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Supporting Information for

Did the COVID-19 Crisis Reduce Free Tropospheric Ozone across the Northern Hemisphere?

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Introduction

The supplementary material presented here gives additional information on:

- the annual progression of observed and CAMS-simulated ozone anomalies in 2020 and in previous years
- the magnitude of tropospheric ozone reductions that might have been caused by the large springtime ozone depletion of the Arctic stratosphere in 2020.
- the numerical values of the average tropospheric ozone reduction observed in 2020 at the individual stations, and simulated by CAMS at the closest gridpoints.

Text S1.

Figure S1 shows the annual cycle of ozone anomalies observed in the years 2000 to 2020, or simulated by the CAMS re-analyses. The observations show unusual, negative anomalies in 2020, whereas CAMS anomalies in 2020 are within the usual range. The variation over the year 2020 is comparable in observations and CAMS, but the observed monthly anomalies in 2020 are 5 to 10% lower than CAMS. This is attributed to the missing COVID-19 emission reductions in the CAMS simulations, which rely on "business as usual" emissions for 2020. Negative CAMS anomalies from March to May 2020 could indicate tropospheric effects of the large Arctic stratospheric ozone depletion in the spring of 2020.

Text S2.

Figure S2 shows the difference between two simulations by the Global Modeling Initiative (GMI) chemistry transport model (Strahan et al., 2019), based on meteorological fields from MERRA2 re-analysis (Gelaro et al., 2017). One simulation includes the large Arctic ozone depletion caused in spring 2020 by heterogeneous chemistry in the polar vortex; the other simulation does not. The difference between both simulations provides an estimate for the effect of 2020 Arctic stratospheric depletion on ozone in the troposphere. According to the simulations, the tropospheric effect is similar at most latitudes north of 40° to 50°N. It is smaller than 1 ppbv (or ≈2%) on average, and is largest in June 2020.

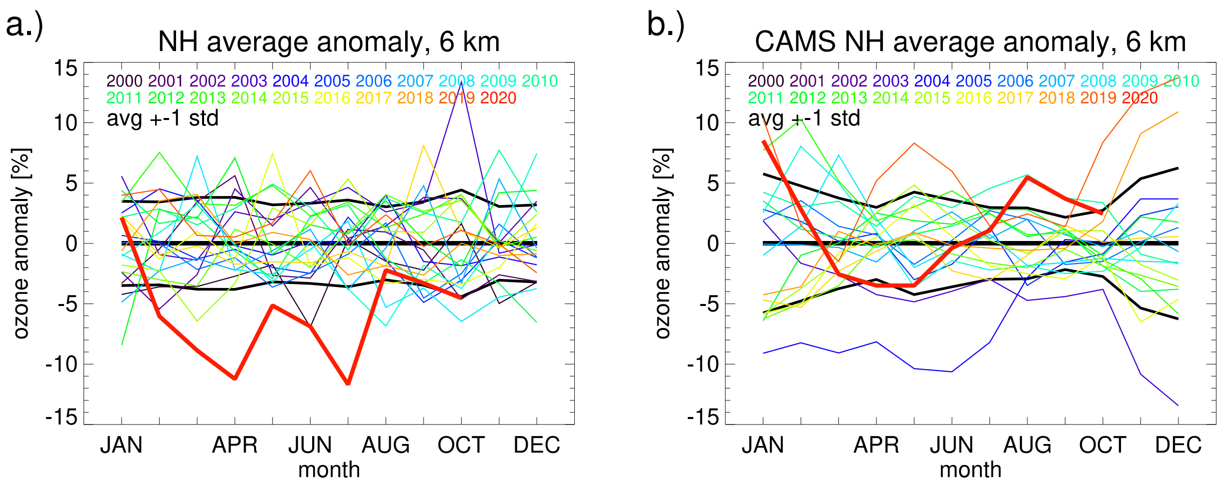

Figure S1. Variation over the year for monthly mean ozone anomalies at 6 km, averaged over all stations north of 15°N (Northern Extra-Tropics). Anomalies are relative to the 2000 to 2020 climatological mean for each calendar month. Colored lines: different years from 2000 to 2020. Thick red line: for the year 2020. Panel a) sonde, FTIR and lidar observations. Panel b) Copernicus Atmosphere Monitoring Service (CAMS) atmospheric composition re-analyses at the grid-points next to the stations. Black lines: average anomaly for each calendar month (zero by definition), and ±1 standard deviations.

