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## Anthropogenic CO<sub>2</sub> emissions assessment of Nile Delta using XCO<sub>2</sub> and SIF data from OCO-2 satellite

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Supplementary material for this article is available [online](#)

### Abstract

We estimate CO<sub>2</sub> emissions from the Nile Delta region of Egypt, using over five years of column-averaged CO<sub>2</sub> dry air mole fraction (XCO<sub>2</sub>) data from the NASA's OCO-2 satellite. The Nile Delta has significant anthropogenic emissions of CO<sub>2</sub> from urban areas and irrigated farming. It is surrounded by the Sahara desert and the Mediterranean Sea, minimizing the confounding influence of CO<sub>2</sub> sources in surrounding areas. We compiled the observed spatial and temporal variations of XCO<sub>2</sub> in the Nile Delta region (XCO<sub>2,del</sub>), and found that values for XCO<sub>2,del</sub> were on average 1.1 ppm higher than XCO<sub>2,des</sub> (mean XCO<sub>2</sub> in desert area). We modelled the expected enhancements of XCO<sub>2</sub> over the Nile Delta based on two global CO<sub>2</sub> emission inventories, EDGAR and ODIAC. Modelled XCO<sub>2</sub> enhancements were much lower, indicating underestimation of CO<sub>2</sub> emissions in the Nile Delta region by mean factors of 4.5 and 3.4 for EDGAR and ODIAC, respectively. Furthermore, we captured a seasonal pattern of XCO<sub>2</sub> enhancement ( $\Delta$ XCO<sub>2</sub>), with significantly lower  $\Delta$ XCO<sub>2</sub> during the summer agriculture season in comparison to other seasons. Additionally, we used solar-induced fluorescence (SIF) measurement from OCO-2 to understand how the CO<sub>2</sub> emissions are related to agricultural activities. Finally, we estimated an average emission of CO<sub>2</sub> from the Nile Delta from 2014–2019 of 470 Mt CO<sub>2</sub>/year, about 1% of global anthropogenic emissions, which is significantly more than estimated hitherto.

## 1. Introduction

Our planet Earth has witnessed about 40% increase in atmospheric CO<sub>2</sub> concentrations since the pre-industrial age. This increase is attributed to anthropogenic activities (IPCC 2013), primarily from combustion of fossil fuels. Agricultural activities are important sources of CO<sub>2</sub> associated with combustion of fossil fuels by farm machinery, biomass burning, and emissions from soil. Soil emissions can be especially high from intensively farmed, irrigated carbon rich soils in river deltas (Telmer and Veizer 1999, Hannam *et al* 2019).

Most global estimates of CO<sub>2</sub> emissions are provided by state-of-the-art emissions inventories

which employ 'bottom-up' methods to quantify emissions, using human activity data and emission factors (Oda and Maksyutov 2011, Janssens–Maenhout *et al* 2019, Peylin *et al* 2013, Boden *et al* 2017, Oda *et al* 2018) as per the directions of IPCC (Intergovernmental Panel on Climate Change). These models have not been extensively tested for intensively farmed areas, like river deltas. Bottom-up methods use energy consumption data sets, such as fossil fuel consumption along with fuel purity, mix, efficiency, etc (see Boden *et al* 2017, Quéré *et al* 2018). There are discrepancies and uncertainties in the reported datasets on national scales (Miller *et al* 2013, Hutyrá *et al* 2014, Liu *et al* 2015), especially for developing countries (Xue and Ren 2012). These discrepancies

can result in ~40% to ~100% uncertainty in emission estimations at the country and the local scales, respectively (Peylin *et al* 2013, Wang *et al* 2013).

Effective monitoring of greenhouse gas emissions is also essential to keep track of humanities long-term emission reduction goals for keeping the global warming below 2 °C compared to pre-industrial levels, as defined in the Paris agreement. Ground-based or airborne monitoring of these emissions can be a tedious and expensive task because of the spatial distribution of various anthropogenic emission sources (Mckain *et al* 2012, Chang *et al* 2014, Lindenmaier *et al* 2014, Chen *et al* 2016, 2020, Viatte *et al* 2017, Luther *et al* 2019). The most promising way to monitor these emissions with consistent precision at different spatial scales is the use of satellite-based measurements (Wang *et al* 2018).

Satellites like SCIAMACHY (Scanning Imaging Absorption Spectrometer for Atmospheric Cartography) and GOSAT (Greenhouse Gases Observing Satellite) have been previously used to detect and analyze anthropogenic CO<sub>2</sub> signatures (Yokota *et al* 2009, Kort *et al* 2012, Schneising *et al* 2013, Janardanan *et al* 2016). These studies generally suggested use of satellite-based observations with better spatial resolution to improve the detection of anthropogenic CO<sub>2</sub> emissions as the enhancement of CO<sub>2</sub> mixing ratio due to localized sources are a small fraction of the background values, thus making it a challenging task for low spatial resolution sensors to detect (Bovensmann *et al* 2010).

Here we use the observations from NASA's OCO-2 (Orbiting Carbon Observatory-2) satellite as a primary monitoring tool to assess the CO<sub>2</sub> emissions in the Nile Delta, one of the most important, intensively farmed regions in the world. The OCO-2 measures column-averaged dry air mole fraction of CO<sub>2</sub> (XCO<sub>2</sub>) with high spatial resolution (~3 km<sup>2</sup>) (Crisp *et al* 2017) and precision (~1 ppm). The megacity Cairo lies just to the south of the Delta. Both are surrounded by desert in three directions, except for the narrow Nile valley leading southward, with the Mediterranean in the north. OCO-2 tracks are situated over and nearby this area making it an excellent target for quantifying emissions using OCO-2 data. Our work builds on previous studies to detect localized emission sources (Yokota *et al* 2009, de Gouw *et al* 2014, Hakkarainen *et al* 2016, 2019, Kuze *et al* 2016, Nassar *et al* 2017, Schwandner *et al* 2017, Ye *et al* 2017, Wang *et al* 2018, Labzovskii *et al* 2019, Reuter *et al* 2019, Zheng *et al* 2019) using OCO-2 data.

We examine the spatiotemporal gradients of XCO<sub>2</sub> between the Nile Delta and surrounding desert over a 5 year period, and compared the observed enhancements to values modeled using global emission inventories. We find that the two investigated inventories underestimate CO<sub>2</sub> emission rates in the region by large factors with significant seasonality during the winter and summer agriculture season. We

conclude that intensively-farmed deltaic areas may be significantly more important in global CO<sub>2</sub> emissions than appreciated hitherto.

