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Key Points:

- NASA satellite data show that spring-summer decreases in tropospheric ozone reported throughout the Northern Hemisphere (NH) in 2020 have repeated again in 2021
- Tropospheric ozone decreases in the NH in 2020 and 2021 produced the lowest recorded tropospheric ozone in the NH since at least year 2005
- NASA satellite measurements of NO_2 suggest that the NH tropospheric ozone losses in both 2020 and 2021 were largely of anthropogenic origin

Supporting Information:

Supporting Information may be found in the online version of this article.

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NASA Satellite Measurements Show Global-Scale Reductions in Free Tropospheric Ozone in 2020 and Again in 2021 During COVID-19

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Abstract NASA satellite measurements show that ozone reductions throughout the Northern Hemisphere (NH) free troposphere reported for spring-summer 2020 during the COronaVIrus Disease 2019 pandemic have occurred again in spring-summer 2021. The satellite measurements show that tropospheric column ozone (TCO) (mostly representative of the free troposphere) for 20°N–60°N during spring-summer for both 2020 and 2021 averaged ∼3 Dobson Units (DU) (or ∼7%–8%) below normal. These ozone reductions in 2020 and 2021 were the lowest in the 2005–2021 record. We also include satellite measurements of tropospheric NO_2 that exhibit reductions of ∼10%–20% in the NH in early spring-to-summer 2020 and 2021, suggesting that reduced pollution was the main cause for the low anomalies in NH TCO in 2020 and 2021. Reductions of TCO ∼2 DU (7%) are also measured in the Southern Hemisphere in austral summer but are not associated with reduced NO_2.

Plain Language Summary The decreases in ozone throughout the NH free troposphere in spring-summer 2020 as reported by several previous studies are shown from satellite measurements to have repeated in spring-summer 2021 with similar extent. The satellite data indicate decreases in tropospheric column ozone (indicative mostly of free tropospheric ozone) of ∼5%–10% throughout the NH in spring-summer months for both 2020 and 2021. These ozone reductions in 2020 and 2021 were the lowest on record for the 2005–2021 time period considered in this study. The satellite data also exhibit smaller decreases in the SH of ∼7% in austral summer (December 2020–February 2021). The anomalous reductions in tropospheric ozone in the NH are shown to be directly correlated with reductions in anthropogenic pollution-related NO_2 during spring-summer 2020 and 2021, but not in the SH in summer. We conclude from our analyses that decreases in pollutants due to reduced human activities including lockdowns during COronaVIrus Disease 2019 likely led to most of the decreases measured in free tropospheric ozone throughout the NH in spring-summer 2020 and 2021.

1. Introduction

In early 2020, soon after the beginning of the global COronaVIrus Disease 2019 (COVID-19) pandemic, extensive international efforts were taken in attempt to reduce the spread of the virus. These efforts included lockdowns and reduced activities of many private and public businesses, schools, and travel. A result was unprecedented decreases in Northern Hemisphere (NH) pollution including important ozone precursors nitrogen oxides (NO_x = nitric oxide [NO] + nitrogen dioxide [NO_2]) and Volatile Organic Compounds (VOCs). The decreases in pollution and subsequent changes in tropospheric ozone, particularly in the NH, has led to a large number of published articles on this subject (e.g., Bauwens et al., 2020; Bouarar et al., 2021; Bray et al., 2021; Campbell et al., 2021; Elshorbany et al., 2021; Jensen et al., 2021; Keller et al., 2021; Liu et al., 2020; Miyazaki et al., 2021; Pakkattil et al., 2021; Sicard et al., 2020; Stavrakou et al., 2021; Steinbrecht et al., 2021). These studies have shown numerous cases of large reductions in NO_2, VOCs, and other pollutants in the troposphere including free-tropospheric ozone during spring-summer 2020 that reached 5%–10% deficits or greater throughout the NH, particularly in urban environments.

Although studies have measured ozone reductions throughout the NH free troposphere in spring-summer 2020, ozone in the boundary layer (BL) during these months has been shown to have instead largely increased in and around urban areas (e.g., Liu et al., 2021; Sicard et al., 2020; Yin et al., 2021, and references therein). These studies suggest that the increases in surface ozone could be due to a weakening of a titration effect on ozone in accordance with 2020 meteorological conditions and relative levels of NO_x versus VOC reductions. Campbell et al. (2021) and Parker et al. (2022) also show increases up to about +40% for near-surface ozone concentrations in spring-summer 2020 over the US in urban environments. Campbell et al. (2021) further describe the complex nature of the BL chemistry (NO_x limited vs. VOC limited) whereby the widespread emission decreases in the US in 2020 in a general sense led to increases of BL ozone in urban areas, but widespread decreases in rural regions.

