THE CASE FOR ACTION ON TROPOSPHERIC OZONE

Integrated action to mitigate climate change, deliver clean air and support food security

CLEAN AIR FUND

CLEAN AIR TASK FORCE

Clean Air Institute

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CONTENTS

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Cover image: Los Angeles skyline / Credit: Daniel Stein, iStock

EXECUTIVE SUMMARY

Tropospheric ozone is a greenhouse gas, super pollutant and air pollutant. It warms the Earth's atmosphere, harms human health when inhaled, and damages crops and forests.

As a greenhouse gas, it is responsible for approximately 0.23°C of present-day warming. Yet dedicated action to reduce tropospheric ozone is absent from the climate policy agenda at a global, regional, and country level. As it's one of the super pollutants driving half of global warming, this needs to change.

Tropospheric ozone is not emitted like many other gases and particles, but rather formed in the atmosphere when sunlight interacts with a suite of other pollutants. The main ingredients driving elevated levels of this toxic air pollutant are methane (a potent greenhouse gas), nitrogen oxides, non-methane volatile organic compounds, and carbon monoxides. These 'precursors' are emitted from a range of sectors, including transport, industry, livestock and energy generation – as well as wildfires.

Reducing tropospheric ozone has untapped potential to mitigate the impact of human-induced climate change over the coming years. At the same time, targeted action can deliver cleaner air, reducing the half a million premature deaths and the $500 billion in economic costs associated with tropospheric ozone each year. Action on tropospheric ozone also improves agricultural yields for staple crops on which billions of people rely, like maize, rice and wheat.

Reducing tropospheric ozone presents a unique challenge as it requires smart and fast action across multiple greenhouse gases and air pollutants, as well as multiple economic sectors. It is a growing and neglected problem that needs an integrated approach on both a local and global level to tackle climate change and air pollution together, alongside accelerated efforts to translate science into policies.

Despite this complexity, progress is possible. This briefing showcases efforts in cities and regions – including Los Angeles, Mexico City, Beijing and Europe - that have successfully reduced levels of tropospheric ozone through targeted pollution control.

There are concrete steps that governments and other decision makers can take now. Many of these are aligned to existing efforts such as the Global Methane Pledge and delivering on World Health Organization (WHO) Air Quality Guidelines. This report explores policies and measures by sector and precursor pollutant, given that each location will experience a different mix of precursors depending on their sources and local conditions.

At the same time, further research and scientific leadership is needed to better understand the considerable benefits of reducing tropospheric ozone and fill knowledge gaps holding us back from mitigating climate change at pace.

Our recommendations for policy makers, scientists, and funders set out action that can be taken now. We urge bold steps to secure the considerable benefits these measures will bring, including faster climate change mitigation, cleaner air for billions of people, and improved global food security.

Tropospheric ozone is responsible for

0.23°C

degrees of present-day warming

Reducing tropospheric ozone can provide a triple win for climate, health and agriculture:

CLIMATE

Reducing tropospheric ozone levels will contribute to avoiding further global temperature rises in the coming decades. Tropospheric ozone levels have increased significantly over the last century. Since 1995, they have gone up between 2-12% per decade, depending on the region, driven largely by rapid industrialisation and urbanisation. They are estimated to have contributed to 0.23°C of global warming from 1750 to the present. Cutting super pollutants, including tropospheric ozone, can mitigate warming nearly four times faster than decarbonisation alone.

Significant actors in climate action are waking up to this urgent issue. Earlier this year, the US and Chinese governments identified the need for technical cooperation and capacity building to develop abatement solutions for tackling tropospheric ozone as part of efforts to combat climate change.[1]

HEALTH

Tackling tropospheric ozone would bring major health benefits by rapidly improving air quality. Tropospheric ozone poses serious health risks. It contributes to respiratory issues, reduces lung function, and exacerbates chronic conditions like asthma, bronchitis and emphysema. It has also been linked to complications in type 2 diabetes and cardiovascular disease.

Nine out of ten people are exposed to tropospheric ozone levels that exceed WHO guideline levels, contributing to almost half a million premature deaths each year. Meeting the WHO's guidelines would save hundreds of thousands of lives and provide economic benefits of up to $500 billion per year, through avoided healthcare costs.

AGRICULTURE

Tropospheric ozone severely damages many staple crops, leading to reduced grain size, fewer seeds, slower growth rates and less resilience to environmental stresses. It also accelerates the leaf aging process and causes plants visible injury, like chlorosis and necrosis.

The result is significant losses in global crop yields. For staples such as wheat, soyabean and maize, total economic losses due to ozone damage could amount to $35 billion annually by 2030, if calculated using 2000 prices. Tackling tropospheric ozone would improve food security globally by increasing yields for the crops that feed billions of people.

Credit: Shourav Sheikh Pixabay

WHAT IS TROPOSPHERIC OZONE?

Tropospheric ozone is a reactive gas that has multiple impacts. Elevated levels of tropospheric ozone simultaneously contribute to global warming and climate change, harm human health, reduce crop yields, and degrade ecosystems.

Unlike many other pollutants, tropospheric ozone is not directly emitted. It is instead formed in the atmosphere when other pollutants chemically react in the presence of sunlight. These precursor pollutants – including methane (a potent greenhouse gas), nitrogen oxides (NOx), non-methane volatile organic compounds (NMVOCs) and carbon monoxide (CO) – are emitted extensively from various shared, human-related activities. Key sources include the transport (including aviation and shipping), industry, livestock and energy sectors – as well as wildfires (see Figure 1).

Tropospheric ozone can be both formed and destroyed quickly in the atmosphere, meaning its levels are always changing. They respond to local levels of precursor pollutants, as well as meteorological and climatic conditions. Due to its abundance in the atmosphere and relatively longer atmospheric lifetime compared to other precursors (around 12 years), methane affects tropospheric ozone strongly at the global scale, including in remote locations like over oceans.[2] Emissions of NMVOCs, NOx and CO drive an associated set of reactions that affect tropospheric ozone levels over the span of hours, days and months. These precursor pollutants affect levels of tropospheric ozone faster and more locally than methane, although they also have important regional effects.

Levels of tropospheric ozone therefore vary significantly across the world and over the course of daily and annual cycles. For example, we see a clear distinction between the northern and southern hemispheres, with historically higher levels in the northern hemisphere associated with its more densely populated regions, extensive urbanisation and industrialisation, and higher total precursor emissions. Locally, tropospheric ozone also differs between urban, rural and industrial areas, driven predominantly by nearby emission sources and local conditions.

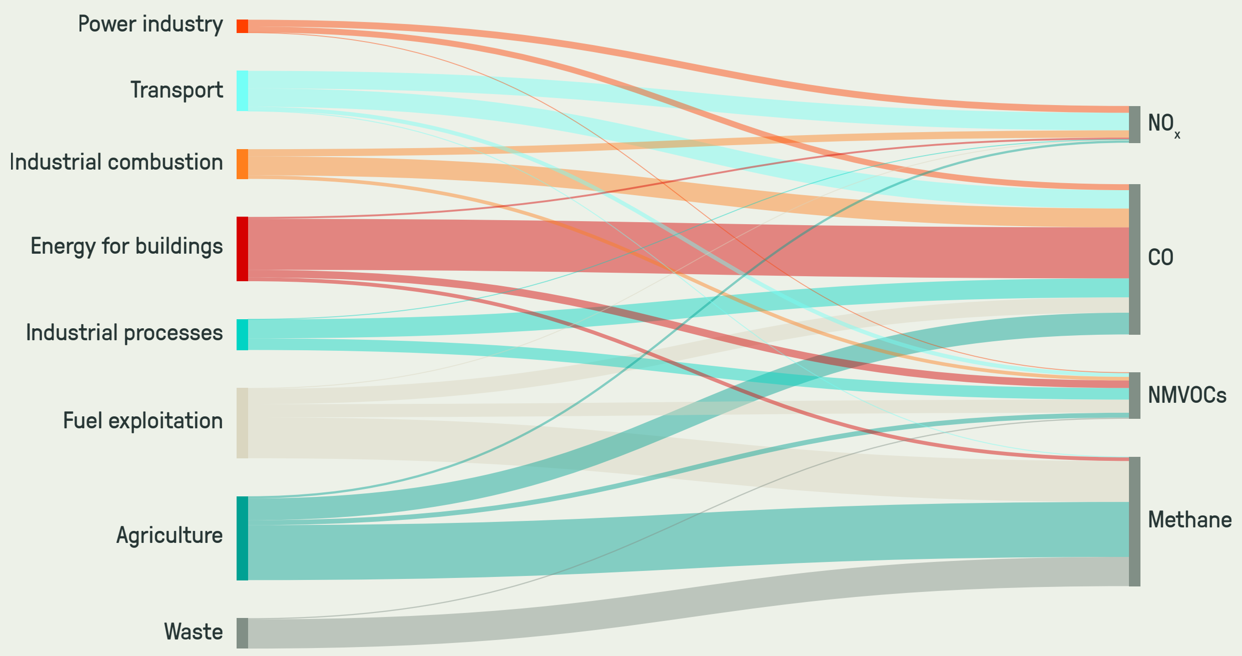
Tropospheric ozone is photochemically and thermally active, meaning its formation and destruction is also determined by temperature and levels of sunlight. This means that the tropics play an important role in tropospheric ozone formation globally.[3] It also means that warmer temperatures linked to climate change are helping to drive periodic episodes of significantly elevated tropospheric ozone levels, resulting in a vicious feedback loop. High ozone levels appear as toxic photochemical smog, which is the brown haze that is often seen above hot, polluted cities.