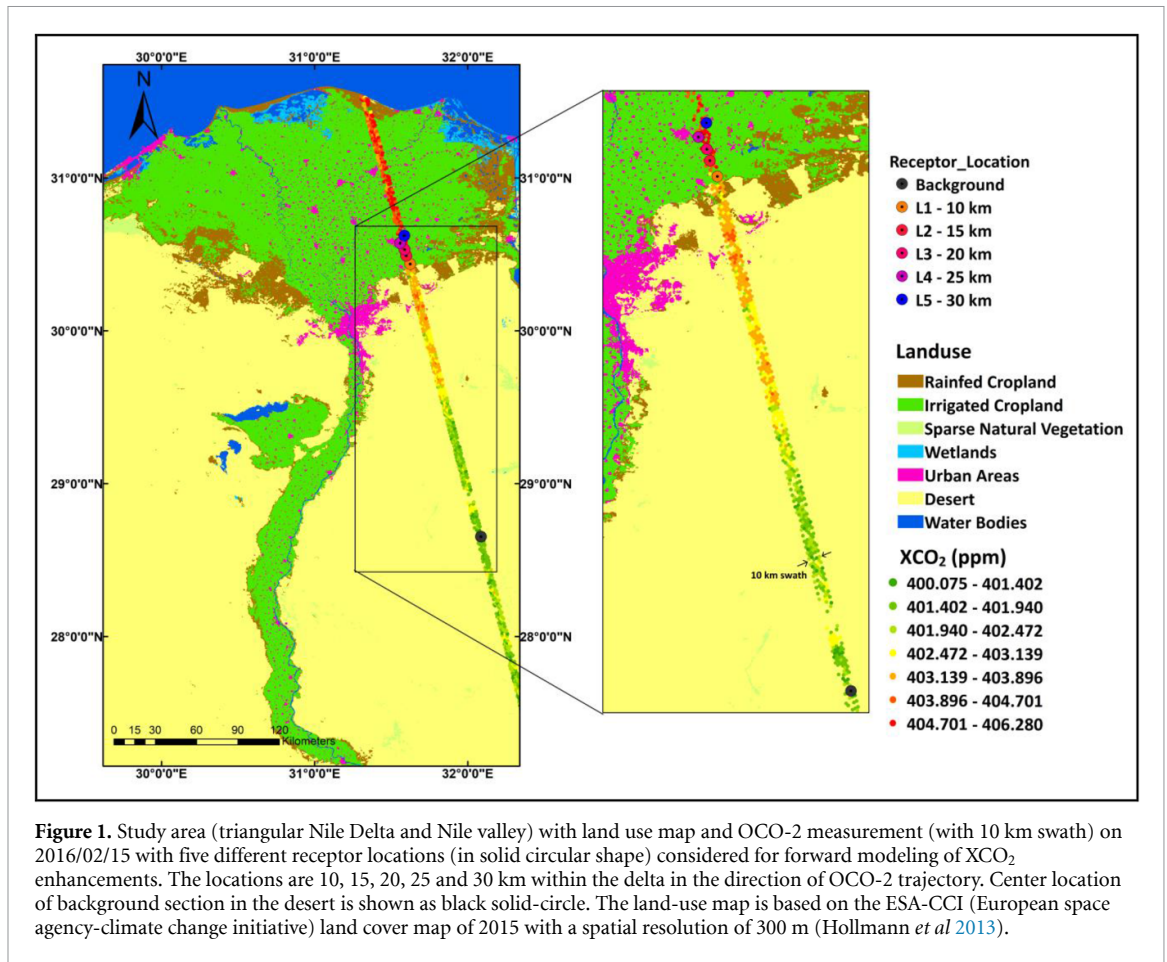
## 2. Data and methods

### 2.1. Study area

The Nile Delta is considered to be one of the oldest cultivated areas in the world, having been continuously cultivated since 3000 B.C. (Negm *et al* 2017). It is a triangular shaped, tide-dominated delta (figure 1(a)) occupying about 2.5% of Egypt's area (~25 000 km<sup>2</sup>) and giving shelter to about 60% of its population (Zeydan 2005, Negm *et al* 2017). Moreover, 96% of Egypt's population is concentrated around Nile Delta (north of Cairo) along with Nile valley (south of Cairo) (Abd El-Kawy *et al* 2011). Since the construction of Aswan High Dam in 1970, the Nile Delta has received less input of nutrients and sediments from the river floods. This shift has resulted in intensive use of fertilizers for agriculture, thereby degrading the soil quality and potentially leading to loss of soil organic matter (Negm *et al* 2017). Furthermore, about 75 000 ha of fertile agricultural land was lost to urbanization within the Nile Delta between 1992 and 2015 (Radwan *et al* 2019). Nevertheless, the Nile Delta produces two-thirds of Egyptian crops (FAOSTAT 2019, [www.fao.org/faostat/en/](http://www.fao.org/faostat/en/)) with its still rich and fertile soil allowing two or more crops over the year (Osama *et al* 2017). Two main growing season in Nile Delta is the winter growing season (peak in January/February) and summer season (peak in July/August). Important winter crops are wheat, vegetable and clover crops, whereas in summer—maize, rice and cotton are extensively grown (El-Beheiry *et al* 2015). The Nile Delta today is mostly characterized by artificially irrigated agriculture and spreaded urban settlements (figure 1(a)), with minimal natural sources or sinks of CO<sub>2</sub>.

### 2.2. OCO-2 satellite data

We used five years of XCO<sub>2</sub> data from NASA's OCO-2 satellite. The OCO-2 satellite was designed to accurately measure XCO<sub>2</sub> at kilometer-scale spatial resolution around 13:30 local time with a repeat cycle of 16 d (Crisp 2015) and 10 km swath (Bhattacharjee and Chen 2020). The satellite uses the Atmospheric CO<sub>2</sub> Observations from Space (ACOS) algorithm (Wunch *et al* 2011a, 2011b, Crisp *et al* 2012, O'Dell *et al* 2012). We used the high quality measurement soundings of the latest version of the OCO-2 Level 2 Version 9 Lite product from September 2014 to July 2019 provided by the NASA's Jet Propulsion Laboratory website (<https://co2.jpl.nasa.gov/build/?dataset=OCO2L2Stdv8&product=FULL#download>). The measurement soundings are obtained using an improved bias-correction approach and are pre- and post-filtered for potentially unreliably measurements (O'Dell *et al* 2018). The downloaded measurement data



**Figure 1.** Study area (triangular Nile Delta and Nile valley) with land use map and OCO-2 measurement (with 10 km swath) on 2016/02/15 with five different receptor locations (in solid circular shape) considered for forward modeling of XCO<sub>2</sub> enhancements. The locations are 10, 15, 20, 25 and 30 km within the delta in the direction of OCO-2 trajectory. Center location of background section in the desert is shown as black solid-circle. The land-use map is based on the ESA-CCI (European space agency-climate change initiative) land cover map of 2015 with a spatial resolution of 300 m (Hollmann *et al* 2013).

also contain surface wind velocity information at each measurement sounding taken from the NASA's GEOS5-FP-IT (Goddard Earth Observing System Version 5-Forward Processing for Instrument Teams). Each trajectory of OCO-2 measurement covers both the delta and desert area (figure S1 (available online at [stacks.iop.org/ERL/15/095010/mmedia](https://stacks.iop.org/ERL/15/095010/mmedia))), which enables us to quantify the spatial (delta-desert) XCO<sub>2</sub> gradient.

In addition to XCO<sub>2</sub> data, we also employed OCO-2's SIF (Solar-induced fluorescence) data. SIF is a signal emitted from plants/crops during photosynthesis, thus indicating photosynthetic activities (Sun *et al* 2017, Shekhar *et al* 2019, Castro *et al* 2020). OCO-2 measures SIF at two wavelengths, 757 nm and 771 nm (Frankenberg *et al* 2014, 2015), based on the infilling of the Fraunhofer lines (Frankenberg *et al* 2011). We used SIF (measured at 757 nm) to help understand how the CO<sub>2</sub> emissions from the Nile Delta were related to agricultural activities.

