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Summary Update 2020 for Policymakers

UNEP Environmental Effects Assessment Panel

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Environmental Effects of Stratospheric Ozone Depletion, UV Radiation, and Interactions with Climate Change: Update 2020

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1 Introduction and background

The Montreal Protocol on Substances that Deplete the Ozone Layer and its amendments have been highly effective in protecting the stratospheric ozone layer and preventing global-scale increases in solar ultraviolet-B radiation (UV-B; wavelengths between 280-315 nm) at Earth's surface [1]. The international agreement of the Montreal Protocol has also been one of the most important societal actions taken to date to mitigate global warming, as many of the ozone-depleting substances and their substitutes that are regulated by the Montreal Protocol are also potent greenhouse gases [2]. Ozone depletion itself contributes to climate change in some regions and climate change is modifying the exposure of humans, plants and animals, and materials to UV-B as well as UV-A radiation (315-400 nm) [3]. Thus, changes in stratospheric ozone, UV radiation and climate are inextricably linked in a number of critical ways that have the potential to influence human health and the environment.

Here we highlight findings from the 2020 Update Assessment by the Environmental Effects Assessment Panel (EEAP) of the Montreal Protocol under the United Nations Environment Programme (UNEP). This document summarises the most recent assessment [4] since that of 2019 [5] and the Quadrennial Assessment (*Photochemical & Photobiological Sciences* **18**, 595-828; also available at https://ozone.unep.org/science/assessment/eeap). The 2020 Update addresses the interactive effects between the stratospheric ozone layer, solar UV radiation, and climate change within the framework of the Montreal Protocol and the United Nations Sustainable Development Goals (SDGs), and in accordance with the Panel's *Terms of Reference* (Box 1) adopted at the Meeting of the Parties to the Montreal Protocol (decision XXXI/2, November 2019).

Box 1. EEAP *Terms of Reference* according to decision XXXI/2, Meeting of the Parties to the Montreal Protocol.

The Parties to the Montreal Protocol request the "*Environmental Effects Assessment Panel, in drafting its 2022 report, to pay particular attention to the most recent scientific information together with future projections and scenarios, to assess the effects from changes in the ozone layer and ultraviolet radiation, and their interaction with the climate system, as well as the effects of breakdown products of controlled substances and their alternatives on:*

1. *The biosphere, biodiversity and ecosystem health, including on biogeochemical processes and global cycles;*
2. *Human health;*
3. *Ecosystem services, agriculture and materials, including for construction, transport, photovoltaic use and microplastics*"

Our findings, which were compiled by 46 EEAP members and co-authors in seven Working Groups and finalised during a virtual meeting held from 17-30 September 2020, demonstrate the continued success of the Montreal Protocol in protecting human health, food security, biogeochemical cycles, natural ecosystems and their services to communities (e.g., productivity of fisheries, biodiversity, conservation, recreation), including decreasing the damage to materials used in construction and fabrics. We continue to observe interactive effects of climate change and UV radiation as a consequence of changes in seasonality, cloud cover, aerosols, snow and ice cover, species distributions, and extreme weather events.

Additionally, we report on the linkages between solar UV radiation, the Montreal Protocol, and the transmission and environmental consequences of the severe acute respiratory syndrome coronavirus 2 (SARS-CoV-2), which is responsible for the COVID-19 pandemic. The findings from this Update reinforce the multiple ways in which the Montreal Protocol is contributing to the attainment of the SDG targets in the areas of climate change, air and water quality, biodiversity and ecosystems, contaminants and materials, and human health (SDG 17.14 Box 2). Below we summarise and highlight issues within this assessment that are of particular relevance to the Parties.

Box 2. The following Sustainable Development Goals (SDGs) and their specific targets (truncated and summarised for brevity) are addressed in this EEAP assessment.

