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Quantifying burning efficiency in megacities using the NO_2/CO ratio from the Tropospheric Monitoring Instrument (TROPOMI)

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S1. Selection of background radius per city

Tehran: Qom is the neighbouring city of Tehran, situated within a radius of 120km in the South West direction from the centre of the city. To avoid this neighbouring source we choose the radius of 180 km to 250km.

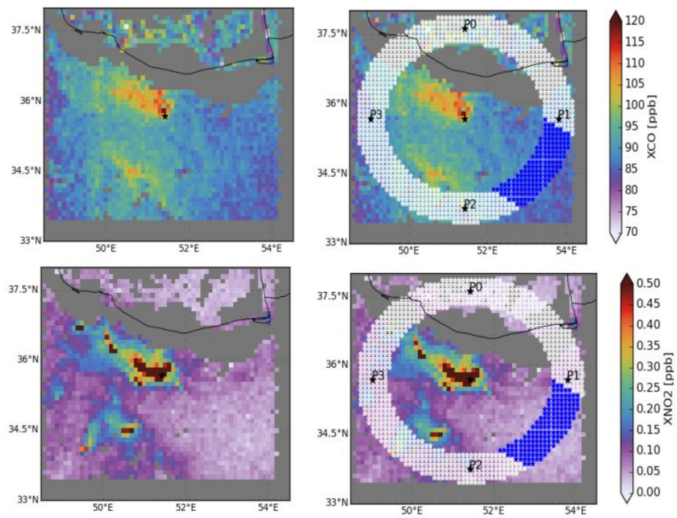

Figure S1. Collocated XCO (top) and XNO_2 (bottom) over Tehran on 8th July, 2018. The black star represents the centre of the city. The white circle in the bottom panel is the background and the blue section represents the upwind background area.

Mexico City: There is no large neighbouring source close to Mexico City in the radius of 180 to 170 km.

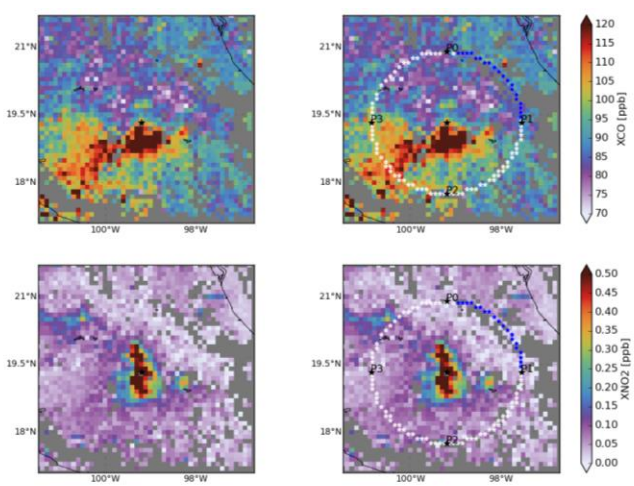

Figure S2. Same as Fig S1 but for Mexico City on 1st June

Cairo: Cairo has large outskirt area and within the radius of 120 km in the North West direction there are dominant CO and NO_2 sources. To avoid these sources we took a radius from 135 to 180 km

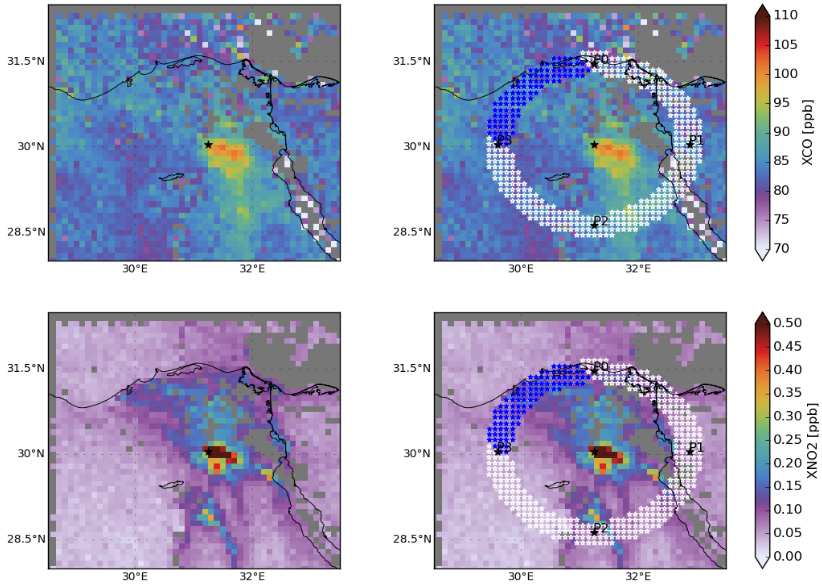

Figure S3. Same as FigS1 but for Cairo on 2nd June

Riyadh: NO_2 and CO emissions from the neighbouring cities Al Hofuf and Buraydah situated at 300km from Riyadh are visible at 200 to 250km from the centre of Riyadh. To avoid these sources we selected the background radius from 100 km to 150 km.

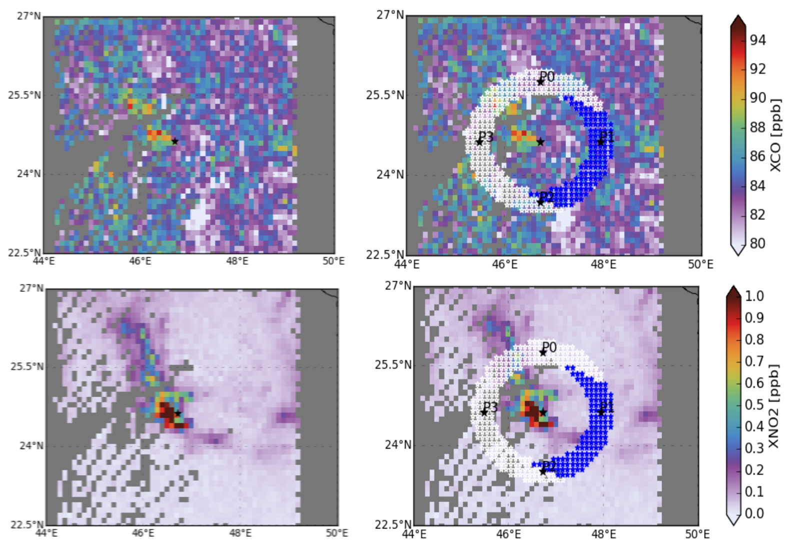

Figure S4. Same as FigS1 but for Riyadh on 6th June, 2018

Lahore: South East is the dominant wind direction. There is no large neighbouring source close to Lahore in the radius of 100 to 150 km.

