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Supporting Information for

NASA satellite measurements show global-scale reductions in free tropospheric ozone in 2020 and again in 2021 during COVID-19

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Additional Supporting Information (Files uploaded separately).

No additional information such as tables, movies, or audio.

Introduction.

The Supporting Information includes additional information beyond the main text regarding the measurements of ozone, NO_2, and aerosols from satellite. The Nino 3.4 El Nino Southern Oscillation (ENSO) index time series is also included as reference.

S1. Measurements of Tropospheric Ozone from EPIC, OMPS, and OMI.

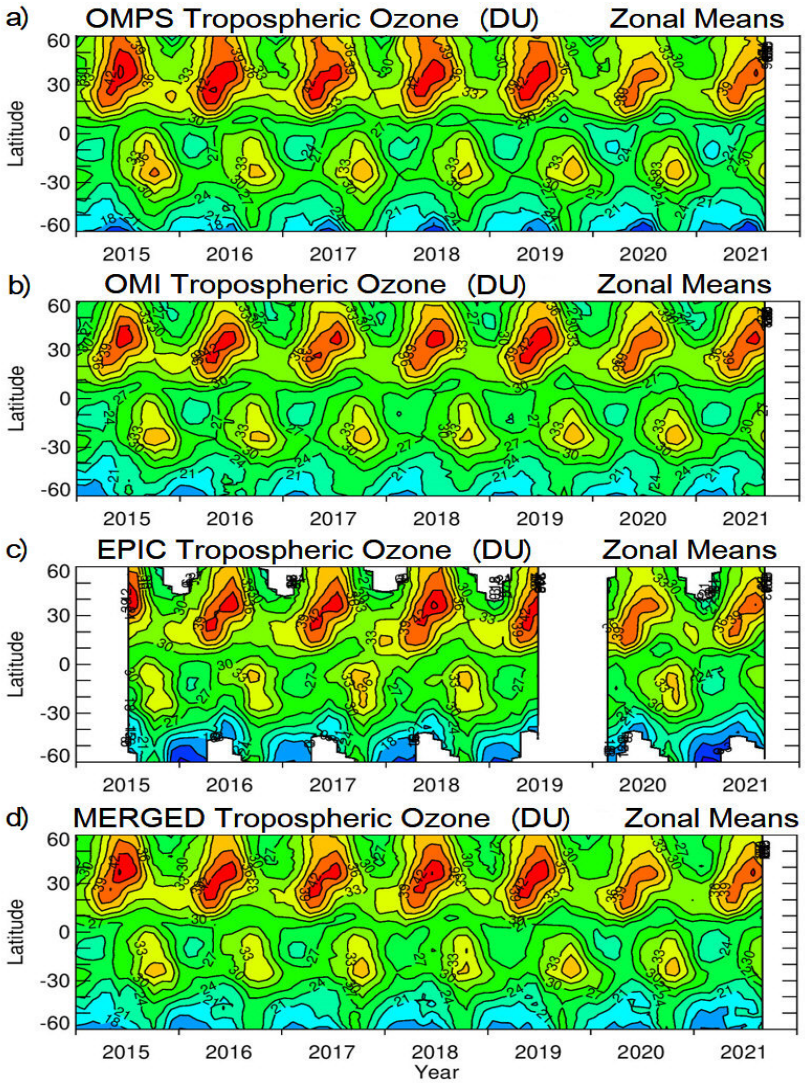

Figure S1. (a) OMPS nadir-mapper monthly zonal-mean TCO (in DU) plotted as latitude versus year. Contour values are indicated and increment by 3 DU. (b) Same as

(a) but for OMI. (c) Same as (a) but for EPIC. (d) Same as (a) but for the merged dataset. The merged TCO is determined by averaging the three individual measurements by their overall daily global coverage (e.g., weightings of 1.0 for OMPS and EPIC, and ~0.7 for OMI). All three top panels for OMPS, OMI, and EPIC (and bottom panel for the merged dataset) indicate anomalous drops in TCO of ~3 DU in years 2020 and 2021 in the NH compared to previous years 2015-2019.