SDG	Targets
2 ZERO HUNGER	2.3 increase productivity of small-scale food producers 2.4 ensure sustainable food production systems 2.5 maintain genetic diversity of agricultural plants and animals
3 GOOD HEALTH AND WELL-BEING	3.3 end epidemics of communicable diseases 3.9 reduce deaths caused by air, soil and water contamination
6 CLEAN WATER AND SANITATION	6.1 achieve access to safe drinking water 6.3 reduce water pollution 6.6 protect water-related ecosystems
7 AFFORDABLE AND CLEAN ENERGY	7.a enhance international cooperation around clean energy
9 INDUSTRY, INNOVATION AND INFRASTRUCTURE	9.4 upgrade industries to be sustainable
11 SUSTAINABLE CITIES AND COMMUNITIES	11.5 reduce deaths caused by disasters 11.6 reduce the environmental impact of cities
12 RESPONSIBLE CONSUMPTION AND PRODUCTION	12.4 achieve environmentally sound management of chemicals and wastes 12.5 reduce waste generation
13 CLIMATE ACTION	13.2 integrate climate change measures into policy 13.3 improve education on climate-change mitigation
14 LIFE BELOW WATER	14.1 reduce marine pollution 14.3 minimise impacts of ocean acidification
15 LIFE ON LAND	15.1 ensure the conservation of terrestrial ecosystems 15.3 combat desertification
17 PARTNERSHIPS FOR THE GOALS	17.14 enhance policy coherence for sustainable development

2 Highlights

2.1 UV radiation and climate change

The 2019 spring-time surface UV radiation (reported as the UV index) at the South Pole was the lowest since the start of measurements in 1991 as the stratospheric ozone hole over Antarctica continues to recover. In the Arctic, unprecedented increases in solar UV radiation in late winter and early spring of 2020 were caused by an exceptionally large stratospheric ozone depletion event. This low-ozone episode was linked to anomalously cold stratospheric temperatures and a strong, long-lived polar vortex in this region, occurring at a time when concentrations of stratospheric halogens (chlorine and bromine released from ozone-depleting substances) are still only about 10% below their peak concentration observed in 2000. For latitudes outside the polar regions, small changes in solar UV radiation over the last several decades have been mostly attributable to changes in cloud cover and aerosols.

Key findings include:

- Results from modeling studies, which incorporate data from the atmosphere, oceans, land surface and sea ice, indicate that the implementation of the Montreal Protocol has prevented global warming of 1°C. By 2050, the Montreal Protocol could avert warming of 1.5 °C to 2 °C over land areas outside polar regions, and between 3 °C and 4 °C over the Arctic (SDG 13.2-3) [6].
- For the past 20 years changes in UV radiation have been small (generally less than *ca.* 4% per decade), because the Montreal Protocol has prevented a continuation of stratospheric ozone depletion that was observed until the mid-1990s. For most regions, changes in cloud cover and aerosols over the past 20 years have had a larger effect on trends in UV radiation than changes in the total ozone column.
- New evidence confirms a strong link between stratospheric ozone depletion over Antarctica and the climate of the Southern Hemisphere. A 2019/2020 Antarctic summer heatwave lasted four months, leading to accelerated snow-melt, which increased the exposure of ecosystems to UV radiation [7] (Figure 1). However, it is not yet certain to what extent, if any, the small ozone hole over Antarctica in 2019 contributed to these extreme Antarctic temperatures or the summer drought in Australia and the devastating wildfires that followed.

