Quantifying NOx emissions in Egypt using TROPOMI observations

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Abstract. Urban areas and industrial facilities, which concentrate most the majority of human activity and industrial production, are major sources of air pollutants, with serious implications for human health and global climate. For most of these pollutants, emission inventories are often highly uncertain, especially in developing countries. Spaceborne observations measurements from the TROPOMI instrument, onboard the Sentinel-5 Precursor satellite, are used to measure-retrieve nitrogen dioxide (NO2) slant column densities with high spatial resolution at a column densities. Here, we use two years of TROPOMI retrievals to map nitrogen oxides (NOx = NO + NO2) emissions in Egypt with a top-down approach approach using the continuity equation in steady state. Emissions are expressed as the sum of a transport term and a sink term representing the three-body reaction comprising NO2 and OH hydroxyl radical (OH). This sink term requires information on the lifetime of NO2, which is calculated with the use of the CAMS near-real-time temperature and hydroxyl radical (OH) OH concentration fields. The applicability of the OH concentration field is evaluated by comparing the lifetime it provides with the lifetime inferred from the fitting of NO2 line density profiles in large plumes with an exponentially modified Gaussian function. This comparison, which is conducted for 20 different samples of NO2 patterns above the city of Riyadh, provides information on the reliability of the CAMS near-real-time OH concentration fields; it also provides the location of the most appropriate vertical level to represent typical pollution sources in industrial areas and megacities in the Middle East region. In Egypt, total derived emissions of NOx are dominated by the sink term. However, but they can be locally dominated by wind transport, especially along the Nile where human activities are concentrated. Megacities and industrial regions clearly appear as the largest sources of NOx emissions in the country. Our top-down model produces estimates whose annual variability infers emissions with a marked annual variability. By looking at the spatial distribution of emissions at the scale of different cities with different industrial characteristics, it appears that this variability is consistent with the national electricity consumption. It is also able to detect lower emissions on Fridays, which are inherent to the social norm of the country, and to quantify the drop in emissions in 2020 due to the COVID-19 pandemic. Overall, our estimations of NOx emissions estimates for Egypt are found to be higher than the CAMS-GLOB-ANT_v4.2 inventory, but and significantly differ in terms of seasonality.

1 Introduction

Economic growth in developing countries has led to a strong increase of urban air pollution (Baklanov et al., 2016 [1]). Among the different pollutants, nitrogen oxides are key species. They are generally the products of fuel combustion, such as the combustion-burning of hydrocarbons in the air at high temperature. The main sources of these compounds are therefore vehicle engines, but also heavy industrial facilities such as power plants, metal smelters and cement plants, iron and steel mills (Tang et al., 2020 [2]) and cement kilns (Kim et al., 2020 [3]). Their accumulation in the lowest layers of the troposphere contributes to the formation of smog and acid rain (Singh et al., 2007 [4]). They also have a significant effect on human health, as they can cause various respiratory diseases (EPA, US., 2016 [5]). To deal with these phenomena, national and regional governments generally enact a series of air pollution control strategies, which typically take the form of bans on certain polluting technologies, with the aim of reducing the concentration of.
pollutants at the local level to targets that must be achieved within a given timeframe. These strategies, which also help driving technological innovation, have had a significant effect in Europe (Crippa et al., 2016 [6]).

In Egypt, population growth, urbanisation, socio-economic development and the associated increase in the vehicle fleet led to a major degradation of air quality in the last decades, especially in highly populated areas such as Greater Cairo and the Nile Delta (Abou El-Magd et al., 2020 [7]), which gather the majority of the population. The Ministry of State for the Environment has thus initiated new policies that aim to reduce pollution levels throughout the country, through technical mitigation of emissions, emission standards for vehicles and intersectoral collaboration (UNEP, 2015 [8]). However, Egypt, like most developing countries, such as Egypt, lacks the local infrastructure to access detailed information on technical factors such as energy consumption or fuel type and technology, leading to discrepancies in inventories (Xue et al., 2012 [9]). As a consequence, the monitoring of emissions, which is important to evaluate the effects of the air pollution control policies, is of limited reliability.

To overcome the uncertainties in the emission inventories, the use of independent observations systems is becoming increasingly prevalent. In this study, we investigate the use of satellite remote sensing of atmospheric concentrations to improve the quantification of NO\textsubscript{x} emissions in Egypt. Spectrally resolved satellite measurements of solar backscattered radiation enable the quantification of NO\textsubscript{2} and other trace gases absorbing in the UV-Visible spectral range based on their characteristic spectral absorption patterns. Tropospheric vertical column densities, i.e. vertically integrated NO\textsubscript{2} concentrations in the troposphere, have been providing information on the spatial distribution of tropospheric NO\textsubscript{2} at global scale for nearly 30 years, allowing the identification of different sources of NO\textsubscript{x} and the quantification of the associated emissions (Leue et al., 2001 [10]; Martin et al., 2003 [11]; Mijling and van der A, 2012 [12]; de Foy et al., 2015 [13]; Goldberg et al., 2019 [14]; Beirle et al., 2019 [15]; Lorente et al., 2019 [16]; Lange et al., 2021 [17]). In October 2017, the Sentinel-5 Precursor satellite was launched. Its main instrument is the TROPOspheric Monitoring Instrument (TROPOMI), which provides tropospheric NO\textsubscript{2} column densities at a high spatial resolution with a large swath width and with a daily frequency (Veefkind et al., 2012 [18]). By applying the steady-state continuity equation (Beirle et al., 2019 [15]; Lama et al., 2019, 2020), it is possible to build a top-down model that directly quantifies NO\textsubscript{x} emissions from these NO\textsubscript{2} column densities, provided that some key parameters (wind, temperature, hydroxyl radical concentration and concentration ratio between NO\textsubscript{x} and NO\textsubscript{2}) are correctly estimated. This model is used to quantify the anthropogenic NO\textsubscript{x} emissions in Egypt for a 2-year period, from November 2018 to November 2020.

This paper is organised as follows: Section 2 provides a description of the datasets used in this study. Section 3 explains the method used to build the model-up and the limits of the method-up model approach used to quantify NO\textsubscript{x} emissions in Egypt. It also presents a method for validating the parameters of the model-model parameters by using NO\textsubscript{2} line density profiles over Riyadh, Saudi Arabia. Section 4 presents the analysis of this validation method. It presents the location of the main NO\textsubscript{x} sources in Egypt and evaluates the vertical sensitivity of the model. It also assesses the ability of the model to show less human activity on Fridays and during the lockdown that took place during the COVID-19 pandemic. It finally confronts the inferred emissions with different inventories in terms of amplitude and seasonality. Section 5 presents our conclusion and general remarks.

2 Instrumentation and data

2.1 TROPOMI NO\textsubscript{2} retrievals

The TROPOspheric Atmosphere Monitoring Instrument (TROPOMI), onboard the European Space Agency’s (ESA) Sentinel-5 Precursor (S-5P) satellite, provides measurements for atmospheric composition. TROPOMI is a spectrometer observing wavelengths in the infrared, visible and ultraviolet light at around 13:30 local time. The UV-Visible spectral band at 405-465 nm is used to retrieve NO\textsubscript{2}. Other spectral bands are used to observe methane, formaldehyde, sulphur dioxide, carbon dioxide and ozone, as well as aerosols and cloud physical properties. The very high spatial resolution offered by TROPOMI (originally 3.5 × 7 km\textsuperscript{2} at nadir, improved to 3.5 × 5.5 km\textsuperscript{2} since 6 August 2019) provides unprecedented information on tropospheric NO\textsubscript{2}. Its large swath width (~ 2600 km) enables making it possible to construct NO\textsubscript{2} images on large spatial scales. Those images greatly improve the potential for detecting highly localised pollution plumes above the ground, identifying small-scale emission sources but also estimating emissions from megacities, industrial facilities and biomass burning. We use TROPOMI NO\textsubscript{2} retrievals (Level 2 data, OFFL stream) from November 2018 to November 2020 over the Middle East and Eastern Mediterranean region Egypt. We also use them over Saudi Arabia, and more specifically over Egypt and the city of Riyadh, Saudi Arabia. The arid climate of this region makes it possible to evaluate the reliability of other parameters. This will be explained in Section 3.3. Both countries have an arid climate, which offers a large number of clear-sky days throughout the year, but also the presence...
of enabling the calculation of monthly averages based on more than 20 observations. They are also the host to many large plumes of pollutants due to high human concentration patterns along rivers and around megacities, which allows us to observe high NO₂ concentrations in the region of interest. To facilitate data filtering, TROPOMI products provide a quality assurance value \( q_a \), which ranges from 0 (no data) to 1 (high-quality data). For our analysis of concentrations, we selected NO₂ retrievals with \( q_a \) values equal to or greater than 0.75, which systematically correspond to clear-sky conditions (Eichmann and Boersma, 2019 [20]). TROPOMI soundings are gridded for this study at a spatial resolution of 0.1° × 0.1° with daily coverage. This resolution is lower than that of the instrument; the gridding thus provides a grid for which most NO₂ columns correspond to one or more measurements. The observed plumes remain correctly resolved. Cells without measurements are infrequent, which facilitates the calculation of derivatives.

