescu & Georgescu, 2013).

In many researches, the spatiotemporal differences of the troposphere vertical column densities (VCDs) $NO_2$ during 2005–2016 was investigated with level of urban development across many large countries such as China. And the relationship between urban development and $NO_2$ pollution analysed by using the night-time light (NTL) data. The NTL data and $NO_2$ column data are both measured by satellite observations (Cui et al., 2019). In addition, the regional variations emissions of $CO_2$ from airports were increased due to the civil aviation sector activities. These emissions evaluated by using geographically weighted regression (GWR) models and ordinary least square (OLS), separately, to investigate spatial heterogeneity, and whether urbanization drives airport $CO_2$ emissions at the city level (Zhang et al., 2019).

The profusion of atmospheric parameters was been measured four decades ago using airplanes, weather balloons, and distributed ground stations. These measurements are cost so much money and staff and incapable to get continuous long term recordings for global climate variability. Therefore, there is a shortage in data for upper and lower troposphere. The satellite remote sensing has useful global and regional coverage's, which raised our capability to analyse the influence of human activity on the climate change and the atmosphere chemical composition. Also, equip continuous data with high temporal and spatial resolution (Lin et al., 2014; Salih, Al-Salihi & Rajab, 2018). Satellite measurements provide necessary information of distributions for the atmospheric trace gases column densities. The satellite tropospheric $NO_2$ data have found prevalent utility. Observational analyses have explained the strong weekly cycles in the observed $NO_2$ (Beirle, Platt, Wenig & Wagner, 2003; Chan et al., 2015), the continental scale outflow and the influence of biomass burning (Ladstaetter--Weissenmayer, Burrows & Perner, 1998; Burrows et al., 1999).

From environmental scenery, Iraq encountering severe problems of fast motorization, deforestation and energy trouble cases a strong rise of $NO_2$ emissions with additional pressure on the local and regional environment. Therefore, a comprehensive spatio-temporal study of tropospheric $NO_2$ over Iraq is an important issue. In order to develop the efficient strategies to minimize its emissions, which from fossil fuel combustion and biomass burning reduce local air quality and affect global tropospheric chemistry. The purposes of this research to analyses the yearly hotspots emissions, tropospheric $NO_2$ monthly distribution, and assess its long term-trends above Iraq employing Ozone Monitoring Instrument (OMI) data during 2005–2014. A trend and air mass trajectory data were analysed over Baghdad city. The results help to analysis and identify the hotspots for territorial $NO_2$ emissions above study area. The annual and monthly mean $NO_2$ maps were generated using GIS software.

## Material and methods

Iraq is a country lies in the western part of Asia, located in southwestern Asia, and take possession of usually the Mesopotamian Plain, situated, between 39° and 49° E longitudes and 29° and 38° N latitudes (a small regions lie west of 39°). An area (Fig. 1) involves of 437,072 $km^2$. The most north areas of the country are made up of mountains; the highest point being at 3,611 m. Tigris and Euphrates rivers, run from the middle of Iraq, taking place from northwest towards southeast where fecund alluvial plains. Iraq has a narrow coastal strip north of the Arabian Gulf with a length of 58 km. Most of Iraq has a hot and arid climate with subtropical influence. The northern mountainous regions have cold winters with occasional heavy snows. Summer temperatures rate above 40°C in most parts of the country and frequently exceed 48°C. Winter temperatures infrequently exceed 21°C with maximums roughly 15–19°C and nighttime lows to 2–5°C. Typically, precipitation is low; except for the northern regions, the rainfall is extremely rare during the summer. The maximum rainfall occurs during the winter months, and most places receive less than 250 mm annually (Metz, 1993; Abed, Al-Salihi & Rajab, 2018).

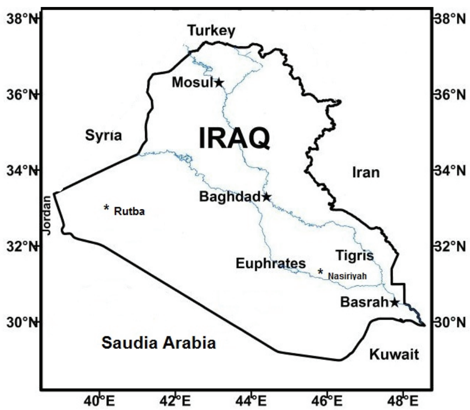



FIGURE 1. The geographical feature of the study area

Ozone Monitoring Instrument is one of the several, flying on-board NASA's Aura satellite put to space on 15 July 2004, with orbital period of around 100 min and has a Sun synchronous polar orbit passes the equator at around 13:30 local time (Zyrichidou et al., 2013). It observes the atmosphere in 60 cross-track ground pixels measuring 13–26 km along track and 24–128 km across track has a 114° field of scenery, which matched to about 2,600 km vast swath on the Earth's surface, providing daily global $NO_2$ maps. Due to the vast swath of the 14–15 orbits per day, OMI realizes global covering nearly in a day (exclude for tropics). It is nadir visibility imaging spectrograph quantify backscattered and direct sunlight in the ultraviolet-visible (UV/VIS) range from 270 to 500 nm with a spectral resolution of about 0.5 nm and its performance and design explained in detail in (Levelt et al., 2006).