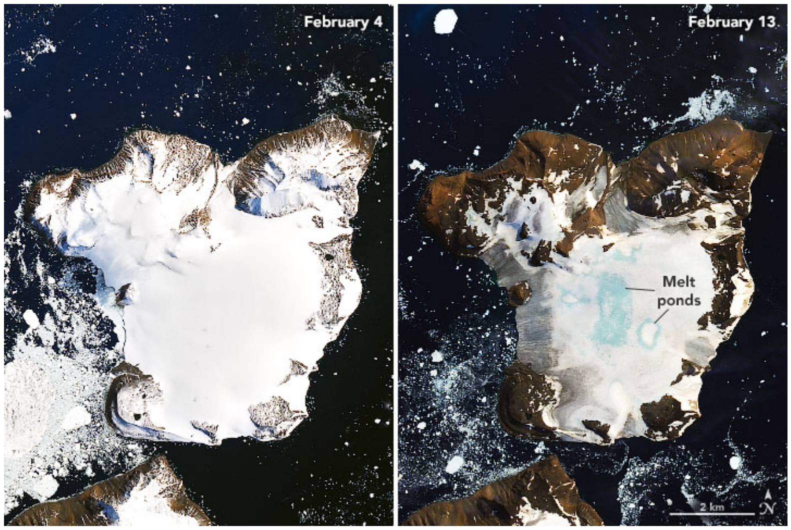

Figure 1. Extensive ice melt, associated with the 2019/2020 Antarctic heatwave, illustrated on Eagle Island between the 4th and 13th February 2020 (left and right panel, respectively). In recent decades, Antarctica has been shielded from some of the effects of global warming by shifts in the climate of the Southern Hemisphere that are related to stratospheric ozone depletion. The Antarctic summer of 2019/2020 provides a recent example where unusual meteorological conditions led to both a small ozone hole and an Antarctic heatwave. Specifically, the anomalously high total column ozone in the austral spring of 2019 resulted from a weak and strongly disturbed polar vortex, which in turn was caused by a large-scale perturbation (or anomaly) of the atmospheric circulation originating in the subtropical Pacific Ocean. Throughout the 2019/2020 summer, high temperatures were recorded across Antarctica, causing ice to melt and resulting in new ice-free areas as illustrated in the right panel above [7].
Image from NASA:
https://earthobservatory.nasa.gov/images/146322/antarcticameltsunderitshottestdaysonrecord.

2.2 Human health

By preventing large increases in UV-B radiation reaching Earth's surface, the Montreal Protocol has influenced human health, both directly and indirectly. For light-skinned people, increased exposure to solar UV radiation can increase the incidence of keratinocyte skin cancers, melanoma (the deadliest form of skin cancer), and diseases of the eye such as cataract. Model estimates indicate that a large number of skin cancers and cataracts have been avoided as a result of the Montreal Protocol (SDG 3.9). Concern about stratospheric ozone, and the international focus on methods to prevent its loss, have contributed to increased investment in sunscreen technology and promotion of strategies to reduce the harmful effects of over-exposure to the sun.

Solar UV radiation may also play a role in inactivating the virus responsible for the COVID-19 pandemic (SARS-CoV-2) and may influence people's immune system response to viral infection. However, available evidence suggests it is unlikely that the Montreal Protocol has had a major effect on the COVID-19 pandemic.

Key findings include:

- Updated modelling studies suggest that, due to the Montreal Protocol, millions of cases of skin cancers and cataracts will be avoided among people born between 1890-2100 in the United States (Box 3) [8]. Similar estimates for other countries are not yet available.
- The incidence of malignant melanoma continues to increase in many developed countries (e.g., Australia, Canada, the United States, Sweden and the United Kingdom), especially in older age groups, whereas there is evidence of a decrease in younger age groups in some countries [9]. The increases in rates of skin cancer are most likely due to trends in behaviour that have led to greater sun exposure, with changes in stratospheric ozone playing a smaller role. Nonetheless, these findings point to the strong sensitivity of skin cancer to increased exposure to UV radiation and the inherent value of protecting the ozone layer.
- Exposure to UV-B radiation contributes to photosensitivity from a number of oral medications (e.g., thiazide, diuretics, quinine, antibiotics, antidepressants) in addition to the major influence of UV-A radiation [10]. Photosensitising drugs may increase the risk of skin cancer, although further studies are required to adequately assess this risk.
- **COVID-19.** SARS-CoV-2 can remain viable on surfaces for several weeks, depending on surface material, temperature and humidity. However, exposure to solar UV radiation can inactivate 90% of these virus particles within 4-20 minutes in conditions that occur under clear skies near midday during summer at mid- to low latitudes. Longer exposures to solar UV radiation would be required for inactivation early or late in the day, during winter, at higher latitudes or if skies were cloudy [11-13]. As the primary mode of transmission of this virus from person to person appears to occur through respiratory droplets and aerosols generated by breathing, sneezing, and coughing [14-16], disinfection of outdoor surfaces through the germicidal effect of solar UV radiation is unlikely to have a major impact on transmission of COVID-19.
- The effects of UV radiation and/or vitamin D on the immune system suggest that these factors may influence the risk of infection or severity of COVID-19. Severe cases of COVID-19 are thought to be caused by an over-reactive immune response to SARS-CoV-2 that leads to multi-organ failure [17], and there is some evidence that incidence of COVID-19 and/or mortality is higher in areas where ambient UV radiation is lower [18-21]. It is plausible that UV-induced generation of vitamin D in the skin is partly responsible for this link as there are studies showing that lower vitamin D status is associated with greater risk or severity of COVID-19 [22-28]. A clear causal link between solar UV radiation, vitamin D production, and the risk and severity of COVID-19 has yet to be established; however, there is arguably sufficient evidence to support recommendations to increase exposure to UV radiation or to implement routine vitamin D supplementation in populations with a high prevalence of vitamin D deficiency.
- In general, the far-reaching, positive outcomes of the implementation of the Montreal Protocol for human health and all life on Earth outweigh any potential advantage that might have been gained by inactivating SARS-CoV-2 with higher amounts of solar UV radiation that would have occurred in the absence of the Montreal Protocol. Furthermore, if vitamin D is found to be causally associated with risk of or outcomes from COVID-19, or if other effects of UV radiation on the immune system are important, care would be required to balance these

beneficial effects of sun exposure against the risks of sunburn and skin cancer. This balance would be more difficult to achieve in a world without the Montreal Protocol.

