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Environmental Effects and Interactions of Stratospheric Ozone Depletion, UV Radiation, and Climate Change. 2018 Assessment Report

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Environmental Effects and Interactions of Stratospheric Ozone Depletion, UV Radiation, and Climate Change. 2018 Assessment Report

Abstract

Executive Summary: Thirty-four years ago, an unprecedented thinning of stratospheric ozone was reported over Antarctica.The risk of a consequent increase in exposure to solar UV-B radiation (UV-B; wavelengths 280-315 nm) raised concerns about potentially disastrous effects on human health and the Earth's environment. In response, the international community mobilised and worked together to understand the causes and find a solution to this dramatic change in the Earth's atmosphere. In 1985, the Vienna Convention for the Protection of the Ozone Layer was signed, which provided the framework for the Montreal Protocol on Substances that Deplete the Ozone Layer, signed in 1987. In these international agreements, the United Nations recognised the fundamental importance of stopping and reversing ozone depletion and preventing its damaging effects. The Montreal Protocol, with its subsequent Amendments and Adjustments, was negotiated to control the consumption and production of anthropogenic ozone-depleting substances. The Parties to the Montreal Protocol base their decisions on scientific, environmental, technical, and economic information provided by three Assessment Panels ...

Keywords

effects, assessment, panel, :, 2018, quadrennial, interactions, environmental, stratospheric, depletion, summary, radiation, climate, change:, uv, executive, ozone

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Executive Summary

Environmental Effects Assessment Panel

2018 Quadrennial Assessment on the interactions of stratospheric ozone depletion, UV radiation, and climate change

Contributions of the Montreal Protocol to a sustainable Earth

P. W. Barnes, C.E. Williamson, R. M. Lucas, S. Madronich, S.A. Robinson, N.D. Paul (Lead Authors), J.F. Bornman, A.F. Bais, B. Sulzberger, S.R. Wilson, A.L. Andrady, P.J. Neale, A.T. Austin, G. Bernhard, R.L. McKenzie, K.R. Solomon, R.E. Neale, P. J. Young, M. Norval, L.E. Rhodes, S. Hylander, K.C. Rose, J. Longstreth, P.J. Aucamp, C. L. Ballaré, R.M. Cory, S.D. Flint, F.R. de Gruijl, D.-P. Häder, A.M. Heikkilä, M.A.K. Jansen, K.K. Pandey, T.M. Robson, C.A. Sinclair, S-Å. Wängberg, R.C. Worrest, S. Yazar, A.R. Young, R G. Zepp

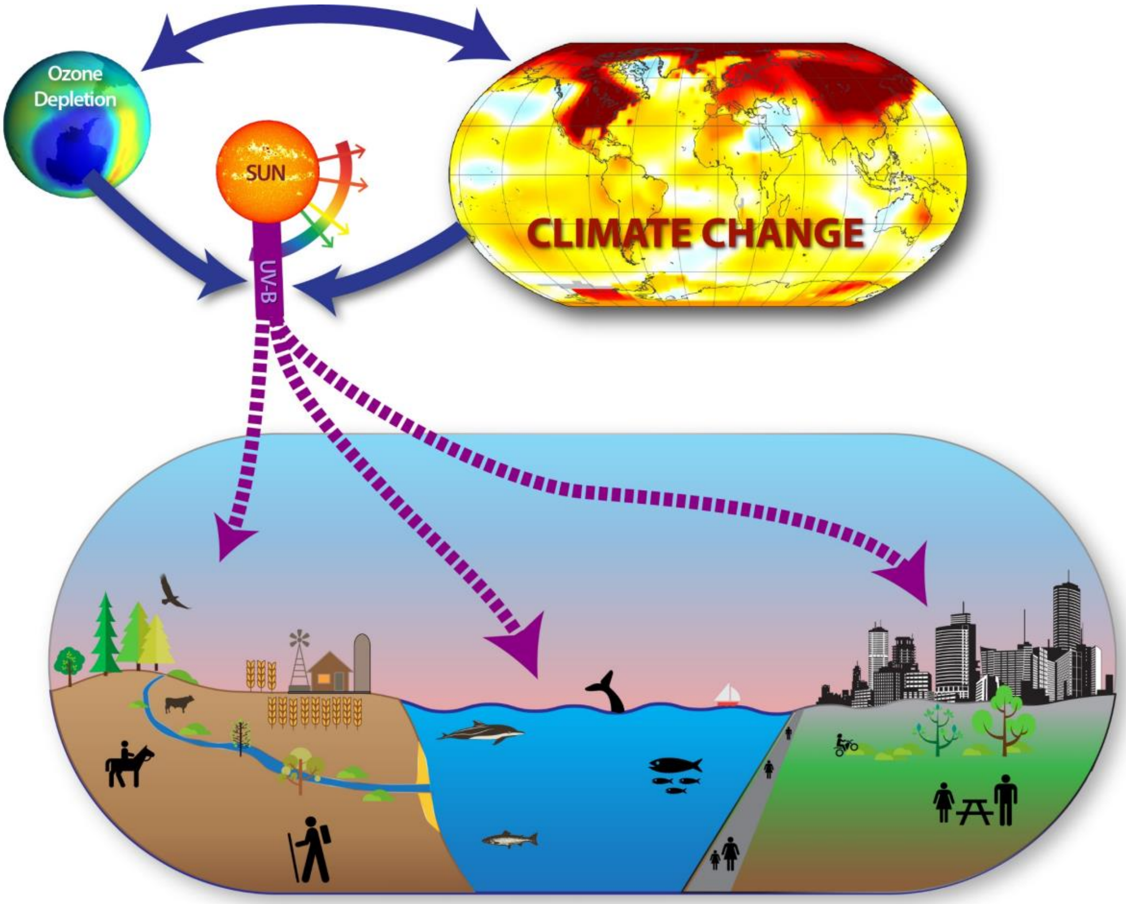

Fig. 1 Linkages between the effects of depletion of stratospheric ozone, climate change, and implications for environment and human health

Stratospheric ozone depletion, the Montreal Protocol, and the Environmental Effects Assessment Panel

Thirty-four years ago, an unprecedented thinning of stratospheric ozone was reported over Antarctica.[21] The risk of a consequent increase in exposure to solar UV-B radiation (UV-B; wavelengths 280–315 nm) raised concerns about potentially disastrous effects on human health and the Earth's environment. In response, the international community mobilised and worked together to understand the causes and find a solution to this dramatic change in the Earth's atmosphere. In 1985, the Vienna Convention for the Protection of the Ozone Layer was signed, which provided the framework for the *Montreal Protocol on Substances that Deplete the Ozone Layer*, signed in 1987. In these international agreements, the United Nations recognised the fundamental importance of stopping and reversing ozone depletion and preventing its damaging effects. The Montreal Protocol, with its subsequent Amendments and Adjustments, was negotiated to control the consumption and production of anthropogenic ozone-depleting substances. The Parties to the Montreal Protocol base their decisions on scientific, environmental, technical, and economic information provided by three Assessment Panels (**Box 1**).

