Decoupling the Effects of Anthropogenic Emission Reductions from the Meteorology and Natural Emissions in TROPOMI NO_2 Retrievals During the 2020 COVID-19 Lockdowns

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Many published studies reported unprecedented reductions in NO_2 tropospheric vertical column densities over the world's most populated cities during the 2020 COVID-19 lockdowns.

In estimating how much of the decline was due to a reduction in anthropogenic sources, there were two important sources of uncertainty in the satellite retrievals that were difficult to account for early on:

1) *A priori NO_2 profiles used in the satellite retrievals were not adjusted for the lower anthropogenic emissions observed during the lockdowns*
2) *Meteorological variability in some cases reduced the apparent decline in anthropogenic emissions and in other cases augmented it*

Geophysical Research Letters

RESEARCH LETTER
10.1029/2020GL089269

Special Section:
The COVID-19 pandemic: Linking health, society and

Disentangling the Impact of the COVID-19 Lockdowns on Urban NO_2 From Natural Variability

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Geophysical Research Letters

RESEARCH LETTER
10.1029/2020GL087978

Special Section:
The COVID-19 pandemic: linking health, society and

Impact of Coronavirus Outbreak on NO_2 Pollution Assessed Using TROPOMI and OMI Observations

M. Bauwens[1], S. Compernolle[1], T. Stavrakou[1], J.-F. Müller[1], J. van Gent[1], H. Eskes[2], P. F. Levelt[2,3], R. van der A[2], J. P. Veefkind[2], J. Vlietinck[1], H. Yu[1], and C. Zehner[4]

JGR Atmospheres

RESEARCH ARTICLE
10.1029/2021JD035440

Tropospheric NO_2 and O_3 Response to COVID-19 Lockdown Restrictions at the National and Urban Scales in Germany

Vigneshkumar Balamurugan[1], Jia Chen[1], Zhen Qu[2], Xiao Bi[1], Johannes Gensheimer[1], Ankit Shekhar[3], Shrutilipi Bhattacharjee[4], and Frank N. Keutsch[2,5]

Key Points:
- During the COVID-19 lockdown period, NO_2 concentrations decreased and O_3 concentrations increased in eight German cities
- The degree of NO_x saturation of

Quantifying urban, industrial, and background changes in NO_2 during the COVID-19 lockdown period based on TROPOMI satellite observations

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SCIENCE ADVANCES | RESEARCH ARTICLE

CORONAVIRUS

Abrupt decline in tropospheric nitrogen dioxide over China after the outbreak of COVID-19

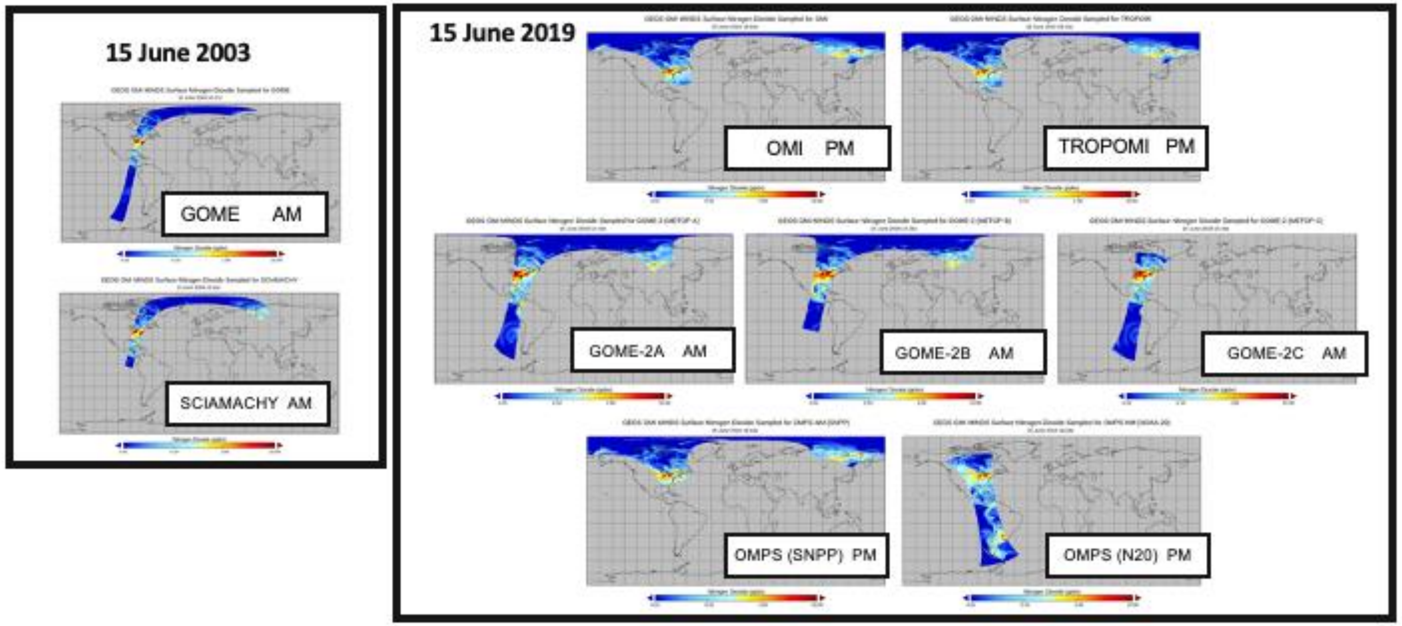
Fei Liu[1,2]*, Aaron Page[3], Sarah A. Strode[1,2], Yasuko Yoshida[2,4], Sungyeon Choi[2,4], Bo Zheng[5], Lok N. Lamsal[1,2], Can Li[2,6], Nickolay A. Krotkov[2], Henk Eskes[7], Ronald van der A[7,8], Pepijn Veefkind[7,9], Pieternel F. Levelt[7,9], Oliver P. Hauser[10]†, Joanna Joiner[2]†