### 2.2 Wind data

The horizontal wind information \( \mathbf{w} = (u, v) \) is taken from the European Centre for Medium-Range Weather Forecasts (ECMWF) ERA5 data archive (fifth generation of atmospheric reanalyses) at a horizontal resolution of 0.25° × 0.25° on 37 pressure levels (Hersbach et al., 2020 [21]). The hourly values have been linearly interpolated to the TROPOMI orbit timestamp and re-gridded to a 0.1° × 0.1° resolution.

### 2.3 CAMS real-time fields

The Copernicus Atmospheric Monitoring Service (CAMS) global near-real-time service provides analyses and forecasts for reactive gases, greenhouse gases and aerosols on 25 pressure levels with a horizontal resolution of 0.4° × 0.4° and a temporal resolution of 3 hours (Huijnen et al., 2016 [22]). For the calculation of NOₓ emissions from TROPOMI observations, we use CAMS concentration fields of nitrogen oxides (NO and NO₂) and hydroxyl radical (OH). We also use the CAMS temperature field \( T \). NO and NO₂ concentrations are used to account for chemical processes that take place in polluted air. Anthropogenic activities produce mainly NO, which is transformed into NO₂ by reaction with ozone \( O_3 \). NO₂ is then photolyzed during the day, reforming NO and producing an oxygen atom \( O \) (Seinfeld, 1989 [23]). This photochemical equilibrium between NO and NO₂ can be highlighted with the NO₂: NO₂ concentration ratio, whose value depends on local conditions, allowing to perform a conversion from NO₂ production to NOₓ emissions. The reason for the use of OH is different. OH is the main oxidant that controls the ability of the atmosphere to remove pollutants such as NO₂ (Logan et al., 1981 [24]). It is mainly produced during daylight hours by interaction between water and atomic oxygen produced by ozone dissociation (Levy, 1971 [25]). In air that is directly influenced by pollution, the second another source of OH is due to a reaction between NO and NO₂. This reaction, referred to as the NO₂ recycling mechanism, illustrates the nonlinear dependence of the OH concentration on NO₂ (Valin et al., 2011 [26]; Lelieveld et al., 2016 [27]). Since the OH lifetime is typically of less than a second, its concentration in the troposphere is very low and difficult to measure. As a consequence, global analyses, which estimate OH concentrations from other variable species (Li et al., 2018 [28]; Wolfe et al., 2019 [29]), provide a natural representation for OH concentrations, but with high associated uncertainties. Therefore, the CAMS OH concentrations are used here to account for the NO₂ oxidation to form nitric acid (HNO₃), whose representation is explained in Section 3.1. Finally, the temperature field is used to control variations in the kinetic parameters (Burkhoffeld et al., 2020 [30]). The hourly values are also linearly interpolated to the TROPOMI orbit timestamp and re-gridded to a 0.1° × 0.1° resolution.

### 2.4 Calculation of urban enhancements

Detecting traces of anthropogenic emissions in TROPOMI NO₂ images is not a straightforward process. The NO₂ signal from a sparsely populated area or a small industrial plant facility may be covered by numerical noise or by the signal generated by natural sources such as lightning (Boersma et al., 2005 [31]). In the absence of anthropogenic sources, TROPOMI observes NO₂ concentrations which constitute a tropospheric background of \( \sim 0.5 \times 10^{15} \) molecules cm\(^{-2}\). At the global scale, this background is the result of different sources. In the lower troposphere, natural NO₂ emissions are mostly due to fires and soil emissions (Yienger et al., 1995 [32]). It is therefore necessary to remove the natural part of the atmospheric signal from the detected NO₂ enhancement (Hoelzemann et al., 2004 [33]). In the upper troposphere however, sources include lightning, convective injection and downwelling from the stratosphere (Ehelt et al., 1992 [34]), but the factors controlling the resulting concentrations are poorly understood. According to state-of-art estimates, anthropogenic NOₓ accounts for most of the emissions at the global scale, whereas natural emissions from fires, soils and lightning are less significant at the global scale and do not exceed a share of 35% combined (Jaeglé et al., 2005 [35]; Müller and Stavrakou, 2005 [36]). Although associated errors can
In eastern China, the non-anthropogenic share of total NO\textsubscript{x} emissions is variable but does not exceed 20\% (Lin, 2012 [37]). Egypt being a desertic region and not very conductive to lightning, we expect the share of those non-anthropogenic emissions to be smaller. To estimate anthropogenic NO\textsubscript{x} emissions, it is therefore necessary to remove this share.

With an atmospheric lifetime of about a few hours, the presence of NO\textsubscript{2} is relatively short. Consequently, the majority of NO\textsubscript{2} is not transported far downwind from its sources. Thus, near-surface NO\textsubscript{2} concentrations are generally high over industrial facilities and densely populated areas that need to be identified. Because Egypt’s population is almost entirely located along the Nile River and its delta, the study of NO\textsubscript{x} emissions in this country cannot therefore be reduced to the study of a small number of point sources, as it would be the case for several other parts of the Middle East region, and must be carried out in the form of a mapping of the country. Further explanation discussion is provided in Section 3.3. To identify urban or industrial areas in Egypt, we use the Socioeconomic Data and Applications Center (SEDAC) GRUMP (Global Rural-Urban Mapping Project) data archive, which comprises eight global datasets, including a population density grid provided at a resolution of 30 arc seconds, with population estimates normalised for the year 2000 (CIESIN, 2019 [38]). We combine this database with field data giving the location of industrial facilities from energy-intensive industries in the region (data have been retrieved from the Global Energy Observatory for oil and gas-fired power plants, from IndustryAbout for aluminium, steel and iron plants and iron smelters, from the work of Elvidge et al., 2016 [39] for flaring sites, and from the work of Steven J. Davis and Dan Tong for cement plants; links are given at the end of this article).

These datasets are used to remove the non-anthropogenic part of the NO\textsubscript{x} emissions signal. We conduct this removal by subtracting the mean emissions over desert and rural areas, areas without human activity from the mean emissions over urban and industrial and densely populated areas. In order to perform this distinction between these two types of areas, our study is carried out using a grid with a resolution of mask within a 0.1° × 0.1° characterised by two types of cells. A grid cell is considered "urban" to be part of the mask if it has a population density higher than a threshold of 100 hab.km\textsuperscript{-2}, or if its centre is close to an industrial facility. Otherwise, the cell is considered to be part of the "rural background", i.e. outside the mask. In order to avoid any smearing that would correspond to abnormally high emissions outside urban areas and industrial centres (which can happen if the wind is...
poorly estimated), transition cells (in the immediate vicinity of the mentioned urban mask cells) are also considered to be urban mask cells. Figure 1 shows the distinction between urban and rural mask cells and background cells on our domain in Egypt that lies between parallels 23°N and 32°N and meridians 29°E and 34°E. Most urban of the mask cells are located in the Nile area. Some urban mask cells are also found on the coast or in isolated parts in the desert. They correspond to remote industrial facilities, including major flaring sites, or sparsely populated industrial centres such as Ain Sokhna’s industrial area. The domain comprises \( n_{\text{rur}} = 3692 \) rural cells and \( n_{\text{urb}} = 949 \) urban, \( n_{\text{rur}} = 949 \) mask cells and \( n_{\text{b}} = 3692 \) background cells. The resulting grid is conveniently used as a mask for the urban enhancement, whose calculation is explained mathematical description of the background removal is outlined in Section 3.4.

### 2.5 Emission inventories

We compare TROPOMI-derived NO\(_x\) emissions to the Emissions Database for Global Atmospheric Research (EDGARv5.0) for 2020 and the CAMS global anthropogenic emissions (CAMS-GLOB-ANT-v4.2) inventory released in 2020. Both datasets provide 0.1° × 0.1° gridded emissions for different sectors on a monthly basis. EDGARv5.0 (Crippa et al., 2019 [7]) is based on activity data (population, energy production, fossil fuel extraction, industrial processes, agricultural statistics, etc.) derived from the International Energy Agency (IEA) and the Food and Agriculture Organization (FAO), corresponding emission factors, national and regional information on technology mix data and end-of-pipe measurements. The inventory covers the years 1970-2015. CAMS-GLOB-ANT-v4.2 (Granier and differs from the previous version EDGARv4.3.2 which does not use splitting factors derived from the Energy Information Administration (EIA) data on fuel consumption of coal, oil and natural gas for specific countries (Crippa et al., 2010 [40], 2020 [41]). CAMS-GLOB-ANT_v4.2 is developed within the framework of the Copernicus Atmospheric Monitoring Service (Granier et al., 2019 [40]). For this inventory, NO\(_x\) emissions are based on various existing sectors in the EDGARv4.3.2 emissions from 2000-2012 which are used as a basis for 2010 emissions and are extrapolated to the current year using 2011-2014 sector-based trends from the Community Emissions Data System (CEDS) inventory (Hoehly et al., 2018 [42]). From one inventory to another, the names and definitions of the sectors may vary. In EDGARv5.0 and CAMS-GLOB-ANT-v4.2, the emissions for a given country are derived from the technology of used, the dependence of emission factors on fuel type, combustion conditions, as well as activity data and low resolution emission factors (Janssens-Maenhout et al., 2019 [43]).

