



Satellite observations for monitoring atmospheric NO₂ in correlation with the existing pollution sources under arid environment

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Abstract

Monitoring of air pollutants using satellite data has been largely improved over the past few decades, which can provide deeper insights into the effects of anthropogenic activities on the air quality. The observations and measurements of atmospheric NO₂ are poorly investigated in North Africa, therefore, the current study applied a multi-proxy approach to better understand of the ambient environment. This approach is based on satellite observations, chemical and biological analyses, and investigative information during fieldworks. The Aura satellite provides the basic data for the current study with fine resolution of atmospheric NO₂ and O₃ concentrations. The obtained results reveal noticeable increases of atmospheric NO₂ values since the 2011, where its emission reaches the peak during summer season that is characterized by high anthropogenic activities. The study area has many sources for NO₂ emissions, such as the urban region, traffic, as well as the NH₃ emission that is in turn converted to NO₂. Although the discharged and spreading wastewater (80,000 m³/day in summer) has a limited role in NO₂ emissions, it represents an indicator of the anthropogenic activities. The wastewater analyses confirm the occurrence of nitrate (NO₃⁻), nitrite (NO₂⁻), and ammonia (NH₄⁺), which provide an appropriate condition for NO₂ release. The analyses of multi-climate datasets (previous records and the expected scenarios) reveal an increase of temperature accompanied by decrease of precipitation which confirmed the existence of climate change. Therefore, the study presents a set of suggestions to mitigate the release of NO_x gases and achieve Net-Zero emissions.

Keywords Nitrogen dioxide (NO₂) · Wastewater · Remote sensing · Environment · Climate change

Introduction

The nitrogen dioxide (NO₂) can be considered as a short-lived pollutant that contribute broadly to the anthropogenic aerosols (Seinfeld and Pandis 2016). Once NO₂ gas is emitted, it stays in the atmosphere for less than a day before being deposited, indicating that the high concentrations are existed close to the source (CAMs 2021). The majority of emission sources are from surface and anthropogenic activities such as traffic, energy production, domestic heating, wastewater,

etc. (Koziel et al. 2006; Aneja et al. 2012; Liu et al. 2017). NO₂ is one of the two gases, with NO (nitrogen monoxide or nitric oxide), that are referred to collectively as nitrogen oxides or NO_x group where nitrogen oxides (NO and NO₂) are considered as key ingredients in urban pollution that affecting human health (EPA 2016) as well as controlling ozone depleting (Ravishankara et al. 2009; Law et al. 2012). The emission of anthropogenic nitrogen (N) compounds to the environment still a matter of great concern with regard to human health (Krupa and Moncrief 2002; Aneja et al. 2008). The anthropogenic activities are leading to emissions of NO_x, N₂O and NH₃ through many sources include volatilization from animal waste, agricultural crops, wastewater and human excreta (Olivier et al. 1998; Zhang et al. 2008; Aneja et al. 2012; Behera et al. 2013). The importance of NO₂ gas is resulted from its role in ground-level concentrations of O₃, in addition to the relationships between anthropogenic activities, climate change and air pollutants such as NO₂ (Restrepo 2021). A study conducted in New York City indicated highest levels of NO₂ in areas with high

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anthropogenic activities such as traffic, density of buildings and built-up land uses (New York City Department of Health and Mental Hygiene 2020). The relationship between the atmospheric NO_2 and COVID-19 pandemic lockdowns was reported in many cities include London, Milan and Paris, where its concentrations were reduced throughout 2020 in comparison with years of 2017–2019 (Collivignarelli et al. 2021). The health influences of NO_2 were well established where long and short exposures of NO_2 are linked with respiratory system diseases and asthma (EPA 2016; EPA 2018). With regard to wastewater, the nitrogen (N) is existed in the form of many compounds include ammonia (NH_4^+), nitrite (NO_2^-) and nitrate (NO_3^-), (Tchobanoglous et al. 2002; Law et al. 2012). Ammonia is emitted to atmosphere from waste and wastewater treatment operations and interacts with aerosols, other gases, and fine particles (Kozziel et al. 2006). Similarly, the N_2O emissions from wastewater account for about 2.8% of the total anthropogenic different sources (IPPC 2007), while the global N_2O emissions from wastewater are expected to raise by about 13% throughout period of 2005–2020 (Law et al. 2012). The emissions of atmospheric N are represented by nitrogen oxides ($\text{NO}_x = \text{NO} + \text{NO}_2$) and NH_3 as well as the most common precursors of nitrogen compounds containing N_2O_5 , HNO_3 , HONO and NO_3^- (Galloway et al. 2004; Pan et al. 2012a, b; Li et al. 2016; Liu et al. 2017). Recently, the satellite observations provide an estimation of atmospheric NO_2 concentrations at ground level including regions where there are no recorded stations

(Restrepo 2021). The data obtained from satellites reveal that concentrations of NO_2 in some different parts over the world are reached the pre-pandemic levels (ESA 2021).

The chosen pilot area (Fig. 1) includes a variety of problems related to the existed wastewater (Fig. 2) where the sewage treatment plant (STR) has a capacity of $25,000 \text{ m}^3/\text{day}$ and it was constructed at a height of 70 m above sea level (Fig. 2e, f). Due to the increase of anthropogenic activities (tourist turnout on Matrouh city) during the summer season (Fig. 2a, b), the plant receives about $80,000 \text{ m}^3/\text{day}$. Consequently, these conditions led to the disposal of wastewater to two tree forests located in the vicinity of the plant (Fig. 2i). During the peak time in the summer, the forests are irrigated with the discharged untreated wastewater where the influent wastewater exceeds the plant capacity. Thus, the wastewater is spreading over the study area in the forms of seepage (Fig. 2g, h) and wastewater overflow (Fig. 2c, d). The seepages are originated as a result to the huge daily discharge of wastewater to the forests which are located above fractured limestone plateau. Therefore, wastewater flows from the highlands (plateau) to lowlands (valleys or drainage lines) through the fractures and forming wide lakes of wastewater (Fig. 2g). These different wastewater sources lead to increase of nitrogen and ammonia emissions to air which later converts to NO_2 . The current study considers the wastewater as an indication to the anthropogenic activities which reaches to peaks during the summer months (May to September). The current study introduces an integrated

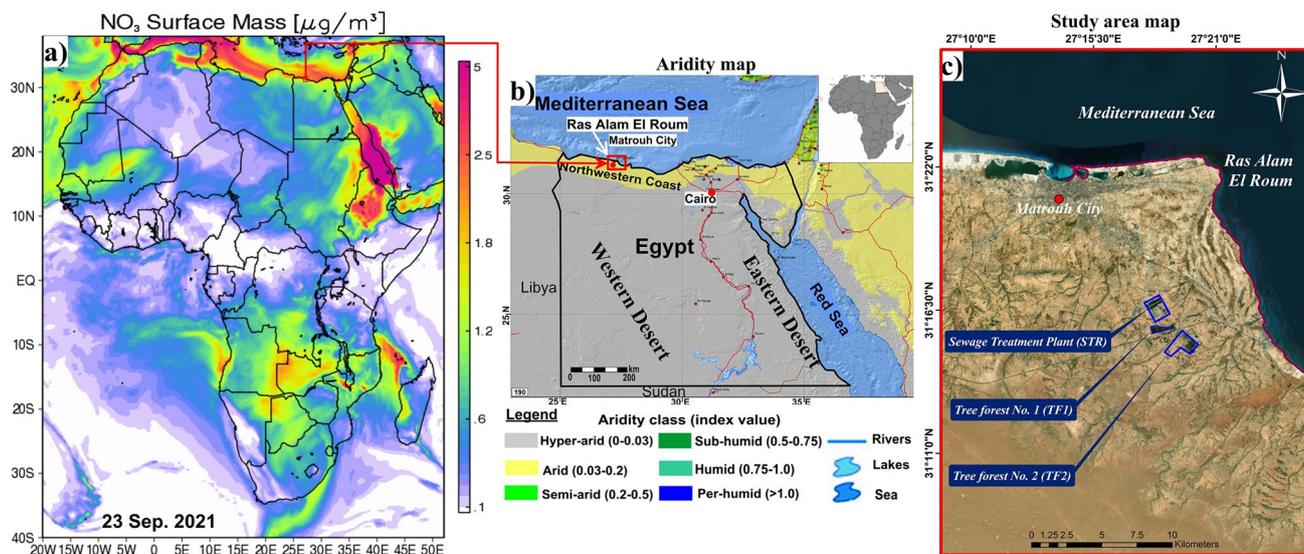


Fig. 1 Key map of the study area. **a** African map of the total mass concentration (in micrograms per cubic meter) of NO_3 in aerosols shows relatively high values of North Africa coast compared to other regions of the continent. This can be attributed to anthropogenic activities along the southern Mediterranean coast as well as the role of the sea in increasing emissions (source: Global modelling and

assimilation office “GMAO”, NASA 2021). **b** Annual aridity index map (2010–2040), where the study area is falling in arid region with aridity index ranges between 0.03 and 0.2 (ICARDA 2010). **c** Sentinel satellite image of the study area “Ras Alam El Roum” shows the main infrastructures of the area

