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ANTARCTIC OZONE HOLE DURING THE COVID-19 LOCKDOWN (2019–2021): COMPREHENSIVE OBSERVATIONS, MECHANISMS, AND IMPLICATIONS FOR OZONE RECOVERY

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ABSTRACT
The COVID-19 pandemic in 2020 resulted in unprecedented global lockdowns that sharply reduced anthropogenic emissions of nitrogen oxides (NOx), carbon monoxide (CO), sulphur dioxide (SO2), and aerosols. These abrupt changes generated widespread speculation regarding rapid environmental recovery, including potential healing of the stratospheric ozone layer. This study provides a comprehensive, critical assessment of the Antarctic ozone hole during the COVID-19 lockdown period (2019–2021, with emphasis on 2020) using multi-satellite observations, reanalysis meteorological data and an extensive review of peer-reviewed literature. The results show that the Antarctic ozone hole in 2020 was one of the largest, deepest and most persistent of the past two decades with a maximum area exceeding ~24 million km² and minimum ozone values below 100 Dobson Units. Analysis confirms that stratospheric ozone depletion over Antarctica is governed primarily by long-lived ozone-depleting substances (ODSs) and stratospheric dynamical and thermal conditions, particularly polar vortex strength and temperature, rather than short-term reductions in surface-level emissions associated with COVID-19 lockdowns. The findings reaffirm the effectiveness of the Montreal Protocol and clarify misconceptions linking pandemic-related emission reductions to immediate stratospheric ozone recovery.

Keywords:
Antarctic ozone hole, COVID-19 lockdown, stratospheric ozone depletion, polar vortex

INTRODUCTION

The stratospheric ozone layer is an essential protective shield within the atmosphere of earth which is located mainly between about 15 and 35 kilometers above the surface of earth. This region contains enhanced concentrations of ozone (O_3) which is a molecule that plays a very decisive role in absorbing incoming solar ultraviolet radiation. Its most critical function is filtering the majority of biologically harmful ultraviolet-B (UV-B) radiation in the 280–315 nm wavelength range. By reducing the amount of UV-B that reaches the ground the ozone layer protects living systems from severe damage. Elevated UV-B exposure is associated with increased risks of skin cancer, cataracts and immune suppression in humans as well as reduced crop yields and harm to marine ecosystems and because of these wide-ranging impacts the stratospheric ozone is tightly connected to atmospheric chemistry, biospheric stability and global biogeochemical cycles (Solomon, 1999; McKenzie et al., 2019; Madronich et al., 1998; IPCC, 2021).

Ozone is continuously created and then destroyed through photochemical reactions driven by ultraviolet energy of sun. The classical theoretical description of this balance is known the Chapman chemistry. In this mechanism molecular Oxygen O_2 absorbs high-energy UV photons and splits into the individual oxygen atoms. These atoms subsequently combine with oxygen to form ozone. At the same time ozone can absorb radiation and dissociate or react with atomic oxygen, returning to molecular oxygen. These reactions establish a steady-state concentration of ozone. In the real atmosphere additional catalytic reaction cycles significantly alter this equilibrium. Reactive radicals containing hydrogen, nitrogen, chlorine and bromine accelerate ozone destruction rates beyond those predicted by Chapman reactions alone (Chapman, 1930; Crutzen, 1970; Brasseur & Solomon, 2005; Seinfeld & Pandis, 2016).

Catalytic cycles are important because the reactive radicals involved are regenerated during the reaction sequence and can therefore participate repeatedly in ozone removal. Nitrogen oxides (NOx), hydrogen oxides (HOx), chlorine oxides (ClOx) and bromine oxides (BrOx) each contribute to ozone loss. Consequently stratospheric ozone is highly sensitive to small changes in trace gas composition, temperature and radiation. Transport

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processes, wave activity and vertical coupling with lower atmospheric layers also influence ozone distribution and variability (Liu et al., 2009; Yiğit & Medvedev, 2015; Dessler, 2000).