Tropospheric $NO_2$ columns are restored by utilizing differential optical absorption spectroscopy (DOAS) analysis in the 405–465 nm spectral range, and has an unreliability of $0.1 \cdot 10^{15}$ molecules per 1 $cm^2$ and it is undervalued by

15–30%. The recapture of $NO_2$ used to record the pure and 0–30% cloudy situations in the air mass element acquired for the simulated $NO_2$ profiles. The seasonal differences of $NO_2$ reclamation from OMI agree with the NASA GSFC's global modelling initiative (GMI) chemical transport model (Levelt et al., 2006).

In this study, ten-year information from January 2005 to December 2014 were utilized to assess and analyse the $NO_2$ distributions above research area. The Baghdad city been selected and fitted with a linear function. Results from the analysis of $NO_2$ concentrations was acquired by OMI satellite ascending Level-3 data. In general, 120 L3 ascending monthly granules loaded to gain the required output. Using OMI website file data, comprising the identical time and location along the satellite course, in a HDF (hierarchical data format) format for monthly basis, were took out from the satellite and organized in schedule utilizing MS Excel. To analysis the annual long-term allocation of tropospheric $NO_2$ above Iraq, the monthly data averaged for the period (2005–2014) of OMI measurements. While for monthly analysis, the data of tropospheric $NO_2$ averaged for the each month along the study period. The GIS software used for plotting the averaged for the each month and annual for the study period.

## Results and discussion

### Annual analysis long-term $NO_2$ data over Iraq

Figure 2 illustrated the annual distribution of tropospheric $NO_2$ over Iraq by the OMI opportunity to monitor urban emissions from space for the study pe-

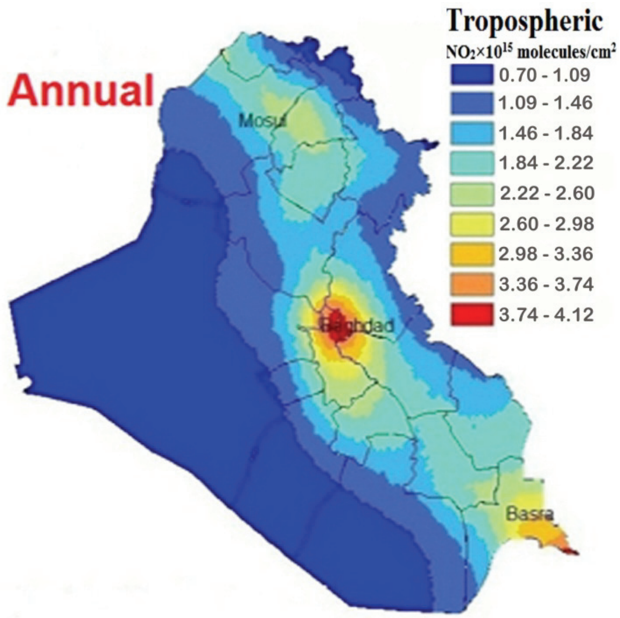



FIGURE 2. Annual mean distributions of tropospheric $NO_2$ over Iraq, produced by the global data of Aura OMI monthly mean tropospheric $NO_2$ during 2005–2014

riod. There is a reduction in the concentration of tropospheric $NO_2$ over western and south western parts of Iraq, less than ($1 \cdot 10^{15}$ molecules per 1 $cm^2$) due to arid desert areas where sand and lack of urban activity. Also the same reduction in the eastern region where the mountainous areas and high-rise mountain peaks, because of less population, urban and industrial activity. There is an increase on troposphere $NO_2$ values at the belt extended from the northern to the southern of Iraq, ranged from $1.46 \cdot 10^{15}$ to $2.22 \cdot 10^{15}$ molecules per 1 $cm^2$. The highest value was at central of Iraq, Baghdad and its sounding regions, more than $2.6 \cdot 10^{15}$ molecules per 1 $cm^2$. The hot spot of pollutions was over Baghdad city (up $3.74 \cdot 10^{15}$ molecules per 1 $cm^2$) due to high population, congestion, wide urban and industrial areas.