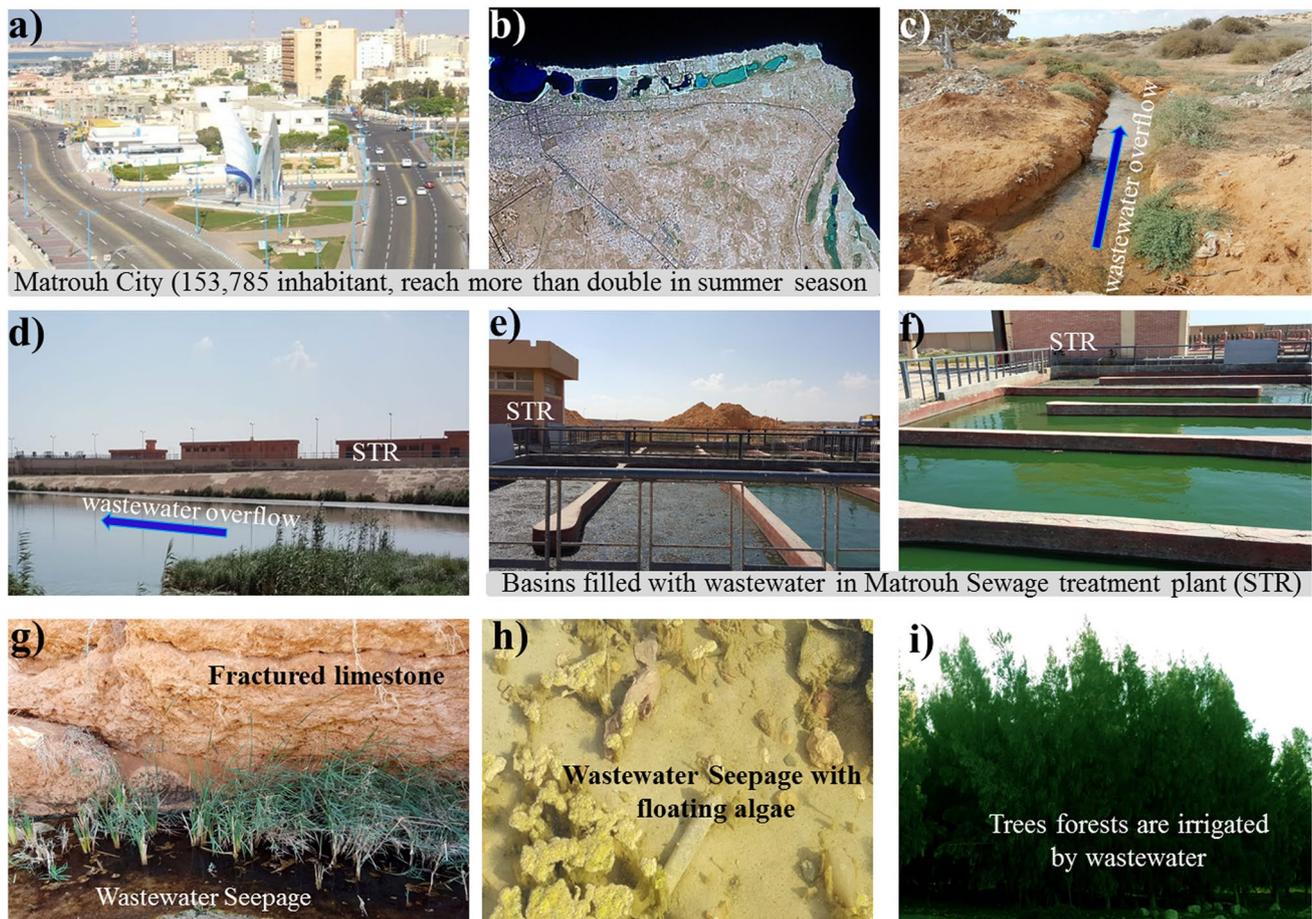


Fig. 2 Field photos indicate the different emission sources existed in the study area

approach based on satellite observations, chemical and biological analyses, and investigative information during fieldwork. This approach is important to evaluate the ambient environment and to understand the contributions of emissions to forming the greenhouse gases and climate changes. The satellite observations in this approach can be considered as modelled data which based on a method called ‘top-down’ where the atmospheric satellite records are along with numerical models for further accuracy enhancement (CAMS 2021). This process is stated as ‘inverse modelling’ where it aims to correspond the observed values with modelled concentrations through conducting the model backwards in time to set and adjust the prior emission sources. Therefore, the current approach is compatible with a study that used the bottom-up information about a single source of NO_2 emitters in Federal Republic of Germany to show how the top-down remote sensing data can be employed to identify a single power plants among other emission sources (Beirle et al. 2019).

The objective of this study was to monitor and understand both of spatial and temporal patterns of atmospheric NO_2

and to clarify the quick response of the NO_2 concentrations to the anthropogenic activities. Also, the study was aiming to investigate the relationship between NO_2 emissions and different climate datasets. In this regard, the study was shed light on the spreading of wastewater over the area ($80,000 \text{ m}^3/\text{day}$ in summer) and discuss its limited role in NH_3 and NO_2 emissions. Finally, the research attempted to present suggestions for the Net-Zero emissions even on local scale with discussing of the stated climate change hazard.

Materials and methods

Study area

This research deals with a pilot area represent the coastal zone of the Southern Mediterranean coast and belonging to the arid environment (Fig. 1, ICARDA 2010). The area is called locally “Ras Alam El Roum” which is existed as a headland in the Mediterranean Sea and includes Matrouh City (the capital of the northwestern coast (Fig. 1). The

area was chosen for the current study where it suffers from extensive wastewater discharges and anthropogenic activities during the summer seasons. Therefore, it was suitable for testing the current research approach that includes correlation between pollution sources and satellite observation to monitor the atmospheric NO_2 . The area is characterized by very low relief, rarely exceeding 100 m, and gentle slope towards the sea. It can be differentiated into two main provinces, the elevated plateau and the coastal where a number of drainage lines (wadis) dissect the plateau and drain to sea. Runoff is possible after rather heavy rains, and a considerable amount of water may percolate to deeper soil layers. The annual runoff amount of the study area was estimated as 2.127 million m^3 (Yousif et al. 2014) where this value is compatible with the results obtained by Klaric et al. (1999), who estimated the surface runoff in the east of the study area as 2.12 million m^3 . The area has summer's warmest months with a mean temperature less than 30 °C and winter's coldest months with a mean temperature above 10 °C (UNESCO 1977). Accordingly, the evaporation rates are related to temperatures where the lowest rate is about 6.9 mm/day (January) and the highest is 8.8 mm/day (September), (Yousif et al. 2014). The recorded climatic data of Matrouh station (Table 1, Egyptian Meteorological Authority "EMA" 2018) reveal that the monthly averages of minimum and maximum temperature are 10.2 °C (January) and 34.9 °C (July), respectively. The average annual precipitation, relative humidity and solar radiation, are recorded as 137.1 mm, 62% and 20.43 MJ/m^2 , respectively. On the other hand, the existing problem statement discusses concisely the reasons and the resulting effects in the study area.

Fieldwork

Fieldwork was achieved in September 2018 and aimed to explore the existing problem in situ where many complains are presented from the inhabitants "Beduin" about the side effect of wastewater in the study area. A survey of the existing wastewater points was carried out, and total 11 water samples were collected. Here, location (GPS), pH value (pH meter model MP230 German), electrical conductivity (EC), and temperature were measured on site. In addition, few groundwater samples are checked with regard to NO_3 content, only to explore if the pollution affect groundwater is polluted or not yet. The water samples were collected also to detect bacteria groups. The samples were collected in a clean, labeled and organized capped polyethylene bottles 200 ml that filled directly without any treatments. Also, the field investigation includes collection of many information about the area, capacity of the Matrouh Sewage plant, high and low touristic seasons of Matrouh city, etc.

Table 1 Average monthly climate records of Matrouh station (land station measurements)

Parameter	Unit	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Average annual
Monthly average of max. temperature	°C	18.8	22	22.6	26.7	32.8	31.5	34.9	31.5	30.9	27.5	24.3	18.7	26.85
Monthly average of min. temperature	°C	10.2	10.8	11.8	13.9	18.7	21.2	22.6	24.5	22.2	19.2	16.6	12	17
Monthly average of total rainfall	mm	24.5	3.3	0	0	0	0	0	0	0	0	42.2	67.1	Total annual 137.1
Monthly average of relative humidity	%	69	67	56	56	54	63	54	71	62	66	58	68	62
Monthly average of solar radiation	MJ/m^2	11.65	15	20.16	23.65	26.4	27.92	27.74	26.42	24	17.61	13.83	10.72	20.43

Source: Egyptian Meteorological Authority (EMA 2018)

MJ megajoule

Chemical and bacteriological analyses

The water samples were analyzed at the laboratory of the Desert Research Center (DRC, Cairo, Egypt) by ion chromatography (ICS-1100, Dionex, Sunnyvale, CA, USA) to determine the major elements and calculate the total dissolved salts of the water (TDS). Nutrients (NO_3^- and NH_4^+) were analyzed using ammonia selective electrode model ISE Digital DM-21. With regard to bacteriological analyses, there are many methods for quantitating bacterial cells, the common one is the bacterial plating, that has allowing live cell detection through colony forming unit (cfu) counts. Therefore, this method was used in the present study to check the existence of bacteria in the investigated water samples. On the other hand, the Most Probable Number (MPN) is also used as a method to determine the concentration of viable microorganisms in a water sample by means of replicate liquid broth growth in ten-fold dilutions. Indeed, this method is commonly used for estimating microbial populations in waters, and it is particularly useful with samples that have particulate material that interferes with plate count enumeration methods. In the current study, MPN method is applied for ensure whether the water samples have bacteria or not.

Remote sensing and GIS applications

The integration between Remote sensing (RS) and geographic information system (GIS) can be considered as effective methods for data collection and data representation, particularly in the environmental studies (Attwa et al. 2021). The Shuttle Radar Topography Mission (SRTM-C) provided the basic data for the current research, as well as satellite images from Landsat (LC8) and sentinel-2 types. The data from satellite images were employed for visual interpretation of surface features and geology of the study area as well as the land use/land cover classifications (LULC). All data (SRTM-C, LC8 and sentinel-2) were projected on the Universal Transverse Mercator (UTM) with the WGS84 datum in GIS for further correlation of features. SRTM-C elevation data were used to create three-dimensional model (3D) of the study area and to build the conceptual model of the study hypotheses. The 3D model was created using the ArcScene 10.4. The spatial analysis of various data was carried out using the ArcGIS 10.4 software to interpolate the data spatially and to convert the data to the requested layers. All maps in the present research were prepared in the ArcGIS 10.4 environment.

Change detection and LULC map

The LCLU changes have direct impacts on both of surface water runoff and groundwater contaminations (Khalil et al. 2021) as well as detection of the area development.