GEOS Global Modeling Initiative (GMI)

GEOS GMI is a full (tropospheric and stratospheric) chemistry CTM run in replay mode, which is constrained by assimilated 3-hr averaged meteorological fields from MERRA-2 [*Orbe et al*., 2017].

Some key features:

- Simulation run at 0.25º longitude x 0.25º latitude resolution globally (~25 km x 25 km)
- Provides 72-layer a priori NO_2 and temperature profiles
- Swath simulator: samples the same longitude, latitude, and time as the measurement



Our Approach

We estimated the mean reductions in TROPOMI Tropospheric NO_2 columns during the 2020 lockdowns by comparing satellite retrievals in 2020 to the same period in 2019. We selected 36 megacities from around the world and considered a 1º x 1º region for two lockdown periods:

1) January 23 to April 1: All seven selected megacities in China
2) March 17 to June 1: All other cities

To account for the 1) changes in the NO_2 anthropogenic emission profiles during the 2020 lockdowns and 2) the effects meteorological variability, we produced three GMI simulations:

- Simulation 1: **2019** with 2019 emissions and 2019 meteorology
- Simulation 2: **2020** with COVID-19 adjusted emissions (Forster et al., *Nature Climate Change*, 2020)
- Simulation 3: **2020BAU** with business-as-usual 2019 emissions and 2020 meteorology

Methodology

- Use the GMI model to disentangle the meteorological and natural emission variability from the anthropogenic emissions in Tropospheric VCDs;

  - ❖ Anthropogenic Emissions: $\overline{\Delta NO2}_{GMI,emis} = \overline{TVCD}_{GMI}[2020] - \overline{TVCD}_{GMI}\ [2020BAU]$
  - ❖ Meteorological Variability: $\overline{\Delta NO2}_{GMI,met} = \overline{TVCD}_{GMI}[2020BAU] - \overline{TVCD}_{GMI}[2019]$

- Estimate the total reduction (% relative to 2019) in mean TROPOMI tropospheric VCDs during the study period using GMI a priori NO_2 profiles adjusted for the lockdowns and corrected for meteorological variability

  - ❖ Change in NO_2 emissions, including meteorological and natural emission variability:

$$\overline{\Delta NO2}_{Tot} = \overline{TVCD}_{Sat}[2020] - \overline{TVCD}_{Sat}[2019]$$

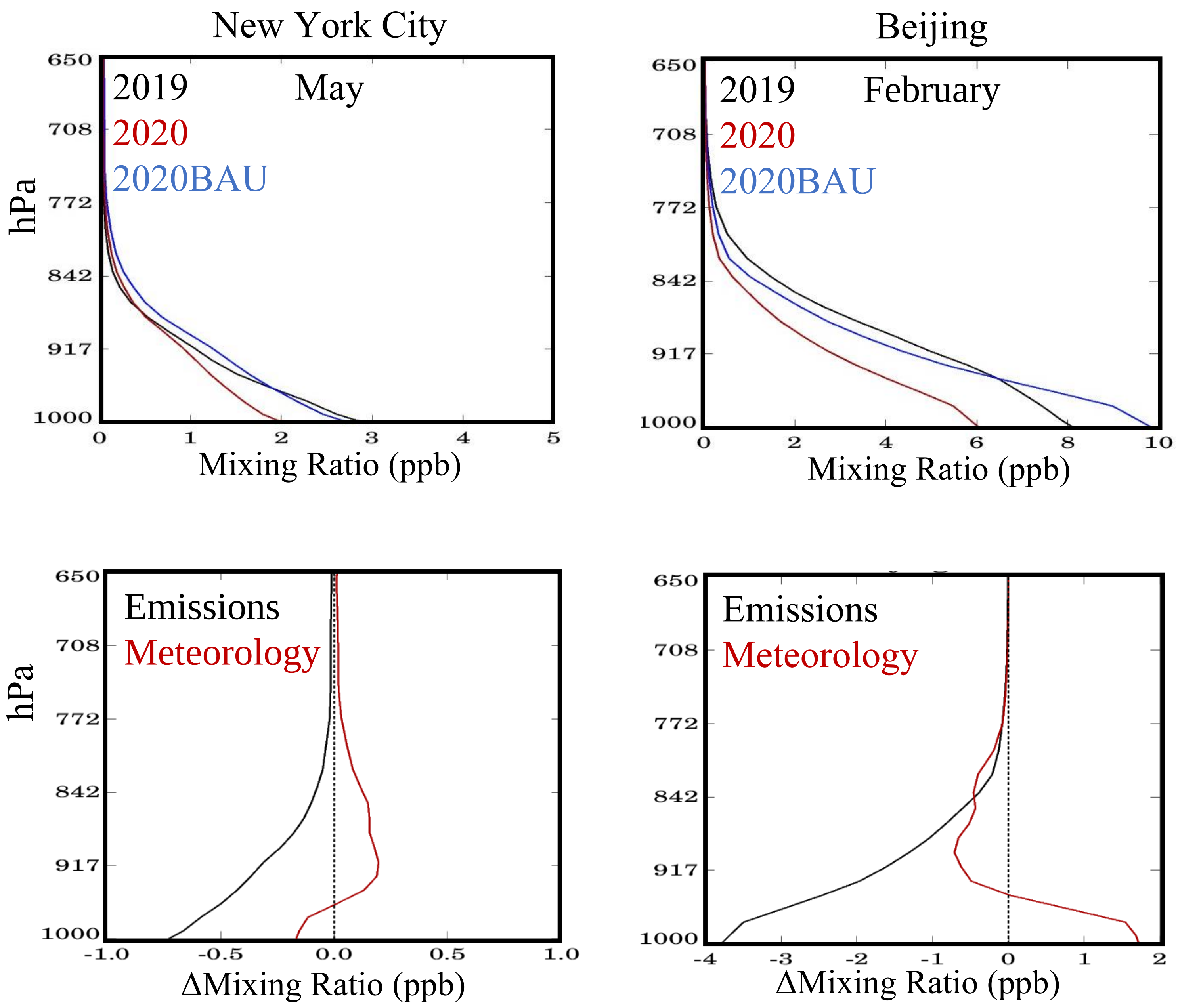
  - ❖ Inferred change in TROPOMI tropospheric NO_2 columns due to anthropogenic NO_2 emissions only (accounting for meteorology):