**Monthly analysis long-term $NO_2$ data over Iraq**

Figure 3 illustrated the average monthly $NO_2$ for winter and spring seasons (December–May) and for summer and autumn seasons (June–November), respectively, over study area for the period 2005–2014. The significant spatial variations of $NO_2$ observed over the most parts of Iraq. The $NO_2$ expertise diverse seasonal variations depend on the weather situations and topography. The seasonal fluctuation in the $NO_2$ varied highly noted among four seasons. A specific checking shows subtle changes in the $NO_2$ spatial types for each season, with higher values for $NO_2$ in the winter and summer than in the spring and autumn seasons. Also, increases in $NO_2$ values observed along the year above the manufacturing and crowded urban regions, i.e. Baghdad and Basra. A less $NO_2$ values happen at the clean desert environment over western and southwest areas, i.e. Anbar and Samawa.

Figure 3a illustrated the highest value of $NO_2$ occurred during the winter (January), especially at central region of Iraq over capital Baghdad and its surrounding areas. Because of the high precipitation rates, which reach to (240 mm), increased the microbial activity that contribute to more soil emissions due to the agricultural fields activities, and the reduction of removing $NO_2$ by photolysis process because of less solar radiation at existence of clouds. In January $NO_2$ increased to its highest value throughout the year at Baghdad was $5.13 \cdot 10^{15}$ molecules per 1 $cm^2$ (red pixels), though it lightly decrease to moderate in March, compare to past months, and low in May. The lowest value was over authentic desert environment over western areas on April $0.92 \cdot 10^{15}$ molecule per 1 $cm^2$ (blue pixels). This variations in the $NO_2$ concentrations during this period (December–May) caused by the human activity, geographic species of the regions and weather fluctuations.

As shown in Figure 3b for the summer and autumn seasons (June–November), a decrease in the $NO_2$ values during September and October, whereas lightly elevate to moderate concentrations of $NO_2$ in August and November, and high in June and July. There was a rising of $NO_2$ concentrations on the southeastern area compared to its measurements on the rest of the areas during June to September. These are because of the emissions by the oil extraction and residues burning in the paddy fields. The highest value placed in this period was over Baghdad

