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Perspective

A synergistic ozone-climate control to address emerging ozone pollution challenges

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SUMMARY

Tropospheric ozone threatens human health and crop yields, exacerbates global warming, and fundamentally changes atmospheric chemistry. Evidence has pointed toward widespread ozone increases in the troposphere, and particularly surface ozone is chemically complex and difficult to abate. Despite past successes in some regions, a solution to new challenges of ozone pollution in a warming climate remains unexplored. In this perspective, by compiling surface measurements at ∼4,300 sites worldwide between 2014 and 2019, we show the emerging global challenge of ozone pollution, featuring the unintentional rise in ozone due to the uncoordinated emissions reduction and increasing climate penalty. On the basis of shared emission sources, interactive chemical mechanisms, and synergistic health effects between ozone pollution and climate warming, we propose a synergistic ozone-climate control strategy incorporating joint control of ozone and fine particulate matter. This new solution presents an opportunity to alleviate tropospheric ozone pollution in the forthcoming low-carbon transition.

INTRODUCTION

Tropospheric ozone is harmful to human health,[1,2] ecosystems,[3,4] and crop yields[5,6] and is a major contributor to climate change.[7,8] Ozone in the troposphere is formed through the reactions of volatile organic compounds (VOCs), carbon monoxide (CO), methane (CH_4), and nitrogen oxides (NO_x) in the presence of sunlight.[9] Ozone formation chemistry is highly nonlinear and can also be affected by fine particulate matter with an aerodynamic diameter of 2.5 μm or less ($PM_{2.5}$). In addition, stratosphere-troposphere exchange (STE) transports ozone to the troposphere and is particularly important in alpine areas and during the winter-spring season.[10–13] Anthropogenic emissions, atmospheric chemistry, and meteorology are key drivers shaping the spatiotemporal patterns of tropospheric ozone. The current tropospheric ozone level is ~40% higher than that of the pre-industrial era, with the highest concentrations and greatest enhancements occurring in the most populated and industrialized mid-latitude band in the Northern Hemisphere.[14–16] Ambient ozone exposure accounted for a total of 365,000 premature deaths (175,000–564,000) globally in 2019 according to the Global Burden of Disease (GBD).[17]

To combat tropospheric ozone pollution, the key is to determine the current challenges, learn from the experience and lessons of historical ozone pollution control, and ultimately to propose actionable solutions. As a global threat, tropospheric ozone has been extensively measured and studied in many regions of the world,[18–22] especially under the framework of the Tropospheric Ozone Assessment Report (TOAR). The TOAR documents comprehensively estimate global ozone pollution and its historical trends and are crucial for recognizing the impacts of ozone on climate, human health, and ecosystems worldwide.[20,22] However, the first-phase TOAR includes only limited ground observation data from large developing countries, such as China and India, and does not include the latest global ozone records (i.e., post 2014). For instance, the recent ozone upsurge in China has attracted increasing attention in the scientific community.[23–25] Several recent studies[25–27] have discussed ozone trends in a global context, while some of them use ozone data for different time periods in different regions because of the limited ozone measurements.

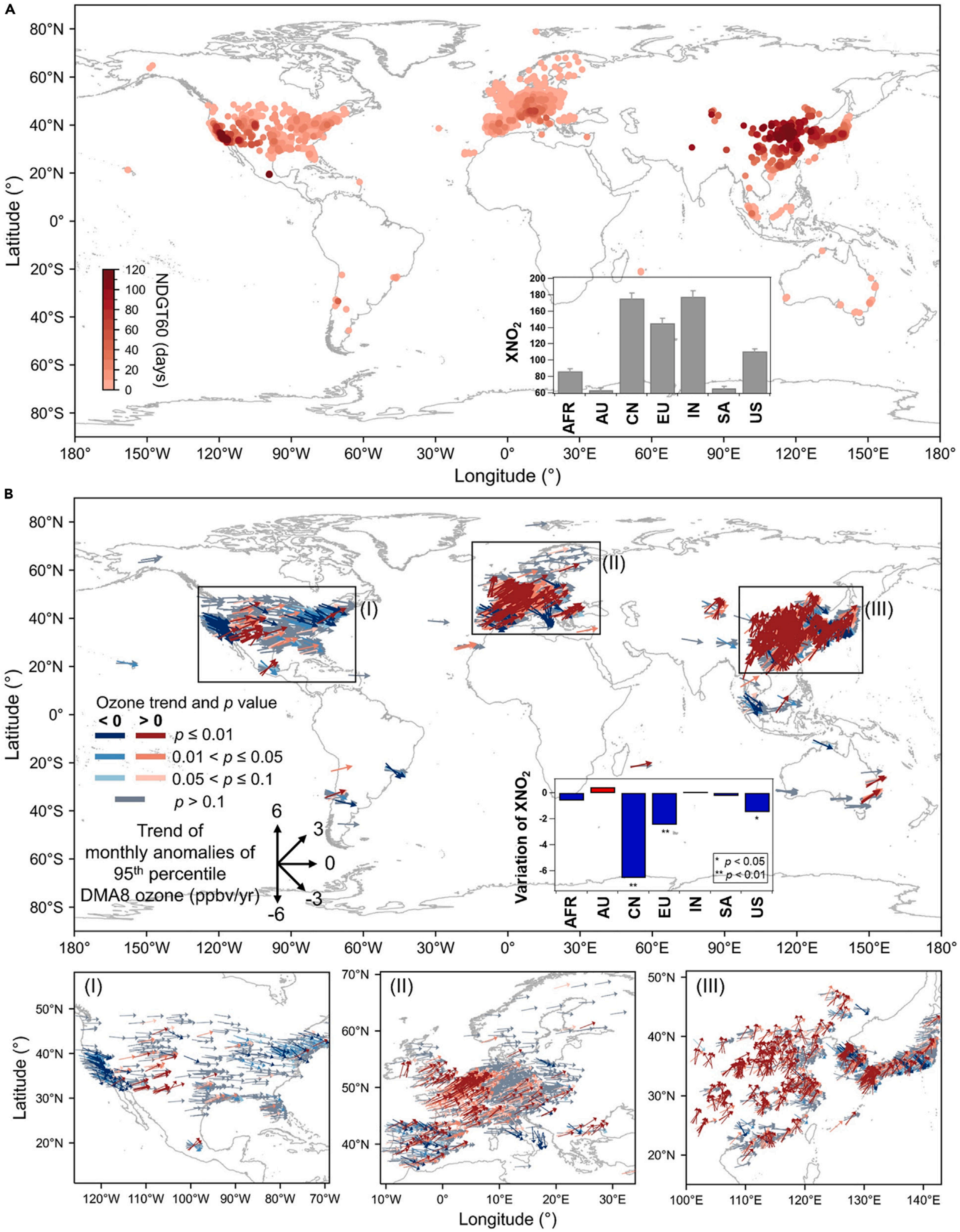
The causes of ozone trends and pollution events in specific regions have been explored in many studies.[23,27–30] However, effective control of ozone pollution is still difficult. With substantial reduction of anthropogenic emissions (e.g., VOCs and NO_x), the peak values of ozone in warm seasons have been generally decreasing in the United States (US) and Europe (EU) since the late 1990s.[28,29] However, neither location has eliminated ozone pollution, and the potential to decrease ozone concentrations by reducing anthropogenic emissions is diminishing. For instance, as reported by the American Lung Association, there were still more than 122 million people in the US exposed to ozone pollution in 2020.[31] In the EU, an increasing trend of urban background ozone has been reported in the last two decades due to the NO_x reduction in a VOC-limited ozone formation regime.[32] The problem is further complicated by high levels of background ozone in some regions (e.g., the western US), intercontinental transport, and climate-driven increase in ozone levels (i.e., climate penalty).[33–36] More notably, tropospheric ozone pollution is increasingly emerging in East Asia and Southeast Asia.[23,26,37] While studies identified changing anthropogenic precursor emissions as the main driver of the ozone increase in these regions,[38–40] emission reduction to mitigate $PM_{2.5}$ pollution has in fact aggravated ozone pollution in China since 2013, partly because of the reduced heterogeneous interactions of chemical radicals with $PM_{2.5}$.[23,24] The dilemma of the rapid rise in ozone caused by the improvement of $PM_{2.5}$ pollution remains unresolved. This situation may occur in some other developing countries, such as India, during the emission reduction period.[41]