The change detection of the study area is created throughout the period from 2005 to 2020 using the satellite images provided through Google Earth engine. The monitored features and infrastructures were plotted on the images using their GPS recodes and the changes were decocted through visual interpretation. On the other hand, the datasets for the LULC of the study are were obtained through the European Space Agency (ESA) where the World Cover images display a global land cover map with 10 m resolution based on combination of both Sentinel-1 and Sentinel-2 data (<https://www.sentinel-hub.com/>).

Satellite data for NO_2 and O_3

The Aura satellite with its sensor Ozone Monitoring Instrument (OMI) provides data for the current research with fine resolution ($0.25^\circ \times 0.25^\circ$) about atmospheric NO_2 and O_3 . The both of NO_2 and O_3 data can be visualized with the interactive NASA tool called Giovanni. The obtained values are expressing about number of molecules of NO_2 in an atmospheric column above cm^2 of surface. The NO_2 data are of Level-3 Gridded Product where pixel level data of good quality are binned and "averaged" into $0.25^\circ \times 0.25^\circ$ global grids (Krotkov et al. 2019). This product contains total column NO_2 . The OMNO2d data are stored in version 5 EOS Hierarchical Data Format (HDF-EOS). Each file contains data from the day lit portion of the orbit (~ 14 orbits), (Lamsal et al. 2021). On the other hand, the O_3 data are provided through The Ozone Monitoring Instrument (OMI) which produce data of Level-3 Aura/OMI Global. This Level-3 produces ozone total column according to Differential Absorption Spectroscopy (DOAS) where the data are characterized by high quality, short path length and its precision (Veefkind 2012). Analyses and visualizations used in in this research are produced through Giovanni online system, developed and maintained via NASA GES DISC (Acker and Leptoukh 2007).

Satellite climate datasets (modelled and measured records)

In the present study, the Tropical Rainfall Measuring Mission (TRMM) Multi-satellite Precipitation Analysis (TMPA), which includes a daily average precipitation rate on a 0.25° grid, was employed to obtain the annual average precipitation. The obtained precipitation data are representing a multiple satellites data and are calibrated with rain gauges as well as passive microwave data and TRMM radar (Huffman et al. 2010). However, several issues could affect the accuracy of TRMM-based estimates of surface rainfall rate in desert environment including limited sampling and limited sensitivity to smaller precipitation events (Kelley 2014). To assess this

deficiency, Kelley (2014) has correlated the TRMM data between 1998 and 2012 over Egypt and other countries in the Sahara with the long-term rain gauge record. The results were indicating similar seasonal patterns in rainfall between the two datasets and hence demonstrated the validity of using TRMM data to estimate long-term precipitation amounts over Egypt. The data are downloaded through Nasa web. Site through Giovanni online ver. 4.35 (<https://giovanni.gsfc.nasa.gov/giovanni/>). The ultra violet (UV) index was obtained through the data of Aura-OMI Spectral Surface (Level-3 daily gridded) at local solar noon with $1.0^\circ \times 1.0^\circ$ grids. On the other hand, in the current research, the modelled data for both temperature and wind speed are used. The measured daily mean satellite data for temperature and wind speed are collected in Modern-Era Retrospective analysis for Research and Applications ver.2 (MERRA-2). This (MERRA-2) represents the latest version of global atmospheric reanalysis of the satellite era produced by NASA Global Modeling and Assimilation Office using the Goddard Earth Observing System Model (GEOS) version 5.12.4. Analyses and visualizations used in in this research are produced through Giovanni online system, developed and maintained via NASA GES DISC (Acker and Leptoukh 2007).

Results

Analyses of the aqueous pollution sources

The collected water samples show variation in their TDS, NO_x and NH_4^+ as well as bacteriological analyses (Table 2). This is due to difference of each sample location (Fig. 3) where some are obtained from the source (nos. 1 and 2) and others have passed through the rocks forming seepages (nos. 4, 8, and 9) and consequently wastewater overflow (3,5,6, 7,10 and 11). The values of the total dissolved salts (TDS) are showing noticeable increasing after getting out the wastewater plant (samples nos. 3–11, Table 2). This is due to the dissolutions and leaching processes where this water is discharged over the plateau and reacting with its calcareous soils and constituent rocks. The concentrations of NO_2^- and NO_3^- are ranging between 8.3, 11.2 (seepage) and 19.7, 26.6 mg/l (influent), respectively (Table 2). The NH_3 is only recorded in the samples from the wastewater plant where the analyses of 2015 show concentrations between 44 and 45 mg/l (HCWW 2015), that are decreases in 2018 to become between 15 and 30 mg/l (DRC 2018) for effluent and influent samples. On the other hand, only four samples are checked to confirm the presence of bacteria, where the total coliform counts are ranging between 42 and 1100 cfu, while MPN ranging between 16 and 280 per 100 ml (Table 2). The importance of ensuring the presence of bacteria is that they

Table 2 Analyses data of the aqueous pollution sources (wastewater) that are recorded in the study area

Aqueous pollution sources	Sample no.	Location “Coordinates”		pH	TDS mg/l	NO_2^- mg/l	NO_3^- mg/l	NH_4^+ mg/l	Total count cfu ^c	MPN ^d Per 100 ml
		Long. (E)	Lat. (N)							
Sewage Treatment plant (STR)	1 Influent	27.3081	31.28138	10.6	3539	19.7	26.6	30 ^a –45 ^b	1100	280
	2 Effluent	27.29817	31.27645	9.2	3540	11.4	15.4	15 ^a –44 ^b	280	84
Wastewater seepage	4	27.326	31.269	7.3	6984	20.8	28	0	n/a	n/a
	8	27.312	31.229	9.7	6789	8.3	11.2	0	n/a	n/a
	9	27.32	31.225	10.2	8943	8.3	11.2	0	108	16
Wastewater overflow	3	27.302	31.296	9.3	9509	12.5	16.8	0	42	42
	5	27.329	31.271	7.0	8047	16.6	22.4	0	n/a	n/a
	6	27.324	31.279	7.5	7487	14.5	19.6	0	n/a	n/a
	7	27.36	31.279	8.0	7004	10.4	14	0	n/a	n/a
	10	27.336	31.258	7.8	3175	19.3	26	0	n/a	n/a
	11	27.35	31.258	8.4	11,659	14.5	19.6	0	n/a	n/a

The locations of the collected samples are illustrated in Fig. 3

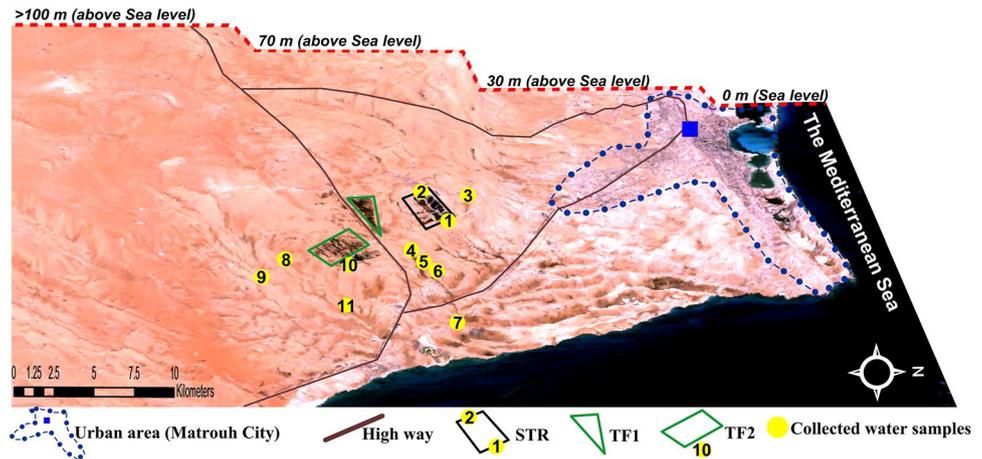
^aIn situ measurement (DRC 2018)

^bIn situ measurement (HCWW 2015)

^ccfu: a colony-forming unit that is used in microbiology to estimate the number of viable bacteria in a sample

^dMPN: most probable number of viable organisms (bacteria) per 100 ml (only viable are enumerated by MPN determination)

Fig. 3 Three-dimensional model (3D) of the study area overlaid by locations of the collected water samples (created through overlaying of Landsat 8 over the digital elevation model “DEM” using Arcscene software)



are necessary for many reactions that take place in wastewater, which result in the emission of ammonia or nitrogen.

Satellite data of NO₂ monitoring

The Aura satellite with its sensor Ozone Monitoring Instrument (OMI) provides daily data for the current research with fine resolution (0.25° × 0.25°) about atmospheric NO₂. The data of time series-area averaged through the period of 2005–2021 show a noticeable increasing of NO₂ values (pulses) after the year of 2011 (Fig. 4a). The present study searched about the reasons for this increasing since this year and till now. The investigation of daily data for atmospheric NO₂ with intervals time each 5 years’ reveals that the highest values are recorded during the period from 1st of May to 31st of August (period 1) throughout the years of 2010 (Fig. 5a), 2015 (Fig. 5b), and 2020 (Fig. 5c). The statistical analyses (Table 3) of the obtained satellite daily mean records (area averaged) of atmospheric NO₂ total column (molecule/cm²) confirm

that the mentioned period (period 1) has the highest maximum (4.68 × 10¹⁵), minimum (2.97 × 10¹⁵), average (3.82 × 10¹⁵) and sum (395 × 10¹⁵) values throughout all years. This period is characterized by high anthropogenic activities related to the summer vacationers which has a direct impact on the amount of discharged wastewater and also the emissions from urban area.

Satellite data of O₃ monitoring

It is scientifically known that there is a relationship between the formation and erosion of the ozone layer and nitrogen dioxide. Consequently, the monitoring of O₃ (same sensor of Aura satellite with similar data resolution) during the same periods in which NO₂ was detected, was significant. The O₃ values show the same increasing since 2011 (Fig. 4b) while the observations of O₃ during 2010 (Fig. 6a), 2015 (Fig. 6b) and 2020 (Fig. 6c), reveal a clear increasing during the period from April to September throughout the years.

