



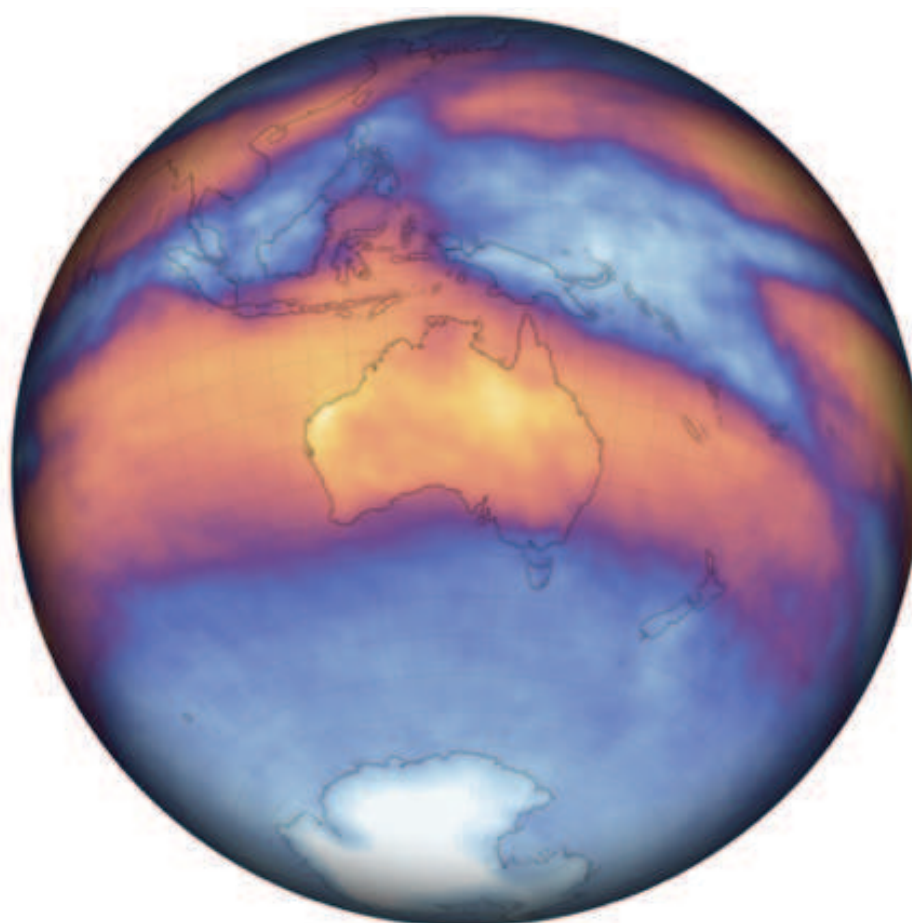
**UNITED NATIONS
ENVIRONMENT PROGRAMME**



Summary Update 2021 for Policymakers

UNEP Environmental Effects Assessment Panel

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Outgoing long-wave radiation, Wm^{-2}



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The image on the cover page shows the high amounts of heat (outgoing longwave radiation) over Australia being emitted into space, contributing to fuelling the November 2019 fires. The fires released aerosols, which reached the stratosphere and spread to other parts of the globe, and also greenhouse gases (carbon dioxide and methane) stored in the vegetation that was burnt.
Image, NASA Earth Observatory.



Environmental Effects of Stratospheric Ozone Depletion, UV Radiation, and Interactions with Climate Change: UNEP Environmental Effects Assessment Panel, Update 2021

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1. Introduction

Highlights of the findings are presented from the 2021 Update Assessment [1] by the Environmental Effects Assessment Panel (EEAP) of the Montreal Protocol under the United Nations Environment Programme (UNEP) in accordance with the *Terms of Reference* from the Parties to the Montreal Protocol (Box 1). The 2021 Update provides the most recent assessment since the 2020 Update [2] and the 2018 Quadrennial Assessment (*Photochemical & Photobiological Sciences* **18**, 595-828; also available at <https://ozone.unep.org/science/assessment/eeap>).

The 2021 Update was compiled by 49 EEAP members and co-authors in seven Working Groups and finalised during a virtual meeting held from 9-17 September 2021. We assessed the interactive effects of changes in stratospheric ozone, UV radiation and climate on human health, food security, biogeochemical cycles, materials used in construction and fabrics, as well as on natural ecosystems and their services (e.g., productivity of fisheries, biodiversity, conservation, recreation).