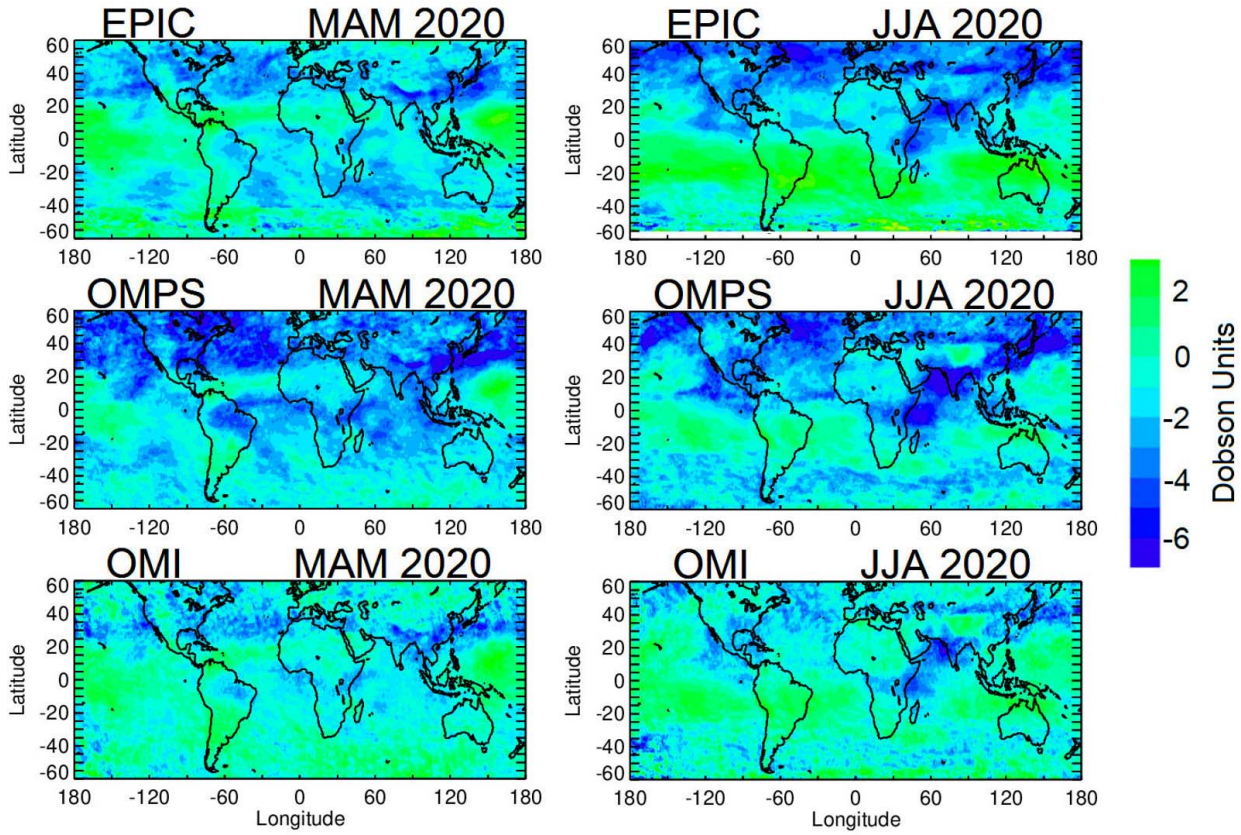

Figure S2. Year 2020 TCO inter-annual anomalies (see main text for calculation method) for March-April-May (MAM) spring season (left three panels) and June-July-August (JJA) summer season (right three panels) for EPIC, OMPS, and OMI measurements (indicated). Color bar indicates that green shades are positive anomalies while blue shades beginning with cyan are negative. Inter-annual anomalies were determined by removing 2016-2019 average gridded monthly seasonal cycles from original gridded monthly mean TCO data.

S2. OMI NO_2 Tropospheric Column Inter-Annual Anomalies.

