# Near-Automated Estimate of City Nitrogen Oxides Emissions Applied to South and Southeast Asia


**Gongda Lu, Eloise A. Marais, Karn Vohra, Rebekah P. Horner**

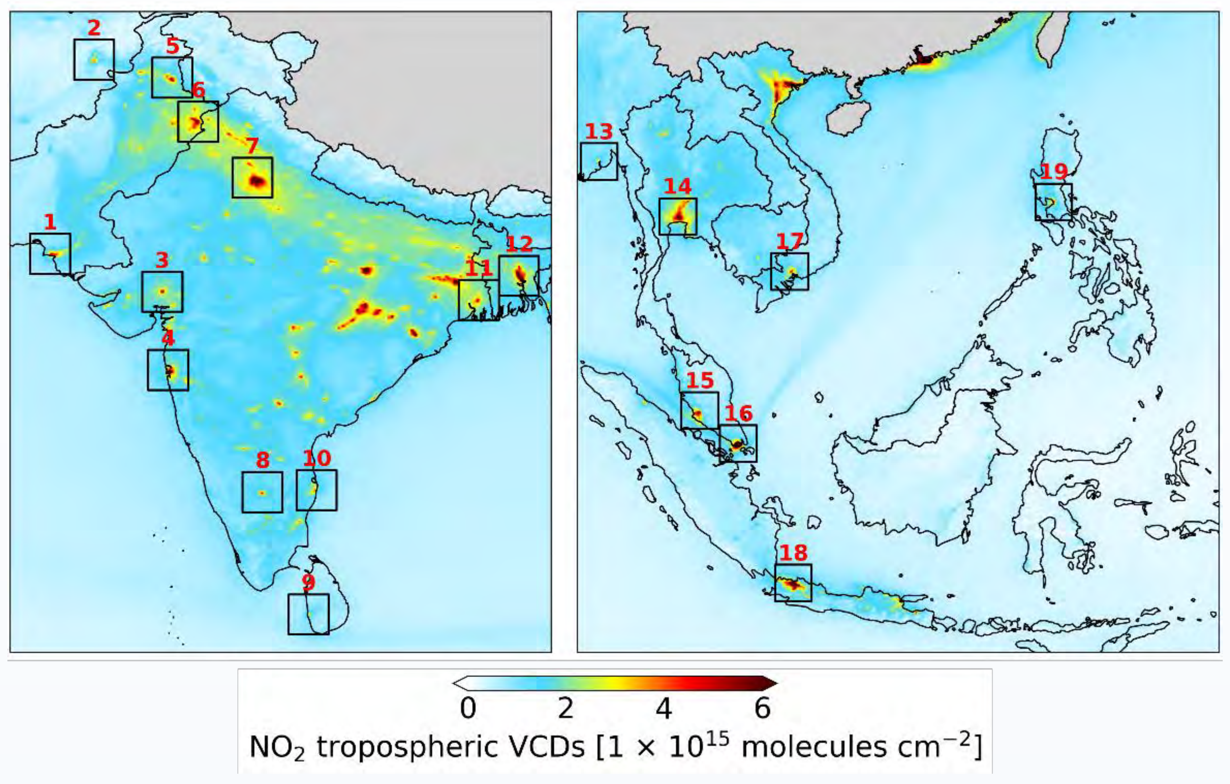
**Department of Geography, UCL, London, UK**


## 1. Introduction

Cities in South and Southeast Asia are developing rapidly, but lack routine, up-to-date, publicly available inventories of air pollutant precursor emissions such as nitrogen oxides ($NO_x$). A well-established approach of deriving city $NO_x$ emissions from satellite observations of nitrogen dioxide ($NO_2$) tropospheric column densities uses wind rotation to align the city plume along a consistent direction and applies a best-fit Gaussian to estimate top-down $NO_x$ emissions. An issue that impacts success of this approach is the manual selection of the sampling area around the city centre. Here, we enhance and automate this approach and use TROPOspheric Monitoring Instrument (TROPOMI) $NO_2$ observations to derive annual and monthly $NO_x$ emissions over 19 cities in South and Southeast Asia and compare them against bottom-up emissions from the Hemispheric Transport of Air Pollution (HTAP).