Based on satellite observations from the TROPOspheric Monitoring Instrument (TROPOMI) and Infrared Atmospheric Sounding Interferometer (IASI) instrument and a model simulation, Stavrakou et al. (2021) identified pollutant reductions in early 2020 over China including peroxyacyl nitrates (PAN) by 21%, NO_2 by 15%–40%, and glyoxal (CHOCHO) by 3%. Bauwens et al. (2020), using TROPOMI and the Ozone Monitoring Instrument (OMI) satellite measurements, identified large drops in NO_2 in early 2020 varying from 20% to 40% relative to the pre-COVID-19 time period over the US, western Europe, South Korea and China. Jensen et al. (2021) identified pollution reductions of 40%–60% for industry and about 70% for traffic over China in early 2020 using TROPOMI and ground-based measurements. Miyazaki et al. (2021), using a chemical data assimilation system, identified drops of 15% in global NO_x with up to 25% regional drops in NO_x for April-May 2020. For VOCs, studies also report large reductions in the NH in 2020. For example, Jensen et al. (2021) found 40%–70% anthropogenic reductions in VOCs in early spring 2020 in Changzhou, China. Pakkattil et al. (2021) used ground measurements to show drops in VOCs in early spring 2020 over major metropolitan cities in India, with up to 82% reductions in the first phase of spring-time lockdown compared to pre-lockdown.

For tropospheric ozone, studies show anomalous reductions during spring-summer 2020 throughout the NH free troposphere. Steinbrecht et al. (2021) identified a 7% reduction of ozone throughout the NH free troposphere during spring-summer 2020 from analysis of ozonesondes, lidar, and a model; they attributed the loss mostly to reductions in ozone precursors, with possibly up to 1/4 of the reductions coming from the record low Arctic stratospheric ozone in winter-spring 2020 injected into the troposphere. Bouarar et al. (2021) used a model simulation to indicate 5%–15% reductions of NH zonally averaged ozone in the free troposphere in winter-spring 2020; they attributed about 1/3 coming from reduction of air traffic, 1/3 from reduction in surface emissions, and 1/3 from meteorological conditions that includes the 2020 Arctic stratospheric ozone depletion. Using satellite data from the Earth Polychromatic Imaging Camera (EPIC) instrument, Kramarova, Newman, et al. (2021), Kramarova, Ziemke, et al. (2021) showed anomalous decreases in zonal-mean tropospheric column ozone (TCO) throughout the NH extra-tropics of about 2–4 Dobson Units (DU) (5%–10%) in spring-summer 2020. Elshorbany et al. (2021) also described reductions of several percent in tropospheric ozone over the continental US using the Ozone Mapping and Profiler Suite (OMPS) satellite data.

There are currently few articles on COVID-related global pollution for year 2021 relative to 2020 and previous years. The general consensus is that global pollution was greater in 2021 compared to 2020, but still lower than in years prior to COVID-19. Saharan et al. (2022) shows higher measured surface pollutants in 2021 in Delhi, India compared to 2020, but still less than pre-COVID; their Table 2 for both March and April shows reductions in CO, O_3, and NO_x during 2021 relative to years 2018 and 2019. Sarmadi et al. (2021) evaluated 87 world city sites in both the NH and SH and state that air quality indices measured for CO, NO_2, and particulate matter (PM) with sizes less than 2.5 and 10 μm ($PM_{2.5}$ and PM_{10}) were overall lower in 2020 by 7.4%–20.5% and higher in 2021 by 4.3%–7.5% when compared to 2019; however, their Figure 3 indicates that $PM_{2.5}$ and PM_{10} for year 2021 still remained low on average for at least 25 city sites (mostly in the NH) when compared to years 2018 and 2019. The International Civil Aviation Organization (ICAO, 2022) shows that world air traffic increased in year 2021 relative to 2020 but remained about 49% below the 2019 level. As comparison, the US Bureau of Transportation Statistics for July 2021 (https://www.bts.gov/newsroom/july-2021-us-airline-traffic-data-0) indicates US passenger air travel (domestic + international) was up 207% from July 2020; however, air travel was still down in July 2021 by 15.5% compared to July 2019, before the pandemic.

This paper provides a global evaluation of reductions in free tropospheric ozone in years 2020 and 2021 during the COVID-19 pandemic using ozone measurements from combined EPIC, OMPS, OMI, and Microwave Limb Sounder (MLS) satellite instruments. A primary motivation is to show that there were large planetary-scale decreases of NH tropospheric ozone in year 2021 that were similar to the decreases in year 2020. Our study also includes satellite observations of NO_2 and aerosols and offers plausible explanations for the tropospheric ozone reductions. Section 2 discusses the tropospheric ozone measurements, Section 3 describes results, and Section 4 summarizes our findings.

2. Tropospheric Ozone Measurements

For deriving TCO, we use measurements of total column ozone from three separate satellite instruments for January 2015—August 2021 when all three measurements overlapped. These three satellite instruments are the Deep Space Climate ObserVatoRy (DSCOVR) EPIC (Herman et al., 2018), the Aura OMI (Levelt et al., 2006), and the Suomi National Polar Partnership (SNPP) OMPS nadir mapper (McPeters et al., 2019). TCO for all three datasets is determined by subtracting stratospheric column ozone (SCO) from total column ozone, where SCO is derived by vertically integrating Global Modeling and Assimilation Office (GMAO) Modern-Era Retrospective analysis for Research and Applications-2 (MERRA-2) assimilated Aura MLS ozone profiles (Gelaro et al., 2017; Wargan et al., 2017) from the top of the atmosphere down to the tropopause. The tropopause pressure is taken from MERRA-2 analyses (GMAO, 2015) using the standard potential vorticity—potential temperature (PV-θ) definition (i.e., 2.5 PV units, 380 K). The SCO synoptic fields from MERRA-2 at 3-hr intervals are space-time co-located on a pixel-by-pixel basis via temporal interpolation for each of the three satellites total ozone measurement footprints independently. All TCO datasets represent daily global maps (outside polar night regions) at 1° latitude × 1° longitude gridding. Details regarding individual TCO measurements for EPIC, OMPS, and OMI with MERRA-2 SCO are discussed by Kramarova, Newman, et al. (2021), Kramarova, Ziemke, et al. (2021) and Elshorbany et al. (2021). The sensitivity of detecting tropospheric ozone for EPIC, OMI, and OMPS is ∼100% above 5 km altitude but decreases to ∼40%-50% for ozone columns below 5 km; TCO measured from the three instruments therefore represents mostly free tropospheric ozone. Uncertainties (1σ precision values) in gridded TCO were determined by 1–1 comparisons with daily ozonesondes, indicating zero to ±4 DU offsets and standard deviations of 2–7 DU (smallest in tropics) for EPIC, OMI, and OMPS TCO measurements; precision for monthly-mean gridded TCO for each product varies ∼0.5–1.5 DU.

