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Large Reductions in Satellite-Derived and Modelled European Lower Tropospheric Ozone During and After the COVID-19 Pandemic (2020–2022)

Matilda. A. Pimlott[1], Richard. J. Pope[1,2], Brian. J. Kerridge[3,4], Richard. Siddans[3,4], Barry. G. Latter[3,4], Lucy. J. Ventress[3,4], Wuhu. Feng[1,5], Martyn. P. Chipperfield[1,2]

[1]School of Earth and Environment, University of Leeds, Leeds, LS2 9JT, UK

[2]National Centre for Earth Observation, University of Leeds, Leeds, LS2 9JT, UK

[3]Remote Sensing Group, STFC Rutherford Appleton Laboratory, Chilton, Oxfordshire, OX11 0QX, UK

[4]National Centre for Earth Observation, STFC Rutherford Appleton Laboratory, Chilton, Oxfordshire, OX11 0QX, UK

[5]National Centre for Atmospheric Science, University of Leeds, Leeds, LS2 9PH, UK

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Corresponding author: Richard J. Pope (R.J.Pope@leeds.ac.uk)

Key Points:

- The European satellite record shows large lower tropospheric spring-summer ozone reductions in 2020–2022, of 11.0%, 8.4% and 14.6%.
- Scaling precursor emissions based on activity data yields large model ozone reductions in the spring-summer of 2020 and 2021.
- In 2020, meteorology contributed ~1/3 of the modelled reduction (low stratosphere-troposphere flux), with ~2/3 from emission reductions.

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Abstract

Activity restrictions during the COVID-19 pandemic caused large reductions in ozone (O_3) precursor emissions. Studies showed large O_3 reductions in the 2020 spring-summer Northern Hemisphere free troposphere coinciding with this emission reduction period. Here, we provide an insight into the European satellite-derived tropospheric O_3 record updated to mid-2023. Rutherford Appleton Laboratory (RAL) retrieval products show large negative anomalies in the spring-summer periods of 2020 – 2022, with the largest in 2022, and smaller reductions in 2023. The Infrared Atmospheric Sounding Interferometer (IASI) showed peak reductions compared to monthly averages of 2.2 DU (11.0%), 1.7 DU (8.4%) and 2.8 DU (14.6%) in 2020, 2021 and 2022, respectively. Scaling model emissions, based on activity reduction data, yields large negative anomalies peaking in May 2020 and 2021. Emissions reduction was the greater influence, explaining ~65% of the decrease, however, the meteorological impact was substantial, driven by a reduced stratosphere-troposphere O_3 exchange flux.

Plain Language Summary

Lockdowns and other measures implemented to limit the spread of COVID-19 reduced human activity, leading to a reduction in emissions from humans, including precursors for tropospheric ozone (O_3), a pollutant and greenhouse gas. Studies have shown a reduction in tropospheric O_3 across the northern hemisphere in the spring-summer of 2020, which coincided with this emission reduction. We provide further evidence of the tropospheric O_3 reduction in 2020, specifically for Europe, using two records derived from satellite instruments. The two records show large reductions in European tropospheric O_3 in the spring-summer of 2020, peaking at ~ 10 – 20 % in May. One record continues into 2023, showing the largest reductions in 2022, the year after the initial 2020/2021 pandemic period, however, the reductions are smaller in the following year of 2023. We use a chemical transport model to distinguish between the impacts of emissions and meteorology in 2020–2021. In both years, emission reductions had greater influence on the O_3 reduction (~2/3), highlighting the importance of emissions in decreasing O_3. However, emissions reductions alone were not responsible for the large O_3 reduction, as there was considerable influence from meteorology (~1/3), mostly from variation in the flux of O_3 from the stratosphere.

1 Introduction

Tropospheric O_3 is an important secondary atmospheric pollutant and short-lived climate forcer, formed in the presence the precursor gases, nitrogen oxides (NO_x, referring to nitrogen dioxide (NO_2) and nitric oxide (NO)) and volatile organic compounds (VOCs), and sunlight (P. S. Monks et al., 2015). Tropospheric O_3 is a persistent health problem in Europe, with 24,000 premature deaths attributed to acute O_3 exposure in 2020 (European Environment Agency, 2022). O_3 is also the 3rd most important greenhouse gas, with an estimated effective radiative forcing of 0.47 W m^{-2} (0.24–0.71 W m^{-2}) between 1750–2019, dominated by changes in tropospheric O_3 (IPCC, 2021; Skeie et al., 2020).

