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

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Abstract

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

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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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74 ***1. Summary***

75   Changes in stratospheric ozone and climate over the past 40+ years have altered the

76 solar ultraviolet (UV) radiation conditions at Earth's surface. Ozone depletion has also driven

77 climate change in the Southern Hemisphere. These, and other changes are interacting in

78 complex ways to affect human health, food and water security, and assorted ecosystem

79 services. Nonetheless, many adverse effects of exposure to high UV radiation have been

80 avoided because of the Montreal Protocol with its amendments and adjustments. This

81 international treaty has also played a significant role in mitigating global climate change. As the

82 ozone layer recovers, climate change will exert an increasing role on influencing surface UV

83 radiation and will modulate how organisms, ecosystems and people respond to UV radiation.

84 The interactions between stratospheric ozone, climate and UV radiation will therefore shift over

85 time; however, the Montreal Protocol will continue to have far-reaching benefits for human well-

86 being and environmental sustainability.

87

88 ***2. Stratospheric ozone depletion, the Montreal Protocol, and the UNEP Environmental***

89 ***Effects Assessment Panel***

90   Warnings that Earth's stratospheric ozone layer could be at risk from

91 chlorofluorocarbons (CFCs) and other anthropogenic substances were first issued by scientists

92 over 40 years ago[1,2]. Soon thereafter, large losses of stratospheric ozone were reported over

93 Antarctica[3] with smaller, but more widespread erosion of stratospheric ozone found over much

94 of the rest of the planet[4]. Subsequent studies clearly linked these ozone losses to the

95 emissions of CFCs and other ozone-depleting substances[5] and, at least over Antarctica, unique

96 atmospheric conditions during winter that facilitate ozone depletion[6,7].

97   In response to the initial concerns about the potentially deleterious effects of elevated

98 surface solar ultraviolet-B radiation (UV-B; 280-315 nm) resulting from ozone depletion, the

99 international community began mobilizing in 1977 to recognize the fundamental importance of

100 stratospheric ozone to life on Earth and to develop and implement policies to preserve the

101 integrity of the ozone layer[8]. Of particular concern was the possibility that exposure to high

102 levels of UV-B would increase the incidence of skin cancer and cataracts in humans, weaken

103 people's immune systems, decrease agricultural productivity and negatively affect sensitive

104 aquatic organisms and ecosystems. The policy solution that emerged to address ozone

105 depletion was the 1985 *Vienna Convention for the Protection of the Ozone Layer*. This

106 convention was followed by the 1987 *Montreal Protocol on Substances that Deplete the Ozone*

107   *Layer*, which was negotiated to control the consumption and production of anthropogenic

108   ozone-depleting substances.

109   The Montreal Protocol was the first multilateral environmental agreement by the United

110   Nations to ever achieve universal ratification (197 parties by 2008). Since its inception, this

111   international accord has been amended and adjusted a number of times by the member Parties

112   to the Montreal Protocol. The Parties base their decisions on scientific, environmental, technical,

113   and economic information provided by three assessment Panels (Box 1). All three panels

114   provide full assessment reports to the Parties every four years (quadrennial reports) and

115   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).

116

117   The implementation of the Montreal Protocol has successfully prevented the

118   uncontrolled global depletion of the stratospheric ozone layer and associated large increases in

119   surface UV-B radiation[9-12] (Box 2). Concentrations of chlorine and bromine from long-lived

120   ozone-depleting substances have been declining in the stratosphere since the late 1990s[12].

121   While significant seasonal ozone depletion over Antarctica has occurred annually since the

122   1980s (called the "ozone hole"), there have been small, but significant, positive trends in total

123   column ozone in Antarctica in spring over the period 2001-2013[12]. Global mean total ozone has

124   been projected to recover to pre-1980 levels by about the middle of the 21st century, assuming