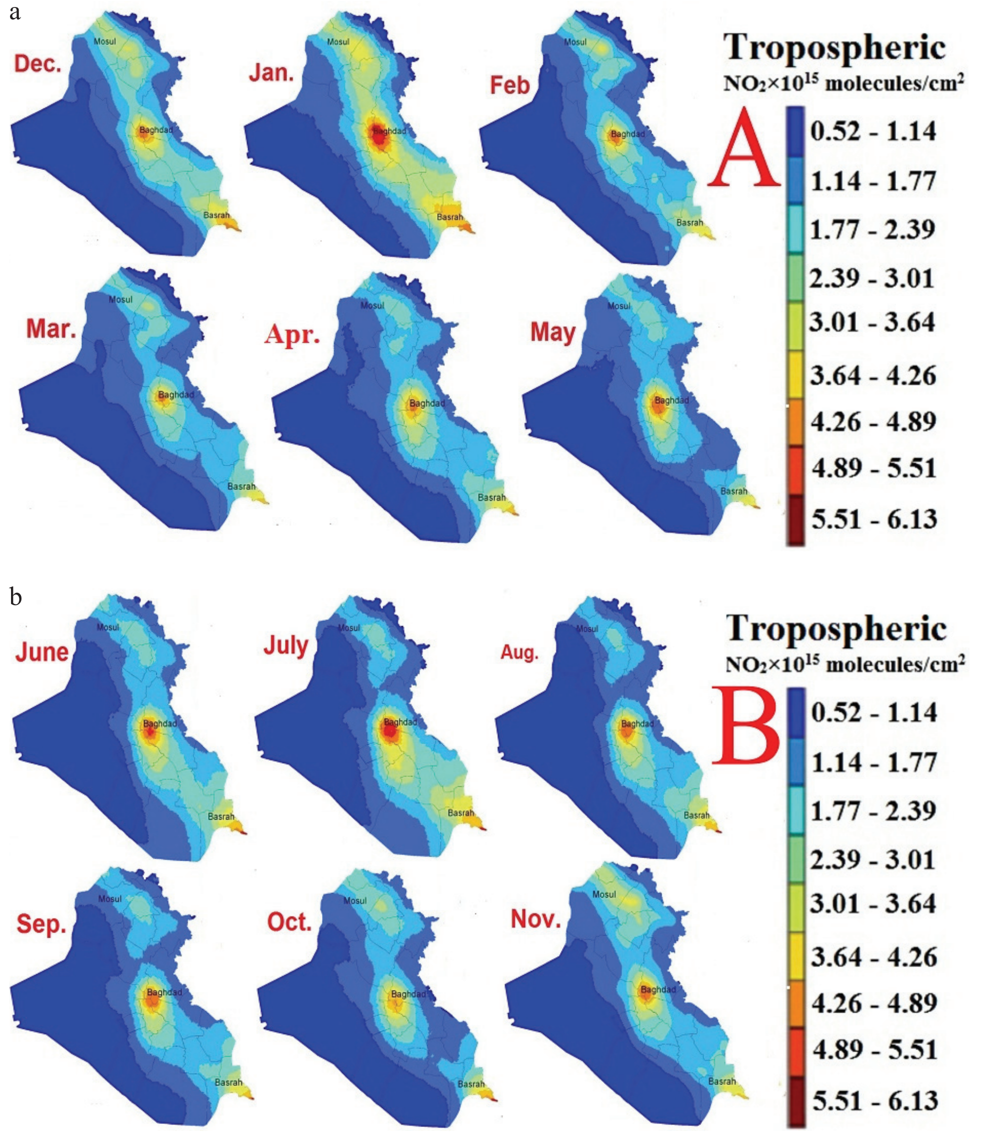



FIGURE 3. The OMI monthly coverage retrieved $NO_2$ in Iraq for the period of 2005–2014: a – for winter and spring seasons (December–May); b – for summer and autumn seasons (June–November)

during July $4.61 \cdot 10^{15}$ molecules per 1 $cm^2$ (red pixels), and the minimal value was in October $0.83 \cdot 10^{15}$ molecules per 1 $cm^2$ (blue pixels) at the western region. The high levels of $NO_2$ appeared in summer months due to the long hour's use of civil and commercial generators because of electrical power shortage with average ranges from 12 to 18 h through the summer days. It is one of the main reasons for increasing the levels of $NO_2$ during this period.

## Trend analysis long-term $NO_2$ data over Baghdad city

The high density of population (1,637 persons per 1 $km^2$), and high population growth from 4.5 million in 2003 to 7.6 million peoples in 2013 (The Ministry of Planning internal report 2014); Baghdad is the economic and administrative centre in Iraq. Moreover, the frequent presence of electric generators in residential due to the lack of electric power, commercial, and industrial neighbourhoods increase the pollution. In addition, the considerable increasing of vehicles from 450,000 in 2003 to 1,350,000 in the year 2014, making it the largest city in Iraq and the second largest city in the Arab world after Cairo. A significant $NO_2$ emission hotspot observed during the study period.

Figure 4 shows the average monthly $NO_2$ for capital Baghdad from January 2005 to December 2014, the formal peak of OMI sensitivity and the vastness of the seasonal changes in troposphere $NO_2$. The seasonal oscillations depend on weather's situations and topography. The seasonal fluctuation in the troposphere $NO_2$ varied appreciably observed between winter and spring seasons. A more appointed checking shows subtle alteration in the $NO_2$ spatial influence for each season, with maximum values for $NO_2$ in the winter. Seasonal fluctuations are visible, but none is as declared or regular through the study period. The highest value existed in this period was on during January ($6.13 \cdot 10^{15}$ molecules per 1 $cm^2$) and the lowest value was during April ($4.2 \cdot 10^{15}$ molecules per 1 $cm^2$). There was evaluation in $NO_2$ values during July, August and October. Such exemplary seasonal cycle is because of the longer lifetime of $NO_x$ through the cooling period, elevated local $NO_x$ emissions from the domestic heating system (with odd behaviour in July) and repeated events of calm and

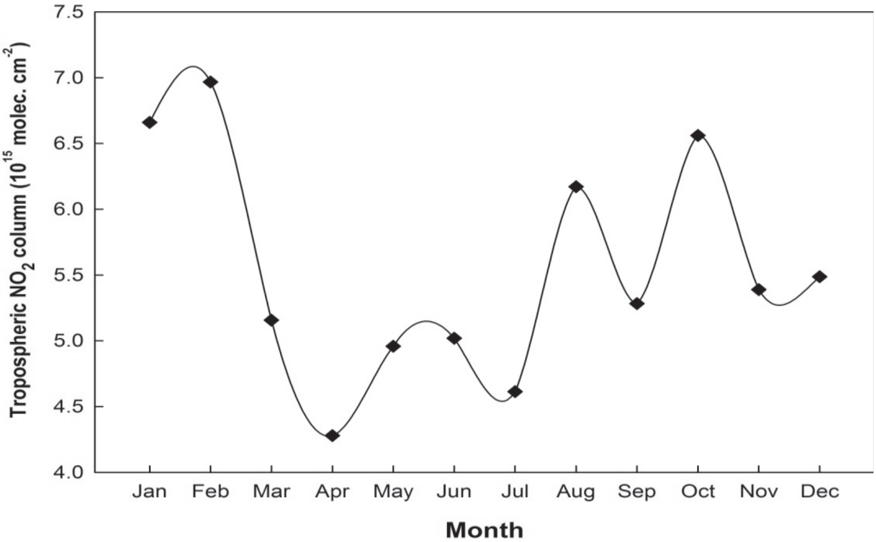



FIGURE 4. Monthly average tropospheric $NO_2$ variations over Baghdad in the period of 2005–2014

temperature inversion, facilitating the cumulating of pollutants during winter time surface air.