Due to a global pandemic caused by COVID-19 (disease from SARS-CoV-2, severe acute respiratory syndrome coronavirus-2), many countries worldwide implemented a ‘lockdown’ of daily life activities to prevent the spread of

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the disease (Forster et al., 2020; WHO, 2020; Zhou et al., 2020). This resulted in a widespread reduction in anthropogenic surface emissions, including O_3 precursor gases. Based on activity data, Forster et al. (2020) estimated a global reduction of ~ 30% for NO_x, 25% for carbon monoxide (CO) and 20% for VOCs in April 2020 and Guevara et al. (2021) estimated reductions of ~ 33% for NO_x and 8% for VOCs in March/April 2020. Furthermore, Guevara et al. (2021) found that countries with the severest lockdowns had even higher average reductions (~ 50% for NO_x, 14% for VOCs).

Reductions in tropospheric O_3 in the spring-summer across the northern hemisphere (NH) free troposphere (FT) was initially described by Steinbrecht et al. (2021). The timing of this reduction coincides with the introduction of lockdowns across Europe, beginning in the spring-summer of 2020 and continuing into 2021. Steinbrecht et al. (2021) found that in 2020, measurements of the NH FT (mostly from ozonesondes) from April–August showed ~7% lower O_3 values, compared to its climatology of 2000–2020. Such a widespread reduction occurring at so many stations had not occurred previously in this time period. Another notable event during winter-spring of 2019/2020 was the very large stratospheric Arctic O_3 depletion caused by a very cold, strong and long-lasting polar vortex (W. Feng et al., 2021; Weber et al., 2021; Wohltmann et al., 2020). Steinbrecht et al. (2021) suggested that this low stratospheric O_3 event contributed to less than 25% of this O_3 negative anomaly, attributing most of the O_3 reduction to emission reductions. Further studies have confirmed low FT O_3 across Europe and the NH using aircraft and ozonesonde measurements (e.g. Chang et al. (2022); Clark et al. (2021)). In contrast, Parrish et al. (2022) suggested that low 2020 tropospheric O_3 could be largely due to a negative trend in baseline tropospheric O_3 since around the mid-2010s, based on Western European surface sites.

From a satellite perspective, Ziemke et al. (2022) found low NH spring-summer FT O_3 from instruments aboard NASA satellites, using a merged instrument record. The tropospheric column O_3 reduction of ~ 7–8% (3 DU) (compared to 2016–2019), was comparatively uniform between 20°N - 60°N and repeated in the next year, 2021. They found a reduction of NH satellite-derived NO_2 (~ 10–20%) in the spring-summer of 2020 and 2021, attributing this as the likely cause of the O_3 reduction. Cuesta et al. (2022) found that satellite-derived lowermost tropospheric O_3 (< 3 km altitude) in the spring (1^{st}–15^{th} April) of 2020 was enhanced across central Europe and northern Italy (typically VOC-limited regions) compared to the previous year (2019) and reduced elsewhere in Europe (typically NO_x-limited regions). An enhancement of O_3 across central Europe in the spring-summer of 2020 was also found at surface monitoring sites (e.g. Ordóñez et al. (2020); Grange et al. (2021)). Apart from Ziemke et al. (2022), there are few studies of 2021 and onwards. One example is from Pey & Cerro (2022), finding reduced background O_3 values over SW Europe (~15% at most sites) in March-April 2020, which was also seen in 2021 but to a lesser extent.

Modelling studies have investigated the impact of emission reduction on FT O_3, using different methods to estimate the size of these emission reductions, which are still uncertain. Bouarar et al. (2021) modelled primary pollutant emission reductions, based on emission reductions from activity data by Doumbia et al. (2021), finding zonally averaged NH FT O_3 to be reduced by 5–15% (2001–2019 baseline). One third of this reduction is attributed to

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reductions in air traffic, one third is attributed to a reduction in surface emissions and the final third is attributed to meteorology, including the low 2020 springtime Arctic stratospheric O_3. Miyazaki et al. (2021) used data assimilation, finding a reduction in the global tropospheric O_3 burden of ~ 2% in May and June 2020.

Here, we present an update to the European tropospheric O_3 record using two satellite products, extending the record to mid-2023, and present the reductions in the lower FT compared to previous years. Using a 3-D chemical transport model, TOMCAT (S. A. Monks et al., 2017), we explore the impact of scaling the anthropogenic surface emissions (from activity data changes) on European tropospheric O_3 in 2020 and 2021. Lastly, we quantify the relative contribution of emissions and meteorology to the modelled reduction in tropospheric O_3.

