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Links between ozone depletion, climate change and solar UV radiation: How the Montreal Protocol is contributing to a more sustainable Earth

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1. Summary

Changes in stratospheric ozone and climate over the past 40+ years have altered the solar ultraviolet (UV) radiation conditions at Earth's surface. Ozone depletion has also driven climate change in the Southern Hemisphere. These, and other changes are interacting in complex ways to affect human health, food and water security, and assorted ecosystem services. Nonetheless, many adverse effects of exposure to high UV radiation have been avoided because of the Montreal Protocol with its amendments and adjustments. This international treaty has also played a significant role in mitigating global climate change. As the ozone layer recovers, climate change will exert an increasing role on influencing surface UV radiation and will modulate how organisms, ecosystems and people respond to UV radiation. 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.

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

Warnings that Earth's stratospheric ozone layer could be at risk from chlorofluorocarbons (CFCs) and other anthropogenic substances were first issued by scientists over 40 years ago[1,2]. Soon thereafter, 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 facilitate 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 fundamental importance 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 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 ozone-depleting substances.

The Montreal Protocol was the first multilateral environmental agreement by the United Nations to ever 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 to 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 four years (quadrennial reports) and shorter, periodic updates in the intervening years as needed.

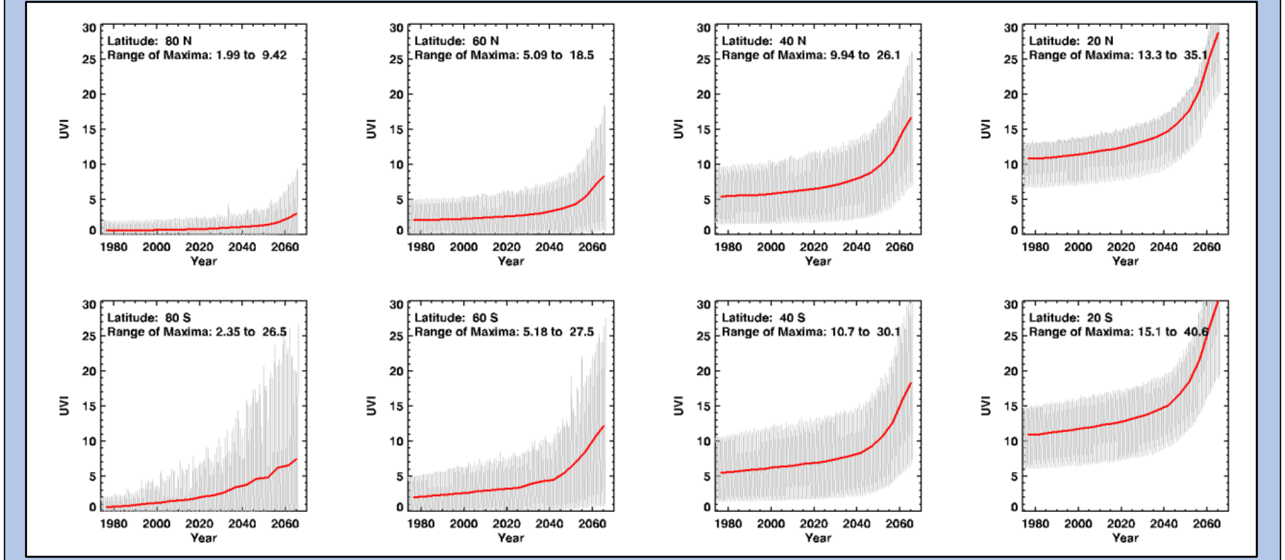
BOX 1. The three assessment panels supporting the Montreal Protocol.

There are three panels established by the Montreal Protocol to assess various aspects of stratospheric ozone depletion. These three Panels have complementary charges. The Scientific Assessment Panel (SAP) assesses the status of the depletion of the ozone layer and relevant atmospheric science issues. The Technology and Economic Assessment Panel (TEAP) 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 (e.g., movement and transformation of carbon and other elements through the biosphere and atmosphere), air quality, and materials for construction and other uses. Additional information on these panels, including their most recent reports, can be found on the United Nations Environment Programme (UNEP) Ozone Secretariat website (https://ozone.unep.org/science/overview).