We derive a "merged" TCO data set by statistically averaging the TCO daily measurements from the three satellite measurements based on the extent of their daily global coverage. This was done by weighting OMPS and EPIC ozone by ∼1.0 and OMI by ∼0.7 because 30% of OMI measurements are missing due to the OMI row anomaly. The reason for generating the merged data is to produce the best overall data set for studying inter-annual changes in TCO. Inter-annual anomalies of TCO were determined relative to a 12-month baseline average TCO field for 2016–2019 (as a function of longitude, latitude, and month). Year 2015 was not included in the baseline TCO calculation due to 2015–2016 being an extreme El Nino event greatly affecting TCO for September–November 2015; also, the EPIC measurements begin June 2015 and are sparse until August 2015. In addition, we analyzed an 18-year extended record of merged TCO by appending the 2015–2021 record with OMI/MLS TCO measurements (Ziemke et al., 2006) for October 2004—December 2014 to evaluate the long-term significance of observed reductions in 2020–2021. Figures and discussion regarding merged TCO and the individual satellite measurements of TCO from EPIC, OMI, and OMPS are provided in the Supporting Information.

3. Results

3.1. Reduction of Zonal Mean Tropospheric Ozone in the NH for Both 2020 and 2021

The satellite data show that the reductions of 5%–10% in free tropospheric ozone throughout the NH in spring-summer 2020, as reported by many studies, has occurred again in spring-summer 2021 (Figure 1). Figure 1a shows TCO monthly time series averaged over the NH for latitudes 20°N–60°N for the three satellite records along with the merged data set. The seasonal cycle in tropospheric ozone is very pronounced in the NH with the seasonal peak in spring-summer months driven by combined effects of spring-summer stratosphere-troposphere exchange (STE) and ozone precursors from natural and anthropogenic sources (de Laat et al., 2005; Lelieveld and Dentener, 2000, and references therein). The large red oval in Figure 1a highlights a ∼3 DU decrease in NH TCO during spring-summer 2020 that was repeated nearly identically in spring-summer 2021. The anomalous decreases in TCO in 2020 and 2021 are illustrated more clearly in Figure 1b which plots inter-annual anomaly time series of merged TCO with respect to 2016–2019 seasonal averages. The right vertical axis in Figure 1b shows that drops of 3 DU of TCO in spring-summer months in both 2020 and 2021 correspond to percentage decreases of ∼7%–8%. These percent decreases are similar to the 7% decreases in free tropospheric ozone throughout the

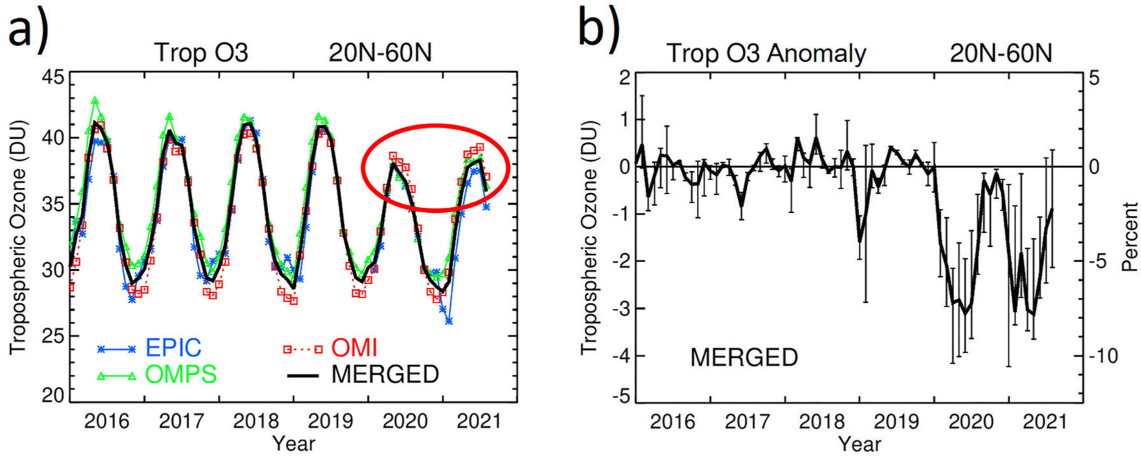

Figure 1. (a) Monthly time series of tropospheric column ozone (TCO) (in DU) averaged over the NH for 20°N–60°N for the three instrument measurements along with the combined EPIC + OMPS + OMI merged time series (indicated). Red oval highlights anomalous drops of ∼3 DU in spring-summer of both 2020 and 2021. (b) Inter-annual anomaly time series of merged monthly TCO (in DU) for 2016–2021 relative to the baseline TCO (see text). Vertical bars show absolute maximum and absolute minimum TCO inter-annual anomalies for the three instruments during each month about the merged mean value.