2 Data and Methods

2.1 Tropospheric Ozone Satellite Datasets

We present satellite-derived O_3 from two satellite instruments, the Infrared Atmospheric Sounding Interferometer (IASI) and the Global Ozone Monitoring Experiment-2 (GOME-2), both aboard EUMETSAT's satellite MetOp-B (Clerbaux et al., 2009; Munro et al., 2016). The MetOp series of satellites have a sun-synchronous, near polar orbit with an equator crossing time of 9:30 local solar time (LST). IASI has a swath width of 2200 km, and in the nadir viewing mode, there are four circular fields of view across-track with a diameter of 12 km, covering a square 50 × 50 km^2 which is scanned across the swath. IASI measures in the infrared (IR) wavelengths (645–2760 cm^{-1}) with a spectral resolution of 0.3 - 0.5 cm^{-1} (Clerbaux et al., 2009). GOME-2 measures in the ultraviolet-visible (UV-Vis) wavelengths (240–790 nm) with a spectral resolution of 0.26 - 0.51 nm, and has a swath width of 1920 km. The field of view is scanned across-track yielding 24 ground-pixels of dimension 80 km (across-track) × 40 km (along-track) (Callies et al., 2000; Munro et al., 2016). For quality assurance, the GOME-2B record was filtered for a geometric cloud fraction of <0.2 (e.g. Miles et al. (2015)) and the IASI-IMS-extended record was filtered for an effective cloud fraction of <0.5 (as in Pope et al. (2021)).

Height-resolved O_3 distributions are retrieved by the Rutherford Appleton Laboratory (RAL) using the IMS-Extended scheme for IASI (detailed in Pope et al. (2021)) and UV-Vis scheme for GOME-2 (detailed in Miles et al. (2015)). Due to an underlying negative tendency in the GOME-2 record, likely from UV degradation of the instrument, we have detrended that record, as shown in **Supplement Text S1** and **Figure S1**. To compare the IASI-IMS-Extended data from MetOp-B (2018–2023) to a longer time-period, we combine the record with IASI-IMS-Extended data from MetOp-A (2008–2017). The MetOp-B record was adjusted according to monthly differences with the MetOp-A record in the overlap year of 2018, as described in **Supplement Text S2** and **Figures S2 and S3**. Here we use lower tropospheric sub-columns of the surface–450 hPa (~6 km altitude) derived from the retrieved profiles, with a focus on Europe. As such, we use a land mask to extract a terrestrial European signal given the direct link between surface O_3, precursors gases and air pollution exposure (see **Supplement Figure S4**).

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2.2 Model Simulations

We use the TOMCAT 3-D chemical transport model to simulate tropospheric O_3 between 2017 and 2021. The model control simulation is for 2017, 2018 and 2019. However, in 2020, the control simulation splits into two scenarios: 1) business-as-usual scenario (BAU) and 2) scaled emission scenario (COVID). For the BAU scenario, the control modelled emissions inventory is used but for the COVID scenario, we apply emission reduction factors (Forster et al., 2020) to model surface and aircraft emissions to account for changes in activity due to the pandemic in 2020 and 2021. However, COVID scaling for emissions are not available beyond 2021, so the model simulations are restricted to 2017-2021. TOMCAT is an off-line model driven by 6-hourly ERA-5 meteorological reanalyses (Hersbach et al., 2020), with a resolution of 2.8° × 2.8° and 31 vertical levels between the surface and 10 hPa, coupled with the Global Model of Aerosol Processes (GLOMAP) (Chipperfield, 2006; Mann et al., 2010; Spracklen et al., 2005). The chemistry scheme includes approximately 80 advected tracers and over 200 chemical reactions (S. A. Monks et al., 2017). Surface emission fields are described in detail in **Supplement Text S4** and **Table S1**. The anthropogenic emissions are from the Coupled Model Intercomparison Project Phase 6 (CMIP6) (L. Feng et al., 2020), whereby after 2014 emissions are based on Shared Socioeconomic Pathways (SSPs) (Gidden et al., 2019; Riahi et al., 2017). In this study, we have used the middle-of-the-road scenario, SSP2-4.5, for the TOMCAT control run between 2017 and 2019, before diverging into the BAU and COVID simulations. For the BAU simulation, the CMIP6 SSP2-4.5 emissions are used but for the COVID simulation, scaling factors for emission reductions from national lockdowns come from Forster et al. (2020) and were applied to the BAU emissions. Forster et al. (2020) used national mobility/activity data to estimate reductions in air pollutant emissions (i.e. NO_x, CO, VOCs, black carbon (BC) and organic carbon (OC)). **Figure 1(a)** highlights the impacts of the scale factors, with substantial decreases evident in European emissions for NO_x, CO and VOCs. **Figure 1(b)** shows that the peak reductions were in April 2020, once most European lockdowns were in effect, with monthly reductions of 0.44 Tg (33%), 0.75 Tg (34%) and 0.06 Tg (29%) of NO_x (as NO_2), CO and NMVOCs (as carbon (C)), respectively. For 2020, a secondary winter emissions reduction occurs at ~ 15–20% as further European lockdowns were imposed to reduce the spread of COVID-19. For 2021, the scaling factors from Forster et al. (2020) suggest that emissions were approximately 10–13% lower than expected but remained consistent throughout the year, suggesting a potential ‘new normal’ of lower precursor emissions. A tracer for stratosphere-troposphere exchange (STE) in the model (O_{3S}) is used to understand the impact of O_3 transport from the stratosphere. In the stratosphere, it is set equal to the model-calculated O_3. The only tropospheric source of the tracer is transport from the stratosphere while its sinks are via photolysis, surface deposition and reactions with HO_2, OH and H_2O through $O(^1D)$ produced from O_{3S} (S. A. Monks et al., 2017). Overall, TOMCAT is a robust and well evaluated CTM having been used in multiple studies of tropospheric O_3 (e.g. Richards et al. (2013), Pope et al. (2021) and Pope et al. (2023)), thus a suitable modelling framework for this study.