There is an intrinsic linkage between tropospheric ozone and climate change.[42–45] However, the synergistic effect of their emission sources, chemical feedback, and control strategies is still underappreciated and requires further understanding and management. The emissions of ozone precursors and greenhouse gases share a large fraction of the same sources.[46] Many chemical and physical processes affecting ozone pollution, such as wildfires, biogenic emissions, droughts, transport of peroxyacetyl nitrate, and STE, are sensitive to climate.[43,45] High ozone episodes occur along with more frequent extreme events in a warming world. For instance, under heatwave conditions in the EU[35] and wildfires related to the warming of the western US,[47] surface ozone levels have become much higher. The COVID-19 pandemic provides a vivid picture of the strong connections between air pollution and the carbon cycle.[45] Considering that climate change is critical for ozone pollution control, it is imperative to bridge the gap between scientific research and actionable solutions to mitigate ozone pollution and climate change in a coordinated way.

In this perspective, we conduct a comprehensive analysis of global surface ozone measurement from 2013-2014 onward and synthesize the current understanding of ozone controls. Two pressing challenges of ozone pollution control posed by multi-pollutant interaction and warming climate are identified, which requires more effective control strategies. Conceptually, we elucidate a synergistic control of ozone with climate incorporating multi-pollutant joint control. This perspective could foster collaboration between air quality and climate communities and inform policymakers to address these ongoing interconnected threats collectively.

CURRENT CHALLENGES OF OZONE POLLUTION CONTROL

The impact of tropospheric ozone on climate largely depends on its tropospheric burden and where ozone changes in the troposphere, while ozone at the ground level threatens human and ecosystem health. According to the Intergovernmental Panel on Climate Change (IPCC) Sixth Assessment Report in 2021, the rapid increase in the tropospheric ozone burden since the pre-industrial period can be mainly attributed to the global increase in anthropogenic ozone precursors.[48] Moreover, the decline in the global tropospheric ozone burden in 2020 due to reduced NO_x emissions during the COVID-19 lockdowns[49] demonstrates the merits of a straightforward approach of regulating precursor emissions to mitigate the tropospheric burden. In response to climate warming, there is high confidence that the tropospheric ozone burden would generally decrease due to



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increased chemical loss by higher water vapor,[50] which nevertheless could be compensated for by the projected increase of STE in the future.[10] In contrast, the change in surface ozone as a result of emissions and climate change is less certain and more chemically complex. For instance, emission reduction has diverse impacts on surface ozone because of the nonlinear chemistry of ozone. Therefore, we focus mainly on surface ozone changes and control strategies.

By compiling ozone measurements at over 4,000 stations worldwide during 2014–2019 (see section ‘‘experimental procedures’’), we highlight the fact that surface ozone pollution is ubiquitous and emerging in the world. Figure 1 shows the global distribution of the number of days with a daily maximum 8-h average (DMA8) ozone greater than 60 parts per billion by volume (ppbv), abbreviated as NDGT60, averaged in warm seasons from 2014 to 2019 and the trends of monthly anomalies of 95th percentile DMA8 ozone during this period. The warm season refers to April–September in the Northern Hemisphere and October–March in the Southern Hemisphere, which also applies to the tropics. The 95th percentile DMA8 ozone, representing high ozone values of regulatory concern,[28,29] were calculated every month using a ‘‘nearest rank’’ method with linear interpolation. The 2014–2019 trend of 95th percentile DMA8 ozone was determined by linear regression of the monthly anomalies. Details about the data processing are available in the section ‘‘experimental procedures.’’

High levels of DMA8 ozone were observed within the band of 30°–50°N (Figure S1), consistent with the observed and modeled results reported elsewhere,[15,20] and approximately in line with the spatial patterns of anthropogenic emissions indicated by tropospheric column densities of nitrogen dioxide (NO_2) (Figure S2). Notably, India, Mexico, China, South Korea, and Japan were the countries that experienced the most frequent ozone exceedance (Table S1), but it should be borne in mind that data were available at only one site in India and the data for Mexico were all collected in Mexico City. In addition, the standard we adopted (60 ppbv) was frequently exceeded in the western US and in high-altitude regions of northern Mediterranean EU (Figure 1A). This adopted threshold is in the middle of worldwide ozone air quality standards (see section ‘‘toward a synergistic ozone-climate control strategy’’). Figure S1 also shows ozone exceedance with reference to the benchmark of 65 ppbv and the World Health Organization (WHO) guidance value of 47 ppbv, and both demonstrate the severity of ozone exposure. More importantly, many parts of the world are experiencing emerging ozone increases that we will later discuss in detail.

We compare recent ozone trends among Asian countries within the same time frame. Approximately half of the stations in China witnessed significant increases in 95th percentile DMA8 ozone between 2014 and 2019, with a national average rate of 2.88 ± 0.14 ppbv/year (Figure 1B; Table S1). The growth rate was higher than that at individual stations in representative Chinese cities during earlier periods or over longer periods.[38,52–54] In Japan and South Korea, significant increases occurred at only 11.5% and 23.9% of all stations that passed data screening criteria, respectively, but the national average rate of increase was still notable in South Korea (0.73 ± 0.17 ppbv/year). The increasing ozone over South Korea has been an enduring issue (see Figure S3 for ozone trends over a longer period of 2000–2019). An observed overall decrease in ground-level ozone in Malaysia (-0.80 ± 0.18 ppbv/year), which was in contrast to the long-term increase in tropospheric ozone burden driven by anthropogenic emissions over Southeast Asia,[55,56] could be attributed to inter-annual meteorological variations (Figure S4). Due to the limited records, it is difficult to draw a solid conclusion on the latest ozone trends in India and Thailand. A suburban site in northern India (Mohali, see section ‘‘experimental procedures’’) recorded a slight decrease in 95th percentile DMA8 ozone (-0.67 ppbv/year, $p > 0.1$) during 2014–2019.