NH in year 2020 reported by Steinbrecht et al. (2021) from ozonesonde data. The 18-year merged TCO record (Figure S7 in Supporting Information S1) indicates that the decreases in NH TCO during spring-summer 2020 and 2021 were larger than in any previous year extending back to year 2005.

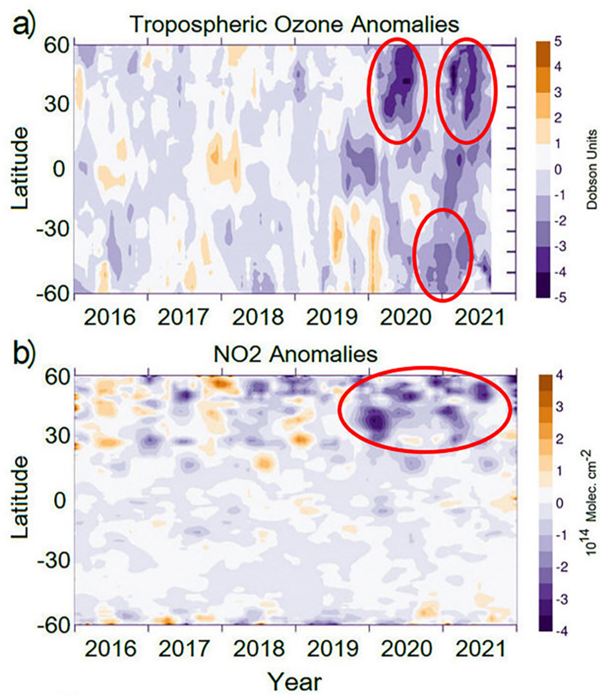

Figure 2. (a) Monthly zonal-mean inter-annual anomalies of merged tropospheric column ozone (TCO) (in DU) for 60°S–60°N and period January 2016-August 2021. Inter-annual changes were derived by subtracting 2016–2019 average seasonal cycles from the data. Red ovals designate months and latitudes where greatest anomalous reductions in extra-tropical TCO in 2020 and 2021 occurred. (b) Similar to (a) but for Ozone Monitoring Instrument NO_2 tropospheric columns in units of 10^{14} mol. cm^{-2}. Red oval highlights anomalous drops in early spring to summer months of both 2020 and 2021 in the NH extra-tropics.

We have compared the anomalous drops in TCO in years 2020–2021 with changes in tropospheric NO_2 (Figure 2) and aerosol measurements to evaluate possible links to pollution including anthropogenic emissions, smoke from biomass burning and wildfires, and Saharan dust (Figure S11 in Supporting Information S1). In Figure 2a the three red ovals highlight anomalous decreases in TCO in the NH during spring-summer 2020 and 2021 (∼3–5 DU in both years) and in the SH (∼2 DU) during summertime (December 2020—February 2021). These drops in TCO are larger than the 1σ average inter-annual variability of ∼1 DU (Figure S9 in Supporting Information S1). In the tropics, decreases in TCO in 2019 are related to a strong positive phase of the Indian Ocean Dipole (IOD) which reduced TCO over tropical Africa and east of Africa due an increase in deep convection east of Africa that lofted low ozone air from the oceanic BL into the free troposphere (Ratna et al., 2021; Figure S10 in Supporting Information S1). A close inspection of Figure 2a indicates that TCO reductions in mid-latitudes were stronger by ∼1 DU in 2020 compared to 2021.

Figure 2b shows corresponding changes in OMI NO_2 (version 4.0, Lamsal et al., 2021). Similar to TCO, largest decreases for NO_2 of -2.0×10^{14} to -4.0×10^{14} mol. cm^{-2} occur in early spring into summer for years 2020 and 2021 in the NH extra-tropics (large red oval). In the SH there are no obvious NO_2 anomalies for any year. Estimated 1σ uncertainty for NO_2 monthly means is about 0.5×10^{13} mol. cm^{-2} (e.g., Marchenko et al., 2015; Figure S3 in Supporting Information S1). The space-time patterns for NH TCO and NO_2 during spring-summer 2020–2021 in Figure 2 generally coincide, but not precisely, perhaps due to effects of titration, chemical lifetimes, and meteorological effects. Similar to TCO, reductions of NO_2 columns in year 2021 in NH mid-latitudes are also smaller than in year 2020 by about 1×10^{14} to 2×10^{14} mol. cm^{-2}.