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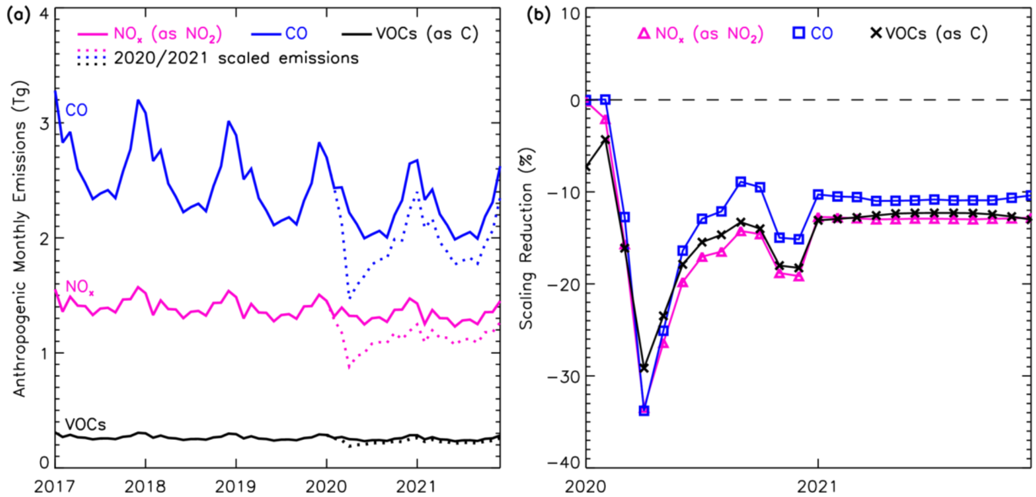

Figure 1. European aggregated anthropogenic monthly emissions of NO_x (as NO_2), CO and NMVOCs (as C) used in the TOMCAT simulations between 2017 and 2021. (a) BAU emissions (solid) and COVID emissions in 2020 and 2021 (dotted) (Tg). (b) Percentage reduction in 2020 and 2021 for NO_x, CO and VOCs in the COVID emissions, relative to the BAU emissions.