The striking rise in China’s ground-level ozone in recent years, which was not observed in other Asian countries, was unlikely to be primarily caused by meteorological variations; this is mutually corroborated by previous modeling studies[23,24] and our model simulations, as shown below. Since 2013, rigorous air pollution control has markedly improved $PM_{2.5}$ air quality in China.[57] However, the ozone upsurge in such a short period was in sharp contrast to the notable reduction in anthropogenic NO_x emissions (Figure 1B). In addition, surface ozone exhibited diverse patterns in response to the rapid decline in NO_x emissions during the COVID-19 lockdown.[49] This highlights a challenge of mitigating ground-level ozone pollution: reducing anthropogenic emissions may inadvertently increase ozone levels.

Due to the efforts to constrain anthropogenic emissions, 95th percentile ozone decreased at the rate of -2 to -1 ppbv/year in the US[28] and –0.42 ppbv/year in the EU[29] during 1998–2013. However, recent ozone records show an emerging ozone increase in the course of anthropogenic emissions reduction in parts of these regions (Figure 1B; Table S1). From 2014 to 2019, while the DMA8 ozone still showed overall decreasing trends in the US, there was a significant ozone increase over the western US; ozone increased at 24.8% of stations with a national average rate of 0.68 ± 0.12 ppbv/year in the EU (mainly in central EU). We further demonstrate that changes in anthropogenic emissions from 2014 to 2019 were likely not responsible for the ozone increase in the EU and the western US (Figure S4). In contrast, the increase in ozone in 2014–2019 in the EU was mainly attributable to meteorological variations, which also caused a recent rise in ozone in southwestern US and Mexico. These findings highlight meteorological impacts on ozone pollution, which may become more significant under a warming climate. Nevertheless, longer periods of measurement

Figure 1. Global distribution of surface ozone levels and trends from 2014 to 2019

(A) Average number of days with daily maximum 8-h average (DMA8) ozone greater than 60 ppbv (NDGT60) per warm season; (B) 2014–2019 trends of monthly anomalies of 95th percentile DMA8 ozone in warm seasons. Inserted graphs in (A) and (B) show average concentrations (XNO_2, unit: 10^{15} molecules/cm^2) and 2014–2019 trends of tropospheric NO_2 columns (unit: 10^{15} molecules/cm^2/year), respectively, and horizontal axis shows abbreviations of countries/regions (AFR, Africa; AU, Australia; CN, China; IN, India; SA, South America). Error bars represent 95% confidence intervals. * and ** stand for significant XNO_2 trends at the confidence level of 95% and 99%, respectively. (I–III) in (B) are zoom-in pictures for regions with significant overlaps of arrows in the US, EU, and East Asia. Color of arrows denotes the signs of ozone trends and ranges of two-tailed p values. Time frames are different for 26.9% of the stations, with a maximum time deviation of 2 years.[51]

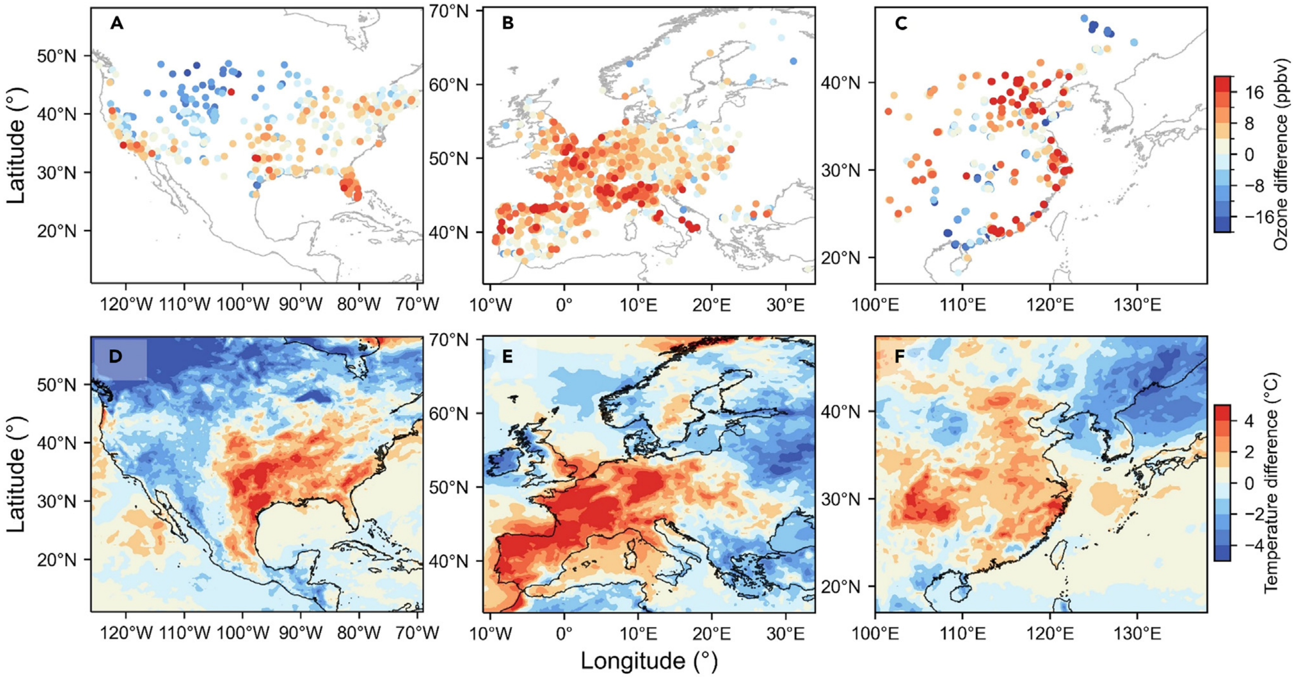

Figure 2. Spatial consistency between summertime ozone and temperature anomalies in extreme heat in 2022
(A–C) The 95th percentile DMA8 ozone concentration anomalies in June–July 2022 relative to 2021 (ppbv). (D–F) The same as (A–C) but for daily maximum surface temperature (°C). (A and D) US, (B and E) EU, and (C and F) East Asia.

data (e.g., 10-year records as recommended by the TOAR) will be necessary for more credible determination of ozone trends.

In addition to global ozone measurements in 2014–2019, we also collected surface ozone data in the summer of 2022 when heat records occurred across the US, EU, and Asia. Figure 2 shows a marked ozone enhancement of 4–16 ppbv in June–July 2022 relative to 2021 over the eastern US, central EU, and eastern China. The close similarity of spatial ozone anomalies and temperature anomalies gives a vivid picture of the role of extreme heat events in ozone pollution.