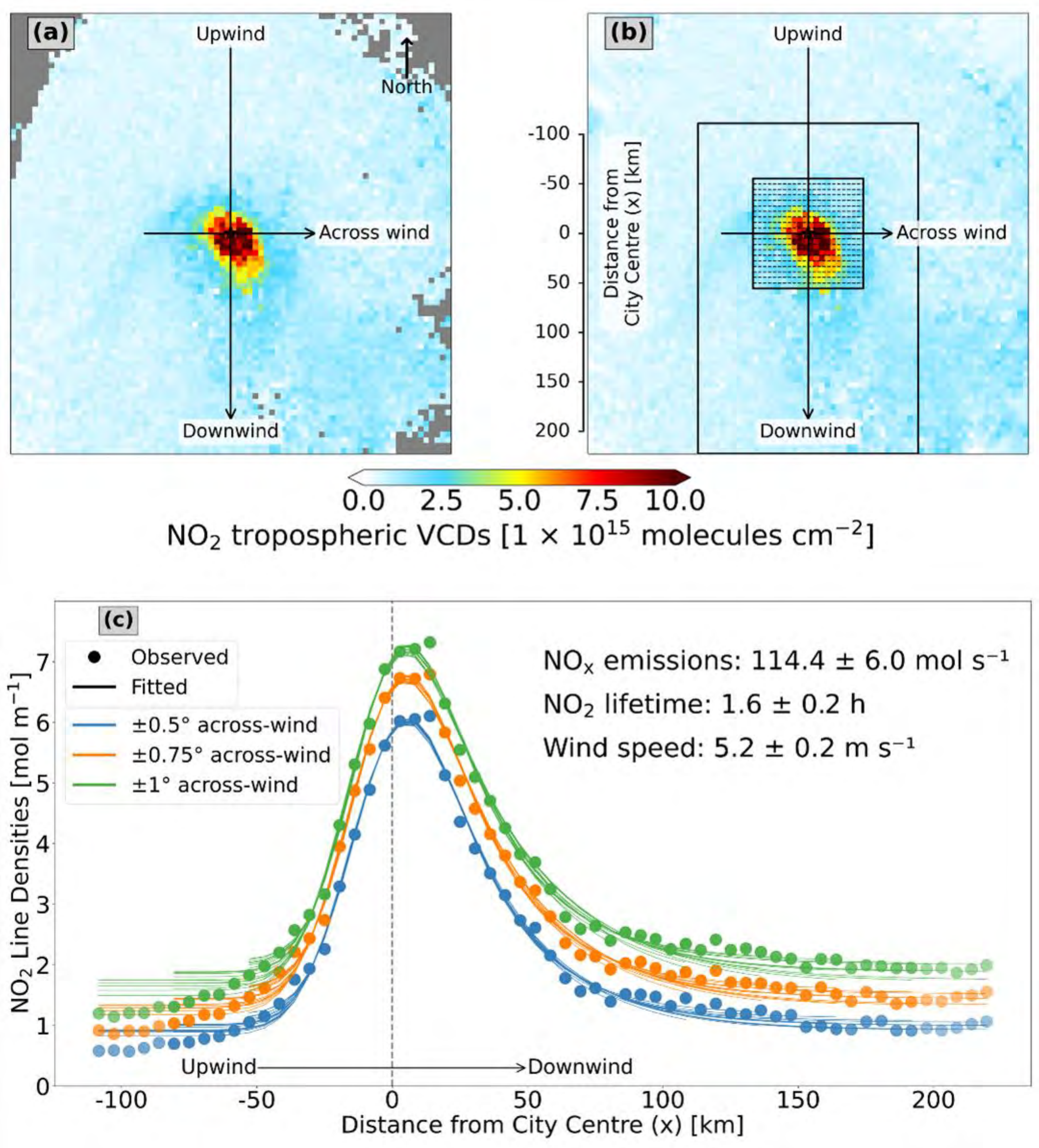
## 2. Methodology

### TROPOMI $NO_2$ and City Selection




Maps show South (left) and Southeast (right) Asia TROPOMI tropospheric $NO_2$ VCDs oversampled to 0.05° × 0.05° for 2019. The selected cities are: Karachi (1), Islamabad (5), and Lahore (6) in Pakistan; Kabul (2) in Afghanistan; Ahmedabad (3), Mumbai (4), Delhi (7), Bangalore (8), Chennai (10), and Kolkata (11) in India; Colombo (9) in Sri Lanka; Dhaka (12) in Bangladesh; Yangon (13) in Myanmar; Bangkok (14) in Thailand; Kuala Lumpur (15) in