3 Results and Discussion

3.1 European Tropospheric Ozone Satellite Record (2008–2023)

We present two satellite-derived lower tropospheric sub-column O_3 records for continental Europe from 2008–2023 (**Figure 2**). During the overlapping years of 2015–2019, the records show an average difference of 2.5 DU, but the variability is well correlated (Pearson's correlation coefficient ~ 0.80). Satellite record inconsistencies are likely due to differences between IR and UV-Vis instruments, the related retrieval schemes and their vertical sensitivities, despite the instruments being aboard the same platform and having the same overpass time. Compared to a monthly baseline of 2015–2019 for GOME-2B and 2008–2019 for IASI-IMS-Extended, the monthly anomalies (**Figure 2(b)**) show good agreement through this overlap period, with the most notable disagreements in winter/spring of 2015 and spring-summer 2016. Both records show large negative anomalies in spring-summer 2020. GOME-2B shows peak negative anomalies of 2.4 DU (18.3%) and 3.0 DU (21.4%) in April and May 2020, respectively, and IASI-IMS-Extended shows slightly smaller negative anomalies of 1.7 DU (9.4%) and 2.2 DU (11.0%) in April and May, respectively. For the records shown in **Figure 2(b)**, two standard deviations (2σ) across the entire monthly record is 2.1 DU for GOME-2B and 1.8 DU for IASI-IMS-Extended. Thus, ~ 95% of the data ranges between the average ± 2σ for the respective records. In both cases, April and May 2020 negative anomalies either match or surpass this range signifying relatively substantial anomalies for these months, highlighting their unusual nature. The reductions continue into the summer of 2020, with both records showing large negative anomalies in July and

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August: 1.7 DU (9.2%) and 1.4 DU (7.2%) for GOME-2B; 1.8 DU (8.3%) and 1.3 DU (6.3%) for IASI-IMS-Extended.

Tropospheric O_3 reductions continue into the spring and summer period of 2021, with the IASI-IMS-Extended record showing negative anomalies in most months of 2021, however, these anomalies are slightly smaller than in 2020. The largest negative anomalies are in April, May and June, at 1.0 DU (5.3%), 1.7 DU (8.4%) and 1.1 DU (5.2%), respectively, with only the reduction in May being close to the average ± 2σ threshold. This recurrence in 2021 of a tropospheric O_3 reduction of similar magnitude to 2020 is consistent with the combined NASA satellite product tropospheric column O_3 record for the 20-60N latitude band reported by Ziemke et al. (2022), which is presented from January–August.

In 2022, the IASI-IMS-Extended record shows even larger negative anomalies in April and May than 2020/2021, of 2.6 DU (15.0%) and 2.8 DU (14.6%), respectively, which are well beyond the average ± 2σ threshold. The negative anomalies continue in June and July, with 1.3 DU (6.5%) and 1.3 DU (6.1%). In 2023, the negative anomalies in spring-summer are smaller compared to 2020–2022, apart from in May, where the negative anomaly is 1.3 DU (6.1%). Broadly, the years of 2020–2023 all show monthly anomalies which are more consistently negative than the previous 12 years. The question of the persistence of low European O_3 values will become evident in future years through extension of these MetOp records.

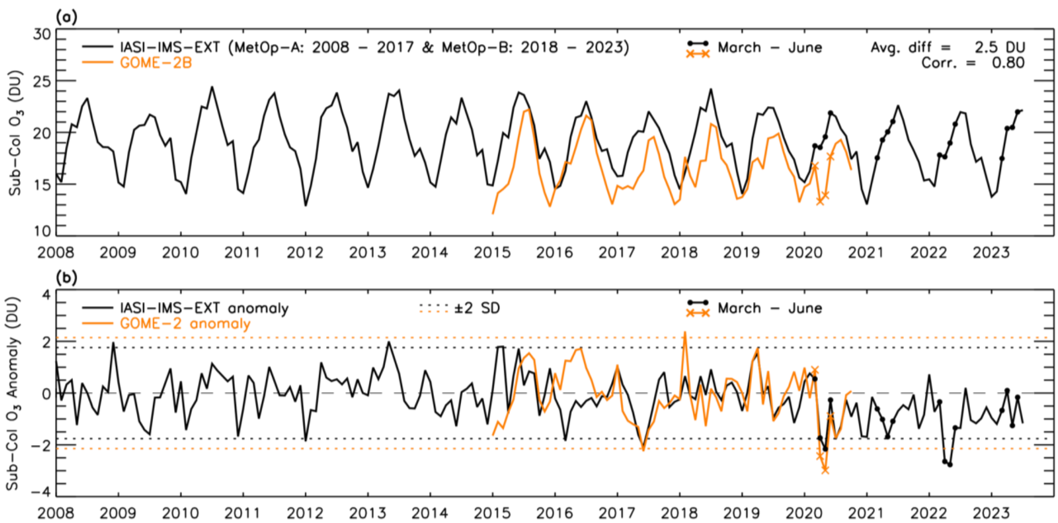

Figure 2. European satellite-derived O_3 from January 2008–July 2023. (a) Monthly average sub-column (surface–450 hPa) O_3 record (DU) from IASI (IASI-IMS-extended, January 2008–July 2023) and GOME-2B (January 2015–October 2020). (b) Monthly mean anomalies for the two records (2015–2019 baseline for GOME-2B, 2008–2019 for IASI-IMS-Extended) (DU). Dotted lines indicate ± 2σ from the average of the record. Filled circles (IASI-IMS-Extended) and crosses (GOME-2B) are shown for the months of March–June in 2020–2023, to highlight the relevant spring/summer periods. Average difference and correlation are based on January 2015–December 2019.