$$\overline{\Delta NO2}_{Sat,emis} = \overline{\Delta NO2}_{Tot} - \overline{\Delta NO2}_{GMI,met}$$

GMI a Priori NO_2 and dNO_2 profiles for 2019, 2020 and 2020BAU

- In the upper two panels:
  - ❖ The 2020 NO_2 profile shows reduced lockdown emissions relative to 2019.
  - ❖ The 2020BAU profile is affected by the 2020 meteorology and the 2019 emissions

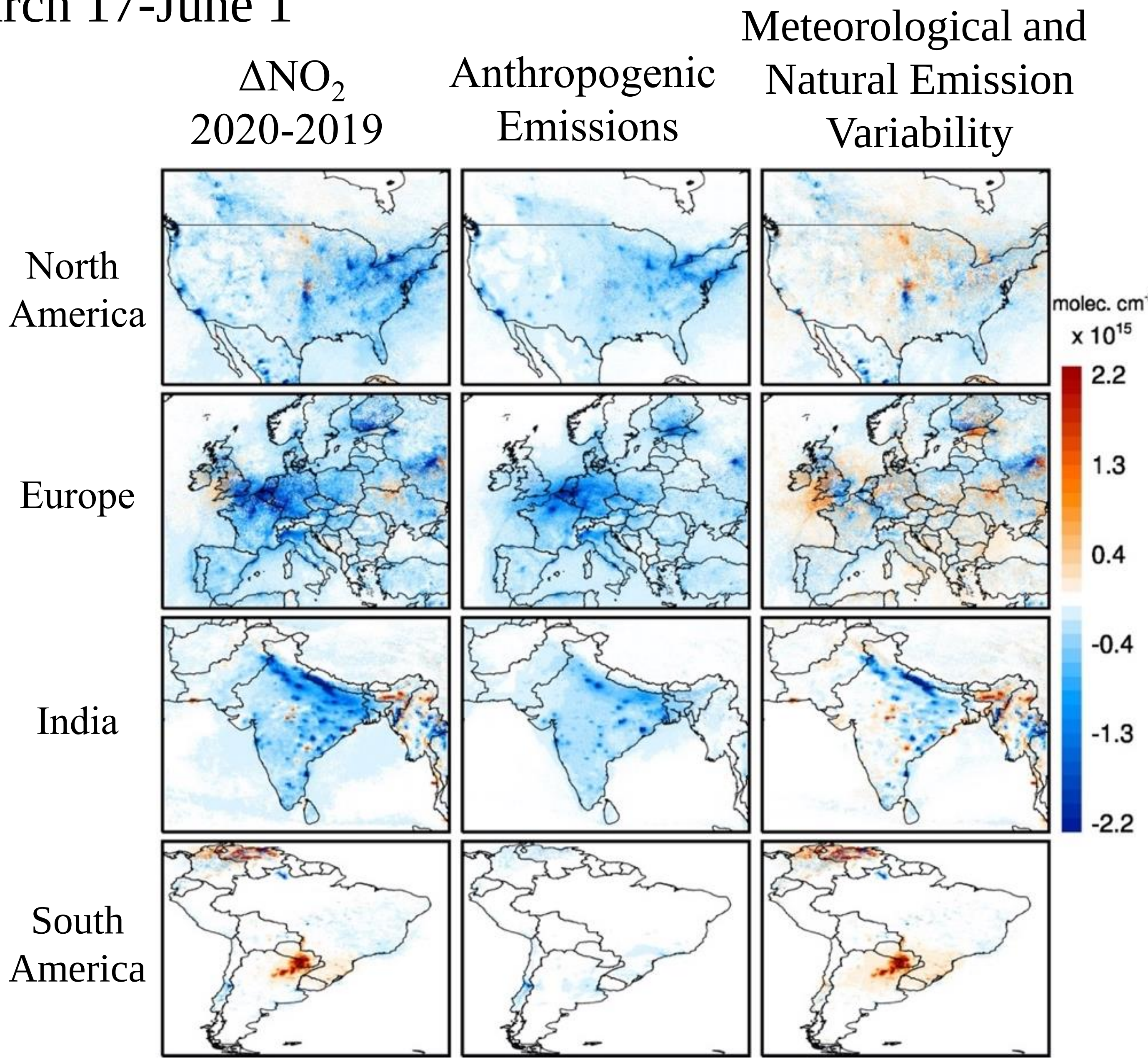
- In the lower two panels:
  - ❖ Anthropogenic emissions display a monotonic decline through the lower troposphere (2020-2020BAU)
  - ❖ Meteorological variability changes sign in the lower boundary layer near the surface (2020BAU-2019)



