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Supporting Information for

Using space-based observations and Lagrangian modeling to evaluate urban carbon dioxide emissions in the Middle East

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Introduction

This document contains supplementary information, including a supporting description of data processing (Text S1), details on an error in ODIAC's representation of the city of Jeddah (Text S2), a figure and table illustrating information about the overpasses used in this study (Figure S1 and Table S1), figures illustrating additional detail to Figure 4 in the main text (Figures S2 and S3), and a figure supporting the discussion in Section 4.1 on our ability to observe enhancements from relatively small cities (Figure S4).

Text S1. Impact of Data Screening with Warn Levels on Scaling Factors

To maximize usable data, we conduct a sensitivity study to assess what level of warn level filtering to apply to the OCO-2 data used in this study. Since we have the densest observational dataset for Riyadh, we use this as a case study. We consider the impact of using data from warn levels 0, 2, 4, and 5 for the 9 overpasses that retain sufficient data density for evaluation when screened at level 0. There is a trade-off between including potentially biased data points (warn level 5) and reducing the data volume such to limit statistics (warn level 0). We find that our scaling factors are not statistically different irrespective of warn level used for Riyadh. At level 0, 2, and 4 with 90% confidence intervals, our scaling factors for FFDAS, ODIAC, EDGAR, and aggregated ODIAC are, respectively: 1.2 (0.5, 1.9), 1.3 (0.5, 2.1), 1.9 (1.0, 2.8), and 1.2 (0.5, 1.9). At level 5, the scaling factors are all the same other than the EDGAR scaling factor, 1.9 (1.0, 2.9), which has a slight increase in its upper bound. The minimal effect of warn level screening on the scaling factors may in part be due to the differential nature of our urban analysis, and/or that we average individual soundings together and consider the variability in the soundings averaged as an uncertainty in our analysis, both of which might mitigate the inclusion of skewed soundings. Given the results of this Riyadh study, we report results using the most generous inclusion of data (warn level 5) in this manuscript.

Text S2. ODIAC Representation Error for the City of Jeddah

ODIAC's representation error of Jeddah's emissions is due to a mismatch between two gas flare nightlight data sources at that particular location. ODIAC uses multiple nighttime light data sources to distribute emissions. Generally speaking, nightlight intensity is used as a proxy for the magnitude of human activities, and correspondingly, CO_2 emissions. However, the pixels associated with gas flares are very bright and thus do not serve as an appropriate proxy for emissions. These bright pixels are thus removed. Gas flares are still included in the ODIAC data product, however; a modified version of NOAA's gas flare nightlight data is used to distribute gas flare emissions country by country. At Jeddah's location, the emissions representation corresponds to a difference between the two gas flare nightlight products. This is a model error in ODIAC and is fixed in the latest version of the product.