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]. While significant seasonal ozone depletion over Antarctica has occurred annually since the 1980s (called the “ozone hole”), there have been small, but significant, positive trends in total column ozone in Antarctica in spring over the period 2001-2013[12]. Global mean total ozone has been projected to recover to pre-1980 levels by about the middle of the 21st century, assuming full compliance with the Montreal Protocol[12]. [13]

BOX 2. Environmental effects in the 'World Avoided'

There are a number of published models addressing the implications and potential outcomes of a 'World Avoided' without 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 GEOS-CCM 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 graphs below) with extreme values of 20 becoming common-place by 2065 over almost all inhabited areas of the planet, and as high as 41 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 Newman and McKenzie[11]. Range of maxima given show pre-1980 *vs.* 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 time-scales 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 250 million cases of skin cancer and more than 45 million cases of cataract in the USA for people born between 1890 and 2100.

While carbon dioxide (CO_2), methane (CH_4) and nitrous oxide (N_2O) are the dominant greenhouse gases emitted by humans, 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]. Modeling studies indicate that in the absence of the Montreal Protocol, global mean temperatures would have risen more than 2°C by 2070 due 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]. However, 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 to date[18-20].

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 stratospheric ozone depletion, but also of the environmental effects of these atmospheric changes. The UNEP Environmental Effects Assessment Panel (EEAP) is specifically charged with providing regular assessments of the state of the science on the environmental effects of stratospheric ozone depletion and consequent changes in UV radiation at Earth's surface, and the interactive effects of climate change.

In this paper, we highlight key findings from the most recent EEAP Quadrennial Assessment Report, and consider the significant policy and societal implications of these environmental effects. We further address the multiple ways by which the Montreal Protocol is contributing to environmental sustainability and 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 exposures of humans and other organisms to UV radiation, how stratospheric ozone depletion is itself contributing to climate change, and the various ways that climate change is affecting how plants, animals and ecosystems respond to UV radiation. Thus, as mandated by the Parties of 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 ozone depletion can be found elsewhere[22]. By focusing on the interactions between stratospheric ozone, UV radiation, and climate, the collated EEAP Assessment complements that of the UN's Intergovernmental Panel on Climate Change[23] to provide a comprehensive assessment on the environmental effects of global changes in Earth's atmosphere.

Figure 1. The United Nations Sustainable Development Goals (SDGs) addressed by the UNEP Environmental Effects Assessment Panel 2018 Quadrennial Report. The findings from this report are summarized in this paper according to five major topics (in circles). These address 11 of the 17 UN 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. More information on these SDGs can be found at: https://www.un.org/sustainabledevelopment/sustainable-development-goals/

3. Key findings and highlights

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

Stratospheric ozone depletion and climate change interact via several direct and indirect pathways that can have consequences for food and water security, human well-being and ecosystem sustainability (Figs. 1, 2). Climate change can modify depletion of stratospheric ozone by perturbing temperature, moisture, and wind speed and direction in the stratosphere and troposphere[24]; and certain greenhouse gases (e.g., N_2O and CH_4) can affect ozone levels.[12] Conversely, it is now clear that ozone depletion in the southern hemisphere is directly contributing to climate change by altering regional atmospheric circulation patterns in this part of the globe[25] which affects weather conditions, sea surface temperatures, ocean currents, and the frequency of wildfires[26-30]. These ozone-driven changes in climate are currently exerting significant impacts on the terrestrial and aquatic ecosystems in this region[31-34] (Box 3). In the northern hemisphere similar, but smaller effects of ozone depletion on climate may exist[35], 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 Earth's surface[35] and the resultant changes in UV-B can directly affect organisms and their environment. Because of the success of the Montreal Protocol, present-day increases in UV-B (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 (e.g., by 2-8% at mid-latitudes depending on season and precise location, and by 35% during the Antarctic October ozone 'hole'[35,36]).