BOX 1. The Environmental Effects Assessment Panel

The Environmental Effects Assessment Panel is one of the three Assessment Panels established by 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 on alternative technologies to replace ozone depleting substances. The Environmental Effects Assessment Panel (EEAP) assesses the full range of potential effects of stratospheric ozone depletion, in conjunction with climate change, on UV radiation at the Earth's surface and consequent effects on human health, aquatic and terrestrial ecosystems, biogeochemical (e.g., carbon, nitrogen, metals, contaminants) cycles, air quality, and materials for construction and other uses. Forty-three scientists from eighteen countries contributed to the 2018 EEAP Quadrennial Assessment.

The implementation of the Montreal Protocol has successfully prevented the global depletion of the stratospheric ozone layer.[94] Concentrations of ozone depleting substances have been declining in the stratosphere since the late 1990s. While significant seasonal ozone depletion over Antarctica has occurred annually since the 1980s (called the "ozone hole"), there have been small, but significant, trends toward higher amounts of total column ozone in Antarctica in spring over the period 2001-2013. Global mean total ozone has been projected to recover to pre-1980s levels by about the middle of the 21st century, assuming full compliance to the Montreal Protocol.[94].

Many of the chemical compounds controlled by the Montreal Protocol are not only ozone depleting substances but also potent greenhouse gases.[53] Modeling studies indicate that, in the absence of the Montreal Protocol, global mean temperatures would have risen by more than 2°C by 2070, due to the warming effects from ozone-depleting substances alone.[25] Furthermore, the adoption of the Kigali Amendment to the Montreal Protocol in 2016 limits the production and consumption of hydrofluorocarbons, powerful greenhouse gases that are used as substitutes to ozone-depleting substances.[64] This amendment has further broadened and strengthened the scope of the Montreal Protocol, creating an effective international treaty that not only addresses stratospheric ozone depletion, but is doing more to protect global climate than any other human actions to date.[11, 60, 83, 96]

One of the important reasons for the success of the Montreal Protocol has been its foundation on high quality science, which not only improves our understanding of the causes and mechanisms of ozone depletion, but also of the potential environmental effects of these atmospheric changes. The Environmental Effects Assessment Panel (EEAP) is specifically charged with providing assessments of the state of the science on the environmental effects of ozone depletion and consequent changes in UV radiation as well as interactions with global climate change (**Box 1**). Because of the direct involvement of the Montreal Protocol in mitigating climate change, as well as the strong physical and biological linkages that exist between the effects of stratospheric ozone depletion and climate change, the Environmental Effects Assessment Panel necessarily addresses the consequences of ozone depletion in the context of a changing global climate.

This Executive Summary presents key findings from the most recent EEAP Quadrennial Assessment and considers the significant societal implications of environmental effects. The multiple ways by which the Montreal Protocol is contributing to environmental sustainability and human health and well-being are highlighted, together with their contribution to, and consistency with, many of the United Nations Sustainable Development Goals (**Box 2**).

BOX 2. The United Nations Sustainable Development Goals (SDGs) addressed by the 2018 Quadrennial Assessment of the Environmental Effects Assessment Panel

Our findings address the following UN Sustainable Development Goals (SDG): **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*. More information on these SDGs can be found at: https://www.un.org/sustainabledevelopment/sustainable-development-goals/

In-depth information on stratospheric ozone depletion and its environmental effects can be found in the full Assessments published by the Ozone Secretariat of the United Nations Environment Programme (https://ozone.unep.org) and elsewhere (Photochemical & Photobiological Sciences journal).[2, 6, 10, 46, 75, 90, 93] By focusing on the interacting effects of stratospheric ozone dynamics, UV radiation, and climate change, the report from the Environmental Effects Assessment Panel complements that of the Intergovernmental Panel on Climate Change (https://www.ipcc.ch; summarised in ref.[59]) to provide a comprehensive assessment of the environmental effects of these global changes in the Earth's atmosphere.

KEY FINDINGS AND HIGHLIGHTS

1 Stratospheric ozone, climate change, and UV radiation at the Earth's surface

Depletion of stratospheric ozone leads to increased UV-B radiation at the Earth's surface (Chapter 1). However, because of the success of the Montreal Protocol,[94] present-day increases in UV-B radiation due to stratospheric ozone depletion have been negligible in the tropics, small (5-10%) at mid-latitudes (30-60°), and large only in polar regions. With the predicted recovery of stratospheric ozone over the next several decades, the clear-sky noontime UV Index[a] is expected to decrease at all latitudes outside the tropics, with the greatest decreases over Antarctica (Chapter 1 and refs[6, 52]) New projections of the UV Index for the end of the 21st century relative to the current decade suggest a decrease by 35% over Antarctica, and up to 6% over mid-latitudes (Chapter 1 and refs[6, 52] These future projections are, however, uncertain because stratospheric ozone levels will be controlled not only by decreasing ozone depleting substances, but also by climate change due to increases in greenhouse gases for the rest of the 21st century.

Future changes in surface solar UV radiation of all wavelengths will depend on changes in clouds, aerosols, and surface reflectivity (e.g., from snow and ice cover) (**Fig. 2**). Climate change is altering cloud cover, with some regions becoming cloudier and others less cloudy.[73] Increased cloud cover generally tends to reduce UV radiation at the Earth's surface, but effects vary, for example, with the type of clouds.[40] Aerosols (solid and liquid particles suspended in the atmosphere (Chapter 6) reduce and scatter UV radiation. The type and amounts of aerosols in the atmosphere are affected by the emissions of air pollutants, volcanic activity, as well as the frequency and extent of wildfires and dust storms, and many other factors that are being affected by climate change (Chapters 1, 5, and refs[6, 75, 91]). In heavily polluted areas (e.g., in southern and eastern Asia), expected improvements in air quality are predicted to result in levels of UV radiation increasing towards pre-industrial levels (i.e., before the occurrence of extensive aerosol pollution), with the extent of changes contingent on curtailing the emissions of air pollutants.