### 3 Method

#### 3.1 Calculation of NO\(_2\) production from TROPOMI observations

As a first step, we use TROPOMI's tropospheric NO\(_2\) column vertical column densities \( \Omega_{\text{NO}_2} \) to derive top-down NO\(_2\) production maps. Vertical column densities \( \Omega_{\text{NO}_2} \) are obtained from TROPOMI slant column densities using an air mass factor (AMF) which is also provided by TROPOMI. Previous studies have shown that the use of the AMF is a source of structural uncertainty in NO\(_2\) retrievals (Boersma et al., 2004 [44]; Lorente et al., 2017 [45]). In polluted environments, this source of uncertainty becomes non-negligible. Here, the AMF does not vary much temporally throughout the studied period, and is around 1.6 for mask cells and around 1.9 for background cells. The difference between the two types of cells is probably due to a different albedo between the urban environment and desert areas.

Using the horizontal wind \( \mathbf{w} \), the NO\(_2\) flux is given as \( \Omega_{\text{NO}_2} \mathbf{w} \). The divergence of this flux is can be added to the local time derivative \( \frac{\partial \Omega_{\text{NO}_2}}{\partial t} \) to balance NO\(_2\) sources \( e_{\text{NO}_2} \) and sinks \( s_{\text{NO}_2} \) according to the continuity equation:

\[
\frac{\partial \Omega_{\text{NO}_2}}{\partial t} + \text{div}(\Omega_{\text{NO}_2} \mathbf{w}) = e_{\text{NO}_2} - s_{\text{NO}_2}
\]

In steady state, the time derivative disappears and the mass balance is reduced to three terms. The source of NO\(_2\) can production can thus be estimated by taking the combined effect of atmospheric transport losses and the different sinks.

For the transport term, we calculate numerical derivatives with a fourth-order central-finite difference formula at each point scheme for each cell \( \Omega_{\text{NO}_2} \) of the domain. For the sink term Moreover, since the local overpass time of TROPOMI occurs in the middle of the day, NO\(_2\) losses are largely dominated by the three-body reaction involving NO\(_2\) and OH (Seinfeld, 1989 [23]). Two channels have been identified for this reaction (Burkholder et al., 2020 [30]), leading to the production of nitric acid HNO\(_3\) and pernitrous acid HOONO:

\[
\begin{align*}
\text{NO}_2 + \text{OH} + \text{M} & \rightarrow \text{HNO}_3 + \text{M} \\
\text{NO}_2 + \text{OH} + \text{M} & \rightarrow \text{HOONO} + \text{M}
\end{align*}
\]

No corrections are made to the TROPOMI observations. Slant column densities are used as vertical densities. This use amounts to neglect the air mass factor, which is a source of structural uncertainty in NO\(_2\) retrievals (Boersma et
\[ \tau = \frac{1}{\bar{k}_{\text{mean}}(T, [M]) \cdot [\text{OH}]} \cdot \frac{1}{\bar{k}_{\text{mean}}(T, [M]) \cdot [\text{OH}]} \]
- NO conversion to NO$_3$, the latter being in thermal equilibrium with NO$_2$ and N$_2$O$_5$. This sink, which takes place via heterogeneous processes, which has a significant contribution during nighttime in the Mediterranean region (Friedrich et al., 2021 [58]), is neglected at 13:30 when OH is almost at close to its daily maximum. Similarly, the production of PAN.

- NO$_2$ reversible reaction with peroxyacetyl radical to produce peroxyacetyl nitrate (Moxim et al., which peaks in 1996 [56]). In the Nile Delta region, PAN concentrations in the lower troposphere are significantly below the global average (Fischer et al., 2014 [59]), suggesting a small yield. Moreover, its production peaks in the late afternoon and early evening (Seinfeld, 1989 [23]). We therefore do not consider this sink in the representation of NO$_2$ emissions at 13:30. Finally, the uptake of 30%. 

- NO$_2$ uptake onto black carbon particles (Longfellow et al., 1999 [57]). This uptake is of limited amount in the Mediterranean region (Friedrich et al., 2021 [58]).

All these processes being neglected not being accounted for, the reaction between NO$_2$ and OH is the only sink that is considered in our calculations to provide a reliable indication of NO$_x$ emissions. Section 4.7 details the consequences of not considering these various minority sinks on the results.

3.2 Interpolation to daily average emissions

All parameters are evaluated at 13:30 local time, which means that the NO$_2$ production is calculated for at the same moment. In Egypt, the maximum and minimum electricity consumption are reached around 20:00 and 6:00 local time respectively, and inter-daily consumption differences have been weakened by the increasing sales of air conditioning and ventilation systems in the past decades (Attia et al., 2012 [60]). The national average daily load profiles provided by the National Egyptian Electricity Holding Company show that the mean daily electricity consumption corresponds approximately to the consumption at 13:30 in the country (EEHC, 2021 [61]). The difference between the two quantities being very small both in summer (about +2 to -3%) and winter (about -2 to -6%), we neglect this difference and consider our inferred emissions as representative of the average activity in Egypt at any time of the year. This assumes that electricity consumption dominates the emissions of the country, or that the other emitting sectors have a similar daily profile. This can be justified. According to CAMS-GLOB-ANT_v4.2, the power sector accounts for 50 to 60% of total NOx emissions in Egypt. EDGARv5.0 presents a lower share (40 to 45% of total emissions). Moreover, for both inventories, the transport sector accounts for the majority of the remaining emissions. According to the traffic congestion index in Cairo (https://www.tomtom.com/en_gb/traffic-index/cairo-traffic/), the congestion level around 13:30 seems to be slightly higher than during the morning peak, but lower than the during night peak. Traffic emissions at this moment of the day could therefore be representative of the average traffic emissions as well.

3.3 Validation of CAMS OH concentration using line density calculations for Riyadh

When the transport term is integrated over large spatial scales, it cancels out due to the mass balance in the continuity equation between NO$_2$ sources and NO$_2$ sinks. At first order, the integration of the inferred emissions over the whole domain (of about 450,000 km$^2$) thus reflects chemical losses of the sink term. In this term, the NO$_2$ lifetime calculation involves the reaction rate $k_{mean}$, whose annual variability is low due to small changes in Egyptian midday temperatures throughout the year, and OH concentration, whose annual variability is highly marked. In Egypt, tropospheric OH concentrations, which are strongly correlated with solar ultraviolet radiation (Rohrer and Berresheim, 2006 [62]) and NO$_2$ emissions, are higher in summer than in winter. To ensure an adequate representation of the OH field by CAMS data, we select a large number of TROPOMI images characterised by a homogeneous wind field, in which we calculate the NO$_2$ lifetime according to Equation (2), where [OH] corresponds to the near-real-time CAMS data and $k_{mean}$ is calculated with the formula from Burkholder-Burkholder et al., 2020 [52]. We compare this value with the lifetime determined by a method initially developed by Beirle et al., 2011 [63], and expanded by Valin et al., 2013 [64] by introducing a rotation of the image to refine the chemical lifetime. This method consists in fitting an exponentially modified Gaussian function (EMG) to NO$_2$ line density profiles. These profiles correspond to the integrated NO$_2$ mean value columns along the mean wind direction in the pollution pattern and centered around the source. They are obtained by rotating TROPOMI images in the mean wind direction and averaging using the values of the nearest columns in a 100 km$^2$ area. Line density profiles are generated on a distance span of 300 km. An example is given in Figure 3. Within the average profile, the NO$_2$ burden and lifetime can be derived from the parameters that describe the best statistical fit. The EMG model is expressed as follows (Lange et al., 2021 [17]):

$$\langle \Omega_{NO_2} \rangle(x, B, A, x_0, \mu, \sigma) = B + \frac{A}{2\pi \sigma} \exp\left(\frac{\mu - x}{x_0} + \frac{\sigma^2}{2\pi \sigma^2}\right) \operatorname{erfc}\left(\frac{1}{\sqrt{2}} \left| \frac{x - \mu}{\sigma} - \frac{\sigma}{x_0} \right| \right)$$

(4)
Here, $x$ is the distance in the downwind-upwind direction, $B$ is the NO$_2$ background, $A$ is the total number of NO$_2$ molecules observed in the vicinity of the point source, $x_0$ is the e-folding distance downwind, representing the exponential length scale of NO$_2$ decay, $\mu$ is the location of the apparent source relative to the centre of the point source, and $\sigma$ is the standard deviation of the Gaussian function, representing the length scale of Gaussian smoothing. Using a non-linear least squares fit, we estimate the five unknown parameters: $A$, $B$, $x_0$, $\mu$, and $\sigma$. Using the mean zonal wind module $\sqrt{w^2}$ of the NO$_2$ line density, the NO$_2$ lifetime $\tau_{fit}$ can be estimated from

$$\tau_{fit} = \frac{x_0}{\langle \sqrt{w^2} \rangle \cdot w_{\text{mean}}}$$

The geography of Egypt does not suit the method described here. The Egyptian population is contiguously concentrated along the Nile, which makes it difficult to define point sources isolated from human activity. Furthermore, large isolated cities such as Alexandria or Suez are too close to the coast for the wind to be considered homogeneous. We therefore use the nearby city of Riyadh, Saudi Arabia ($24.684^\circ$N, 46.720$^\circ$E) to perform the comparison between the CAMS-induced lifetime and the fit-induced lifetime. Riyadh has been the focus of anterior studies (Valin et al., 2013 [64], Beirle et al., 2019 [15]), and is particularly suitable for several reasons. Firstly, Riyadh is a city within the latitudinal extend of Egypt ($1600$ km from Cairo) — has with a climate which is similar to the typical Egyptian climate. Secondly, NO$_2$ tropospheric columns over Riyadh are high ($\sim 9 \times 10^{15}$ molecules.cm$^{-2}$), leading to retrievals with a high signal-to-noise ratio. Third, Riyadh is far from the coast, and its flat terrain makes the surrounding wind fields rather homogeneous during most of the year.