### 2.3. Emission inventories

We computed the expected values of XCO<sub>2</sub> over the Delta, compared to surrounding desert areas, using two CO<sub>2</sub> emission inventories, EDGAR (Emissions Database for Global Atmospheric Research) and ODIAC (Open-source Data Inventory for Anthropogenic CO<sub>2</sub>). Both are constructed based on the

IPCC methodology. The latest version of EDGAR v5.0 (Crippa *et al* 2020) was recently made available. It provides global annual CO<sub>2</sub> emissions at 0.1° × 0.1° spatial resolution until 2018. EDGAR emissions are calculated using a bottom-up methodology: the inventory scales activity data, which is based on international annual statistics with the best-available emission factors. Then, it uses the monthly share and spatial proxies such as population and road density to downscale the national or state-level data to a finer spatial resolution. We used the CO<sub>2</sub>\_excl\_short-cycle\_org\_C variable of the EDGAR v5.0 which includes total CO<sub>2</sub> emissions (in kgCO<sub>2</sub> (m<sup>2</sup> s)<sup>-1</sup>) from the considered fossil fuel sources such as fossil fuel combustion, various non-metallic mineral processes like cement production, various metallic and chemical production processes, urea productions and agricultural liming processes. The EDGAR v5.0 dataset was downloaded from the European Commission's Joint Research Centre-EDGAR website ([https://edgar.jrc.ec.europa.eu/overview.php?v=50\\_GHG](https://edgar.jrc.ec.europa.eu/overview.php?v=50_GHG)). Mean EDGAR emissions over the Nile Delta from 2014–2018 was 108 Mt CO<sub>2</sub>/year.

The latest ODIAC v2019 provides monthly CO<sub>2</sub> emissions (in tons of Carbon/(km<sup>2</sup>-month)) from fossil fuel combustions at a much higher spatial resolution of 1 km × 1 km (GeoTIFF file format) till the end of 2018 (Oda *et al* 2018).

A hybrid approach is implemented to construct the ODIAC emission inventory, which integrates national emission estimates produced by CDIAC (Carbon Dioxide Information Analysis Center, Andres *et al* 1996) and nightlight data with individual power plant emissions/location profiles (Oda and Maksyutov 2011). The ODIAC v2019 dataset was downloaded from the CGER-NIES (Center for Global Environmental Research, National Institute for Environmental Studies) website ([http://db.cger.nies.go.jp/dataset/ODIAC/DL\\_odiacc2019.html](http://db.cger.nies.go.jp/dataset/ODIAC/DL_odiacc2019.html)).

Since neither the EDGAR nor the ODIAC dataset was fully available for the time period of this study (September 2014–July 2019), we used the latest available data point for each inventory for the remaining time period, i.e. the EDGAR and ODIAC estimates of 2018 were used for the year of 2019. It is important to note that neither of these two emission inventories include CO<sub>2</sub> emission from agricultural soil degradation. Both EDGAR and ODIAC emission datasets are widely used by the international carbon cycle research community (Quéré *et al* 2018). Mean ODIAC emissions over the Nile Delta from September 2014–July 2019 was 136.5 Mt CO<sub>2</sub>/year. Figure S3 shows the CO<sub>2</sub> emission map for Nile Delta as per EDGAR and ODIAC.

## 2.4. Modelling methods

To simulate the enhancement of XCO<sub>2</sub> values from the local CO<sub>2</sub> emissions sources we employed a forward model based on the emission inventories and an atmospheric transport model.

For any location, the XCO<sub>2</sub> can be modelled as the sum of the initial background concentration and the enhancement due to the upstream sources and sinks (Gerbig *et al* 2003, Hu *et al* 2018a). Equations (1) and (2) describe our calculations:

$$XCO_{2,fm} = XCO_{2,bkg} + XCO_{2,enh} \quad (1)$$

$$XCO_{2,enh} = \sum_{i=1}^{N_x} \sum_{j=1}^{N_y} [footprint(x_i, y_j) \times emission(x_i, y_j)] \quad (2)$$

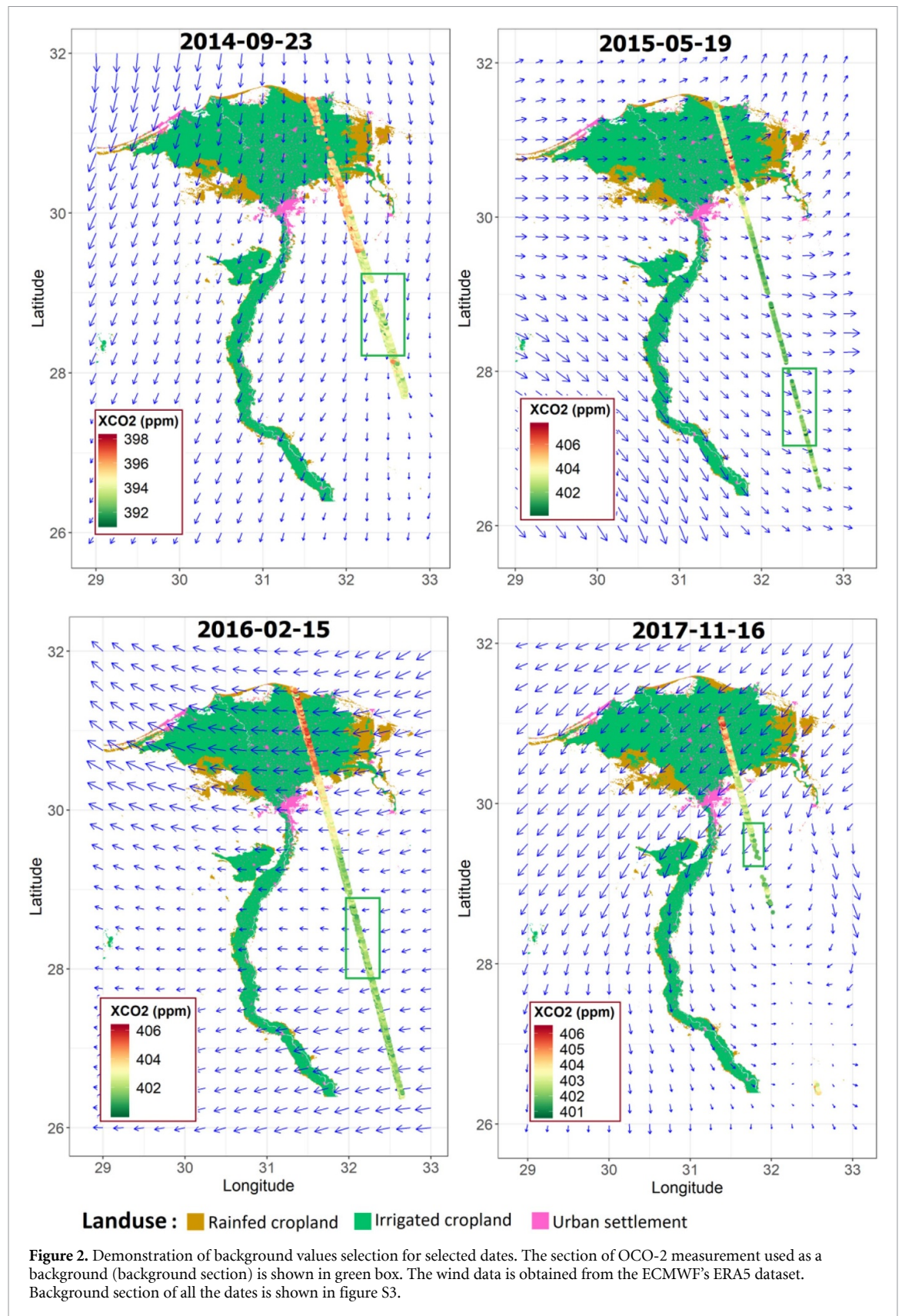
where, XCO<sub>2,fm</sub> is the forward modelled concentration for any location, XCO<sub>2,bkg</sub> is an initial background XCO<sub>2</sub> value and XCO<sub>2,enh</sub> is the enhancement due to upstream CO<sub>2</sub> emission sources. The ‘footprint’ is obtained from an atmospheric transport model and the ‘emission’ data are obtained from the emission inventories (more information below). Therefore, XCO<sub>2,enh</sub> is the summation of the enhancements caused by all locations (x<sub>i</sub>, y<sub>j</sub>): i = 1, 2, ... N<sub>x</sub>; j = 1, 2, ... N<sub>y</sub>, in the study domain containing the Nile Delta and valley (Latitude:[26, 32]; Longitude:[29, 33]). For the case of simplicity here, we have neglected the effect of sinks on XCO<sub>2,enh</sub> as the Nile Delta