High surface reflectance from snow or ice cover can enhance incident surface UV radiation because some of the reflected UV radiation is scattered back to the surface by air molecules, aerosols, and clouds in the atmosphere.[35] However, climate change-driven reductions in ice or snow cover in polar regions and mountains reduce the reflection of UV radiation from the Earth's surface and thus may reduce above-ground UV radiation in these regions (Chapter 1).

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[a] UV Index is an international standard measure of the strength of sunburn-producing UV radiation at a particular place and time.

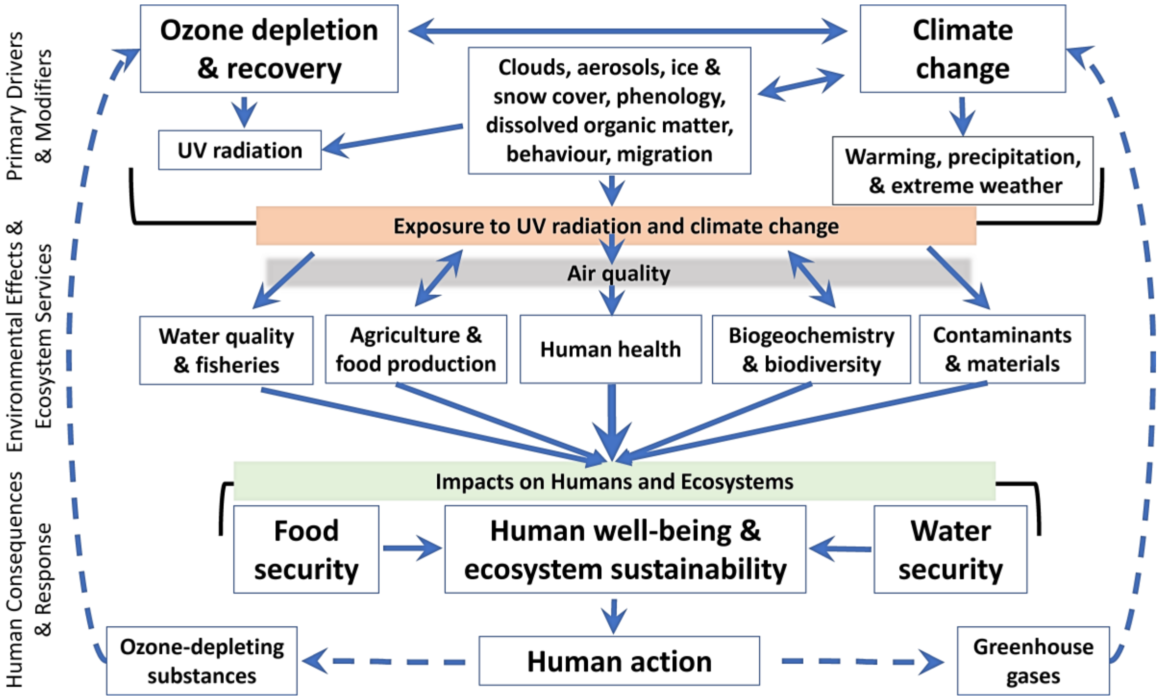


Fig. 2 Linkages between stratospheric ozone depletion, UV radiation, and climate change, including environmental effects and potential consequences for human well-being, food and water security, and the sustainability of ecosystems (solid lines), with important feedback effects driven by human action (double-arrow solid lines) and other processes (dashed lines).

1.1 Exposure to UV radiation and effects of climate change on exposure

The effect of UV radiation on organisms (including humans), natural organic matter, contaminants and materials depends on their exposure to the radiation (**Fig. 2**). This is determined by several factors besides stratospheric ozone depletion, including the effects of global climate change (Chapters 1 and 5, and refs[6, 75, 92]). Unlike stratospheric ozone depletion, these climate change-driven effects modify exposure not just to UV-B radiation but also to solar radiation in the ultraviolet-A (UV-A; 315-400 nm) and visible (400-700 nm) parts of the solar spectrum. These changes are important as many of the environmental and health effects caused by exposure to UV-B radiation are also influenced, to varying degrees, by UV-A and visible radiation (Chapters 2, 3, and 4).

For human health, behaviour is an important regulator of exposure to UV radiation. The exposure of individuals to UV radiation varies from one-tenth to ten times the average for the population,[26] depending on the time people spend indoors *vs* outdoors and under shade structures. The exposure of the skin or eyes further depends on the use of sun protection such as clothing or sunglasses. Warming temperatures and changing precipitation as a result of climate change will alter human behaviours in relation to sun exposure,[95] but the direction and magnitude of effect is likely to be highly variable across the globe. The dose of UV radiation to biological structures in the skin is mediated by skin pigmentation, with darker skin providing significant protection against skin cancers. If humans are displaced, for example, due to climate-change induced sea-level rise,[70] (e.g., darker-skinned people moving from low to higher latitudes) they will encounter conditions of UV radiation that may be different to those to which they are accustomed.

Vegetation cover modifies the amount of sunlight reaching many terrestrial organisms e.g.,[63] and shading influences the exposure of construction materials to UV radiation. Modifications of that cover, for example, as a result of drought, fire, and pest-induced die-back of forest canopies induced by climate change will have profound effects on the exposure of terrestrial organisms to UV radiation.e.g.,[63] In addition, shifts in the seasonal timing of critical life cycle events such as plant flowering, spring bud-burst in trees, and animal emergence and breeding[15, 22, 77] will change exposure to UV radiation as UV radiation naturally varies with season.

As plants and animals move poleward,[22] into higher elevations,[72] or deeper into lakes, and oceans[81] in response to climate change, they are exposed to conditions of UV radiation that may be different to those to which they are adapted. Furthermore, reductions in ice or snow cover in polar regions as a result of global warming will increase the exposure to UV radiation of soils and aquatic ecosystems that would previously have been below the snow or ice.[35]

The penetration of UV radiation into aquatic ecosystems depends on the transparency of water, the amount of dissolved organic matter, and ice cover.[89, 91]. Increases in extreme weather events that increase the input of dissolved organic matter and sediments into coastal and inland waters can reduce water clarity, reducing exposure of aquatic ecosystems to UV radiation.[89, 91] Reductions in the thickness and duration of snow and ice cover and global changes in the depth of the warmer, surface mixed layers of lakes and oceans, are altering the levels of exposure of aquatic organisms to UV radiation (Chapter 4). Previously, climate change was expected to increase exposure to UV radiation by causing shallower mixed layers, but new data show deeper mixed layers in lakes and oceans in some regions and shallower mixed layers in others (Chapter 4).