Independent of stratospheric ozone variations, climate change is increasingly contributing to changes in incident surface UV-B radiation[35,37] (Fig. 2). Unlike stratospheric ozone depletion, these climate change-driven effects influence 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 can be either ameliorated or accentuated, to varying degrees, by UV-A and visible radiation[31,32,38].

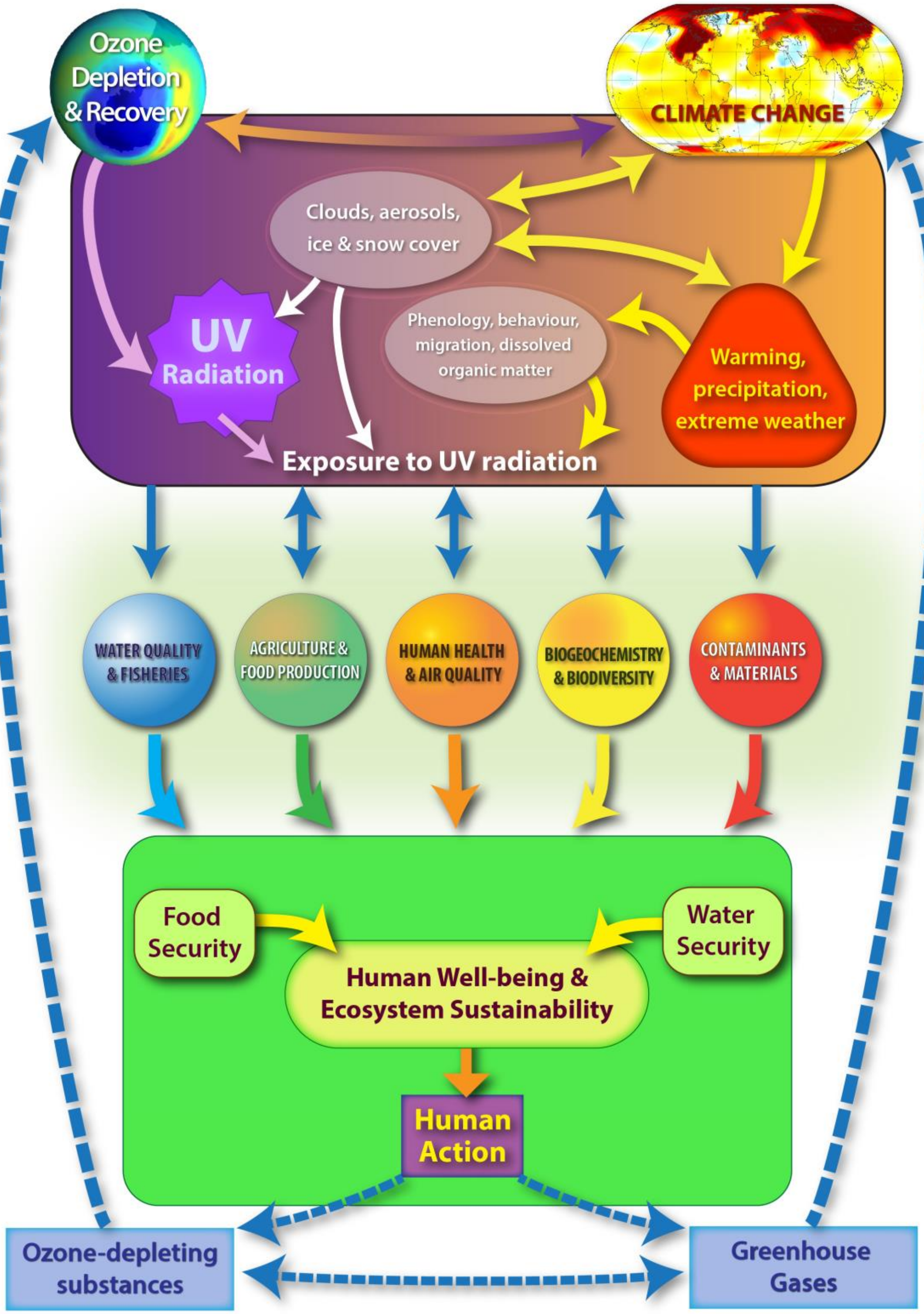


Figure 2. Links between stratospheric ozone depletion, UV radiation, and climate change, including environmental effects and potential consequences for food and water security, human well-being and the sustainability of ecosystems. Direct effects are shown as solid lines with feed-back effects indicated by double arrows. Important effects driven by human action are shown as dashed lines.