Change in GMI Tropospheric NO_2 Columns 2020-2019

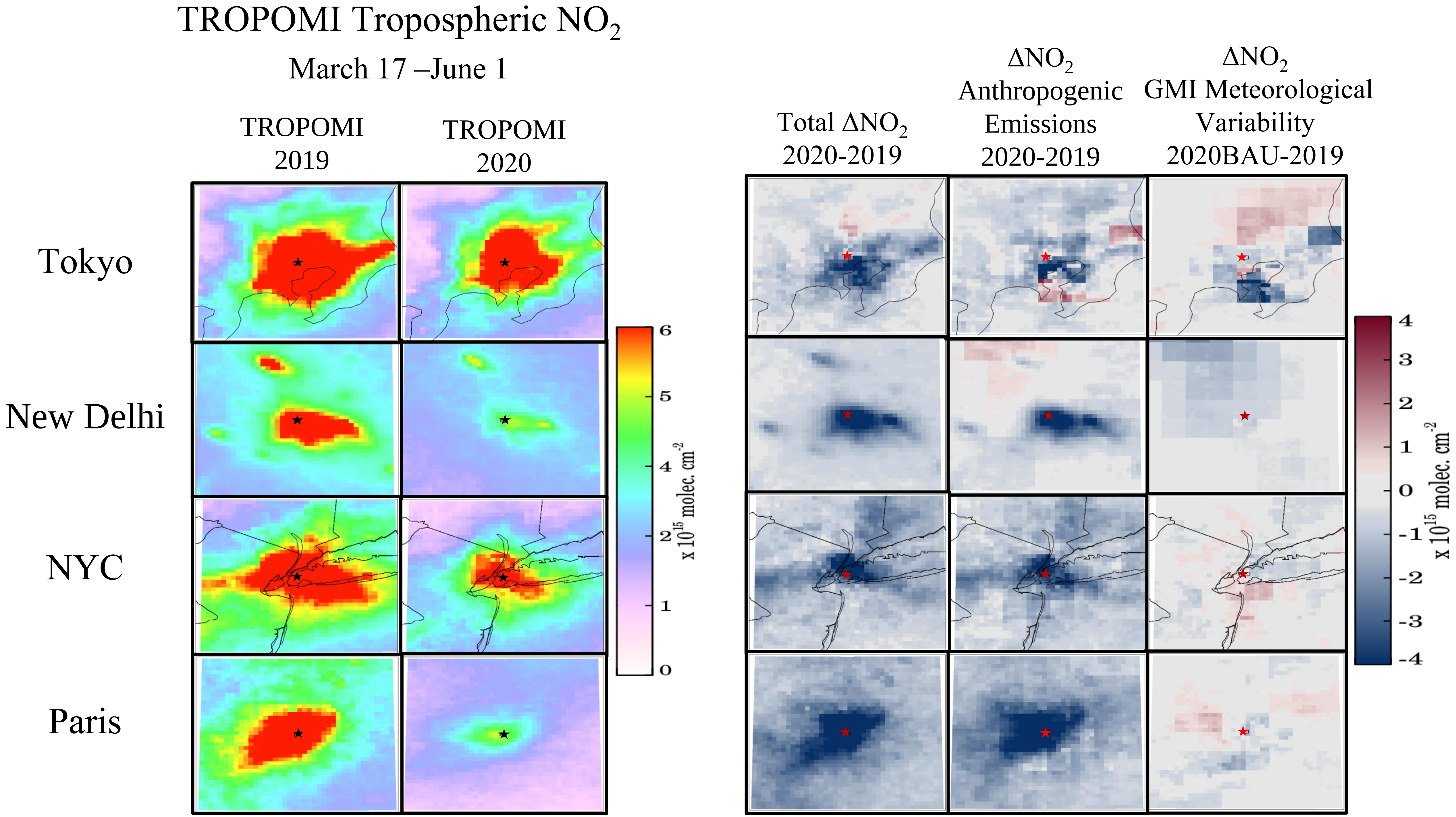
March 17-June 1

- Large reductions in anthropogenic emissions around urban areas (blue)
- In the GMI total change, there are some positive ΔNO_2 regions (red). These regions were affected by meteorological and natural emission variability
  - ❖ Biomass burning in South America
  - ❖ Natural emission variability in the central US
  - ❖ Meteorological variability in Europe and India