> “... responsible for half a million premature deaths every year

The complex mix of precursor pollutants, emissions sources and environmental factors means that reducing tropospheric ozone poses a challenge for scientists and policy makers at all levels. Not all reductions of precursor emissions will correspond to local reductions in tropospheric ozone levels.[4,5] The region's specific mix of precursor pollutants and meteorological and climatic conditions determines whether reducing methane, NOx, NMVOCs and/or CO is the most effective route. In certain cases, a decrease in a precursor emission may even increase local tropospheric ozone levels. Effects may also look different at ground-level compared to higher altitude parts of the troposphere, resulting in different health and climate benefits. This aspect of tropospheric ozone mitigation requires further scientific research, to fill the knowledge gaps that could undermine effective policy and decision making.

The pollutants and emission sources that cause ozone formation in the troposphere also cause multiple other environmental challenges. For example, NOx contributes to the formation of particulate matter, which is responsible for over 8 million premature deaths every year, and methane is a greenhouse gas in its own right.

FIGURE 1: RELATIONSHIP BETWEEN GLOBAL TROPOSPHERIC OZONE PRECURSOR POLLUTANT EMISSIONS AND THEIR ASSOCIATED EMISSION SOURCES AND SUB-SECTORS.



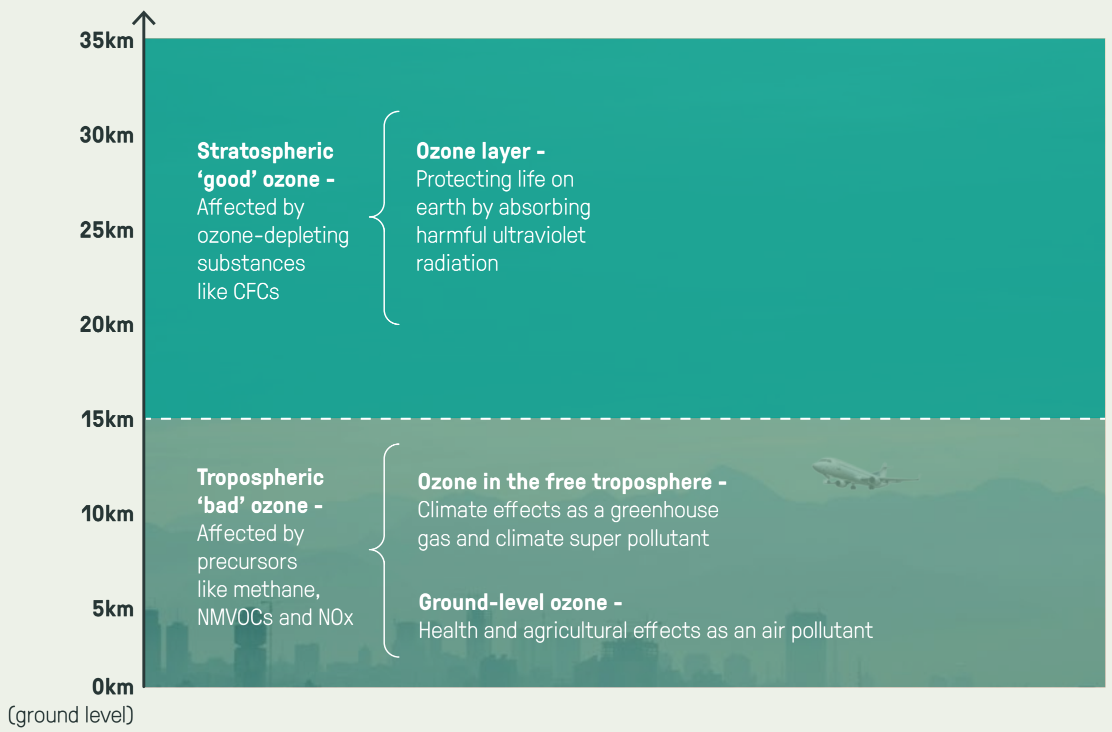
Data source: EDGAR emission inventory. Note figure does not include emissions from wildfires.

BOX 1: 'GOOD' OZONE VERSUS 'BAD' OZONE

Ozone can mainly be found in two layers of the Earth's atmosphere. Tropospheric ozone, or 'bad' ozone, refers to ozone that is present in the atmosphere up to about 15 kilometers above ground-level. In this layer, ozone acts as a greenhouse gas and super pollutant, contributing significantly to global warming by absorbing infrared radiation and thereby heating the surrounding air. At the bottom of this layer – the Earth's surface – tropospheric ozone is often referred to as 'ground-level ozone'. Here, it is responsible for almost half a million premature deaths per year and substantial reductions in agricultural crop yields.

Ozone plays a very different role in the stratosphere – the layer of the atmosphere from approximately 15 to 40 kilometers above the Earth's surface. Here, ozone protects us by absorbing harmful ultraviolet radiation through the ozone layer. This is the 'good' ozone layer that is protected by the internationally negotiated Montreal Protocol. Stratospheric ('good') and tropospheric ('bad') ozone are interlinked. The good news is that we can simultaneously protect the beneficial ozone layer while acting to reduce harmful tropospheric ozone levels. There is also growing evidence that increasing levels of tropospheric ozone and other greenhouse gases may erode stratospheric ozone, thereby increasing the importance and urgency of action on tropospheric ozone and climate change more broadly.[7]

FIGURE 2: THE MULTIPLE ROLES AND NAMES OF OZONE AT DIFFERENT LEVELS OF THE EARTH'S ATMOSPHERE.




Heavy traffic during a morning commuting hours in Jakarta, Indonesia. Credit: Aji Styawan/Climate Visuals

WHY ACT ON TROPOSPHERIC OZONE?

1. A potential win-win-win for climate, health and agriculture

IMPACTS OF THE TROPOSPHERIC OZONE ON CLIMATE, HEALTH, AGRICULTURE AND ECOSYSTEMS:

0.23°C
global warming to date

500,000
premature deaths per year

$0.5 trillion
economic costs per year

Up to 26%
loss in global crop yields

11%
loss in forest productivity

CLIMATE CHANGE

Reducing tropospheric ozone levels is important for slowing temperature rise in the coming decades.