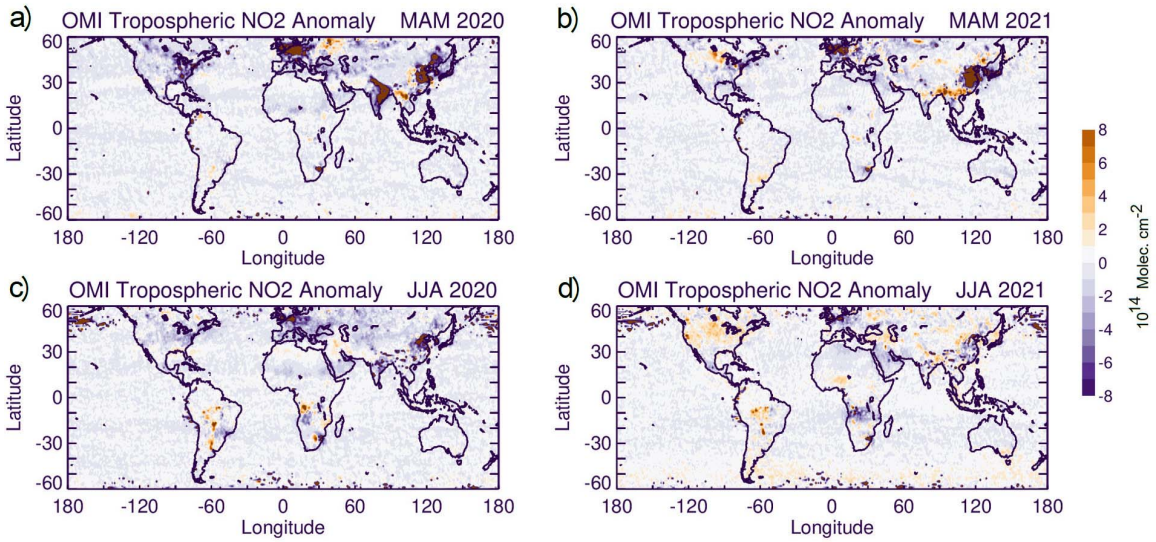

Figure S3. Year 2020 OMI column NO_2 inter-annual anomalies for (a) March-April-May (MAM) spring season and (c) June-July-August (JJA) summer season. All NO_2 column anomalies (units 10^{14} molec. cm^{-2}) are calculated by subtracting the 2016-2019 baseline seasonal NO_2 averages. (b) and (d) are the same as (a) and (c), respectively, but for year 2021. Color bar indicates that orange-red shades represent positive anomalies while blue shades are negative anomalies. Uncertainty (1σ precision) for OMI NO_2 footprint measurements is about 35% (e.g., Marchenko et al., 2015, and references therein), that is, ~0.3×10^{14} molec. cm^{-2}. It follows that 1σ uncertainties for monthly-mean NO_2 are then about 0.3×10^{14} molec. cm^{-2}/sqrt(30) = 0.5×10^{13} molec. cm^{-2}. The regional negative anomalies for NO_2 in Fig. S3 shaded dark blue up to -8×10^{14} molec. cm^{-2} lie well outside monthly 1σ uncertainties.

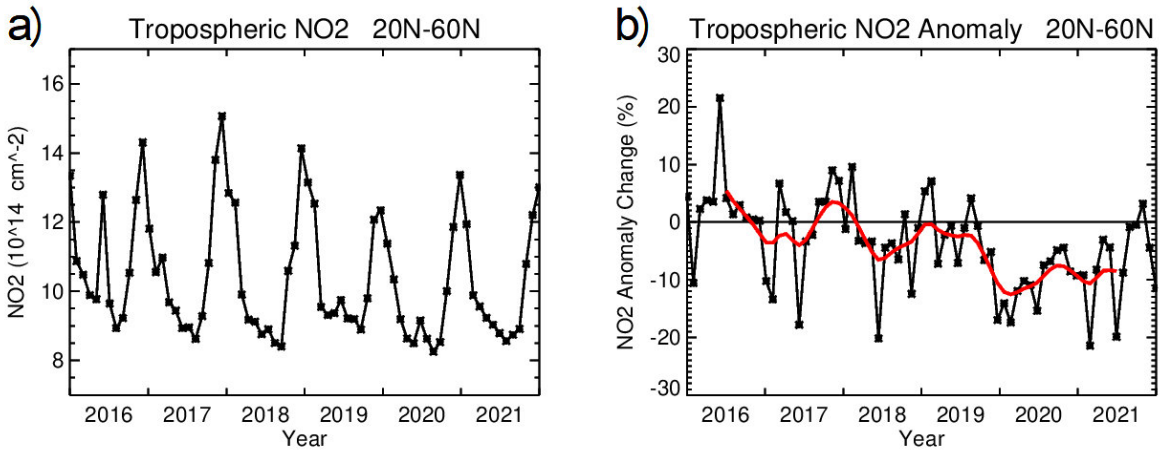

Figure S4. (a) Monthly time series of column NO_2 (in units 10^{14} molec. cm^{-2}) for 2016-2021 averaged over the NH for 20°N-60°N (similar to Fig. 1 of the main text for TCO). (b) Inter-annual anomaly time series of the monthly NO_2 from (a) derived using baseline of 2016-2019 NO_2 data. The smooth red curve represents a 12-month running mean of the inter-annual data.