Table 3 Statistical data of the Satellite daily mean records (area averaged) of atmospheric NO₂ total column with 5 years’ interval where the data are classified over 3 periods related to anthropogenic activities

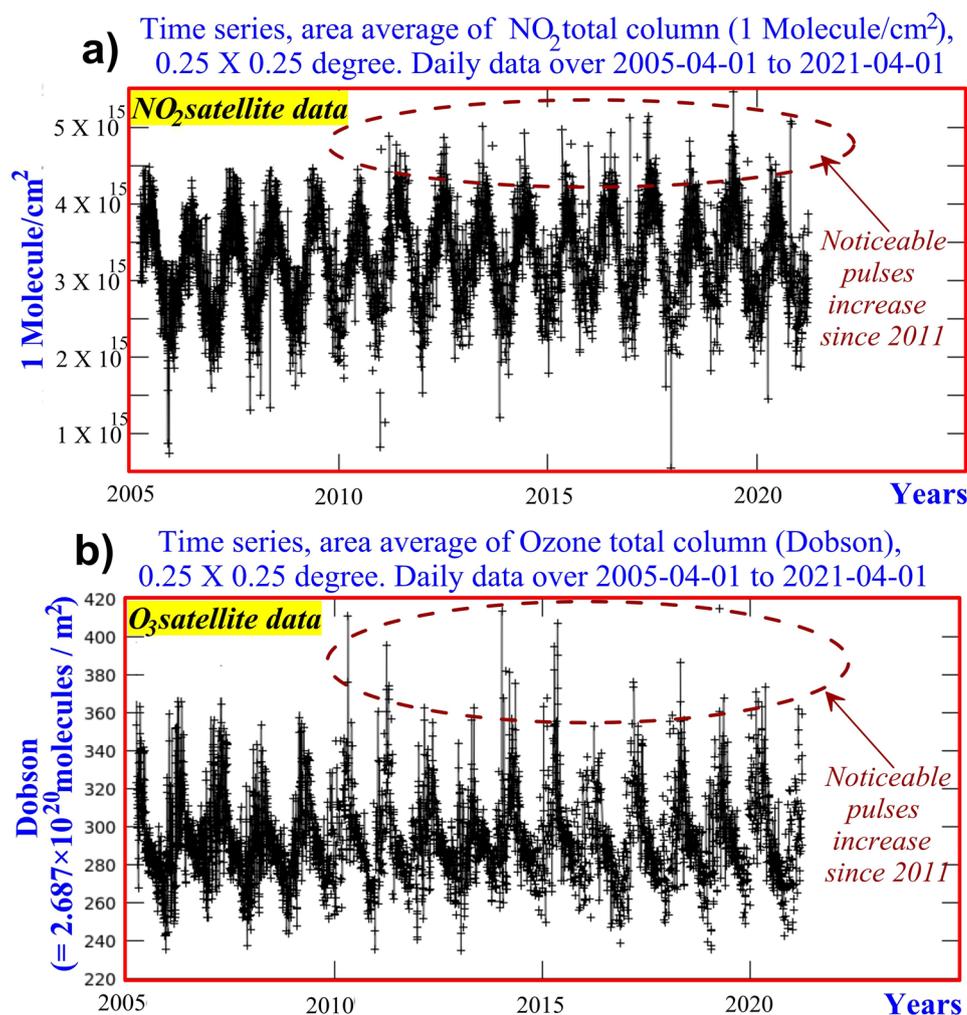
Years	Values of NO ₂ total column (molecule/cm ²) over 3 periods of year. All NO ₂ values are multiplied by (10 ¹⁵)											
	Period 1 (1 Jan.–30 Apr.)				Period 2 (1 May–31 Aug.)				Period 3 (1 Sep.–31 Dec)			
	Low anthropogenic activities related only to local residents				High anthropogenic activities related to the summer vacationers				Low anthropogenic activities related only to local residents			
	Min	Max	Year sum	Year average	Min	Max	Year sum	Year average	Min	Max	Year sum	Year average
2010	1.74	3.96	183	2.9	<u>2.47</u>	4.45	294	3.63	0.832	3.86	205	2.8
2015	1.8	3.68	206	2.9	<u>2.92</u>	4.68	395	3.82	2.06	4.44	226	2.1
2020	1.45	4.2	231	3	<u>2.97</u>	4.52	370	3.7	1.9	3.58	223	2.89

The highest values of all records are marked by bold

The highest minimum values are marked by underline

The anthropogenic activities are classified according to our confirmed annually information of the study area, taking into account the wastewater as an indicator of these activities (25,000 m³/day in periods 1 and 2, while in period 3 reaches to 80,000 m³/day)

Fig. 4 Satellite data of NO_2 and O_3 total column (Aura satellite with its sensor Ozone Monitoring Instrument “OMI”), produced through NASA Global Modeling and Assimilation Office (GMAO) where analyses and visualizations are achieved through Giovanni NASA online system



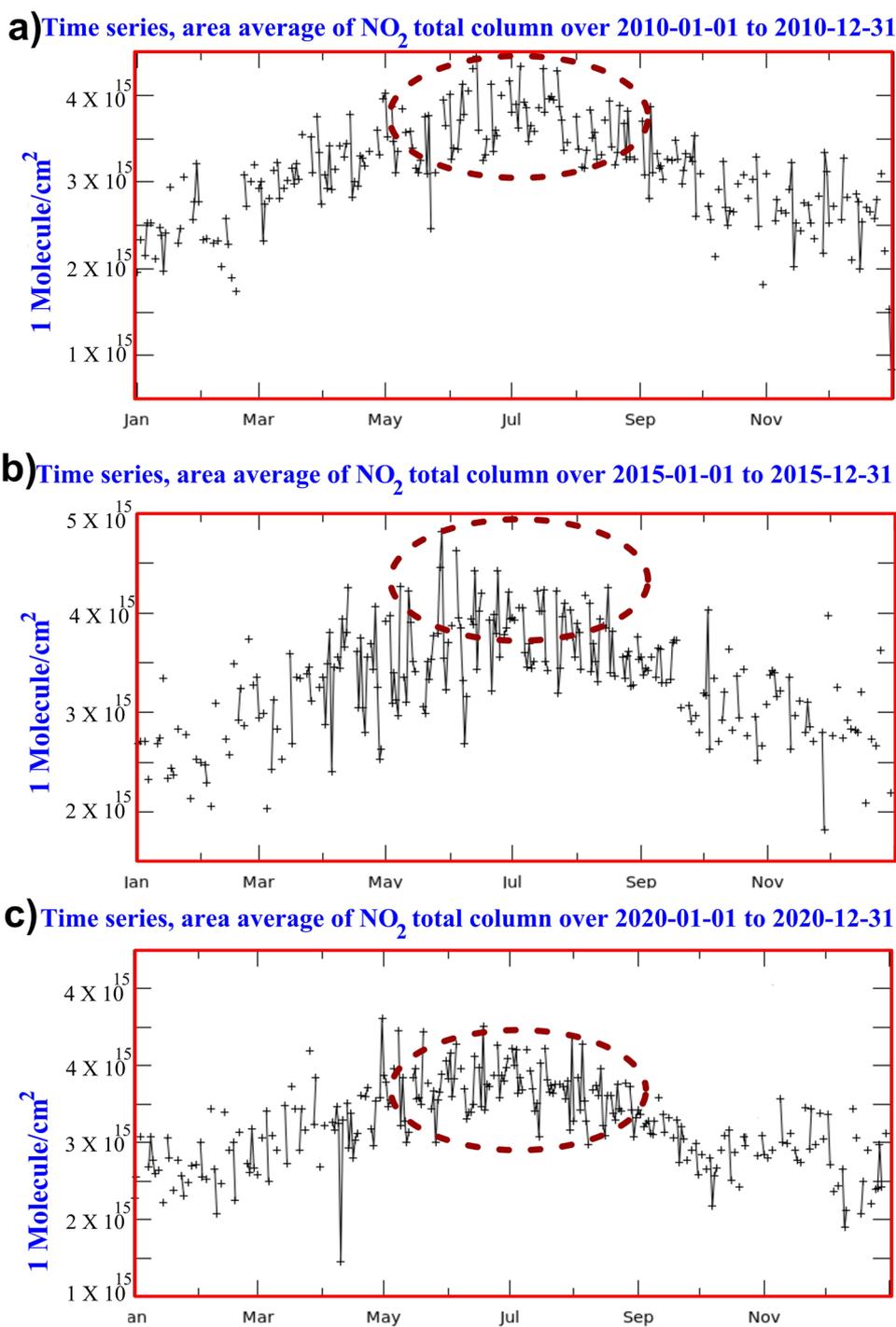
Analyses of change detection and land use/land cover map (LULC)

The past 2 decades witnessed a significant increase in the Egyptian population, which was linked to urban expansion over agricultural land expenditures (Radwan et al. 2019). The monitoring of satellite image since 2005–2020 (Fig. 7a–f) reveal that two forest trees were created since 2011 (Fig. 7c). The field investigation reveals that the two forests were established to receive the excess of wastewater (about $80,000 \text{ m}^3/\text{day}$) that exceeds the capacity of the treatment plant ($25,000 \text{ m}^3/\text{day}$) in the summer season. The images also indicate that the trees forest become denser with appearance of wastewater seepage and overflow around their areas (Fig. 7e, f). The LULC map (2021) shows the current situation of the study area where the urban land use represents about 40% of total area, with the spread of many wastewater sources (Fig. 7g, h).