is characterized by minimal or no natural vegetation, and net emissions are plainly positive. To study the XCO<sub>2</sub> enhancement in the Nile Delta we applied a local regression smoothing (LOESS, Jacoby 2000) with loess parameter (span) of 0.15 to the XCO<sub>2</sub> concentrations along the OCO-2 trajectory (latitude-wise) for each measurement day, and these locally regressed XCO<sub>2</sub> (XCO<sub>2,0</sub>) values were used for further calculation.

Since OCO-2 measures XCO<sub>2</sub> along a narrow swath of 10 km (figure 1), selection of background concentration (XCO<sub>2,bkg</sub>) can be tedious. In this study, we leveraged the wind data from ECMWF’s ERA5 dataset (Copernicus Climate Change Service (C3S) 2017) to select a particular section of one degree latitude range (background section) of XCO<sub>2</sub> values in the desert that did not pass over the Nile Delta as XCO<sub>2,bkg</sub>. The selection of ‘background section’ was semi-automated for all the 32 dates. The semi-automated process involved visual inspection and automated selection of the background section. The detailed procedure is given in supplementary section S1. Figure 2 illustrates the background section for few dates. For example on 2014-09-23, the wind direction is north, contaminating the proximate observations with CO<sub>2</sub> from the Delta, so we selected the lower section of OCO-2 measurements (shown in green box in figure 2), where the wind was coming from the east side. Similarly, for 2015-05-19, the selected section does not have any influence from Nile Delta and minimal influence from the Nile valley. The mean of the locally smoothed XCO<sub>2</sub> values within this section was taken as a XCO<sub>2,bkg</sub> for each day. The selected background section for all the other dates is shown in figure S3.

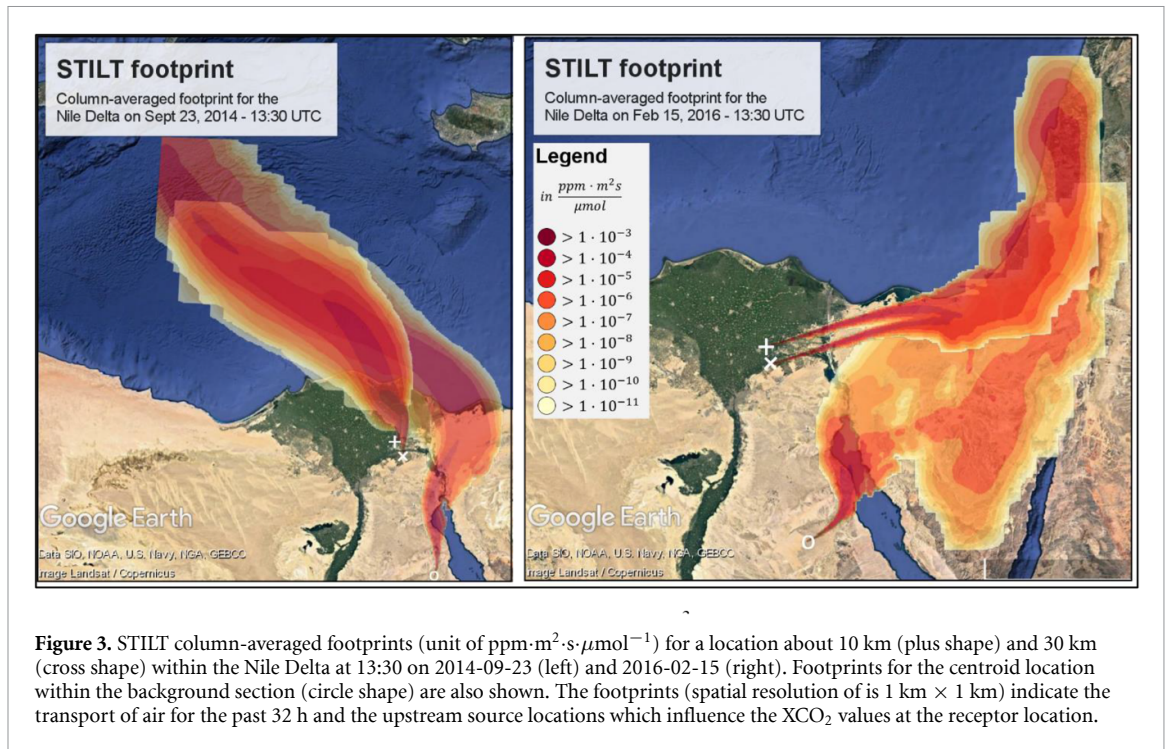
Calculation of XCO<sub>2,enh</sub> requires footprint information from the atmospheric transport model, and local emission data. The geographic distributions of emissions were adopted from EDGAR and ODIAC (section 2.2). Here, we simulated the footprints using the STILT (Stochastic Time-Inverted Lagrangian Transport) model that is based on HYSPLIT model (Lin *et al* 2003, Fasoli *et al* 2018, Wu *et al* 2018). The STILT model simulates convective and diffusive air transport patterns by releasing a certain amount of particles (N) from a receptor (i.e. an observation location in this case) and tracking the particles backwards in time (Hu *et al* 2018b). Thus, the STILT footprints are equivalent to the sensitivity of XCO<sub>2</sub> (unit of ppm·m<sup>2</sup>·s·μmol<sup>-1</sup>) at the receptor location with respect to changes in surface flux (Gerbig *et al* 2003).

Our STILT simulation was based on ERA5 meteorological data and we chose a backward time of 32 h and N = 500 particles and 11 vertical levels for each receptor location. Figure 3 shows column averaged STILT footprints for 2014-09-23 and 2016-02-15 at 13:30 (local overpass time of OCO-2). Finally for each OCO-2 trajectory we chose 5 receptor locations



within the Nile Delta at a distance of 10, 15, 20, 25 and 30 km along the OCO-2 trajectory to calculate  $XCO_{2, fm}$  (in ppm), which is the accumulated  $CO_2$  enhancement occurring over the 32 h back trajectory at the receptor location due to emissions from the

upstream sources. Figure 1 shows the receptor locations along the delta and within the background section for OCO-2 measurements on 2016-02-15. It is also evident from figure 3 that the footprints of the background receptor are not influenced by the Nile



**Figure 3.** STILT column-averaged footprints (unit of  $\text{ppm}\cdot\text{m}^2\cdot\text{s}\cdot\mu\text{mol}^{-1}$ ) for a location about 10 km (plus shape) and 30 km (cross shape) within the Nile Delta at 13:30 on 2014-09-23 (left) and 2016-02-15 (right). Footprints for the centroid location within the background section (circle shape) are also shown. The footprints (spatial resolution of is  $1\text{ km} \times 1\text{ km}$ ) indicate the transport of air for the past 32 h and the upstream source locations which influence the  $\text{XCO}_2$  values at the receptor location.