Tropospheric ozone is one of the super pollutants[i] that are collectively responsible for nearly half of global warming to date.[7] Ozone alone is responsible for approximately 0.23°C[ii] of warming since pre-industrial times. About 40% of this warming is contributed by methane-mediated ozone formation and 56% from NMVOCs, CO and NOx-mediated ozone formation.[8]

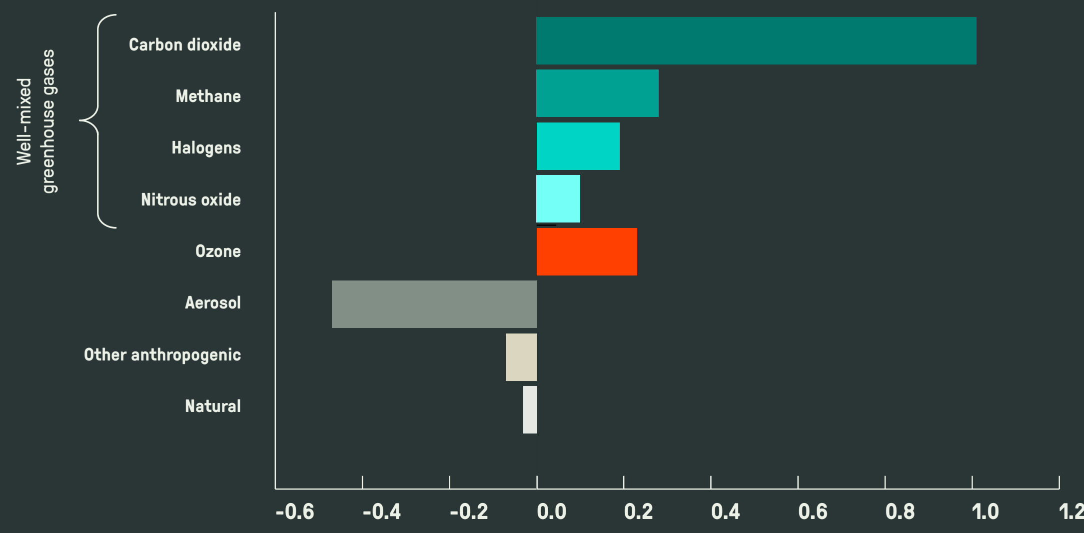
Cutting super pollutants, including tropospheric ozone, can mitigate warming nearly four times faster than decarbonisation alone by 2050.[9] Alongside deep decarbonisation programmes, targeted measures to tackle the pollutants that drive elevated levels of tropospheric ozone must be an important component of global climate strategy. Even in a decarbonisation scenario combining targeted measures for tropospheric ozone precursors with emission reduction programmes in the energy, waste and agricultural sectors, methane would still contribute 0.19°C of avoided warming by 2050. For other precursors to tropospheric ozone (NMVOCs, CO and NOx), it would be 0.11°C[10,11]

The climate effects of tropospheric ozone are felt most strongly in regions where levels are highest. In India, increases in tropospheric ozone levels are associated with localised warming of up to an estimated 0.5°C from 2005 to 2020.[12] Over China, tropospheric ozone is estimated to have increased surface temperatures by 0.43°C from 1951 to 2000; it is also linked to changes in the east Asia summer monsoon.[13] It contributes to ocean warming as well, accounting for 18% of the historical warming observed in the Southern Ocean.[14] This warming trend has had significant consequences, including contributing to the melting of Antarctic ice, a key cause of rising sea levels.[15]

Despite the potential for near-term climate mitigation from reducing tropospheric ozone, significant gaps remain in our understanding and ability to realise this avoided warming, particularly with regard to policies and measures tackling NMVOCs, CO and NOx emissions. Further research is needed to increase our understanding of the climate effects and feedback loops related to tropospheric ozone, looking at how and where its precursors interact in the atmosphere, with a particular focus on regional climate impacts.

It is important to note that all tropospheric ozone precursors are short-lived climate forcers that affect climate change in multiple ways. NOx, for example, also affects methane levels and this interaction is associated with a net warming effect.[16] Pollutants are also often co-emitted with other greenhouse gases and air pollutants. Policies and measures should consider multi-pollutant effects, including tropospheric ozone response.

FIGURE 3: THE CONTRIBUTION OF CLIMATE FORCING AGENTS TO 2019 TEMPERATURE CHANGE RELATIVE TO 1750.



Data source: IPCC, 2021, Chapter 7, Figure 7.7

i Super pollutants are warming agents that are far more potent than CO2 per ton. They include methane, tropospheric ozone, fluorinated gases (F-gases; such as HFCs), nitrous oxide (N2O), and black carbon. All super pollutants, other than N2O are also short-lived climate pollutants.

ii Warming to date estimate is from IPCC Assessment Report 6, Chapter 7, with a mean value of 0.23°C following a concentration-based calculation method. This value captures climate forcing of tropospheric ozone (large positive forcing) and stratospheric ozone (small mostly negative forcing). A similar value (0.25°C) can be calculated through data provided in IPCC Assessment Report 6, Chapter 6 by extrapolating from tropospheric ozone precursor emission contributions to warming.

AIR POLLUTION AND HEALTH

Tackling tropospheric ozone will have profound benefits for public health by improving air quality.

Ground-level ozone poses serious health risks, particularly for children, the elderly and outdoor workers. As evidenced by a large body of scientific research,[17] it contributes to respiratory issues, reduces lung function and exacerbates chronic conditions – like asthma, bronchitis and emphysema. Ozone exposure has also been linked to complications of type 2 diabetes and cardiovascular disease.

Nine out of ten people are exposed to tropospheric ozone levels that exceed the World Health Organization (WHO) guideline levels, contributing to almost half a million premature deaths each year.[18] It is estimated that the annual global cost of these health impacts exceeds half a trillion US dollars.[iii] There is some evidence that this figure could be significantly higher when considering additional causes of death.[19]

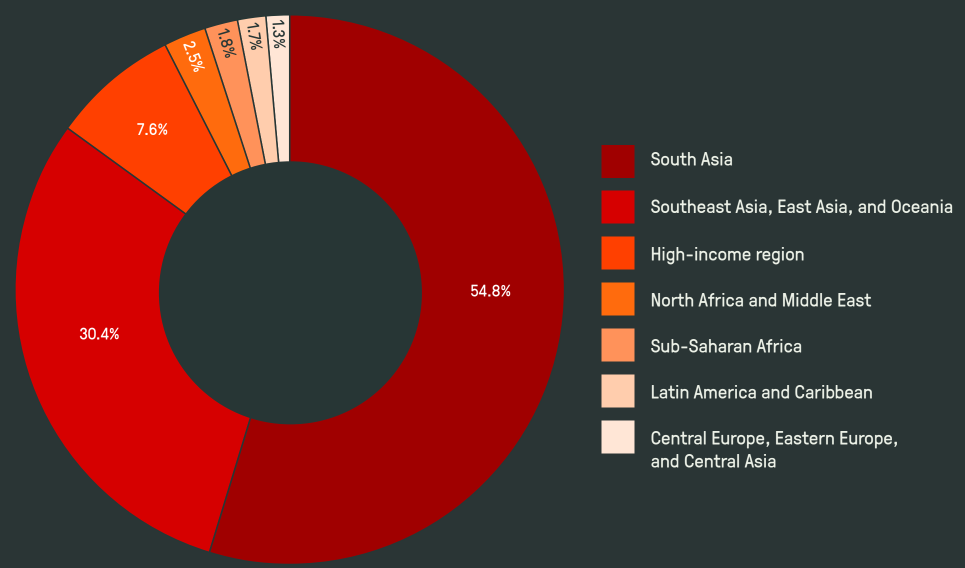
Millions of residents of Jakarta have for the past several months suffered from some of the worst air pollution in the world. Credit: Aji Styawan/Climate Visuals

While the Global South experiences a disproportionate burden of the health impacts of ground-level ozone, high-income regions are significantly affected too.[20] The highest levels of ozone exposure are found in South Asia, North Africa and the Middle East, and Sub-Saharan Africa. Qatar, Nepal and India experience the highest levels of population exposure. South Asia accounts for 55% of ozone-attributable deaths, followed by east Asia. India and China together represent 75% of global ozone-attributable deaths. High-income regions account for 8% of ozone-attributable deaths, with North America having the third largest regional mortality rate due to tropospheric ozone (4 deaths per 100,000), followed by Western Europe.[21]

Reducing levels of ground-level ozone can yield significant health benefits and promote health equity. WHO guidelines and interim targets provide a framework for governments to set their own objectives and put in place plans to cut ground-level ozone. Achieving WHO guidelines for ozone globally could prevent up to half a million premature deaths per year. It could also help address health issues linked to rising temperatures – such as infectious diseases, cardiovascular problems and heat-related mortality – and food insecurity, a primary cause of undernutrition.[22]

Moreover, many of the policies and measures to reduce tropospheric ozone precursors simultaneously reduce other harmful air pollutants, including PM2.5 and black carbon. Considering PM2.5 and ozone, air pollution contributes to more than eight million premature deaths each year and over $8 trillion of economic costs.[23,24] Policies and measures should consider the multi-pollutant effects on air pollution and public health, as well as climate response.