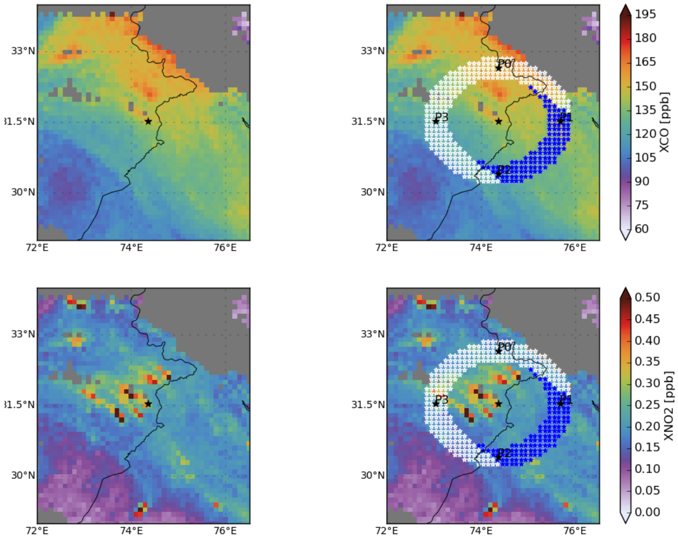

Figure S5. Same as FigS1 but for Lahore on 1st of June, 2018

Los Angeles:

There is no strong neighbouring source in between the radius of 200km to 250. Therefore we choose this radius as the background and outskirt radius. The use of SICOR algorithm on the SCIAMACHY CO retrievals with low level clouds improves the detection of enhancement of CO over the Ocean (Borsdorff et al., 2018).

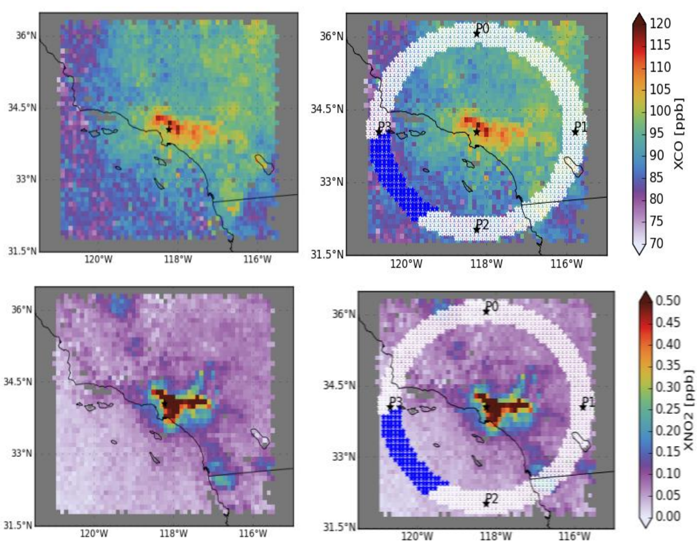

Figure S6. Same as Fig S1 but for Los Angeles on 1st of June, 2018

S2. Upwind background selection

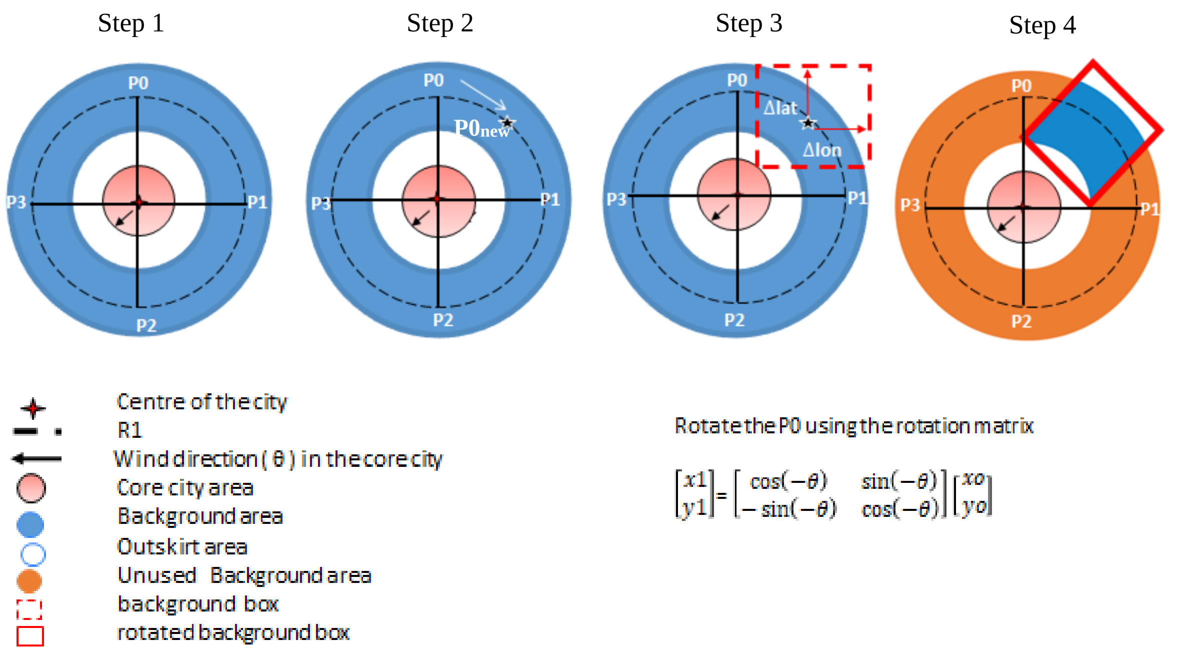

Figure S7. Schematic representation of the procedure used for selecting the upwind background. The centre of the city is represented by red star. The city, outskirt and background radii (see Table 1) are used to divide the city into three parts i.e. the core city (red circle), outskirt (white circle) and background region (blue circle), respectively. Step 1. Selection of radius R1, the mean of outskirt and background radii. Select the points P0, P1, P2, P3 where the north, east, south and west wind directions (θ) intersect at the outer rim of the dashed circle with radius R1. The black arrow symbolises an average wind direction over the core city region,. Step 2. The rotation of P0 with θ in reference to the city centre and generate the new point ($P0_{new}$). Step 3. Select the square box in the background area using Δlat and Δlon provided in Table1. Step 4. Rotate the square box using wind direction (θ) in the core city area in reference to the $P0_{new}$ and select the fraction of the upwind region.