125   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.
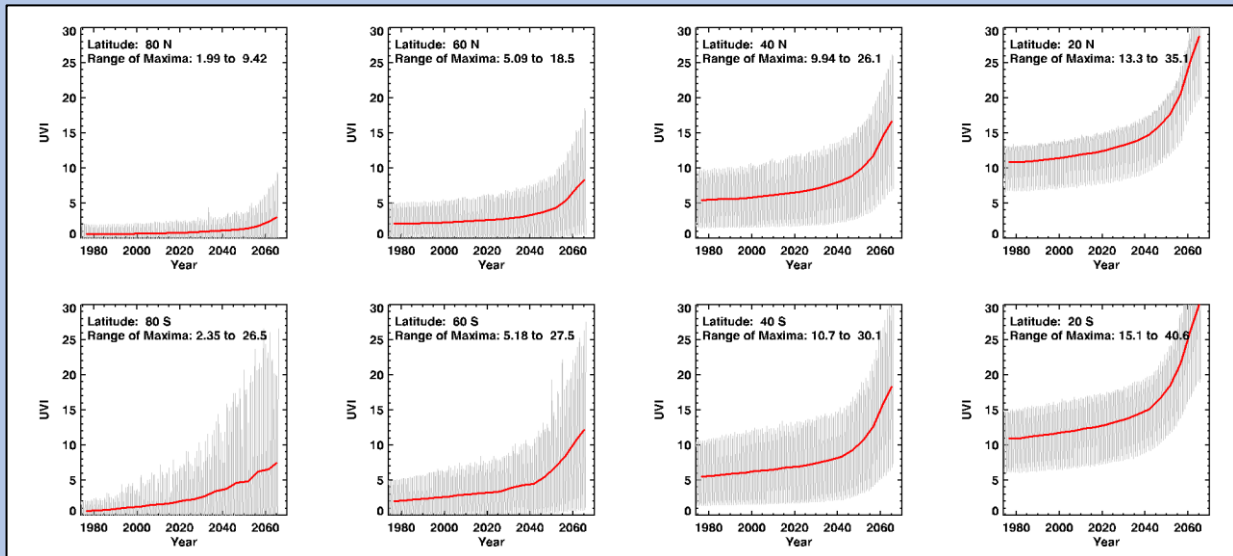
The graphs show calculated surface monthly (grey lines) and annual mean (red line) UVI values for clear skies at different latitudes without the Montreal Protocol, based on the model in Newman and McKenzie[11]. Range of maxima given show pre-1980 *vs.* 2065 data.

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.

126

127   While carbon dioxide (CO_2), methane (CH_4) and nitrous oxide (N_2O) are the dominant

128   greenhouse gases emitted by humans, most of the ozone-depleting substances controlled by

129   the Montreal Protocol (CFCs and others) are also potent greenhouse gases that contribute to

130   global warming[14]. Modeling studies indicate that in the absence of the Montreal Protocol, global

131   mean temperatures would have risen more than 2°C by 2070 due to the warming effects from

132   ozone-depleting substances alone[15]. The adoption of the Kigali Amendment to the Montreal

133   Protocol in 2016 limits the production and consumption of hydrofluorocarbons (HFCs), which

134   are non-ozone depleting substitutes for CFCs[16]. However, HFCs are potent greenhouse gases

135   and limiting emissions of these compounds could further reduce global temperatures as much

136   as 0.5 °C by the end of this century[17]. This Amendment has thus further broadened and

137   strengthened the scope of the Montreal Protocol, adding to an effective international treaty that

138   not only addresses stratospheric ozone depletion, but is doing more to mitigate global climate

139   change than any other human action to date[18-20].

140   One of the important reasons for the success of the Montreal Protocol has been its

141   foundation on high quality science, which not only improves our understanding of the causes

142   and mechanisms of stratospheric ozone depletion, but also of the environmental effects of these

143   atmospheric changes. The UNEP Environmental Effects Assessment Panel (EEAP) is

144   specifically charged with providing regular assessments of the state of the science on the

145   environmental effects of stratospheric ozone depletion and consequent changes in UV radiation

146   at Earth's surface, and the interactive effects of climate change.