These climate change-driven effects can result in either increases or decreases in exposures to solar UV radiation, depending on location, time of year, individual species, and other circumstances. Changes in exposure and sensitivity to solar UV radiation, driven by ongoing changes in stratospheric ozone and climate, have the potential to affect humans, life on Earth and the environment, including materials used in infrastructure and for other purposes, with consequences for the health and well-being of people and ecosystem sustainability. Some of these effects are highlighted below. These findings, together with others described in the current Quadrennial Assessment of 2018, address 11 of the 17 United Nations Sustainable Development Goals (**Box 2**).

2 Consequences of changing exposure to UV radiation on humans and the environment

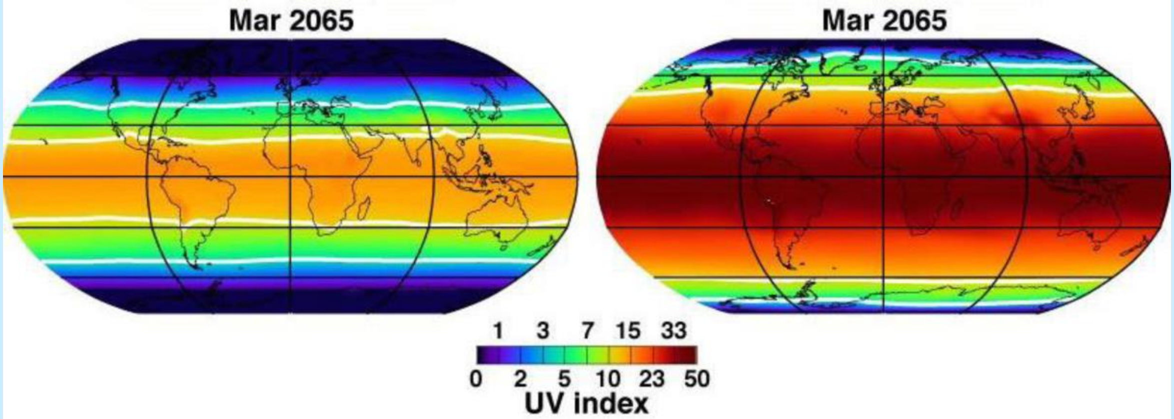
2.1 Effects on human health

Higher exposure to UV radiation increases the incidence of skin cancers and other UV-induced human diseases, such as cataracts and photosensitivity disorders (Chapter 2). Increases in the incidence of skin cancer over the last century appear largely attributable to changes in behaviour that increase exposure to UV radiation; these changes highlight how susceptible human populations are to higher exposure to UV radiation, as would have occurred with uncontrolled depletion of stratospheric ozone. Skin cancer is the most common cancer in many developed countries with predominantly light-skinned populations (Chapter 2). For example, there are over 90,000 new skin cancers compared with *ca* 3000 new cases of colorectal cancer in New Zealand each year. Skin cancer is also the most expensive cancer in many of these countries (Chapter 2). The estimated cost of treating cutaneous malignant melanoma in the USA was estimated at *ca* USD 457 million in 2011 and predicted to increase to *ca* USD 1.6 billion in 2030.[28] Exposure to UV radiation accounts for 60-96% of the risk of developing cutaneous malignant melanoma in light-skinned populations. It is estimated that *ca* 168,000 new melanomas in 2012 were attributable to 'excess' exposure to UV radiation (above that of a historical population with minimal exposure), as a result of population changes in lifestyle, from sun avoidance to sun-seeking behaviour.[4] Modelling studies show that implementation of the Montreal Protocol has avoided devastating effects on human health, including large increases in skin cancer incidence in light-skinned populations, resulting from high levels of UV radiation (e.g., UVI > 40 in the tropics by 2065.[54]) **(Box 3)**.

BOX 3. Environmental effects in the 'world avoided'

This assessment focusses largely on the environmental effects of changes in stratospheric ozone that have occurred, and are predicted to occur, due to the effective implementation of the Montreal Protocol and its Amendments. At present, lack of relevant research has prevented us from more fully assessing the health and environmental impacts that would have resulted if the stratospheric ozone layer had not been protected by actions of the Montreal protocol. However, it is worth noting that current understanding of this 'world avoided', provides the context for the effects observed with the successful implementation of the Montreal Protocol.

Several modelling studies reported changes in the stratospheric ozone layer that would have occurred without the Montreal Protocol, i.e., in a 'world avoided' scenario (for example,[55]). 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. This collapse in global stratospheric ozone would have resulted in UV Index values above the current extreme of 25 becoming common-place over almost all inhabited areas of the planet, and as high as 40 in the tropics, nearly five times the UV Index that is currently considered 'extreme' by the World Health Organization. Illustrated below is the comparison of the predicted UV Index (UVI; left) with that of the 'world avoided' (right) (from ref.[54]).



Combining these models of stratospheric ozone and UV radiation with understanding of the links between exposure to excessive UV radiation and the risk of skin cancers has allowed some quantitative estimates of the incidence of skin cancer in the 'world avoided'. Although different studies have considered different time-scales and/or different geographical regions, the successful implementation of the Montreal Protocol has prevented many millions of cases of skin cancers. For example, a report by the United States Environment Protection Agency,[82] showed that when compared with a situation of no policy controls, full implementation of the Montreal Protocol and its Amendments has avoided more than 250 million cases of skin cancer in the USA alone. The same report estimates that the Montreal Protocol will have prevented more than 45 million cases of cataracts in the USA. Substantial gaps in our knowledge currently limit our ability to quantitatively assess the full range of human and environmental benefits of the successful implementation of the Montreal Protocol.

Exposure to UV radiation contributes to the development of cataract, the leading cause of vision impairment globally (12.6 million blind and 52.6 million visually impaired due to cataract in 2015).[23] Particularly in low-income countries – often with high ambient UV radiation – access to cataract surgery may be limited, making this not only a major health concern but a major source of loss of livelihood and economic damage. The role of exposure to UV *vs* visible radiation in age-related macular degeneration remains unclear. Nevertheless, in aging populations worldwide, this is a major cause of visual impairment that currently has limited treatment options. Understanding risk factors and thus potential prevention is of critical importance (Chapter 2).

