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Ozone depletion, ultraviolet radiation, climate change and prospects for a sustainable future

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Changes in stratospheric ozone and climate over the past 40-plus years have altered the solar ultraviolet (UV) radiation conditions at the Earth's surface. Ozone depletion has also contributed to climate change across the Southern Hemisphere. These changes are interacting in complex ways to affect human health, food and water security, and ecosystem services. Many adverse effects of high UV exposure have been avoided thanks to the Montreal Protocol with its Amendments and Adjustments, which have effectively controlled the production and use of ozone-depleting substances. This international treaty has also played an important role in mitigating climate change. Climate change is modifying UV exposure and affecting how people and ecosystems respond to UV; these effects will become more pronounced in the future. The interactions between stratospheric ozone, climate and UV radiation will therefore shift over time; however, the Montreal Protocol will continue to have far-reaching benefits for human well-being and environmental sustainability.

Warnings that Earth's stratospheric ozone layer could be at risk from chlorofluorocarbons (CFCs) and other anthropogenic substances were first issued by scientists in the early 1970s[1,2]. Soon thereafter (in 1985), large losses of stratospheric ozone were reported over Antarctica[3] with smaller but more widespread erosion of stratospheric ozone found over much of the rest of the planet[4]. Subsequent studies clearly linked these ozone losses to the emissions of CFCs and other ozone-depleting substances[5] and, at least over Antarctica, unique atmospheric conditions during winter that lead to ozone depletion[6,7].

In response to the initial concerns about the potentially deleterious effects of elevated surface solar ultraviolet-B radiation (UV-B; 280–315 nm) resulting from ozone depletion, the international community began mobilizing in 1977 to recognize the importance

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Box 1 | The three assessment panels supporting the Montreal Protocol

There are three panels under the Montreal Protocol to assess various aspects of stratospheric ozone depletion. These three panels have complementary charges. The Scientific Assessment Panel assesses the status of the depletion of the ozone layer and relevant atmospheric science issues. The Technology and Economic Assessment Panel provides technical and economic information to the Parties on alternative technologies to replace ozone-depleting substances. The Environmental Effects Assessment Panel (EEAP) considers the full range of potential effects of stratospheric ozone depletion, UV radiation and the interactive effects of climate change on human health, aquatic and terrestrial ecosystems, biogeochemical cycles, air quality, and materials for construction and other uses. Additional information on these panels, including their most recent assessments, can be found on the website of the UNEP Ozone Secretariat (https://ozone.unep.org/science/overview).

of stratospheric ozone to life on Earth, and to develop and implement policies to preserve the integrity of the ozone layer[8]. Of particular concern was the possibility that exposure to high levels of UV-B would increase the incidence of skin cancer and cataracts in humans, weaken people's immune systems, decrease agricultural productivity, and negatively affect sensitive aquatic organisms and ecosystems. The policy solution that emerged to address stratospheric ozone depletion was the 1985 Vienna Convention for the Protection of the Ozone Layer. This convention was followed by the 1987 Montreal Protocol on Substances that Deplete the Ozone Layer, which was negotiated to control the consumption and production of anthropogenic substances that deplete ozone.

Montreal Protocol and UNEP EEAP

The Montreal Protocol was the first multilateral environmental agreement by the United Nations to achieve universal ratification (197 Parties by 2008). Since its inception, this international accord has been amended and adjusted a number of times by the member Parties of the Montreal Protocol. The Parties base their decisions on scientific, environmental, technical and economic information provided by three assessment panels (Box 1). All three panels provide full assessment reports to the Parties every 4 years (quadrennial reports) and shorter, periodic updates in the intervening years as needed.

The implementation of the Montreal Protocol has successfully prevented the uncontrolled global depletion of the stratospheric ozone layer and associated large increases in surface UV-B radiation[9–12] (Box 2). Concentrations of chlorine and bromine from long-lived ozone-depleting substances have been declining in the stratosphere since the late 1990s[12]. Although considerable seasonal ozone depletion over Antarctica (the 'ozone hole') has occurred annually since the 1980s, there have been small but noteworthy positive trends in total column ozone in Antarctica in spring over the period 2001–2013[12]. Global mean total ozone is projected to recover to pre-1980 levels by the middle of the twenty-first century, assuming full compliance with the Montreal Protocol[12].

Although carbon dioxide, methane and nitrous oxide are the dominant greenhouse gases emitted by human activity, most of the ozone-depleting substances controlled by the Montreal Protocol (CFCs and others) are also potent greenhouse gases that contribute to global warming[14]. Modelling studies indicate that in the absence of the Montreal Protocol, global mean temperatures would have risen more than 2 °C by 2070 owing to the warming effects from ozone-depleting substances alone[15]. The adoption of the Kigali Amendment to the Montreal Protocol in 2016 limits the production and consumption of hydrofluorocarbons (HFCs), which are non-ozone-depleting substitutes for CFCs[16]. HFCs are potent greenhouse gases, and limiting emissions of these compounds could further reduce global temperatures as much as 0.5 °C by the end of this century[17]. This Amendment has thus further broadened and strengthened the scope of the Montreal Protocol, adding to an effective international treaty that not only addresses stratospheric ozone depletion, but is doing more to mitigate global climate change than any other human action so far[18–20].