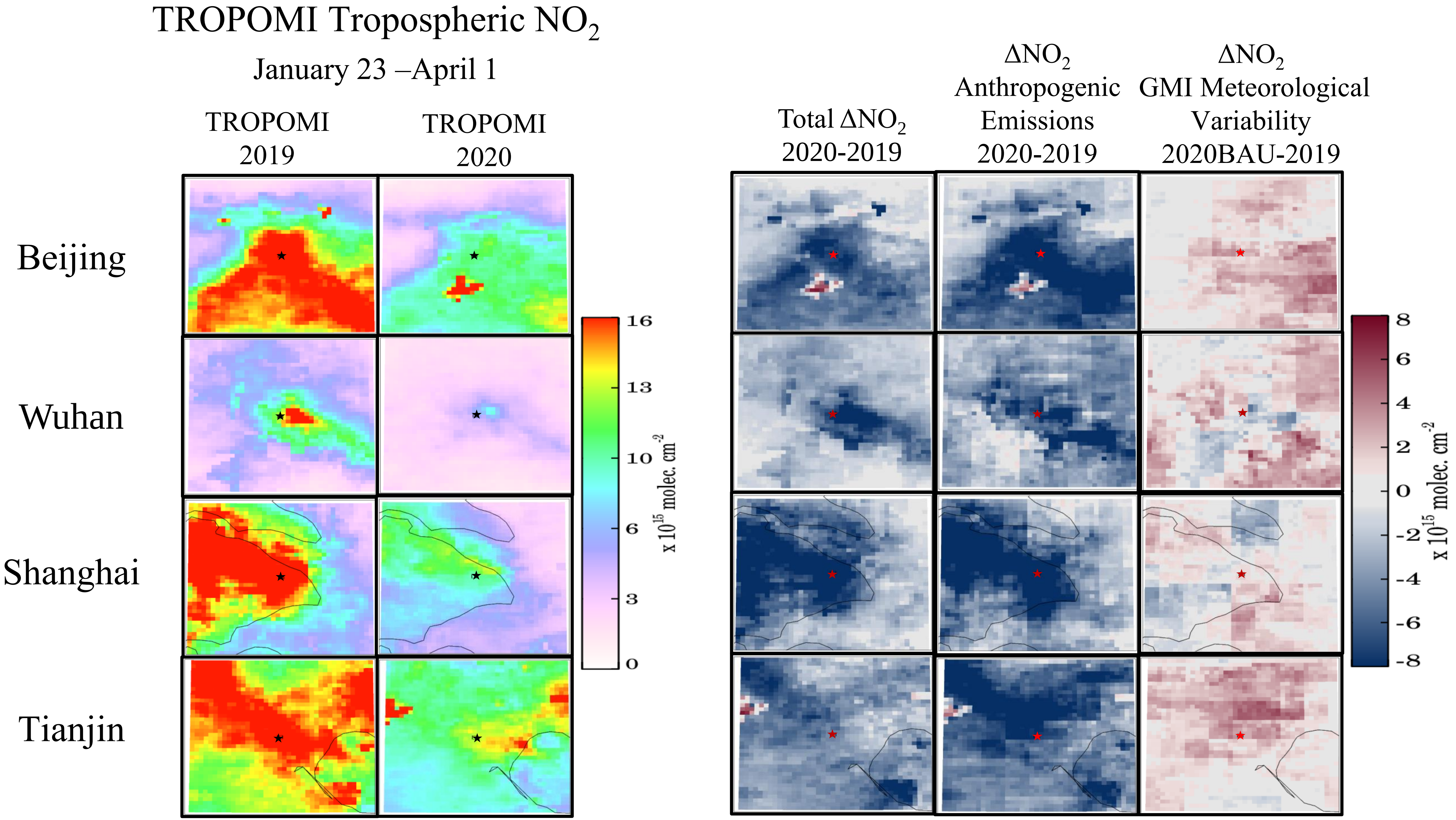


The NASA NO_2 Algorithm Adapted for TROPOMI

- Used NO_2 slant column densities (SCD) in Version 2.3.1 (S5P_PAL)
- Air mass factors (AMF) were calculated using v. 4.0 of the NASA NO_2 algorithm:
  - ❖ GLER – derived from MODIS data (MODIS BRDF/Albedo Product MCD43), accounts for anisotropic variations caused by bidirectional reflectance distribution function (BRDF) effects that vary with sun-satellite geometry and surface characteristics (see Wenhan Qin's poster)
  - ❖ Fresco – re-calculate Fresco cloud parameters using GLER data for NO_2 spectral window (440 nm) to correct for the effect of surface reflectivity
  - ❖ Daily GMI: NO_2 profiles, temperature profiles, surface and tropopause pressures
- Stratosphere-Troposphere separation — data driven approach (Buscela et al., 2013)
- Re-gridded data at 0.05º longitude x 0.05º latitude for the TROPOMI and GMI (qa_value > 0.75)