FIGURE 4: PERCENTAGE OF OZONE-ATTRIBUTANLE PREMATURE DEATHS BY REGION IN 2019.[IV]



Data source: Global Burden of Disease (GBD) results tool.

iii In 2022, the World Bank published a report detailing the global cost of health damages—both mortality and morbidity—associated with ambient and household PM2.5 pollution, which amounted to $8.1 trillion in 2019. To estimate the monetary valuation of ozone-attributable mortality globally, we utilized data from this report to calculate the Value of Statistical Life (VSL) for each country, alongside the Global Burden of Disease (GBD) Study's estimate of 469,793 ozone-attributable deaths in 2019. We calculated VSL for 179 of the 204 countries and territories included in the GBD Study, as data was unavailable for the remaining 25 countries. The VSL ranged from $0.04 million in Burundi to $9.9 million in Luxembourg. The total cost of ozone-attributable mortality in 2019 surpassed half a trillion USD, reaching $553,465,000,000. This figure is considered conservative, as it excludes the economic impacts of health effects in 25 countries and accounts only for mortality.

iv. Regions refer to the Global Burden of Disease super regions GBD super regions. The seven GBD super-regions are grouped based on cause of death patterns.

AGRICULTURE AND ECOSYSTEMS

Tropospheric ozone affects food security by reducing crop yields and harming forests and other important ecosystems.

Ozone enters plants through pores (stomata) in their leaves. Once inside, it causes oxidative stress. It interferes with physiological functions – like photosynthesis and nutrient transport – resulting in reduced grain size, fewer seeds and slower growth rates.[25] These pores can become slower to respond to environmental stresses and less resilient, making them more susceptible to diseases.[26] It can cause crops visible injuries, like chlorosis, necrosis and accelerated leaf aging.

These effects result in significant losses in crop yields globally, particularly for sensitive staple crops like wheat, soybean, and maize. The Intergovernmental Panel on Climate Change (IPCC) estimates under a high future emissions scenario that projected global yield losses by 2030 could range from 5-26% for wheat, 15-19% for soybean, and 4-9% for maize. The total economic loss for these three crops in 2030 could amount to up to 35 billion USD (in 2000 values).[27] Figure X showcases regional estimations in crop losses, with particularly higher upper limit values for wheat in east Asia, south Asia and Europe – and for soyabeans in Sub-Saharan Africa.

In addition to tropospheric ozone's direct links to agricultural loss, it also has indirect effects on broader climate challenges related to agriculture. If farmers face significant decreases in crop yields, they may increase their fertiliser use, which raises emissions of nitrous oxide (N20) – another super pollutant - and leads to more warming. Furthermore, farmers could choose to compensate for reduced crop yields by cutting down forests to expand agricultural land, damaging the forest's role as a carbon sink.[28]

As climate change and geopolitics strain food trade and food security globally, tackling tropospheric ozone presents a way to increase crop yields and support farmers. This is an important benefit for the agriculture sector, which is under growing pressure to change its practices to cut emissions.

Trees are also affected by ozone, damaging their ability to absorb carbon dioxide from the atmosphere and store it. Globally, primary productivity in forest trees is reduced by up to 11% due to elevated ozone levels.[29] Productivity in forests is an indicator of how much carbon a forest has sequestered or stored. As forests risk moving from net carbon sinks to net carbon sources, reducing tropospheric ozone also presents a way to protect forests and maximise carbon sequestration through healthier ecosystems.[30]

It is important to note that tropospheric ozone's effects on agriculture and forests are not linear. Many other factors are also at play and they can compound or lessen its impact. Factors like fertilisation due to increasing CO2 levels, temperature, water availability, soil nutrients, and fertiliser application also significantly affect crop yields and other issues related to food security and climate change.[31]

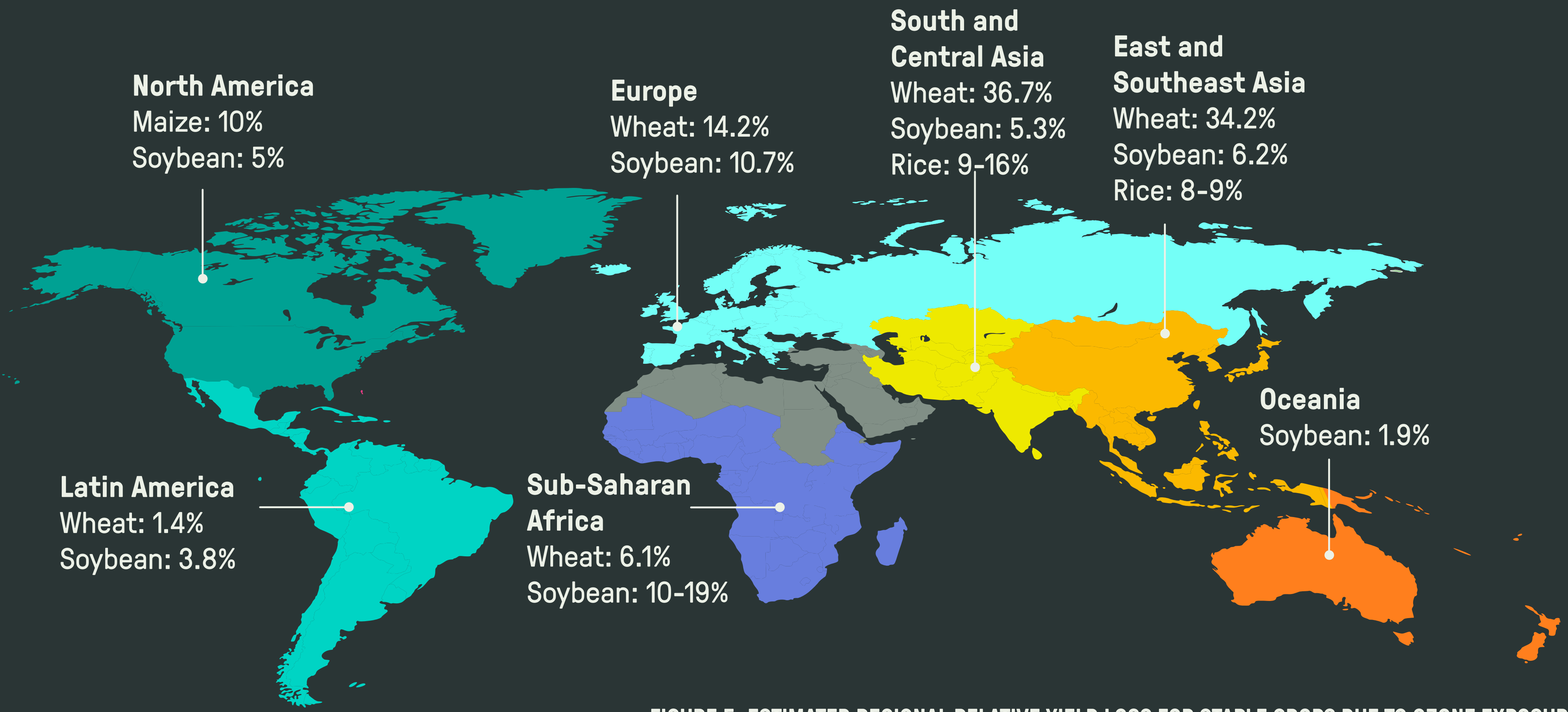


FIGURE 5: ESTIMATED REGIONAL RELATIVE YIELD LOSS FOR STAPLE CROPS DUE TO OZONE EXPOSURE.