Below, we highlight key findings from the most recent Quadrennial Assessment by the Environmental Effects Assessment Panel (EEAP) of the United Nations Environment Programme (UNEP), which reports on the state of the science on the environmental effects of stratospheric ozone depletion and consequent changes in UV radiation at the Earth's surface, and the interactive effects of climate change. We specifically consider the policy and societal implications of these effects, and address the multiple ways by which the Montreal Protocol is contributing to environmental sustainability and to human health and well-being. Given the accelerating pace of climate change[21], we also consider the increasing role that climate change is playing in influencing exposure of humans and other organisms to UV radiation, how stratospheric ozone depletion is itself contributing to climate change, and the various ways in which climate change is affecting how plants, animals and ecosystems respond to UV radiation. Thus, as mandated by the Parties to the Montreal Protocol, we consider a wide range of the environmental effects that are linked to changes in stratospheric ozone, climate and solar UV radiation. Our findings address many of the United Nations Sustainable Development Goals (Fig. 1). More in-depth information on the environmental effects of stratospheric ozone depletion can be found elsewhere[22–28]. By focusing on the interactions between stratospheric ozone, UV radiation and climate, the collated EEAP Assessment complements those of the Scientific Assessment Panel[12] and the UN Intergovernmental Panel on Climate Change[29] to provide a comprehensive assessment on the causes and consequences of global changes in the Earth's atmosphere.

Stratospheric ozone, climate change and UV radiation

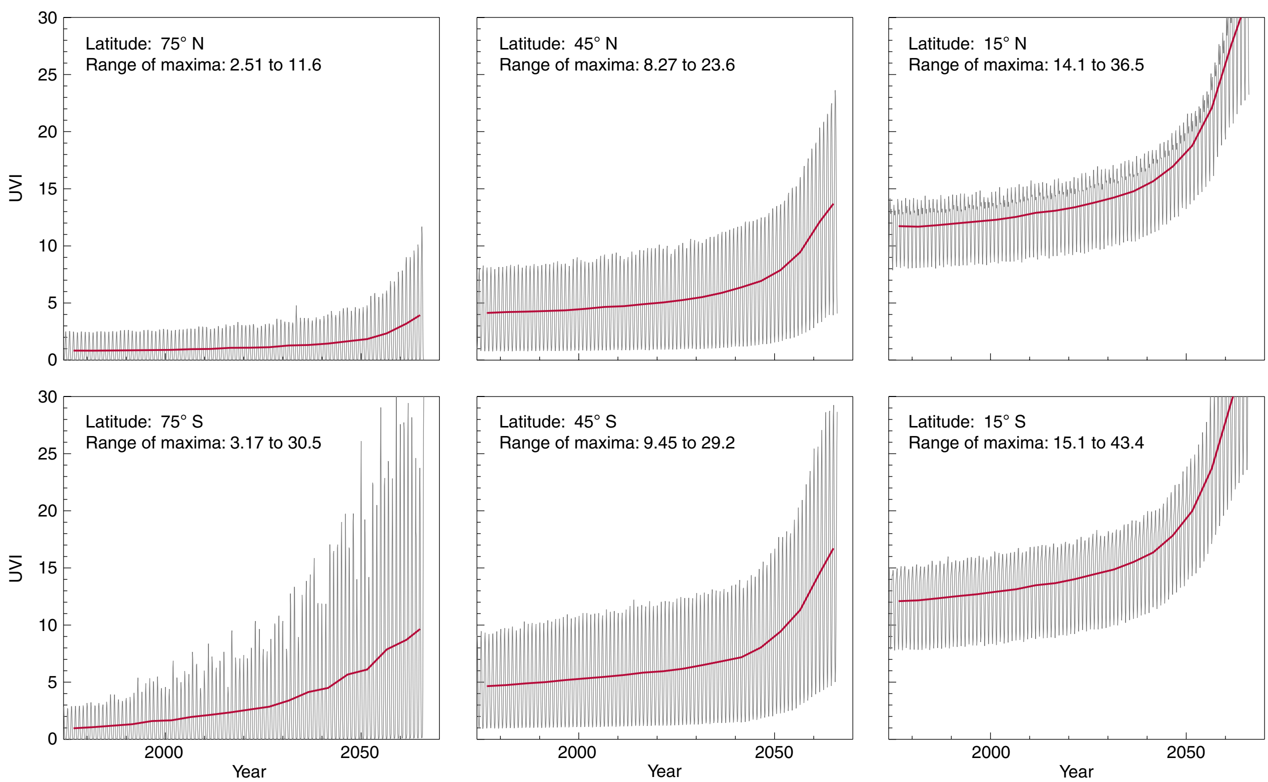
Stratospheric ozone depletion and climate change interact through direct and indirect pathways that can have consequences for food and water security, human well-being and ecosystem sustainability (Figs. 1 and 2). Climate change can modify the depletion of stratospheric ozone by perturbing temperature, moisture, and wind speed and direction in the stratosphere and troposphere[30]. Certain greenhouse gases (such as N_2O and CH_4) also modify the chemistry that regulates ozone levels[12]. Conversely, it is now clear that ozone depletion is directly contributing to climate change across much of the Southern Hemisphere by altering atmospheric circulation patterns in this part of the globe[31], which affect weather conditions, sea surface temperatures, ocean currents and the frequency of wildfires in multiple regions[32–36]. These ozone-driven changes in climate are in turn exerting impacts on the terrestrial and aquatic ecosystems in this region[24,25,37,38] (Box 3). In the Northern Hemisphere, similar but smaller effects of ozone depletion on climate may exist[27], but year-to-year variability in the meteorology is greater than in the Southern Hemisphere, and there are no reports as yet linking these changes to environmental impacts.

Depletion of stratospheric ozone leads to increased UV-B radiation at the Earth's surface[27] that can then directly affect organisms and their environment. Because of the success of the Montreal Protocol, present-day increases in UV-B radiation (quantified as clear-sky UV Index) due to stratospheric ozone depletion have been negligible in the tropics, small (5–10%) at mid-latitudes and large only in Antarctica. As stratospheric ozone recovers over the next several decades[12], the clear-sky noon-time UV Index is expected to decrease (for example, by 2–8% at mid-latitudes depending on season and precise location, and by 35% during the Antarctic October ozone 'hole'[27,39]).