Wildfires can generate several tropospheric ozone precursors including NO_x, CH_4, VOCs, and CO. We analyzed anomalies in OMPS Aerosol Index (AI)

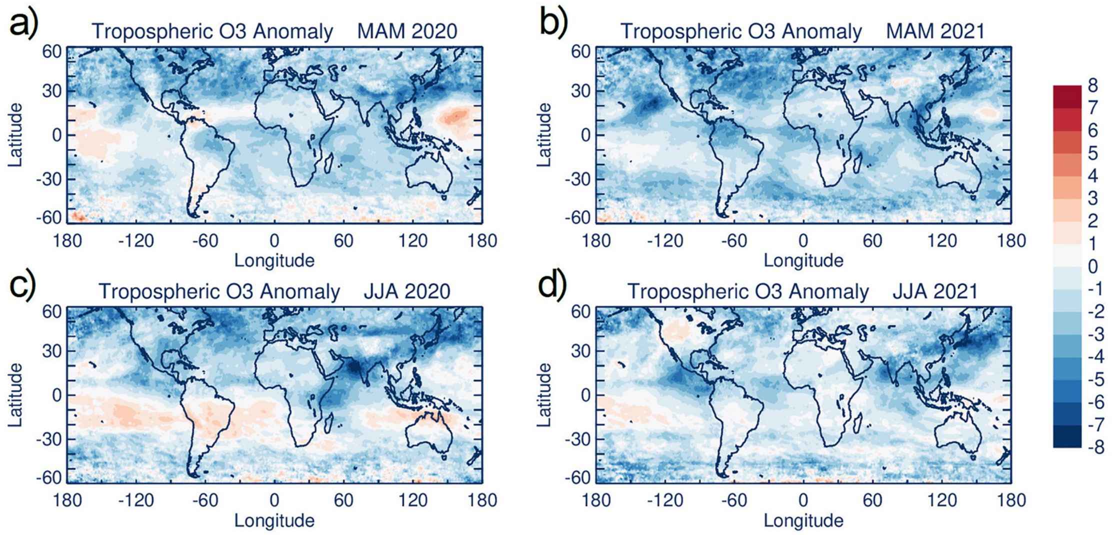

Figure 3. Year 2020 tropospheric column ozone (TCO) inter-annual anomalies (see text) for (a) March-April-May (MAM) spring season and (c) June-July-August (JJA) summer season. (b) and (d) are the same as (a) and (c), respectively, but for year 2021. All TCO (in DU) is derived from merged data with anomalies based on removing 2016–2019 average seasonal cycles.

(Torres et al., 2018), shown in Figure S11 in Supporting Information S1. Positive anomalies in AI indicate the presence of absorbing aerosols such as smoke and dust. The NH wildfires in both years 2020 and 2021 caused positive anomalies in AI with the peak extent in August–September, coinciding with the disappearance of TCO negative anomalies (Figure S11 in Supporting Information S1); this suggests that smoke from wildfires may have aided the return of tropospheric ozone toward normal late summer/autumn amounts in both 2020 and 2021. Meteorological conditions that control the strength of STE were anomalous in NH in spring 2020 (e.g., Lawrence et al., 2020), but 2021 conditions were close to climatological means, suggesting STE is not driving the anomalies. Therefore, we conclude from Figure 2 that it is plausible that decreases in TCO in the NH in spring-summer of 2020 and 2021 are attributed largely to decreases in emissions (e.g., NO_2 in both years) and reduced photochemical production of ozone in the troposphere, although wildfires may have mitigated the impact in late summer and autumn.

We did not find any clear connection in the SH between TCO decreases and negative anomalies in either NO_2 or smoke aerosols (Figure S11 in Supporting Information S1). The decreases of TCO in the SH in 2020–2021 may have been related to anomalies in STE in the presence of a strong and long-lasting Antarctic polar vortex in the SH in October-December 2020 that resulted in substantial stratospheric ozone loss (Kramarova, Newman, et al., 2021; Kramarova, Ziemke, et al., 2021; Stone et al., 2021); however, establishing such a connection requires modeling and is beyond the scope of our study.

3.2. Global Patterns of Tropospheric Ozone in Spring-Summer 2020 and 2021

Figure 3 shows spatial distributions of inter-annual TCO anomalies averaged separately for NH spring (Figures 3a and 3b) and NH summer (Figures 3c and 3d) of 2020 and 2021. Decreases in TCO for both spring and summer 2020 (Figures 3a and 3c) occur over the entire NH as was noted earlier for Figure 2a. The NH TCO negative anomaly patterns are similar in spring 2020 and 2021 with variations of −1 DU to −5 DU (Figures 3a and 3b), however the TCO decreases in summer 2021 (Figure 3d) are smaller than in summer 2020 (Figure 3c) by ∼2 DU throughout the NH mid-high latitudes (Figure S12 in Supporting Information S1), Positive changes in TCO up to +2 DU (shaded orange) in the SH occurred in summer 2020; these positive TCO anomalies coincide with increases in NO_2 over S. America and Africa in this same latitude band (Figure S3c in Supporting Information S1), suggesting an increase in production and long-range transport of tropospheric ozone.

In summer 2021, negative TCO anomalies (Figure 3d) are mostly observed over Asia, and TCO changes are positive over some parts of the Asian continent and over the western-central US (shaded orange). The TCO increases over the US of ∼1–2 DU (Figure 3d) coincide with similar increases in NO_2 over the US in summer 2021 (Figure

S3d in Supporting Information S1). The intense wildfires over California in July-September 2021 (Figure S11 in Supporting Information S1) could have contributed to the positive TCO anomalies over the US in summer 2021.

4. Summary and Discussion

Combined satellite measurements from EPIC, OMPS, OMI, and MLS instruments show that the anomalous reductions in free tropospheric ozone throughout the NH reported for spring-summer 2020 have occurred again in spring-summer 2021. Due to limited sensitivity for detecting BL ozone variability (~40%–50%), the satellite-derived TCO largely represents ozone in the free troposphere. Satellite measurements of OMI NO_2 and OMPS aerosol index were also included to evaluate the role of pollution from anthropogenic emissions and wildfires on observed changes in TCO.