Malaysia; the sovereign city Singapore (16); Ho Chi Minh City (17) in Vietnam; Jakarta (18) in Indonesia; and Manila in the Philippines (19).

### Wind Rotation and Exponential Modified Gaussian (EMG) Fit




$$F(x|a, x_0, \mu_x, \sigma_x, B) = \frac{a}{2x_0}\exp\left(\frac{\mu_x}{x_0} + \frac{\sigma_x^2}{2x_0^2} - \frac{x}{x_0}\right)\mathrm{erfc}\left(-\frac{1}{\sqrt{2}}\left[\frac{x-\mu_x}{\sigma_x} - \frac{\sigma_x}{x_0}\right]\right) + B \quad (1)$$

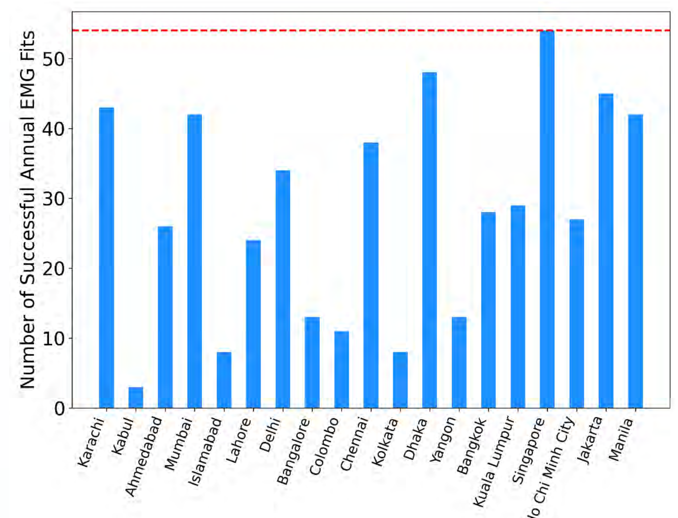
$$\tau_{NO_2} = \frac{x_0}{\omega} \quad (2)$$