S3. Nino 3.4 Index Time Series for Tropical ENSO Variability.

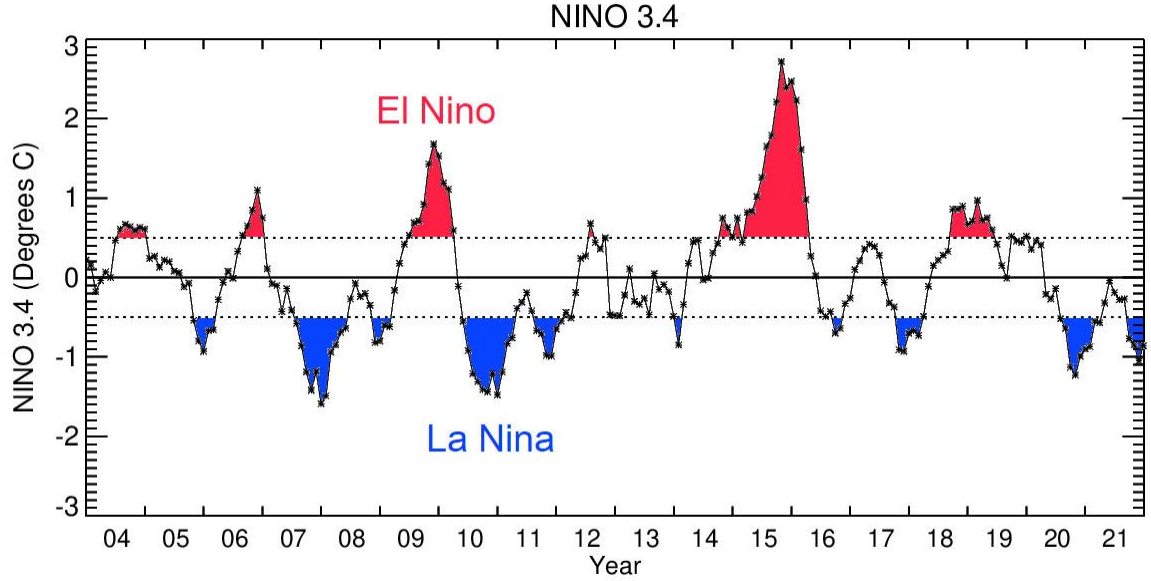

Figure S5. Nino 3.4 index of El Nino Southern Oscillation (ENSO) temperature anomalies in degrees Celsius. The Nino 3.4 data is from the National Oceanic and Atmospheric Administration (NOAA)

(https://www.cpc.ncep.noaa.gov/data/indices/sstoi.indices/). Red (blue) denotes Nino 3.4 temperature anomaly greater than (less than) 0.5 C^o (-0.5 C^o) (e.g., dashed horizontal lines). An official El Nino (La Nina) event occurs when the Nino 3.4 temperature anomaly for five or more consecutive months is greater than (less than) 0.5 C^o (-0.5 C^o).

S4. The Extended Merged Record (2004-2021) of TCO.