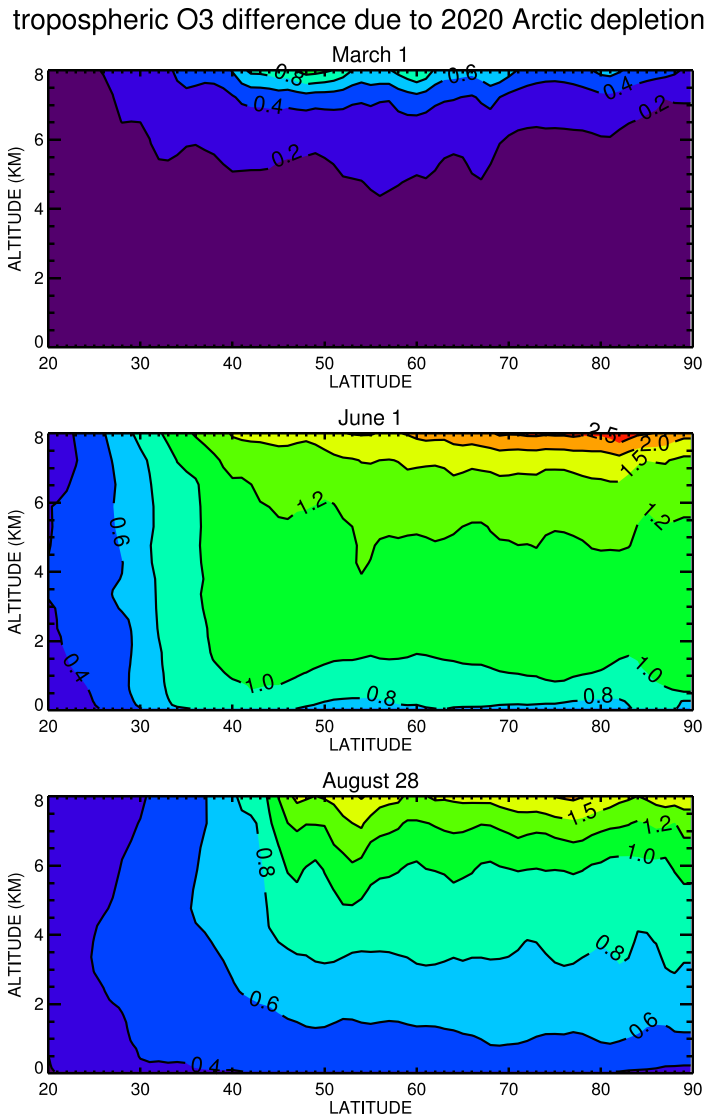

Figure S2. Latitude - altitude cross sections of tropospheric ozone reductions (in ppbv), attributed to the large Arctic springtime stratospheric ozone depletion of 2020. Latitudes go from 20°N to 90°N. Altitudes go from 0 km to 8 km. Top panel is for March 1^{st}, middle panel for June 1^{st}, bottom panel for August 28^{th}. Results are from two simulations by the Global Modeling Initiative (GMI) chemistry transport model (Strahan et al., 2019), based on meteorological fields from the MERRA2 re-analysis (Gelaro et al., 2017). One simulation includes ozone depletion caused by heterogeneous chemistry in the Arctic polar vortex. The other simulation does not. The plotted difference gives an estimate, how much the large Arctic stratospheric ozone depletion in spring 2020 contributed to reduced ozone in the troposphere.