As the fitting algorithm is very sensitive to any disturbance that might be induced by NO$_2$ production from other point sources, it is necessary to identify heavy industrial facilities in the area. As Riyadh is also an industrial area, many power plants are with several power plants located close to the city centre. Figure 2 shows the location of the most important emitters in the region, which include five gas-fired power plants (PP7, PP8, PP9, PP10 and PP14), one oil-fired power plant (PP4) and one cement plant (CP). The five gas power plants, with a total capacity of more than $10\,GW$, are located in the periphery of the city. These power plants are sufficiently far away from the city centre for TROPOMI to distinguish their own emissions from those of Riyadh’s centre itself with a resolution of $0.1^\circ \times 0.1^\circ$, which is not the case for CP and PP4 which are located in the city centre. It is therefore appropriate to restrict the study of NO$_2$ patterns over Riyadh to days for which the emissions from the city centre and those from the gas power plants do not overlap. This is the case when the wind blows steadily and homogeneously in a north-south direction. Within about $150$ km around the city centre, we thus calculate the average zonal wind given by ERA5 and consider the observation as reliable if the mean angle ($\theta$) of the observations deviates by less than $40^\circ$ from the north or the south, with a standard deviation $\sigma_{\theta}$ of less than $36^\circ$. This condition generally leads to a selection of observations with large wind speeds, low winds speeds being often associated with more variable directions. This ensures the NO$_2$ decay to be dominated by chemical removal and not by the variability of the wind (Valin et al., 2013 [64]). Finally, we select observations with clear-sky conditions downstream of the flow (with at least 80% downstream cells with $q_a > 0.75$).

Figure 2: Map of Riyadh’s city centre with the surrounding power plants (PP4, 7, 8, 9, 10 and 14) and cement plant (CP). The map has been extracted from Google Maps.
Our $0.1^\circ \times 0.1^\circ$ gridding ensures that retrieved lifetimes are governed by physical decay of NO$_2$ and not an artifact of the spatial resolution (Valin et al., 2011 [26]). The fitting procedure is very sensitive to the wind direction. Instead of manually correcting the ERA5 wind field for individual NO$_2$ patterns, we use another procedure: the curve fitting is performed for every sample with three different rotation angles, corresponding to the wind direction with a correction of $-10\,^\circ$, $0\,^\circ$ or $10\,^\circ$. A record is kept if one of these three fits leads to a determination correlation with the corresponding NO$_2$ line density whose coefficient is greater than 0.97. Among the remaining samples, we keep those with a value of $\tau_{\text{fit}}$ greater than 1.0 hr (considered sufficiently high to be relevant). An example of curve fitting is given in Figure 3.

![Figure 3: Estimation of the NO$_2$ lifetime from a pattern above Riyadh on 03/08/2020: (left) NO$_2$ plume rotated with its wind direction around the source (cross star) to an upwind-downwind pattern. Grey boxes centered around black points indicate the spatial extent. (Right) Corresponding line densities (points) representing the downwind evolution of NO$_2$ as function of the distance to Riyadh’s city centre, and the corresponding fit according to the exponentially modified Gaussian function (dashed line).](image)

The phenomena under study here take place in the planetary boundary layer (PBL), which in this region has a midday height of about 2 km (Filioglou et al., 2020 [65]). TROPOMI observations only provide information on the total NO$_2$ content of the tropospheric column, without providing information on the vertical distribution of concentrations. Extracting emissions from concentrations therefore requires a selection on the height at which wind, temperature and OH data are taken. Lama et al., 2020 [19] and Lorente et al., 2019 [16] conducted similar studies using the boundary layer average wind, while Beirle et al., 2019 [15] chose a vertical level of about 450 m above ground. Because vertical transport of NO$_x$, which is emitted mainly from combustion engines and industrial stacks, is generally minor compared to horizontal transport, NO$_x$ is confined to the first few hundred metres above ground level. Using PBL-averaged data poses a problem of consistency as wind, temperature and OH concentration values vary significantly within the PBL. As a consequence, we compare the CAMS-induced lifetime $\tau$ and the fit-induced lifetime $\tau_{\text{fit}}$ using the parameters ($w$, [OH] and $T$) at two different vertical levels: a medium level $A$ at 925 hPa (about 770 m above ground level), and a bottom level $B$ at 987.5 hPa (about 210 m). These levels are interpolated from four and two ECMWF or CAMS consecutive pressure levels respectively (1000-850 hPa for level $A$ and 1000-975 hPa for level $B$). Most urban mask cells having an altitude between 0 and 150 m, the corresponding pressure variations are small (up to $\sim 16$ hPa), which allows us to neglect the effects of topography on the position of pressure levels. Figure 4 sums up the selection method for the comparison of method lifetimes.
We calculate NO\textsubscript{x} emissions on the entire domain from NO\textsubscript{2} production by using CAMS NO and NO\textsubscript{2} concentrations. These quantities are not intended to replace TROPOMI observations; they are used to apply the concentration ratio [NO\textsubscript{x}]/[NO\textsubscript{2}] = ([NO]+[NO\textsubscript{2}])/[NO\textsubscript{2}] to account for the conversion of NO\textsubscript{2} to NO and vice versa. As diurnal NO concentrations in urban areas generally range from 2 to 10 ppb to 150 ppb (Khoder, 2008 [66]), the characteristic stabilization time of this ratio ranges from 1 to 20 minutes (never exceeds a few minutes; Graedel et al., 1976 [67]; Seinfeld and Pandis, 2006 [68]). This time being lower than the order of magnitude of the inter-mesh transport time (about 30 min considering the resolution used and the mean wind module in the region), we can reasonably neglect the effect of the stabilization time of the conversion factor on the total composition of the emissions and treat each cell of the grid independently from its neighbours. Beirle et al., 2019 [15] found an annual average of 1.32 for this conversion factor, but CAMS data shows small deviations from this value over Egyptian urban areas, as urban concentrations depend on local conditions. We therefore calculate NO\textsubscript{x} emissions for each cell of the domain, the following equation as follows:

$$\epsilon_{NO_x} = \frac{[NO_x]}{[NO_2]} \epsilon_{NO_2}$$

For convenience, quantities $\frac{[NO_x]}{[NO_2]} \text{div}(\Omega_{NO_2} w)$ and $\frac{[NO_x]}{[NO_2]} \Omega_{NO_2}/\tau$ represent the respective contributions of the transport and the sink terms to total NO\textsubscript{x} emissions. We finally obtain the emissions related to human activity at the scale of the country $E_{NO_x}$ by removing the influence of arithmetic mean value of NO\textsubscript{x} emissions above background cells from total emissions:

$$E_{NO_x} = \epsilon_{NO_x} - \frac{1}{n_b} \sum_{i=1}^{n_b} \epsilon_{NO_x,i}$$

These removed emissions are linked to the NO\textsubscript{2} background detected by TROPOMI and the possible non-anthropogenic sources of estimated by TROPOMI and do not correspond to anthropogenic emissions. They provide the value of what must be subtracted from the estimates to obtain emissions related to human activity. Such a removal assumes that other processes involved in NO\textsubscript{x} budgets lead to similar emissions inside and outside the mask, which is not evident, as the majority of background cells are located in the desert or the ocean while the majority of mask cells are located near the Nile River. However, as the processes involved in natural NO\textsubscript{x} sources lead to emissions much smaller than anthropogenic emissions in polluted areas, we neglect this difference in the following calculations. An alternative would be to calculate an average concentration for the background cells and subtract the corresponding
value from the column densities before calculating the emissions. This would pose further reliability problems: for instance, very high NO\textsubscript{2} concentrations could appear outside the mask due to wind transport (an example is shown on Figure 1). They would lead to an overestimation of the NO\textsubscript{2} background and thus to an underestimation of the anthropogenic emissions.

Neglecting the part of the country that lies outside the domain, the average surface emissions from Egypt’s anthropogenic activity total emissions from the anthropogenic activity of Egypt can then be obtained by integrating

\[ E_{NOx} = \frac{1}{n_{urb}} \sum_{i=1}^{n_{urb}} e_{NOx,i} - \frac{1}{n_{rur}} \sum_{j=1}^{n_{rur}} e_{NOx,j} \]

on the whole domain. For robust statistics, these derived emissions can be averaged monthly, enabling a month-by-month comparison with bottom-up inventories. The linearity of the averaging processes ensures the interchangeability of temporal and spatial averages. A monthly average is relevant because it aggregates enough data to limit the high inter-day variability due to changing wind patterns or differences between week days and week-ends. In addition, it enables the study of monthly NO\textsubscript{x} emission profiles which reflect changes in human activities throughout the year due to temperature changes, economic constraints and cultural norms. The use of the average value for rural cells as a “background” that is subtracted from the emission estimates for urban cells assumes that all natural processes in NO\textsubscript{x} emissions lead to similar amounts for both types of cells, which is not trivial, as the vast majority of rural cells are located in desert, mountainous or oceanic areas while the vast majority of urban cells are located near the Nile valley or the Mediterranean coast. However, as the processes involved in natural NO\textsubscript{x} sources lead to emissions smaller than anthropogenic emissions in polluted areas (e.g. Lin, 2012 [37] for China), we neglect this difference in the following calculations. Finally, the total anthropogenic NO\textsubscript{x} emissions of the domain can be obtained by multiplying \( E_{NOx} \) by the cumulative area covered by the urban cells (approximately 95,000 km\textsuperscript{2}).