Data source: Estimates have been collated from the latest available literature. Regional values are scaled up from national- and regional-level studies, where needed..[32,33,34,35,36]

2. A growing problem that is forecast to get worse

Since pre-industrial times, tropospheric ozone levels have increased by approximately 40%.[37] Recently, tropospheric ozone has increased by 2-12% per decade, depending on the region. This increase largely comes from human-led activities linked to rapid industrialisation and urbanisation that emit high levels of tropospheric ozone precursors. The largest increases in tropospheric ozone can be found in the Persian Gulf, India, east Asia, northern South America, and south-east Asia.[38]

Action on ground-level ozone has proven effective in some areas. Data compiled from numerous surface sites suggests widespread decreases in ground-level ozone in the US and western Europe, associated with decades-long policies to improve air quality.[39,40] However, in other regions, like mainland China, surface monitoring sites show high ground-level ozone levels and a trend towards further increases.[41] This is despite a recent significant reduction in emissions of NOx over the same period from 2013 to 2017, highlighting the complexity around precursor sources. Similar increases have been recorded in other countries in east Asia (for example, in the Republic of Korea and Japan), as well as in India.[42] In terms of health, these increases in ground-level ozone levels have resulted in a 38% rise in the global ozone-attributable mortality rate between 1990 and 2019.[43]

Over the coming decades, changes in tropospheric ozone will depend on the policy pathways that are taken towards decarbonisation, methane mitigation and pollution reduction. The extent to which tropospheric ozone responses and causes are prioritised in such policy decision making will be critical. High emission scenarios forecast increases in global tropospheric ozone levels by 2050 from 2015 levels, including rises of 8% and 5% over south Asia and the Middle East respectively. In a lower methane emission version of this scenario, an 11% global reduction of tropospheric ozone is forecast over the same time period.[44] If emissions of NOx, NMVOCs and CO are also reduced, that global decrease grows to 19%.[45,46,47] Recent trends in the US and Western Europe show that, with concerted attention, larger and faster decreases are possible.[48]

As well as complex responses of tropospheric ozone to future socio-economic pathways, a further challenge is that a warming climate will also, in turn, affect tropospheric ozone levels. Uncertainty exists around how this will play out at either a local or global level.[49]

We need to get smarter about how to tackle this problem in a way that benefits both climate and health,. Specifically, we must embed this issue within decision making on key emissions sources of these precursor pollutants (see Section 4). The opportunity for near-term climate mitigation and cleaner air necessitates a closer look.

> “ Since pre-industrial times, tropospheric ozone levels have increased by approximately 40%.

3. A gap in global climate and air pollution strategy

Tropospheric ozone is challenging to abate due to its complex photochemical formation, the varied source profiles of its precursor pollutants, the environmental conditions that promote its formation, and the ability of it and its precursors to travel long distances – affecting regions and communities far from where it was formed or its precursors emitted. Reducing ozone formation in the troposphere therefore requires integrated climate and air quality policies with multi-stakeholder cooperation and a multi-pollutant approach. This would lay the groundwork for wider integrated action across climate change mitigation and air quality management. As it stands, major gaps exist.

CLIMATE CHANGE

Lots of research has been done and policies launched to tackle tropospheric ozone concentrations since it was recognized as harmful to human health in the 1950s. However, there has been insufficient recognition of the links between local air quality and global climate change. As a result, there are limited studies on tropospheric ozone's climate effects and feedback loops at a local, regional and global level.

Despite being a greenhouse gas, tropospheric ozone is not part of the Paris Agreement or acknowledged in commitments on 'all greenhouse gases'.[50] Few national emissions reduction plans, known as Nationally Determined Contributions (NDCs), mention tropospheric ozone, with notable exceptions including those of Tunisia and Micronesia. Tropospheric ozone precursors are mentioned in more NDCs, including those of Nigeria, Tonga and Morocco.[51] However, most tropospheric ozone precursors are not generally part of climate reporting through the United Nations Framework Convention on Climate Change (UNFCCC), with many countries lacking national and sub-national emission inventories.

Over many years, climate policies have failed to properly consider the synergies and interactions between climate-oriented and air-pollution oriented measures. However, it is clear that both problems should be considered together and that super pollutants like tropospheric ozone, methane and black carbon are key to this.

The IPCC is developing a Methodology Report on Inventories for Short-Lived Climate Forcers by 2027, which will include guidance for governments to report on tropospheric ozone precursor emissions.[52] Some governments, including Mexico, have taken a lead by integrating tropospheric ozone precursors emissions into national inventories and measurement, reporting and verification (MRV) processes alongside greenhouse gases.[53] Through the first-of-its-kind Alliance for Clean Air, run by the World Economic Forum to galvanise private sector action, some multi-national companies are now also reporting on their emissions of tropospheric ozone precursors.[54]

AIR POLLUTION AND HEALTH

Historically the tropospheric ozone problem has been approached from an air pollution and health perspective. Following WHO guidance, some governments – including China, the European Union, Mexico, South Africa, USA and the UK - have adopted limit values for short-term tropospheric ozone. Yet most country targets are less ambitious than the WHO guidelines. To the best of our knowledge, the guideline for long-term exposure, introduced in the WHO Guidelines in 2021, has not yet been incorporated into any national air quality standards

Regional forums and networks – such as the United Nations Economic Commission for Europe (UNECE) Convention on Long-range Transboundary Air Pollution (LRTAP) and the Acid Deposition Monitoring Network in East Asia (EANET) – have long track records of international cooperation on air pollution, including tropospheric ozone. Parties to the Gothenburg Protocol under the LRTAP convention have set emission reduction commitments on precursors NOx and NMVOCs, but not on methane or CO – although it is currently under revision, which presents an opportunity to do so.

Fine particulate matter (PM2.5) has the greatest direct impact on health and is therefore often used as a proxy indicator for exposure to air pollution. Alongside actions to address PM2.5, ways of measuring and tackling tropospheric ozone and its precursors need to be considered and strengthened in regional, national and local air quality management strategies that comprehensively address all sources of air pollution.

Generally, there is a need for increased awareness of tropospheric ozone – in terms of its rising exposure levels, health effects and broader impacts – among climate stakeholders, so they can strengthen collective efforts to address it.

AGRICULTURE AND ECOSYSTEMS

One of the factors contributing to the limited action taken to mitigate the effects of ozone on vegetation is the lack of monitoring in rural areas, particularly in developing countries.[55] This absence of data hinders accurate assessment of ozone's impact on national food security and the degradation of ecosystem services, such as carbon sequestration and biodiversity.[56] Similarly, research on the impacts of ozone on crops is limited to a subset of regions. More must be done to explore and communicate its impacts on crops and ecosystems with food, agriculture and biodiversity stakeholders across wider geographies.

HOW TO ACT ON TROPOSPHERIC OZONE?

We know enough about the harmful effects of the emission sources of tropospheric ozone precursors to act on them now. However, important open questions remain on the policies and measures that will maximise potential climate, health and agricultural benefits over the coming years, particularly considering variations in local contexts and climate and clean air efforts.[57]

Tropospheric ozone concentrations are influenced by both regional and local sources and fluctuate based on complex chemical reactions. Effective control strategies must be designed for the mix of precursor pollutant emissions and the scale of interest. Strategies therefore require locally relevant data sources, along with clear guidance and tools to inform decision making. Both these areas require further work. Coordinating efforts, from a subnational to international level, is also important when considering how emission changes will affect tropospheric ozone both locally and further from the source.

Emission reduction actions often also involve trade-offs. For example, the substitution of biofuels to reduce net carbon dioxide emissions may inadvertently increase emissions of tropospheric ozone precursors.

Similarly, technological advancements towards the use of hydrogen in combustion engines would drive more NOx emissions than advancements towards hydrogen fuel cells. It is consequently important that an integrated and multi-pollutant approach is taken when considering policies and measures to reduce greenhouse gas, super pollutant and air pollutant emissions. In particular, it can be a missed opportunity or have unintended consequences when climate mitigation efforts do not consider responses in tropospheric ozone levels.

In terms of policies and measures, the precursors of tropospheric ozone stem from a wide range of sectors that are summarised in Table 1 below. Many of the policy levers may already be components of government net zero and/or clean air strategies. Some sources, such as NMVOC emissions from the chemical industry, highlight areas where additional and targeted efforts may be required to bring down tropospheric ozone. In others, such as the aviation sector, understanding the effect of NOx emissions on tropospheric ozone levels is critical to fully understand and act on the climate impacts of these emissions.