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3.2 TOMCAT Model Experiments (2017–2021)

In 2020, scaling the emissions according to the mobility data estimates in Forster et al. (2020) (TOMCAT COVID scenario) caused a monthly reduction in tropospheric O_3 from March to December (**Figure 3(a)**). During January and February, the COVID and BAU scenarios are very similar, however, from March onwards the COVID scenario shows a negative difference compared to the BAU scenario, which peaks at 2.0 DU (8.3%) lower in May. This negative difference then reduces through the year to December (0.7 DU, 4.1%). In 2021, the COVID scenario shows consistent reductions in all months of the year, starting at 0.6 DU (3.4%) in January, peaking at 1.0 DU (4.3%) in May, and getting slightly smaller towards the end of the year, ending with 0.6 DU (3.2%) in December. The temporal pattern of the reduction is similar to the reduction in surface emissions (**Figure 1**), although with much smaller percentage decreases (peak of ~30% for surface emissions and ~8% for the resulting O_3 sub-column). This highlights the large emission reductions required for a sizeable reduction in European tropospheric O_3.

To identify the impact of meteorology in 2020, the scaled emissions in 2020 were used in three separate simulations with the meteorology of 2017, 2018 and 2019, with an average of these three scaled emission simulations shown in **Figure 3(b)**. The 2020 COVID scenario record is broadly lower than the 2017/2018/2019 averaged scaled emission scenario, despite using the same surface emissions, which indicates that the meteorology of 2020 had a large impact on the tropospheric O_3 reduction. The impact of meteorology in 2020 is greatest in the spring-summer, as the differences between these two timeseries is largest from February–July, peaking at a 1.1 DU difference in May. This demonstrates the importance of meteorology to the resulting O_3 in the spring-summer of 2020. The records are much more consistent from August to the end of the year, with absolute differences below 0.6 DU, indicating a reduced impact from meteorology in the second half of the year.

In comparison with the previous 3 years (2017–2019), the BAU scenario in 2020 and 2021 has lower peak spring-summer values of O_3, especially compared to the high O_3 values in 2019 (**Figure 3(a)**). The spring-summer of 2020 shows negative anomalies in the BAU scenario of up to 1.4 DU (-5.8%) (**Figure 3(c)**). April, May and July show the largest reductions, which are around the value of the average ± 2σ threshold (± 1.3 DU, 6.2%). The spring-summer BAU scenario reductions are repeated in 2021 from January–June, peaking at 1.2 DU (4.9%) in May. Any variation in the BAU scenario is due to meteorology and also variation in the BAU surface emissions used. As shown in **Figure 1**, the BAU emissions only vary by a small amount from year to year, e.g. the average total annual anthropogenic emission difference between consecutive years across the simulation time period is 0.33 Tg (2.0%) for NO_x, 1.3 Tg (4.4%) for CO and 0.06 Tg (1.8%) for VOCs. With consistent BAU emissions, meteorology is the dominant control in the BAU scenario and had a large impact on the simulated tropospheric O_3 in the spring and summer of 2020.

The COVID scenario shows large negative anomalies in 2020, peaking at 3.3 DU (15.4%) in May 2020 (**Figure 3c**), which is much more than the average ± 2σ threshold (± 1.9 DU, 9.0%). Comparing the BAU and COVID scenarios suggests that ~1 DU of the negative anomaly is due to meteorology (and small variations in BAU emissions) and the

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remaining contribution (~ 1–2 DU in spring-summer) of the negative anomaly is due to the scaled emissions for 2020. To further quantify the relative contributions, the difference between the anomalies for the BAU and COVID scenario as a relative percentage of the COVID scenario for 2020 (i.e. 100 × (BAU - COVID)/COVID) is shown in **Figure 4(a)**. We performed this quantification for spring-summer months showing a negative anomaly in both scenarios (March–August 2020 and March–June 2021). These values represent the contribution of the emission reduction to the negative anomalies seen in the COVID scenario, and the corresponding contribution of meteorology (and small differences in the BAU emissions). The contribution of emissions to the COVID scenario in spring-summer 2020 is 53% (March), 67% (April), 59% (May), 71% (June), 55% (July) and 87% (August), with an average of 65% across these months. Therefore, scaling the emissions is the dominant influence during this period. In 2021, the COVID scenario also shows large negative anomalies, peaking at 2.2 DU (9.6%) in May. Scaling the emissions contributed towards 86%, 48%, 47% and 80% for March–June, respectively, of the scaled negative anomaly (average of 65%), with the rest due to meteorology (and BAU emissions).