Topics of particular relevance in this Update Assessment include:

- ◆ Effects of anomalously low concentrations of stratospheric ozone observed in 2020 over Antarctica and the Arctic on surface UV-B radiation
- ◆ Climate benefits of the Montreal Protocol in protecting climate through effects on the productivity and carbon sequestration of Earth's vegetation
- ◆ Effects of solar UV radiation on human health and the COVID-19 pandemic
- ◆ Consequences of increases in the prevalence and intensity of extreme climate events on surface UV radiation and on the health and biodiversity of aquatic and terrestrial ecosystems
- ◆ Effects of UV radiation on the breakdown of contaminants, and controlled substances and their alternatives.

As in past assessments, we address the interactive effects between changes in the stratospheric ozone layer, solar UV radiation, and climate within the framework of the Montreal Protocol and the United Nations Sustainable Development Goals (SDGs; Box 2).

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”*

Box 2. The following Sustainable Development Goals (SDGs) and their specific targets 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 Stratospheric ozone, UV radiation and climate change

The Montreal Protocol continues to play a critical role in protecting the stratospheric ozone layer and climate, and in preventing large increases in surface UV radiation. However, substantial interannual variability in stratospheric ozone, UV radiation and extreme weather is occurring due to changes in climate caused by increases in atmospheric greenhouse gases (GHGs). Despite large year-to-year variability, recovery of the Antarctic ozone hole is still projected by the middle of this century. Further studies have reinforced the linkages between the size of the Antarctic ozone hole and climate in the Southern Hemisphere that have contributed to recent extreme weather events and wildfires.

Key findings include:

Antarctica

- ◆ The lack of large-scale perturbations in atmospheric circulation during the 2020 austral spring (September – November 2020) resulted in a cold and stable stratospheric vortex over Antarctica, which created conditions favourable for persistent ozone depletion [3]. Additionally, ozone loss in early spring enhanced the strength and persistence of the polar vortex later [4]. These conditions led to the longest-lived Antarctic ozone hole in the observational record and unusually high levels of UV-B radiation in this region [3,5] (Fig. 1).
- ◆ Despite the abnormally low stratospheric ozone and high UV-B radiation in late spring of 2020, the healing of the Antarctic ozone hole due to the implementation of the Montreal Protocol is still on track. This is evidenced by the observed continuing decline in stratospheric ozone depletion during September—the key month for chemical ozone destruction [3]—and the general trend of all metrics quantifying Antarctic ozone depletion, pointing towards recovery of the ozone hole [6].
- ◆ The unusual warming of the Antarctic stratosphere in September 2019 favoured the extremely dry conditions observed during the summer of 2019/2020 in the Southern Hemisphere [7] that then contributed to the devastating “2019/2020 Black Summer” wildfires in Australia [8]. Additional studies [9-11] have reinforced the link between the uncommonly weak Antarctic vortex in 2019 and the ensuing dry weather in the Southern Hemisphere. However, extreme weather events in this region in the future are expected to be more affected by increases in the concentration of GHGs and warming of the tropical upper troposphere than by stratospheric ozone [12].

Arctic

- ◆ Unprecedented Arctic ozone depletion occurred in March-April 2020 and contributed to abnormally high springtime temperatures across Asia and Europe [13]. This loss of ozone affected circulation patterns of winds around the Arctic [14] and led to more high-level clouds that enhance downwelling thermal radiation [15], thereby contributing to the melting of snow and ice at the surface. A decrease in snow cover would lead to less UV radiation at the surface because less UV radiation would be reflected upwards and subsequently scattered downward by air molecules. Large year-to-year variations in Arctic ozone depletion and UV radiation, driven by differences in meteorological conditions and rising GHGs, are expected to continue to occur throughout the 21st century despite measures resulting from the Montreal Protocol [16,17].