Box 2 | Environmental effects in the 'World Avoided'

There are a number of published models addressing the implications and potential outcomes of the 'World Avoided' due to the Montreal Protocol[9]. All point to progressive loss of stratospheric ozone that would have accelerated over time and extended to affect the entire planet by the second half of this century. For example, the Goddard Earth Observing System chemistry-climate model (GEOSCCM) World Avoided simulation[11] used here assumes that ozone-depleting substances continue to increase by 3% per year, beginning in 1974. This collapse in the total global ozone column would have resulted in clear-sky UV Index (UVI) values increasing sharply after 2050 at most latitudes (see figure) with extreme values of 20 becoming commonplace by 2065 over almost all inhabited areas of the planet, and as high as 43 in the tropics[11], more than four times the UVI that is currently considered 'extreme' by the World Health Organization. The graphs show calculated surface monthly (grey lines) and annual mean (red line) UVI values for clear skies at different latitudes without the Montreal Protocol, based on the model in ref. [11]. The range of maxima given shows pre-1980 data versus 2065 data.

Combining these models of ozone and UV radiation with the understanding of the links between exposure to excessive UV radiation and the risk of skin cancers has allowed some estimates of the incidence of skin cancer in the World Avoided. Different studies have considered different timescales and/or different geographical regions, but all conclude that the successful implementation of the Montreal Protocol will have prevented many millions of cases of skin cancers. For example, a report by the United States Environmental Protection Agency[13] showed that when compared with a situation of no policy controls, full implementation of the Montreal Protocol and its Amendments is expected to avoid more than 280 million cases of skin cancer, about 1.6 million skin cancer deaths, and more than 45 million cases of cataract in the United States for people born between 1890 and 2100.



Independent of stratospheric ozone variations, climate change is increasingly contributing to changes in incident surface UV-B radiation[27,40] (Fig. 2). Unlike stratospheric ozone depletion, these effects driven by climate change modify the amount of surface solar radiation not just in the UV-B but also in the ultraviolet-A (UV-A; 315–400 nm) and visible (400–700 nm) parts of the spectrum. These changes are important, as many of the environmental and health effects caused by UV-B radiation can be either ameliorated or accentuated, to varying degrees, by UV-A and visible radiation[23–25].

Future changes in incident surface solar UV radiation (UV-B and UV-A) will depend strongly on changes in aerosols (solid and liquid particles suspended in the atmosphere), clouds and surface reflectivity (for example, snow and ice cover). Climate change is altering cloud cover, with some regions becoming cloudier and others less cloudy[41]. Increased cloud cover generally tends to reduce UV radiation at the Earth's surface, but effects vary depending on the types of clouds[42] and their position relative to that of the Sun[43]. Aerosols[28] reduce and scatter UV radiation; the type and amounts of aerosols in the atmosphere are affected by volcanic activity, the emissions of air pollutants, the frequency and extent of wildfires and dust storms, and other factors, many of which are affected by climate change[26,27,44]. In heavily polluted areas (such as southern and eastern Asia), improvements in air quality resulting from measures to control the emissions of air pollutants are expected to increase levels of UV radiation to near pre-industrial levels (that is, before extensive aerosol pollution); the extent of these changes is contingent on

Fig. 1 | The Sustainable Development Goals (SDGs) addressed by the UNEP Environmental Effects Assessment Panel 2018 Quadrennial Report. The findings from the Assessment are summarized in this paper according to five major topics (in circles). These address 11 of the 17 United Nations SDGs (in numbered squares): 2, zero hunger; 3, good health and well-being; 6, clean water and sanitation; 7, affordable and clean energy; 9, industry, innovation and infrastructure; 11, sustainable cities and communities; 12, responsible consumption and production; 13, climate action; 14, life below water; 15, life on land; and 17, partnerships for the goals. Credit: SDG icons, United Nations (UN/SDG).

the degree to which future emissions of air pollutants are curtailed. High surface reflectance from snow or ice cover can enhance incident UV radiation because some of the reflected UV radiation is scattered back to the surface by aerosols and clouds in the atmosphere. Consequently, climate-change-driven reductions in ice or snow cover, which are occurring in polar regions and mountains, are likely to decrease surface UV radiation in these areas[27]. At the same time, this will increase the UV exposure of soils and waters that are no longer covered by snow or ice.

UV radiation exposure and climate change

The direct effects of UV radiation on organisms, including humans, and on materials depend on levels of exposure to UV radiation. This is determined by several factors, including many that are influenced by climate change (Fig. 2). Importantly, these climate-change-driven effects can result in either increases or decreases in exposures to solar UV radiation, depending on location, time of year and other circumstances. Some of the most important regulators of exposure to UV radiation are as follows.

- Behaviour: the exposure of individual humans to UV radiation ranges from one-tenth of, to ten times, the average for the population[45], depending on the time that people spend indoors versus outdoors, and under shade structures. The exposure of the skin or eyes to UV radiation further depends on the use of sun protection such as clothing or sunglasses; the UV radiation dose received by cells and tissues within the skin is influenced by pigmentation of the skin and use of sunscreens[23]. Warmer temperatures and changing precipitation patterns resulting from climate change will alter patterns of exposure to sunlight[46], but the direction and magnitude of this effect will vary globally. Many animals, such as insects, fish and birds, can sense UV radiation and use this 'visual' information to avoid exposure to prolonged periods of high UV radiation[47,48].
- In response to climate change, many animals and plants are migrating or shifting their ranges to higher latitudes and elevations[49,50], while increases in exposure to UV radiation lead zooplankton to migrate into deeper waters[51–54]. Because of the natural gradients in solar UV radiation that exist with latitude, altitude and water depth[25,27], these shifts in distributions will expose organisms to conditions of UV radiation to which they are unaccustomed.
- Climate change is altering phenology, including plant flowering, spring bud-burst in trees, and emergence and breeding of animals[49,55]. As solar UV radiation varies naturally with seasons, such alterations in the timing of critical life-cycle events will affect exposures to UV radiation.