Reductions in NH TCO during spring 2021 were similar to spring 2020; however, reductions in NH TCO in summer 2021 were not as large and uniformly spread as in summer 2020. There were in fact regions of positive TCO anomalies in summer 2021, especially over the US which coincided with regional increases in OMI NO_2 and intense wildfires. Most of the decreases in NH TCO in spring-summer 2020 and 2021 occurred over ocean, downwind of continental pollution sources, indicating effects of long-range transport. Average decreases in 20°N–60°N TCO in spring-summer 2020 and 2021 were ∼3 DU (∼7%-8%) relative to 2016–2019 average ozone levels, which were larger than the typical 1–1.5 DU inter-annual variabilities seen in the previous years since 2005 (Figure S9 in Supporting Information S1). Regional reductions in NH TCO measured for 2020 and 2021 varied up to ∼3–5 DU (∼7%-13%).

Anomalous reductions in TCO of about 2 DU (∼7%) were measured in the SH centered around austral summer (December 2020—February 2021). These decreases did not coincide with similar decreases in OMI tropospheric NO_2. Other factors such as an unusually large and long-lasting Antarctic ozone hole during September–December 2020 and subsequent stratospheric injection of anomalously low ozone air into the troposphere might be responsible for the low anomalies in SH TCO. A quantitative evaluation of SH TCO anomalies would require a modeling simulation which is beyond the scope of this study.

We also analyzed a merged 18-year extended record (October 2004–December 2021) of TCO to evaluate the significance of the reductions in TCO in 2020 and 2021 in relation to previous years (Figures S6 and S7 in Supporting Information S1). We found that the decreases in TCO in the NH averaged over 20°N-60°N during spring-summer 2020 and 2021 were greater than for any previous year since 2005 despite the presence of a decadal positive trend in NH tropospheric ozone averaging ∼1.5 DU decade^{-1} (Figure S7 in Supporting Information S1).

There are several important implications for these results. The 2014 Inter-governmental Panel on Climate Change (IPCC, 2014) report lists tropospheric ozone as the third most influential greenhouse gas following methane and carbon dioxide, with tropospheric ozone contributing on average to net warming of the atmosphere by about +0.4 W m^{-2}. The reductions in TCO throughout the NH in spring-summer 2020 and 2021 of ∼7%-8% on average (and up to 7%–13% regionally) have therefore had a proportionately sizable effect in reducing atmospheric warming and an opposite offsetting effect on the increases in warming due to positive trends in tropospheric ozone over the last two decades. The amplitude of the seasonal cycle in NH TCO was reduced by about 15% in 2020 and 2021 (i.e., about 3 DU out of 20 DU) relative to previous years. These changes will have an impact on calculations of long-term seasonal trends in tropospheric ozone. The reduction in TCO in 2020 and 2021 provide a valuable reference for evaluating model simulations that use reported emission inventories to simulate changes in tropospheric ozone and other trace gas concentrations.

Data Availability Statement

The data description for MLS v4.2 ozone and links to the data can be obtained from the following websites: https://mls.jpl.nasa.gov/ (NASA MLS division, 2022) and https://disc.gsfc.nasa.gov/ (NASA MLS science research group, 2022). The MERRA-2 GMI model description and access are available from https://acd-ext.gsfc.nasa.gov/Projects/GEOSCCM/MERRA2GMI/ (Code 614 GMI modeling group, 2022). EPIC tropospheric ozone data are available from the Langley ASDC data portal (https://asdc.larc.nasa.gov/). Tropospheric ozone data for OMI and OMPS are available from the NASA GSFC Code 614 webpage https://acd-ext.gsfc.nasa.gov/Data_services/cloud_slice/.

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References

Bauwens, M., Compernolle, S. T., Müller, J.-F., van Gent, J., Eskes, H., Levelt, P. F., et al. (2020). Impact of coronavirus outbreak on NO_2 pollution assessed using TROPOMI and OMI observations. *Geophysical Research Letters*, *47*, e2020GL087978. https://doi.org/10.1029/2020GL087978

Bouarar, I., Gaubert, B., Brasseur, G. P., Steinbrecht, W., Doumbia, T., Tilmes, S., et al. (2021). Ozone anomalies in the free troposphere during the COVID-19 pandemic. *Geophysical Research Letters*, *48*(16), e2021GL094204. https://doi.org/10.1029/2021GL094204

Bray, C. D., Nahas, A., Battye, W. H., & Aneja, V. P. (2021). Impact of lockdown during the COVID-19 outbreak on multi-scale air quality. *Atmospheric Environment*, *254*, 118386. https://doi.org/10.1016/j.atmosenv.2021.118386

Campbell, P. C., Tong, D., Tang, Y., Baker, B., Lee, P., Saylor, R., et al. (2021). Impacts of the COVID-19 economic slowdown on ozone pollution in the U.S. atmospheric environment. https://doi.org/10.1016/j.atmosenv.2021.118713

de Laat, A. T. J., Aben, I., & Roelofs, G. J. (2005). A model perspective on total tropospheric O_3 column variability and implications for satellite observations. *Journal of Geophysical Research*, *110*(D13), D13303. https://doi.org/10.1029/2004JD005264