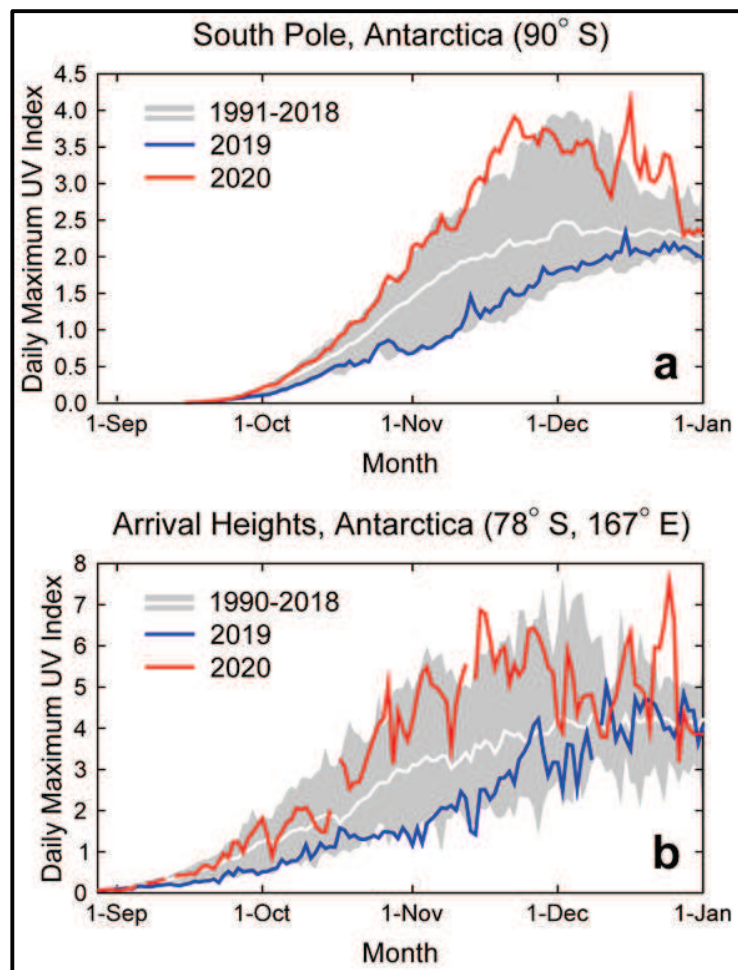


Figure 1. Daily maximum UV index (UVI) measured at the South Pole (a) and Arrival Heights (b) in 2019 (blue line) and 2020 (red line) compared with the average (white line) and the range (grey shading) of daily maximum observations of the years indicated in the legends. The UVI was calculated from spectra measured by SUV-100 spectroradiometers. Up to 2009, the instruments were part of the NSF UV monitoring network [18] and they are now a node in the NOAA Antarctic UV Monitoring Network (<https://www.esrl.noaa.gov/gmd/grad/antuv/>). Consistent data processing methods were applied for all years [19,20]. In 2020, the UVI was typically above the long-term average at both sites due to the sustained and deep ozone hole in that year. Conversely, the UVI in 2019 was close to the lower limit of historical observations because warming of the Antarctic stratosphere produced one of the smallest ozone holes on record in that year [2,3].

2.2 Climate benefits of the Montreal Protocol

Key finding:

- ◆ A recent modelling study indicates that the Montreal Protocol has benefitted Earth's climate by preventing large increases in UV-B radiation that would have had catastrophic effects on photosynthesis and carbon storage in land plants [21]. Although there are significant uncertainties in these findings, these model simulations estimated that without the Montreal Protocol carbon storage by vegetation would have decreased by 325-690 billion tonnes and this would have increased atmospheric carbon dioxide (CO₂) concentrations by an additional 115-235 parts per million by the end of the century. This increase in atmospheric CO₂ would have resulted in an additional rise in global mean surface temperature of 0.5-1.0 °C.

2.3 Human health

By protecting the stratospheric ozone layer, the Montreal Protocol has reduced the damaging health effects of excessive exposure to solar UV radiation. However, there are health benefits of moderate exposure to UV radiation, most notably vitamin D production. It is likely that by avoiding large increases in UV-B radiation, the Montreal Protocol has allowed humans to safely tolerate time outdoors, thereby gaining the benefits of sun exposure. This may have reduced the risk or severity of several diseases, particularly those related to immune function, such as multiple sclerosis (MS) and COVID-19.