The climate penalty for ozone in the EU over a longer period (1960–2018) was also highlighted by a recent study.[35] Additionally, simulations revealed an increase in ozone in the mid-latitudes of the Southern Hemisphere. In particular, obvious but statistically insignificant increases of ozone in Australia were simulated, due to the heatwave and bushfires in 2019–2020 (Figure S4).[58] In the long term, studies identified continuous growth of tropospheric ozone in the Southern Hemisphere since 1990, which was partially driven by global warming.[59] Therefore, the ozone increases in regions driven by meteorological variations underline another major challenge of mitigating ozone pollution: climate change is making ozone abatement more difficult.

The current challenges of ozone pollution can be summarized as follows. On one hand, in regions with intensive anthropogenic emissions, reducing the emissions without considering the complex chemical processes among air pollutants may lead to ozone increases due to the nonlinear relationships between ozone and its precursors and the interactions with $PM_{2.5}$. On the other hand, the climate penalty becomes relatively important, particularly over regions where the potential to reduce anthropogenic emissions is getting lower. These challenges are further illustrated below by reviewing the lessons of ozone control failures.

EXPERIENCE AND LESSONS OF OZONE CONTROL

Ozone pollution is mainly driven by anthropogenic emissions through complex chemical and physical processes (Figure 3) that are exacerbated by the ever-changing climate. To guide policymakers' ozone control strategies, substantial efforts have been made in past decades to understand the anthropogenic drivers of ozone pollution and its sensitivity to perturbations in NO_x and VOC emissions (i.e., ozone isopleths).

The staged successes achieved by EU and the US in reducing peak concentrations of ozone demonstrate that ozone pollution can be effectively alleviated by controlling anthropogenic emissions of ozone precursors.[27,60,61] We have summarized in Figure 4 the key strategies that have been implemented to mitigate ozone pollution by EU and the US in the past four decades. These efforts have achieved a notable decline in DMA8 ozone in the EU and the US.[28,29,62,63] VOC and NO_x emissions in the EU have been declining consistently since 1990 (Figure S5), actioned by an international agreement to reduce these emissions within the EU to mitigate ozone pollution and its transboundary transport.[64,65] Multi-pollutant control has long been adopted and updated over time through initiatives such as the Gothenburg Protocol and the National Emissions Ceilings Directive. However, ozone concentrations over the EU were not efficiently reduced during the past decade, and they even increased slightly over the southern EU (e.g., Madrid). In the US, control of NO_x emissions was not effective before 2000, while VOC emissions had begun to decrease two decades earlier. During

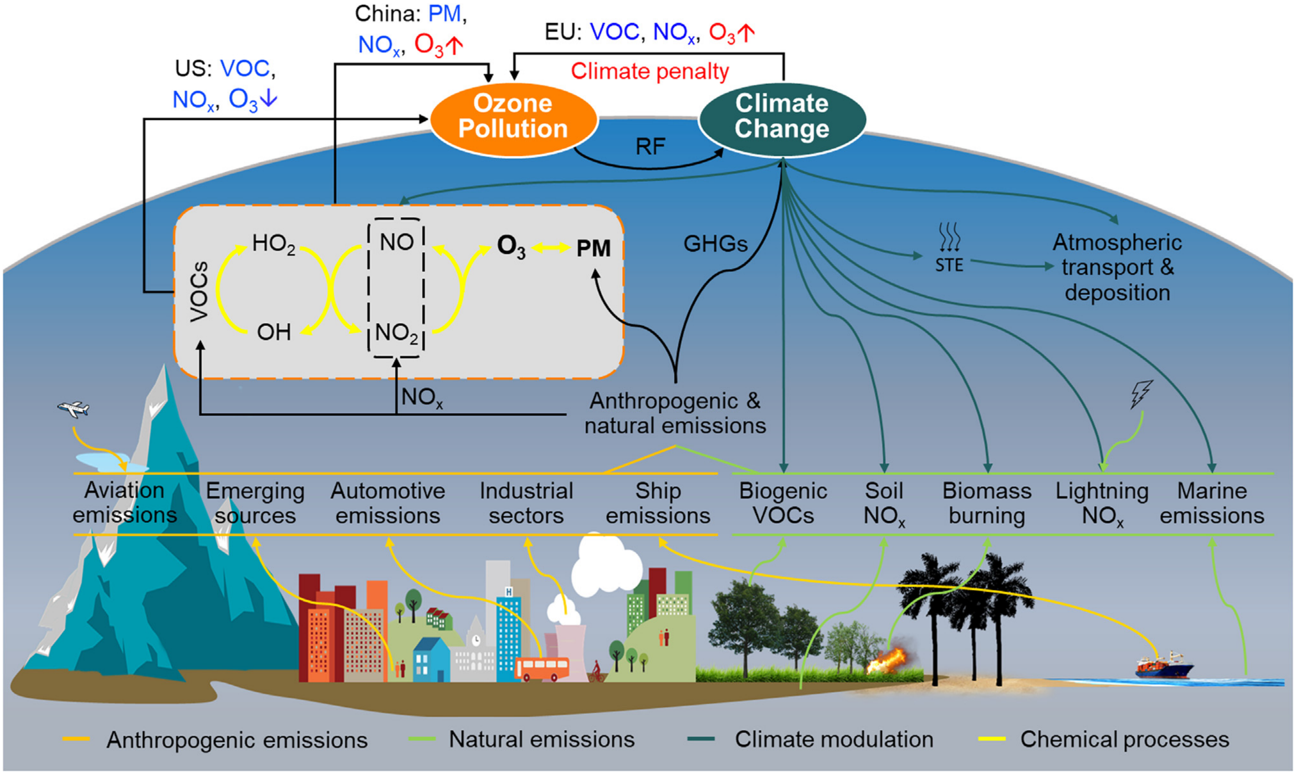

Figure 3. Factors and processes regulating tropospheric ozone pollution

Anthropogenic and natural emissions lead to ozone production through complex chemical reactions (NO_x and radical cycles); particulate matter (PM) interacts with ozone; and a warming climate modulates ozone production by affecting natural emissions, chemistry, and physical processes. Surface ozone levels vary diversely (red font for increase and blue for decrease) in response to anthropogenic emission reduction and climate change in the US, China, and EU. RF, radiative forcing; GHGs, greenhouse gases; OH, hydroxyl radical; HO_2, hydroperoxyl radical. Alkoxyl (RO) and peroxyl (RO_2) radicals are omitted.

this period, the decrease in the 95th percentile ozone concentration mainly occurred over the western US (i.e., Los Angeles). The recognized importance of NO_x transport on ozone formation motivated the promulgation of the NO_x State Implementation Plan (SIP) Call in 1998 by the US Environmental Protection Agency. By enacting increasingly strict regulation of power plant NO_x emissions and the reduction in NO_x from vehicles,[66,67] the NO_x-targeted policy led to successful ozone control after 2000 from regional to city scale across the US (Figures 4 and S6). It is also notable that the improvement in ozone air quality over the US and EU tended to slow down or even reverse after 2010, despite continued reductions in emissions. This dilemma might be largely attributable to climate change and continued rise in global CH_4 levels.