147   In this paper, we highlight key findings from the most recent EEAP Quadrennial

148   Assessment Report, and consider the significant policy and societal implications of these

149   environmental effects. We further address the multiple ways by which the Montreal Protocol is

150   contributing to environmental sustainability and human health and well-being. Given the

151   accelerating pace of climate change[21], we also consider the increasing role that climate change

152   is playing in influencing exposures of humans and other organisms to UV radiation, how

153   stratospheric ozone depletion is itself contributing to climate change, and the various ways that

154   climate change is affecting how plants, animals and ecosystems respond to UV radiation. Thus,

155   as mandated by the Parties of the Montreal Protocol, we consider a wide range of the

156   environmental effects that are linked to changes in stratospheric ozone, climate and solar UV

157   radiation. Our findings address many of the United Nations Sustainable Development Goals

158   (Fig. 1). More in-depth information on the environmental effects of ozone depletion can be found

159   elsewhere[22]. By focusing on the interactions between stratospheric ozone, UV radiation, and

160   climate, the collated EEAP Assessment complements that of the UN's Intergovernmental Panel

161   on Climate Change[23] to provide a comprehensive assessment on the environmental effects of

162   global changes in Earth's atmosphere.

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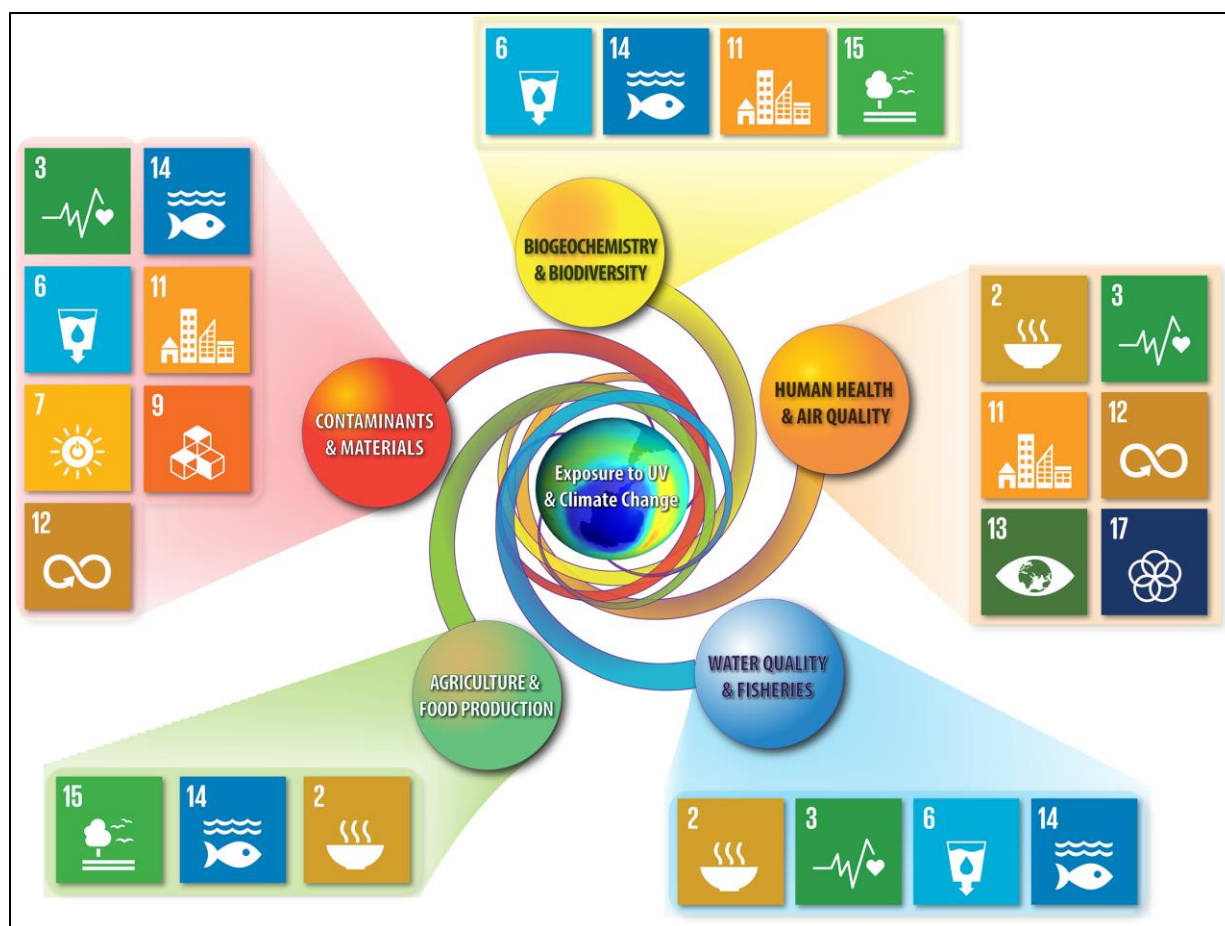
Figure 1. The United Nations Sustainable Development Goals (SDGs) addressed by the UNEP Environmental Effects Assessment Panel 2018 Quadrennial Report. The findings from this report are summarized in this paper according to five major topics (in circles). These address 11 of the 17 UN SDGs (in numbered 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].

