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Satellite-based fossil fuel CO_2 emissions detection over metropolitan areas: a multi-model analysis of OCO-2 data over Lahore, Pakistan

Ruixue Lei[1], Sha Feng[2], Alexandre Danjou[3], Grégoire Broquet[3], Dien Wu[4], John Lin[5], Christopher O'Dell[6], and Thomas Lauvaux[3]

[1]Department of Meteorology and Atmospheric Science, The Pennsylvania State University, University Park, PA, 16802, USA
[2]Atmospheric Sciences and Global Change Division, Pacific Northwest National Laboratory, Richland, WA, 99352, USA
[3]Laboratoire des Sciences du Climat et de l'Environnement, CEA, CNRS, UVSQ/IPSL, Université Paris-Saclay, Orme des Merisiers, 91191 Gif-sur-Yvette cedex, France
[4]Division of Geological and Planetary Sciences, California Institute of Technology, Pasadena, USA
[5]Department of Atmospheric Sciences, University of Utah, Salt Lake City, UT 84132, USA
[6]Cooperative Institute for Research in the Atmosphere, Colorado State University, Fort Collins, CO, USA

Atmospheric Carbon dioxide (CO_2) has reached 150% of its pre-industrial level and has contributed to more than 60% of the global direct radiative forcing from Greenhouse Gases (GHGs). Global fossil fuel CO_2 (CO_{2ff}) emissions exceeded 38 Gt in 2020 accounting for more than 77% of fossil fuel greenhouse gas emissions. City areas, where gathering more than 55% of the global population, alone contributed to more than 70% of anthropogenic CO_{2ff} emissions. Proper management of fossil fuel sources designed to achieve the 2.0-degree temperature threshold of the Paris Agreement requires accurate monitoring of emissions from major metropolitan areas globally to track this commitment. Satellite-based inversion is unique among the "top-down" approaches, potentially allowing us to track and monitor fossil fuel emission changes over cities globally. However, its accuracy is still limited by incomplete background information, cloud blockages, aerosol contaminations, and uncertainties in models and priori fluxes.

To evaluate the current potential of space-based quantification techniques, we present the first attempt to monitor long-term changes in CO_{2ff} emissions based on the OCO-2 satellite measurements over a fast-growing Asian metropolitan area: Lahore, Pakistan. We first examined the OCO-2 data availability at the global scale. About 17% of OCO-2 soundings are marked as high-quality soundings by quality flags over the global 70 most populated cities. Cloud blockage and aerosol contamination are the two main causes of data loss. As an attempt to recover additional retrievals, we evaluated the effectiveness of OCO-2 quality flags at the city level by comparing the satellite/reference ratios derived from three independent methods (WRF-Chem, X-STILT, and Flux cross-sectional integration method), all based on the ODIAC inventory. The satellite/reference ratios of the high-quality tracks better converged across the three methods compared to the all-

data tracks with reduced uncertainties in emissions. Thus, we conclude that OCO-2 quality flags are highly relevant to filter unrealistic OCO-2 retrievals even at local scales, although originally designed for global-scale studies. All three methods consistently suggested that the ratio medians are greater than 1, which implies that the ODIAC slightly underestimated the CO_{2ff} emissions over Lahore. The posterior CO_{2ff} emission trend was about 734 kt C/year (i.e., an annual 6.7% increase), while the a priori emission ODIAC showed that the trend was about 650 kt C/year (i.e., an annual 5.9% increase). The 10,000 Monte Carlo simulations of the Mann-Kendall upward trend test showed that less than 10% prior uncertainty for 8 tracks (or less than 20% prior uncertainty for 25 tracks) is required to achieve a greater-than-50% trend significant possibility at a 95% confidence level. It implies that the trend is driven by the prior rather than the optimized emissions. The key to improving the role of satellite and model in emission trend detection is to obtain more high-quality tracks near metropolitan areas to achieve significant constraints from X_{CO2} retrievals.