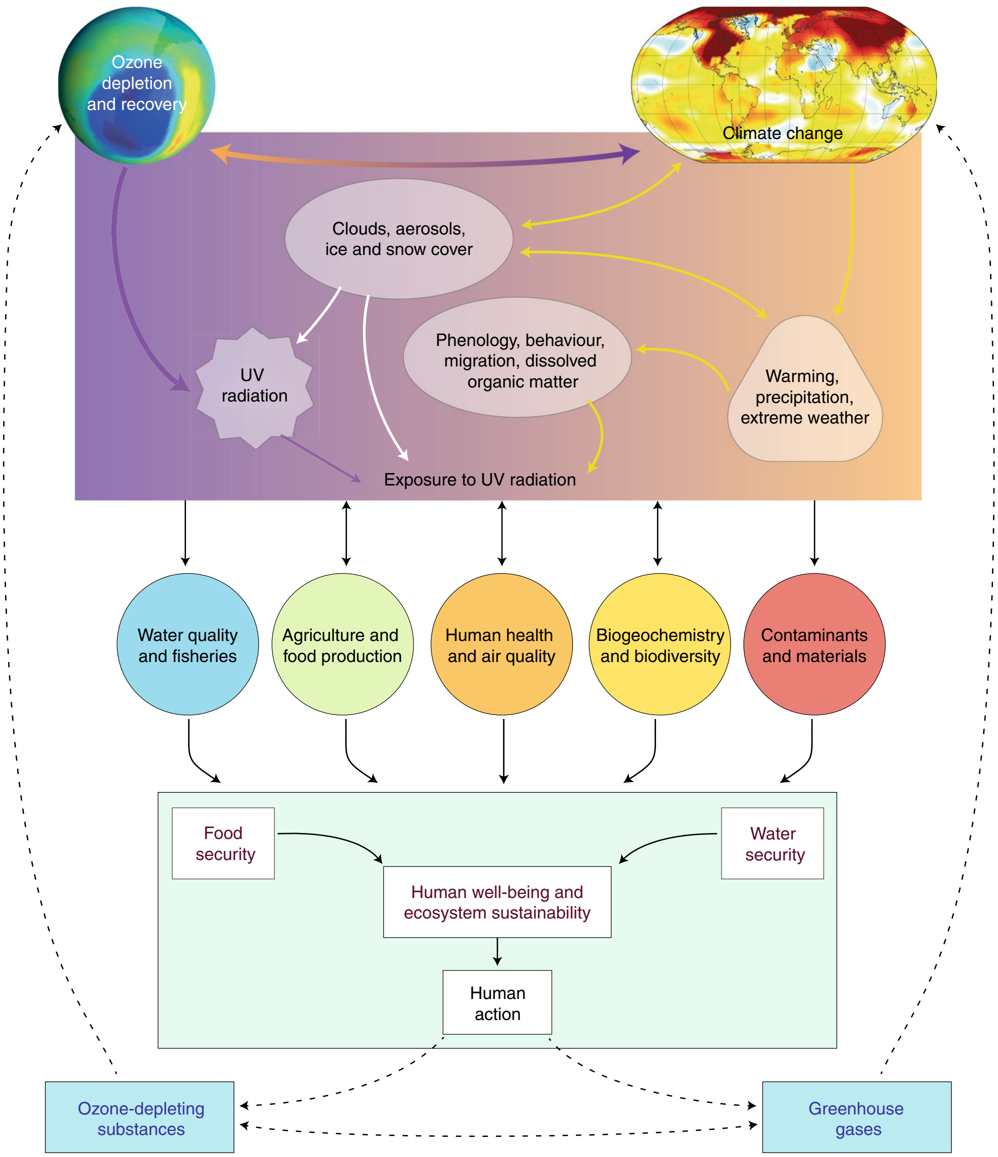


Fig. 2 | Links between stratospheric ozone depletion, UV radiation and climate change. These links have consequences for the environment, food and water security, human well-being and the sustainability of ecosystems. Direct effects are shown as solid lines with feedback effects indicated by double arrows. Important effects driven by human action are shown as dashed lines. The climate change map indicates surface temperature anomalies for February 2017 compared with the base period of 1951–1980[101,102]. The image of stratospheric ozone shows total ozone over Antarctica for 6 September 2000, reproduced from ref. [103], NASA Earth Observatory. Additional information on data used for this image is provided by NASA Ozone Watch[104]. Climate change world map reproduced from refs. [101,102], NASA GISTEMP data.

- Modifications in vegetation cover (for example, from drought, fire, pest-induced die-back of forest canopies or invasion of grasslands by shrubs) driven by changes in climate and land use alter the amount of sunlight and UV radiation reaching many ground-dwelling terrestrial organisms[56].
- Reductions in snow and ice cover and the timing of melt driven by climate change are modifying surface UV reflectance and increasing the penetration of UV radiation into rivers, lakes, oceans and wetlands in temperate, alpine and polar regions[57]. Additionally, increases in extreme weather events (for example, heavy rainfall and floods) lead to greater input of dissolved organic matter and sediments into coastal and inland waters that can reduce the clarity of water and exposure of aquatic organisms to UV radiation[25,58]. In contrast, in some lakes and oceans where climate warming is leading to shallower mixing depths, exposure to UV radiation in the surface mixed layer is increasing[25].

Environmental effects of changing exposure to UV

Changes in exposure to solar UV radiation have the potential to affect materials, humans and many other organisms in ways that have consequences for the health and well-being of people, and the sustainability of ecosystems (Fig. 1). Below we highlight some of these effects as identified in the recent UNEP EEAP Quadrennial Assessment.