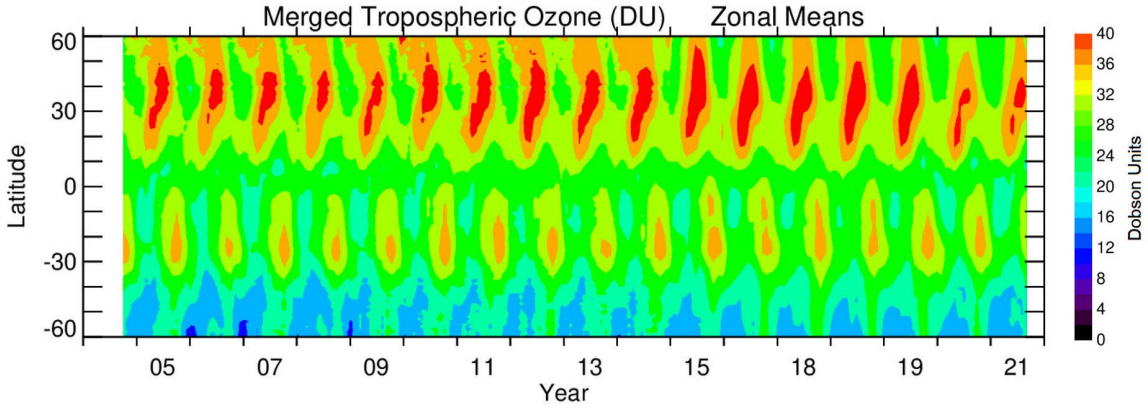

Figure S6. Extended long-record record of TCO derived by appending OMI/MLS TCO for October 2004-December 2014 to the merged OMPS+OMI+EPIC TCO for January 2015-December 2021 (see text). Aura OMI/MLS measurements of monthly TCO for October 2004 – December 2014 (Ziemke et al., 2006) were appended to the OMPS+OMI+EPIC 2015-2021 merged TCO record to evaluate anomalous changes in 2020 and 2021 relative to all years dating back to 2004. The OMI/MLS TCO in 2004-2016 were adjusted using 48-month mean differences (2016-2019) between OMI/MLS and the merged OMI/OMPS/EPIC TCO at each 1^o latitude spacing.

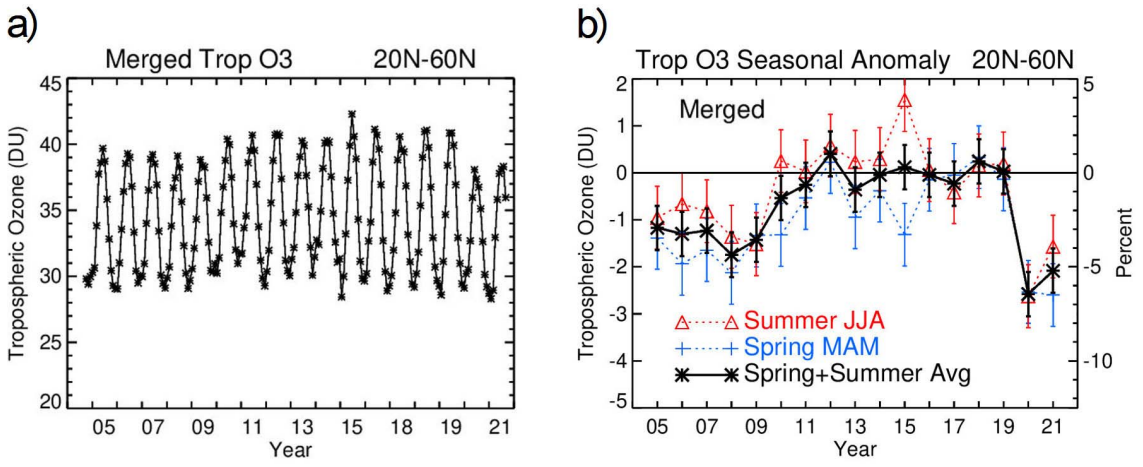

Figure S7. (a) Monthly time series of TCO (in DU) averaged over the NH for 20°N-60°N for August 2004 – August 2021. (b) Corresponding inter-annual anomaly time series of TCO (in DU) derived by subtracting 2016-2019 seasonal means for NH spring (MAM), NH summer (JJA), and the spring-summer average. Vertical bars represent ±1σ standard deviation values.

S5. Calculated Standard Deviations for TCO Inter-Annual Anomalies.

Temporal standard deviations were calculated for the monthly inter-annual anomalies of TCO by season, both regionally (Fig. S8), and as zonal means of these regional values (Fig. S9). Standard deviations were calculated from the 48-month baseline 2016-2019 time period inter-annual measurements. The largest standard deviations in Fig. S8 lie mostly in tropical latitudes. Regional standard deviations outside the tropics in Fig. S8 lie in the range 1-1.5 DU (blue shades). When zonally averaged, the seasonal standard deviations in Fig. S8 are around 1 DU in all seasons as indicated in Fig. S9.