4 Results and discussion

4.1 Line densities and NO\textsubscript{2} lifetime

Here we compare the results of the TROPOMI line densities fits for Riyadh to the lifetime calculated by Equation (2) using CAMS OH data. The two years of TROPOMI observations (from November 2018 to November 2020) provide a wide variety of profiles. For level B, Figure 4 also provides the number of samples that are being kept at each stage of the process. Of the 731 observations available, 203 have a wind direction in the cone with a north-south orientation with an aperture of 40° (i.e. between 340° and 20° or between 160° and 200°). Of the remaining observations, 166 have occurred with a sufficiently clear sky to be retained. The criterion of weak variability for the wind direction brings to 91 the number of observations that are kept by the method. On these 91 observations, the line density profiles are calculated and the fits applied. According to Equation (5), the lifetime is calculated using the mean wind module around the point source. The two lifetimes are calculated with the parameters taken at the medium level A or at the top level B. Of the 91 fits obtained, 52-51 are of high quality (correlation coefficient between fit function and line density profile greater than 0.97) for level A and 52-52 for level B. 39 of these fits lead to a lifetime \( \tau_{fit} \) greater than 1.0 hr for both levels (they do not necessarily correspond to the same days). For level A and 41 for level level B. All remaining samples correspond to atmospheric conditions with moderate to fast winds, with a module ranging between 2 and 11 m/s (with an average of 5.9 m/s) for level A and between 3 and 8 m/s (with an average of 5.4 m/s) for level B.

These lifetimes are compared to the corresponding lifetimes obtained from CAMS data in Figure 5 for each sample, which is divided into seasons for a more convenient comparison. The use of level A leads to a noticeable underestimation of the NO\textsubscript{x} lifetime in autumn compared to the lifetime calculated with the fitting method. This same level leads to an overestimation of the lifetime lifetime overestimations in winter. This trend is not found with the use of level B, which leads to a better reproduction of the lifetimes calculated with the fitting method for the available seasons. Figure 5 shows a linear regression between the two calculated lifetimes. The results are scattered, with a correlation coefficient higher for level B (0.4700.408) than for level A (0.1390.220). When the intercept of the regression line is forced to zero, the resulting slope is closer to 1 for level B (0.9520.998) than for level A (1.086-1.071).
Figure 5: (left) Comparison between CAMS-derived NO\(_2\) lifetimes and lifetimes from NO\(_2\) line density fittings with EMG function above Riyadh city centre, for level A (a) and B (c). The samples presented correspond to patterns in clear-sky conditions for which the mean wind is in the north-south direction with a low variance, and for which the correlation between line density profile and fit gives a correlation coefficient of more than 0.97 and a lifetime of more than 1.0 hr. NO\(_2\) patterns during the summers of 2019 and 2020 do not have these conditions during the summers of 2019 and 2020. Dashed lines separate the groups of observations by season. (right) Comparison between the two calculated lifetimes for level A (b) and B (d). A linear regression with an intercept forced to be zero is displayed with a green dashed line.

Level B is therefore the one that leads to the best match between the lifetime calculated with Equation (2) and the lifetime calculated from line densities. The results that are presented in the following sections (except for Section 4.3) are therefore results of calculations performed with parameters (\(w\), [OH], \(T\) and \([\text{NO}\_x]/[\text{NO}\_2]\) estimated at level B. Nevertheless, it should be noted that no summer observations were included in the comparison. The main reason for this is the wind direction: of the 188 summer days observed, 178 of them have a mean wind direction outside the north-south cone over central Riyadh. On the remaining ten days (one for summer 2019 and nine for summer 2020), the ERA5 wind direction is too variable for the fit to be considered relevant, or the fit results in a correlation coefficient below 0.97. Thus it is not clear how correctly the NO\(_2\) lifetime would be calculated during both summer periods by Equation (2). With OH concentrations being the main driver of this lifetime, we cannot assess the relevance of the representation of OH concentrations by CAMS data during summer days in the study.

4.2 Mapping of Egypt’s NO\(_x\) emissions

The top-down emission model is then applied to the Egyptian domain with CAMS OH concentration and temperature fields for lifetime calculations. For each cell, NO\(_x\) emissions are calculated according to Equation (6), resulting in a mapping of Egypt’s emissions. The obtained values are averaged monthly from November 2018 to November 2020. Figure 6 shows a composition of the emissions map with the transport term and the sink term for the months of January and July 2019. The corresponding anthropogenic emissions, calculated according to Equation (7), are added. The Nile appears on transport term maps: the divergence calculation complies with what is expected from a line density of emitters, i.e. a clear separation of zones of positive divergence from zones of negative divergence with a separation line corresponding to the course of the river. The fact that the negative divergence zones are areas of negative and positive divergence are respectively located to the east of the river and the positive divergence zones to the west and the west...
of the river is the result of the wind being predominantly towards in the northeast and southeast quadrants during the overflight of the regional component of the wind being positive most of the time. Some point sources like Cairo, Alexandria, Asyut or Aswan are easily identifiable. The sink term, directly proportional to the TROPOMI slant column densities, also highlights these cities. However, unlike the transport term, which has a similar spatial pattern from month to month, the sink term is clearly stronger in summer than in winter. This is mainly due to a higher lifetime in winter than in summer (4.00 hr - 4.94 hr on average in January 2019 and 2.15 hr - 2.62 hr in July 2019) while the average TROPOMI NO₂ concentrations are slightly higher during winter (1.687 - 1.071 × 10^{15} molecules.cm^{-2} for January 2019 and 1.440 - 0.899 × 10^{15} molecules.cm^{-2} for July 2019). Over the whole domain, the mean transport term varies throughout the studied period between $-0.035 × 10^{15} - 0.014 × 10^{15}$ molecules.cm^{-2}.h^{-1} (January-December 2019) and $0.026 × 10^{15} - 0.015 × 10^{15}$ molecules.cm^{-2}.h^{-1} (May 2020). Thus, it hardly contributes to the NOₓ emission budget, the mean chemical sink term alone varying between $0.451 × 10^{15} - 0.223 × 10^{15}$ molecules.cm^{-2}.h^{-1} (January 2020) and $1.121 × 10^{15} - 0.534 × 10^{15}$ molecules.cm^{-2}.h^{-1} (September 2020).

Several cities in the country are thus highlighted as the main emitters of the country, such as Cairo, Alexandria, Beni Suef, Asyut or Aswan. The industrial area of Ain-Sokhna, located southwest of Suez, also appears as a main emitter. Table 1 compares the monthly values for the sink term and the absolute value of the transport term above five major cities of the country, with populations ranging from 40 - 200,000 to 10 - 20 million inhabitants, as well as Ain-Sokhna’s area. The mean values for TROPOMI column densities are also provided. According to the results, the capital city of Cairo is by far the largest emitter in the country, largely due to its large population, resulting in high traffic emissions, but also to its intensive industrial activity. Alexandria, the country’s second largest city, is not

![Figure 6: Construction of NOₓ emissions above most of Egypt’s territory: (top) transport term (A), sink term (B), and the resulting surface emissions (C), being counted as total and the corresponding anthropogenic emissions after non-anthropogenic background removal (D) for January 2019. (bottom) transport term (D), sink term (E), and the resulting surface emissions (F) for July 2019.](image-url)
necessarily the second largest emitter, as its emissions are comparable to those of smaller cities such as Beni Suef or Asyut. However, the three cities concentrate a large amount of industrial activity: Alexandria hosts several oil and gas power plants and a small number of cement factories, while Beni Suef is close to several oil and gas power plants and hosts several flaring sites. Similarly, the city centre of Asyut is close to two oil and gas-fired power plants and a cement factory. This seems to indicate that industrial activity might be the main cause of NO\textsubscript{x} emissions differences between these cities, before population size. This explains why NO\textsubscript{x} emissions from these three cities are comparable to those of the industrial area of Ain Sokhna, which includes several cement plants, iron smelters and oil and gas plants. It might also explain why Aswan, which has a population that is comparable to Beni Suef or Asyut, but which does not have any major industrial site, has slightly lower emissions than the two other cities. An additional analysis of the differences between Asyut and Aswan is provided in Section 4.6. Finally, the Gulf of Suez displays relatively large emissions, which might be attributed to the shipping sector, the region being a major gateway for international trade. Because it also hosts several flaring sites, these emissions might also be due to the oil and gas extraction activity. Although these cities and areas can be described as high-emission sites, the term responsible for these emissions differ from one site to the other. Figure 7 shows the contribution of the transport term (taken in absolute value) to total emissions for January and July 2019. Because wind fields are relatively homogeneous along the Nile on spatial scales of less than 100 km, NO\textsubscript{2} concentration gradients perceived by TROPOMI in the region mainly contribute to the increase of the transport term which can reach similar values as the sink term. Conversely, desert. However, it is never significantly higher than the sink term: due to a spread of the emissions over large urban areas, the behaviour of these cities is therefore different from that of a point source for which the transport term would be very high (Beirle et al., 2021 [69]).