The resulting trend estimate for monthly average tropospheric $NO_2$ column over Baghdad provides a linear growth rate 9.8% per year (growth is the percentage calculated with respect to the mean $NO_2$ column, $5.71 \cdot 10^{15}$ molecules per 1 $cm^2$, as shown in the Figure 5. There is a progressive increase in the $NO_2$ values with distinct growth rate variations observed during the study period. An increasing, long-term trend in $NO_2$ attributed to the human activity; combustion of fossil fuels and a significant net flux of $NO_2$ to the atmosphere because of land use changes, such as agricultural activities in the paddy fields. Year-to-year variations in $NO_2$ emissions relatively increased because of different sources, comprising agricultural, motor vehicles and other manufacturer sources.

The mean, minimum and maximum annual $NO_2$ are presented in Figure 6, which present a graph of a month-long series of the $NO_2$ from the mean (solid line and square mark), minimum (solid line and circular mark), and maximum (dotted line) for hotspot over Baghdad city in the period from January 2005 till December 2014. Observed a stagnation feature as obvious during 2005 until 2009, and then increased significantly the rest of the study period. This due to increase of anthropogenic emissions and large economic activities in Baghdad, leading to rapid increase of tropospheric $NO_2$. To reach the highest levels 1.8, 2.3, 2.8 times for minimum, annual mean and maximum values compare to 2005 values.

Finally, the influences of air mass transportation on controlling of tropospheric $NO_2$ concentration investigated. Baghdad city selected as hotspot point, 24-hour backward and forward trajectory analysis employing NOAA HYSPLIT (hybrid signal-particle Lagrangian integrated trajectory) model at 500 m and 3,000 m above ground level. The trajectories observed for 8 November 2013

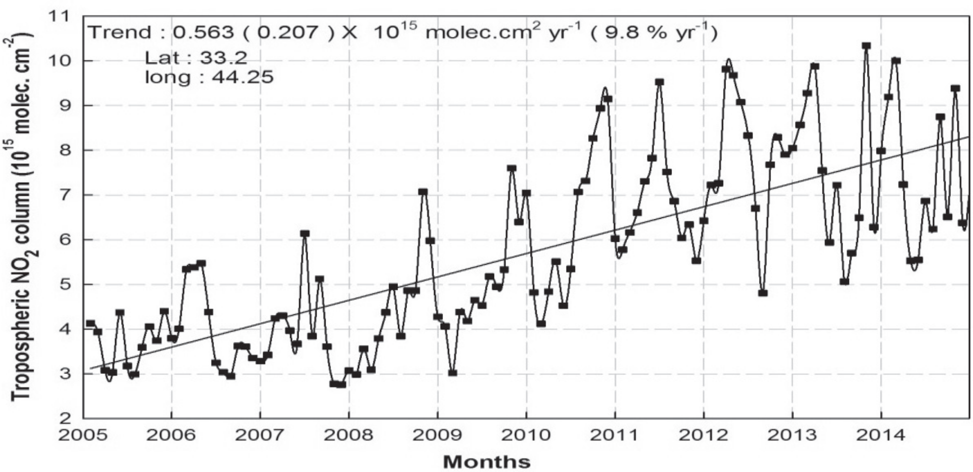



FIGURE 5. Time series of monthly mean tropospheric $NO_2$ over Baghdad for the period from January 2005 to December 2014