Delta area. Ultimately we compared the  $\text{XCO}_{2,\text{fm}}$  with the LOESS smoothed OCO-2's  $\text{XCO}_2$  value at the receptor locations ( $\text{XCO}_{2,0}$ ) for each OCO-2 trajectory over study period (2014–2019) to estimate  $\text{CO}_2$  emissions based on the two inventory data.

### 3. Results and discussions

#### 3.1. Spatiotemporal variation of $\text{XCO}_2$ and SIF

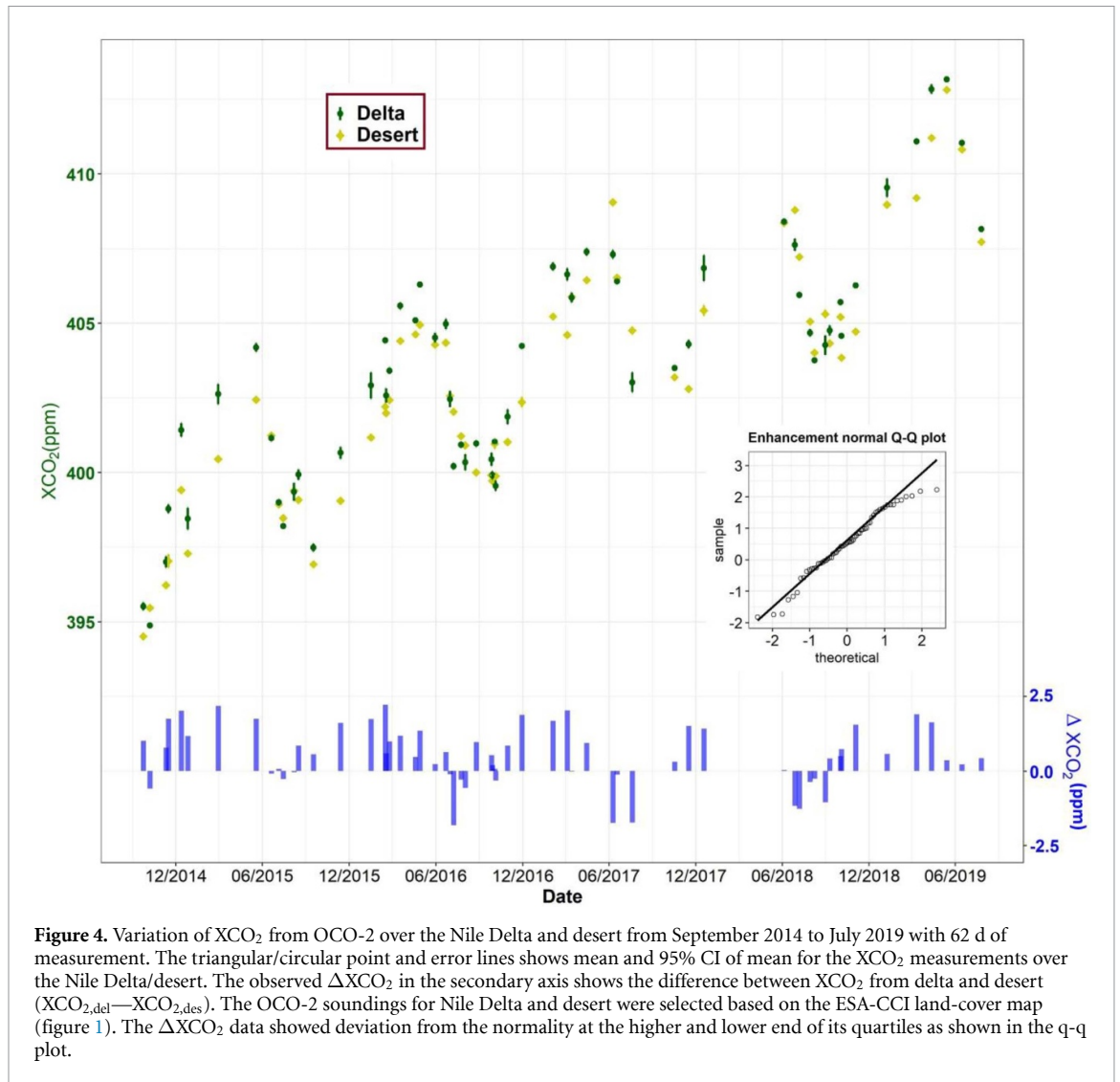
We studied 62 d of OCO-2 measurements over the Nile Delta and desert area spanning five years of observations. We observed the expected steady seasonal cycle in  $\text{XCO}_2$  concentration over the delta ( $\text{XCO}_{2,\text{del}}$ ) and the desert ( $\text{XCO}_{2,\text{des}}$ ) from 2014 to 2019 (figure 4). About 80% of the measurements showed a mean  $\text{XCO}_{2,\text{del}}$  of 1.11 (0.83,1.21) (95% confidence interval) ppm higher than mean  $\text{XCO}_{2,\text{des}}$  with a maximum  $\Delta\text{XCO}_2$  ( $\text{XCO}_{2,\text{del}} - \text{XCO}_{2,\text{des}}$ ), of 2.2 ppm. Expectedly, consistent higher SIF values in the Nile Delta indicated the agricultural production (figure S4), with high SIF values during the months of peak of winter growing season (DJF) and summer growing season (JJA), but the latter season showed significantly lower  $\Delta\text{XCO}_2$  values (figure 5). This seasonal pattern of  $\Delta\text{XCO}_2$  can be attributed to the river flow dynamics and crops grown in the winter and summer season. The delta receives sediment and carbon-rich water during the winter season from the Aswan high dam (El Gamal and Zaki 2017), which is recycled and also used in the summer season. The emissions from newly arrived carbon-rich soil (carbon source) could result in high  $\Delta\text{XCO}_2$ . However in summer, high photosynthetic activity of well-irrigated maize and rice during the mid-day could be

a significant carbon sink (Rana *et al* 2016, She *et al* 2017) with reduced  $\text{CO}_2$  emission from soil, thereby resulting in lower  $\text{XCO}_2$  values in the delta. A detailed study combined with cropping pattern and river flow dynamics could give insight that is more accurate. On average higher SIF values correlated with higher  $\text{XCO}_2$ , which might not be expected for forest, but because of all the fossil fuel and soil  $\text{CO}_2$  emissions associated with the farming and irrigation in the Nile Delta (figure 5 and S5).