Impacts on human health and air quality. Higher exposure to solar UV radiation increases the incidence of skin cancers and other UV-induced human diseases such as cataracts[23]. Although increases in the incidence of skin cancer over the last century seem largely attributable to changes in behaviour that increase exposure to UV radiation, these changes highlight how susceptible some human populations would have been to uncontrolled depletion of stratospheric ozone. Skin cancer is the most common cancer in many developed

Box 3 | Environmental effects of ozone-driven climate change in the Southern Hemisphere

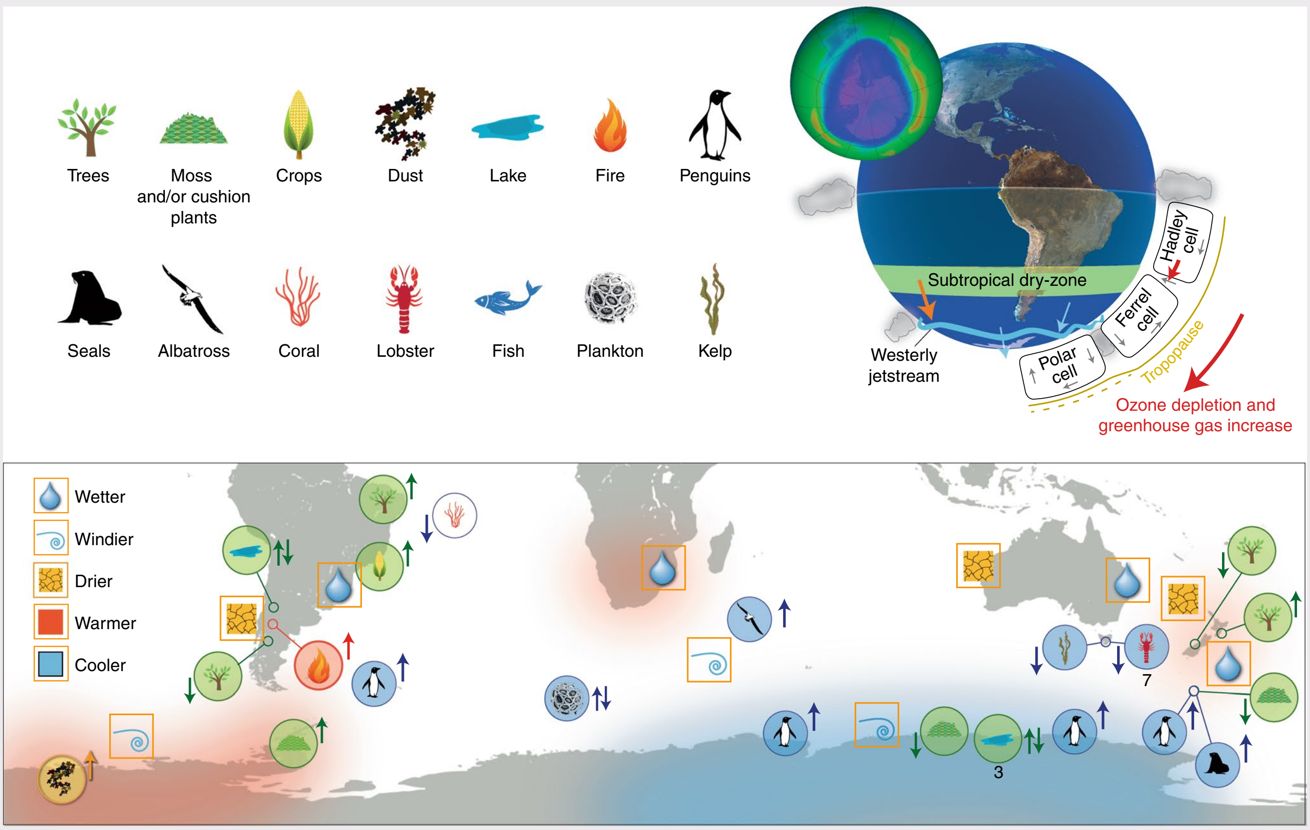
Stratospheric ozone depletion has been a dominant driver of changes in summer climate in the Southern Hemisphere over the later part of the twentieth century, moving the winds and associated latitudinal bands of high and low rainfall further south[29–36,38]. As a result, aquatic and terrestrial ecosystems, including agriculture, have been affected in several ways[24,25].

For instance, the productivity of the Southern Ocean is changing; decreasing over much of the ocean, but increasing in other areas. More productive areas already support increased growth, survival and reproduction of sea birds and mammals including albatross, several species of penguins and elephant seals. Regional increases in oceanic productivity are likely to support increased fisheries. In contrast, warmer sea surface temperatures related to these climate shifts may be correlated with declines in kelp beds in Tasmania and corals in Brazil[25].

On land, changing patterns of rainfall have resulted in increased agricultural productivity in some regions (for example, southeastern South America) and drought conditions in others (for example, Chile)[24]. Drier conditions have resulted in increased salinity in lakes and changed lake fauna in East Antarctica and the eastern Andes[24,25]. On the Antarctic Peninsula, productivity of terrestrial ecosystems has increased with warmer and wetter conditions, whereas productivity in East Antarctica has responded negatively to cooling and drying[37].

Although our understanding of the extent of these impacts has improved considerably in the past several years, there are likely to be many other impacts that have not yet been quantified. Actions under the Montreal Protocol have moderated these climatic and subsequent ecosystem changes, by limiting stratospheric ozone depletion as well as reducing greenhouse gases. Without the Montreal Protocol and its Amendments, similar climatic changes would probably have become manifest across the globe and would have been more extreme in the Southern Hemisphere. As the ozone 'hole' recovers, some of these effects may be reversed.