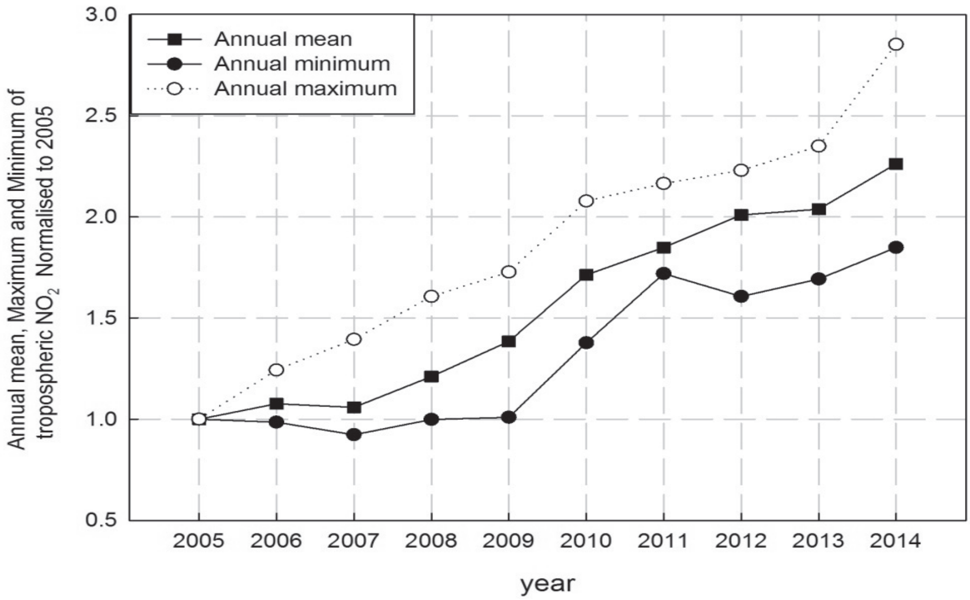


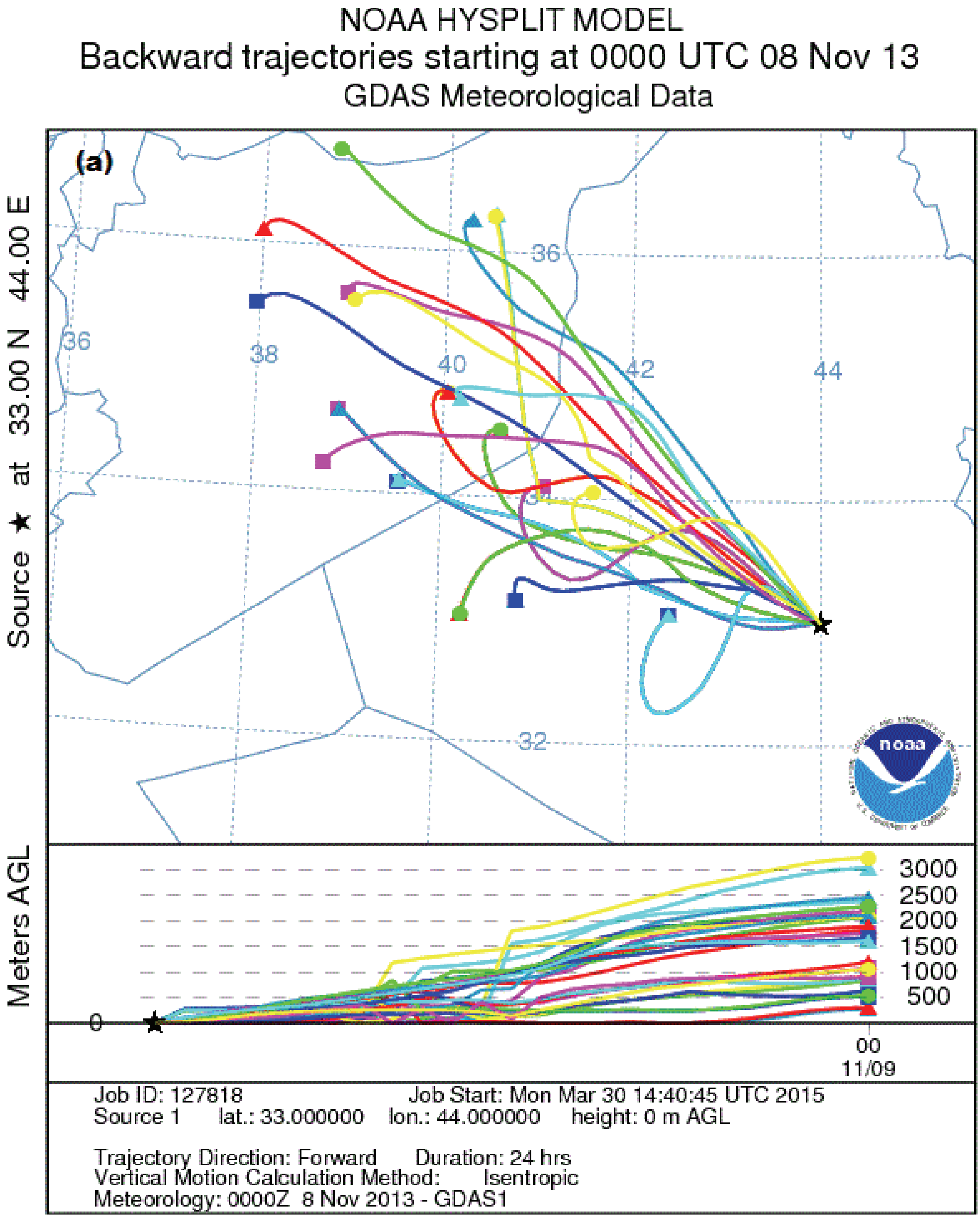

FIGURE 6. Observed the mean (solid line and square mark), minimum (solid line and circular mark), and maximum (dotted line) temporal evolutions of tropospheric $NO_2$ in the period of 2005–2014 for Baghdad

shown in Figure 7 at 500 m the ground level. Over Baghdad shown significant increasing trend of 9.8% per year and high values observed in winter and summer.