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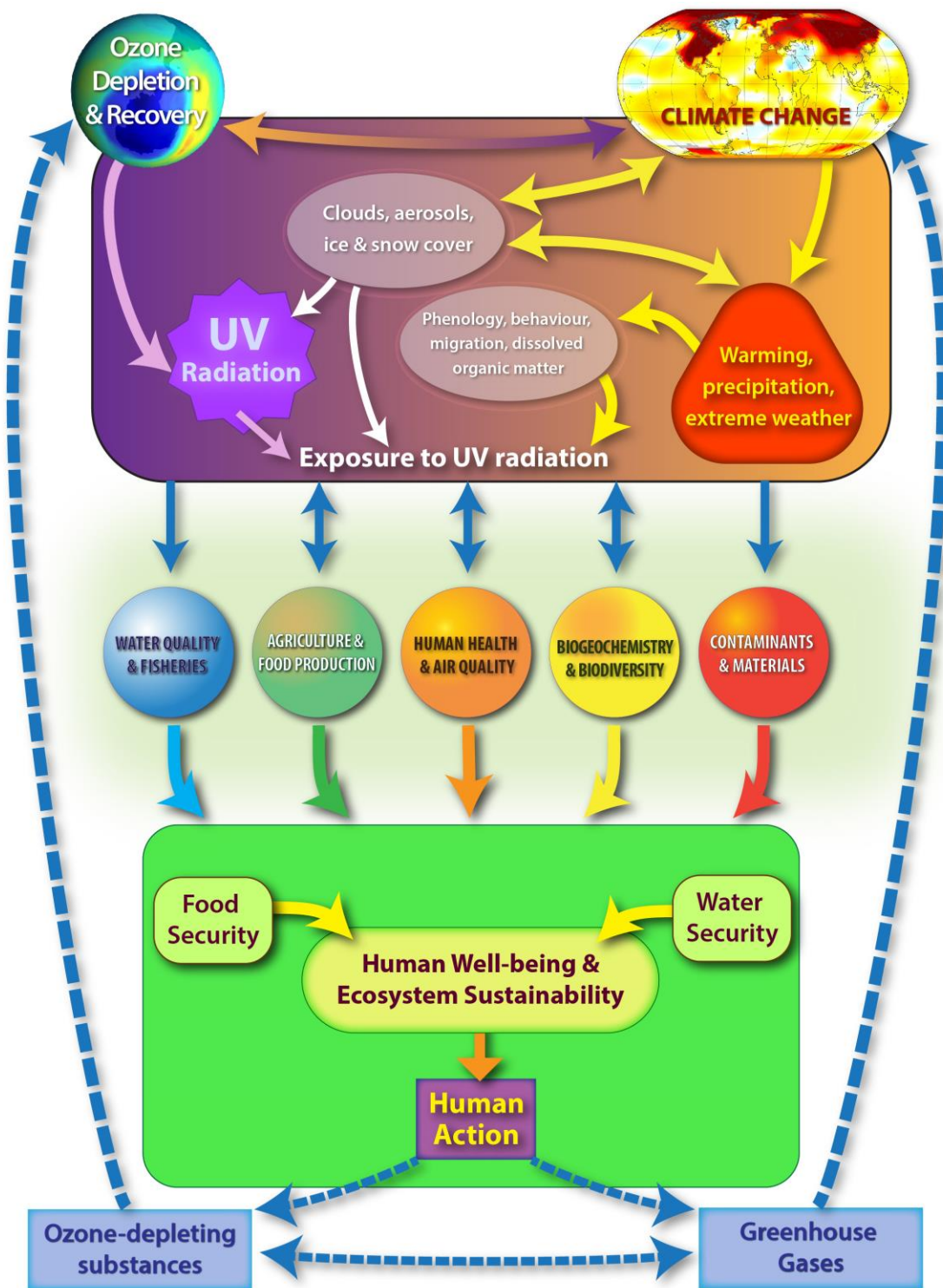