Concern about high levels of UV-B radiation because of stratospheric ozone depletion was an important driver for the development of programs for sun protection in many countries. These programs focus on promoting changes in people's behaviour, supported by structural and policy-level interventions.[68] Sun protection programs have been shown to be highly cost-effective in preventing skin cancers.[27] Behavioural strategies need to be informed by the real-time level of ambient UV radiation (provided by the UVI) and include controlling time outdoors together with using clothing, hats, sunscreen and sunglasses to reduce exposure to UV radiation. Behavioural changes can be facilitated by providing shade in public spaces such as parks, swimming pools, and schools, and improving access to sunscreen.[68]

Exposure to UV radiation also has benefits for human health. For example, exposure of the skin to UV radiation results in the production of vitamin D and is the major source of this vitamin for much of the world's population. Vitamin D is critical to healthy bones, particularly during infancy and childhood. There is also growing evidence of a range of other benefits of exposure to UV radiation through both vitamin D and non-vitamin D pathways; for example, for systemic autoimmune diseases (such as multiple sclerosis),[45] in the prevention of myopia (short sightedness; Chapter 2), and reducing non-cancer mortality.[43] Recent research suggests that the benefits for reduced mortality may be substantial.[44]

Gaps in our knowledge prevent calculations of the amount of UV radiation necessary to balance the risks with benefits, particularly as this likely varies according to age, sex, skin type, and location. Projected changes in climate will alter the balance of risks *vs* benefits for human populations living in different regions. 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 not just UV-B radiation, but all wavelengths of solar radiation, and related risks of skin cancer and cataract (Chapter 2).

2.2 Effects on air quality

UV radiation drives photochemical reactions of many emitted chemical compounds, generating secondary pollutants, including ground-level ozone and some types of particulate pollutants. Future recovery of stratospheric ozone and climate may change ground-level ozone via decreases in UV radiation and increases in downward transport of stratospheric ozone (Chapter 6), with important consequences for human health and the environment. Modelling studies for the USA indicate that reductions in UV radiation due to stratospheric ozone recovery will lead to decreased ground-level ozone in some urban areas but slight increases elsewhere.[30]

Changes in UV radiation and climate can have major impacts on human health by affecting air quality (Chapter 6). A number of recent international assessments have concluded that poor air quality is a significant global health issue and is estimated to be the largest cause of deaths globally due to an environmental factor; for example, exposure to fine particulate matter ($PM_{2.5}$) caused 4.2 million deaths in 2015.[14] Because large populations are already affected by poor air quality, even small relative changes in UV radiation can have significant consequences for public health.

2.3 Effects on agriculture and food production

There is little evidence to suggest that modest increases in solar UV radiation have any substantial negative effect on crop yield and plant productivity (Chapter 3). How food production would have been impacted by large increases in solar UV radiation in the absence of the Montreal Protocol is unclear. One analysis, based on data from a number of field studies conducted in regions where stratospheric ozone depletion is most pronounced (i.e., high latitudes), concluded that a 20% increase in UV radiation equivalent to a 10% reduction in stratospheric ozone would reduce plant production by only about 6% (i.e., a 1% reduction in growth for every 3% increase in UV radiation).[7] To what extent this relationship would hold for levels of UV radiation > 2-fold higher than present (i.e., the "world avoided" scenario (Box 3)) is uncertain and represents an important knowledge gap.

It is likely that by contributing to the mitigation of climate change through phasing out of the ozone depleting substances and some of their substitutes that increase global warming, the Montreal Protocol has reduced the vulnerability of agricultural crops to rising temperatures, drought, and extreme weather events.[3] It is now clear that ozone depletion in the southern hemisphere is altering regional atmospheric circulation patterns in this part of the globe[94] which, in turn, affect weather conditions, sea surface temperatures, ocean currents, and the frequency of wildfires.[13, 31, 38, 41, 58] At a regional scale, increases in rainfall in the southern hemisphere, driven by stratospheric ozone depletion and climate change, have been linked to increases in agricultural productivity in South America (**Box 4**); however, these beneficial effects may reverse as the stratospheric ozone 'hole' recovers. In the northern hemisphere, similar, but smaller, effects of stratospheric ozone depletion on climate may be occurring (Chapter 1), but there are no reports as yet linking these changes to environmental effects.

Climate change factors including drought, high temperatures, and rising carbon dioxide levels can modify how UV radiation affects crop plants, but effects are complex and often contingent on growth conditions. In some cases these factors can increase sensitivity to UV radiation (e.g., elevated carbon dioxide can weaken defenses against UV radiation in maize.[87] In other cases, exposure to UV radiation can alter the effects of climate change, such as increasing the tolerances of crop plants to drought.[67] Reduced UV radiation resulting from the recovery of stratospheric ozone may lead to increases in ground-level ozone in rural areas that could negatively affect crop yields (Chapter 6). Understanding these, and other, UV-climate change interactions can inform growers and breeders as to relevant agricultural practices for maintaining crop yields in the face of evolving environmental change.

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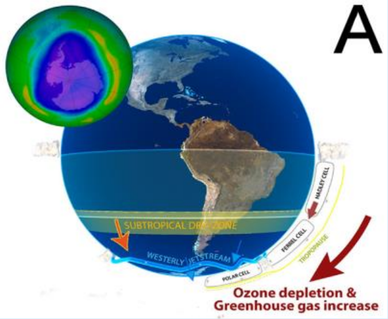
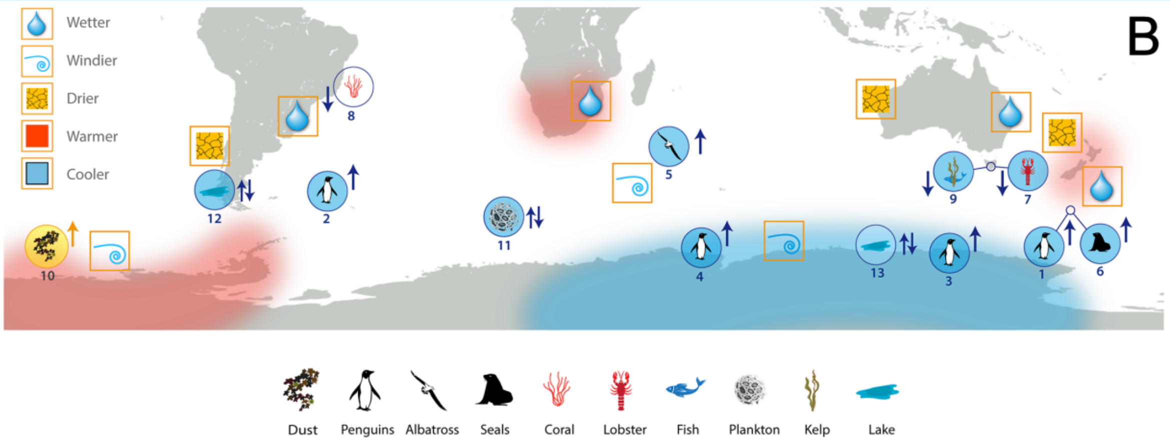
BOX 4. Environmental effects of ozone-driven climate change in the southern