These historically successful control strategies in the EU and the US highlight the necessity for regional efforts in ozone control. There is also notable urban-rural differentiation in observed ozone trends around the world,[29,68–71] highlighting the demand for targeted control strategies to reduce urban and rural ozone exposure. In recent decades, with the effective regulation of combustion emissions, some previously unappreciated emission sources are becoming increasingly important.[72,73] Recent studies have demonstrated that volatile chemical products (VCPs), an overlooked source of various organic compounds, are emerging as an important driver of current ozone pollution in developed megacities across North America and EU.[73,74] Therefore, control of VCP emissions is becoming recognized as increasingly important in academic communities.[75]

In China, controls of key ozone precursors (NO_x and VOCs) started 10–30 years later than in the EU and the US, and priority was given to reducing NO_x emissions (Figure 4). Although $PM_{2.5}$ pollution has significantly decreased in response to stringent control measures since 2013, urban ozone levels experienced an extensive increase at the same time, making China the country with the fastest ozone increase in the world. This worsening ozone pollution, which has partly offset the health benefits from improved $PM_{2.5}$ pollution, poses a new challenge to air quality management in China. Recent studies[23,24,76] indicated that the post-2013 decline in $PM_{2.5}$ and NO_x concentrations resulted in an increase in urban ozone in China due to reduced uptake of HO_2 on $PM_{2.5}$, enhanced irradiance, and accelerated ozone production in a VOC-limited regime in response to decreased NO_x emissions (Figure 3).

It is worth noting that the unintentional rise in ozone was not obvious in the course of the decline of $PM_{2.5}$ and NO_x in the US and EU, contrary to the recent ozone dilemma in China. First, such a discrepancy can likely be explained by the simultaneous or even earlier control of VOC emissions in the US and EU (Figure 4). Second, NO_x reduction led to a shift of ozone formation chemistry toward an NO_x-limited regime in the US and EU,[77] improving the ozone benefit for NO_x reduction; however, this did

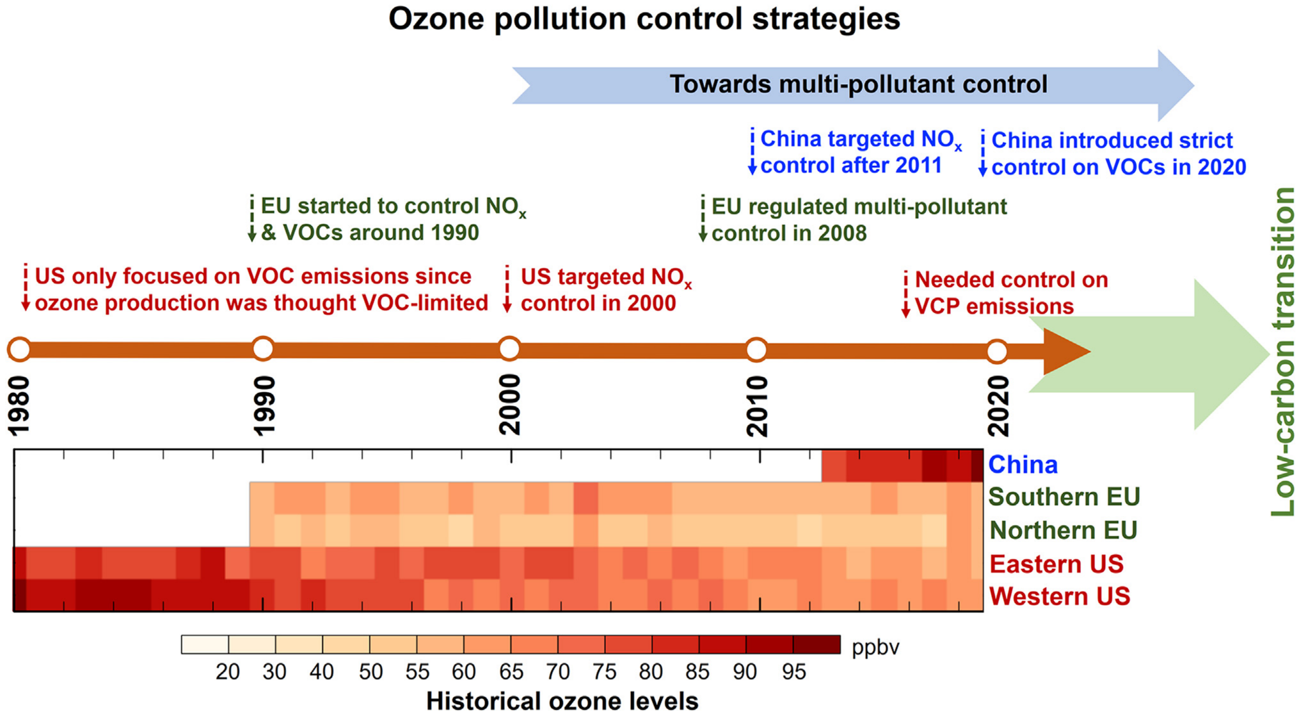

Figure 4. Historical progress of ozone pollution controls in the US, EU, and China

The 95th percentile of ground-level DMA8 ozone (ppbv) in warm seasons is averaged over the western US (west of 100°W), eastern US (east of 100°W), northern EU (north of 50°N), southern EU (south of 50°N), and China.

not happen in large Chinese urban agglomerations until recent years (e.g., 2019).[78] The weak sensitivity to NO_x reduction might relate to the still-high emissions of NO_x from combustion and other sources, such as agricultural soil NO_x in North China.[79] Third, $PM_{2.5}$ reduction had a greater impact on ozone in China because of the much higher $PM_{2.5}$ concentration.[76] The short-term ozone increase in China since 2013 was also related to meteorological variability.[24,80] Nevertheless, while the dominant factors affecting the growth of urban ozone in China during 2014–2019 are still debated and deserve further investigation,[23,81–83] air quality management in China indicates that joint ozone-$PM_{2.5}$ control strategies are urgently needed.[76,78,81] A recent study[41] proposed a new ozone formation regime (i.e., the aerosol-inhibited regime), which highlights the important role of aerosol suppression in ozone formation under high-$PM_{2.5}$ conditions. Moreover, $PM_{2.5}$ and ozone pollution dominate the population health risks attributable to air pollution.[17] These findings pinpoint the urgency to develop effective multi-pollutant control (i.e., joint ozone-$PM_{2.5}$ control), especially in regions exposed to high levels of $PM_{2.5}$ and ozone.

Ozone pollution is also modulated by changing climate through the influence of natural emissions, chemical processes, transport patterns, and other processes, such as temperature-related peroxyacyl nitrate decomposition,[84] humidity-related ozone consumption,[50] and drought-related ozone deposition on vegetation[35] (Figure 3). In addition, climate warming would increase hydroxyl radical (OH) levels and then affect CH_4 levels, which influence the global ozone trend. Therefore, climate change could affect long-term ozone trends. In East Asia, a modeling study[85] demonstrated that climate change accounted for a 2–10 ppbv ozone increase in summer during 1981–2011, which was a notable enhancement, although still much lower than that attributed to rising anthropogenic emissions in this region. In the EU, a significant climate change penalty was highlighted, which offset the ozone decrease gained from emission reductions by 0.3–0.5 ppbv/year during 1979–2015.[35] The increase in ozone in the Southern Hemisphere, primarily driven by STE during 1990–2015, was also likely related to climate change, as global warming caused the poleward expansion of the Hadley circulation.[59] The increase in global mean temperature slowed down before 2013 (a global warming hiatus) and then returned and kept rising after that, offering a window to examine the sensitivity of ozone pollution to climate warming. Figure S7 compares the climate-driven ozone trend during and after the hiatus (2005–2013 and 2014–2019, respectively), as determined by model simulations with fixed anthropogenic emissions but varying meteorology from 2005 to 2019. The latter period exhibited a notable ozone increase over most of the US, EU, and China, relative to the warming hiatus period.