Routine inspection of the ambient air quality monitoring station managed by South African Weather Services.
Credit: Gulshan Khan / Climate Visuals

SECTOR	POLICY LEVERS	POLLUTANTS MITIGATED
Oil, gas and coal sectors	• Promote programmes for the systematic detection and repair of gas pipeline leaks, the installation of emission control technologies in generation plants, the replacement of obsolete equipment with more efficient alternatives, and the elimination of practices such as flaring gas, except in cases of emergency.[58] • Install methane extraction systems in coal mines to capture methane before it disperses into the atmosphere.[59] • Promote policies that incentivise investment in methane capture and utilisation technologies, such as energy generation or the production of other products.	Tropospheric ozone precursors: Methane, CO, NOx, NMVOC Other air pollutants: PM2.5, PM10 Other climate pollutants: black carbon (BC), N2O, CO2
Power industry	• Accelerate transition to renewable energy sources and clean technologies, accompanied by strict emission standards for existing power plants.[60] • Incorporate energy efficiency programs that lead to the reduction of electricity consumption in the sector. • Implement effective behaviour changes measures to promote energy saving practices that reduce electricity demand.	Tropospheric ozone precursors: NOx, CO Other air pollutants: PM2.5, PM10, SO2 Other climate pollutants: BC, N2O, CO2
Industrial combustion	• Implement advanced abatement technologies to reduce the level of waste gases produced by fossil fuels combustion. Effective NOx emission control methods include low-NOx burning, natural gas reburning, catalytic and non-catalytic reduction, excess air control, overfire air combustion modification, flue gas recirculation, and off-stoichiometric combustion.[61] • Mandate the implementation of continuous emission monitoring systems (CEMS) in large industrial facilities.[62] • Introduce progressive taxes on NOx emissions, based on the volume of production.[63]	Tropospheric ozone precursors: NOx, CO, NMVOC, Methane Other air pollutants: PM2.5, PM10, SO2 Other climate pollutants: BC, N2O, CO2
Industrial processes **(organic chemical and cement Industry)**	• Establish standards and control equipment for manufacturing industries that rely highly on organic solvents. • Promote the adoption of alternative fuels and improvement in energy efficiency to reduce direct emissions and precursors of tropospheric ozone.[64]	Tropospheric ozone precursors: NOx, CO, NMVOC Other air pollutants: PM2.5, PM10 Other climate pollutants: BC, N2O, CO2
Fuel supply chain	• Enforce measures to control evaporative emissions throughout the gasoline and gas supply chain from production to distribution.[65]	Tropospheric ozone precursors: NMVOC, Methane
Agriculture sector - Livestock	• Enhance animal husbandry practices, including improving feeding, health management, nutrition and breeding. • Incorporate methane-reducing feed additives. • Adopt manure management practices – such as the use of solid-liquid separators, decreased storage time, storage pond covers, appropriate use of anaerobic digesters and advanced additives and technologies.	Tropospheric ozone precursors: Methane Other climate pollutants: N2O
Agriculture sector - Crops	• Improve water management in rice cultivation through direct seeding, methane-inhibiting additives, composting rice straw, and alternative hybrid species in rice production. • Promote the use of slow-release fertilisers and precise application technologies to minimise nitrous oxide emissions, potent greenhouse gas and ozone-depleting substances. • Promote sustainable practices, such as reducing tillage, covering crops and crops rotation to enhance soil health, reduce erosion and increase carbon sequestration.[66] • Advocate to replace on-site burning with alternative strategies that preserve soil integrity and minimise erosion, while reducing the release of pollutants, including tropospheric ozone precursors.[67]	Tropospheric ozone precursors: Methane, NOx, VOC Other air pollutants: PM2.5, PM10, NH3 Other climate pollutants: N2O
Solid waste	• Implement strategies to reduce organic and recyclable waste in landfills by promoting sustainable practices, including composting, anaerobic digestion at different scales, circular economy programmes, and waste reuse. Promote programs for the prevention or prohibition of open burning of waste.	Tropospheric ozone precursors: Methane, NMVOC, CO Other air pollutants: NH3, PM2.5, SO2 Other climate pollutants: BC
Road transport	• Encourage a shift towards cleaner transportation by prioritising the use of non-motorised vehicles and implementing strategies that reduce reliance on private vehicles. • Promote the widespread adoption of electric vehicles, including autonomous self driving vehciles ones, and expand electric public transportation networks. Prioritise the substitution of fossil fuels with cleaner alternatives, such as green hydrogen and biofuels, to significantly reduce NOx, VOC and CO emissions.[68,69] • Develop stringent regulations for NOx emissions from diesel-powered vehicles, particularly the heavy-duty road transport and off-road vehicles used in the construction and agricultural sectors.[70] • Promote programmes for low-emission zones.[71] • Promote mandatory emissions inspection/maintenance programmes.	Tropospheric ozone precursors: CO, NOx, NMVOC Other air pollutants: PM2.5, PM10 Other climate pollutants: BC, CO2
Wildfires	• Wildfires release high levels of tropospheric ozone precursors into the atmosphere. To mitigate firs risks, strategies include: • Manage fuel loads with prescribed burns and controlled grazing, using advanced detection systems like UAVs and remote sensing.[72] • Promote preventive measures like educational campaigns and fire-resistant land-use planning.[73] • Strengthen coordination among agencies, communities, and landowners. • Invest in fire behaviour research and improve firefighting capabilities with training and upgraded equipment.[74]	Tropospheric ozone precursors: Methane, CO, NOx, NMVOC Other air pollutants: PM2.5, PM10 Other climate pollutants: BC, N2O, CO2
Energy for buildings	**Rural environments** • Promote the adoption of eco-friendly stoves and fireplaces that ventilate fumes outdoors. To replace firewood as fuel, encourage the use of solar panels and electric heating to power cooking, food preservation and heating. • Strengthen education programmes that centre on sustainable practices,responsible firewood consumption and reforestation initiatives.[75] **Urban environments** • Promote the transition to more efficient appliances and improve the thermal insulation of homes. • Encourage programmes to replace conventional electrical and gas systems – such as stoves, water heaters and air conditioning – with solar energy systems.[76] • Incorporate sustainable technologies for new housing into building regulations.[77]	Tropospheric ozone precursors: Methane, CO, NOx, NMVOC Other air pollutants: PM2.5, PM10 Other climate pollutants: BC, N2O, CO2
Aviation	• A comprehensive approach to aviation requires developing Sustainable Aviation Fuels (SAFs) and hydrogen programmes. • Implement energy efficiency initiatives for ground facilities using alternative energy sources. • Implement certification processes for next-generation aircraft. • Establish binding emission reduction targets for the aviation sector to ensure measurable progress and accountability.[78]	Tropospheric ozone precursors: Methane, CO, NOx, NMVOC Other air pollutants: PM2.5, PM10 Other climate pollutants: BC, N2O, CO2

CASE STUDIES

Cities and regions have achieved reductions in tropospheric ozone, with some being more sustained than others. Identifying effective practices and lessons from these regions can contribute to developing comprehensive solutions for others.

It is notable that most case studies and available information stem from a focus on ground-level ozone from the air pollution community. There is a significant gap in evaluation and leadership on tropospheric ozone from a climate change perspective, as well as a fundamental need for integrated action to tackle the problem comprehensively.

LOS ANGELES, MEXICO CITY, BEIJING AND EUROPE PRESENT DIFFERENT APPROACHES TO TACKLING TROPOSPHERIC OZONE. WHILE THESE EXAMPLES EACH TELL A DIFFERENT STORY, THERE ARE KEY LEARNINGS ACROSS THESE CASE STUDIES:

- Successful mitigation efforts rely on: comprehensive scientific information; locally and continuously collected data; regional and local integrated emissions inventories; political will; economic and technological resources; and coordination and cooperation between multiple actors.
- Historically, tropospheric ozone mitigation has been driven through the implementation of ambitious air quality management standards. Integrated approaches, where links with climate change mitigation efforts have been made, represent best practices.
- Although there have been achievements in reducing tropospheric ozone precursors, challenges persist, underscoring the need for continued efforts.
- Effective management of tropospheric ozone requires enhanced monitoring and modelling capacity building to address the trade-offs among strategies aimed at controlling various emission sources and sectors. Mitigation strategies must be specific to locations and pollution mixes. As the precursors and sources change over time, they must also be dynamic, so that authorities can take continuous action to reduce tropospheric ozone.
- The climate benefit of tropospheric ozone mitigation is often overlooked. Few evaluations of the climate benefits of tackling tropospheric ozone across different scales have been conducted in this area, highlighting a significant evidence gap. Acknowledging the multiple climate benefits of tropospheric ozone mitigation is essential for designing measures that address multiple objectives, including air quality and climate change.

Credit: Pedro Marroquinn on Unsplash - Los Angeles

Los Angeles Basin

Los Angeles is perhaps the most famous example of pollution control measures aimed at tackling tropospheric ozone.

From 1987 to 2000, daily maximum eight-hour average concentrations of tropospheric ozone across the Californian city decreased by 32%.

Since the 1980s, NMVOC emissions from transport and chemical products (for example, pesticides) reduced by up to 70%. NOx and emissions from transport reduced by more than 50% over the same period.