hemisphere.

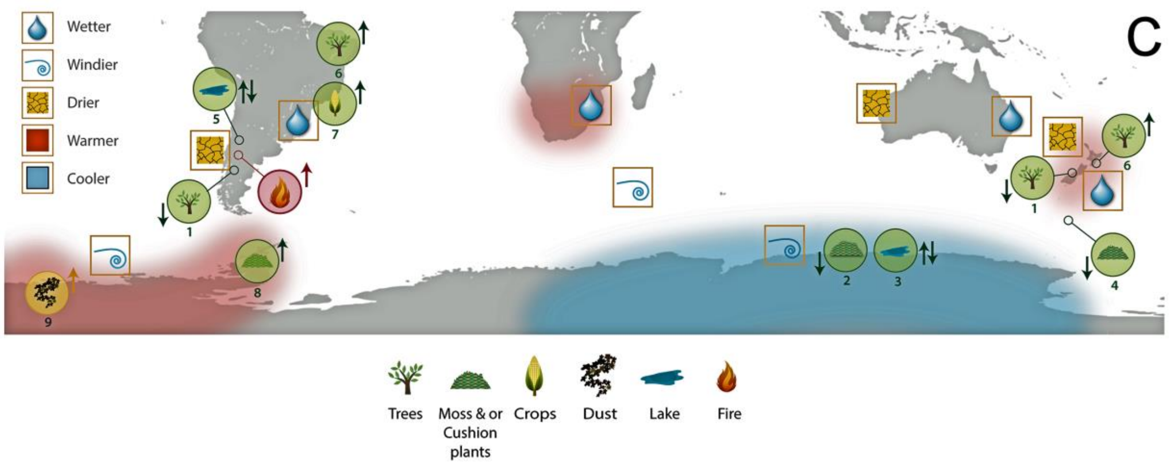


Stratospheric ozone depletion and increases in greenhouse gases have both had measurable impacts on southern hemisphere climate, moving the winds and associated latitudinal bands of high and low rainfall further south (**A**). As a result, aquatic and terrestrial ecosystems, including agriculture, have been affected in several ways (**B**). For instance, the productivity of the Southern Ocean is changing, decreasing over much of the ocean, but increasing in other areas with corresponding changes in carbon dioxide uptake from the atmosphere.



Arrows indicate direction of effects on biodiversity, up = positive, down = negative effects, two-way arrows indicate changed biodiversity.

On land, changing rainfall patterns have resulted in increased agricultural productivity in some regions and drought conditions in others (**C**). Drier conditions have resulted in increasing salinity in lakes and changed lake fauna in East Antarctica and the eastern Andes.



Arrows indicate direction of effects on biodiversity, up = positive, down = negative effects, two-way arrows indicate changed biodiversity.

UV radiation can also have beneficial effects on plants and these effects are often mediated by specific photoreceptors that act to regulate plant growth and development.[34] These non-damaging effects include alterations in plant chemistry that then lead to changes in the nutritional quality of food[74] and plant resistance against pests and pathogens.[20] Consequently, decreases in exposure to UV radiation as a result of changes in stratospheric ozone and climate or changing agricultural practices (e.g., planting dates or sowing densities), may reduce plant defenses and thereby affect food security in ways other than just the direct effects on yield.[8] For certain vegetable crops, UV radiation is increasingly being used to manipulate plant hardiness, food quality and pest resistance.[85]

2.4 Effects on water quality and fisheries

Changes in exposure to UV radiation and mixing depths are altering the fundamental structure of aquatic ecosystems and consequently their ecosystem services (e.g., water quality, fisheries productivity) in regionally-specific ways. The larvae of many commercially important fish species are clear-bodied and sensitive to damage induced by UV radiation. This sensitivity, combined with the distribution of these larvae in surface waters with high exposure to UV radiation, has the potential to reduce the survival of first-year fish and subsequent harvest potential for fisheries.[32] 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.[79]

Heavy precipitation and melting of glaciers and permafrost associated with climate change are increasing the concentration and colour of UV-absorbing dissolved organic matter and particulates (Chapters 4 and 5). This is leading to 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.[89] 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 provides critical food resources for fish.[81, 91]

2.5 Effects on biogeochemical cycles, climate system feedbacks, and biodiversity

Changes in stratospheric ozone and climate affect biogeochemical cycles driven by sunlight and, in turn, greenhouse gases and water quality. Exposure to solar UV and visible radiation can accelerate the decomposition of natural organic matter (NOM, e.g., terrestrial plant litter, aquatic detritus, and dissolved organic matter), and the transformation of contaminants (see section 2.6). Photodegradation of NOM results in the emission of greenhouse gases including carbon dioxide and nitrous oxide.[5, 17] Increases in droughts, wildfires, and thawing of permafrost soils driven by climate change have the potential to increase photodegradation (for example,[1]), thereby fueling a positive feedback on global warming; however, the scale of this effect remains an important knowledge gap (Chapter 5).

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 (Chapters 3 and 4). UV radiation also modifies herbivory and predator-prey interactions, which then alter trophic interactions, energy transfer, and the food webs in ecosystems.[42] Presently, ozone-driven changes in regional climate in the southern hemisphere[3, 13, 31, 38, 39, 41, 58, 65] are threatening the habitat and survival of a number of species that grow in the unique high-elevation woodlands of the South American Altiplano[19] as well as for mosses and other plant communities in Antarctica,[66] but enhancing reproductive success of some marine birds and mammals (ref.[86], Box 4). 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 and can cause declines in the health and stability of ecosystems and the services they provide to humans.[91]

2.6 Effects on contaminants and materials

Escalating releases of contaminants into the environment combined with changes in climate and stratospheric ozone impact human health and terrestrial and aquatic ecosystems.