Table 1: Comparison between the transport term and the sink term above different cities among the 20 most populous cities in Egypt, as well as the industrial area of Ain Sokhna located 45 km southwest of Suez for January and July 2019. Numbers - TROPOMI vertical NO\textsubscript{2} columns, NO\textsubscript{x} emissions and population densities correspond to average values within 18 km from the city centre. The value for the mean TROPOMI NO\textsubscript{2} column density is also given. The population density of the corresponding governorate (2020 value) is noted as a comparison. Unit M stands for a quantity of 10\textsuperscript{15} molecules (NO\textsubscript{2} or NO\textsubscript{x}).

<table>
<thead>
<tr>
<th>City</th>
<th>Population density (khab/km\textsuperscript{2})</th>
<th>Jan. 2019</th>
<th></th>
<th></th>
<th>Jul. 2019</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>(habitants per square kilometer)</td>
<td>(\Omega)\textsubscript{NO} \textsubscript{2}</td>
<td>Transport (M)\textsubscript{NO\textsubscript{2}} \text{cm} \textsuperscript{-2}</td>
<td>Sink (M)\textsubscript{NO\textsubscript{2}} \text{cm} \textsuperscript{-2}</td>
<td>Transport (M)\textsubscript{NO\textsubscript{2}} \textsuperscript{-1}</td>
</tr>
<tr>
<td>Alexandria</td>
<td>3.2-9.133</td>
<td>5.569-3.034</td>
<td>2.047-1.719</td>
<td>4.188-0.975</td>
<td>2.518-1.674</td>
</tr>
<tr>
<td>Asyut</td>
<td>4.6-1.644</td>
<td>4.334-1.708</td>
<td>2.999-0.679</td>
<td>4.299-0.718</td>
<td>4.558-2.137</td>
</tr>
<tr>
<td>Aswan</td>
<td>4.6-3.19</td>
<td>2.615-0.976</td>
<td>0.431-0.182</td>
<td>1.521-0.473</td>
<td>2.475-0.871</td>
</tr>
<tr>
<td>Beni Suef</td>
<td>3.2-2.056</td>
<td>2.747-2.950</td>
<td>0.751-0.364</td>
<td>2.643-1.080</td>
<td>1.683-0.321</td>
</tr>
<tr>
<td>Ain Sokhna</td>
<td>(industrial area) 5</td>
<td>8.159-3.133</td>
<td>1.585-1.256</td>
<td>2.548-1.115</td>
<td>5.216-2.56</td>
</tr>
</tbody>
</table>

Figure 7: Share of the absolute value of the transport term in the sum of the sink term and the absolute value of the transport term above most of Egypt’s territory, indicating the local importance of the transport term in NO\textsubscript{x} emissions above urban areas mask cells. The average of this ratio is shown for January 2019 (A) and July 2019 (B).
Desert areas such as the Libyan Desert, the Eastern Desert and the Sinai region, (located respectively to the west, east and northeast of the Nile) show a very low value for the transport term compared to the sink term, due to the homogeneity of both the wind field and the detected NO$_2$ concentrations in these areas. Finally, a strong predominance of the transport term can be observed near coastal regions even without the presence of emitters nearby due to changing winds—As a consequence, most cities in the country are characterised by a transport term which can locally be of the same order of magnitude as the sink term, especially during the winter season. In the case of the Gulf of Suez, the transport term can be 1 to 2 times higher than the sink term, which varies between 0.5 and 1.0-0.4 and 1.2 $\times 10^{15}$ molecules.cm$^{-2}$.h$^{-1}$. Those values are slightly higher than the average emissions above rural background cells areas due to the sink term (about $0.4-0.6 \times 10^{15}$ molecules.cm$^{-2}$.h$^{-1}$ in winter and $0.7-0.9 \times 10^{15}$ molecules.cm$^{-2}$.h$^{-1}$ in summer). It is also observed that TROPOMI NO$_2$ column densities above this zone are relatively homogeneous, which indicates that the high value for the sink term is due to abrupt changes in wind direction, which is consistent with the presence of the coast. Consequently, explained by a visible gradient of the TROPOMI NO$_2$ column densities. The region thus acts as a very thin line of emitters. Nevertheless, this predominance might also be partly due to a poor representation of the wind field by ERA5, caused by the $0.25^\circ \times 0.25^\circ$ spatial resolution of the data (i.e.—The low resolution of ERA-5 (about 26 km in this region, which is the same order of magnitude as the width of the channel) might misrepresent the transport term may misrepresent the wind near the coast, creating artificial gradients.

### 4.3 Vertical analysis

Here we investigate the influence of the choice of the vertical level in the representation of the model parameters. This influence is of considerable importance, as NO$_x$ sources in urban areas can be located at different altitudes. For instance, emissions from the road sector from tailpipes are located at ground level, whereas NO$_x$ from power plants and industrial facilities can be emitted from stacks, which are usually located between 50 and 300 m above the ground. The results of Section 4.1 results showed that level B was more appropriate for the representation of the NO$_2$ lifetime. This level is therefore chosen as a reference for the comparison. We study the effect of a transition from level B to level A for each of the 3 parameters involved in the representation of the sink term, i.e. temperature $T$, hydroxyl radical concentration [OH] and concentration ratio [NO$_3$]/[NO$_2$]. The results for the averages over urban and rural areas mask cells and background cells are given for the months of January, April, July and October 2019 in Table 2. As the wind field is only involved in the transport term whose spatial integration nearly leads to zero, the influence of this parameter is not studied.

<table>
<thead>
<tr>
<th>Title</th>
<th>Sink term ($10^{15}$ molecules.cm$^{-2}$.h$^{-1}$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>[NO$_3$]</td>
<td>[NO$_2$]</td>
</tr>
<tr>
<td>T, [OH]</td>
<td>1.289-0.859</td>
</tr>
<tr>
<td>[NO$_3$]</td>
<td>1.519-0.899</td>
</tr>
<tr>
<td>T, [OH]</td>
<td>0.968-0.769</td>
</tr>
<tr>
<td>NO$_3$</td>
<td>NO$_2$</td>
</tr>
</tbody>
</table>

Table 2: Analysis of the effect of a vertical change in the parameters used to estimate the sink term in NO$_x$ emissions: temperature, hydroxyl radical concentration, and NO$_3$/NO$_2$ concentration ratio. The comparison is conducted between the estimated quantities for level B and level A. The comparison is conducted for mask cells (MASK) and background cells (BKGD) for four months of the year 2019. Values within brackets represent the variation from the base case for which all quantities are estimated at level B.

The transition to the level A generally results in a decrease in temperature, leading to an increase in the reaction rate $k_{	ext{mean}}$, thus an increase in the emissions from the sink term. This transition has only a small influence on the total NO$_x$ emission estimates, with the total mask and background cells emissions increasing by 4 to 6%. The effect is slightly more pronounced in urban areas, due to a steeper vertical temperature profile in these areas. The influence of OH goes in the opposite direction: its concentration decreases strongly with altitude, weakening the sink term. The share of emissions due to the sink term being proportional to this parameter, the effect of the vertical is very pronounced. Thus, the transition to level A weakens the sink term by 4 to 6% in summer (with an average of -6.0% for This weakening is particularly visible during winter months, for which the emissions are lower by up to 14%.

In summer however, the months June, July, August and by 9 to 26% in winter (with an average of 15.7% for the
months December-January/February). This weakening seems more pronounced over urban areas than over rural areas from March to October, and more pronounced over rural areas than over urban areas during the rest of the year. The effect is hardly noticeable. Finally, the influence of the NO\textsubscript{x}:NO\textsubscript{2} ratio is negligible on the NO\textsubscript{x} emission estimates. Thus, the transition to level A results in an increase in the sink term of 2–4%, due to a decrease in both concentrations of NO and NO\textsubscript{2} with respect to the vertical but with a greater decrease for NO\textsubscript{2}. This vertical study confirms the crucial importance of the OH concentration in the accurate representation of NO\textsubscript{x} emissions. OH concentration appears here as the crucial unimportant driver of the sink term, which is much more sensitive to vertical differences than temperature or the NO\textsubscript{x}:NO\textsubscript{2} concentration ratio.

### 4.4 Weekly cycle

In Egypt, the official rest day is Friday, and the economic activity of the country is a priori lower during this day than during the other days of the week. We therefore try to characterise this feature, by evaluating the weekly cycle of NO\textsubscript{x} emissions. We use the TROPOMI-inferred emissions to obtain averages per day of the week. We use the quality assurance \( q_0 \) of TROPOMI retrievals to ignore the days for which more than 20% of the domain has low-quality data (this happens 43 times in 2018/2019 and 28 times in 2019/2020). Such a filtering avoids accounting for the days when a large part of the urban and industrial areas are covered by clouds. However, it misses situations where small clouds are localised over large emitters, in which case the corresponding emissions are underestimated. Figure 8 shows the resulting daily emissions for the period November 2018 - November 2019 and November 2019 - November 2020. NO\textsubscript{x} emissions are expressed in mass terms as NO. A Friday minimum is observed, defining a marked weekly cycle. This trend is also observed for mean NO\textsubscript{2} column densities, for which no intra-weekly variation is observed. Over the 2018-2019 period, Fridays have average emissions of 0.478 ± 0.408-0.811 ± 0.408 kt, which is lower than average emissions for the rest of the week, which reach 1.270 ± 0.533-0.997 ± 0.533 kt. A similar trend is observed in 2019-2020, for which the average for Fridays is 0.850 ± 0.357-0.704 ± 0.357 kt and the average for other days is 1.067 ± 0.449-0.921 ± 0.449 kt. The difference in emissions between the two periods is due to smaller emissions in December 2019, January 2020 and February 2020 that are discussed in Section 4.5. On average, Friday emissions correspond to a ratio of 0.810:0.837 (i.e. a value of 0.81–0.83 after normalisation on the seven days of the week) for the entire domain. This result is consistent with the values obtained by Stavrakou et al., 2020 [70], who used TROPOMI data and another emission model to calculate a ratio of 0.71:7 for Cairo and 0.89:7 for Alexandria in 2017.