Future changes in incident surface solar UV radiation (UV-B and UV-A) will depend strongly on changes in aerosols, clouds, and surface reflectivity (e.g., snow and ice cover). Climate change is altering cloud cover with some regions becoming cloudier and others less cloudy[39]. Increased cloud cover generally tends to reduce UV radiation at Earth's surface, but effects vary with type of clouds[40] and their position relative to that of the sun[41]. Aerosols (solid and liquid particles suspended in the atmosphere[42]) 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[35,43,44]. In heavily polluted areas (e.g., 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 (i.e., before extensive aerosol pollution); the extent of these changes is contingent on the degree to which emissions of air pollutants in the future 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 is occurring in polar regions and mountains, will likely decrease surface UV radiation in these areas[35]. At the same time, this will increase the UV exposure of soils and waters that would previously have been covered by snow or ice.

3.2 UV radiation exposure and climate change

The direct effects of UV radiation on organisms, including humans, and materials depend on levels of exposure to UV radiation. This is determined by a number of 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, individual species, and other circumstances. Some of the most important regulators of exposure to UV radiation include:

- Behavior: The exposure of humans to UV radiation ranges from one-tenth to ten times the average for the population[45], depending on the time people spend indoors *vs* 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[38]. Warmer temperatures and changing precipitation patterns resulting from climate change will alter patterns of exposure to the sun in humans[46], but the direction and magnitude of this effect is likely to be highly variable globally. Many animals, such as insects, fish and birds, can sense UV radiation and use this ‘visual’ information to select suitable habitats and 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 leads 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[32,35], 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[49,55,56]. As solar UV radiation varies naturally with seasons, such alterations in the timing of critical life-cycle events will affect UV exposures.
- Modifications in vegetation cover (e.g., 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[57].
- Reductions in snow and ice cover and the timing of melt driven by climate change is modifying surface UV reflectance and increasing the penetration of UV radiation into rivers, lakes, oceans, and wetlands in temperate, alpine, and polar regions[58]. Additionally, increases in extreme weather events (e.g., heavy rainfall and floods) increase the 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[32,59]. 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[32].

3.3. Environmental effects of changing exposure to UV radiation

Changes in exposure to solar UV radiation, driven by ongoing changes in stratospheric ozone and climate, 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 sustainability of ecosystems (Fig. 1). Below we highlight some of these effects as identified in the recent UNEP EEAP Quadrennial Assessment[22].

3.3.1. 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 and photosensitivity disorders[38]. While increases in the incidence of skin cancer over the last century appear largely attributable to changes in behavior 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 countries with predominantly light-skinned populations[38]. Melanoma accounts for less than 5% of skin cancers, but has a much higher mortality than other skin cancers and accounts for approximately 60,000 deaths worldwide each year. Exposure to UV radiation accounts for 60-96% of the risk of developing cutaneous malignant melanoma in light-skinned populations; globally, ca.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[60]. To date, stratospheric ozone depletion is expected to increase these numbers by a few percent[61] when integrated over a lifetime of exposure. Much larger increases in skin cancer incidence would already be occurring in the absence of the Montreal Protocol[11,13] (Box 2).