TROPOMI Tropospheric NO_2
March 17 –June 1
TROPOMI 2019
TROPOMI 2020
Tokyo
New Delhi
NYC
Paris
6
5
4
2
1
0
x 10^{15} molec. cm^{-2}
Total ΔNO_2 2020-2019
ΔNO_2 Anthropogenic Emissions 2020-2019
ΔNO_2 GMI Meteorological Variability 2020BAU-2019
4
3
2
1
0
-1
-2
-3
-4
x 10^{15} molec. cm^{-2}

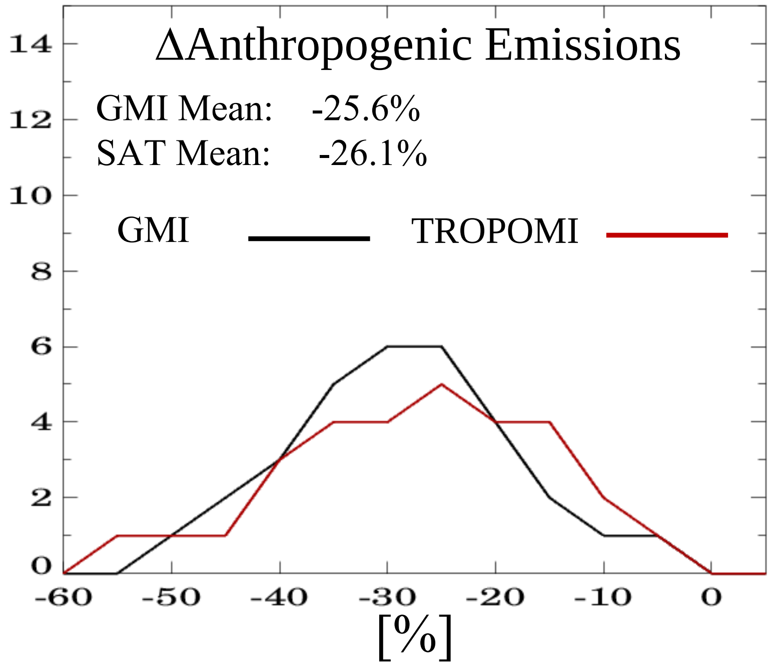

TROPOMI Tropospheric NO_2
January 23 –April 1
TROPOMI 2019
TROPOMI 2020
Total ΔNO_2 2020-2019
ΔNO_2 Anthropogenic Emissions 2020-2019
ΔNO_2 GMI Meteorological Variability 2020BAU-2019
Beijing
Wuhan
Shanghai
Tianjin
16
13
10
6
3
0
x 10^{15} molec. cm^{-2}
8
6
4
2
0
-2
-4
-6
-8
x 10^{15} molec. cm^{-2}

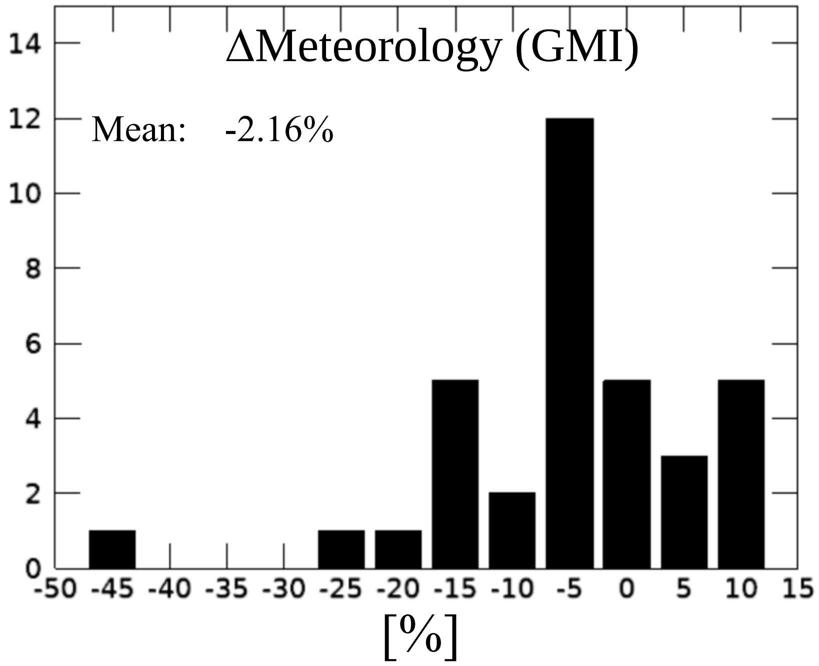
Summary of TROPOMI and GMI NO_2 Reductions for 22 Selected Cities