Elshorbany, Y. Y., Kapper, H. C., Ziemke, J. R., & Parr, S. A. (2021). The status of air quality in the United States during the COVID-19 pandemic: A remote sensing perspective. *Remote Sensing*, *13*(3), 369. https://doi.org/10.3390/rs13030369

Gelaro, R., McCarty, W., Suárez, M. J., Todling, R., Molod, A., Takacs, L., et al. (2017). The modern-era retrospective analysis for research and applications, version 2 (MERRA-2). *Journal of Climate*, *30*(14), 5419–5454. https://doi.org/10.1175/JCLI-D-16-0758.1

Global Modeling and Assimilation Office (GMAO). (2015). *MERRA-2 tavg3_3d_asm_nv: 3d, 3-hourly, time-averaged, model-level, assimilation, assimilated meteorological fields V5.12.4, Greenbelt, MD, USA*. Goddard Earth Sciences Data and Information Services Center (GES DISC). https://doi.org/10.5067/SUOQESM06LPK

Herman, J., Huang, L., McPeters, R., Ziemke, J., Cede, A., & Blank, K. (2018). Synoptic ozone, cloud reflectivity, and erythemal irradiance from sunrise to sunset for the whole earth as viewed by the DSCOVR spacecraft from the Earth-sun Lagrange 1 orbit. *Atmospheric Measurement Techniques*, *11*, 177–194. https://doi.org/10.5194/amt-11-177-2018

Inter-Governmental Panel on Climate Change (IPCC). (2014). Fifth assessment report. Retrieved from https://www.ipcc.ch/

International Civil Aviation Organization (ICAO) report. (2022). The impact of COVID-19 on global air passenger traffic in 2021. Retrieved from https://unitingaviation.com/news/economic-development/the-impact-of-covid-19-on-global-air-passenger-traffic-in-2021/

Jensen, A., Liu, Z., Tan, W., Dix, B., Chen, T., Koss, A., et al. (2021). Measurements of volatile organic compounds during the COVID-19 lockdown in Changzhou, China. *Geophysical Research Letters*, *48*(20), e2021GL095560. https://doi.org/10.1029/2021GL095560

Keller, C. A., Evans, M. J., Knowland, K. E., Hasenkopf, C. A., Modekurty, S., Lucchesi, R. A., et al. (2021). Global impact of COVID-19 restrictions on the surface concentrations of nitrogen dioxide and ozone. *Atmospheric Chemistry and Physics*, *21*(5), 3555–3592. https://doi.org/10.5194/acp-21-3555-2021

Kramarova, N., Newman, P. A., Nash, E. R., Strahan, S. E., Long, C. S., Johnson, B., et al. (2021). 2020 Antarctic ozone hole [in "State of the Climate in 2020"]. *Bulletin America Meteorology Social*, *102*(8), S345–S349. https://doi.org/10.1175/BAMS-D-21-0081.1

Kramarova, N. A., Ziemke, J. R., Huang, L.-K., Herman, J. R., Wargan, K., Seftor, C. J., et al. (2021). Evaluation of version 3 total and tropospheric ozone columns from EPIC on DSCOVR for studying regional scale ozone variations. *Frontiers in Remote Sensing*, *2*, 734071. https://doi.org/10.3389/frsen.2021.734071

Lamsal, L. N., Krotkov, N. A., Vasilkov, A., Marchenko, S., Qin, W., Yang, E.-S., et al. (2021). Ozone Monitoring Instrument (OMI) Aura nitrogen dioxide standard product version 4.0 with improved surface and cloud treatments. *Atmospheric Measurement Techniques*, *14*(1), 455–479. https://doi.org/10.5194/amt-14-455-2021

Lawrence, Z. D., Perlwitz, J., Butler, A. H., Manney, G. L., Newman, P. A., Lee, S. H., & Nash, E. R. (2020). The remarkably strong Arctic stratospheric polar vortex of winter 2020: Links to record-breaking Arctic oscillation and ozone loss. *Journal of Geophysical Research: Atmospheres*, *125*(22), e2020JD033271. https://doi.org/10.1029/2020JD033271

Lelieveld, J., & Dentener, F. J. (2000). What controls tropospheric ozone? *Journal of Geophysical Research*, *105*(D3), 3531–3551. https://doi.org/10.1029/1999JD901011

Levelt, P. F., van den Oord, H. G. H. J., Dobber, M. R., Malkki, A., Visser, H., de Vries, J., et al. (2006). The ozone monitoring instrument. *IEEE Transactions on Geoscience and Remote Sensing*, *44*(5), 1093–1101. https://doi.org/10.1109/TGRS.2006.872333

Liu, F., Page, A., Strode, S. A., Yoshida, Y., Choi, S., Zheng, B., et al. (2020). Abrupt decline in tropospheric nitrogen dioxide over China after the outbreak of COVID-19. *Science Advances*, *6*, 28. https://doi.org/10.1126/sciadv.abc2992

Liu, Y., Wang, T., Stavrakou, T., Elguindi, N., Doumbia, T., Granier, C., et al. (2021). Diverse response of surface ozone to COVID-19 lockdown in China. *The Science of the Total Environment*, *789*, 147739. https://doi.org/10.1016/j.scitotenv.2021.147739