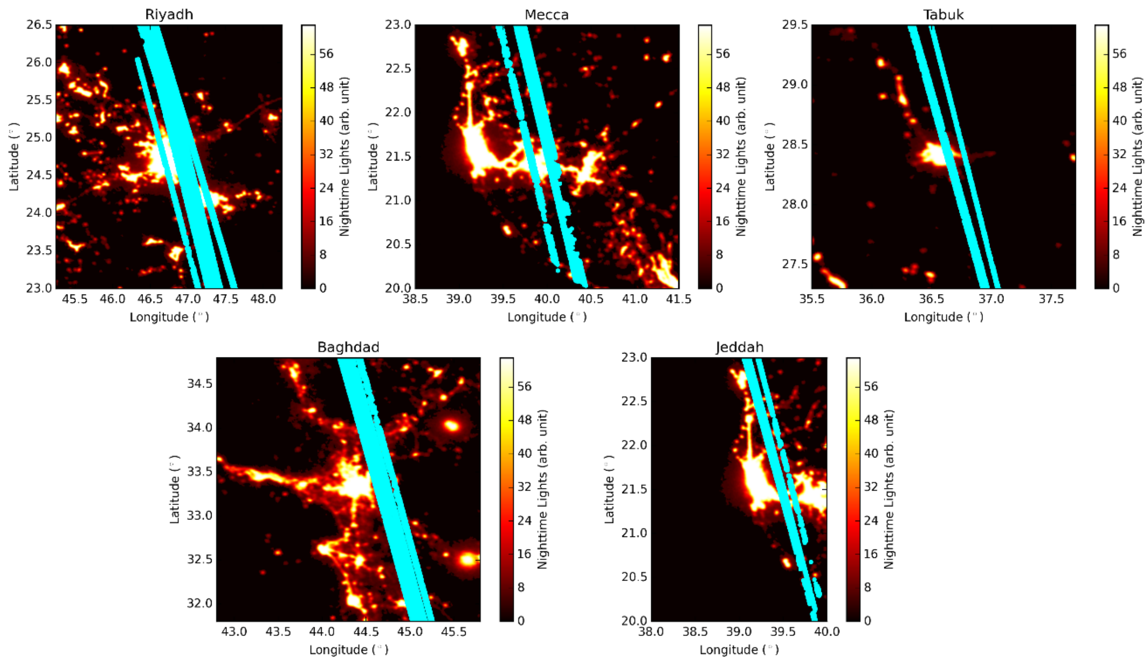

Figure S1. All studied overpasses (light blue), overlaid upon the cities of interest, which represented by nighttime lights. The cities of interest are centered within each subplot; in particular, Mecca is the central high-intensity unit of the three shown in its corresponding subplot.