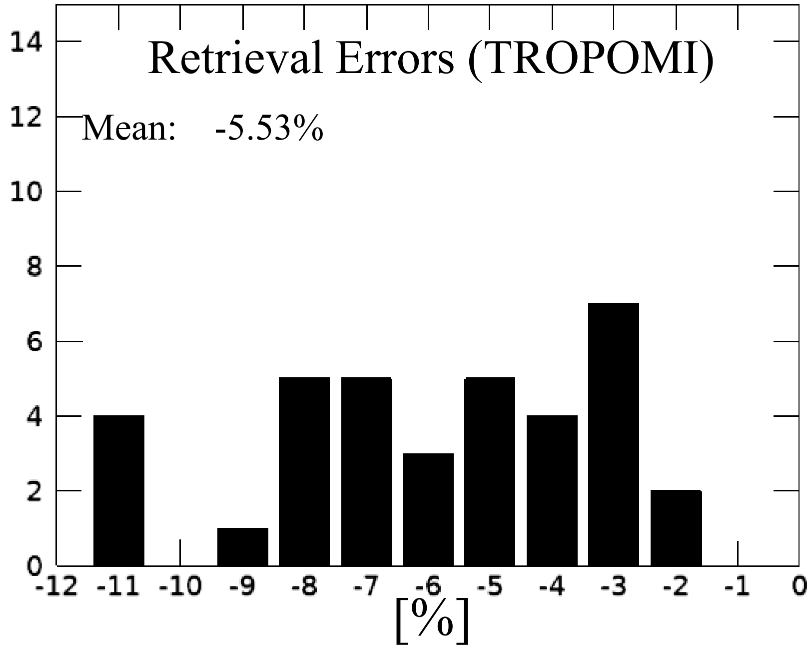
- TROPOMI and GMI yield consistent results with respect to the change in Tropospheric VCDs but some larger differences exist
- Meteorological variability was significant for many cities
  - The NO_2 reductions in anthropogenic emissions for five of the Chinese cities in the study was much greater than originally thought
  - In other cases, the net reductions were notably less due to meteorology, e.g., New Delhi
- Retrieval errors (RE) incurred in using BAU a priori files were systematically negative and contributed as much as ~10% error
  - RE: $\overline{\mathrm{RE}}_{Sat} = \overline{TVCD}_{Sat}[2020] - \overline{TVCD}_{Sat}[2020BAU]$
- Sampling biases (SB) incurred as a result of selective sampling (qa_value > 0.7) accounted for up to 10% error
  - SB: $\overline{SB}_{GMI} = \overline{TVCD}_{GMI,T_{All}} - \overline{TVCD}_{GMI,T_{Sub}}$

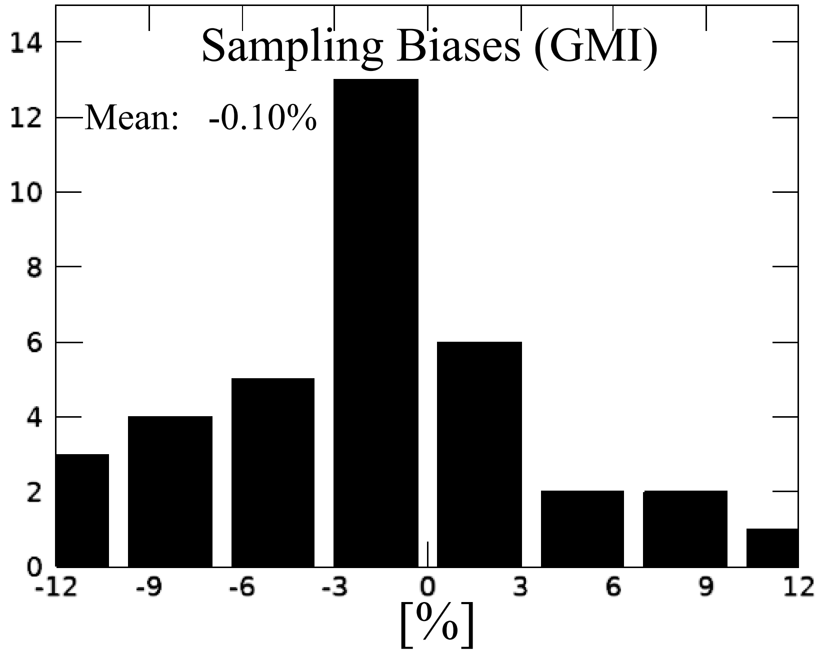
City	Total Change in TropVCD (incl. Met)		Change in Anthropogenic TropVCD		MET	RE	SB
	TROP %	GMI %	TROP %	GMI %	GMI %	TROP %	GMI %
Tokyo	-18.2	-25.9	-15.1	-22.8	-3.1	-3.5	-3.9
New York City	-31.5	-32.8	-30.2	-31.5	-1.3	-7.5	1.0
New Delhi	-28.2	-36.9	-14.7	-23.4	-13.5	-4.7	1.6
Lima	-52.0	-29.4	-49.9	-27.3	-2.1	-4.5	1.4
Moscow	-20.6	-32.7	-6.7	-18.8	-13.9	-2.9	1.0
Lagos	-17.0	4.0	-29.3	-8.3	12.3	-4.9	-6.9
Cairo	-11.6	-28.5	-11.8	-28.7	0.2	-6.3	0.6
Kolkata	-22.3	-28.3	-28.3	-34.3	6.0	-10.6	-2.0
Paris	-49.6	-52.4	-44.9	-47.7	-4.7	-6.8	1.7
Seoul	-26.6	-21.4	-17.3	-12.1	-9.3	-1.4	2.7
Mexico City	-25.7	-35.0	-13.8	-23.1	-11.9	-7.0	1.1
Istanbul	-37.9	-27.2	-37.4	-26.7	-0.5	-6.9	-1.8
Manila	-34.5	-27.6	-27.0	-20.1	-7.5	-10.3	5.1
Kinshasa	6.9	13.8	-7.6	-0.7	14.5	-1.6	-6.3
Lahore	-21.2	-33.0	2.6	-9.2	-23.8	-3.1	-1.9
Tehran	-28.3	-39.6	-26.8	-38.1	-1.5	-4.3	1.0
Chongqing	-7.0	-19.8	-21.0	-33.8	14.0	-3.6	-4.7
Shanghai	-44.4	-27.5	-51.5	-34.6	7.1	-1.7	4.7
Wuhan	-53.1	-29.0	-64.1	-40.0	11.0	-2.6	-2.3
Beijing	-32.1	-21.5	-46.5	-35.9	14.4	-3.5	-8.2
Tianjin	-28.0	-21.6	-41.5	-35.1	13.5	-2.2	-10.9
Guangzhou	-44.0	-36.5	-32.6	-25.1	-11.4	-2.1	10.1