Key findings include:

- ◆ A recent study involving a global database found that skin cancer continues to exert a considerable burden on the human population with an estimated 4.0 million basal cell carcinomas, 2.4 million cutaneous squamous cell carcinomas, and 0.3 million malignant melanomas in 2019 [22]. However, there is evidence that the incidence of melanoma has stabilised in some countries (New Zealand), while declining in other countries (Canada, Italy, and England), at least in younger age groups [23-26].
- ◆ Findings from a recent meta-analysis that included 45 published studies indicate that eye diseases related to exposure to UV radiation continue to be a major cause of impaired vision with about an 8% prevalence of two types of UV-related cataract (nuclear and cortical) in adults over 20 years of age and 25-31% in those over 60 years of age; however, there is considerable variability in cataract incidence among regions [27].
- ◆ Exposure to UV radiation is increasingly being recognised as having beneficial effects in the suppression of pathogenic immune responses [28]. In one recent study of 946 people with relapsing remitting MS or Clinically Isolated Syndrome, a precursor of MS, individuals that lived in regions with relatively low solar UV radiation exhibited more severe MS conditions than those living in regions of high UV [29]. In another study, infants exposed to UV radiation showed a reduced risk of eczema, independent of vitamin D levels [30].
- ◆ Vitamin D deficiency continues to be a global concern, but one possible benefit of climate change is a decrease in vitamin-D deficiency in temperate climates [31]. Results from a recent study in Germany indicated that increased temperatures resulting from climate change may reduce the prevalence of vitamin D deficiency [32].
- ◆ Research continues to explore whether a link exists between UV radiation and the spread and severity of COVID-19 [e.g., 33,34]. While it is possible that solar UV radiation could deactivate the virus responsible for COVID-19 (SARS-CoV-2) [2], it is more likely that UV radiation influences COVID-19 through effects on immunity and metabolism [2]. Higher ambient UV radiation has been associated with reduced incidence and severity [35,36]. However, it is difficult to disentangle the effect of UV radiation from socio-political controls and other climatic factors such as temperature. At the present time it appears that the Montreal Protocol has had, a relatively minor effect on the COVID-19 pandemic.

2.4 Extreme climate events, UV radiation and ecosystems

Extreme climate events (ECEs), such as severe droughts, catastrophic storms and floods, unprecedented heat waves, and devastating wildfires, are increasing in severity and frequency because of climate change [27]. These events are disrupting the stability, productivity, and biodiversity of terrestrial and aquatic ecosystems [e.g., 37,38,39], and leading to changes in the exposure to UV radiation of plants and animals [40]. UV radiation can exacerbate the detrimental effects of ECEs and increase the emission of greenhouse gases from the biosphere. On the other hand, ECEs that decrease exposure to UV radiation may reduce some of its beneficial effects in terrestrial and aquatic ecosystems. Technological interventions in the climate system (i.e., geoengineering) to mitigate climate change could lead to additional ECEs, which could potentially have wide-ranging unintended impacts on ecosystems.

Key findings include:

- ◆ ECEs can change the exposure to UV radiation of terrestrial organisms and ecosystems by altering atmospheric conditions (e.g., cloud cover and aerosols), land cover (e.g., snow, ice, and vegetation), and the timing of development in organisms (i.e., phenology) (Fig. 2). In some cases, ECEs cause increases in the exposure of terrestrial ecosystems to solar UV radiation (e.g., from loss of forest cover due to storms), whereas in others UV exposure decreases (e.g., from increases in aerosols from wildfires) (Fig. 2). These changes in UV radiation can occur over short or long time periods, manifesting in acute or chronic ecosystem effects, respectively. Increases in solar UV radiation caused by ECEs occur together with other climate factors (e.g., temperature and moisture availability) and may reduce biodiversity, increase greenhouse gas emissions, and decrease the productivity and growth of crops and wild plant species [41-43]. These effects would likely be much more severe in the absence of the Montreal Protocol [21].
- ◆ Extreme precipitation events are increasing inputs of dissolved organic matter (DOM) into aquatic ecosystems. DOM strongly absorbs UV-B radiation, shielding undesirable parasites, pathogens, and their vectors from the disinfecting effects of UV-B radiation [44,45]. Exposure to solar UV radiation decreases the survival of mosquito larvae [138], and extreme precipitation events may also increase the number and persistence of shallow pools, which are important breeding habitats for mosquitos. These findings suggest that increases in heavy precipitation related to climate change may act as a double-edged sword by increasing the refuge for UV-sensitive pathogens from the disinfecting UV radiation and by creating more suitable habitats for mosquitoes, which are important vectors of disease in many regions of the world.
- ◆ Solar Radiation Modification (SRM) is one proposed type of geoengineering aimed at mitigating climate change by reducing the amount of solar radiation reaching Earth's surface. In principle, this would be achieved by cloud brightening, thinning of cirrus clouds, or injection of sulphate aerosols into the stratosphere [46]. Modelling studies indicate that, in addition to changes in climate, SRM would cause ozone depletion in polar regions and increased ozone in the tropics and mid-latitudes [47-49]. While this intervention could offset some of the rapidly warming climate conditions, it would likely lead to several disruptions in natural and agricultural ecosystems that could compromise food production and essential ecosystem services [50].