High-ozone episodes are also accompanied by increasingly frequent climate extremes. For instance, ozone pollution episodes were frequent during the 2003 European mega-drought, and ecosystem-atmosphere interactions were responsible for the exacerbated ozone pollution over the EU.[35] Similarly, ozone extremes in October 2010 over the southeast US were also found to be climate driven with drying and warming conditions.[86] This is confirmed in Figure S4, showing that ozone pollution in the EU, the US, and Australia (wildfires, Figure S8) is highly sensitive to meteorological variations. Moreover, the recent frequent wildfires in the western US greatly enhanced ozone production in

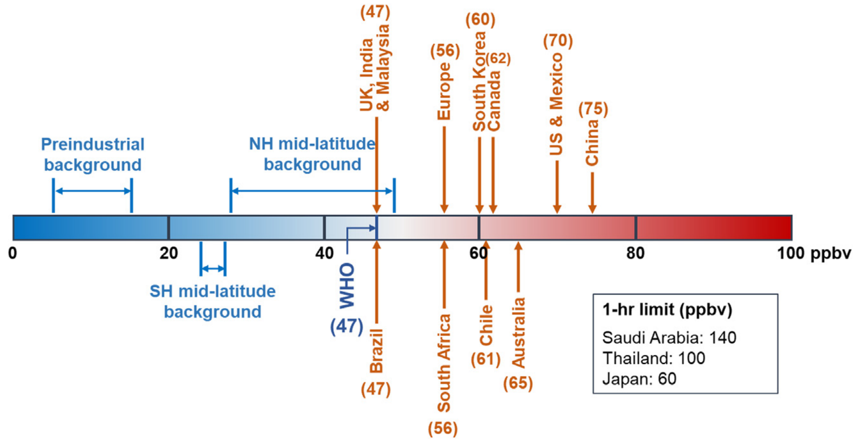

Figure 5. Current ambient ozone air quality standard in various countries and the standard recommended by the WHO

Numbers in parentheses are the limits for DMA8 ozone (ppbv). Ozone standard is in the unit of $\mu g\ m^{-3}$ in Brazil (100 $\mu g\ m^{-3}$), China (160 $\mu g\ m^{-3}$), EU (120 $\mu g\ m^{-3}$), India (100 $\mu g\ m^{-3}$), Malaysia (100 $\mu g\ m^{-3}$), and WHO (100 $\mu g\ m^{-3}$), which has been converted to ppbv under standard conditions (1,013 hPa, 273 K). Also shown are the background ozone ranges in the Northern Hemisphere (NH), Southern Hemisphere (SH), and pre-industrial era.[19,94] Inserted box shows 1-h ozone limits for representative countries where DMA8 ozone standards are not available.

downwind urban regions,[47,87] and climate warming has contributed to increasingly frequent wildfire events.[88,89] Overall, these climate-driven ozone episodes are challenging ozone pollution control in developed regions where anthropogenic emission reductions are slowing down.[67] Considering that hot and dry summers that are conducive to ozone episodes[90,91] are more frequent under climate change, it is necessary to control ozone pollution and mitigate climate change in a coordinated way.

Toward a synergistic ozone-climate control strategy

Setting air quality standards is the regulatory basis for ozone control. Figure 5 summarizes the current ozone air-quality standards worldwide. The limit for DMA8 ozone varies in a wide range from 47 to 75 ppbv. There are large gaps between the limits in most countries and the guidance value of the WHO. This is true of the US (70 ppbv), where ozone control has been in place for decades. Notably, even the background ozone levels in the Northern Hemisphere could exceed the WHO guidance value, demonstrating the need for international joint efforts to reduce anthropogenic emissions. Moreover, the observed DMA8 ozone frequently exceeds the WHO guidance value, especially in the Northern Hemisphere (Figure S1). The health risks of ozone exposure[92,93] highlight the importance of developing health-oriented ozone control strategies.

As discussed above, ozone pollution is closely related to climate.[42–45] In response to the climate crisis, low-carbon ambition has become the main theme of the world.[95] Here, we elucidate a strategy that synergizes ozone control with climate, as presented in Figure 6. The synergistic control is grounded upon synergies between ozone and climate in at least three aspects: emission, mechanism, and policy. Ozone precursors and greenhouse gases can be co-emitted from many sources (emission), and there is mounting evidence for the interaction between ozone and climate (mechanism).[7,8,35,86] Thus, their co-benefits are expected through implementing coordinated control strategies (policy). However, little has been attempted beyond CH_4 emission controls.[96,97]

Health effect is a common endpoint of climate change and ozone exposure, as climate change is the single biggest threat to human health and ozone exposure causes ~0.4 million premature deaths annually.[17,98] Other air pollutants that interact with climate and ozone, such as $PM_{2.5}$, could contribute to even higher health risks.[17] More importantly, the health effects of climate and ozone pollution are largely synergistic: climate warming threatens the population by the more frequent occurrence of heat stress, and ozone pollution tends to worsen on hot days. Therefore, we propose to take health risk as the fulcrum of policy levers to enhance the motivation of the synergistic control. Health-oriented management of climate and air quality have previously been investigated separately.[99,100] In this strategy, a holistic management system based on the total health risk of climate and air pollution (including ozone) would effectively promote synergistic ozone-climate control.

However, comprehensive research is needed to further understand the foundation of synergistic control with health-oriented management. In brief, with the reduction of conventional fossil-fuel-related emissions, emerging sources, such as VCPs, may still sustain a high potential for ozone formation.[73,74] While the radiative forcing of tropospheric ozone is relatively certain, the mechanisms by which climate mediates ozone are complex, and more quantitative and integrated research is necessary. In addition, other air pollutants, such as $PM_{2.5}$, complicate the ozone-climate interaction. In terms of policy coordination, ozone benefit while reducing global warming is not taken for granted. Thus, balanced emission reduction schemes are required. Moreover, appropriate assessment methodologies that reflect the overall health risks of climate change and ozone pollution should be developed.