The contribution of O_3 from STE to the troposphere in the model sub-column is calculated by TOMCAT as a tracer which represents stratospheric O_3 that has entered the troposphere and is controlled by tropospheric sink processes. We calculate a sub-column based on this contribution (STE-sub-column), shown in **Figure 3(a)**, varying between 1.5–4.0 DU from 2017–2021. We find a large negative anomaly in model stratosphere-troposphere O_3 exchange (STE) in the spring-summer of 2020 (**Figure 3(d)**), of 1.3 DU in both April and May (52.5% and 60.5%, respectively). The STE-sub-column absolute negative anomaly is a similar value or larger than the lower tropospheric sub-column anomaly from March - August in 2020, suggesting that during this period, low STE contribution was a substantial factor in the BAU scenario lower tropospheric sub-column O_3 reduction. In the months where the STE-sub-column absolute anomaly is larger than the BAU anomaly, the other controlling factors in the BAU simulation O_3 are likely around neutral or even slightly positive. The stratospheric O_3 used in the model simulation is a climatology, therefore, any variation on the STE contribution is from variation in the STE flux. In 2021, the negative anomaly in STE-sub-column is smaller than for 2020, reaching a peak value of 0.7 DU (21.5%) in April (**Figure 3(d)**). The STE-sub-column negative anomaly is also not larger than for the lower tropospheric sub-column in 2021, suggesting that the STE reduction had a smaller impact on the negative lower tropospheric sub-column anomalies seen in 2021, in comparison with 2020.

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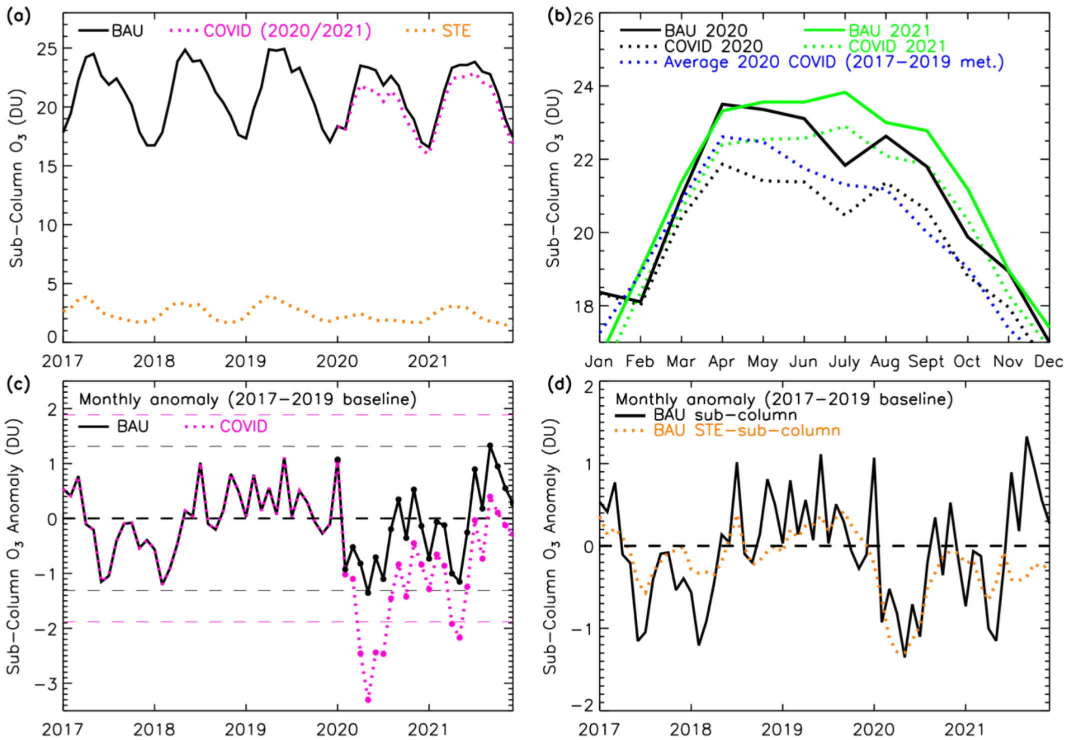