Station	**Latitude (deg N)**	**Longitude (deg E)**	**observed average anomaly 2020 [%]**	**CAMS average anomaly 2020 [%]**
Alert, Canada	82.50	-62.34	N/A	-5.5
Eureka, Canada	80.05	-86.42	N/A	-5.8
Ny-Ålesund, Norway	78.92	11.92	-9.6	-5.5
Ny-Ålesund FTIR, Norway	*78.92*	*11.92*	*-15.5*	*-5.5*
Thule FTIR, Greenland	*76.53*	*-68.74*	*-9.3*	*-3.2*
Resolute, Canada	74.72	-94.98	N/A	-4.5
Scoresbysund, Greenland	70.48	-21.95	-22.9	-4.4
Kiruna FTIR, Sweden	*67.41*	*20.41*	*-4.1*	*-4.1*
Sodankylä, Finland	67.36	26.63	-11.9	-4.2
Lerwick, United Kingdom	60.13	-1.18	-8.0	-2.6
Churchill, Canada	58.74	-93.82	N/A	-2.4
Edmonton, Canada	53.55	-114.10	N/A	-0.2
Goose Bay, Canada	53.29	-60.39	N/A	-0.7
Bremen FTIR, Germany	*53.13*	*8.85*	*-8.2*	*-1.3*
Legionowo, Poland	52.40	20.97	-5.8	-2.6
Lindenberg, Germany	52.22	14.12	-11.1	-2.3
DeBilt, Netherlands	52.10	5.18	-6.0	-0.9
Valentia, Ireland	51.94	-10.25	-5.5	-0.5
Uccle, Belgium	50.80	4.36	-6.6	-0.4
Hohenpeissenberg, Germany	47.80	11.01	-10.3	-0.6
Zugspitze FTIR, Germany	*47.42*	*10.98*	*-8.1*	*0.3*
Jungfraujoch FTIR, Switzerland	*46.55*	*7.98*	*-5.7*	*3.9*
Payerne, Switzerland	46.81	6.94	-10.2	0.2
Haute Provence, France	43.92	5.71	-5.1	-0.5
Haute Provence LIDAR, France	*43.92*	*5.71*	*-1.6*	*-0.5*
Toronto FTIR, Canada	*43.66*	*-79.40*	*-4.9*	*-0.1*
Trinidad Head, California, USA	41.05	-124.15	-12.0	-1.3
Madrid, Spain	40.45	-3.72	-6.3	0.4
Boulder, Colorado, USA	39.99	-105.26	-4.3	7.8
Boulder FTIR, Colorado, USA	*39.99*	*-105.26*	*-9.8*	*7.8*
Tateno (Tsukuba), Japan	36.05	140.13	-3.6	0.5
Table Mountain LIDAR, California, USA	*34.40*	*-117.70*	*-2.6*	*4.7*
Izana, Tenerife, Spain	28.41	-16.53	-1.6	0.0

Izana FTIR, Tenerife, Spain	*28.30*	*-16.48*	*-6.3*	*0.0*
Hong Kong, China	22.31	114.17	0.0	3.2
Hilo, Hawaii, USA	19.72	-155.07	-1.7	5.6
Mauna Loa FTIR, Hawaii, USA	*19.54*	*-155.58*	*N/A*	*5.6*
Northern extratropical station average ±standard deviation	50.94 ±16.98	-29.57 ±66.63	**-7.5 ±4.6**	**-0.5 ±3.6**
Paramaribo, Suriname	5.81	-55.21	-1.0	3.6
Pago Pago, American Samoa	-14.25	-170.56	-10.8	-3.0
Suva, Fiji	-18.13	178.32	-5.8	-5.2
Wollongong FTIR, Australia	*-34.41*	*150.88*	*0.3*	*0.8*
Broadmeadows, Australia	-37.69	144.95	1.3	2.3
Lauder, New Zealand	-45.04	169.68	-1.4	1.4
Lauder FTIR, New Zealand	*-45.04*	*169.68*	*3.7*	*1.4*
Macquarie Island, Australia	-54.50	158.94	1.7	3.0
Tropical and Southern Hemisphere station average ±standard deviation	-30.41 ±20.00	93.33 ±131.40	**-1.5 ±4.7**	**0.5 ±3.1**

Table S1. Similar to Table 1, but showing the average April to August, 1 to 8 km, tropospheric ozone anomaly observed in 2020 at each station, and simulated at the CAMS grid-point next to the station. Two additional rows (**bold-face**) show the 2020 tropospheric anomaly averaged over all northern extratropical stations, and averaged over Tropical and Southern Hemisphere stations.