S3. Plume rotation

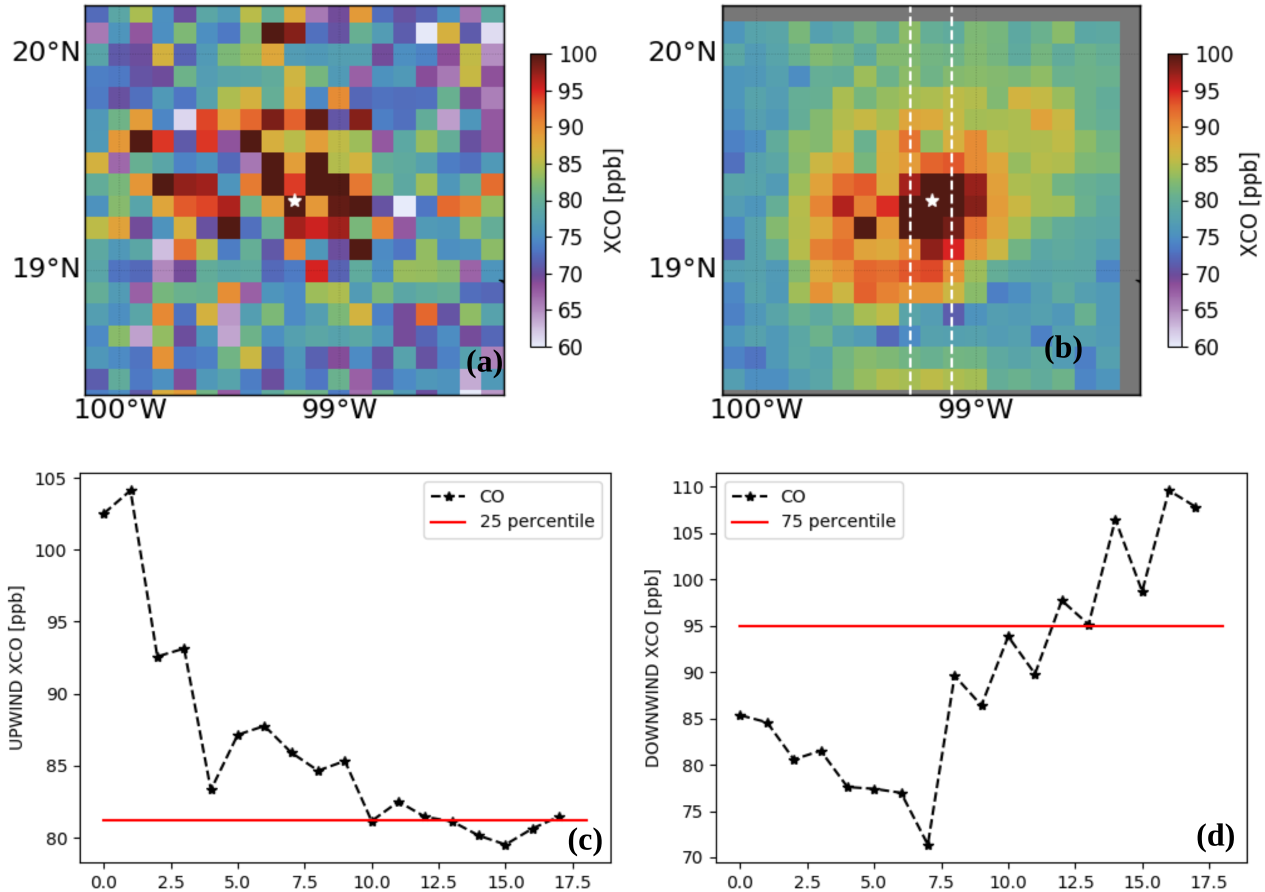

Figure S8. TROPOMI derived XCO a) averaged over June-August, 2018 b) plume rotated over Mexico, c) Upwind and d) downwind region. The white star in top panel is the centre of Mexico City. The white lines in panel (b) represent the 20x100km^2 area to determine the column enhancement in the city. The area to the North and South of the city centre is upwind and downwind region respectively. The red line in panel c) and d) represents the 25 percentile and 75 percentile respectively. CO retrievals are gridded in 0.1˚x0.1˚.