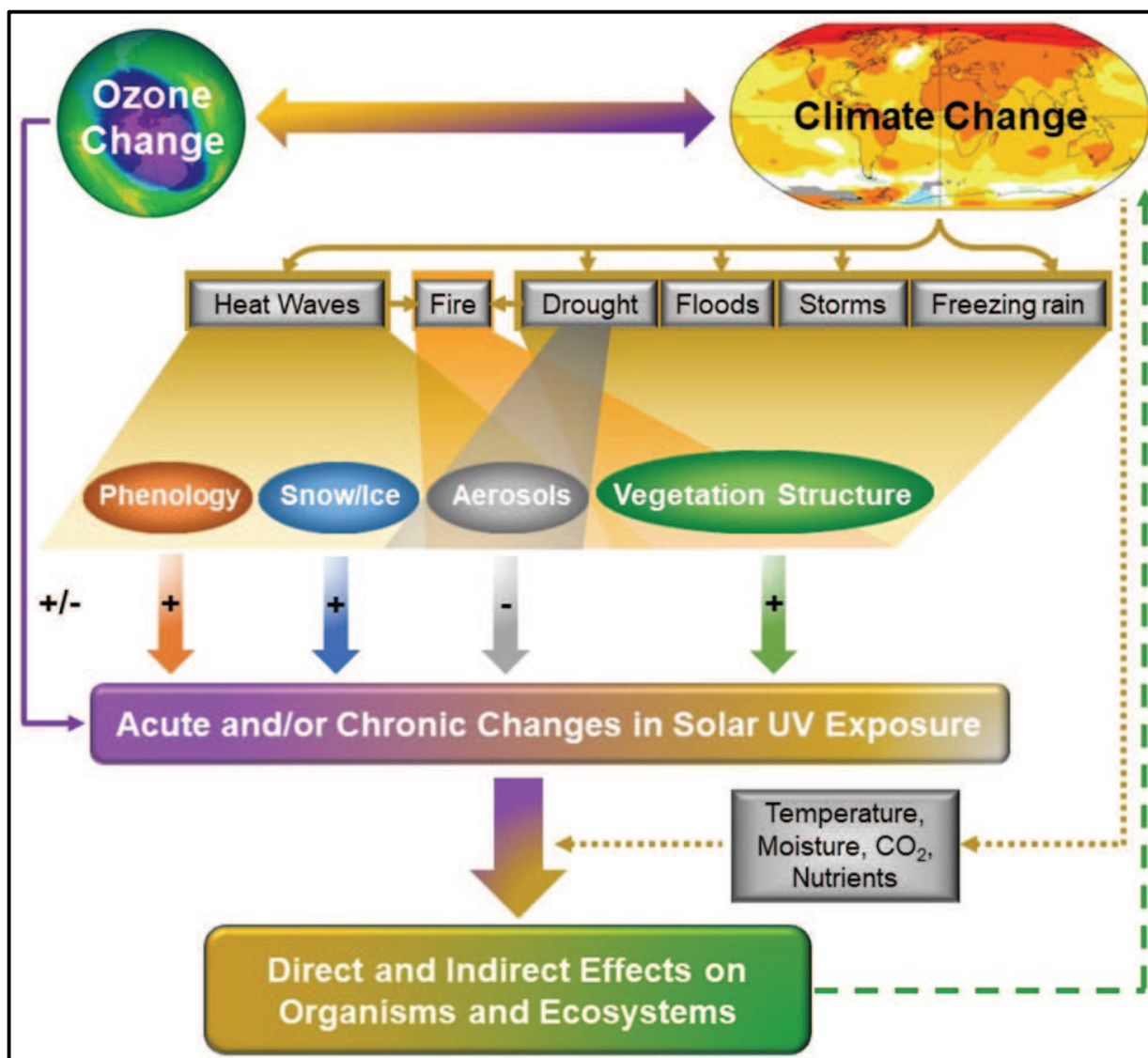


Figure 2. Pathways by which extreme climate events (ECEs) driven by changes in stratospheric ozone and climate can modify exposures and responses of terrestrial organisms and ecosystems to solar UV radiation (solid lines). Dotted line shows modulating effects of climate change factors in response to UV radiation, while dashed line indicates feedback effects of the biosphere on the climate system. Increases in exposure to UV radiation are shown as plus signs (+), and decreases as negative signs (-).

2.5 Materials, contaminants, and breakdown products

Solar UV radiation contributes to the breakdown of dead organic matter in aquatic and terrestrial ecosystems, and this process releases carbon dioxide, methane, and other greenhouse gases to the atmosphere. Natural and synthetic materials, such as wood and plastics used in building materials, can also be degraded by UV radiation, as well as textiles; although new technologies have been developed that can minimise these effects. However, the production of plastics and accumulation of micro- and nanoplastics in the environment continues to be of concern. UV-driven photodegradation of some of the compounds controlled by the Montreal Protocol (e.g., hydrofluorocarbons (HFCs)) produce contaminants such as trifluoroacetic acid (TFA), but concentrations of these breakdown products in the environment are currently deemed too low to be a concern for human health or the environment.

Key findings include:

- ◆ Photodegradation of DOM by UV radiation produces methane (CH₄) in marine ecosystems (Fig. 3). Recent analyses indicate that this process emits 118 Gg of methane per year, representing 20-60% of the open oceanic methane emissions. These emissions are far lower in coastal, sub-polar and polar regions, where the considerably lower reactivity of terrestrially derived DOM dampens the process [51]. The photochemical release of CH₄ maintains super-saturated concentrations in the upper ocean and sustains oceanic CH₄ emissions to the atmosphere. The photochemical processes therefore explain the oceanic methane paradox, namely, the presence of high concentrations of methane in oxygen-rich surface waters, where methane-producing microorganisms cannot survive.
- ◆ Solar UV radiation is a key driver of the breakdown of many contaminants in the environment and can enhance the toxicity of some pollutants, while reducing the toxicity of others. In aquatic environments, exposure to UV radiation can increase the toxicity of polycyclic aromatic hydrocarbons (PAHs) found in oil spills and some pesticides [52-54]. On the other hand, in agricultural ecosystems UV radiation facilitates the breakdown of certain pesticides, which are commonly applied to crops to control pests but can negatively affect non-target organisms [55].