Chemical processes of NH_3 – NO_2

The NO_2 gas can be emitted from ammonia through three processes. The first one is the air oxidation of the emitted NH_3 from wastewater or other sources to the atmosphere (Green pathway, Fig. 8). The second one is what so-called autotrophic nitrification where the NH_4^+ (aqueous) will be oxidized to NO_2^- via hydroxylamine (NH_2OH) as their predominant in wastewater, then NO_2^- release NO as an intermediate through denitrification pathway (Chandran et al. 2011; Ni et al. 2013; Ni and Yuan 2015) (Brown pathway Fig. 8). The emitted NO can be oxidized by O_2 to NO_2 (gas) or reacted with N_2 to N_2O (gas). The third process occurs when nitrite (NO_2^-) is further oxidized to nitrate (NO_3^-). In this process, the nitrates and/or nitrites are converted through heterotrophic nitrification to nitrogen (N_2) gas (Ni and Yuan 2015) where many factors could affect the process such as organic matter, pH

Fig. 5 Detailed satellite records of NO₂ throughout 2010, 2015 and 2020 (Aura satellite with OMI)

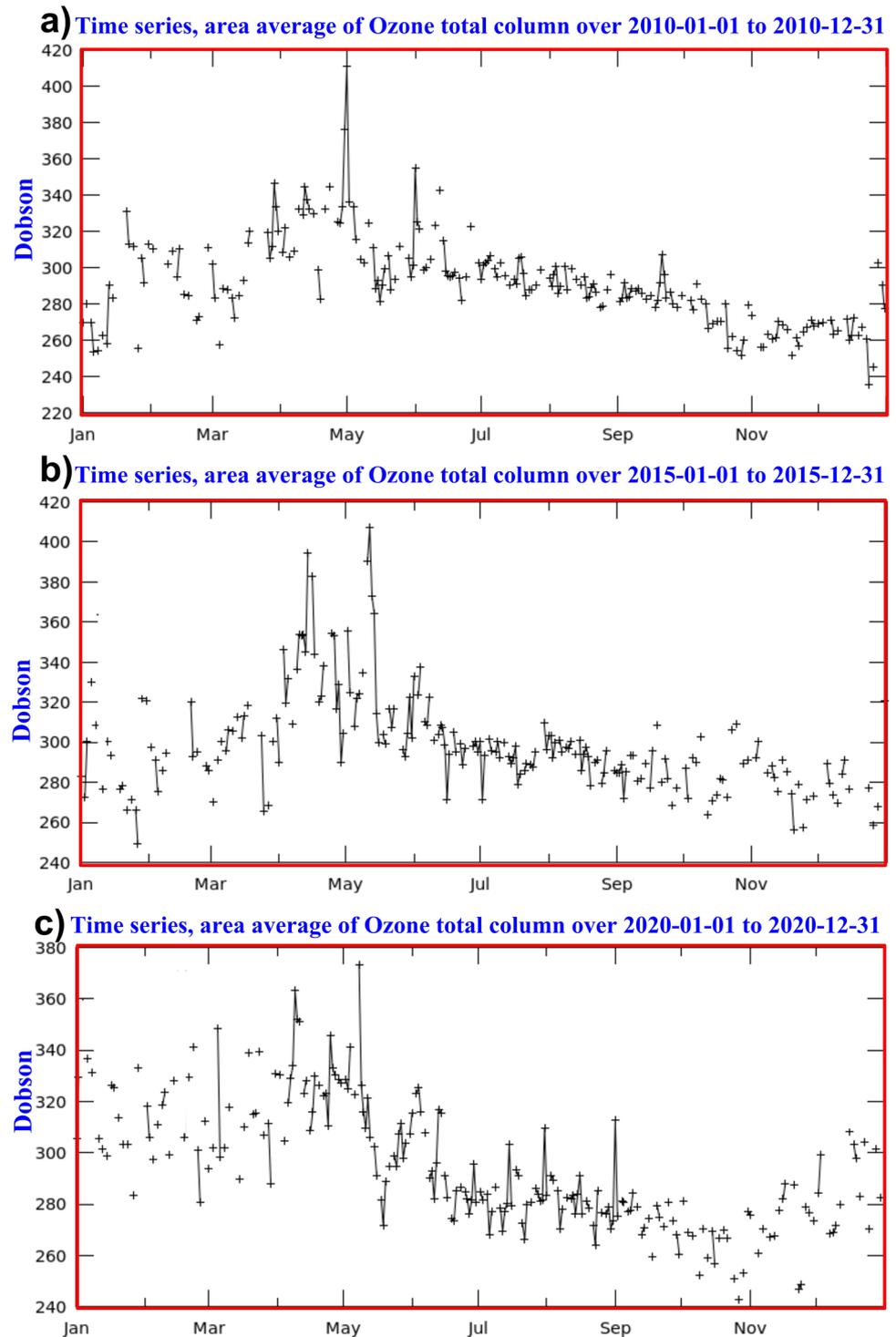


levels, ratios of chemical oxygen demand (COD) to N, etc. (Lu and Chandran 2010; Pan et al. 2012a, b), (Red pathway Fig. 8). In the present study, nitrate (NO₃⁻), nitrite (NO₂⁻), and ammonia (NH₄⁺) are detected in the wastewater (Table 2) which provide the appropriate conditions for the occurrence of the three processes, or at least one of them, to release NO₂.

Chemical relationship of NO₂-O₃

The investigation of O₃ concentrations in troposphere is complicated by many factors overall the nonlinearity of the ozone production to its sources, primarily from the emission of NO₂ and volatile organic compound (VOC), (Sillman 1999). The study area has many sources for NO₂ emission

Fig. 6 Detailed satellite records of O_3 throughout 2010, 2015 and 2020 (Aura satellite with OMI)



(Fig. 9a–e) where it can be produced directly from some sources, and others emit NH_3 which are converting to NO_2 (The chemical equations are illustrated in Figs. 8 and 9). The NO_2 splits through photochemical reaction (UV) to nitric oxide (NO) and oxygen atom (O) which is quickly attaches with atmospheric oxygen (O_2) and form ozone (O_3). The short life of O_3 causes its break down to O_2 and O. The

natural nitric oxide (NO) will bind to the valent oxygen atom (O) and forming NO_2 again (Fig. 9).

Climate datasets

In the present study, four climatic parameters are investigated through the satellite data of temperature (Fig. 10a),

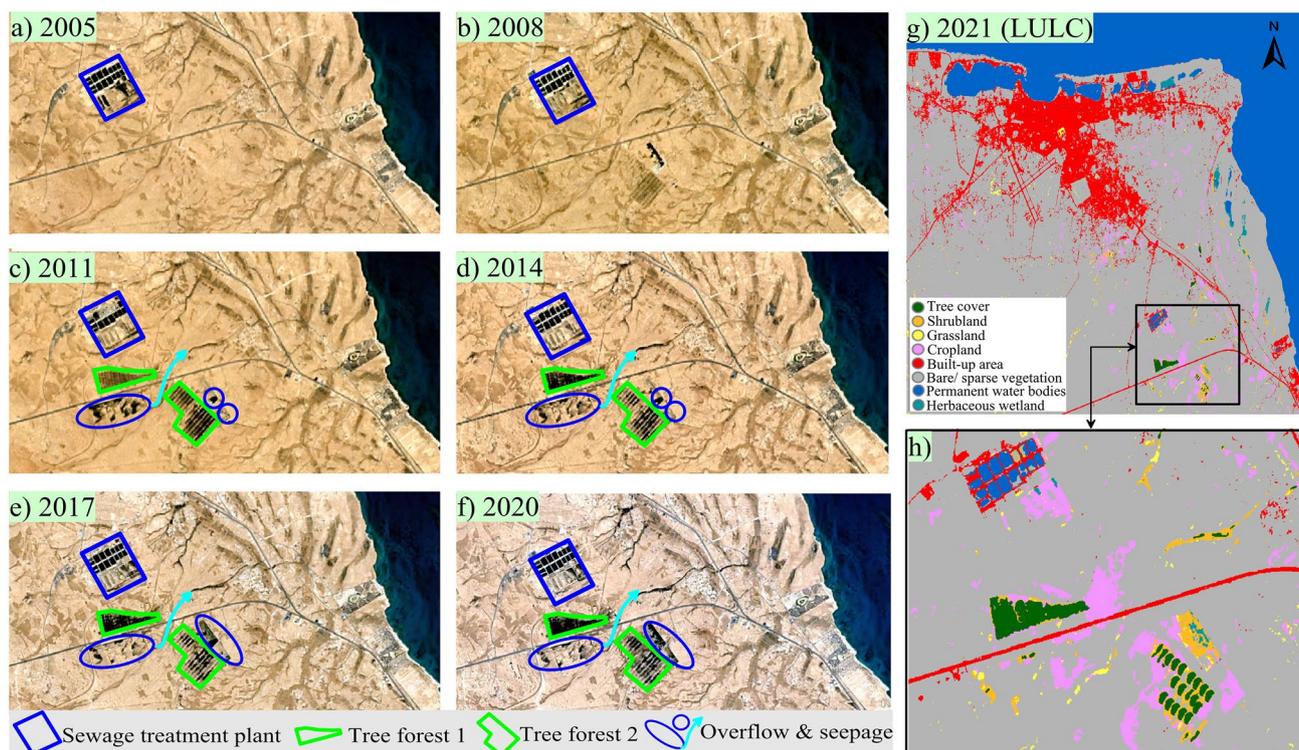


Fig. 7 Satellite images show the changes detection of the study throughout the period from 2005 to 2020 (a–f) reveal that two forest trees were created since 2011. **g, h** Recent land use/land map (LULC 2021) which were created with 10 m resolution based on combination

of both Sentinel-1 and Sentinel-2 data and obtained through the European Space Agency (ESA). The LULC shows the current situation of the study area where the urban land use represents about 35% of total area, with the spread of many wastewater sources