$$E_{NO_x} = \gamma \times \frac{a}{\tau_{NO_2}} \quad (3)$$

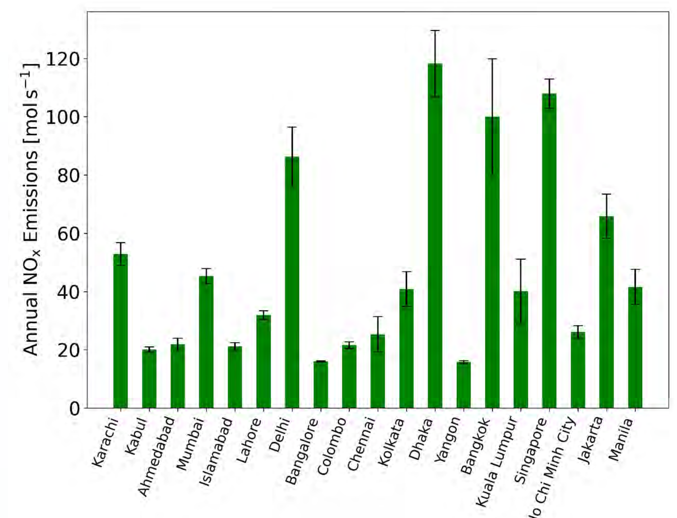
Illustration of major steps in the wind rotation and the Exponential Modified Gaussian (EMG) fit to derive $NO_x$ emissions for Singapore in September 2019. The main steps in each panel are wind rotate and grid windy scene TROPOMI $NO_2$ pixels to 0.05° × 0.05° (a), fill data gaps (b), and fit the EMG function (Eq. (1)) (solid lines) to observed line densities (filled circles) (c). Black rectangles in (b) show the extent of the largest and smallest sampling areas and the dashed lines in the smallest area show the 0.05° increments used to calculate the line densities in (c). All 54 successful EMG fits, 18 for each across-wind area, are shown in (c). Values in (c) give the mean and standard deviations of the city $NO_x$ emissions (Eq. (3)), effective $NO_2$ lifetime (Eq. (2)), and ERA5 wind speed below 900 hPa. The $R^2$ is ≥ 0.98 for all successful fits in (c).

## 3. Successful EMG Fits, Annual and Monthly $NO_x$ Emissions

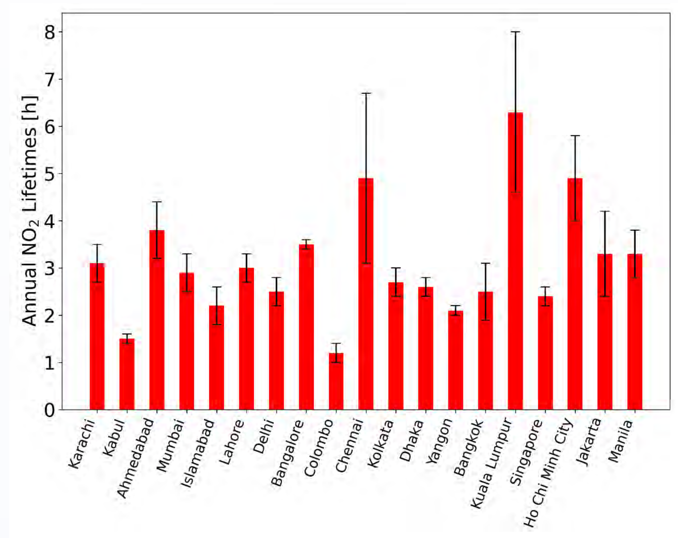
**Number of Successful Annual EMG Fits**