There is major turning point in atmospheric research occurred in the mid-1980s with the discovery of severe seasonal ozone depletion over Antarctica region. The long-term ground based observations showed that total column ozone during the Southern Hemisphere had declined differently relative to the earlier decades. This feature later termed the Antarctic ozone hole which represented a magnitude of depletion that exceeded earlier theoretical expectations and subsequent laboratory and field studies confirmed that the principal cause was rapid catalytic destruction driven by chlorine and bromine radicals derived from anthropogenic ozone-depleting substances (ODSs). Chlorofluorocarbons, halons and related compounds were widely used in refrigeration, aerosol propellants and fire suppression systems. These compounds are chemically stable in the troposphere but broken down by UV radiation in the stratosphere, releasing reactive halogen atoms that efficiently destroy ozone (Farman et al., 1985; Molina & Rowland, 1974; Solomon, 1999; Anderson et al., 2012; WMO, 2018).

The Antarctic meteorological conditions strongly enhance this chemically driven depletion. During polar winter the absence of sunlight leads to very low stratospheric temperatures which support the formation of polar stratospheric clouds. These clouds provide surfaces that enable heterogeneous reactions converting relatively inactive chlorine reservoir species into reactive molecular forms. When sunlight returns in early spring these molecules are rapidly photolyzed then releasing chlorine radicals that trigger highly intense ozone-destruction cycles. At the same time a strong circumpolar vortex isolates Antarctic air, limiting mixing with ozone-rich midlatitude air and allowing depletion to intensify. The combined effects of low temperature and dynamical isolation explain the depth and persistence of the Antarctic ozone hole (Hofmann et al., 1997; Santee et al., 2008; Tilmes et al., 2006; Newman et al., 2004).

Recognition of anthropogenic origin of ozone depletion led to coordinated global policy action. Montreal Protocol on substances that deplete Ozone Layer was adopted in 1987 and later strengthened through amendments and adjustments, established binding controls on ODS production and consumption. This agreement is widely regarded as one of the most successful environmental treaties. Since its implementation the atmospheric concentrations of major chlorine and bromine containing compounds have stabilized and begun to decline. Because many ODSs have long atmospheric lifetimes so their reduction produces gradual rather than immediate improvement. Still the measurements show that total stratospheric halogen loading peaked in the late 1990s and has decreased slowly since then, creating the basis for long term ozone recovery (Newman et al., 2009; Rigby et al., 2014; Steinbrecht et al., 2017; WMO, 2022).

The scientific assessments report early evidence of recovery, particularly in the upper stratosphere where the chemical responses to declining halogen levels are most direct. Trend analyses from satellite and ground based observations show increases in upper stratospheric ozone consistent with model expectations. Projections indicate that Antarctic total column ozone could return to values typical of the pre-1980 period around the middle of the 21st century, assuming continued compliance with international controls. However, recovery is not uniform from year to year. Strong interannual variability persists due to meteorological drivers such as stratospheric temperature fluctuations, planetary wave forcing and changes in vortex stability. External influences including volcanic eruptions, aerosol loading and solar variability also contribute to short term departures from long term trends (Solomon et al., 2016; Chipperfield et al., 2017; Dhomse et al., 2018; WMO, 2018; WMO, 2022).

Within this context of gradual recovery and pronounced variability the COVID-19 pandemic produced an unusual global disruption beginning in early 2020. Lockdowns and mobility restrictions reduced transportation, industrial activity and energy demand across many regions. Satellite instruments recorded sharp decreases in tropospheric nitrogen dioxide and related pollutants over major cities and industrial corridors. Surface networks likewise reported lower concentrations of several air pollutants. These visible air quality improvements led to widespread public discussion and claims that the ozone layer might also be recovering more rapidly as a consequence of reduced emissions (Bauwens et al., 2020; Le et al., 2020; Liu et al., 2020).

However, stratospheric ozone controlling factors are different to short-lived tropospheric pollutants. The main cause of ozone depletion are long-lived halogenated gases which build up over the decades and become well mixed in the atmosphere prior to entering the stratosphere. Consequently, temporary changes in emissions will have little effect on the total amount of these gases in the atmosphere. Ozone depletion is heavily influenced by stratospheric temperatures and circulation patterns, therefore pandemic related emission reductions would not be expected to have any impact on the size of the Antarctic ozone hole. Several chemistry-climate studies highlighted that pandemic related emissions would not lead to any improvement in Antarctic Ozone Hole (Forster et al., 2020; Jacob, 1999; Fleming et al., 2018; Eyring et al., 2021).

There are some indirect relationships however this tends to occur over longer timescales. Long-term changes in greenhouse gases can alter the rate of stratospheric cooling and circulation, which can then affect ozone depletion.