![Weekly profiles of anthropogenic NO\textsubscript{x} emissions for Egypt using TROPOMI observations in 2018-2019 (purple line) and 2019-2020 (green line). Thin grey lines represent individual weeks. Days for which less than 80% of the domain counts low quality observations (\( q_0 < 0.75 \)) are not represented.](image)

### 4.5 Impacts of lockdown during COVID-19

The ongoing global outbreak of COVID-19 forced many countries around the world to implement unprecedented public health responses, including travel restrictions, quarantines, curfews and lockdowns. Such measures have helped to counter the spread of the virus and have, meanwhile, caused high reductions in global demand for fossil fuels (IEA, 2020 [71]). They also led to a fall in the levels of NO\textsubscript{2} and other air pollutants across the globe (Venter et al., 2020 [72]).
Several studies have estimated the impact of these events on the air pollution levels in the urban centres of the country: from in-situ measurements, El-Sheekh et al., 2021 [77] estimated that NO₂ concentrations had dropped by 25.9% in Alexandria’s city centre after the start of the lockdown on March 13th, while El-Magd et al., 2020 [78] used OMI retrievals to estimate a 45.5% reduction of NO₂ concentrations for the entire country during the spring compared to 2018 and 2019 average values. However, due to a changing lifetime of NO₂, reductions in the concentrations of NO₂ might not be entirely due to a decrease in NOₓ emissions, which leads us to focus on the variation of NOₓ emissions during this singular period. Using our top-down emission model, reductions in total NOₓ emissions of 34.6%, 17.4% and 16.6% [20], 11.8% and 13.5% are observed for the respective months of March, April and May 2020 compared to the equivalent months in 2019. This drop of emissions in 2020 compared to 2019 calculated by the model also correspond to a decrease in observed NO₂ columns. However, no significant changes in OH concentrations seem to appear: on average, from 2019 to 2020, CAMS near-real-time data shows a decrease of 5.5% for OH concentration over the urban-mask cells for the period March/April/May, while TROPOMI retrievals above urban areas-mask cells show a decrease in NO₂ column densities of 21.6% over the same period. However, these effects observed for the months of March, April and May 2020 are not repeated in June 2020, for which emissions show an increase of 42.5–15.8% compared to June 2019. This increase-rise is largely the result of an increase in the difference between urban and rural average emissions (as calculated according to Equation 7) average estimates inside and outside the mask. Indeed, the urban term of emissions within the mask in June 2020 is higher than that are higher than those of June 2019, due to an increase in TROPOMI urban concentrations concentrations above mask cells (+217.7%) while the NO₂ lifetime is almost unchanged (+0.43%). The rural term Emissions outside the mask varies in the opposite direction: a decrease in TROPOMI rural concentrations (-7.6% background concentrations (-5.4%) is observed while NO₂ lifetime increases strongly (+11-16.0%). This increase in June emissions seems to indicate that the lift on restrictions allowed a catch-up of the economic activity which has be-was sufficiently strong to generate higher emissions in 2020 than in 2019.

4.6 Annual cycle and comparison to inventories

Here, we attempt to compare our TROPOMI-derived NOₓ emissions to emissions from CAMS and EDGAR CAMS-GLOB-ANT_v4.2 and EDGARv5.0 inventories. Figure shows the total anthropogenic NOₓ emissions over the urban-mask cells from November 2018 to November 2020 (i.e. a period of two years), with the average anthropogenic emissions-calculated according to Equation (7). As indicated in Section 3.2, the emissions, calculated at 13:30 local time, are representative of the average daily consumption in Egypt. The total calculated for each month therefore corresponds to the NOₓ production by human activities in Egyptian urban and industrial areas-the country. After aggregating the different sectors of activity, CAMS and EDGAR inventories directly provide the anthropogenic NOₓ emissions over the same area-domain. All NOₓ emissions are expressed in mass terms as NO. We note that the EDGAR inventory does not cover the period 2018-2020 (the inventory ends in last available year of the inventory is 2015). On Figure, EDGAR emissions corresponding to the period between November 2013 and November 2015 are displayed, i.e. with a delay of the preceding 5 years compared to TROPOMI-derived emissions and CAMS estimates.
TROPOMI-derived emissions are lower than the inventory estimates between November 2019 and February 2020, higher than the CAMS inventory estimates. The top-down model estimates total emissions of 697.6 kt over the 24 months, which is 45.9 kt higher than CAMS for the same period (651.6 kt). This difference is primarily localized in the first 12 months, for which TROPOMI-inferred emissions are always higher than the inventories and show higher values in summer than during the rest of the year. The next 12 months show similar emissions in summer but much lower values in winter. In particular, the difference is significant in December 2019 and January 2020 (respectively 51.8% and 55.76.5% and 66.5% of CAMS levels). These emissions also contrast with other winter emissions, with a total of 31.7 kt for 2019-12/2020-01 against 53.3 kt for 2018-12/2019-01 and 57.7 kt for 2020-12/2021-01. In the computations, this decrease drop for winter 2019/2020 is mainly due to a relatively low value of the OH concentration which reaches 5.86–4.61 x 10^6 molecules.cm^-3 on average for these two months, with 4.95–December 2019 and January 2020, with 4.29 x 10^6 molecules.cm^-3 above urban areas and 6.09 x 10^6 molecules.cm^-3 over rural areas background cells. They were respectively 6.96, 6.94 and 6.97–5.29, 5.74 and 5.18 x 10^6 molecules.cm^-3 for the previous year (December 2018–January 2019) and 7.24, 6.94 and 7.31–2018-12/2019-01) and 5.11, 4.90 and 5.16 x 10^6 molecules.cm^-3 for the year before (December 2017–January 2018 subsequent year (2020-12/2021-01). A decrease in tropospheric columns (41.3% for urban areas and 4.1% for rural areas. 18.5% for mask cells and 7.6% for background cells compared to winter 2018/2019) also contributes to this drop. The accuracy of the inferred emissions for winter 2019/2020 can therefore be questioned.

Except for this singular period, TROPOMI derived emissions are higher than the CAMS inventory estimates. The top-down model estimates total emissions of 814.5 kt over the 24 months, which is 162.9 kt higher than CAMS for the same period (651.6 kt). Of these 162.9 kt, 125.2 kt are emitted during the first 12 months (before the underestimation period) and 37.7 kt during the 12 following months. The average value for top-down NOx emissions are 25.0% higher than CAMS estimates. TROPOMI inferred emissions show an annual variability, thus the emissions seem to follow...
First sight, the annual variability of TROPOMI-inferred emissions, which describes a one-year seasonal cycle where emissions are higher in summer than in winter. These results, at first sight, seem cycle with higher emissions in summer, seems to be correlated with power emissions which dominate the use of fossil fuels in Egypt (Abdallah et al., 2020 [79]). These power emissions are due to the country’s residential electricity consumption (Attia et al., 2012 [60]; Elharidi et al., 2013 [80]; Nassief, 2014 [81]). They also meet the needs of industry. Summer peaks in electricity consumption are mostly driven by temperature, for instance the, as illustrated by the increasing sales of air conditioning and ventilation systems have been increasing for several decades (Walba et al., 2018 [82]). The use of air conditioning in cars, which requires an additional amount of fuel, could also contribute to the increase of NOx emissions in summer. However, To support this hypothesis, we use our model on two smaller domains centered around the two cities of Asyut and Aswan. The corresponding domains are displayed on Figure 1. Both cities have similar demographic features, with populations of about 467,000 and 315,000 inhabitants in 2021 and human densities of about 3,000 and 1,600 inhabitants per square kilometer respectively. However, their industrial features largely differ. There is no large fossil fuel-fired power plant in Aswan, where most of the electricity is produced by a hydroelectric dam, whereas Asyut counts three oil and gas power plants of various capacities (90, 650 and 1500 MW) in its urban area. Both cities have a cement plant, but the one in Asyut has a larger production capacity (5.7 Mt/yr in Asyut, 0.8 Mt/yr in Aswan). Our model is used following the same procedure as for the main domain. The background removal is done at the scale of the country. A seasonal cycle appears for Asyut, with a minimum for winter months and a maximum for summer months. This cycle seems slightly shifted from the one observed for the entire country, for which May emissions are as important as those of summer months. We also note that the decrease in emissions for winter 2019/2020 is less marked than for the emissions of the whole country, and of a similar value to the previous winter. This suggests that national NOx emissions are indeed lower during winter, but that the values obtained for winter 2019/2020 are particularly low. We also find that the seasonality of the emissions is more pronounced for the Asyut domain than for the country as a whole. The case of Aswan is different. Emissions within the corresponding domain are significantly lower than for Asyut. The signal-to-noise ratio being higher, it is difficult to characterise an annual cycle, but the results do not seem to indicate low emissions in winter and high emissions in summer. This identification of a seasonal cycle identical to that of the entire country for a city with several power plants, and the absence of such a cycle in a city without any, strengthens the hypothesis that the power sector plays a major role in Egyptian NOx emissions.