Trajectory analysis (Fig. 7) illustrate the seasonal changes in the troposphere $NO_2$ vibrate highly between winter and summer seasons. In winter, the evaluations due to anthropogenic emission of thermal heating used excessively during cold season. In addition, the subsequent plumes contributed from Europe bring by northwesterly wind driven by the passage of a strong synoptically forced cold front. Whereas during summer, the high $NO_2$ because of hot weather, the local emissions affect from the oil extraction at central and southern regions. In addition, the emissions from large paddy fields and the substantial contribution of anthropogenic from Turkey and Europe carried by eastward wind. The lowest $NO_2$ values detected during the monsoon interval mostly related to the rains.

## Conclusions and summary

Nitrogen dioxide recognized as one of the main pollutants that degrade air quality. The objective of this study was to analysis the $NO_2$ distributions over Iraq. We have start to examine the fortune information contained in the more than ten-year (2005–2014) satellite data. The $NO_2$ concentrations strongly correlated with weather situations. From annual $NO_2$ distributions, there is a reduction in tropospheric $NO_2$ over western and south western parts of Iraq, less than $1 \cdot 10^{15}$ molecules per 1 $cm^2$, and the same


NOAA HYSPLIT MODEL
Backward trajectories starting at 0000 UTC 08 Nov 13
GDAS Meteorological Data
(a)
Source ★ at 33.00 N 44.00 E
36
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32
Meters AGL
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11/09
Job ID: 127818
Job Start: Mon Mar 30 14:40:45 UTC 2015
Source 1 lat.: 33.000000 lon.: 44.000000 height: 0 m AGL
Trajectory Direction: Forward Duration: 24 hrs
Vertical Motion Calculation Method: Isentropic
Meteorology: 0000Z 8 Nov 2013 - GDAS1