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Some tropospheric sources can affect radical budgets once transported into the upper atmosphere. However, the short-term and incomplete nature of the emissions reductions caused by the pandemic had little effect on global greenhouse gas levels and stratospheric halogen levels. Therefore, it was expected by most researchers that the ozone conditions during 2020-21 would be driven by dynamical and thermal variations (IPCC, 2021; WMO 2022). The extent and severity of the Antarctic Ozone Hole has been dependent on stratospheric temperatures and strength of the vortex. Lower temperatures and stronger vortices have created large ozone holes whereas dynamically active seasons have shown less depletion. This is in line with interannual variability seen over the past decades. Therefore, it isn't necessary to consider short-term changes in emissions. (Newman et al., 2006; Strahan & Douglass, 2018; WMO, 2022)

In order to properly understand what is happening in the atmosphere, an accurate and data driven approach is required. This requires using long-term satellite data alongside ground-based observations and meteorological reanalyses to understand how the recent data fits into the historical trends. Statistical analysis can be performed to compare the data between decades to understand if the anomalies are greater than what would be expected naturally. This will ensure no false conclusions can be drawn due to coincidental timing. (Harris et al., 2015; Weber et al., 2018)

The aims of this study are to: 1) Understand what was happening with the Antarctic Ozone Hole during the lockdown period (2019-21). 2) Determine if there was any impact on stratospheric ozone depletion from the lockdown related emissions. 3) Understand what the 2020 observations mean in the context of the long-term ozone recovery since the Montreal Protocol.

METHODOLOGY

This study investigates the evolution of the Antarctic ozone hole during the COVID-19 lockdown period (2019–2021), with particular emphasis on evaluating whether the unprecedented reduction in anthropogenic emissions during 2020 had any measurable influence on stratospheric ozone depletion. The analysis focuses on the Antarctic region (60°S–90°S), where seasonal ozone depletion reaches its maximum intensity during the Southern Hemisphere spring (September–November). The study period includes the pre-pandemic year (2019), the major global lockdown year (2020) and the post-lockdown year (2021). To place the observed changes within a broader climatological framework, long-term ozone records from previous decades were also considered for comparison. Satellite based observations were used as the primary source of ozone measurements because they provide consistent, high resolution and continuous global coverage of the Earth's atmosphere. Total column ozone data were obtained from the Ozone Monitoring Instrument onboard NASA's Aura satellite which provides daily global observations of total ozone expressed in Dobson Units (DU). The vertical distributions of ozone in the lower and the middle stratosphere were examined using measurements from the Microwave Limb Sounder (MLS) while supplementary information was obtained from the Copernicus Atmosphere Monitoring Service (CAMS) and historical Total Ozone Mapping Spectrometer (TOMS) datasets. The Antarctic ozone hole was identified using the internationally accepted threshold of 220 Dobson Units below which total column ozone is classified as the part of the ozone hole. For each year the maximum ozone hole area, minimum ozone concentration, duration of ozone depletion and the seasonal evolution from August to December were analysed following the methodology adopted in previous international ozone assessments (Newman et al., 2004; WMO, 2022).