Marchenko, S., Krotkov, N. A., Lamsal, L. N., Celarier, E. A., Swartz, W. H., & Bucsela, E. J. (2015). Revising the slant column density retrieval of nitrogen dioxide observed by the Ozone Monitoring Instrument. *Journal of Geophysical Research*, *120*(11), 5670–5692. https://doi.org/10.1002/2014jd022913

McPeters, R. D., Frith, S. M., Kramarova, N. A., Ziemke, J. R., & Labow, G. J. (2019). Trend quality ozone from NPP OMPS: The version 2 processing. *Atmospheric Measurement Techniques*, *12*, 977–985. https://doi.org/10.5194/amt-12-977-2019

Miyazaki, K., Bowman, K., Sekiya, T., Takigawa, M., Neu, J. L., Sudo, K., et al. (2021). Global tropospheric ozone responses to reduced NO_x emissions linked to the COVID-19 worldwide lockdowns. *Science Advances*, *7*(24), eabf7460. https://doi.org/10.1126/sciadv.abf7460

Pakkattil, A., Muhsin, M., & Ravi Varma, M. K. (2021). COVID-19 lockdown: Effects on selected volatile organic compound (VOC) emissions over the major Indian metro cities. *Urban Climate*, *37*, 100838. https://doi.org/10.1016/j.uclim.2021.100838

Parker, L. K., Johnson, J., Grant, J., Vennam, P., Parikh, R., Chien, C.-J., & Morris, R. (2022). Ozone trends and the ability of models to reproduce the 2020 ozone concentrations in the south coast air basin in southern California under the COVID-19 restrictions. *Atmosphere*, *13*(4), 528. https://doi.org/10.3390/atmos13040528

Ratna, S. B., Cherchi, A., Osborn, T. J., Joshi, M., & Uppara, U. (2021). The extreme positive Indian Ocean dipole of 2019 and associated Indian summer monsoon rainfall response. *Geophysical Research Letters*, *48*(2), e2020GL091497. https://doi.org/10.1029/2020GL091497

Saharan, U. S., Kumar, R., Tripathy, P., Sateesh, M., Garg, J., Sharma, S. K., & Mandai, T. K. (2022). Drivers of air pollution variability during second wave of COVID-19 in Delhi, India. *Urban Climate*, *41*, 101059. https://doi.org/10.1016/j.uclim.2021.101059

Sarmadi, M., Rahimi, S., Rezaei, M., Sanaei, D., & Dianatinasab, M. (2021). Air quality index variation before and after the onset of COVID-19 pandemic: A comprehensive study on 87 capital, industrial and polluted cities of the world. *Environmental Sciences Europe*, *33*(1), 134. https://doi.org/10.1186/s12302-021-00575-y

Sicard, P., De Marco, A., Agathokleous, E., Feng, Z., Xu, X., Paoletti, E., et al. (2020). Amplified ozone pollution in cities during the COVID-19 lockdown. *The Science of the Total Environment*, *735*, 139542. https://doi.org/10.1016/j.scitotenv.2020.139542

Stavrakou, T., Müller, J.-F., Bauwens, M., Doumbia, T., Elguindi, N., Darras, S., et al. (2021). Atmospheric impacts of COVID-19 on NO_x and VOC levels over China based on TROPOMI and IASI satellite data and modeling. *Atmosphere*, *12*(8), 946. https://doi.org/10.3390/atmos12080946

Steinbrecht, W., Kubistin, D., Plass-Dülmer, C., Davies, J., Tarasick, D. W., von der Gathen, P., et al. (2021). COVID-19 crisis reduces free tropospheric ozone across the Northern Hemisphere. *Geophysical Research Letters*, *48*(5), e2020GL091987. https://doi.org/10.1029/2020GL091987

Stone, K. A., Solomon, S., Kinnison, D. E., & Mills, M. J. (2021). On recent large Antarctic ozone holes and ozone recovery metrics. *Geophysical Research Letters*, *48*, e2021GL095232. https://doi.org/10.1029/2021GL095232

Torres, O., Bhartia, P. K., Jethva, H., & Ahn, C. (2018). Impact of the ozone monitoring instrument row anomaly on the long-term record of aerosol products. *Atmospheric Measurement Techniques*, *11*(5), 2701–2715. https://doi.org/10.5194/amt-11-2701-2018

Wargan, K., Labow, G., Frith, S., Pawson, S., Livesey, N., & Partyka, G. (2017). Evaluation of the ozone fields in NASA's MERRA-2 reanalysis. *Journal of Climate*, *30*(8), 2961–2988. https://doi.org/10.1175/JCLI-D-16-0699.1

Yin, H., Liu, C., Hu, Q., Liu, T., Wang, S., Gao, M., et al. (2021). Opposite impact of emission reduction during the COVID-19 lockdown period on the surface concentrations of PM2.5 and O3 in Wuhan, China. *Environmental Pollution*, *289*, 117899. https://doi.org/10.1016/j.envpol.2021.117899

Ziemke, J. R., Chandra, S., Duncan, B. N., Froidevaux, L., Bhartia, P. K., Levelt, P. F., & Waters, J. W. (2006). Tropospheric ozone determined from Aura OMI and MLS: Evaluation of measurements and comparison with the global modeling initiative's chemical transport model. *Journal of Geophysical Research*, *111*(D19), D19303. https://doi.org/10.1029/2006JD007089