The OCO-2 clearly captured the latitudinal variation of  $\text{XCO}_2$  concentrations along its trajectory as depicted in figure 6. Transportation of  $\text{CO}_2$  plumes from emission sources in the delta region including Cairo city and Nile valley by the wind resulted in comparatively high  $\text{XCO}_2$  values in the downwind desert area. For example, on 2015-05-19 the  $\text{CO}_2$  emissions from Cairo results in as much as 3 ppm higher  $\text{XCO}_2$  values in the downwind desert area compared to the southern desert, with minimum influence from the Nile Delta or valley (figure 6). Furthermore, emissions from the Nile valley clearly resulted in elevated  $\text{XCO}_2$  values in the downwind desert area, for example on 2018-11-03 (figure 6, latitude:  $\sim 26.5$  deg.). Such wind transport of  $\text{CO}_2$  plume resulted in high  $\text{XCO}_2$  values in the desert region. Thus, OCO-2's  $\text{XCO}_2$  measurement clearly demonstrates the capability to measure local enhancement in  $\text{XCO}_2$  values.

#### 3.2. Forward modeling of emission inventories

Out of the 62 d of OCO-2 measurements, many days had sparse measurements over the Nile Delta and desert area, making it difficult to select background  $\text{XCO}_2$  values. Therefore, before performing the forward modeling of emission inventories to calculate



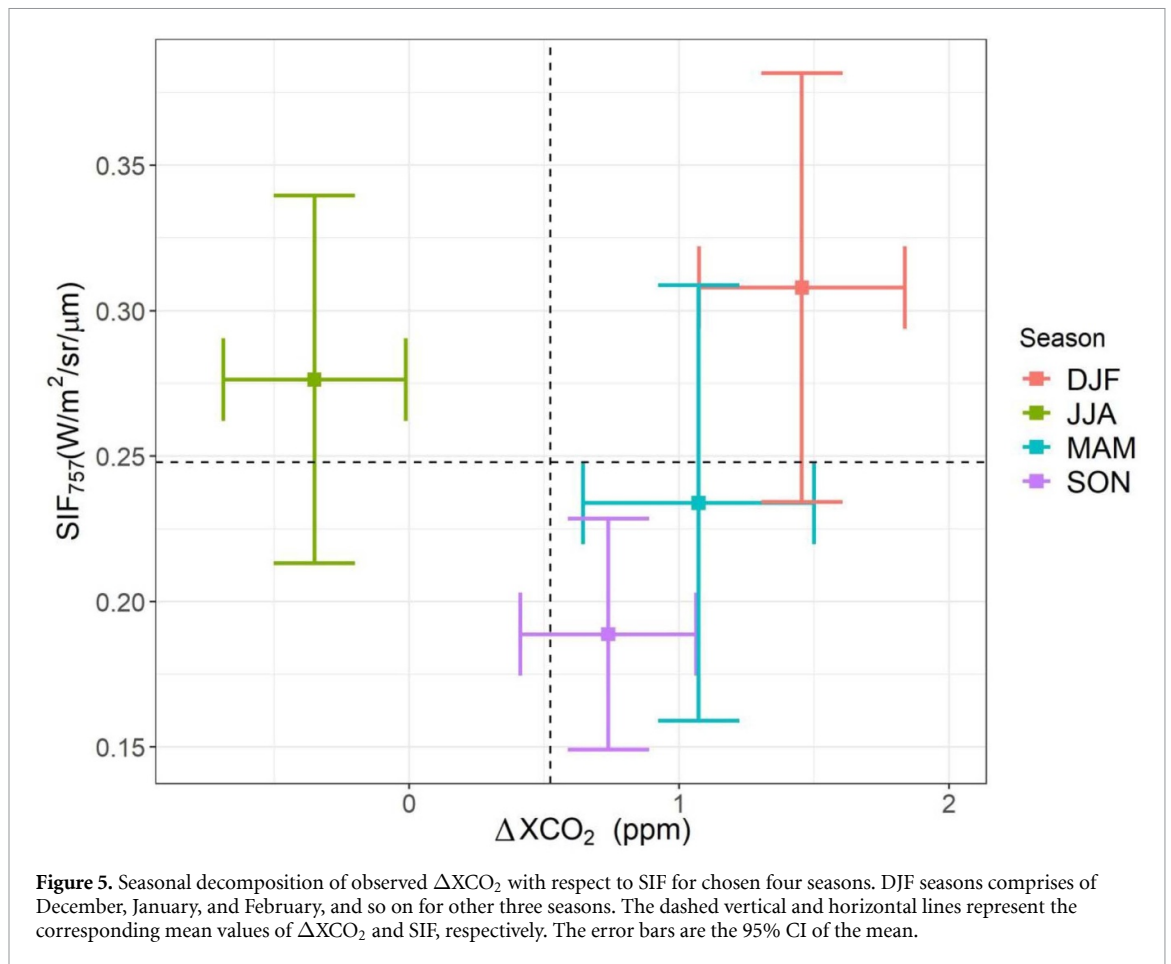
**Figure 4.** Variation of  $XCO_2$  from OCO-2 over the Nile Delta and desert from September 2014 to July 2019 with 62 d of measurement. The triangular/circular point and error lines shows mean and 95% CI of mean for the  $XCO_2$  measurements over the Nile Delta/desert. The observed  $\Delta XCO_2$  in the secondary axis shows the difference between  $XCO_2$  from delta and desert ( $XCO_{2,del} - XCO_{2,des}$ ). The OCO-2 soundings for Nile Delta and desert were selected based on the ESA-CCI land-cover map (figure 1). The  $\Delta XCO_2$  data showed deviation from the normality at the higher and lower end of its quartiles as shown in the q-q plot.

$XCO_{2,m}$ , we applied a threshold criteria of minimum 100 and 200 measurements over the Nile Delta and desert area, respectively. Finally, 32 d satisfied the above criteria. Correspondingly, we performed forward modeling calculations on 5 locations at 32 different dates from 2014 to 2019. Two out of 32 d (2017-06-09 and 2018-07-07) showed consistently higher measurement values in the desert area resulting in higher  $XCO_{2,bkg}$  values compared to the  $XCO_{2,O}$  values at the receptor locations. These two dates occur during the peak of summer growing season and might indicate the agricultural crops grown (e.g. maize) in summer as a  $CO_2$  sink.

For all 32 dates at 5 locations (total 160 receptor locations), the observed enhancements ( $XCO_{2,O} - XCO_{2,bkg}$ ) averaged 1.21 (1.05, 1.36) ppm. The calculated enhancements were much lower, 0.27 (0.23, 0.32) ppm and 0.36 (0.31, 0.43) ppm based on EDGAR and ODIAC, respectively (figure 7). Very prominent enhancements of as high as 1.7 ppm and 4 ppm by EDGAR and ODIAC, respectively were obtained for receptor location in the Cairo city (figure 7).

Over the 32 d of study, 23 d showed underestimation of modelled enhancement (figure 8), which indicates high underestimation of  $CO_2$  emission by the emission inventories. Our calculations indicate an underestimation by a mean emission factor (MEF) (95% confidence interval) of 4.53 (4.34, 4.68) and 3.36 (3.19, 3.45) (calculated as a ratio of the mean observed enhancement over all the days, divided by the mean modelled enhancement for all days, and bootstrapped) for EDGAR and ODIAC, respectively. Based on these calculated MEFs we also estimated the  $CO_2$  emissions from the Nile Delta based on scaling up the two emission inventories. Our estimates of mean  $CO_2$  emission are about 489 Mt  $CO_2$ /year and 457 Mt  $CO_2$ /year based on EDGAR and ODIAC inventory over the study period (September 2014–July 2019).