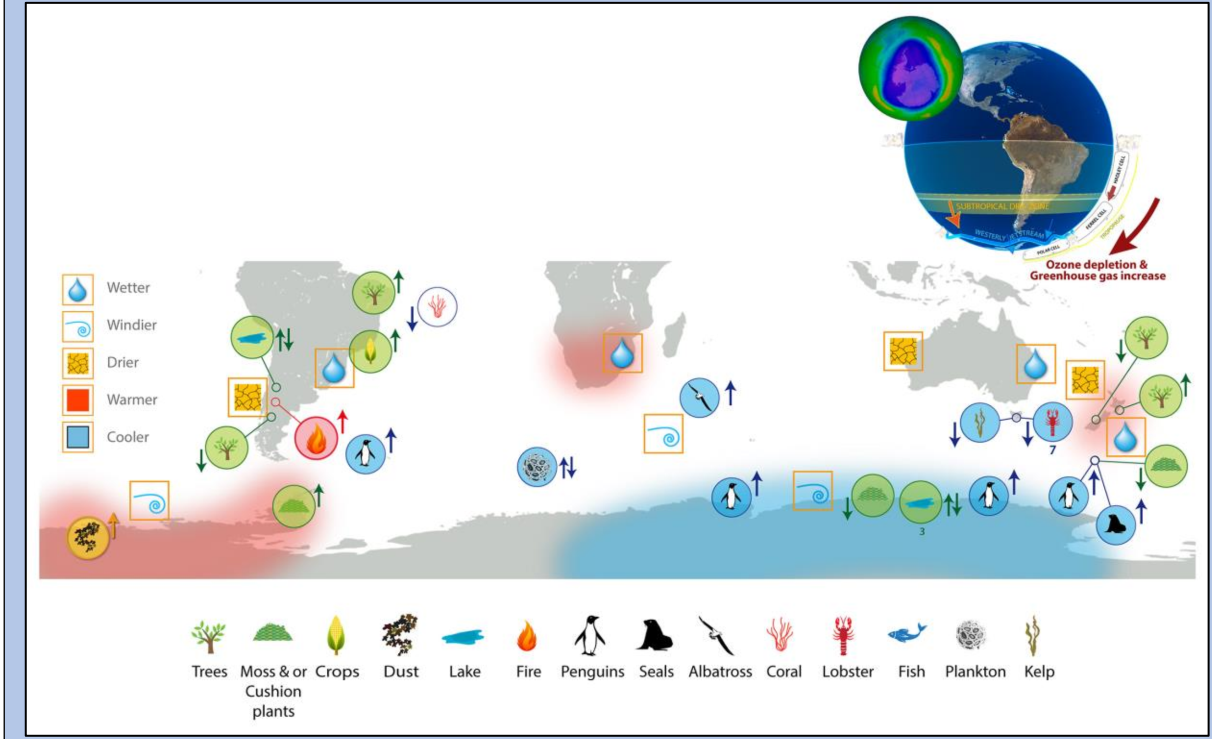
Exposure to UV radiation contributes to the development of cataract, the leading cause of impaired vision worldwide (12.6 million blind and 52.6 million visually impaired due to cataract in 2015)[62]. Particularly in low income countries – often with high ambient UV radiation – access to cataract surgery may be limited, making this a major health concern. The role of exposure to UV radiation for age-related macular degeneration, another major cause of visual impairment globally and particularly in older people, remains unclear[38].

Concern about high levels of UV-B radiation as a consequence 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 behavior, supported by structural and policy-level interventions[63]. Sun protection programs have been shown to be highly cost effective in preventing skin cancers[64]. Behavioral strategies need to be informed by the real-time level of ambient UV radiation (provided by the UV Index) and include controlling time outdoors together with using clothing, hats, sunscreen and sunglasses to reduce exposure to UV radiation. Behavioral changes can be facilitated by providing shade in public spaces such as parks, swimming pools, sports fields and playgrounds, and access to sunscreen[63].

Changes in UV radiation and climate can further impact human health by influencing air quality[42]. A number of recent international assessments have concluded that poor air quality is the largest cause of deaths globally due to environmental factors[42]. Together with nitrogen oxides (NOx) and volatile organic compounds (VOCs), UV radiation is a key factor in the formation and destruction of ground-level ozone and some types of 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[42]. Modelling studies for the USA indicate that reductions in UV radiation due to stratospheric ozone recovery will lead to somewhat lower ground-level ozone in some urban areas but slight increases elsewhere[65]. Although these changes in ground-level ozone are estimated to be small (ca. 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 significant consequences for public health.