S4. CO and NO_2 enhancements over megacities from a single TROPOMI overpass

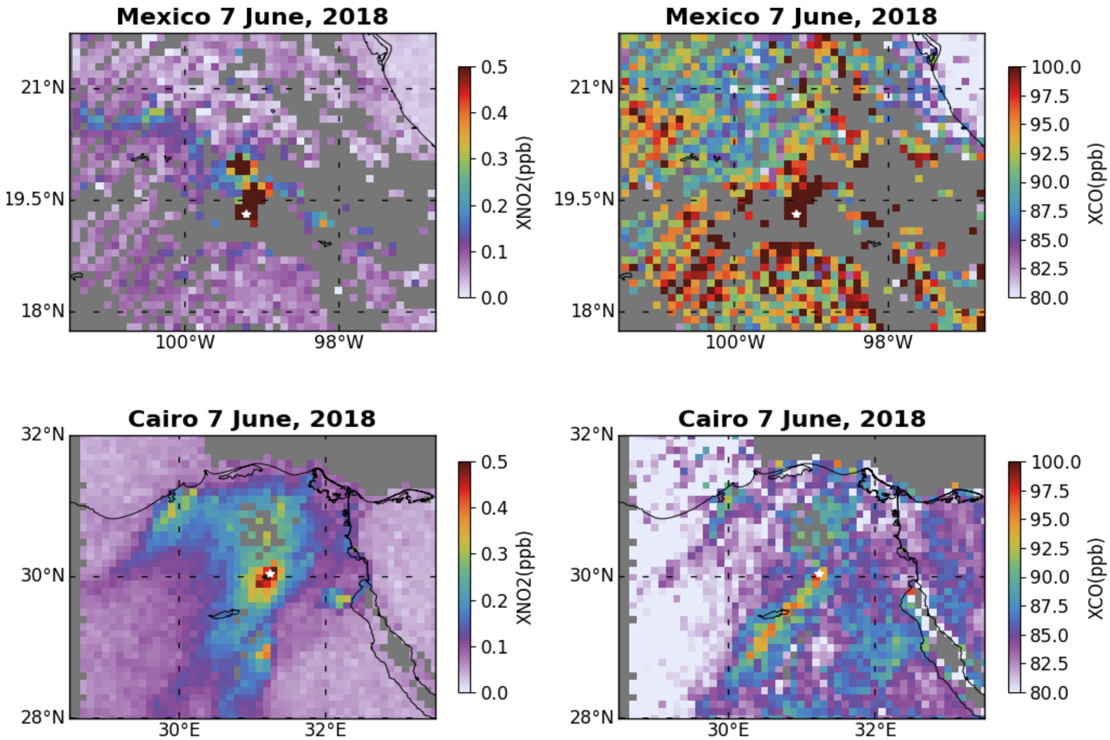

Figure S9. Collocated XCO and XNO_2 for 7 June, 2018 over Mexico (top) and Cairo (bottom).The white star represents the city centre. CO and NO_2 retrievals are gridded at 0.1˚x0.1˚ resolution.

S5. Correlation between TROPOMI, EDGAR and MACCity

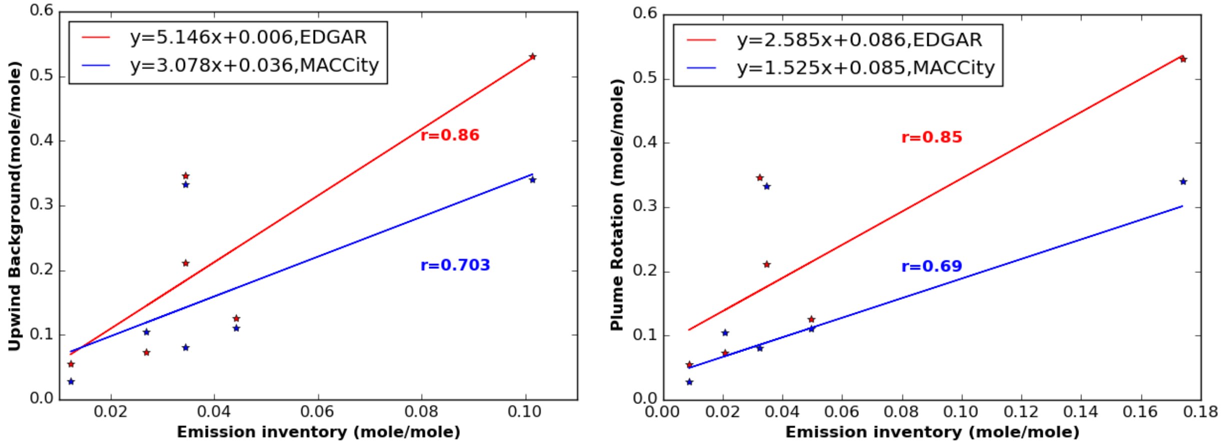

Figure S10. TROPOMI derived ($\Delta X_{NO2}/\Delta X_{CO}$) column enhancement ratio using the Upwind Background (left) and Plume rotation method (right) versus inventory NO_2/CO emission ratio and corresponding regression lines for MACCity (blue) and TROPOMI (red).