Figure 2. Links between stratospheric ozone depletion, UV radiation, and climate change, including environmental effects and potential consequences for food and water security, human well-being and the sustainability of ecosystems. Direct effects are shown as solid lines with feedback effects indicated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

200   Future changes in incident surface solar UV radiation (UV-B and UV-A) will depend

201   strongly on changes in aerosols, clouds, and surface reflectivity (e.g., snow and ice cover).

202   Climate change is altering cloud cover with some regions becoming cloudier and others less

203   cloudy[39]. Increased cloud cover generally tends to reduce UV radiation at Earth's surface, but

204   effects vary with type of clouds[40] and their position relative to that of the sun[41]. Aerosols (solid

205   and liquid particles suspended in the atmosphere[42]) reduce and scatter UV radiation; the type

206   and amounts of aerosols in the atmosphere are affected by volcanic activity, the emissions of air

207   pollutants, the frequency and extent of wildfires and dust storms, and other factors, many of

208   which are affected by climate change[35,43,44]. In heavily polluted areas (e.g., southern and

209   eastern Asia), improvements in air quality resulting from measures to control the emissions of

210   air pollutants are expected to increase levels of UV radiation to near pre-industrial levels (i.e.,

211   before extensive aerosol pollution); the extent of these changes is contingent on the degree to

212   which emissions of air pollutants in the future are curtailed. High surface reflectance from snow

213   or ice cover can enhance incident UV radiation because some of the reflected UV radiation is

214   scattered back to the surface by aerosols and clouds in the atmosphere. Consequently, climate

215   change-driven reductions in ice or snow cover, which is occurring in polar regions and

216   mountains, will likely decrease surface UV radiation in these areas[35]. At the same time, this will

217   increase the UV exposure of soils and waters that would previously have been covered by snow

218   or ice.

219

220   *3.2 UV radiation exposure and climate change*

221   The direct effects of UV radiation on organisms, including humans, and materials

222   depend on levels of exposure to UV radiation. This is determined by a number of factors,

223   including many that are influenced by climate change (Fig. 2). Importantly, these climate

224   change-driven effects can result in either increases or decreases in exposures to solar UV

225   radiation, depending on location, time of year, individual species, and other circumstances.

226   Some of the most important regulators of exposure to UV radiation include:

227   • Behavior: The exposure of humans to UV radiation ranges from one-tenth to ten

228   times the average for the population[45], depending on the time people spend indoors

229   *vs* outdoors and under shade structures. The exposure of the skin or eyes to UV

230   radiation further depends on the use of sun protection such as clothing or

231   sunglasses; the UV radiation dose received by cells and tissues within the skin is

232   influenced by pigmentation of the skin and use of sunscreens[38]. Warmer

233   temperatures and changing precipitation patterns resulting from climate change will

234   alter patterns of exposure to the sun in humans[46], but the direction and magnitude of

235   this effect is likely to be highly variable globally. Many animals, such as insects, fish

236   and birds, can sense UV radiation and use this 'visual' information to select suitable

237   habitats and avoid exposure to prolonged periods of high UV radiation[47,48].