Box 3. Estimated number of skin cancers and cataracts avoided due to implementation of the Montreal Protocol, relative to no regulation of ozone-depleting substances (ODS) through the lifetimes of people born between 1890 and 2100 in the United States.

	Health effects avoided by the Montreal Protocol as amended and adjusted, compared to no ODS regulation	
Incidence of skin cancer		
	Keratinocyte	432,000,000
	Melanoma	11,000,000
	Total	443,000,000
Mortality from skin cancer		
	Keratinocyte	800,000
	Melanoma	1,500,000
	Total	2,300,000
Incidence of cataract		63,000,000

Note: Incidence estimates are rounded to the nearest million; mortality estimates are rounded to the nearest hundred thousand. Totals may not sum due to independent rounding. From the U.S. Environmental Protection Agency [8].

2.3 Air quality and contaminants

UV radiation is a major contributor to the formation of air pollution, which has been identified as a critical issue in human health world-wide (SDG 11.6). However, UV radiation also plays a role in cleansing the atmosphere of pollutants, and air pollution can affect the penetration of UV radiation to Earth's surface. Thus, changes in stratospheric ozone and climate can have complex, and sometimes opposing, effects on different types of air pollution. Solar UV radiation also plays an important role in the breakdown of contaminants and plastics in aquatic and terrestrial ecosystems (SDG 14.1), but the ecological and human health consequences of these transformations are not yet well understood. The current low concentration of trifluoroacetic acid (TFA) produced by the degradation of several hydrofluorocarbons (HFCs) and hydrofluoroolefins (HFOs), is currently judged not to pose a risk to human health or to the environment.

Key findings include:

- Improvements in some aspects of air quality (e.g., particulate matter) have occurred in some regions (e.g., China) because stringent measures to control pollution have led to long-term reductions in emissions of nitrogen oxides and sulfur dioxide (SDG 12.4). The recent economic slowdowns caused by efforts to control COVID-19 outbreaks have further reduced emission of these compounds. However, ground-level ozone has increased in these same regions, in part due to the greater transmission of solar UV radiation through the cleaner air [29-31]. Likewise, reductions in water pollution associated with COVID-19 lockdown have led to increased clarity in some lakes [32].
- Trifluoroacetic acid continues to be found in the environment, including in remote regions, although concentrations are currently very unlikely to have adverse toxicological consequences for humans and ecosystems [33,34]. While TFA is formed from the HFCs and HFOs regulated under the Montreal Protocol, a large amount of TFA was naturally formed over millions of years and has accumulated in the oceans. An unknown amount originates from fugitive emissions from chemical manufacture, waste disposal sites, laboratory use, and degradation of pharmaceuticals, pesticides, and industrial chemicals containing the trifluoromethyl group.
- Solar UV radiation can cause the breakdown of a number of chemical contaminants in aquatic environments, thereby reducing their concentrations, but harmful (toxic and carcinogenic) by-products can result from these transformations [35]. For example, exposure to solar UV radiation increases the toxicity of oil pollutants to reef organisms; ocean acidification and warming can further enhance the toxicity of these oil contaminants [36].
- When plastics are exposed to solar UV radiation they break down into potentially toxic microplastics (SDG 6.3, 6.6 and 12.4) [37]. Microplastics are ubiquitous in the environment and are of growing concern, especially in aquatic ecosystems [38-40] (Figure 2). Widely distributed plastics, such as polyethylene and polystyrene (trademark Styrofoam), can also be chemically transformed by solar UV radiation, releasing carbon dioxide and dissolved organic carbon, which could contribute to global warming [41].
- Heavy metal ions in aquatic systems are concentrated by microplastics after exposure to UV radiation, and this could increase their toxicity to organisms [37]. However, the biological and ecological effects of nano- and microplastics have not been well studied and information is therefore lacking at present.