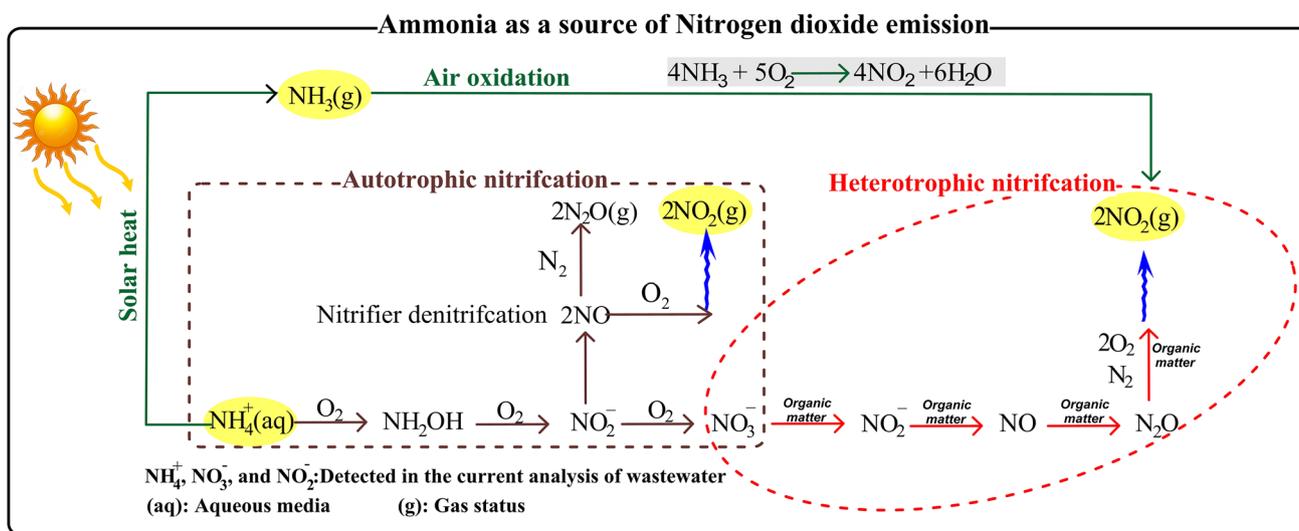


Fig. 8 A simplified representation of the involved chemical processes to release NO_2 through NH_3 in wastewater (modified after Ni and Yuan 2015)

precipitation (Fig. 10b), wind speed (Fig. 10c), and UV index (Fig. 10d). The main reason for displaying these parameters is to explore if there are any changes before

and after year of 2011 where the noticeable increasing of NO_2 and O_3 values are recorded. The data for temperature and wind speed are based on the more accurate model

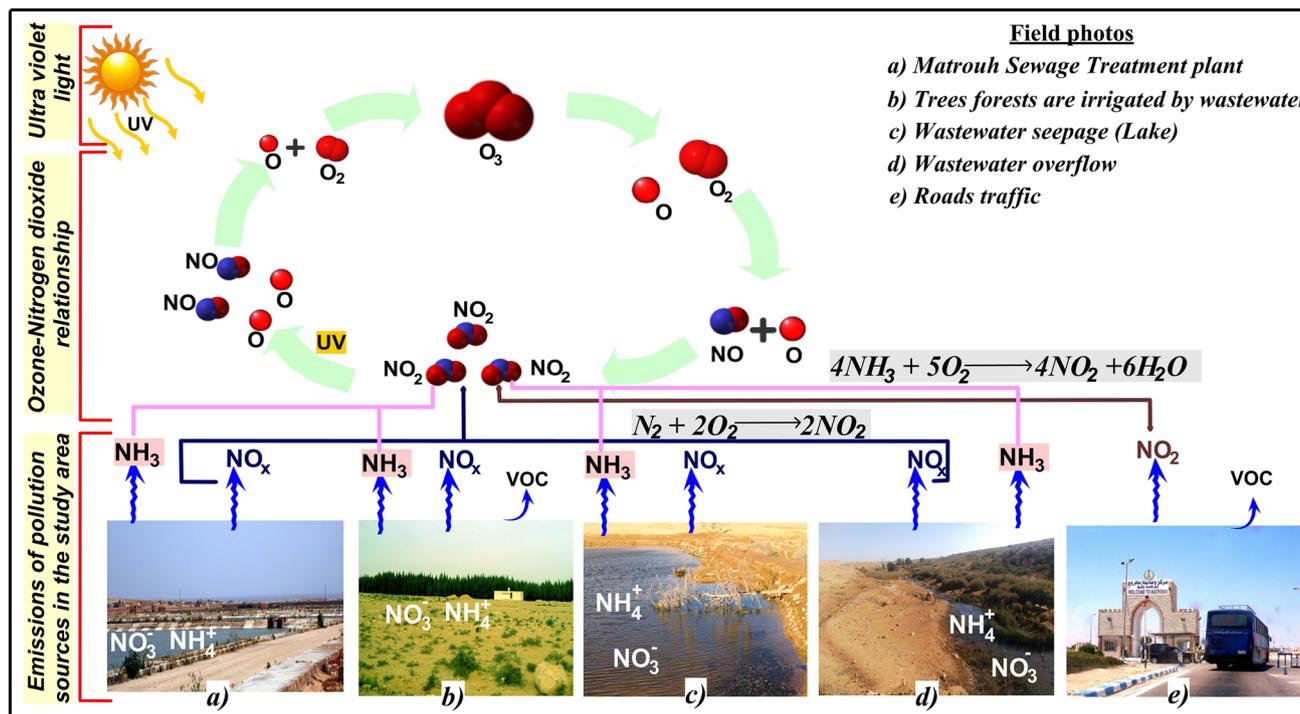


Fig. 9 Conceptual model shows the relationship between NO_2 and O_3 supported by field photos of emissions sources

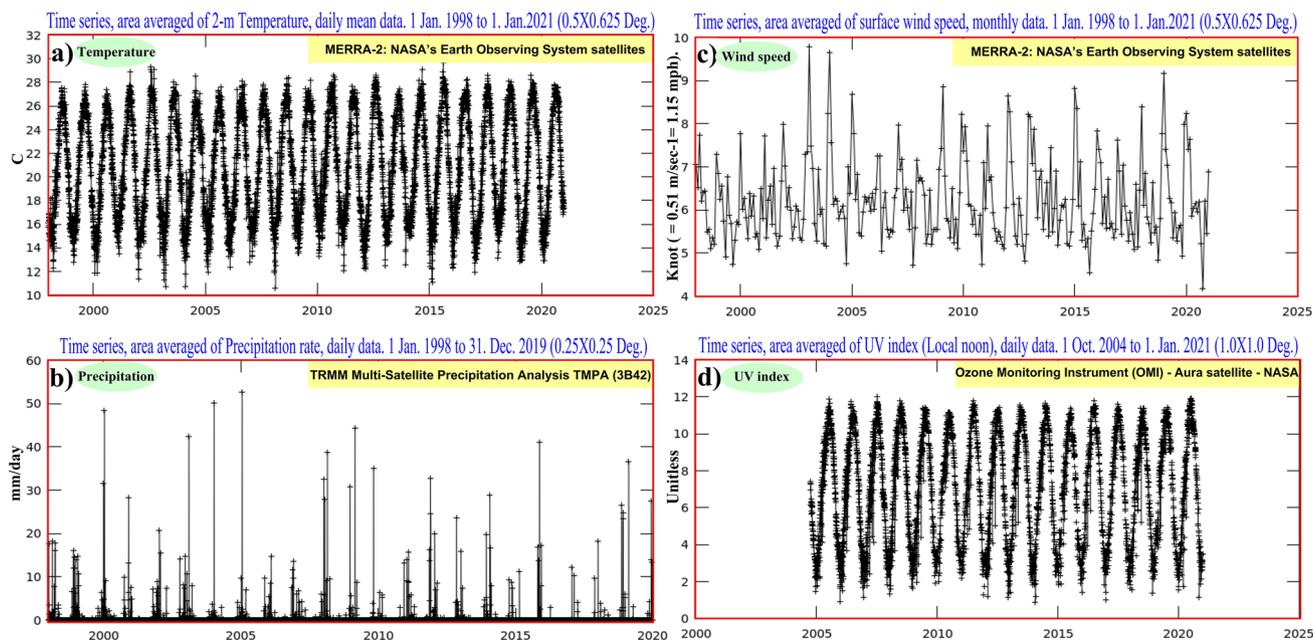


Fig. 10 Climate datasets of temperature, precipitation, wind speed, and UV index over the study area. The data of temperature and wind speed (a, d) are based on the MERRA-2 model which using daily statistics (GMAO, NASA). The data for precipitation (TRMM data) and

UV index (b, c) are based on multi satellite precipitation reanalyzes and Aura satellite, respectively. These data reveal that no noticeable changes throughout the monitoring periods for all parameters

“MERRA-2 model” which using daily statistics, such as daily mean and represents the latest version of global atmospheric reanalysis for the satellite era produced by NASA Global Modeling and Assimilation Office (GMAO). The data for precipitation (TRMM data) and UV index are based on multi satellite precipitation reanalyzes and Aura satellite, respectively. These data reveal that mean daily temperature is around 28 °C (max.) and 12 °C (min) without any noticeable changes throughout 23 years. The similar situation for precipitation where the daily data reflect that the area is subjected to some daily events during winter seasons with amounts between 30 and 50 mm/day. The analyses of wind speed data indicate that the main storms are occurring in the winter (December and January) and spring (March and April). Finally, the UV index shows the same trend with values between 1 (winter) and 12 (summer) throughout the period from 2004 to 2021.

Relationship of NO₂—temperature

The detailed data of the mean daily temperature values with time interval each 5 years during 2010 (Fig. 11a), 2015 (Fig. 11b) and 2020 (Fig. 11c), are investigated due to that the high values of NO₂ and O₃ are recorded during summer seasons (since May to September each year). Therefore, the current study attempts to find out the relation between NO₂ and temperature and reaches to the following:

- The highest values of mean daily air temperature at 2 m above earth are recorded during July and October, while the highest values of NO₂ are recorded during 1st May–31st of August (compare Fig. 5 with Fig. 11).
- The temperature trends did not show any changes before and after 2011.
- To confirm that the temperature is not the main factor for the recorded increasing of NO₂ values, a bivariate analysis (statistical) is used for the two variables (T and NO₂), during 2010 (Fig. 11d), 2015 (Fig. 11e) and 2020 (Fig. 11f). The bivariate relation shows correlation coefficient (R) with values ≤ 0.4 which indicate weak correlation.