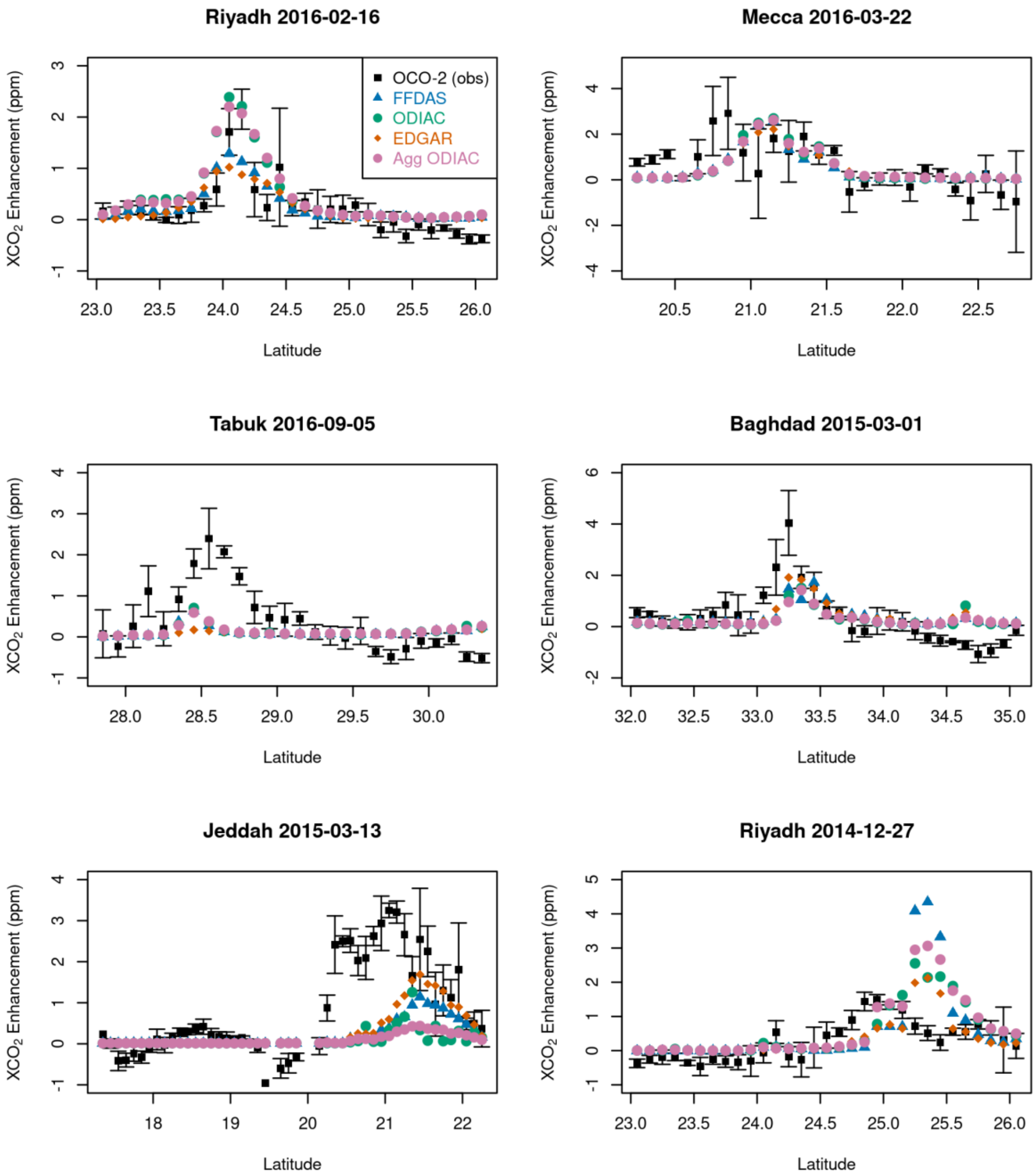

Figure S2. Enhancements of sample observed and modeled overpasses for different cities and days, as in Figure 4 but with uncertainties on the observations. The uncertainties are derived from the spread of the OCO-2 data, with each uncertainty value representing the standard deviation of the observed points whose medians are used in each plotted observed point.

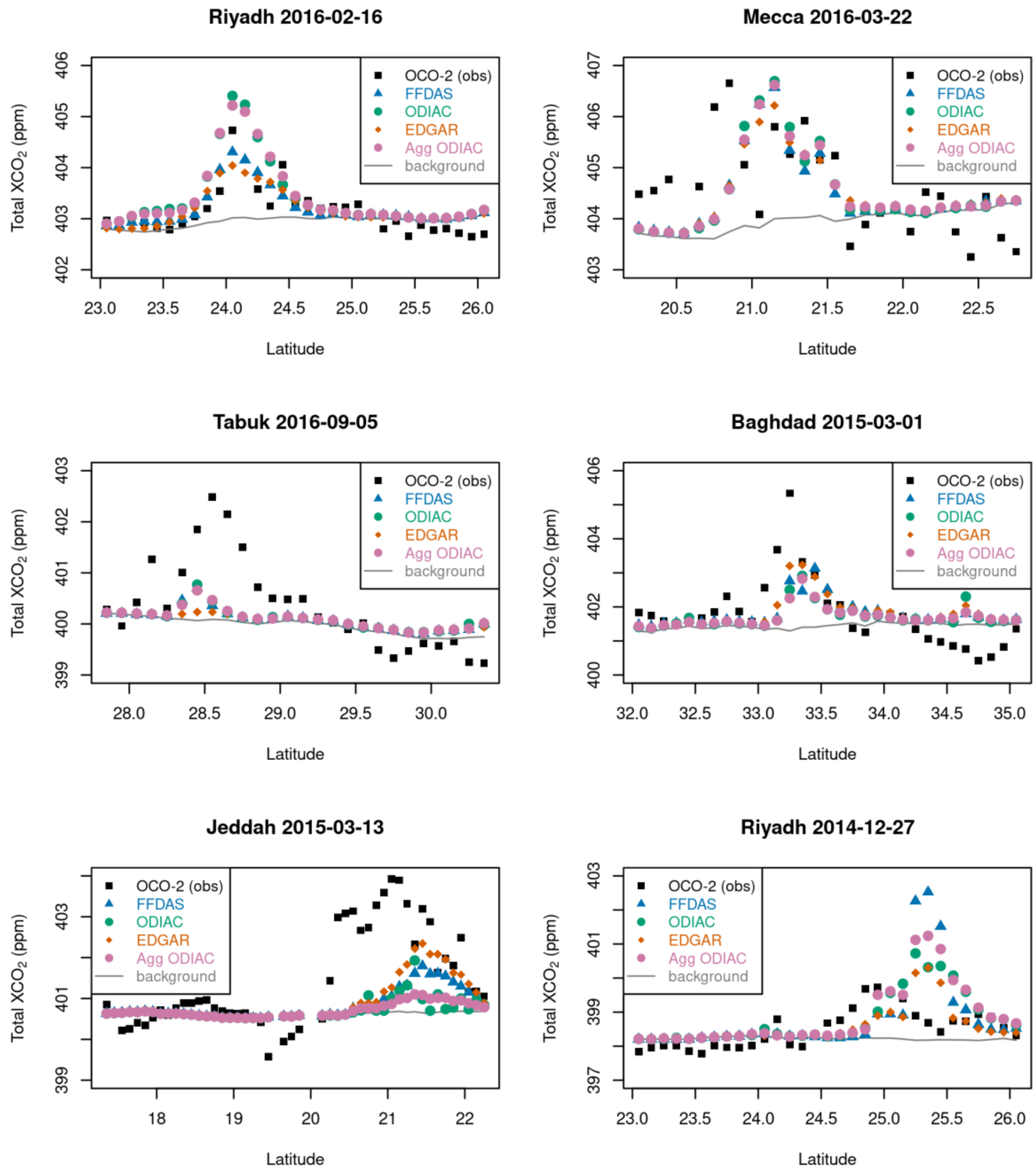

Figure S3. Total XCO2 for sample observed (black) and modeled (other colors) overpasses for different cities and days, matching those of Figure 4.