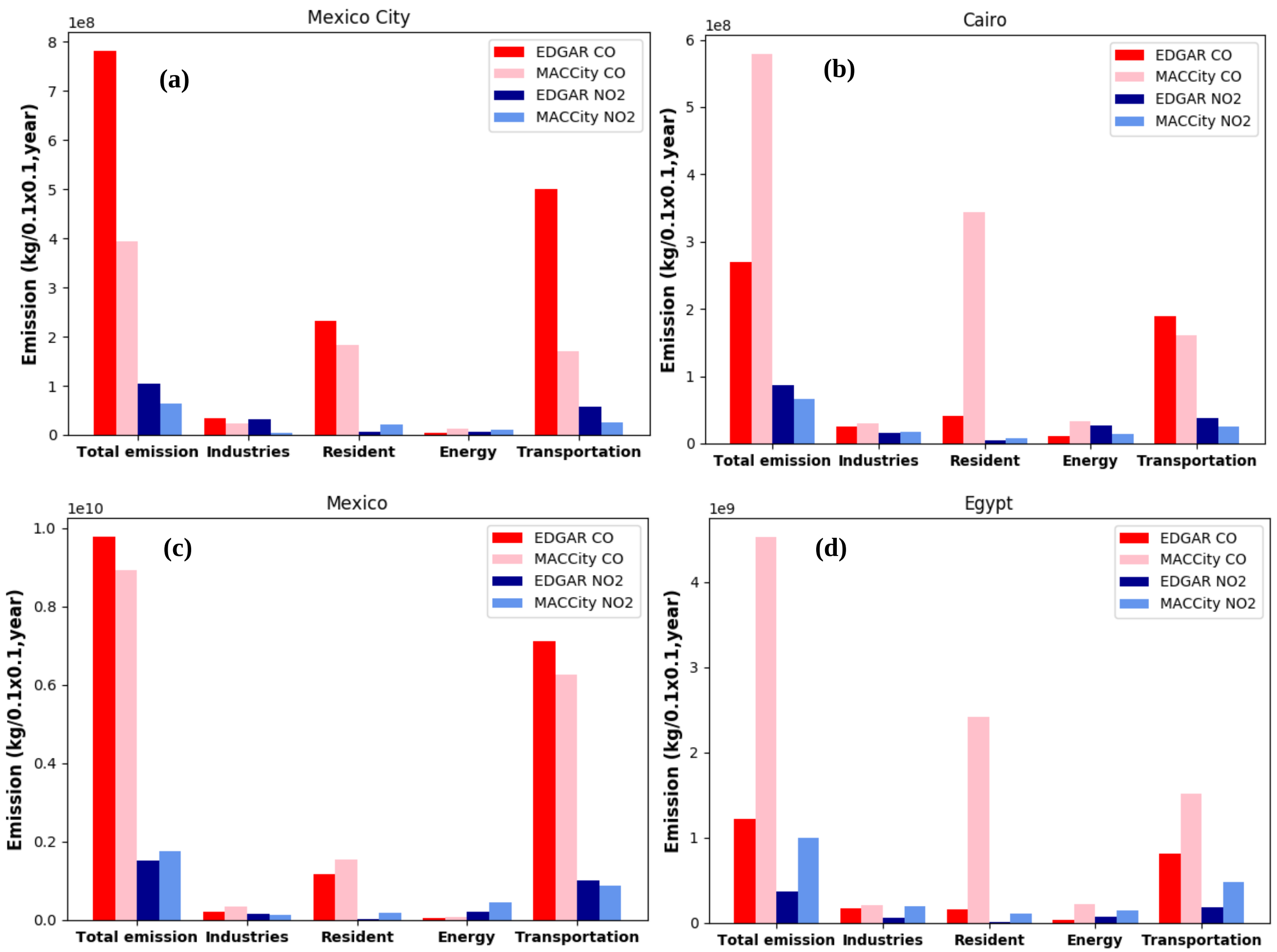

Figure S11. Comparison of EDGAR and MACCity CO and NO_2 emissions by sector for a. Mexico City b. Cairo c. Mexico and d. Egypt

S6. Comparison of TROPOMI derived CO and NO_2 with CAMS CO and NO_2

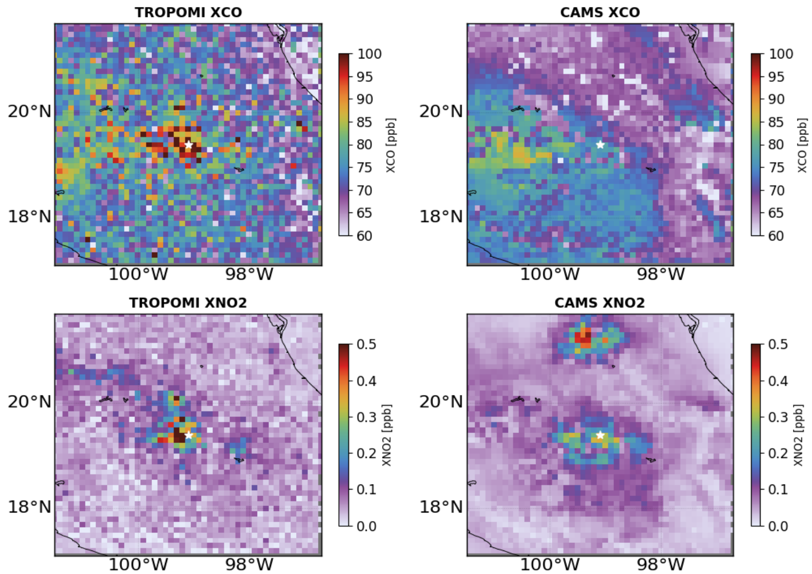

Figure S12. Collocated XCO (top) and XNO_2 (bottom) averaged for June-August, 2018 over Mexico City comparing TROPOMI (left) and CAMS (right). The white star represents the centre of the city.

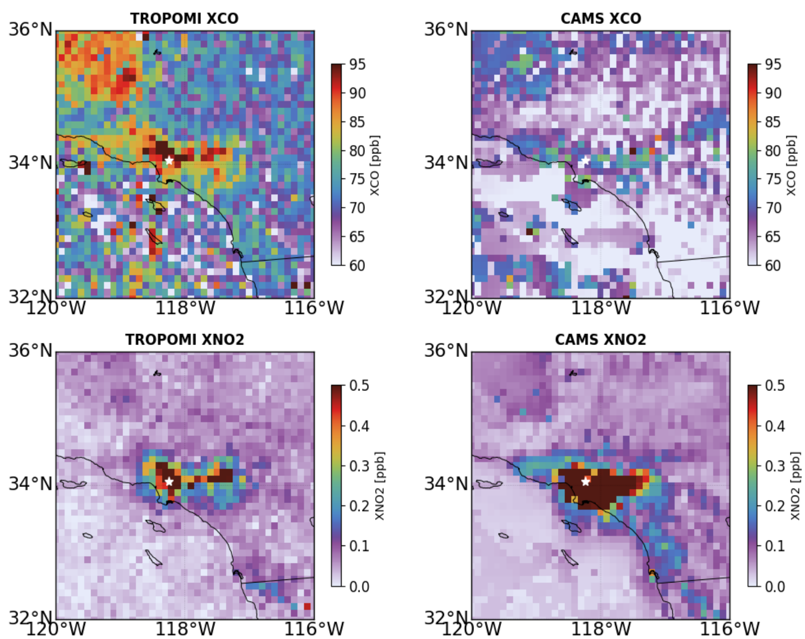

Figure S13. Same as FigS12 but for Los Angeles

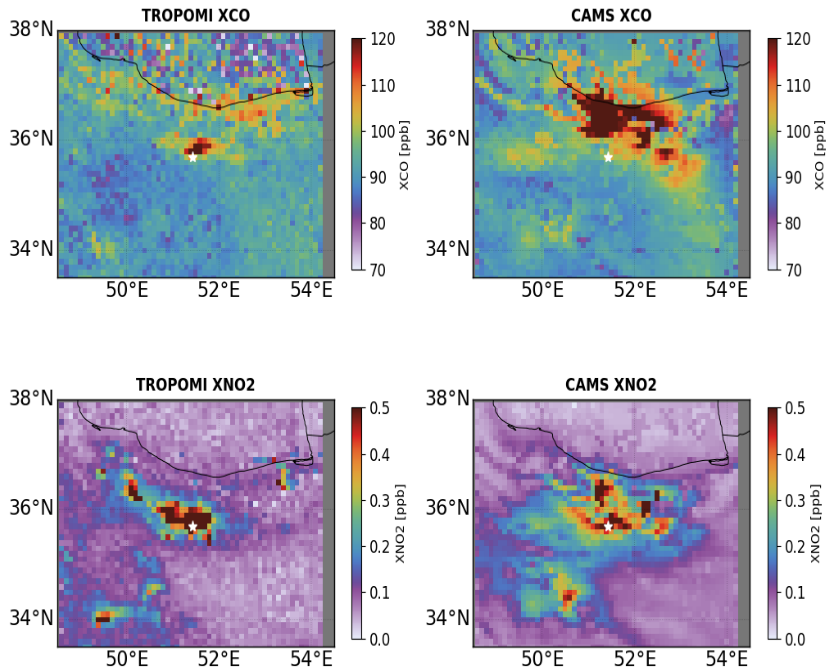

Figure S14. Same as Figure S12 for Tehran.