Discussion

NO₂ correlated with pollutants and anthropogenic activities

In the last decades, the satellite platforms employed for recording and observation of atmospheric gases (such as NO₂, O₃, SO₂, HCHO, etc.) have broadly developed. The satellite observations can provide a daily observation with global coverage of inaccessible areas where ground-level measurements are not available (Dimitrievici et al. 2017). The current study presents an approach for monitoring atmospheric NO₂ in correlation with pollution sources

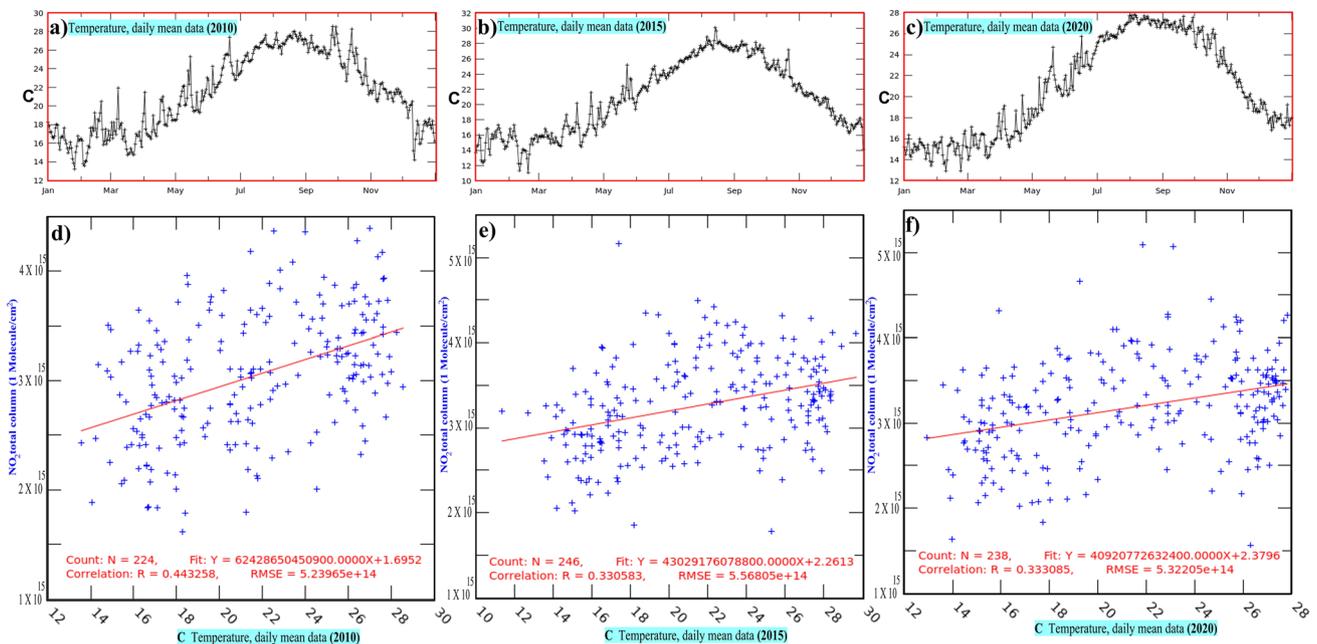


Fig. 11 Detailed data of the mean daily temperature values with time interval each 5 years (a–c) where temperature trends have not shown any changes. d–f Bivariate relationships for the two variables (T and

NO₂), during 2010 (d), 2015 (e) and 2020 (f) that indicate correlation coefficient (R) with values ≤ 0.4 (weak correlation)

within a specific area. The obtained results indicate a noticeable increasing of NO_2 values since 2011 (Figs. 4, 5). Therefore, the change detection was essential to explore what has happened. The satellite images during the period of 2005 to 2020 reflect existence of two forests since 2011 (Fig. 7) while the investigative information about the area situation indicate significant increase in the amount of wastewater over the capacity of treatment plant. The present study considers the wastewater as an indication for the anthropogenic activities. This is due to the correlation between the summer season and the discharged wastewater (positive relationship). Consequently, the increasing of NO_2 values during the summer seasons can be interpreted as result to the high anthropogenic activities in Matrouh city and its vicinities as well as the daily huge spreading of wastewater over the study area (Table 3). In this regard, the chemical analyses (Table 2) confirmed the existence of NO_3 , NO_2 , and NH_3 in different wastewater sources while the biological analyses indicate the presence of bacteria groups which are necessary for the transformation of NH_3 to N_2O and NO_2 (Figs. 8, 9). NO_x gases are representing a family of 7 compounds but indeed, U.S Environmental Protection Agency considers only NO_2 as alternative for this family where it is the most common form of NO_x gases which are generated by anthropogenic (human) activities (EPA 1999). The emitted NO_2 is reacting in the air (in the presence of UV) to form O_3 and NO , then recycle NO to NO_2 , so each molecule of NO_2 can produce O_3 many times (EPA 1997). Actually, the ozone that we want to minimize is tropospheric ozone (ozone in the ambient air that we breathe), while the stratospheric ozone in the upper atmosphere protects earth from sun ionizing radiation. On the other hand, the interpretation of the different climatic parameters (Fig. 10) that may affect the emission of NO_2 , reveal that these parameters show the same trend during the monitoring period (2004–2021). Special attention was payed for temperature and NO_2 emission where the data indicate that no matching between temperature and NO_2 and it is not the responsible of the high noticeable values since 2011 (Fig. 11). Although, we have to take in consideration the secondary role of temperature in increasing evaporation, the primary reason for raising NH_3 emissions is attributed to different wastewater spreading over the area and the high anthropogenic activities during the summer season.

Impact of NO_2 on greenhouse gases, climate change and groundwater

The climate change has rather less concern than other existed crises due to its gradual process where its effect is not immediate and people still underestimate this issue, whereas some others deny the phenomenon existence (Islam et al. 2021). The obtained results (Fig. 12a, b), from the analyses of multi-climate datasets (NCEP 2015; ERA 2015),

reveal that there are increases of temperature accompanied by decreasing in precipitation amounts in North Africa (Yousif 2021). The same situation is applicable in the study area through the previous climate records and the expected future scenarios (Fig. 12c–f). This change in climate particularly the decreasing in rainfall affected the study area in form of drought, over-pumping of groundwater and random drilling of wells to compensate the shortage of rainfall amounts. The stated climate change in the study area, is due to global warming which is related to greenhouse gases. In general, the greenhouse gases can be subdivided into two groups: the direct greenhouse gases (CO_2 , N_2O , CH_4) and the indirect greenhouse gases (VOC, NO_2 , NO , CO , SO_2) (Satein 2009). The direct group is acting to increase global warming through absorbing and trapping infrared radiation emitted from earth and atmosphere, and then reflect the radiation back to the earth surface which cause its (U.S. Global Change Research Program 2009). The indirect group is also affecting on the global warming through the producing of direct greenhouse gases by reactions with other chemical compounds (EPA 2009). However, the NO_2 gas is not only air pollutant, but also reacts in the atmosphere to form O_3 and acid rain (EPA 1999). In this context, the presented conceptual model (Fig. 13) explain the contribution of NO_2 gas in producing the greenhouse gases such as N_2O and O_3 which accordingly lead to climate change in the form of raising temperature and reducing rainfall (Fig. 12). This change affects the groundwater where it causes decreasing of the aquifers recharge rates (as a result to rainfall changes) and also increase stress on the groundwater pumping (as a result to temperature changes), (Fig. 13). The N_2O emissions can participate significantly to the carbon footprint of wastewater treatment plants (Ni and Yuan 2015). It should be taken in consideration that an emission factor of NO_x with 1.0% will raise the carbon footprint of a wastewater by about 30% (de Haas and Hartley 2004; Law et al. 2012). Consequently, the creation of reliable predictive tools to mitigate NO_x emission from wastewater and other anthropogenic activities, is necessary for achieving Net-Zero emissions of greenhouse gases (Ni and Yuan 2015; Ni et al. 2013).

Strategies for Net-Zero emissions

In the opinion of the Science Based Target initiative (SBTi 2019), the Net-Zero Emissions can be achieved when the greenhouse gases emissions are balanced by anthropogenic removals throughout a certain period (Pineda and Faria 2019). According to Paris Agreement, the target of decreasing the global warming by 1.5 °C through reducing CO emissions alone, is not sufficient. Therefore, the Net-Zero emissions can be considered the suitable solution for future climate change mitigation. However, COP (2021) stated that for mitigation action, the Parties are