We note that some features of the industrial activities in the region-country might be counteracting this trend. For some sectors such as cement or steel, production is lower in summer, due to the physical wear experienced by workers due to heat, but also due to certain periods of leave. Given the importance of industrial activities in the production of NOx shown in Section 4.2, this aspect cannot be neglected. The transport sector could also counteract the observed trend: although the use of air conditioning in cars increase NOx emissions of the sector, the observed mean traffic in the country is higher between November and February and lower between June and August, especially in Cairo which gathers most of the population. In the absence of additional data, it therefore seems difficult to conclude on the relevance-amplitude of the seasonal cycle that seems to be produced by our top-down model. This caution is all the more necessary as CAMS and EDGAR inventories show different seasonal cycles in show seasonal cycles for NOx emissions, with different dynamics than those displayed by TROPOMI emissions: while the EDGAR inventory predicts a maximum of emissions in December or January and a minimum in April, the CAMS inventory shows two local maxima each year in May and November and two local minima in February and September. The amplitude of the cycle is higher in EDGAR than in CAMS.corresponding cycles is much lower in those inventories, representing 14.2% of the average value for emissions estimates in for EDGAR and 12.4% in CAMS. These differences between the model and the inventories do not give us any information on the seasonality of NOx emissions that should be found in the outputs of our top-down model for CAMS. Those values must be compared to the amplitude displayed by TROPOMI-inferred emissions, for which the maximum/minimum ratio is about 1.8 if winter 2019/2020 is excluded, and 2.7 if it is included.

4.7 Uncertainties and assessments of the previous results

The estimation of NOx emissions is based on the use of several quantities with varying uncertainties. The error bars shown in Figures 5 and 9 are thus calculated from uncertainty statistics whose references are presented in this section. Since these references do not specify the exact nature of these statistics, we assume they correspond to standard deviations. The uncertainty of tropospheric NO2 columns under polluted conditions is dominated by the sensitivity of satellite observations to lower tropospheric air masses, expressed by the tropospheric air-mass factor (AMF). The AMF depends on the viewing geometry, surface albedo, NO2 vertical profile, and cloud characteristics (Lorente et al., 2017 [45]; Ecker et al., 2019 [26]). The column relative uncertainty due to the AMF is of the order of 30% (Boersma et
S-5P validation activities indicate that TROPOMI tropospheric NO$_2$ columns are systematically biased low by about 30%-50% over cities (Compernolle et al., 2018 [83]), which is most likely related to the a priori profiles used within the operational retrieval that do not reflect well the NO$_2$ peak close to ground. For the Middle East region, the impact of the a priori profile is less critical, as surface albedo is generally high and cloud fractions are generally low. Thus, we expect no such bias, and consider a relative uncertainty of 30% for the tropospheric column. Other uncertainties must be taken into account: the transition from NO$_2$ TROPOMI columns to NO$_x$ emissions requires parameters which appear in Equation (2) and Equation (3). For both zonal and meridional wind components, we assume an uncertainty of wind module. Uncertainties are generally of about 1 m/s for components taken at precise altitudes (Coburn et al., 2019 [84]— Beirle et al., 2019 [15]). Here, we assume an uncertainty of 3 m/s for both zonal and meridional wind components. For [OH], the analysis of different methods conducted by Huijnen et al., 2019 [85] showed smaller differences for low latitudes than for extratropics, but still significant. We thus take a relative uncertainty of 30% for OH concentration. For the reaction rate $k_{\text{rate}}\text{mean}$, the value of the corresponding relative uncertainty has been estimated by Burkholder et al., 2020 [30]. Because the sensitivity test conducted Finally, we use the sensitivity tests performed in Section 4.3 shows that changing the temperature vertically only changes the results by 2-3%, and because vertical temperature gradients are much stronger than horizontal temperature gradients, then the uncertainty related to the horizontal temperature field is small. Therefore, we neglect the impact of temperature on final uncertainty. As a consequence, the to assess the uncertainty associated with the choice of the vertical level. The cumulative effects on the final emissions of the three parameters studied, in particular the OH concentration, lead to a relative uncertainty that varies from month to month between 7 and 18%. The propagation of these different uncertainties on the monthly estimates of NO$_x$ emissions in Egypt leads to an expanded uncertainty between 40 and 44.17 and 51.5%. For lifetimes calculated with the EMG function fitting, the corresponding expanded uncertainty ranges between 18% and 79%.

We acknowledge the fact that our treatment of uncertainties is simplified there NO$_x$ is simplified. Many minor sinks highlighted in Section 3.1 are neglected in the calculations, and the corresponding uncertainty are not taken into account. Moreover, among the remaining sources of uncertainties. In particular, anthropogenic VOC emissions, which remove NO$_x$ from the atmosphere, compete with the oxidation by OH for the representation of NO$_x$ loss. These emissions are difficult to estimate and the corresponding sink is complex to model. Taking this reaction into account would a priori lead to a strengthening of the sink term and thus to an increase of the major ones are treated with fixed values for relative uncertainties, which leads to absolute uncertainties that are roughly proportional to monthly emissions. As a result, the confidence interval displayed on Figure is larger in summer than in winter (with a length of 6.0 kt in January 2020 and of 17.4 kt for July 2020), and the drop in emissions for winter 2019-2020 appears as a persistent feature of the model outputs. If this drop is realistic, then our top down model provides a method for improving national inventories. If it is not, then several assumptions of our model NO$_x$ emissions estimates. Other assumptions in the model are also simplifications. For instance, obtaining anthropogenic emissions by subtracting the average emissions over background cells assumes that the non-anthropogenic sources of NO$_x$ are similar inside and outside the mask, which is not true, since a large part of the mask cells correspond to croplands. For these cells, soil emissions may play a non-negligible role in the natural NO$_2$ budget. As a consequence, mean background emissions that are removed from NO$_x$ emissions estimates above mask cells might be under-estimated. Finally, the reliability of the data used can be questioned. For instance, because this drop-The representation of the wind is crucial to avoid creating artificial patterns in the transport term. The OH concentration, which is proportional to the intensity of the sink term, is also important. We have shown that OH concentrations are partially responsible for an important drop in NO$_x$ emissions in the winter of 2019/2020 that may be unreal in NO$_x$ emissions in the winter of 2019/2020 that may be unreal. Because this decrease is largely due to variations in OH concentrations provided by CAMS, whose reliability has been evaluated for Riyadh, then the transposability hypothesis between Riyadh and Egypt may be subject to wider discussion. A better understanding of OH levels in Egypt, supported by in situ measurements, might answer these questions and allow to improve our model, further discussion.

5 Conclusions

In this study, we investigated the potential of a top-down model of NO$_x$ emissions based on TROPOMI retrievals at high resolution over Egypt. The model is based on the study of a transport term and a sink term that requires different parameters to be calculated. Among those parameters, the concentration in OH, involved in the calculation of the NO$_2$ mixed lifetime, is of fundamental importance. The comparison between the two ways of calculating the lifetime of NO$_2$ shows that lifetimes derived from OH concentrations and NO$_2$ lifetimes derived from EMG function fittings of line density profiles shows that the OH concentration provided by CAMS data is reasonably reliable for the
country. Parameters are therefore taken in the first 200 m of the planetary boundary layer, because it is where OH shows the best consistency. However, the vertical sensitivity linked to this parameters remains high. Results illustrate the importance of the transport term at local scale, which is of the same order of magnitude as the sink term above large cities and industrial facilities; it ceases to be relevant only at the country’s scale scale of the whole country. The top-down model is able to characterise declines in human activities, whether they are due to restrictions during the COVID-19 pandemic or to Friday rest. It also estimates higher emissions during summer. These high emissions might may be interpreted by a higher consumption of electricity driven by air-conditioning during hot days, but it remains unclear whether this pattern clearly reproduces changes in human activity, in particular because the different emission inventories show different seasonals. These inventories also differ in the amount of total emissions: the average value for TROPOMI-derived NO\textsubscript{x} emissions is 25.0\% 7.0\% higher than CAMS-CAMS-GLOB-ANT\_v4.2 estimates. This discrepancy could be solved resolved by comparing the results of the model and inventory estimates to industrial production or electricity consumption data at the scale of countries or regions.

This study demonstrates the potential of TROPOMI data for evaluating NO\textsubscript{x} emissions in the EMME–Middle East region. More generally, it demonstrates the importance of the contribution of independent observation systems to overcome the weaknesses of emission inventories, provided that the local chemistry is well understood and modelled. The development of similar applications for different species is likely to allow a better monitoring of global anthropogenic emissions, therefore helping companies and countries to report their anthropogenic emissions of air pollutants and greenhouse gases as part of their strategies and obligations to tackle air pollution issues and climate change.

Data availability.
TROPOMI product: http://www.tropomi.eu/data-products/data-access
ERA5 reanalysis: https://cds.climate.copernicus.eu/cdsapp!/dataset/reanalysis-era5-pressure-levels-monthly-means
Oil and gas power plants: http://globalenergyobservatory.org/
Industrial facilities: https://www.industryabout.com
Flaring sites: https://eogdata.mines.edu/download_global_flare.html
CAMS-GLOB-ANT\_v4.2: https://permalink.aeris-data.fr/CAMS-GLOB-ANT
EDGARv5.0: https://edgar.jrc.ec.europa.eu/dataset_ap50

Competing interests. The authors declare that they have no conflict of interest.

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References