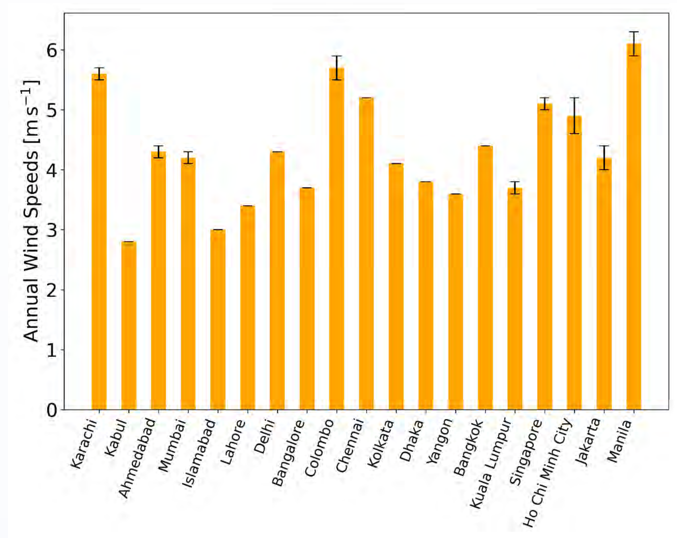

**Annual $NO_x$ Emissions with Standard Deviations**




**Annual Effective $NO_2$ Lifetimes with Standard Deviations**

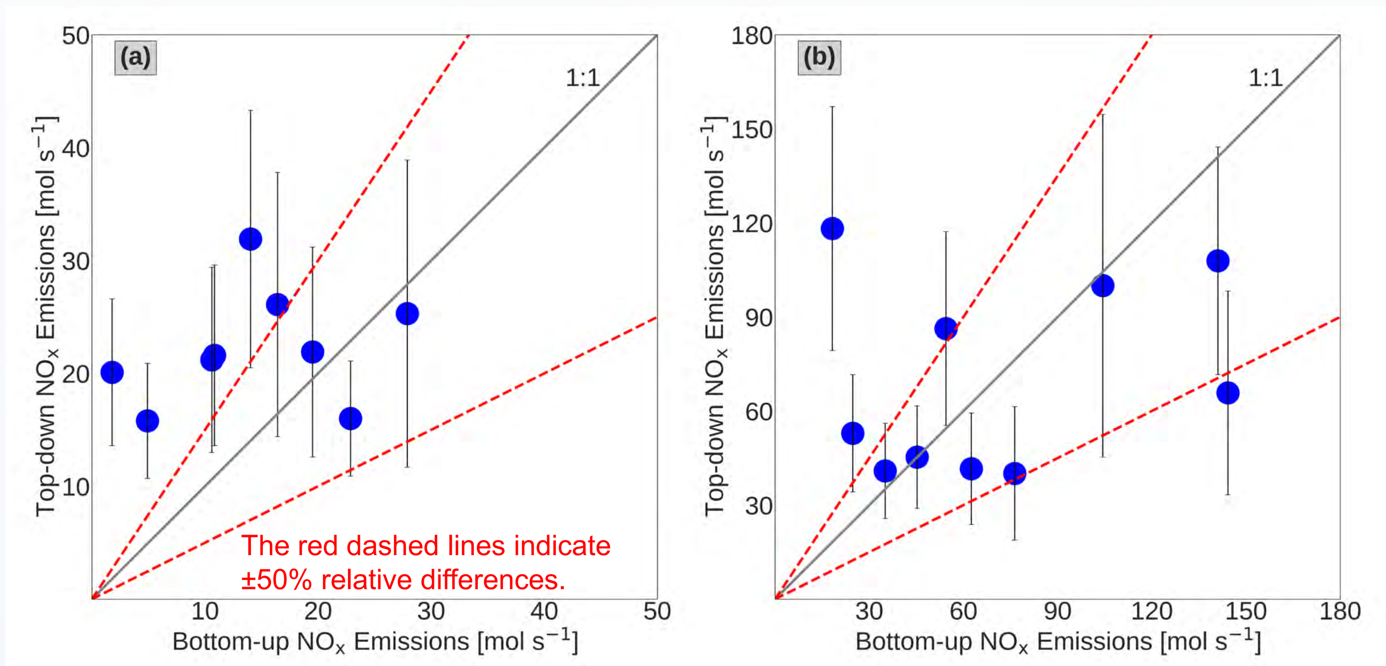



**Annual Wind Speeds with Standard Deviations**



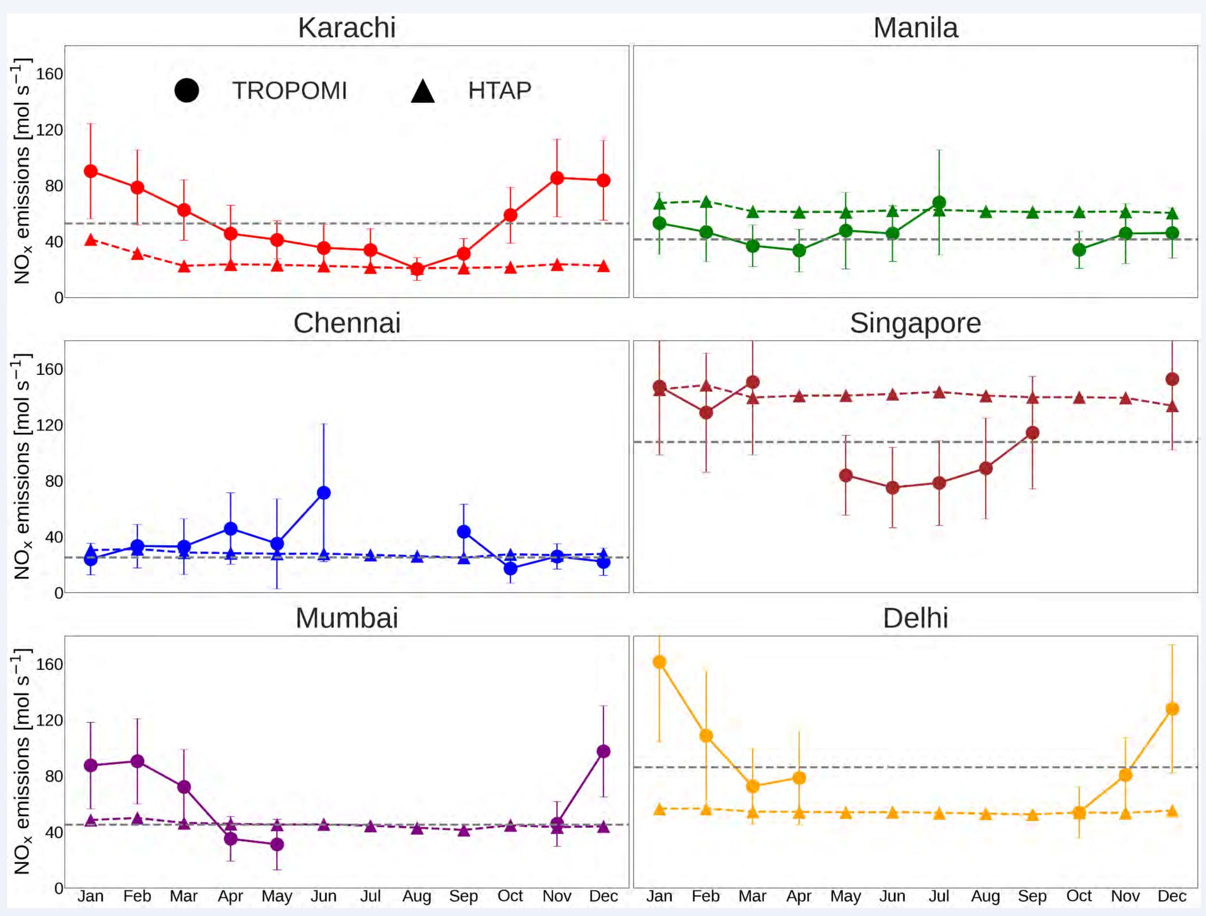

Our method increases success of annual emissions from 40-60% to 100%

**Comparison of Annual Top-down and Bottom-up $NO_x$ Emissions from HTAP**




The relative difference between our top-down estimates HTAP are < 50% for 9 cities, within 50-100% for 5 cities, and much greater for Karachi (114%), Lahore (127%), Yangon (3.2 times), Dhaka (6.5 times), and Kabul (10-fold).

**Monthly Top-down and Bottom-up $NO_x$ emissions**




Top-down monthly emissions typically peak in cold season months, while bottom-up emissions lack monthly variability resulting from seasonality in demand for $NO_x$-producing combustion sources.

## 4. Conclusions

- Our refined method of deriving city $NO_x$ emissions addresses issues of sampling area selection, automates the applications and improves the success.
- Annual emissions are mostly under 50 mol $s^{-1}$, with exceptions in Karachi, Delhi, Jakarta, Bangkok, Dhaka, and Singapore. The discrepancies between top-down and bottom-up estimates are less than 50% discrepancy for 9 cities, 50-100% for 5 cities, and much higher for 5 others.
- Top-down monthly emissions reveals monthly variability that is missing from bottom-up emissions.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