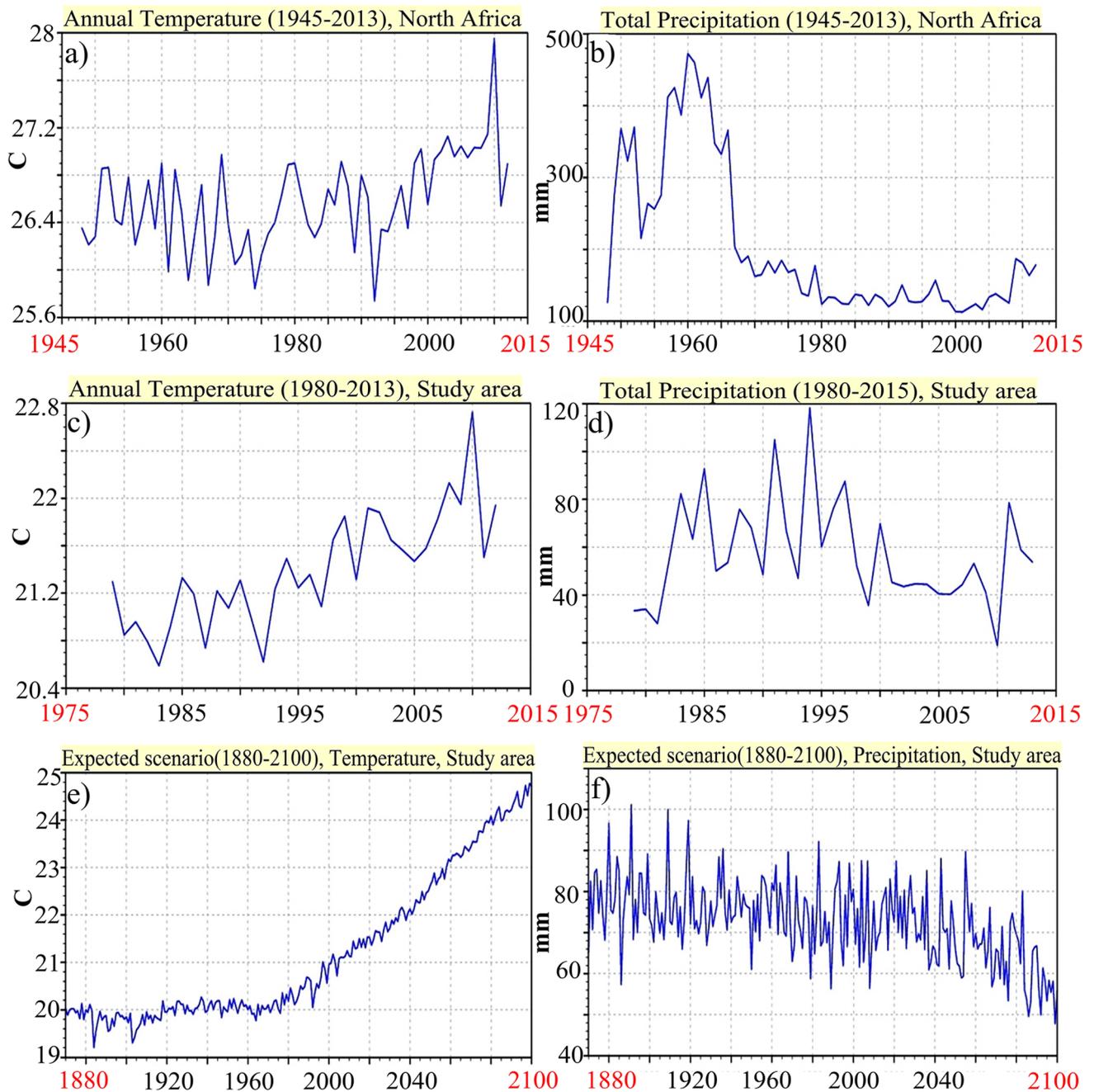


Fig. 12 Plots of temperature and precipitation of North Africa (a, b) and the study area (c, d) as well as modelled expected scenarios till 2100 (e, f). The data show that climate change is existed through the

general trend of increasing temperature and decreasing rainfall for long periods (sources: climate reanalyzer, <https://ClimateReanalyzer.org>, Climate Change Institute, NCEP 2015; ERA 2015)

invited to strengthen their emissions reductions and to align their climate action pledges according to the previous Paris Agreement. In this context, the current study pay attention to what is called” local emissions” which can contribute even a small part to increasing of greenhouse gases and climate change. Although, the climate issue is global, the local emissions from different sources (such as wastewater and anthropogenic activities) have an impact on local and

global environment, particularly when these emissions are continuous and cumulative. Therefore, the study suggests to monitor each emissions source through satellite observations followed by chemical and biological analyses. The satellite observations show an effective tool to monitor, identify and evaluate the ambient air. As we clarified in Table 3, the satellite can provide a daily record which can be statically analyzed and define the high emissions peak. The study suggests

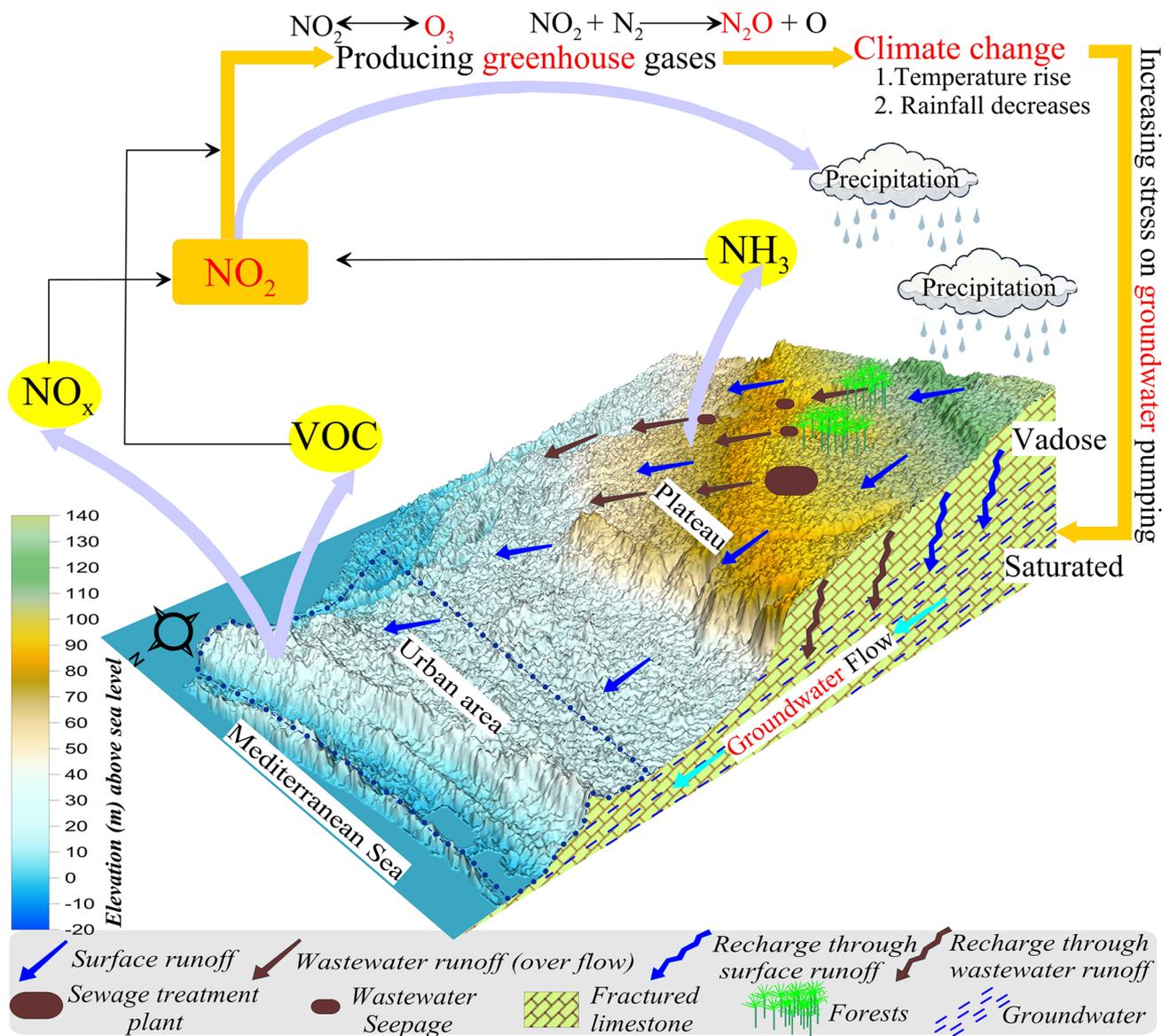


Fig. 13 Conceptual model explains the sources of NO_2 emissions in the study area and its contribution in producing the greenhouse gases such as N_2O and O_3 that are led to climate change (changes in tem-

perature and rainfall, refer to Fig. 12). This change affects the groundwater through decreasing of the recharge rates and increase stress on the groundwater pumping (as a result to high temperature)

to start from this point (i.e. satellite observations) to monitor both of direct and indirect greenhouse gases to take an action for climate change mitigation through the Net-Zero Emissions. In additions, the authors believe that the term “climate change” implies that the climate of our earth planet is changing, and that we are facing a change in climate due to cosmic natural causes and we are victims of it. There is no truth in this content, we suggest that the correct title is “deteriorate of the earth’s climate by man.” Indeed, this viewpoint is aiming to let each person takes responsibility about the emissions increasing and to realize his contribution to climate change and the negative effects that may result.

Conclusions

The significance of atmospheric NO_2 is attributed to its main control on the ground-level concentrations of O_3 . Also, it is involved in many processes related to the formation of greenhouse gases, where it is considered as one of the air pollutants associated with anthropogenic activities. The current research presents an approach to evaluate the ambient environment and to understand the contribution of local emissions to form the greenhouses gases. This approach depends on different datasets including; satellite data for NO_2 and O_3 gases as well as different climate datasets,

chemical and biological analyses, and investigative information that was collected during fieldwork. In this context, our approach can be considered as an attempt to monitor the different emission sources under arid conditions and to clarify the rapid response of NO_2 concentrations to the anthropogenic activities in specific regions. The time series-area averaged data show a noticeable increasing of NO_2 values since a specific year (i.e., 2011), and therefore, the study examined the reasons for this increase through an investigation of daily data records in correlation with change detection and LULC maps. The peak values of NO_2 are related to high anthropogenic activities resulted from the summer vacationers, which has a direct impact on the amount of discharged wastewater and also the emissions from urban areas. The climate change issue was investigated through climate datasets over North Africa and the study area where there is an increasing trend of temperature associated with decreasing of precipitation. Therefore, it leads to drought, over-pumping of groundwater and random drilling to compensate the shortage of rainfall amounts. The inferred climate change impacts in the study area are attributed to greenhouse gases-induced global warming. Consequently, the creation of reliable predictive tools to mitigate NO_x emissions from different sources is necessary for achieving Net-Zero emissions of greenhouse gases. The satellite observations are proven to be an effective tool to monitor, identify and evaluate the ambient air and to provide daily records that can be statically analyzed and used to define high emission peaks. The current study suggests employing different satellite observations to monitor different emissions and identifying their sources to take an action for climate change mitigation through the Net-Zero Emissions. The presented approach is applicable for application over other regions under arid conditions.

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Declarations

Conflict of interest The authors have no competing interests to declare that are relevant to the content of this article.

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