UV radiation is one of the key factors that influences the biogeochemical cycling of contaminants and their degradation via direct and indirect photoreactions. However, effects of climate change, such as heavy precipitation events or droughts also have large impacts on the photodegradation of contaminants by decreasing or increasing their exposure to solar UV radiation. Moreover, increased or decreased runoff of coloured dissolved organic matter affects the balance between direct and indirect photoreactions in aquatic ecosystems (Chapter 5). These effects of climate change depend on local conditions, posing challenges for prediction and management of contaminant effects on human health and the environment.

Exposure to UV-B radiation plays a critical role in altering the toxicity of contaminants (Chapters 4 and 5). Exposure to UV radiation increases the toxicity of contaminants such as pesticides and polycyclic aromatic hydrocarbons (PAHs) to aquatic organisms such as fish and amphibians. In contrast, exposure to UV-B radiation transforms the most toxic form of methylmercury to forms that are less toxic, reducing the accumulation of mercury in fish. However, potential long-term increases in dissolved organic matter will decrease underwater exposure to UV radiation in inland waters in some regions, such as southern Norway. This may then contribute to the already observed increases in methylmercury in fish that would likely occur as a consequence of reduced water transparency to UV radiation.[62] Solar radiation also plays a major role in the degradation of many organic pollutants and water-borne pathogens (Chapter 5). This process of photodegradation by solar UV radiation may be affected by changes in stratospheric ozone, but other factors such as dissolved organic matter are more important in regulating underwater UV radiation and so have a greater effect on photodegradation (Chapter 5). Advances in modeling approaches 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 suite of approaches to sun protection for humans. However, it is now recognised that sunscreens wash into coastal waters, with potential effects on aquatic ecosystems. The toxicity of artificial sunscreens to corals,[78] sea urchins,[16] fish,[24] and other aquatic organisms, has led the state of Hawaii, USA, to pass legislation banning the use of some sunscreens, and the European Union to consider similar legislation.[88]

Microplastics (plastic particles < 5mm) 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.[12] Microplastics are formed by the UV-induced degradation and breakdown of plastic products and rubbish exposed to sunlight. Microplastic pollutants occur in up to 20% or more of fish marketed globally for human consumption.[80] Although the toxicity of microplastics and smaller nanoplastics is unknown, higher temperatures and levels of UV radiation accelerate the fragmentation of plastics, potentially threatening food security.

Exposure to solar UV radiation damages the functional integrity and shortens the service lifetimes of organic materials used in construction, such as plastics and wood that are routinely exposed, e.g., in roofing and pipelines (Chapter 7). Until very recently, plastics used in packaging and building were selected and optimised on the basis of durability and performance (Chapter 7). However, the present focus on increased sustainability, for example, the trend towards ‘green buildings’, now requires such choices to be environmentally acceptable as well. This includes the increased use of wood, which is renewable, carbon-neutral and low in embodied energy, in place of plastics, where appropriate. Some of these materials are vulnerable to accelerated aging under exposure to UV radiation. Current efforts are moving forward to identify and develop novel, safer, effective, and ‘greener’ additives (colourants, plasticisers, and stabilisers) for plastic materials and wood coatings. Harsher weathering climates, as predicted due to climate change, would require even more effort along this direction.

Trifluoracetic acid (TFA), a substance regulated under the Montreal Protocol, is produced naturally and commercially. There are multiple anthropogenic sources that will release trifluoroacetic acid (TFA) into the environment. Sources relevant to the Montreal Protocol include the substitutes for CFCs, the HCFCs, HFCs, and HFOs. These chemicals are known to degrade to TFA in the atmosphere (**Fig. 3**; **Box 5**) but contribute to only a slight increase in TFA concentrations in surface water. This is not expected to pose a risk to humans or the environment.[71]

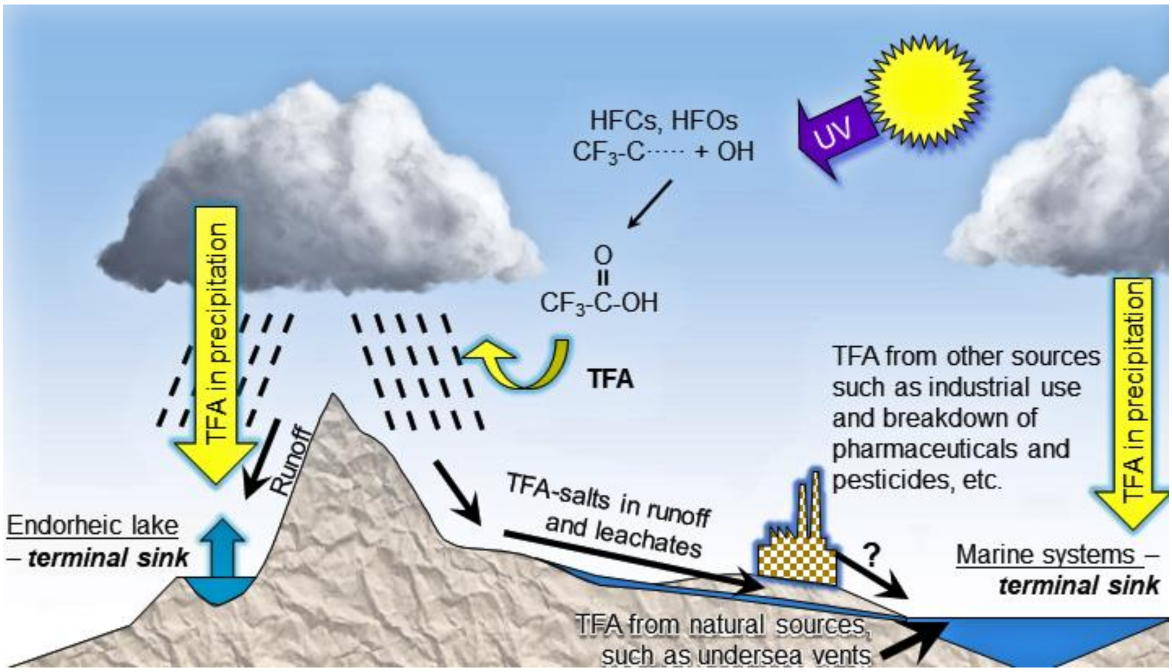


Fig. 3 Trifluoracetic acid (TFA) formed from HFCs and HFOs in the atmosphere will rapidly partition from air to water in the atmosphere. It will combine with cations in soil and surface water and accumulate in endorheic water bodies (salt lakes) and the oceans (modified from ref.[71], with permission).