Our estimate compares relatively well with recent  $CO_2$  emissions of about 1500 Mt  $CO_2$ /year estimated from Yangtze River Delta in 2013 based on remote sensing (nighttime light) and statistical data (socioeconomic indicators) by Zhou *et al* (2019) as shown in table 1. The Yangtze River Delta is



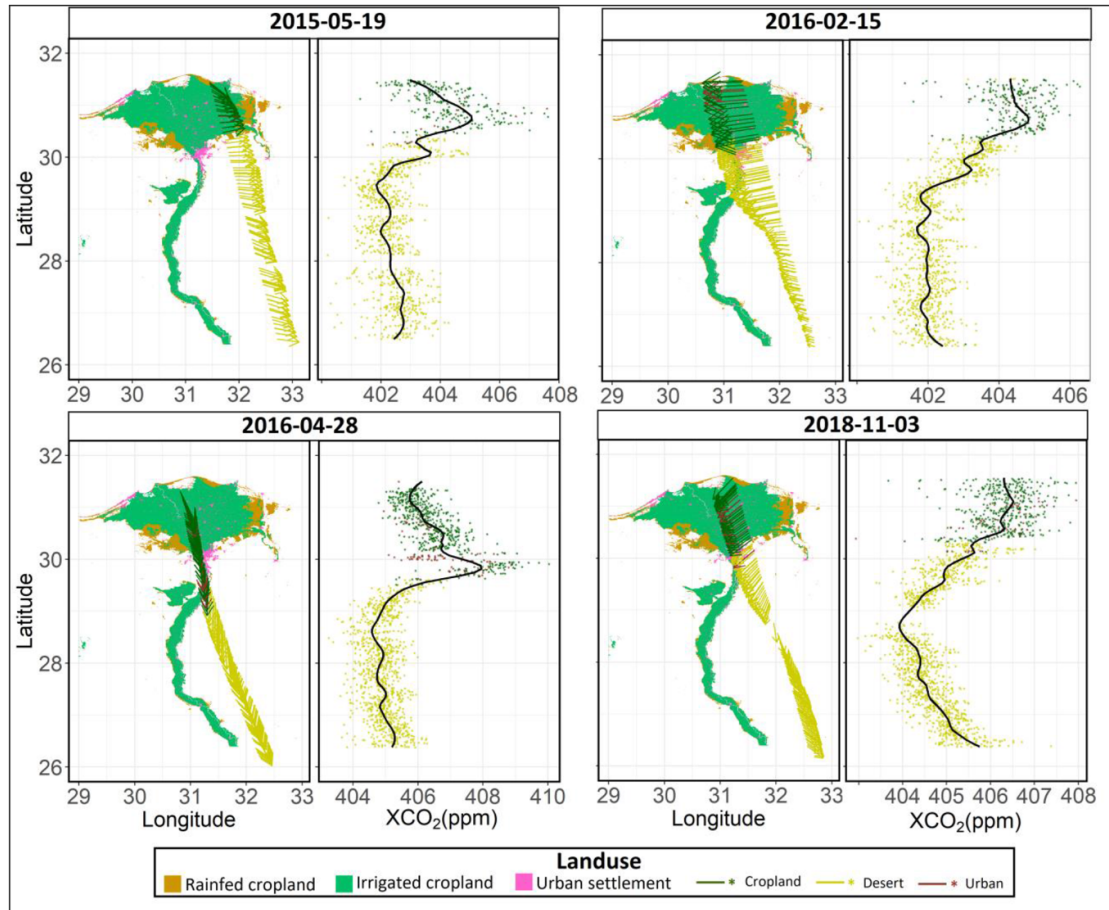
about 4 times larger than Nile Delta and is similarly characterized by intense urbanization and agricultural activity. However, our emissions estimates are quite high as compared to values obtained for the Pearl River Delta (table 1). Xu *et al* (2018) used urbanization indicators (like land, population and economic urbanization) to estimate carbon emissions in Pearl River Delta and also highlighted uncertainties in emission estimates due to selection of indicators (Peng *et al* 2017). None of the above studies included emissions from exploited/degrading carbon-rich agriculture soils, which may be a significant source in Nile Delta.

Uncertainties in  $CO_2$  emission inventories have been reported for developing countries, e.g. India and China (Guan *et al* 2012, Xue and Ren 2012, Janardanan *et al* 2016), and have mostly been attributed to uncertainties in the national level energy statistics and human activity data used to construct inventory data sets. Furthermore, the plot of  $\Delta XCO_2$  and SIF (indication of agriculture activity) in figures 5 and S5, clearly shows seasonal differences, especially for the two main growing season (winter and summer) with lower  $XCO_2$  for the Delta during the summer growing season. We also calculated the seasonal MEFs for each season and found that the factors for the JJA season (MEF  $\sim 1.05$ ) was significantly lower than MAM season (MEF  $\sim 5-8$ ), and SON season

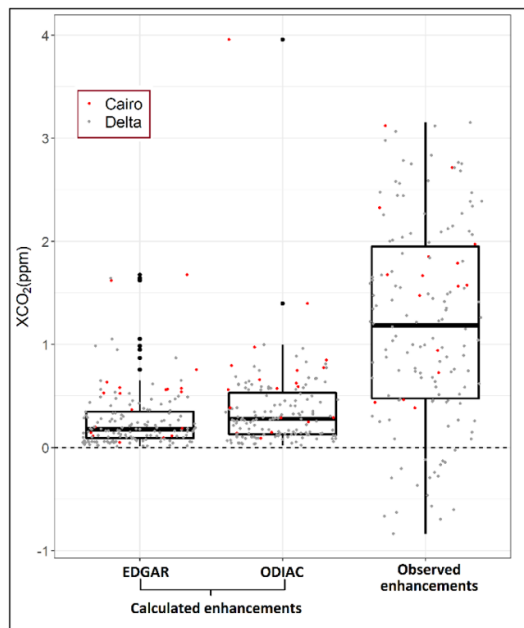
(MEF  $\sim 6-11$ ) (see table S1). However, for DJF season, only two OCO-2 measurements dates have sufficient observations over the Nile Delta and desert area for the emission assessments (2015-02-15 and 2017-02-03). There are very high differences between modelled and observed  $XCO_2$  enhancements ( $>2$  ppm in figure 8), which resulted in very high MEF ( $\sim 30$  to 50, see table S1), which may be biased due to less measurement samples. Nevertheless, such strong signal of seasonal variation of  $XCO_2$  can be attributed directly or indirectly to agricultural farming and irrigation activities associated with the sediment-rich river inflow that occurs during the winter season.

Direct agriculture emissions include tillage enhanced soil respiration and crop residue burning, whereas indirect emission comes from fossil fuel consumption by farm machineries for various inter-cultural activities like tilling, weeding, harvesting etc, and pumps for irrigation. In 2010, as per report from EAS (2014), irrigation pumps (mostly diesel pumps) were used in 75% of the cultivated area. El-Gafy and El-Bably (2016) measured an average emission of 6.55  $tCO_2/ha$  from on-farm diesel pumps used for irrigation.

Apart from agricultural activities, anthropogenic emissions from transportation, industrial and household use (combined energy statistics) of various distributed cities in the Nile Delta might also



**Figure 6.** Latitudinal variation of XCO<sub>2</sub> in the Nile Delta and desert and wind direction at 13:30 for a few selected dates. Black solid line is the local regression (loess) smoothed result with span = 0.15. The urban settlement in the lower end of the delta area is the Cairo megacity. The arrows represent the wind direction at the OCO-2 measurement points.