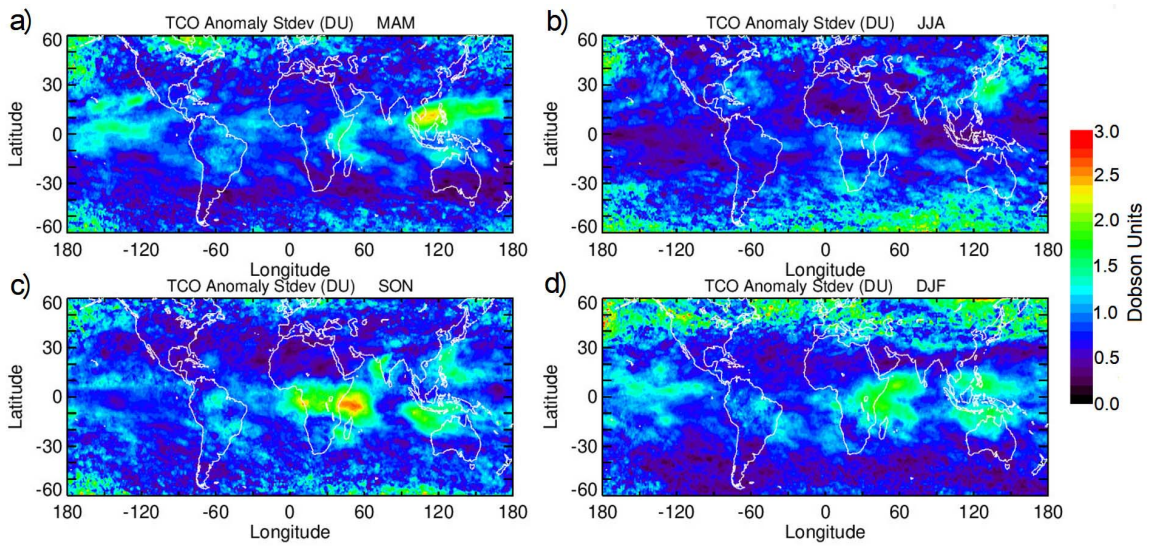

Figure S8. (a) Calculated standard deviations (in DU) of TCO inter-annual anomalies for March-April-May (MAM). (b, c, d) Same as (a), but for seasons JJA, SON, DJF, respectively. All standard deviations were calculated from the 48-month baseline 2016-2019 time period. Dark blue shades indicate values less than 1 DU.

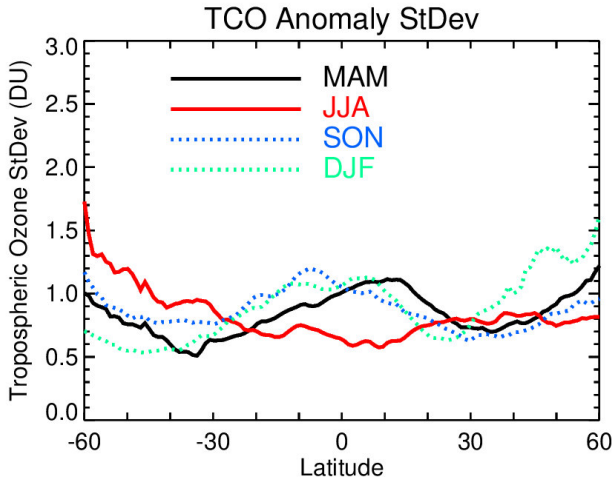

Figure S9. Calculated standard deviations (in DU) of TCO inter-annual anomalies for MAM, JJA, SON, and DJF seasons (indicated). These line plots represent zonal averages of the regional standard deviations plotted in Figure S8.

S6. Extreme Indian Ocean Dipole Positive Phase Event During 2019.