The climate-synergistic control strategy applies to both high- and low-emission scenarios, incorporating short-term and long-term efforts to reduce the combined health risks. Multi-pollutant (i.e., ozone-$PM_{2.5}$) joint control is at the heart of the strategy in the high-emission scenario, driven by reducing $PM_{2.5}$ and ozone concurrently. We expect it to resolve the challenge of an unintentional ozone upsurge amid a rapid decline in anthropogenic emissions. Meanwhile, climate change can be mitigated through simultaneous reductions in greenhouse gas emissions. To prevent high health risks caused by extreme events, we recommend the application of early warning and forecast systems that integrate weather, $PM_{2.5}$, and ozone predictions so that short-term emergency measures can be taken. Prototypes of such systems are available in some countries (e.g., the US). Existing global modeling capacities for weather and air quality may help upgrade the systems for large-scale extreme

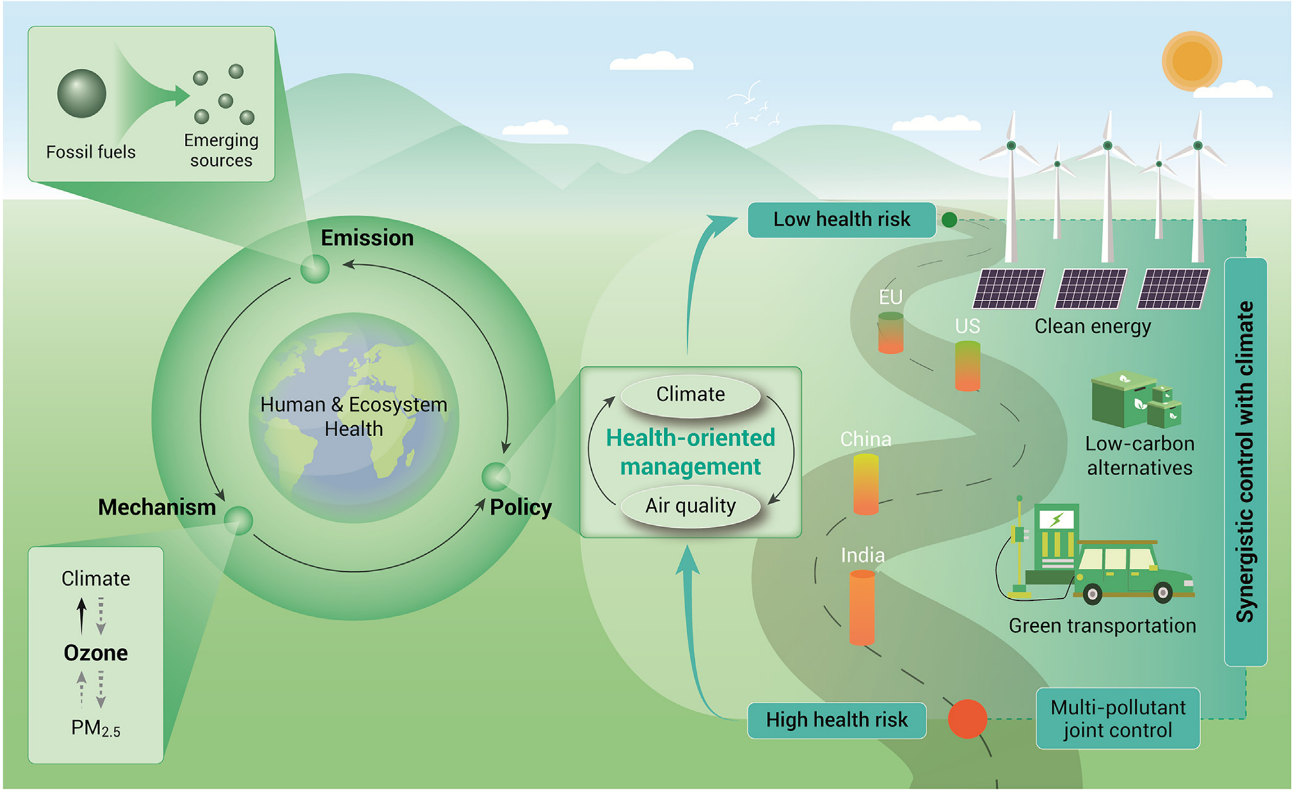

Figure 6. Schematics of a joint ozone-climate control strategy
The synergy is built on three aspects: emission, mechanism, and policy. Policy is a response not only to emissions but also to the mechanisms of ozone-climate interactions that are regulated by emissions. A health-oriented management system is proposed to integrate climate and air quality actions through promoting clean energy, green transportation, and low-carbon alternatives. India, China, the US, and EU are labeled to represent different stages of social development and environmental management.

events, such as the heat waves in the summer of 2022. In the low-emission scenario, the potential to control ozone by reducing anthropogenic emissions is limited. Climate change, however, exerts a significant impact on ozone pollution, as seen in the elevated ozone levels during the heat waves in the EU and wildfires in the western US.[35,47] There is a demand for a more sophisticated and climate-synergistic ozone control strategy, which should be implemented under an international framework and may take longer than the existing strategies. We propose to form ozone groups within global climate communities, such as the IPCC, to promote the concept and research of synergistic ozone-climate control. International cooperation is also crucial for low-emission countries through reducing the transboundary impacts.

As specific initiatives, efforts can be made to promote green transportation, clean energy, and low-carbon alternatives. Electric vehicles (EVs) are free of tailpipe emissions of both ozone precursors (e.g., VOCs and NO_x) and greenhouse gases (e.g., carbon dioxide), thus decreasing the climate and ozone impacts of the transportation sector. Nevertheless, EVs are not necessarily zero emission, because emissions from power generation to charge them must also be considered. Increasing the share of clean energy and energy efficiency helps reduce emissions from power plants and industries, which are important anthropogenic drivers of climate and ozone. While there is increasing awareness that the burning of fossil fuels should be reduced or better managed, sources that are overlooked or whose emissions are concealed may emerge as fossil fuel emissions decrease, such as asphalt and coating applications.[73,101] These emerging sources provide VOCs to sustain ozone formation and may also emit greenhouse gases. Development and use of low-carbon alternatives may be a promising solution to this problem.

The abovementioned measures are being implemented in some countries. Taking China as an example, the national EV stock accounted for 48% of the global total in 2021, although it is still a small part of the fleet.[102] The central and local governments have introduced a series of policies to promote EVs, such as a mandate of 12% EVs in manufactured or imported vehicles, subsidies, and tax exemptions. The ozone and health benefits of fleet electrification in China have been demonstrated, although the assessment did not cover the entire life cycle of EVs, especially the production phase.[103] China is also leading the world in the production of clean energy, with 29% of total power generation coming from renewables in 2021.[104] It was found that decarbonizing power generation by deploying EVs would greatly improve air quality (including ozone reduction) and increase climate benefits.[105] In Hong Kong, limiting VOC content in solvent products has been proved to be effective in reducing local ozone production.[106] Despite such efforts, revolutionary progress is yet to come.

Shared emission sources, interactive chemical mechanisms, and importantly synergistic health effects between ozone pollution and climate change lay the foundation for the proposed joint ozone-climate control. A best policy option may be a portfolio of measures to minimize overall health risks within an acceptable cost-effective range. As elucidated previously, this control strategy is adaptable to various stages of social development from high- to low-emission scenarios. Moreover, to build on current global mechanisms to combat climate change and ozone collaborative research, such as the TOAR, we call for extensive international big science programs and cross-disciplinary research, synthesizing innovative ideas in related fields. Overall, by leveraging the dynamics of climate mitigation, the proposed synergistic ozone-climate control strategy promises to address the current challenges of worldwide ozone pollution.