Statistical Summary: ΔNO_2 and Errors







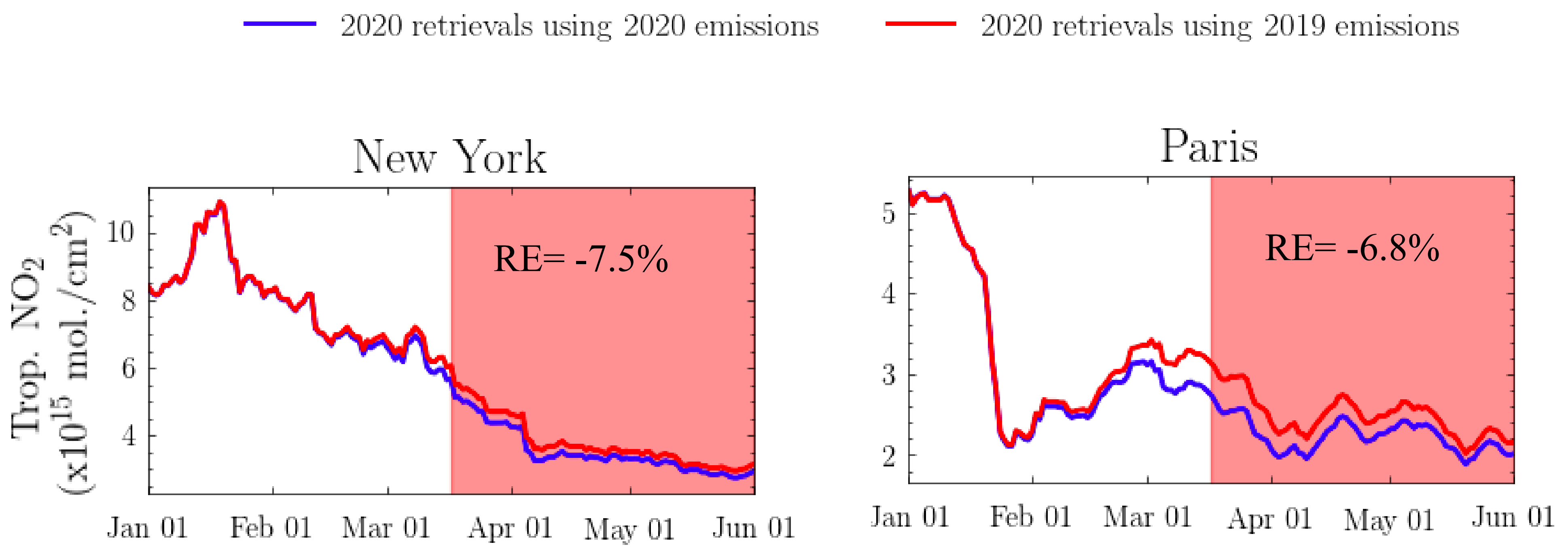


Conclusions

- For 36 megacities, we estimated NO_2 reductions in the TROPOMI tropospheric VCD columns during the COVID-19 lockdown periods by using three GMI simulations to separate the anthropogenic emissions from the meteorological and natural emission variability
- The effects of meteorological variability significantly impacted the mean estimates for many of the selected cities: Meteorological effects were non-uniformly distributed within the study region and ranged between -40.5 % (Chennai) and 15% (Beijing)
- We found that when using the BAU NO_2 GMI profile information in place of lockdown-corrected emissions, the errors were systematically negative and ranged from -1.4% (Seoul) to -11.0% (Mumbai)
- Sampling Biases due to selective sampling were randomly distributed around zero and ranged between ±10%

Backup Slides

Satellite Retrieval Errors



- Retrieval error: $\overline{\mathrm{RE}}_{Sat} = \overline{TVCD}_{Sat}[2020] - \overline{TVCD}_{Sat}[BAU]$

Satellite retrieval error represents the differences in the two time series plots