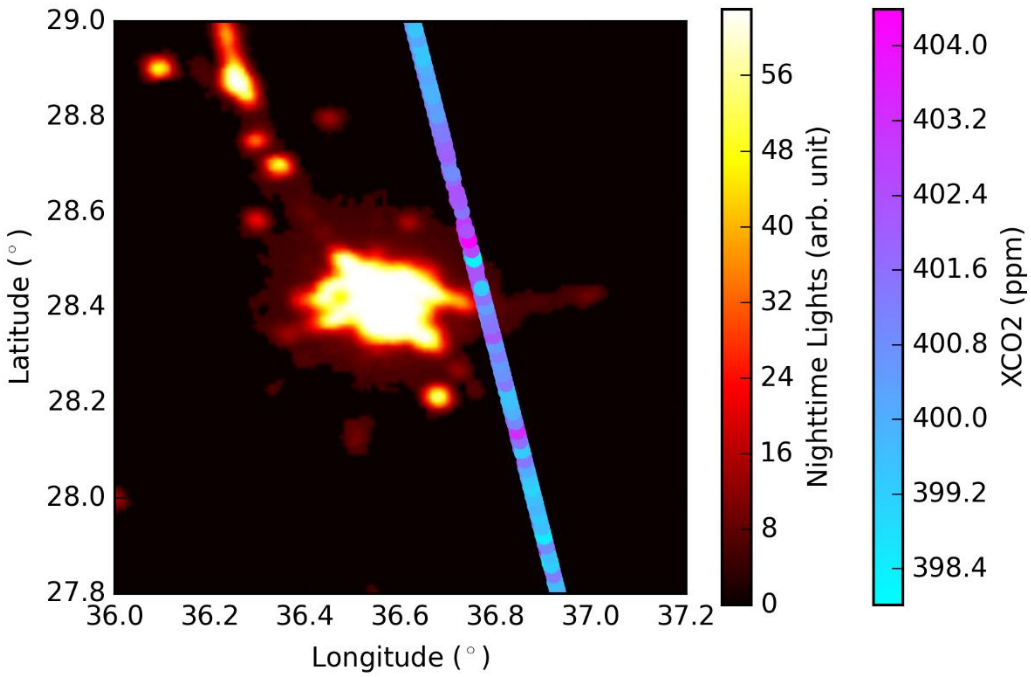

Figure S4. OCO-2 observations of XCO_2 on 2016-09-05 overlaid on gridded nighttime lights of the city of Tabuk, Saudi Arabia.

City	*Date*	*Hour (UTC)*	*Observation Mode*
Riyadh	2014-12-27	10	Nadir
Riyadh	2014-12-29	10	Glint
Riyadh	2015-01-28	10	Nadir
Riyadh	2015-03-01	10	Nadir
Riyadh	2015-08-17	10	Glint
Riyadh	2015-09-09	10	Nadir
Riyadh	2015-12-16	10	Glint
Riyadh	2016-02-16	10	Nadir
Riyadh	2016-05-22	10	Nadir
Riyadh	2016-07-25	10	Nadir
Riyadh	2016-10-29	10	Nadir
Mecca	2014-09-25	11	Nadir
Mecca	2014-11-12	11	Nadir
Mecca	2015-11-15	11	Nadir
Mecca	2016-02-19	11	Nadir
Mecca	2016-03-22	11	Nadir
Mecca	2017-04-10	11	Nadir
Tabuk	2015-05-23	11	Glint
Tabuk	2016-09-05	11	Nadir
Tabuk	2017-04-17	11	Nadir
Baghdad	2015-03-01	10	Nadir
Baghdad	2015-05-20	10	Nadir
Baghdad	2015-11-12	10	Nadir
Jeddah	2015-03-13	11	Glint
Jeddah	2015-04-14	11	Glint
Jeddah	2016-02-28	11	Glint

Table S1. Information on all overpasses used in this study: city, date, hour (UTC) at which observations were made, and observation mode.