Figure 3. TOMCAT European lower tropospheric sub-column O_3 (surface–450 hPa) between 2017 and 2021 (DU). (a) Monthly sub-column O_3 averages for the BAU sub-column (solid, black) and STE-contribution sub-column (dotted, orange). The COVID scenario is shown in 2020 and 2021 (pink dotted). (b) BAU (solid, black) and COVID scenario (dotted) records for 2020 (black), 2021 (green), with the 2017/2018/2019 averaged COVID scenario (2020 scaled emissions, dark blue, dotted). (c) BAU (solid, black) and COVID (pink, dotted) O_3 anomalies (baseline of 2017–2019). Horizonal dashed lines indicate ± 2σ from the average of the record. (d) As panel (c) with the inclusion of monthly O_3 anomalies of the STE-contribution sub-column (orange, dotted).

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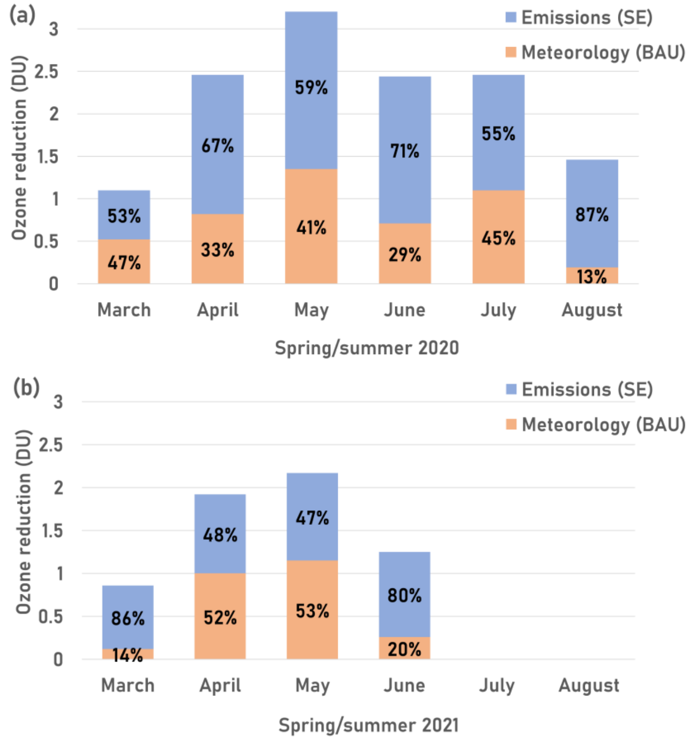

Figure 4. Contribution of scaled emissions and meteorology/BAU emissions to the TOMCAT lower tropospheric sub-column O_3 reduction from March–August in (a) 2020 and (b) 2021. The total reduction (DU) is the COVID scenario negative anomaly, with the relative contribution of meteorology/BAU emissions shown in orange and the contribution of scaled emissions shown in blue. The percentage relative contribution is labelled onto each bar section.

4 Conclusions

Our study represents the first extended investigation of the COVID-19 pandemic impacts on European lower tropospheric O_3 (surface-450 hPa) up to mid-2023. Satellite records show a substantially prolonged European average decrease in spring-summer lower tropospheric in 2020, 2021 and 2022 (and to a lesser extent in 2023) peaking at ~ 1.5–3.0 DU. Modelled reductions, using scaled emissions in the TOMCAT CTM to account for changes in precursor trace gas emissions, are consistent for 2020 and 2021. The simulations showed that in April/May 2020, ~2/3 of the negative anomaly could be attributed to scaling the emissions, with the remaining reduction being attributed to meteorological processes; largely through a reduction in the flux of stratospheric O_3 into the troposphere. Further investigation is required to quantify the drivers of the large 2022 reductions in tropospheric O_3, which could be meteorological variability and/or the stabilisation of emissions below pre-2020 levels (i.e. a new normal in human activity post-COVID).

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Data Availability

The IASI-IMS and GOME-2 data is available via the NERC Centre for Environmental Data Analysis (CEDA) Jasmin platform subject to data requests. However, the IASI-IMS data and TOMCAT simulations used in this study are available on Zenodo at https://zenodo.org/records/10424302 (Pimlott et al., 2024).

Author Contributions

MAP and RJP conceptualised, planned and undertook the research study. BJK, RS, BGL and LJV provided the data and advice on using the products. MAP performed the TOMCAT model simulations with support from MPC and WF. MAP prepared the manuscript with contributions from all co-authors.

Conflicts of Interest

The authors declare no conflicts of interest.

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