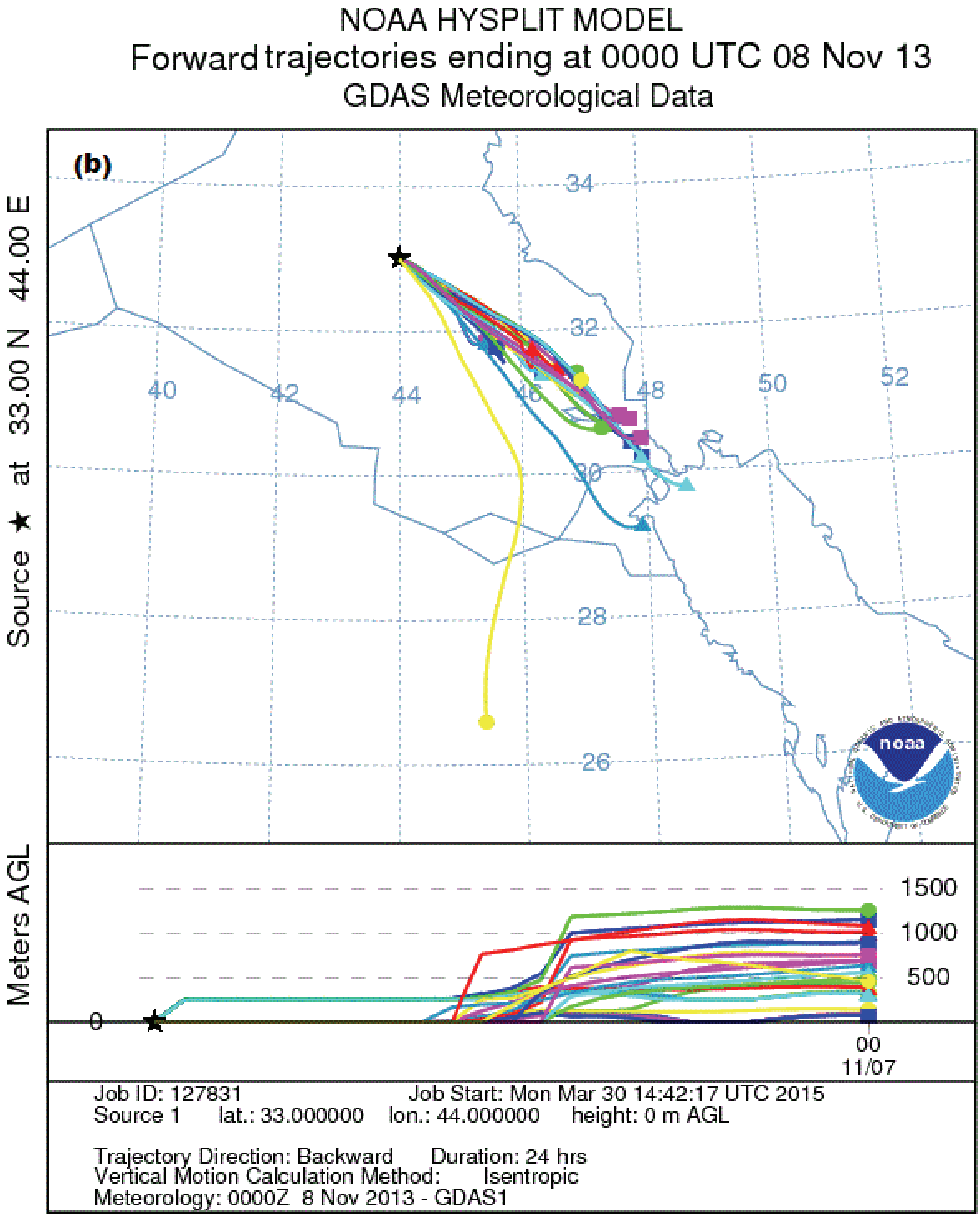


FIGURE 7. Twenty four-hour backward and forward air mass trajectories hotspots for Baghdad on 8 November 2013 at 00:00 UTC above 500 m, calculated using NOAA's hybrid single particle Lagrangian integrated trajectory – HYSPLIT model – GDAS (the hot spot marked with stars): a – backward trajectories; b – forward trajectories

reduction in the eastern region where the mountainous areas and high-rise mountain peaks. There is an increase on troposphere $NO_2$ values at the belt extended from the northern to the southern of Iraq, ranged from $1.46 \cdot 10^{15}$ to $2.22 \cdot 10^{15}$ molecules per 1 $cm^2$. The highest value was more than $2.6 \cdot 10^{15}$ molecules per 1 $cm^2$ at central of Iraq. The hot spot of pollutions was over Baghdad city (up $3.74 \cdot 10^{15}$ molecules per 1 $cm^2$).

The monthly distributions shows significant spatial variations of $NO_2$ detected over the most parts of Iraq and a different of seasonal variations depend on the weather situations and topography. The higher concentrations for $NO_2$ in the winter and summer than in the spring and autumn seasons, and the elevation in $NO_2$ values noted during the year over the manufacturing and crowded urban regions. The variation in the $NO_2$ values on December–May period due to the human activity, geographic nature of the areas and weather variations. While during June–November period, the highest value was on July at Baghdad $4.61 \cdot 10^{15}$ molecules per 1 $cm^2$, and the less value in October $0.83 \cdot 10^{15}$ molecules per 1 $cm^2$, at the western region. The resulting trend estimate over Baghdad for monthly average tropospheric $NO_2$ column provides a linear growth rate 9.8% annually. Long-term trend in $NO_2$ attributed to the human activity; combustion of fossil fuels and a significant net flux of $NO_2$ to the atmosphere. Trajectory analysis illustrate the seasonal variation in the troposphere $NO_2$ varied appreciably observed between winter and spring seasons. The lowest $NO_2$ values was during the monsoon period mostly related to the rains. The OMI data and the satellite measurements are can measure the elevations of the troposphere $NO_2$ concentrations above different areas.


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## Summary

**Analysis of tropospheric $NO_2$ over Iraq using OMI satellite measurements.** Tropospheric nitrogen dioxide ($NO_2$) is a trace gas with important impact on atmospheric chemistry, human health and a key pollutant in particular cities, measured from space since the mid-1990s by the GOME, SCIAMACHY, OMI, and GOME-2 instruments. This study present ten years (monthly and yearly averaged) dataset from Ozone Monitoring Instrument (OMI) used to investigate tropospheric $NO_2$ characteristics and variations over Iraq during 2005–2014. Annual $NO_2$ shows an elevation from the northern to the southern and highest values was at central parts of Iraq. Monthly distributions revels higher values $NO_2$ in winter and summer than spring and autumn seasons, and rising $NO_2$ throughout study period over industrial and crowded urban zones. The trend analysis over Baghdad shows a linear growth rate 9.8% per year with an annual average ($5.6 \cdot 10^{15}$ molecules per 1 $cm^2$). The air mass trajectory analysis as hotspot regions shows seasonal fluctuations between winter and summer seasons depend on weather conditions and topography. The increased $NO_2$ values in winter are due to anthropogenic emissions and subsequent plumes from Europe. In addition, in summer because of hot weather and large paddy fields emissions. The lowest $NO_2$ value was at monsoon period mostly linked to the rains. The OMI data and satellite information are able to observe the troposphere $NO_2$ elevation at different regions.

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