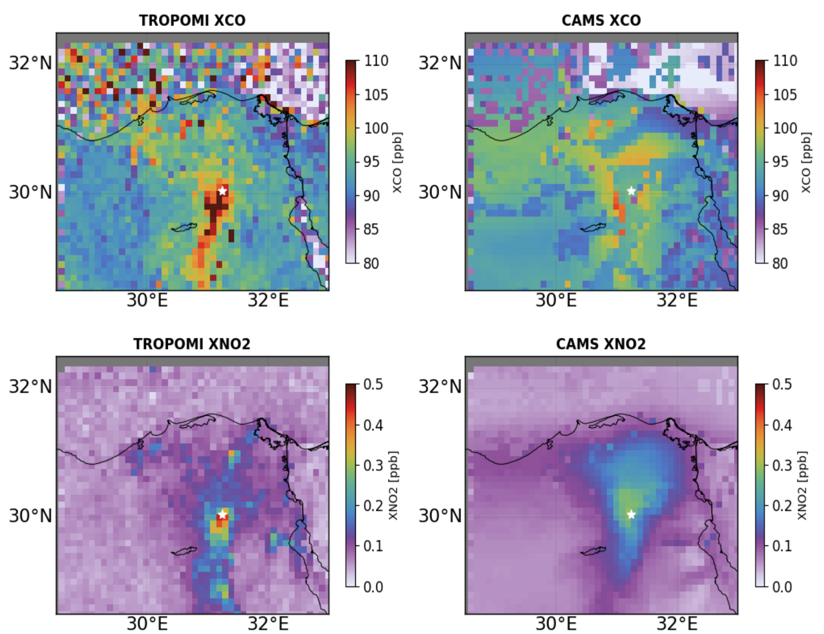

Figure S15. Same as Figure S12 but for Cairo

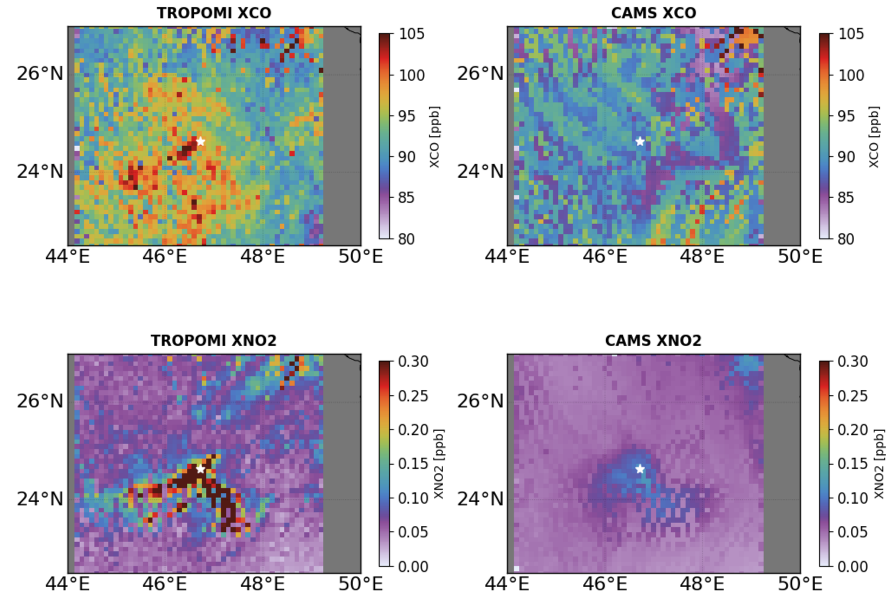

Figure S16. Same as Figure S12 but for Riyadh

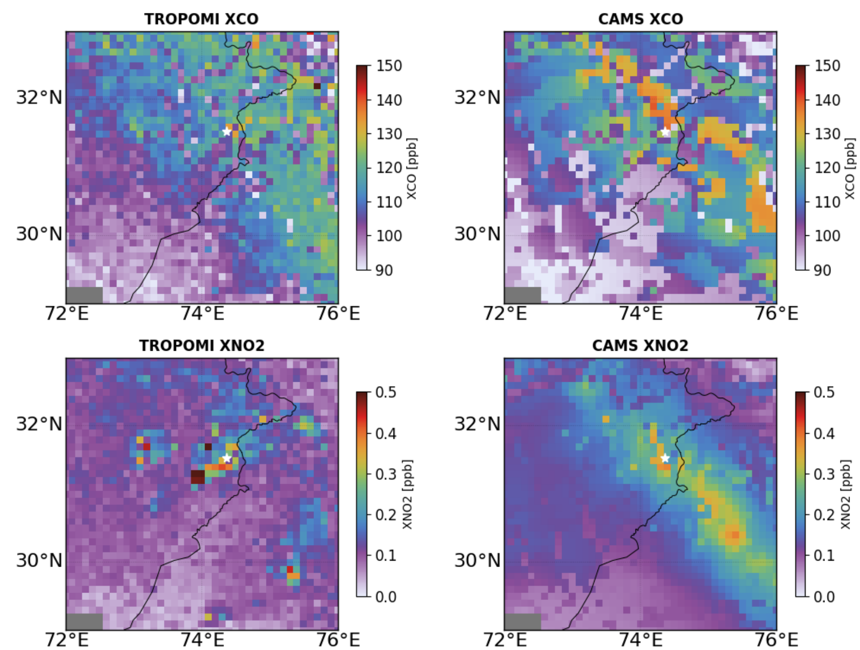

Figure S17. Same as Figure S12 but for Lahore

Table S1. Summary of TROPOMI and inventory derived NO_2/CO ratios. Estimates for TROPOMI are given using the upwind background and plume rotation methods, with and without corrections.