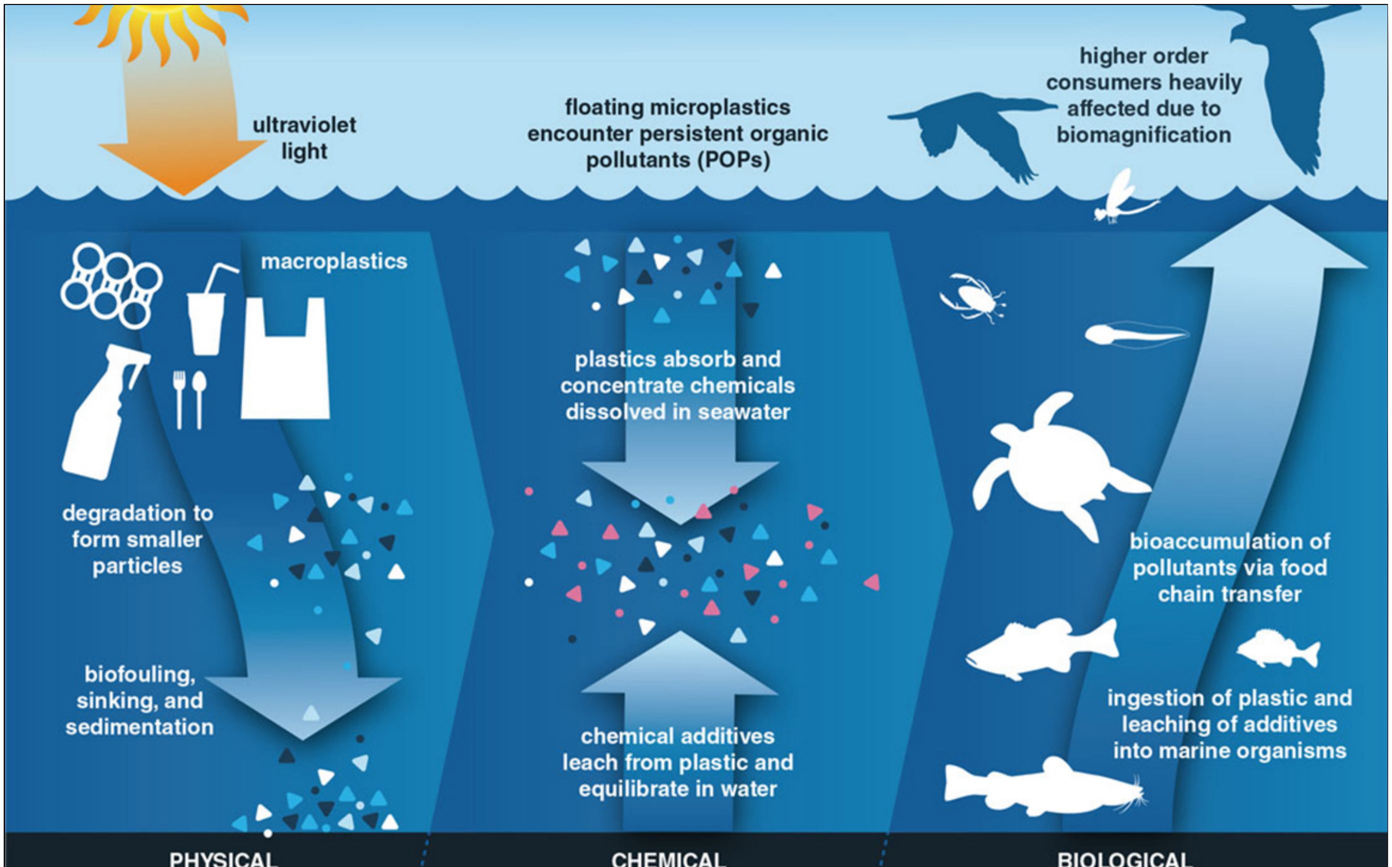

Figure 2. Formation and impacts of microplastics in the ocean environment. Microplastics are ubiquitous in the environment with amounts increasing rapidly. As of 2016, about 19-23 million tonnes, or 11% of all plastic waste, entered aquatic ecosystems. If trends continue this may grow to 90 million tonnes per year by 2030 [40]. Image courtesy of Mason (2019) [39].