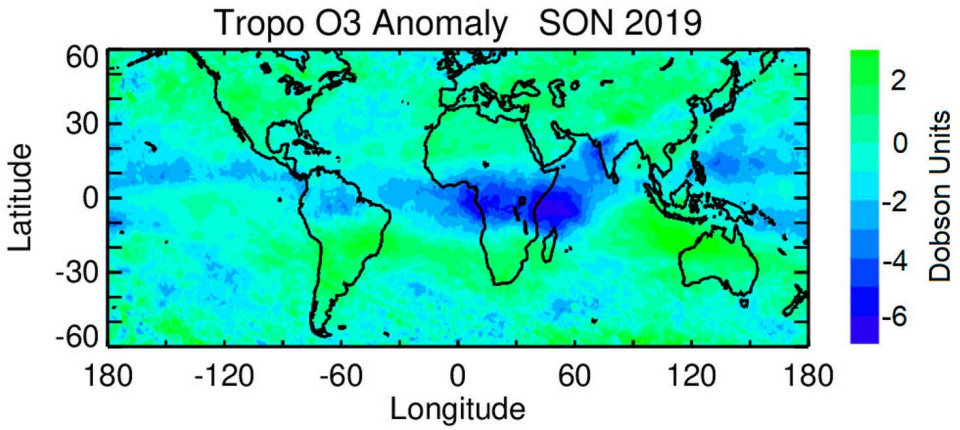

Figure S10. Merged TCO inter-annual anomalies (in DU) seasonally averaged for September-October-November 2019 showing effects form intense Indian Ocean Dipole (IOD) positive-phase event which decreased TCO over tropical Africa and east of Africa. The reduced TCO was due to increased deep convection causing upward transport of low concentrations of ozone and ozone precursors from the oceanic BL east of Africa. These reductions in TCO about Africa created the negative anomaly in tropical zonal-mean TCO in 2019 seen in Fig. 2.

S7. Aerosol Index Anomalies.

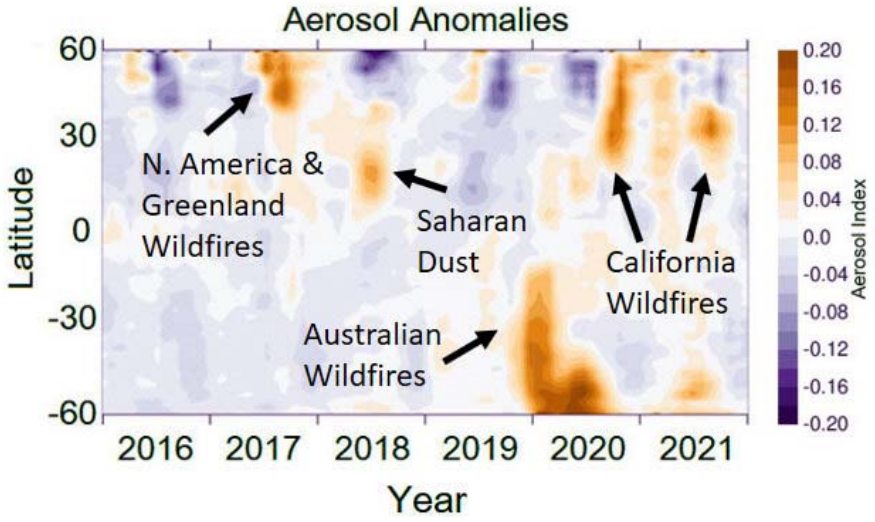

Figure S11. Monthly zonal-mean inter-annual anomalies of OMPS nadir-mapper Aerosol Index (no units) for 60°S-60°N and period January 2016-August 2021. Inter-annual changes were calculated by subtracting 2016-2019 average seasonal cycles from

the data. Positive anomalies indicate smoke and dust aerosols in the atmosphere. The intense Australian wildfires beginning late 2019 coincide with positive SH TCO anomalies of about 2 DU for January-February 2020 in Fig. 2a.

S8. Seasonal Differences of 2021 Minus 2020 TCO Anomalies.

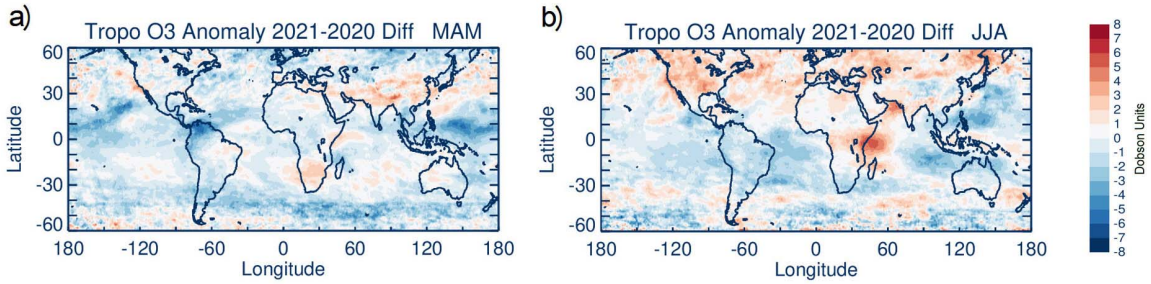

Figure S12. (a) Year 2021 minus year 2020 differences (in Dobson Units) for MAM season shown in Fig. 3 in main text. (b) Same as (a) but for JJA season.