EXPERIMENTAL PROCEDURES

Resource availability

Lead contact

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Materials availability

This study did not generate new unique materials.

Data and code availability

Surface measurement data of global ozone concentration have been deposited at Figshare under https://doi.org/10.6084/m9.figshare.23292365.v1 and are publicly available. Any additional information required to reanalyze the data reported in this paper is available from the lead contact upon request. Further information and requests for resources should be directed to and will be fulfilled by the lead contact, Hai Guo (hai.guo@polyu.edu.hk).

Data collection

In this study, ozone data were collected from over 8,000 air-quality monitoring stations across 48 countries. After applying the screening criteria described below, ozone data from 4,308 stations were used for analysis. The short-term data mainly covered the period of 2014–2019, with a time deviation of 1–2 years. Ozone data spanning longer periods were accessible at fewer stations in some countries. Most of the stations were located in areas significantly or moderately influenced by anthropogenic emissions. About 76% of them were the same as those adopted in the TOAR,[107] particularly in the US and EU, but we included those recently enabled in China and Malaysia. The study analyzed the levels and latest trends of monthly 95th percentile DMA8 ozone during 2014–2019. However, readers are reminded that the time frame was 2013–2017 for all the stations in Japan and 2014–2018 for four stations in Victoria, Australia, and all stations in Malaysia, due to data availability.[51]

We also compared 2014–2019 ozone trends with 2000–2019 ozone trends (Figure S3) over the US, EU, South Korea, Mexico, Malaysia, Japan, and Australia, and the data sources are documented in an online data repository.[51] To relate historical emission reductions with ozone changes, ozone measurements were collected for the US from 1980 onward (https://aqs.epa.gov/aqsweb/airdata/download_files.html) and for EU from 1990 onward (TOAR data at https://doi.org/10.1594/PANGAEA.876110 and European Environment Agency data at https://discomap.eea.europa.eu/map/fme/AirQualityExport.htm). Temperature data used in Figure 2 were obtained from the European Centre for Medium-range Weather Forecasts (ERA5) reanalysis data, available at https://cds.climate.copernicus.eu/cdsapp#!/dataset/reanalysis-era5-single-levels?tab=overview.

Data screening

Ultraviolet photometric techniques were used to measure ozone at all stations, and the measurement and quality-control protocols recommended by the US Environmental Protection Agency were primarily followed. We calculated the 8-h average ozone for any eight consecutive hours of data, as long as the data completeness was not lower than 75%. Each 8-h average was assigned to the day on which it began (i.e., the calculation started for 0:00–7:00). The last 8-h average of 1 day represented the average for the inclusive interval from 23:00 to 06:00, which started at 23:00 local time (LT) and ended at 06:00 LT on the next day. The DMA8 ozone was determined for days with at least 12 valid 8-h average ozone data points. The monthly average and monthly 95th percentile DMA8 ozone values were calculated only if there were at least 20 DMA8 ozone values available for that month. Stations with monthly data completeness below 85% were excluded. The number of stations was reduced from over 8,000 in 48 countries to 4,308 in 37 countries after data screening.

Ozone metrics and trends

Thresholds of 65 ppbv, 60 ppbv, and the WHO standard of 47 ppbv were used as ozone metrics to screen high DMA8 ozone values. The number of days with DMA8 ozone exceeding 60 ppbv in a warm season, for instance, was labeled as NDGT60. It was then averaged over years to obtain the NDGT60 at each station per warm season, which was further averaged over all the stations in a same nation to obtain the national average NDGT60 per warm season.

To reduce the effect of seasonal variability, we used the anomalies of monthly 95th percentile DMA8 ozone to draw the ozone trends. The anomaly for a given month was calculated as the 95th percentile of DMA8 ozone in that month minus the average of 95th percentile DMA8 ozone over the same month of different years during the study period. The 95th percentile of DMA8 ozone was selected to represent high values of ozone and has been widely adopted in the air-quality community. It was calculated for ~30 values every month, not for ~180 values every warm season. In this study, the 95th percentile in a month was a value between the second and third highest values in most cases. The first, second, or third highest value was not used to avoid arbitrariness.

Linear least-squares regression was applied to the monthly anomalies, in line with the method previously used by Cooper et al. to calculate global ozone trends.[20] The calculations were restricted to warm seasons. National average trend of 95th percentile DMA8 ozone was also calculated by averaging the monthly 95th percentile DMA8 ozone across all eligible stations, calculating the anomalies, and conducting linear regressions. The ozone trends, two-tailed p values, and time frames for the regressions are also documented in Lyu et al.[51] Because we performed the regressions for ozone anomalies against time and did not make correlations for the time series of ozone anomalies over any two staggered time periods, autocorrelation was not an issue of concern in this study.

Goddard Earth Observing System-Chemistry (GEOS-Chem) modeling

The global GEOS-Chem chemical transport model was applied to simulate the 2014–2019 trends of tropospheric ozone driven by changes in meteorology and anthropogenic emissions between 2014 and 2019. The model ran with detailed O_3-NO_x-VOC-aerosol chemistry (version 12.3.2; https://zenodo.org/record/2658178), driven by MERRA-2 assimilated meteorological data. Simulations were conducted at a horizontal resolution of 2° latitude by 2.5° longitude and 47 vertical layers up to 0.01 hPa. The model configurations for anthropogenic and natural emissions were similar to those of Li et al.[23] For the first sensitivity simulation, anthropogenic emissions were fixed at the 2014 level and meteorology was allowed to change. The second sensitivity simulation was performed with the anthropogenic emissions changed from 2014 to 2019 and the meteorological conditions were fixed at the 2014 level. All the simulations had a spin-up of 6 months. Similar to the 2014–2019 simulations, to further estimate the climate-driven ozone during and after the global warming hiatus, we performed a set of simulations from 2005 to 2019 with varying meteorology but fixed anthropogenic emissions.

SUPPLEMENTAL INFORMATION

Supplemental information can be found online at https://doi.org/10.1016/j.oneear.2023.07.004.

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and discussion. No organization or program will be responsible for the results generated from their data.

AUTHOR CONTRIBUTIONS

X.P.L. and K.L. performed the study and drafted and revised the manuscript. H.G. led the project, oversaw the interpretation of the results, and revised the manuscript. L.M. co-led the project and revised the manuscript. B.Z. and Y.Z. undertook the data analysis. F.J., C.C., A.G., X.X., T.W., X.L., T.Z., X.Q., M.S., L.X., N.W., J.C., J.G., F.C., I.S., B.S., and D.B. provided comments, interpretations, and manuscript revisions. S.C., M.T.L., D.S., V.S., P.K., B.M., and R.S. provided relevant data, comments, and interpretations.

DECLARATION OF INTERESTS

The authors declare no competing interests.

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