Cities	Upwind ratio ± error	Upwind ratio (OH corrected ratio)	Upwind ratio (OH +A)	Plume rotation ratio ± error	Plume rotation ratio (OH corrected ratio)	Plume rotation ratio (OH +A)	MACCity ratio	EDGAR ratio
Tehran	0.040± 0.0018	0.15± 0.01	0.17± 0.011	0.038± 0.007	0.14± 0.006	0.16± 0.007	0.12	0.13
Mexico city	0.025± 0.002	0.073± 0.006	0.087± 0.0080	0.023± 0.006	0.068± 0.005	0.081± 0.006	0.10	0.073
Cairo	0.037± 0.003	0.12± 0.012	0.13± 0.013	0.034± 0.006	0.10± 0.0028	0.11± 0.003	0.08	0.345
Riyadh	0.13± 0.017	0.42± 0.11	0.47± 0.12	0.11± 0.01	0.34± 0.058	0.38± 0.07	0.34	0.70
Lahore	0.010± 0.0015	0.055± 0.009	0.060± 0.01	0.012± 0.0007	0.062± 0.005	0.069± 0.006	0.028	0.055
Los Angeles	0.030± 0.003	0.074± 0.005	0.082± 0.006	0.034± 0.0026	0.084± 0.001	0.094± 0.001	0.33	0.211

Table S2. The CAMS derived influence of the averaging kernel (A) on the total column NO_2/CO ratio. The error bar represents 1σ uncertainties calculated by bootstrapping method.

City	Days	NO_2/CO A =1 (B)	NO_2/CO TROPOMI A(C)	Relative difference ((B-C)/B)*100 (%)
Tehran	July 03, 04 August 20	0.0158 ±0.002	0.013 ±0.002	9.0± 1.2
Mexico City	June-August	0.024 ±0.003	0.02± 0.0016	9.0±2.7
Cairo	August,09, 15,16,21,22,31	0.082 ± 0.0062	0.074 ±0.00861	10.0±4.4
Riyadh	June03,08,24,26, July 03,05,06,07, 12,19,22,24,28, August 18,19,20,22, 28,30	0.107859 ±0.01	0.09 ±0.03	10.3±4.1
Lahore	June 06 July 06 August 19, 29, 30	0.0047 ± 0.0003	0.003352 ±0.0005	9.0±0.4
Los Angeles	June-August	0.095 ±0.015	0.085 ±0.02	10.5±4.2

Table S3. Estimated uncertainties in TROPOMI derived emission ratios. The total uncertainty is derived by summing the individual components in quadrature

City	S5P TROPOMI NO_2 uncertainty (A) (%)	Wind direction and Wind speed (B) (%)	Boundary layer OH concentration (C) (%)	Predefined background area (D) (%)	$A_{influence}$ Correction (E) (%)	Total effect on ER ($\sqrt{(A^2+B^2+C^2+D^2+E^2)}$) (%)
Tehran	30	10.5	8.4	3.0	1.2	±33.03
Mexico City	30	7.5	10	9.0	2.7	±33.83
Cairo	30	2.3	8.4	13.0	4.4	±34.12
Riyadh	30	6.0	12.5	9.1	4.1	±34.5
Lahore	30	6.5	15.0	10.0	0.4	±35.6
Los Angeles	30	10.0	8.3	8.8	4.2	±34.1

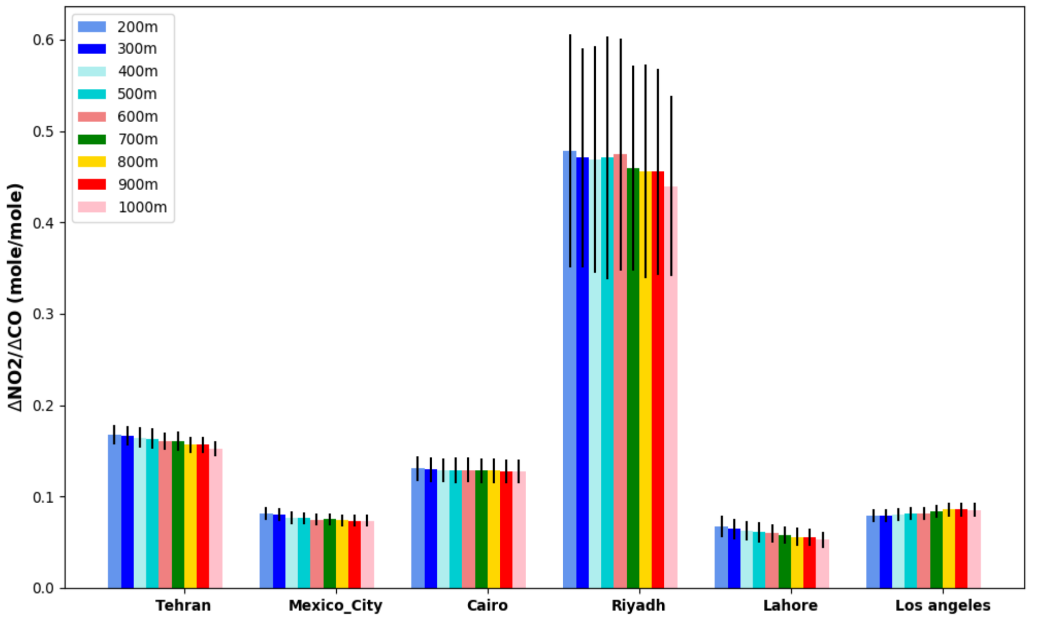

Figure S18. TROPOMI derived Upwind Background Corrected Emission Ratio for six megacities using average wind speed and direction calculated from surface till 200m to 1000m. The error bar represents 1σ uncertainties calculated using boot strapping.