Exposure to UV radiation also has benefits for human health, the most important being its role in the biosynthesis of vitamin D in the skin. 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 and visible radiation through both vitamin D and non-vitamin D pathways; for example, in systemic autoimmune diseases (such as multiple sclerosis) and non-cancer mortality, and in the prevention of myopia[38]. Gaps in our knowledge prevent calculations of the dose of UV radiation necessary to balance the risks with benefits, particularly as this varies according to age, sex, skin type, and location. Nevertheless, climate change will likely alter the balance of risks vs. benefits for human populations living in different regions[35,38]. For example, lower ambient UV-B 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. 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.

BOX 3. Environmental effects of ozone-driven climate change in the southern hemisphere.



Stratospheric ozone depletion has been a dominant driver of changes in Southern Hemisphere summer climate over the later part of the 20th Century, moving the winds and associated latitudinal bands of high and low rainfall further south[23-30,34] (inset globe). As a result, aquatic and terrestrial ecosystems, including agriculture, have been affected in several ways[31,32]. For instance, the productivity of the Southern Ocean is changing, decreasing over much of the ocean, but increasing in other areas with corresponding effects on the uptake of carbon dioxide from the atmosphere. 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 are correlated with declines in kelp beds in Tasmania and corals in Brazil[32]. On land, changing patterns of rainfall have resulted in increased agricultural productivity in some regions (e.g., SE South America) and drought conditions in others (e.g., Chile)[31]. Drier conditions have resulted in increasing salinity in lakes and changed lake fauna in East Antarctica and the eastern Andes[31,32]. On the Antarctic Peninsula, productivity of terrestrial ecosystems has increased with warmer and wetter conditions, while productivity in East Antarctica has responded negatively to cooling and drying[33]. While our understanding of the extent of these impacts has improved considerably in the past several years, there are likely 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 likely 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. Image updated and adapted from Robinson and Erickson[34] with icons depicting the location and types of organisms or environmental factors influenced by ozone-driven climate change and the arrows showing the direction of these effects.

3.3.2 Impacts on agriculture and food production

There is little evidence to suggest that modest increase in solar UV radiation by itself has had any substantial negative effect on crop yield and plant productivity[31]. It is unclear how food production would have been impacted 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 (i.e., high latitudes), concluded that a 20% increase in UV radiation equivalent to about a 10% reduction in stratospheric ozone has only reduced plant production by ca. 6% (i.e., a 1% reduction in growth for every 3% increase in UV radiation)[66]. To what extent this relationship would hold for levels of UV radiation >2-fold higher than present (i.e., the 'World Avoided' scenario; Box 2[11]) is uncertain, but would be an obvious major concern under such a scenario.

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. However, on a regional scale, changes in southern hemisphere rainfall, driven by ozone depletion and climate change, have been linked to both increases and decreases in plant productivity (Box 3) and these effects may reverse 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, influence plants, but 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[67]. In other cases, exposure to UV radiation can increase tolerance of plants to drought[68]. Increases in ground-level ozone resulting from reduced UV radiation resulting from the recovery of stratospheric ozone could also negatively affect crop yields[42]. Understanding these, and other UV-climate change interactions 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 as mediated by specific photoreceptors that regulate plant growth and development[69]. These non-damaging effects include alterations in plant chemistry, leading to changes in the nutritional quality of food[70] and increased plant defenses against pests and pathogens[71]. Consequently, conditions that decrease the exposure of crop plants to UV radiation (e.g., climate change, ozone recovery, shifting planting dates or increased sowing densities), could reduce plant defenses and thereby affect food security in ways other than just the direct effects on yield[72]. 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 certain cases, resistance to pests[73].