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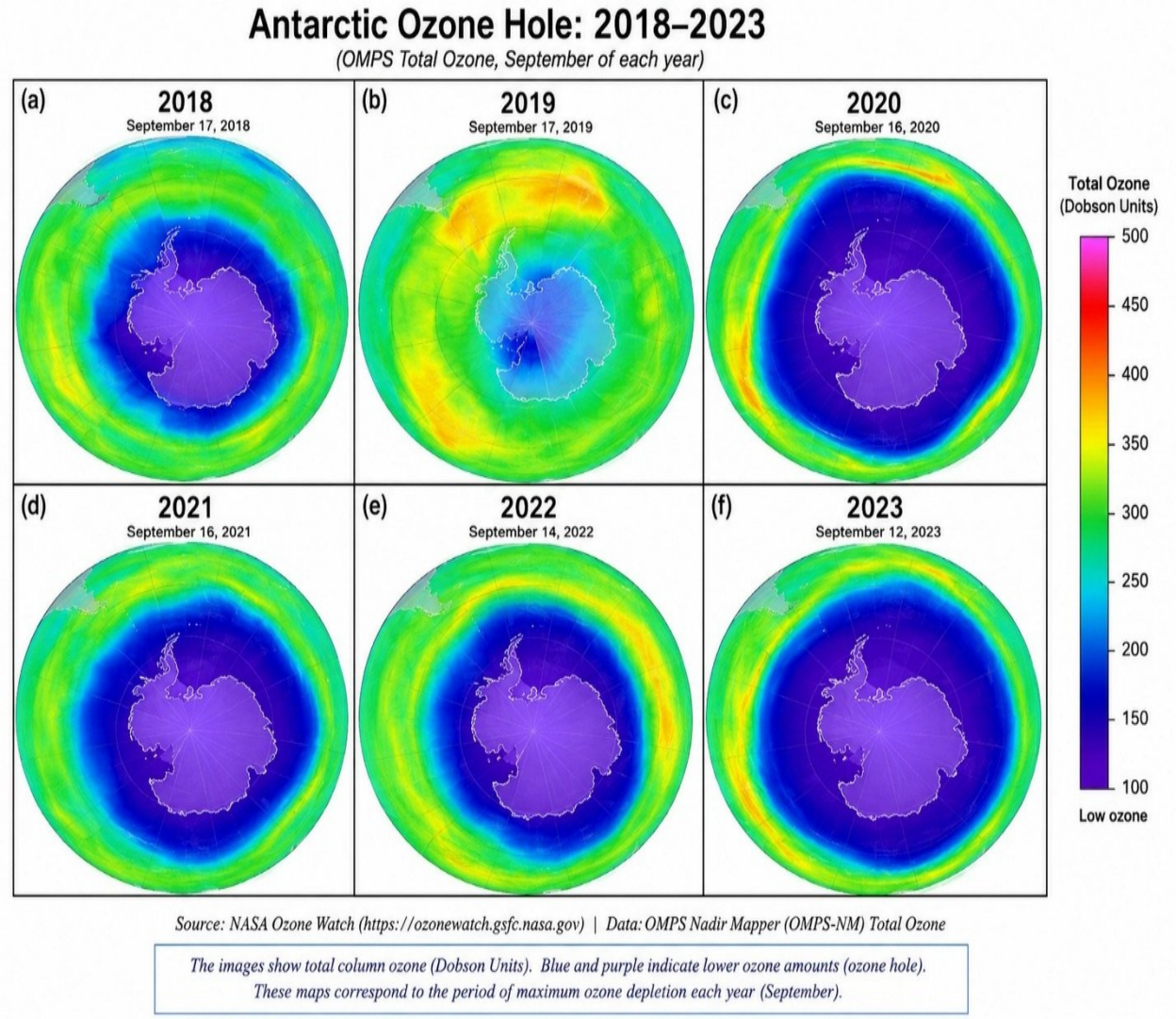


Figure 1- Temporal evolution of the Antarctic ozone hole during the peak depletion season (September) from 2018 to 2023. The composite illustrates substantial interannual variability in total column ozone over Antarctica. The unusually small ozone hole in 2019 resulted from a rare sudden stratospheric warming event, whereas the extensive ozone holes observed during 2020–2023 were associated with persistent cold stratospheric temperatures and a strong polar vortex. The comparison indicates that the COVID-19 lockdown did not produce an immediate measurable effect on Antarctic ozone depletion.

Ozone depletion in the atmosphere was analysed using atmospheric reanalysis data to understand the meteorological causes behind ozone variation from year to year. Meteorological data was retrieved from two sources: the European Centre for Medium-Range Weather Forecasts (ECMWF) ERA5 reanalysis and NASA's Modern-Era Retrospective Analysis for Research and Applications Version 2 (MERRA-2). Both of these datasets represent a physically consistent model of the atmosphere and are often used in studies relating to polar ozone. Lower-stratospheric temperatures (50hPa) were specifically looked at as temperatures below around -78°C will cause polar stratospheric clouds (PSCs) to form. These act as surfaces for heterogeneous reactions converting non-reactive chlorine into highly reactive chlorine radicals which can rapidly deplete ozone. In addition, the strength of the polar vortex was assessed in Antarctica. A strong polar vortex reduces the amount of ozone rich mid-latitude air that can be transported into the polar region (Solomon, 1999; Newman et al., 2006).

