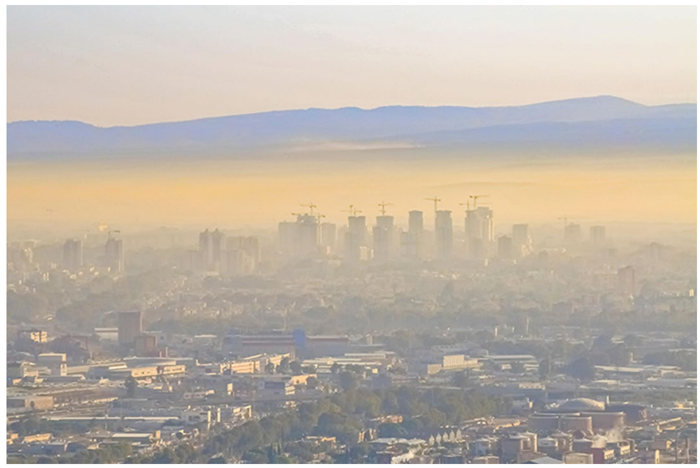
The two faces of ozone

In the upper atmosphere, ozone is essential to protect the planet through absorption of ultraviolet radiation; but at ground level, ozone is a pollutant, and increasing anthropogenic emissions are resulting in higher levels. Reducing emissions would mitigate the harmful effects of ozone as well as potentially increasing a natural carbon sink.



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Ozone is probably most associated with its high abundance in the Earth's upper atmosphere. The ozone layer in the stratosphere absorbs much of the incoming solar ultraviolet radiation and came into the wider general consciousness in the 1980s with the discovery that it was seasonally thinning. This led to the 1987 Montreal Protocol on Substances that Deplete the Ozone Layer, an example of a successful international environmental protection agreement. The phase-out of chlorofluorocarbons and halons, through the transition and eventual phase-out of less ozone-damaging substances such as hydrofluorocarbons, has seen declines in their emissions, with stabilization and now ongoing recovery of the ozone layer. These ozone-depleting substances (ODS) are themselves potent greenhouse gases and, with their atmospheric lifespan of 50–100 years, have contributed to global warming, but to what extent? In a Letter in this issue, Lorenzo Polvani and co-authors investigate the role that these ODS have played in Arctic warming from 1955 to 2015. The model results show that a substantial fraction, almost 0.8 °C of the Arctic surface warming and nearly 0.7×10^6 km^2 loss of sea ice, has been caused by ODS. Removal of these emissions by the Montreal Protocol has in fact helped to mitigate a warming gas, meaning that the protocol has had a role not only in helping to restore the ozone layer, but also in climate action, with warming approximately a third smaller owing to the absence of increasing ODS.

Moving closer to Earth, ozone is a pollutant. Formed by the reaction of sunlight with anthropogenic emissions of carbon monoxide, volatile organic compounds, methane and nitrogen oxides, it can present a respiratory health risk and has a damaging effect on crops and ecosystems.

As the climate changes, ozone is just one factor influencing vegetation. Understanding its interactions with other factors — such as CO_2 changes, temperature and precipitation, nutrient availability and pollination efficiency as well as distributions of microbial and insect species — is important to predict and prepare for impacts on food production and ecosystem services. Exposure to ozone is predicted to increase under a high emissions scenario for all major biomes, and even under RCP4.5 there is increased exposure for 50% of terrestrial ecosystems (Fuhrer, J. et al. *Ecol. Evol.* **6**, 8785–8799; 2016).

Crop response to ozone is varied, with wheat typically seeing a decline in harvest yields, and overall crop yields are predicted to decline by about 10% by 2050; impacts of ozone can include changes in cellular carbon allocation, visible injury and reduced photosynthesis (L. D. Emberson et al. *Eur. J. Agron.* **100**, 19–34; 2018). Although there is limited evidence for fruits, nuts and seeds, the available data on these yield impacts show that ozone and temperature have a consistently negative effect (C. Alae-Carew et al. *Environ. Res. Lett.* https://doi.org/10.1088/1748-9326/ab5cc0; 2019). Understanding regional pollution levels and the effects of ozone is important to ensure food and nutritional security into the future.

As emissions continue to cause increases in ground-level ozone, reductions in emissions are needed to decrease this pollutant, but natural reactive halogens (chlorine, bromine and iodine species) already act to partially reduce the ozone burden. Natural halogens are primarily released from the ocean, from phytoplankton and algae and from abiotic sources. How these processes will change in the future is considered in an Article in this issue by Fernando Iglesias-Suarez and colleagues. Currently, halogens deplete around 13% of lower-atmosphere ozone, and this value is predicted to stay constant into the future, as increasing halogen levels are offset by regional differences in ozone distribution and loss.

Reducing emissions would also reduce ozone damage to vegetation, which would enhance the land carbon sink. In their Letter in this issue, Nadine Unger and collaborators consider the benefits to gross primary productivity, or photosynthesis, of a 50% cut in emissions from the seven sectors that are the largest sources of anthropogenic ozone precursors. Emissions reductions in road transport and the energy sector would have the most impact in eastern China, the eastern United States, Europe and globally, highlighting that mitigating ozone vegetation damage would not only benefit food security and health but also enhance a carbon sink.

Cutting ODS emissions has worked to protect the ozone layer, with the added benefit that removing the increasing atmospheric concentration of those potent greenhouse gases has avoided additional warming. Ozone can be a less-discussed by-product of antrhopogenic emissions, but the benefit of reducing emissions to minimize its polluting effects on health and vegetation could be substantial. ❐

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