- ◆ TFA likely has natural geochemical sources, is widely used in industry and research laboratories, and is a by-product of the synthesis and degradation of fluorinated and perfluorinated compounds (PFCs) [56,57]. TFA has recently been found in precipitation, surface waters, and indoor dust in China [58-61], although concentrations are below those considered toxic. No additional studies on the toxicity of TFA to organisms have been reported, but prior research has shown that this compound is not highly toxic to mammals and aquatic organisms, although some plants and algae may be sensitive [56]. At present, it is not possible to quantify the proportion of anthropogenic sources of TFA resulting from substances not falling under the purview of the Montreal Protocol, but available evidence indicates that this breakdown product is of minimal risk to human health.
- ◆ The degradation of plastic debris and litter is accelerated by solar UV radiation as well as by high temperatures, and this process can increase the generation of microplastics and nanoplastics in the environment [2]. Recent studies have detected microplastic contaminants in human placental and lung tissue [62-64], although the implications for human health are not yet clear. While it is well known that exposure of plastics to solar UV radiation can generate micro- and nanoplastics, the quantitative importance of this process has not been established, which limits our ability to adequately assess the global influence of UV radiation and the Montreal Protocol on plastic pollution.
- ◆ Novel technologies have been developed to protect building products from UV-driven photodegradation and to reduce the transmission of solar UV radiation through textiles. One innovative technology involves replacing the lignin fraction of wood with synthetic or biopolymers to obtain highly transparent wood composites [65-67] with the aim to improve UV stabilisation of building materials and reduce the demand for valuable timber species. Graphene and its oxides are popular nanoscale materials that are added as fillers to certain materials for their electrical, mechanical, and anti-microbial properties. They also provide enhanced UV stability [68,69] and their production is more sustainable than that of conventional materials, such as carbon black [70].