Icons show the location and types of organisms or environmental factors influenced by ozone-driven climate change, and the arrows show the direction of these effects. Icons reproduced courtesy of Andrew Netherwood. Globe image showing atmospheric circulation patterns and map of Southern Hemisphere adapted from ref. [38], Wiley. Ozone hole over Antarctica, September 2006, courtesy of NASA Ozone Watch.



countries with predominantly light-skinned populations[23]. Melanoma accounts for less than 5% of skin cancers, but it has a much higher mortality rate than other skin cancers and accounts for about 60,000 deaths worldwide each year. Exposure to UV radiation accounts for 60–95% of the risk of developing cutaneous malignant melanoma in light-skinned populations; globally, around 168,000 new melanomas in 2012 were attributable to 'excess' exposure to UV radiation (above that of a historical population with minimal exposure), corresponding to 76% of all new melanoma cases[59]. Stratospheric ozone depletion is expected to increase these numbers by a few percent[60] when integrated over a lifetime. Much larger increases in skin cancer incidence would already be occurring in the absence of the Montreal Protocol[11,13] (Box 2).

Exposure to UV radiation contributes to the development of cataract, the leading cause of impaired vision worldwide (12.6 million were blind and 52.6 million were visually impaired because of cataract in 2015)[61]. This is a major health concern particularly in low income countries with often high ambient UV radiation and limited access to cataract surgery. The role of exposure to UV radiation in age-related macular degeneration, another major cause of visual impairment globally, remains unclear[23].

Concern about high levels of UV-B radiation as a consequence of stratospheric ozone depletion was an important driver for the development of programmes for sun protection in many countries. These programmes focus on promoting changes in behaviour through structural and policy-level interventions[62] and have been highly cost-effective in preventing skin cancers[63]. Behavioural strategies need to be informed by the real-time level of ambient UV radiation (provided by the UV Index) and include controlling time outdoors and the use of clothing, hats, sunscreen and sunglasses to reduce exposure. These changes can be made easier by providing shade in public spaces such as parks, swimming pools, sports fields and playgrounds, and access to sunscreen[62].

Changes in UV radiation and climate can further affect human health by modifying air quality[28]. Several recent international assessments have concluded that poor air quality is the largest global cause of deaths due to environmental factors[28]. Together with nitrogen oxides and volatile organic compounds, UV radiation is a key factor in the formation and destruction of ground-level ozone and some particulate pollutants. Future recovery of stratospheric ozone and changes in climate may alter ground-level ozone via decreases in UV radiation and increases in downward transport of stratospheric ozone[28]. Modelling studies for the United States indicate that reductions in UV radiation due to stratospheric ozone recovery will lead to lower ground-level ozone in some urban areas but slight increases elsewhere[64]. Although these changes in ground-level ozone are estimated to be small (about 1% of current ground-level amounts), large populations are already affected by poor air quality, such that even small relative changes in air quality could have consequences for public health.

Exposure to UV radiation also has benefits for human health, the most well-known being its role in vitamin D synthesis, which is critical to healthy bones, particularly during infancy and childhood. There is also growing evidence of other benefits of exposure to UV and visible radiation in systemic autoimmune diseases (such as multiple sclerosis), non-cancer mortality and in the prevention of myopia[23]. The dose of UV radiation necessary to balance the risks with benefits varies according to age, sex, skin type, and location. Climate change is also likely to alter the balance of risks versus benefits for human populations living in different regions[23,27]. For example, lower ambient UV-B radiation at high latitudes will increase the risk of vitamin D deficiency where this risk is already substantial. Conversely, warmer temperatures may encourage people in cooler regions to spend more time outdoors, increasing exposure to UV-B radiation. Reductions in snow and ice cover could reduce the exposure of the eyes to UV radiation, possibly decreasing the risk of damage to the eyes.

Impacts on agriculture and food production. There is little evidence to suggest that a modest increase in solar UV radiation by itself has had any substantial negative effect on crop yield and plant productivity[24]. It is unclear how food production would have been affected by the large increases in solar UV radiation in the absence of the Montreal Protocol. One analysis, based on data from a number of field studies conducted in regions where stratospheric ozone depletion is most pronounced (that is, high latitudes), concluded that a 20% increase in UV radiation equivalent to about a 10% reduction in stratospheric ozone has reduced plant production by only about 6%[65]. To what extent this relationship would hold for levels of UV radiation more than twice that at present (that is, the 'World Avoided' scenario; Box 2)[11] is uncertain but would have been an obvious concern.

It is likely that by contributing to the mitigation of climate change, the Montreal Protocol and its Amendments have reduced the vulnerability of agricultural crops to rising temperatures, drought and extreme weather events. In some regions of the Southern Hemisphere, changes in rainfall caused by the combined effects of rising greenhouse gases and ozone depletion have been linked to both increases and decreases in plant productivity (Box 3), and these effects may reverse somewhat as the ozone 'hole' recovers. Exposure to UV radiation can also modify how climate change factors, including drought, high temperatures and rising carbon dioxide levels, affect plants, but the effects are complex and often contingent on growth conditions. For example, in some cases, increased UV radiation can reduce the stimulatory effects of elevated carbon dioxide on plant growth[66]. In other cases, exposure to UV radiation can increase tolerance of plants to drought[67]. Increases in ground-level ozone due to reduced UV radiation resulting from the recovery of stratospheric ozone could also negatively affect crop yields[28]. Understanding these and other interactions between UV and climate change can inform growers and breeders about agricultural practices that could aid in maintaining crop yields in the face of evolving environmental change.

UV radiation can also have beneficial effects on plants mediated by specific photoreceptors that regulate plant growth and development[68]. These non-damaging effects include alterations in plant chemistry that can modify the nutritional quality of food[69], as well as plant defences against pests and pathogens[70]. Consequently, conditions that decrease the exposure of crop plants to UV radiation (for example, cloud cover, stratospheric ozone recovery, shifting planting dates or increased sowing densities) could reduce plant defences and thereby affect food security in ways other than just the direct effects on yield[71]. For certain vegetable crops grown in greenhouses and other controlled-environments, UV radiation from lamps is increasingly being used to manipulate plant hardiness, food quality and, in some cases, resistance to pests[72].