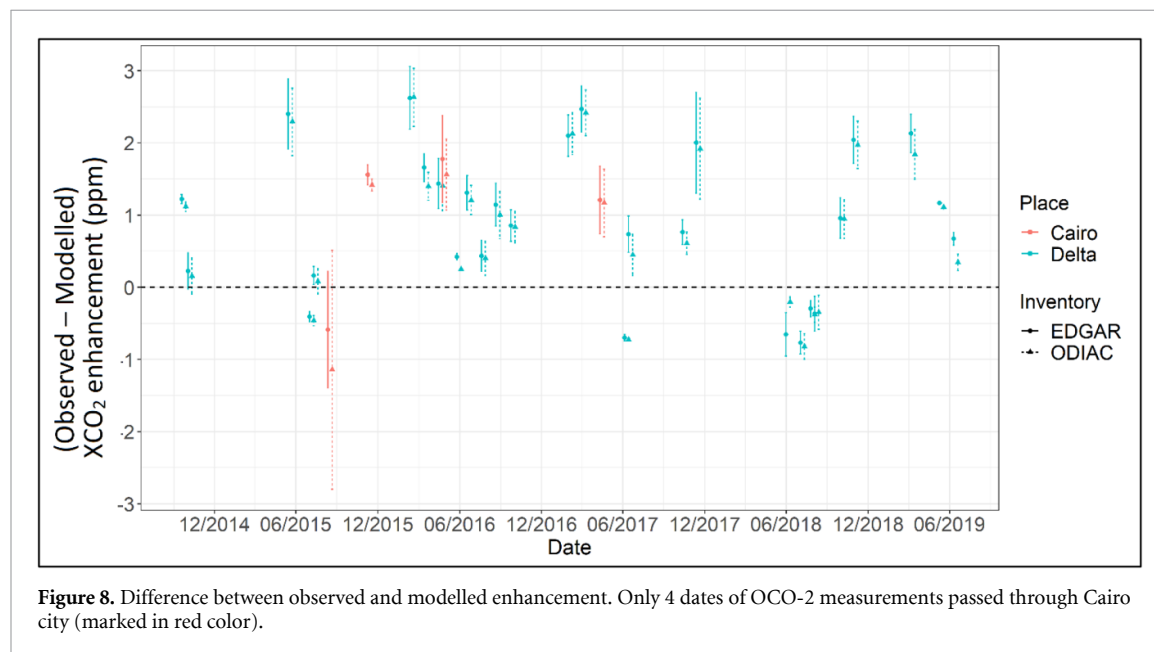


**Figure 7.** Comparison of modelled/calculated XCO<sub>2</sub> enhancements ( $XCO_{2,enh}$ ) using the EDGAR and the ODIAC emission inventories with the observed enhancements ( $XCO_{2,o} - XCO_{2,bkg}$ ) for receptor locations. Red dots represents receptor location in Cairo megacity, whereas grey dots are for receptor locations at Nile Delta excluding Cairo megacity. The horizontal line inside the box plots represent the median value.

**Table 1.** Comparison of CO<sub>2</sub> emissions from Nile Delta with other river delta.

	Nile Delta	Pearl River Delta	Yangtze River Delta
<b>Country</b>	Egypt	China	China
<b>Area (km<sup>2</sup>)</b>	~25 000	~40 000	~110 000
<b>Population (millions)</b>	39	56	96
<b>Year</b>	2014–2019	2014	2013
<b>Data</b>	OCO-2 XCO <sub>2</sub>	Urbanization indicators	City Panel remote sensing and statistical data
<b>Emission estimate (Mt CO<sub>2</sub>/year)</b>	473 <sup>a</sup>	151	1450
<b>Reference</b>	Present study	Xu <i>et al</i> (2018)	Zhou <i>et al</i> (2019)

<sup>a</sup>Average of CO<sub>2</sub> emission based on EDGAR and ODIAC data



**Figure 8.** Difference between observed and modelled enhancement. Only 4 dates of OCO-2 measurements passed through Cairo city (marked in red color).

be under-reported in these global emission inventories (Guan *et al* 2012). Gately and Hutyra (2017) argued that global emission inventories (like ODIAC) appear to deflect from spatial patterns in source activity in comparison to national scale inventories, and thus the former might not accurately represent anthropogenic emissions at subnational or urban scales. Our calculated delta emissions are based on yearly (for EDGAR) and monthly (ODIAC) average of CO<sub>2</sub> emissions, whereas the OCO-2 XCO<sub>2</sub> measurements are instantaneous, at 13:30 local time. This can result in under-/over-estimation of calculated enhancements as CO<sub>2</sub> emissions vary diurnally, weekly and seasonally, especially for urban areas. Burri *et al* (2009) measured CO<sub>2</sub> fluxes using the eddy covariance method at the University of Cairo and showed that the CO<sub>2</sub> fluxes have a significant diurnal and weekly variation, with peak CO<sub>2</sub> flux occurring between 14:00 and 16:00 and minimum flux on Friday (rest day due to Muslim prayer day on Friday). In our study, ODIAC performed a little better compared to EDGAR, as the former gives monthly average estimates and thus has the capability to capture the seasonal variability of CO<sub>2</sub> emissions, which cannot be implied for the latter.

## 4. Conclusions

Our study assesses CO<sub>2</sub> emissions from the Nile Delta, which is particularly characterized by anthropogenic activities such as agriculture and urbanization, using the OCO-2 satellite observations of atmospheric CO<sub>2</sub> concentrations. We found that emission inventory-based modelled XCO<sub>2</sub> values were significantly lower than the satellite-based observed XCO<sub>2</sub> values in the Nile Delta (factor 4.53 [4.34, 4.68] for EDGAR and 3.36 [3.19, 3.45] for ODIAC), indicating underestimation of CO<sub>2</sub> emissions reported in the emission inventory. We combined XCO<sub>2</sub> data with SIF to relate CO<sub>2</sub> emissions from agricultural production in the Nile Delta. Our emission estimate for the Nile Delta was about 1% of the global anthropogenic CO<sub>2</sub> emission and was comparable to the scaled CO<sub>2</sub> emissions estimated for the Yangtze River Delta considering the differences in size. Our results are particularly important in the context of uncertainties in national level reported energy/activity statistics for developing nations, which results in underestimation of their CO<sub>2</sub> emissions by the state-of-the-art emission inventories. Our study provides an approach for verification of bottom-up emission inventories

using satellite-based XCO<sub>2</sub> measurement over consistently emitting local and regional sources. The latest OCO satellite, OCO-3 (launched in May 2019 and data available since January 2020), which also measures XCO<sub>2</sub> and SIF, captures data of larger area (100 km × 100 km) in a snapshot mode with the same high spatial resolution, thus providing the opportunity to assess spatial variability of carbon emissions of larger area based on our approach. Based on the findings of our study, we recommend eddy covariance flux measurements in such a carbon-rich delta to quantify the seasonality of CO<sub>2</sub> emissions, which could be used to improve the emission inventories. Finally, we call for more research in estimating possible uncertainties and thereby improve the accuracy of the emission inventories especially for countries with intense agriculture activities.

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## Data availability statement

The data that support the findings of this study are openly available at the OCO-2 data portal at <https://co2.jpl.nasa.gov/#mission=OCO-2>

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