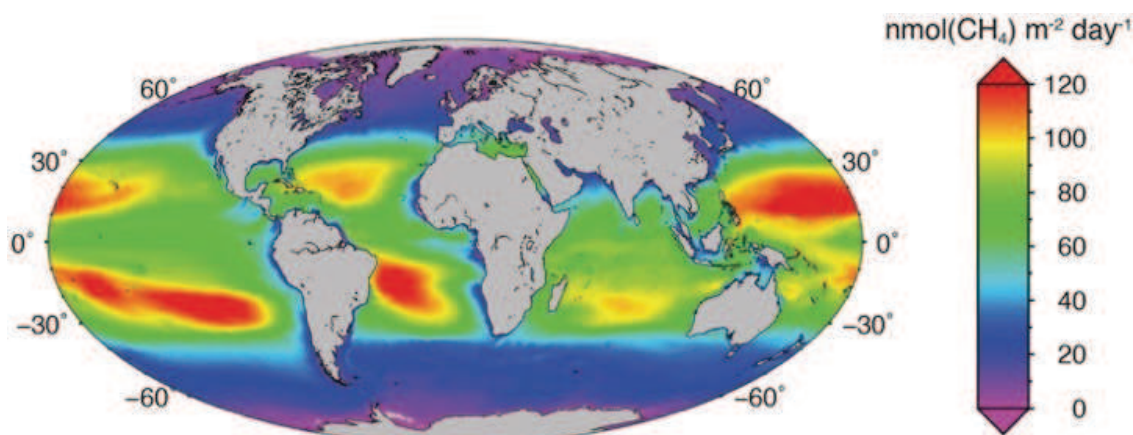


Figure 3. Photoproduction rate of methane from dissolved organic matter (DOM) at the ocean surface (top 150 m) (Figure by Rachele Ossola, adapted from Li et al. [51]).

3. Conclusions

The summary findings highlighted in this Update, together with those described in our full Update Assessment [1], reveal the diversity of ways that changes in stratospheric ozone, UV radiation and climate interact to influence human health and the environment. While exposure to solar UV radiation, and, in particular, the short wavelength UV-B radiation, is widely regarded as having deleterious effects on humans and other organisms, our findings here and elsewhere [71] also reveal that modest exposure to UV radiation can have beneficial effects on human health, food quality and plant defense against pests, the disinfection of waters, and the conversion of toxic contaminants to more benign by-products. It is clear, however, that maintaining an optimal balance between the positive and negative effects of solar UV radiation would have been difficult, if not impossible, without the Montreal Protocol. The Montreal Protocol and its Amendments therefore continue to play a vital role in protecting humans, aquatic and terrestrial ecosystems, and natural and synthetic materials from the deleterious effects of elevated solar UV-B radiation resulting from stratospheric ozone depletion [72,73]. Evidence also continues to mount showing that the Montreal Protocol is directly and indirectly protecting Earth's climate and mitigating some of the negative consequences of climate change [21,74].

Since our last Update Assessment, the world has experienced additional extreme events (e.g., heat waves, droughts, and hurricanes) and events resulting from a combination of weather extremes and other drivers (e.g., wildfires) that have all contributed to increasing societal and environmental risk. As recently reported by the Intergovernmental Panel on Climate Change (IPCC) [46], these events, often collectively referred to as “Extreme Climate Events”, are expected to increase in frequency and intensity in the future because of anthropogenic climate change. The ECEs, together with other aspects of climate change, can change the exposure to UV radiation of humans, plants and animals, and materials to a greater degree than the expected changes in the stratospheric ozone layer—assuming continued and full compliance with the Montreal Protocol. Nonetheless, while the full extent of the environmental effects of these climate-UV interactions are unknown at present, the Montreal Protocol continues to make a valuable contribution to the development of a sustainable future by addressing many of the SDG targets established in the 2030 Agenda for Sustainable Development (Box 2).

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Declarations of interest

The authors have no conflicts of interest.

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