Impacts on water quality and fisheries. Climate change is altering the mixing patterns in the water columns of lakes and oceans, with deeper mixed layers in some regions and shallower mixed layers in others. These changes in turn are altering the UV exposure and fundamental structure of aquatic ecosystems and consequently their ecosystem services (for example, water quality, productivity of fisheries) in regionally specific ways[25]. The sensitivity to damage induced by UV radiation for the transparent larvae of many commercially important fish species, combined with the distribution of these larvae in high-UV surface waters, have the potential to reduce juvenile survival and subsequent fisheries' harvests[73]. In contrast, reductions in the transparency of clear-water lakes to UV radiation may increase the potential for invasions of UV-sensitive warm-water species that can negatively affect native species[74].

Climate-change-related increases in heavy precipitation and melting of glaciers and permafrost are increasing the concentration and colour of UV-absorbing dissolved organic matter and particulates[25,26]. This is causing the 'browning' of many inland and coastal waters, with consequent loss of the valuable ecosystem service in which solar UV radiation disinfects surface waters of parasites and pathogens[58]. Region-specific increases in the frequency and duration of droughts have the opposite effect, increasing water clarity and enhancing solar disinfection, as well as altering the depth distribution of plankton that provide critical food resources for fish[44,51].

Impacts on biogeochemical cycles, climate-system feedbacks and biodiversity. Solar UV radiation inhibits primary production in the surface waters of the oceans by as much as 20%, reducing carbon fixation rates in one of the most important biogeochemical cycles on Earth[75,76]. Exposure to solar UV and visible radiation can also accelerate the decomposition of natural organic matter (for example, terrestrial plant litter, aquatic detritus and dissolved organic matter) through the process of photodegradation, resulting in the emission of greenhouse gases including carbon dioxide and nitrous oxide[77,78]. Climate-change-driven increases in droughts, wildfires, and thawing of permafrost soils have the potential to increase photodegradation[26,79], thereby fuelling a positive feedback on global warming; however, the scale of this effect remains an important knowledge gap.

Species of aquatic and terrestrial organisms differ in their tolerances to UV radiation, and these differences can lead to alterations in the composition and diversity of ecological communities under conditions of elevated UV radiation[24,25]. UV radiation also modifies herbivory and predator–prey interactions, which then alters trophic interactions, energy transfer and the food webs in ecosystems[80]. At present, changes in regional climate, caused in part by ozone depletion, are threatening the habitat and survival of a number of species found only in the Southern Hemisphere. These include plants growing in the unique high-elevation woodlands of the South American Altiplano[81], and moss and other plant communities in Antarctica[37]. At the same time, the ozone-driven changes in climate are enhancing the reproductive success of some marine birds and mammals (Box 3)[24,25]. To what extent the Montreal Protocol has specifically contributed to the maintenance of biodiversity in ecosystems is unknown, but losses in species diversity in aquatic ecosystems are known to be linked to high exposure to UV radiation, which can then lead to a decline in the health and stability of these systems[44].

Impacts on contaminants and materials. Solar UV radiation plays a critical role in altering the toxicity of contaminants[25,26]. Exposure to UV radiation increases the toxicity of contaminants such as pesticides and polycyclic aromatic hydrocarbons to aquatic organisms but, more commonly, results in the formation of less toxic breakdown products. For example, UV-B radiation transforms the most toxic form of methyl mercury to forms that are less toxic, reducing the accumulation of mercury in fish[82]. Although the degradation of many pollutants and water-borne pathogens by solar UV radiation is affected by changes in stratospheric ozone, other factors such as dissolved organic matter are more important in regulating penetration of UV radiation into water, and hence photodegradation of these pollutants[26]. Advances in modelling are allowing improved quantification of the effects of global changes on the fate of aquatic pollutants.

Sunscreens are in widespread use, including in cosmetics, as part of the approach to UV protection for humans. They wash into coastal and inland waters, with potential effects on these aquatic ecosystems. The toxicity of artificial sunscreens to corals[83], sea urchins[84], fish[85] and other aquatic organisms, has led Palau, the State of Hawaii and the city of Key West in Florida, USA, to ban the use of some sunscreens. Similar legislation is under consideration by the European Union[86].

Microplastics (defined as plastic particles under 5 mm) are now ubiquitous in the world's oceans and pose an emerging serious threat to marine ecosystems, with many organisms now known to ingest them[87]. Formed by the UV-induced degradation of plastics exposed to sunlight, microplastics occur in up to 20% or more of fish marketed globally for human consumption[88]. Although the toxicity of microplastics is unknown, higher temperatures and increased exposure to UV radiation accelerate the fragmentation of plastics, potentially threatening food and water security.

Until very recently, plastics used in packaging and building materials were selected and optimized on the basis of durability and performance[22]. However, the present focus on increased sustainability, with the trend towards 'green' buildings, now requires such choices to be environmentally acceptable as well. This includes the increased use of wood, which can be renewable, carbon-neutral and low in embodied energy compared with plastics. Many of these materials are vulnerable to accelerated ageing when exposed to UV radiation. At present, industrial activities are aimed at identifying and developing safer, effective and 'greener' additives (colorants, plasticizers and stabilizers) for plastic materials and wood coatings, but continued research and development is required to further combat harsher weathering resulting from climate change.