BOX 5. The environmental effects of replacements for ozone depleting substances

One of the advantages of chlorofluorocarbons (CFCs) was that they were inert in the lower atmosphere and had no direct impact on air quality. Their replacements have been specifically chosen to be less stable, and since these compounds are directly relevant to the implementation of the Montreal Protocol, their impacts on air and environmental quality need to be considered. Focusing on refrigeration, these replacements include hydrofluorocarbons (HFCs) and hydrofluoroolefins (HFOs), hydrocarbons and ammonia.

BOX 5. Continued

HFCs and HFOs

Trifluoracetic acid (TFA) is a persistent substance that is formed in the atmosphere from several HCFCs, HFCs, and HFOs. There are also many other sources of TFA in the environment, but since they are unregulated, there are virtually no data on global production and release to the environment.[69] HFCs degrade slowly in the atmosphere (1-100 years) and so become globally distributed. By contrast, HFO-1234yf degrades to TFA rapidly (days - weeks). As a result, breakdown will occur closer to the regions where HFO-1234yf is released. This potential results in localised, higher concentrations of TFA in surface waters than from HFCs.[36, 47, 84] Even so, there is no evidence to date to suggest that these local depositions of TFA will result in risks to the environment, especially when eventual dilution occurs in the oceans.

Estimates of production of TFA in China, the USA, and Europe[84] and assuming no dilution, would be several orders of magnitude less than the chronic “no observable effect concentration” (NOEC) of 10,000,000 ng L^{-1} for TFA-Na salt from a microcosm study.[29]

Overall, there is no new evidence that contradicts the conclusion of our previous Assessments that exposure to current and projected concentrations of salts of TFA in surface waters present a minimal risk to the health of humans and the environment. A recent review of this topic [56] reached a similar conclusion.

Hydrocarbons

The release of hydrocarbons (such as propane and n-butane) used as ODS replacements will add to the burden of hydrocarbons in the atmosphere, and potentially increase the concentration of ground-level ozone.

There are few estimates of the effects of emissions of hydrocarbon refrigerants on air quality in the refereed literature. One recent assessment for three cities in the USA[37] highlights current uncertainty, providing a “worst case” increase in tropospheric ozone of around 13 µg m^{-3}, but a realistic estimate of 0.3 µg m^{-3}. These figures compare with a current annual peak tropospheric ozone concentration greater than 120 µg m^{-3}(Chapter 6).

Ammonia

Ammonia in the atmosphere reacts with several compounds to produce aerosols and hence increase concentrations of particulate air pollutants ($PM_{2.5}$). However, full replacement of current emissions of CFCs, HCFCs, and HFCs by ammonia (estimated to total 170,000 tonnes per annum: G. Velders, personal. comm., Feb. 2018; (Chapter 6) is small compared to estimated annual ammonia emissions from agriculture (34,500,000 tonnes,[9]) or from industrial and residential activities (8,500,000 tonnes,[49]).

3 Conclusions and knowledge gaps

The Montreal Protocol has been successful in preventing the global depletion of stratospheric ozone and consequently large-scale increases in solar UV-B radiation and has therefore prevented major adverse impacts on human health and the environment (**Box 3**).

We remain confident in our qualitative predictions of the effects on human health and the environment that have been avoided largely because the Montreal Protocol has successfully controlled stratospheric ozone depletion. However, quantification of many of the benefits deriving from the success of the Montreal Protocol remains a major challenge, and the future trends in UV radiation exposure remain uncertain considering climate change and the extent of human response.

Unexpected increases in emissions of CFC-11 that were recently reported[51] are currently expected to have only small effects on stratospheric ozone depletion,[94] and therefore also on human health or the environment. However, were such unexpected emissions to persist and increase in the future, or new threats emerge, effects on human health and the environment could be substantial. New threats might include "geoengineering" activities proposed to combat the warming caused by greenhouse gases,[33] which could have consequences for UV radiation reaching the Earth's surface. In particular, proposals to inject sulfuric aerosols into the stratosphere to reduce solar radiation at the Earth's surface[18] would likely have important side effects for stratospheric ozone and UV radiation. Sulfate aerosols could accelerate stratospheric ozone loss if substantial amounts of ODSs remain in the atmosphere. The combined changes in absorption by ozone and scattering by sulfate would have spectrally complex consequences for the transmission of UV radiation to ground-level, and the ratio of direct to diffuse UV radiation would be systematically larger.[48, 57, 76]

Meeting the challenge of improved quantification of the environmental effects of future changes in stratospheric ozone requires addressing several significant gaps in current knowledge. First, we need a better understanding of the relative effectiveness of different wavelengths of solar radiation (i.e. the biological spectral weighting functions) in altering the fundamental responses of a diversity of organisms. This would allow better attribution of changes to exposure, specifically to UV-B radiation (and thus related to stratospheric ozone depletion), rather than to solar radiation more generally. Second, we need a better understanding of dose-response relationships across the breadth of effects on human health and the environment. Taken together, these would support improved scaling and modeling of the effects of stratospheric ozone depletion and climate change on living organisms and their ecosystems, and materials such as plastics, wood structures, and clothing.

As a result of shifting geographic ranges (including migration of humans and other species that is induced by climate change) and changes in seasonal timing of life-cycle events due to climate change, it is apparent that many organisms, including human populations, will experience different and interactive combinations of UV radiation and other environmental factors. These environmental changes will occur together with alterations in community structure,[61] which will then indirectly affect growth, reproduction, and survival. 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 on human behaviour and societal responses that are difficult to predict.

The focus of concern regarding elevated exposure to UV radiation has historically been on human health. Beyond the importance of terrestrial and aquatic ecosystems in providing critical 'ecosystem services' for human well-being, environmental sustainability and the maintenance of biodiversity are critical to maintaining a healthy planet.[50] The topics covered by the Environmental Effects Assessment Panel embrace some of the complexity and inter-relatedness of our living planet, while the success of the Montreal Protocol demonstrates that globally united and successful action on complex environmental issues is possible.

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