Los Angeles has succeeded thanks to a comprehensive state-wide strategy that deployed a wide variety of tools and policy measures. Key components of this strategy include:

1. The Regional Clean Air Incentives Markets (RECLAIM) Program employs market-based mechanisms to reduce industrial NOx and SOx emissions.
2. The Carl Moyer Memorial Program provides financial incentives for low-emission technology adoption across 35 local air districts.
3. The Consumer Products Regulatory Program targets NMVOC emissions from household and personal care products.

These innovative approaches operate under the California Air Resources Board, which coordinates 15 air basins and 25 air districts through enhanced technical, managerial and legal capacities. The policies are designed to ensure effective implementation across diverse populations, aiming to protect the most vulnerable and disadvantaged communities from disproportionate pollution impacts. California's regulatory framework continues to set a precedent for air quality programmes in other states.

Progress in reducing tropospheric ozone in Los Angeles and across California more broadly has stalled in recent years, despite reductions in precursors. Some studies link the climate change phenomena that are increasingly frequent in California – like heat waves, droughts and wildfires – to increases in local ozone levels.

Nationally, legal challenges to the US Environmental Protection Agency's authority to set emissions standards and regulations will have real-world implications for state- and city-level authorities. In June 2024, the US Supreme Court blocked the EPA's 'good neighbour' policy aimed at reducing ozone emissions across neighbouring states. The litigation around this policy continues.

Mexico City Metropolitan Area

The Mexico City Metropolitan Area (MCMA), one of the world's largest cities, faced severe air quality challenges in the early 1990s. In 1992, the United Nations Environment Programme (UNEP) and WHO declared it the world's most polluted city.[79]

In response, Mexico implemented a comprehensive regulatory framework. The General Law of Ecological Equilibrium and Environmental Protection established clear jurisdictional responsibilities across federal, state and local governments to address the high levels of air pollution, including tropospheric ozone. To address the issues in the MCMA, a regional approach was adopted, establishing the Environmental Metropolitan Commission to coordinate action in the greater area.

Regulations throughout the 1990s targeted key tropospheric ozone precursors, specifically NMVOCs and NOx, with the transportation sector identified as their primary source. The city took action to improve vehicle technology and fuel quality by promoting emission control systems and reformulating gasoline to limit the content of reactive NMVOCs. The authorities also promoted: public transportation, limiting private vehicle use, and enhancing urban planning and environmental education. They also reduced emissions in key industries by substituting heavy fuel oil for natural gas and reducing leakages.

Implemented from 1990 onwards, the interventions yielded significant improvements:

- Days exceeding the ground-level ozone standard (>70 ppb) decreased from 80% (1990) to 50% (2010). Peak hourly ozone levels dropped from 85-185 ppb (1990) to 57-92 ppb (2015).
- Between 1990 and 2015, ozone concentrations decreased over 30% (1 hour maximum – peak ozone months).
- Other criteria pollutants also showed marked reductions in their concentration between 1990 and 2015: CO (92%), NO2 (50%), SO2 (99%), and PM10 (92%).[80]

Despite notable differences in institutional capacity, financial resources and technical expertise, the MCMA drew lessons from Los Angeles, which began its air cleanup efforts two decades earlier. It adopted similar strategies and emission control technologies.[81]

Mexico City's progress in reducing ozone is best exemplified by the public health impacts experienced by city residents. For example, tropospheric ozone in Mexico City between 1990 and 2015 prevented approximately 4,100 premature deaths and increased life expectancy by almost two years.[82] The years of life lost from premature death and lived in poor health dropped from a maximum of 143 in 1990 to 42 for every 100,000 inhabitants.[83]

However, since 2010 no further reductions in tropospheric ozone have been achieved. Nowadays, 60-70% of the days still experience peak ozone concentrations above the levels that are deemed healthy by local authorities. This tells us that while the previous control measures proved that a large and complex city can improve its air quality and reduce local levels of tropospheric ozone, a different mix of precursor pollutants and emission sources – as well as a growing urban sprawl over different landscapes and in a changing climate – have limited their effectiveness and prevented further reductions in ozone concentrations.

Beijing and surrounding areas

Beijing encompasses diverse geographical zones, from its urban core to rural periphery, meaning that air pollution patterns differ across the Chinese city. From 1998 to 2022, its population grew by 76.5% and energy consumption increased by 82%, but the annual average concentrations of key pollutants decreased dramatically: SO2 by 97%, NO2 by 69%, PM10 by 71%, and tropospheric ozone by a smaller 6.6% (eight-hour maximum, 90th percentile).[84]

The city's approach to air quality management has become increasingly sophisticated, focusing on integrated strategies for controlling PM2.5 and tropospheric ozone with carbon mitigation goals.[85] Control actions between 2013-2017 achieved 43% reduction in NOx emissions – mainly through vehicle and coal-fired boiler controls – and 42% reduction in NMVOC emissions, through industrial, residential and mobile source controls.

Importantly, Beijing, Tianjin, and 26 surrounding municipalities operate under an innovative regional framework designed to coordinate responses to harmful pollutants, including tropospheric ozone. This framework encompasses integrated planning, standardised monitoring, coordinated emergency responses, and real-time data sharing across jurisdictions. It has significantly improved air quality across the entire region and can serve as a model for other large metropolitan areas facing airshed pollution challenges.

A key learning from Beijing is the development of economic incentive policies that provide financial support for pollution control measures through subsidies, fees, incentives and pricing. Additionally, Beijing has significantly increased its financial investment in air quality, multiplying it tenfold in eight years.

Despite these improvements, the variations of tropospheric ozone levels in Beijing are significant, and the impacts of policies aimed at reducing tropospheric ozone have not been consistent across the area in and around Beijing. The city still experiences ozone concentrations that exceed recommended guidelines; high pollution days continue to pose significant health risks. Like Mexico City, changes in pollution sources – driven by past clean air actions among other factors - have influenced tropospheric ozone levels. The next phase of Beijing's air pollution control strategy will simultaneously address air quality standards and climate targets, specifically focusing on the dual impacts of tropospheric ozone on climate and air quality.[86]

Credit: Henry Chen on Unsplash - Beijing at night

Europe

The European Union presents a crucial example of regional policies and cooperation to tackle tropospheric ozone. The United Nations Economic Commission for Europe (UNECE) established the first regional environmental convention, the Convention on Long Range Transboundary Air Pollution (CLR-TAP) in 1983, with a focus on reducing emissions and the long-range transport of harmful pollutants, initially across Europe and North America. Under the CLR-TAP sits the Gothenburg Protocol to Abate Acidification, Eutrophication and Ground-level Ozone. Agreed in 1999 and amended in 2012, this legally binding legislation sets country level emissions ceilings for NOx, SO2, NMVOCs, ammonia (NH3) and fine particulate matter (PM2.5). It requires Parties with the greatest emissions, emissions that have more severe human health or environmental impacts, and/or emissions that are relatively cheap to reduce to make the biggest reductions.[87] 27 UNECE Parties are signatories of the Gothenburg Protocol.

The European Union also regulates ozone and its precursors via other legislation, including the National Emissions Ceiling Directive and Commitments, the Ambient Air Quality Directive, and other regional emissions reduction targets and regulations across industry, transport and power generation.

Significant progress has been made in reducing tropospheric ozone precursor emissions across the EU under this suite of regional legislation. NOx and NMVOC emissions have declined by 50% and more than 30% respectively between 2005 and 2022.[88] Ground-level ozone levels across the region are susceptible to a high degree of fluctuation. However, data from the European Environment Agency (EEA) illustrates a gradual overall downward trend in urban population exposure to elevated ozone concentrations from a high of 64% in 2003 to 19% in 2022.[89]

This decrease is significant, but if compared to other pollutants like NO2, for example, less than 1% of the EU population was exposed to levels exceeding the EU air quality limits. Despite these significant improvements in European air quality over the past 30 years, tropospheric ozone remains one of the more challenging pollutants to tackle.

The Gothenburg Protocol is currently undergoing a revision, presenting opportunities for parties to raise ambition on emission reduction commitments on tropospheric ozone precursor pollutants and to set new, binding targets on harmful pollutants that are not yet explicitly covered, like methane and black carbon.

Around 70% of the highly polluting residential heat sources in Gieraltowice, Poland have been replaced. The remaining ones are still heavily polluting the air, especially in the evenings when residents return home and start heating up their homes. Credit: Anna Liminowicz/Climate Visuals

RECOMMENDATIONS

Recommendations are provided below for policy makers, researchers and funders. These steps can help mitigate climate change in the coming decades, deliver cleaner air for billions of people, and improve global food security.