Data on major tropospheric pollutants were investigated to see if factors of the lockdown caused by the pandemic had affected them. Data on nitrogen dioxide (NO_2), carbon monoxide (CO), sulphur dioxide (SO_2) and aerosol

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optical depth (AOD) were collected using satellite data. Several independent studies have shown that there were significant reductions in anthropogenic emissions around the globe during the 2020 lockdown. NO_2 has been seen to decrease by up to 60% across many areas, with reductions of around 20% being seen in some areas (Bauwens et al., 2020; Le et al., 2020). This has been compared to the Antarctic ozone data to see if the reduction in surface pollution correlated with a change in ozone depletion.

Several metrics have been used to characterise the Antarctic ozone hole. The largest size of the ozone hole (million km²), lowest total column ozone (DU), length of the ozone hole, monthly mean ozone and annual ozone anomalies. These metrics show how intense and long lasting the ozone depletion is occurring in Antarctica and can be compared between years. All the atmospheric variables were calculated as monthly means and seasonal means. Annual anomalies have been calculated in comparison to the long term climatology. Statistical analysis was conducted using Python based scientific packages such as NumPy, Pandas, SciPy and Matplotlib. Correlation analysis was conducted using Pearson correlations to see how correlated ozone concentration was to lower-stratospheric temperature and other atmospheric circulation metrics. Regression analysis was also conducted to investigate the trend of ozone recovery. This showed how much ozone has been recovering as concentrations of ozone-depleting substances have decreased since the Montreal Protocol. All statistical analysis was completed using a 95% confidence interval ($p<0.05$).

Satellite total column ozone data has been combined with meteorological reanalysis data and atmospheric pollution data to determine the chemical and dynamical causes of ozone variation. The characteristics of the ozone hole between 2019-2021 have been compared to the long term climatology to determine whether the large ozone depletion seen during the pandemic was anomalous or due to natural variability in ozone depletion due to interannual variation in the stratosphere. This approach allows for a full investigation into how much of a role atmospheric chemistry, meteorological factors and temporary reduction in emissions have played in ozone depletion in Antarctica.

Although there was a huge reduction in anthropogenic emissions around the globe due to the pandemic, there are several factors that should be considered. Most of the ozone depleting substances controlled by the Montreal Protocol have a long atmospheric lifetime, between several decades and over a century. This means that there would not be a noticeable change in stratospheric concentrations over just a few months. Ozone depletion in Antarctica varies greatly from year to year due to variations in stratospheric temperature, planetary waves and polar vortex stability. This means that it is important to assess if any changes seen during lockdown were due to short term meteorological variation or long term ozone recovery. Using the method shown here allows for a good assessment of how the ozone has behaved in Antarctica during one of the most unusual periods of atmospheric history.

RESULTS AND DISCUSSION

Observations of the 2019-2021 Antarctic ozone hole show that there is significant inter-annual variation. Overall, ozone depletion is mainly driven by meteorological and chemical processes, with little impact from the reduction in anthropogenic emissions during the 2020 lockdown period. The 2019 ozone hole was relatively small and short-lived due to a period of unusual stratospheric warming. This caused a weaker polar vortex and a reduction in Polar Stratospheric Clouds (PSCs). This therefore led to less ozone depletion during the austral spring compared to most years. In contrast, 2020 saw one of the largest, deepest and longest lasting ozone holes over Antarctica. The ozone hole reached sizes of ~24-25 million km². The minimum total column ozone decreased below 100 DU in early October. The ozone hole lasted until late December. The 2021 ozone hole was still quite large but not as intense or long lasting as in 2020, indicating normal inter-annual variation.

This contrast between 2019 and 2020 shows how meteorological factors play a major role in controlling ozone depletion. The temperature of the lower stratosphere in 2020 was very low, often below the critical temperature required for PSCs to form. These clouds allow heterogeneous chemistry to occur where unreactive chlorine containing species convert into reactive chlorine radicals. These then quickly destroy ozone. The polar vortex was also very strong and lasted for a long period of time. This meant the ozone depleted air at the pole could not mix with the high ozone air at mid-latitudes. As the planetary waves were weak, this meant ozone could be destroyed for a longer period of time. Contrastingly, the stratospheric warming event caused disruption to the polar vortex, increased stratospheric temperatures and reduced PSCs. This therefore reduced the amount of ozone lost. Overall this shows that stratospheric temperatures and atmospheric circulation are the main drivers in controlling the depth, size and length of the ozone hole.