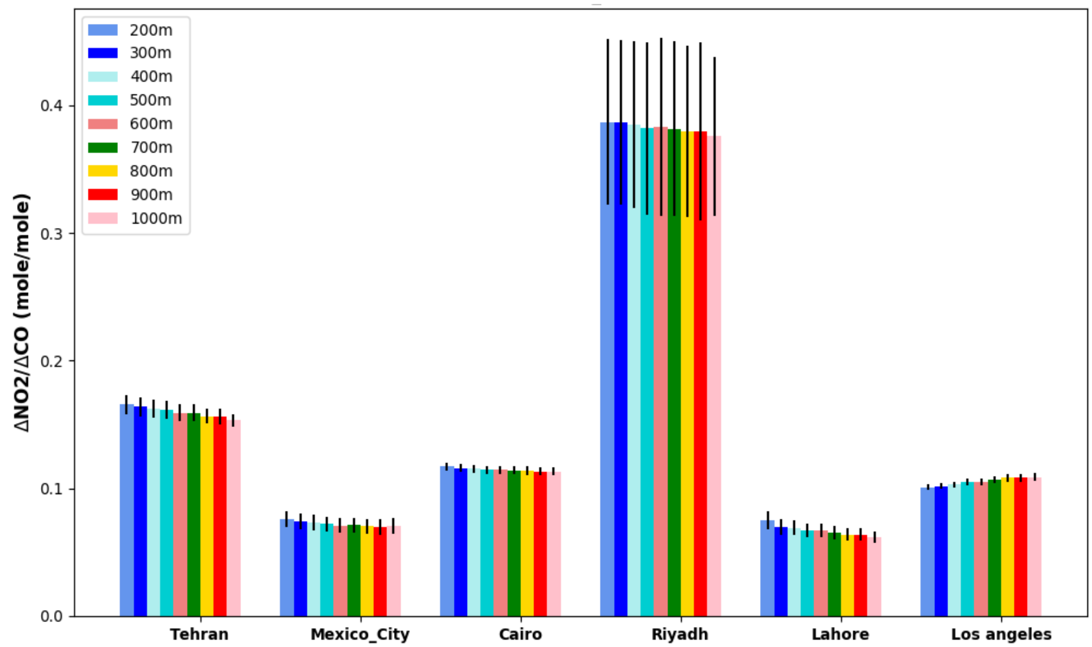

Figure S19. Same as Fig S11 but the emission ratio is plume rotation corrected emission ratio

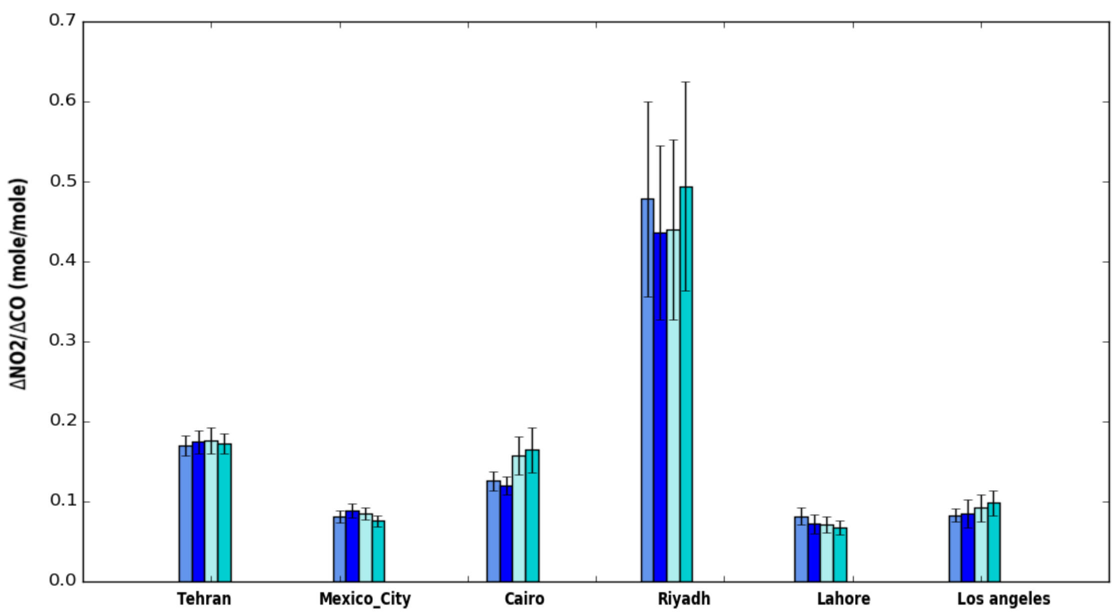

Figure S20. Upwind Background Corrected Emission ratio derived for six megacities using four different background and outskirt radius. For the initial step the outskirt and background radius for Tehran: 180 km and 190 km, Mexico City: 170km and 180km, Cairo: 135km and 145 km, Riyadh: 100km and 110 km, Lahore: 100km and 110km and Los Angeles: 200 km and 210 km. In every step the background and outskirt radius is increased by 10km.During this process Δlat and Δlon is 1.0˚, 1.0 ˚.

Table S4. Selected ground based measurement sites in Mexico City and Los Angeles

Mexico	
Station	Location (Latitude, longitude)
Alcoman (ACO)	19.635501, -98.912003
Atizapan(ATI)	19.576963, -99.254133
Camarones (CAM)	19.4684, -99.1698
Centro de Ciencias de la Atmósfera (CCA)	19.468404, -99.176111
Cuajimalpa (CUA)	19.365313, -99.291705
FES Acatlán (FAC)	19.482473, -99.243524
Iztacalco (IZT)	19.384413, -99.117641
La Presa (LPR)	19.53473, -99.11772
Montecillo (MON)	19.460415, -98.902853
Merced (MER)	19.42461, -99.119594
Mguel Hidalgo (MGH)	19.41162, -99.20266
Pedregal (PED)	19.32515, -99.2041
San Agustín (SAG)	19.532968, -99.030324
Tlalnepantla (TLA)	19.529077, -99.204597
Tlahuac (TAH)	19.246459, -99.010564
Tultitlán (TLI)	19.602542, -99.177173
UAM Xochimilco (UAX)	19.304441, -99.103629
UAM Iztapalapa (UIZ)	19.360794, -99.07388
Villa de las Flores (VIF)	19.658223, -99.09659
Xalostoc (XAL)	19.525995, -99.0824
Los Angeles	
Azusa	34.13648 -117.92392
Lancaster-43301 Division Street	34.66959 -118.13068
Compton-700 North Bullis Road	33.901445 -118.204989
Glendora-Laurel	34.14437 -117.85038
Los Angeles-North Main Street	34.06653 -118.22676
Los Angeles-Westchester Parkway	33.95507 -118.43049
Pasadena-S Wilson Avenue	34.13265 -118.12714
Pico Rivera-4144 San Gabriel	34.01029 -118.0685
Pomona	34.06698 -117.75138
Reseda	34.1992 -118.53275
Santa Clarita	34.38337 -118.52839
West Los Angeles-VA Hospital	34.05109 -118.4564