Policymaking and regulation

Leadership and fast action on tropospheric ozone is fundamental to mitigating the worst effects of climate change and air pollution, alongside deep decarbonisation, cutting other super pollutants, and action on air pollution more broadly. Policy makers should:

SHOW INTERNATIONAL LEADERSHIP AND AMBITION ON CLIMATE AND HEALTH:

- Push for tropospheric ozone and other non-CO2 pollutants to be robustly included within UNFCCC processes and reporting, building on the outcome of the UN's 2023 Global Stocktake (Decision 1/CMA.5, 2023) that calls on parties to contribute to an accelerated and substantial reduction of non-CO2 emissions by 2030.
- Join and deliver on the Global Methane Pledge.
- Integrate, as a requirement, methane emission reductions within the economy-wide greenhouse gas emissions target and include additional measures and separate targets to reduce emissions of tropospheric ozone precursors in updated Nationally Determined Contributions.[90]
- Champion the development and uptake of the 2027 IPCC Methodology Report on Inventories for Short-Lived Climate Forcers. Countries that already have sophisticated and greenhouse-gas-air quality integrated emissions inventories should see themselves as 'early adopters'.
- Deliver on the aims of the Paris Agreement and UNFCCC Nairobi Work Programme by embedding health and sustainable development in governmental negotiations and the response to the threat of climate change.
- Adopt, support and strengthen regional and airshed approaches to tackling air pollution, such as:
  - Setting binding and ambitious updated emission reduction commitments on NMVOCs and NOx and new emission reduction commitments on methane and black carbon through the UNECE Gothenburg Protocol revision process.
  - Support efforts and spotlight tropospheric ozone and other super pollutants in regional programmes, such as the UN ESCAP Regional Action Plan on Air Pollution and the UNEA-mandated Africa Clean Air Programme.

TAKE AN INTEGRATED, MULTI-POLLUTANT APPROACH TO CLIMATE CHANGE AND AIR POLLUTION:

- Design and develop policies and measures based on multi-pollutant effects, considering specific emission sources and how they affect co-emitted pollutants, primary emissions and the secondary formation of pollutants. This means, for example, that efforts to reduce PM2.5 should consider the impact on tropospheric ozone and that air pollution policy and management instruments should be integrated with those of climate change.
- Enable effective cross-government collaboration to facilitate an integrated national and subnational approach:
  - Develop integrated emissions inventories covering all greenhouse gases, super pollutants and air pollutants. Openly share data and compilation methods through relevant regional and global frameworks, such as the Biennial Transparency Reports.
  - Develop and maintain monitoring networks for tropospheric ozone and other air pollutants, using available data to inform both air quality and climate change mitigation plans.
  - Ensure work on methane, often led by climate change departments, and tropospheric ozone and its other precursor pollutants, often led by environmental and air pollution departments, is integrated to ensure policy making holistically considers all relevant pollutants.

IMPLEMENT BOLD, COMPREHENSIVE MEASURES TO ADDRESS TROPOSPHERIC OZONE PRECURSOR SOURCES:

- Understand and analyse sources of tropospheric ozone precursors, identifying additional measures directed at sources that may not be covered elsewhere, for example in chemical industries or through use of solvents.
- Update and enforce tropospheric ozone concentration standards in line with WHO guidelines and interim targets.
- Accelerate the transition to cleaner energy sources and improve energy efficiency:
  - Implement and enforce stricter emission standards across all air pollutants, greenhouse gases and super pollutants.
  - Define strategic actions for the key sectors contributing to tropospheric ozone precursor emissions.
  - Accelerate energy efficiency programmes and transition to cleaner energy sources.
  - Design and implement innovative programmes, such as: employing market-based mechanisms to reduce industrial emissions; providing financial incentives for low-emission technology adoption; and developing regulatory programmes that target decreases in precursor emissions in key sectors.
- Tailor policies to local contexts and emission sources. Design and reinforce frameworks supporting subnational to national level action.

Science and research

We now know enough to accelerate action to reduce tropospheric ozone precursors. However, some important questions remain unanswered and key issues unresolved. Addressing these will both improve knowledge and enable better decisions and policy design that maximises the potential benefits for climate, health and agriculture.

It is essential for decision makers and scientists to work together with a long-term vision. The technical complexities involved in tropospheric ozone formation and its interactions with meteorological and climatic factors mean that further science and research is critical to informing effective policy approaches and measures. This is necessary so interventions can evolve and be adapted as our understanding improves and as wider decarbonisation policies take effect. International collaboration among the scientific community is crucial for supporting and building capacities in regions with scarcer technical capabilities.

GRANTING BODIES (PUBLIC OR PRIVATE) SHOULD SUPPORT FURTHER SCIENTIFIC RESEARCH FOCUSING ON TACKLING THE MOST PERTINENT QUESTIONS TO INFORM CLIMATE AND CLEAN AIR STRATEGIES:

- Advancing understanding of the climate responses of tropospheric ozone precursors. Building on the summary provided in IPCC Assessment Report 6, further work is needed to elaborate on the distinct climate effects of NMVOCs, CO and NOX by country and region, including temperature responses and other regional climate effects.
- Analysing policy pathways to maximise climate and health benefits. Fundamental gaps exist in our understanding of the climate effects of policies and measures substantially reducing emissions of tropospheric ozone precursors across multiple sectors. An updated iteration of the UNEP-WMO Integrated Assessment of Black Carbon and Tropospheric Ozone could generate evidence-informed policy guidance. Critically, we need to support studies that help answer fundamentals question including: 'Alongside deep decarbonisation, what additional mitigation policies and measures are required to tackle tropospheric ozone precursors to keep the world on a pathway that is 1.5°C aligned?'.
- Generating tools and guidance to support policy makers. Considerable work is needed to deliver actionable science that policy makers can use to inform decision making on which precursor emissions might provide the most effective route to tackling tropospheric ozone at a local, regional and global level. Datasets and models exist to advance this, but targeted studies need to be conducted to identify and develop parametrisations and tools that can be used by policy makers. Regime categorisations - guidance based on the local chemical balance e.g. NOx- or VOC-limited - is a promising approach, requiring further work and tailoring to local contexts.
- Advancing monitoring and measurements of tropospheric ozone and its precursors. More investment in monitoring is needed to enhance our understanding of regional and global fluctuations in tropospheric ozone – including in rural areas to help improve analysis of effects on agriculture and ecosystems.

- Improving emissions factors for tropospheric ozone precursor pollutants. Further work on emissions factors and activity data is needed to improve emissions estimates and inventories, taking into account the wide range of different source sectors and how emissions might differ within these. Focus should be placed on regions where less research work has been done and with a view to inputting into existing guidance for governments and businesses.
- Further building the health evidence base. Decades of research have established a strong link between ozone exposure and respiratory health effects. However, there is a pressing need for long-term epidemiological studies in low- and middle-income countries to better understand ozone's impact on all-cause mortality.[91]

Funding and technical support

Work to reduce outdoor air pollution is significantly underfunded worldwide, receiving less than 1% of all international development funding between 2018 and 2022.[97] Efforts to reduce tropospheric ozone and its precursors should be supported by donor countries, multilateral development banks (MDBs) and philanthropic foundations through grants and concessional development financing, so that recipient countries do not suffer fiscal stress. To effectively reduce tropospheric ozone and its precursors, a systematic funding and capacity building approach is essential, incorporating various sources, as follows:

1. Strengthen traditional financing mechanisms: Enhance existing environmental sector financing, such as emissions compensation, fossil fuel taxes, and other dedicated taxes to support air quality management.
2. Create market conditions: Encourage private sector participation in financing initiatives aligned with air quality and climate change policies.
3. Design and implement subsidies and transfers: Provide direct government aid to cities and private entities to support air quality and climate policies.
4. Build capacity for bankable mitigation projects: Develop skills and structures, particularly in developing countries with access to less resources and expertise, to create a project pipeline eligible for international development and climate funds.

INTERNATIONAL COOPERATION EFFORTS SHOULD INCLUDE:

- Encourage an integral view on atmospheric pollution among project selection criteria: Development and climate funds should adopt comprehensive approaches to solve air pollution with local and global benefits. Project enabling criteria, similar to existing gender and social guidelines, should be developed.

Routine inspection of the ambient air quality monitoring station managed by South African Weather Services.
Credit: Gulshan Khan / Climate Visuals

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