3.3.3 Impacts on water quality and fisheries

Climate change is altering the mixing patterns in the water column of lakes and oceans, with deeper mixed layers in some regions and shallower mixed layers in others. These changes are altering the UV exposure and fundamental structure of aquatic ecosystems and consequently their ecosystem services (e.g., water quality, productivity of fisheries) in regionally specific ways[32]. 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 population sizes and subsequent harvest potential for fisheries[74]. 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[75].

Climate change-related increases in heavy precipitation and melting of glaciers and permafrost are increasing the concentration and color of UV-absorbing dissolved organic matter and particulates[32,43]. 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 microbial pathogens[59]. 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].

3.3.4 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[76,77]. Exposure to solar UV and visible radiation can also accelerate the decomposition of natural organic matter (e.g., 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[78,79]. Climate change-driven increases in droughts, wildfires, and thawing of permafrost soils have the potential to increase photodegradation[43,80], thereby fueling 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[31,32]. UV radiation also modifies herbivory and predator-prey interactions, which then alters trophic interactions, energy transfer, and the food webs in ecosystems[81]. Presently, ozone-driven changes in regional climate in the southern hemisphere are threatening the habitat and survival of a number of species. These include plants growing in the unique high-elevation woodlands of the South American Altiplano[82] and moss and other plant communities in Antarctica[33]. At the same time, the ozone-driven changes in climate are enhancing reproductive success of some marine birds and mammals[31,32](Box 3). 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].

3.3.5 Impacts on contaminants and materials

Solar UV radiation plays a critical role in altering the toxicity of contaminants[32,43]. Exposure to UV radiation can increase the toxicity of contaminants such as pesticides and polycyclic aromatic hydrocarbons (PAHs) 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[83]. 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[43]. 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 UV protection for humans. It is now recognized that sunscreens wash into coastal waters, with potential effects on aquatic ecosystems. The toxicity of artificial sunscreens to corals[84], sea urchins[85], fish[86], and other aquatic organisms, has led Palau, the State of Hawaii, USA, 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[87].

Microplastics (defined as 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[88]. Microplastics are formed by the UV-induced degradation and breakdown of plastic products exposed to sunlight. Microplastic pollutants occur in up to 20% or more of fish marketed globally for human consumption[89]. Although the toxicity of microplastics is unknown, higher temperatures and increased exposure to UV radiation accelerate the fragmentation of plastics, potentially threatening food security.

Until very recently, plastics used in packaging and building materials were selected and optimized on the basis of durability and performance[90]. 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, in place of plastics. Many of the materials used are vulnerable to accelerated aging when exposed to UV radiation. At present, industrial activities are aimed at identifying and developing novel, 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 produce damage to organisms. Because no sinks in the atmosphere or in surface soils and waters have been identified, concern has been raised about its potential accumulation over time in sensitive environments (e.g., salt lakes, wetlands, vernal pools). Large natural sources of TFA have been invoked to explain high TFA concentrations in deep oceanic waters[91] that have 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 to 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[92].

4. 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 and decreases in different regions.[12] The return of column ozone to 1980 levels is expected to occur in the 2030s and 2050s respectively over northern- and southern-hemisphere mid-latitudes and around the 2060s in Antarctica[12,93,94]. 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 at 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[95] 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. New 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 Earth's surface[96] 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[35,97-99].

Meeting the challenge of improving 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 fundamental responses of humans and other species to UV radiation, particularly how organisms respond to the different wavelengths of UV radiation. Second, we need to better understand the full scope of not only the adverse (e.g., skin cancer, impaired vision and unfavorable ecosystem changes), but the beneficial effects (e.g., vitamin D, defense 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[100]. Taken together, all three would increase our ability to develop models that could be used to quantify effects of UV radiation on living organisms and materials on scales ranging from individuals to ecosystems and the planet.

As a consequence of rapid climate change, many organisms, including humans, are being exposed to novel 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[101], 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 behavior 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 for human health and well-being, environmental sustainability and the maintenance of biodiversity are also important at a higher level if we are to maintain a healthy planet[102]. 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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