2.4 Biodiversity, food security and ecosystem services

Changes in stratospheric ozone and climate have the potential to affect food security, biodiversity, and the services provided by ecosystems. Solar UV radiation contributes to the breakdown of natural organic matter in aquatic and terrestrial ecosystems (SDG 14.1), and the subsequent release of carbon dioxide (CO_2) and other greenhouse gases to the atmosphere. Available evidence indicates that through the regulation of ozone-depleting substances and greenhouse gases, the Montreal Protocol has significantly slowed climate change by reducing the emissions of greenhouse gases from the biosphere.

Key findings include:

- Solar UV radiation and climate change can reduce the variety and availability of suitable habitats for plants and animals, which may lead to their extinction (SDG 2.4 and 15.1) [42,43].
- Thawing in the Arctic is disrupting ecosystems and exposing large amounts of organic matter to solar UV radiation (SDG 15.3). The decomposition of this previously frozen soil (permafrost) releases greenhouse gases such as carbon dioxide and methane [44]; the organic matter from peatlands decomposes to release nitrous oxide [45], a major ozone-depleting substance and greenhouse gas. Global warming and solar UV radiation are thus both contributing to emissions of gases in Arctic ecosystems, and these can increase climate change and stratospheric ozone depletion.
- Penetration of UV-B radiation will increase in historically ice-covered lakes and polar oceans as Earth continues to warm and the ice-free period of these aquatic ecosystems lengthens [46]. Exposure to UV radiation in lakes and the ocean, especially in areas that are nutrient-enriched from agricultural and urban runoff, encourages the growth and toxicity of harmful algal blooms [47,48] with potential adverse consequences for humans and wildlife.
- Solar UV radiation has multiple negative effects on all life cycle stages of fish, causing developmental abnormalities, decreases in growth and body condition, lesions in skin and eyes, and, in some cases death [49]. The corresponding reductions in fish survival, growth, and reproduction have as yet unquantified implications for the yield of commercial and recreational fisheries that provide critical supplies of food to much of the world's population.
- Loss of forests in the tropics, due mainly to deforestation, is increasing by about 2,100 square kilometres/year, exposing dead plant material (litter) to solar radiation, including the UV component [50]. Exposure to UV radiation causes the litter to degrade, which can accelerate the emissions of carbon dioxide and other greenhouse gases (e.g., nitrous oxide), contributing to global warming [51].
- UV-B radiation, together with the consequences of climate change, such as drought and increased temperature, can affect plant growth, pathogen and pest defense, and the quality of food crops [52,53]. These effects vary greatly with species and environmental conditions, although extremely high levels of solar UV-B radiation, as would have occurred without the Montreal Protocol, would likely have posed a significant risk to agricultural productivity.

3 Conclusions

Since our last Update [5], the world has experienced a number of extreme or anomalous events of historical importance, including an unusually small Antarctic ozone hole in 2019, a large and prolonged depletion of both Arctic and Antarctic ozone[1] in 2020 during springtime, record-setting temperatures, heat waves, droughts, devastating wildfires, and an unprecedented number of tropical/subtropical cyclones (hurricanes). In addition, the ongoing COVID-19 pandemic has claimed more than 1.8 million human lives as of December 2020 and inflicted economic hardship on millions of people around the world. Many of these events have been linked to climate change [54,55] and most have, in some way, altered the exposure of humans, plants and animals to solar UV radiation, air pollution and climate change factors.

The full environmental and health effects of these events in 2020 are not yet known. Nevertheless, our findings from a wide array of scientific disciplines confirm the importance of the Montreal Protocol in mitigating many of the potentially deleterious effects of climate change and increases in solar UV radiation resulting from stratospheric ozone depletion on human health and the environment. In today's rapidly changing world, this treaty thus continues to play a critical role in protecting Earth's inhabitants and ecosystems by addressing many of the SDG targets established in the 2030 Agenda for Sustainable Development.

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[1] The World Meteorological Organization reported on 6 January 2021 that the 2020 Antarctic ozone hole was the longest-lasting and one of the largest and deepest holes since monitoring of the ozone layer began 40 years ago (https://public.wmo.int/en/media/news/record-breaking-2020-ozone-hole-closes). These results were published after the cutoff date of this Update and are therefore not discussed further. Measurements of the surface UV radiation in Antarctica for this period are not yet available.

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Declaration of interest

The authors have no conflicts of interest.