Some compounds being used as substitutes for CFCs, such as hydrochlorofluorocarbons (HCFCs), HFCs and hydrofluoroolefins (HFOs), are known to degrade to trifluoroacetic acid (TFA) in the atmosphere. TFA is a strong acid, and in sufficiently large concentrations could negatively affect organisms. Because no sinks in the atmosphere have been identified, concern has been raised about its potential accumulation over time in sensitive environments (such as salt lakes, wetlands and vernal pools). Large natural sources of TFA have been invoked to explain high TFA concentrations in deep oceanic waters[89] that have had no contact with atmospheric gases for several millennia. Anthropogenic sources include pesticides, pharmaceuticals and industrial reagents. Current estimates indicate that any incremental TFA burden from the CFC substitutes would be minor compared with the other natural and anthropogenic sources, and the overall TFA concentrations (from all sources) are expected to remain well below levels harmful to the environment[90].

Conclusions and knowledge gaps

The Montreal Protocol has prevented the global depletion of stratospheric ozone and consequently large-scale increases in solar UV-B radiation. Changes in the ozone layer over the next few decades are expected to be variable, with increases (recovery) likely at polar and mid-latitudes and decreases possible in the tropics[12]. The return of total column ozone to 1980 levels is expected to occur in the 2030s and 2050s over mid-latitudes in the Northern and Southern Hemispheres, respectively, and around the 2060s in Antarctica[12,91,92]. Tropical column ozone is not expected to recover to 1980 levels by 2100, with some models predicting declining stratospheric ozone beginning in 2050 at these latitudes[12]. However, these negative ozone deviations are projected to be small (<2%) and would, in the worst-case scenario, result in increases in surface UV-B radiation of less than 2.5%[27]. Thus, because of the Montreal Protocol, we have averted a 'worst-case' scenario of stratospheric-ozone destruction, prevented the resultant high levels of UV-B radiation at the Earth's surface, and so avoided major environmental and health impacts (Box 2).

We are confident in our qualitative predictions of the environmental effects that have been avoided as a result of the implementation of the Montreal Protocol. However, quantification of many of the environmental benefits resulting from the success of the Montreal Protocol remains a challenge. The same knowledge gaps that constrain modelling of most environmental effects in the 'World Avoided' scenario also constrain quantification of the potential impacts of any current or future threats to the ozone layer. At present, no quantitative estimates are available on the effects of the recently reported unexpected increases in emissions of CFC-11[93] on stratospheric ozone, UV radiation or the environment. However, were such unexpected emissions to persist and increase in the future, or new threats emerge, environmental and health impacts could be substantial. Other threats to the integrity of the stratospheric ozone layer include 'geoengineering' activities proposed for combating warming caused by greenhouse gases, which could have consequences for UV radiation. In particular, proposals to inject sulfate aerosols into the stratosphere to reduce solar radiation at the Earth's surface[94] would likely reduce stratospheric ozone at most latitudes. The combined effect of increased scattering by the aerosols and reduced absorption by ozone would then lead to complex net changes in surface UV-B radiation[27,95–97].

Meeting the challenge of improving quantification of the environmental effects of future changes in stratospheric ozone requires addressing several key gaps in current knowledge. First, we need a better understanding of the fundamental responses of humans and other species to UV radiation, particularly how organisms respond to its different wavelengths. Second, we need to understand the full scope of not only the adverse effects (such as skin cancer, impaired vision and unfavourable ecosystem changes), but also the beneficial effects (such as vitamin D synthesis, defence against plant pests and purification of surface waters) of UV radiation on humans and other organisms. Third, we need long-term, large-scale field studies to better understand how changes in UV radiation, together with other climate-change factors, including extreme events, affect intact ecosystems[98]. Taken together, all three would increase our ability to develop models that could be used to quantify the effects of UV radiation on living organisms and materials on scales ranging from individuals to ecosystems to the planet as a whole.

As a consequence of rapid climate change, many organisms, including humans, are being exposed to new and interactive combinations of UV radiation and other environmental factors. These environmental changes will continue into the future and will result in alterations in the structure and composition of ecological communities[99], which will then indirectly affect the growth, reproduction and survival of many species. How humans and ecosystems respond to changes in UV radiation against this backdrop of simultaneous, multi-factor environmental change remains a major knowledge gap. Quantifying these effects is extremely challenging, where many of the outcomes are contingent upon human behaviour and societal responses that are difficult to predict or measure (Fig. 2).

The focus of concern regarding increased exposure to UV radiation has historically been on human health. However, terrestrial and aquatic ecosystems provide essential services on which human health and well-being ultimately depend. In addition to being critical to our well-being, environmental sustainability and the maintenance of biodiversity are also important at a higher level if we are to maintain a healthy planet[100]. The topics covered by the UNEP EEAP Quadrennial Assessment Report embrace the full complexity and inter-relatedness of our living planet, and the outcomes of the Montreal Protocol (and Amendments and Adjustments) demonstrate that globally united and successful actions on complex environmental issues are possible.

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Author contributions

All authors helped in the development and review of this paper. The lead authors P.W.B., C.E.W., R.M.L., S.A.R., S.M. and N.D.P. played major roles in conceptualizing and writing the document. P.W.B. organized and coordinated the paper and integrated comments and revisions on all the drafts. C.E.W., R.M.L., J.F.B., A.F.B., B.S., S.R.W. and A.L.A. provided content with the assistance of S.M., S.A.R., G.H.B., R.L.M., P.J.A., A.M.H., P.J.Y. (stratospheric ozone effects on UV and ozone-driven climate change), R.E.N., F.R.deG., M.N., L.E.R., C.A.S., S.Y., A.R.Y. (human health), P.W.B., S.A.R., C.L.B., S.D.F., M.A.K.J., T.M.R. (agriculture and terrestrial ecosystems), P.J.N., S.H., K.C.R., R.M.C., D.-P.H., S-Å.W., R.C.W. (fisheries and aquatic ecosystems), A.T.A., R.G.Z. (biogeochemistry and contaminants), K.R.S., J.L. (air quality and toxicology) and K.K.P. (materials). R.L.M. conducted the UV simulation modelling.

Competing interests

The authors declare no competing interests.

Additional information

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