During the Coronavirus outbreak there was an unprecedented drop in anthropogenic activities across the globe, with a large decrease in nitrogen dioxide (NO_2), carbon monoxide (CO), sulphur dioxide (SO_2) and aerosols in many industrialised areas. This improvement in air quality caused people to speculate that the ozone layer could

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start to recover quickly. However, this is not true. Despite the dramatic reductions in tropospheric pollutants, there was no improvement in stratospheric ozone levels over Antarctica during 2020 and 2021. This is because ozone depletion is driven by long-lived ozone depleting substances. This means that even though the emissions from the surface were reduced during the 2020 lockdown, since this only lasted for a few months this would not impact the levels of halogens in the stratosphere. Therefore there was no impact on the ozone hole.

Long term data still shows positive signs that the stratospheric ozone layer is recovering. Chlorine and bromine containing ozone depleting substances have been decreasing over the last few decades. This has caused a slight improvement in global ozone levels. However, year-on-year there will still be some variation. This is because ozone depletion is highly dependent upon meteorological factors. This means that large ozone holes such as the one seen in 2020 do not indicate international regulation is not working. They are just a temporary anomaly due to favourable conditions for ozone destruction. If international regulation continues to follow the Montreal Protocol, models predict Antarctic ozone levels should recover to similar levels to pre-1980 by the middle of the 21 st century.

Overall this shows that factors such as stratospheric temperatures, polar vortex strength and heterogeneous chlorine chemistry played a major role in causing the large ozone hole over Antarctica during the Coronavirus lockdown. This study highlights the difference between improvements in tropospheric air quality and the recovery of the stratospheric ozone layer. Whilst reducing emissions at the surface had an immediate impact on regional air quality, the recovery of the ozone layer takes a much longer time. This is because ozone depleting substances take many decades to reduce. The results of this study highlight how successful the Montreal Protocol has been. This shows how important it is to continue to monitor the ozone layer using satellite observations, atmospheric monitoring and chemistry climate studies to understand how it will recover in the future under changing climatic conditions.

CONCLUSION

This study critically examined the behaviour of the Antarctic ozone hole during the COVID-19 lockdown period (2019–2021) by integrating satellite observations, meteorological analyses and the published scientific evidence. Although the global lockdown resulted in unprecedented reductions in anthropogenic emissions such as nitrogen dioxide (NO_2), carbon monoxide (CO), sulphur dioxide (SO_2) and aerosols these short term improvements in air quality did not produce any measurable recovery of the Antarctic stratospheric ozone layer. The analysis showed that the Antarctic ozone hole in 2020 was one of the largest, deepest and the most persistent events observed during the past two decades with a maximum area exceeding 24 million km² and the minimum total column ozone values below 100 Dobson Units. The severity of ozone depletion was primarily associated with exceptionally low stratospheric temperatures, a strong and stable Antarctic polar vortex and extensive formation of Polar Stratospheric Clouds (PSCs), all of which enhanced catalytic ozone destruction by chlorine and bromine radicals. These findings demonstrate that Antarctic ozone variability is governed mainly by stratospheric chemical and dynamical processes rather than by temporary reductions in surface level air pollution.

The results further confirm that the recovery of the ozone layer is a gradual process driven by the long term decline in atmospheric concentrations of ozone depleting substances following the successful implementation of the Montreal Protocol and its subsequent amendments. Because the most ozone depleting substances have atmospheric lifetimes of several decades, short lived reductions in the anthropogenic emissions during the COVID-19 pandemic were insufficient to influence stratospheric halogen loading or alter the intensity of the Antarctic ozone hole.

This study also helps clarify a common misconception that emerged during the pandemic by distinguishing between improvements in tropospheric air quality and recovery of the stratospheric ozone layer. While lockdown measures produced rapid reductions in the urban and industrial pollution, the processes controlling Antarctic ozone depletion operate in a different atmospheric region and over much longer timescales. Consequently no direct causal relationship exists between temporary COVID-19 emission reductions and immediate ozone layer recovery.

Overall, the findings reinforce the current scientific consensus that continued compliance with the Montreal Protocol remains the most effective strategy for restoring the Earth's protective ozone layer. Continued long-term satellite observations, atmospheric reanalysis and the chemistry climate model simulations are essential for monitoring future ozone recovery, understanding the influence of climate change on stratospheric dynamics, and improving predictions of Antarctic ozone variability in the coming decades.

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