238 • In response to climate change, many animals and plants are migrating or shifting

239   their ranges to higher latitudes and elevations[49,50], while increases in exposure to UV

240   radiation leads zooplankton to migrate into deeper waters[51-54]. Because of the

241   natural gradients in solar UV radiation that exist with latitude, altitude and water

242   depth[32,35], these shifts in distributions will expose organisms to conditions of UV

243   radiation to which they are unaccustomed.

244 • Climate change is altering phenology, including plant flowering, spring bud-burst in

245   trees, and emergence and breeding of animals[49,55,56]. As solar UV radiation varies

246   naturally with seasons, such alterations in the timing of critical life-cycle events will

247   affect UV exposures.

248 • Modifications in vegetation cover (e.g., drought, fire, pest-induced die-back of forest

249   canopies or invasion of grasslands by shrubs) driven by changes in climate and land

250   use alter the amount of sunlight and UV radiation reaching many ground-dwelling

251   terrestrial organisms[57].

252 • Reductions in snow and ice cover and the timing of melt driven by climate change is

253   modifying surface UV reflectance and increasing the penetration of UV radiation into

254   rivers, lakes, oceans, and wetlands in temperate, alpine, and polar regions[58].

255   Additionally, increases in extreme weather events (e.g., heavy rainfall and floods)

256   increase the input of dissolved organic matter and sediments into coastal and inland

257   waters that can reduce the clarity of water and exposure of aquatic organisms to UV

258   radiation[32,59]. In contrast, in some lakes and oceans where climate warming is

259   leading to shallower mixing depths, exposure to UV radiation in the surface mixed

260   layer is increasing[32].

261

262 *3.3. Environmental effects of changing exposure to UV radiation*

263   Changes in exposure to solar UV radiation, driven by ongoing changes in stratospheric

264 ozone and climate, have the potential to affect materials, humans, and many other organisms in

265 ways that have consequences for the health and well-being of people and sustainability of

266 ecosystems (Fig. 1). Below we highlight some of these effects as identified in the recent UNEP

267 EEAP Quadrennial Assessment[22].

268

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].

300

301   Changes in UV radiation and climate can further impact human health by influencing air
302   quality[42]. A number of recent international assessments have concluded that poor air quality is
303   the largest cause of deaths globally due to environmental factors[42]. Together with nitrogen
304   oxides (NOx) and volatile organic compounds (VOCs), UV radiation is a key factor in the
305   formation and destruction of ground-level ozone and some types of particulate pollutants. Future
306   recovery of stratospheric ozone and changes in climate may alter ground-level ozone via
307   decreases in UV radiation and increases in downward transport of stratospheric ozone[42].
308   Modelling studies for the USA indicate that reductions in UV radiation due to stratospheric
309   ozone recovery will lead to somewhat lower ground-level ozone in some urban areas but slight
310   increases elsewhere[65]. Although these changes in ground-level ozone are estimated to be small
311   (ca. 1% of current ground-level amounts), large populations are already affected by poor air
312   quality, such that even small relative changes in air quality could have significant consequences
313   for public health.
314   Exposure to UV radiation also has benefits for human health, the most important being
315   its role in the biosynthesis of vitamin D in the skin. Vitamin D is critical to healthy bones,
316   particularly during infancy and childhood. There is also growing evidence of a range of other
317   benefits of exposure to UV and visible radiation through both vitamin D and non-vitamin D
318   pathways; for example, in systemic autoimmune diseases (such as multiple sclerosis) and non-
319   cancer mortality, and in the prevention of myopia[38]. Gaps in our knowledge prevent calculations
320   of the dose of UV radiation necessary to balance the risks with benefits, particularly as this
321   varies according to age, sex, skin type, and location. Nevertheless, climate change will likely
322   alter the balance of risks vs. benefits for human populations living in different regions[35,38]. For
323   example, lower ambient UV-B at high latitudes will increase the risk of vitamin D deficiency
324   where this risk is already substantial. Conversely, warmer temperatures may encourage people
325   in cooler regions to spend more time outdoors, increasing exposure to UV-B. Reductions in
326   snow and ice cover could reduce the exposure of the eyes to UV radiation, possibly decreasing
327   the risk of damage to the eyes.
328

BOX 3. Environmental effects of ozone-driven climate change in the southern hemisphere.
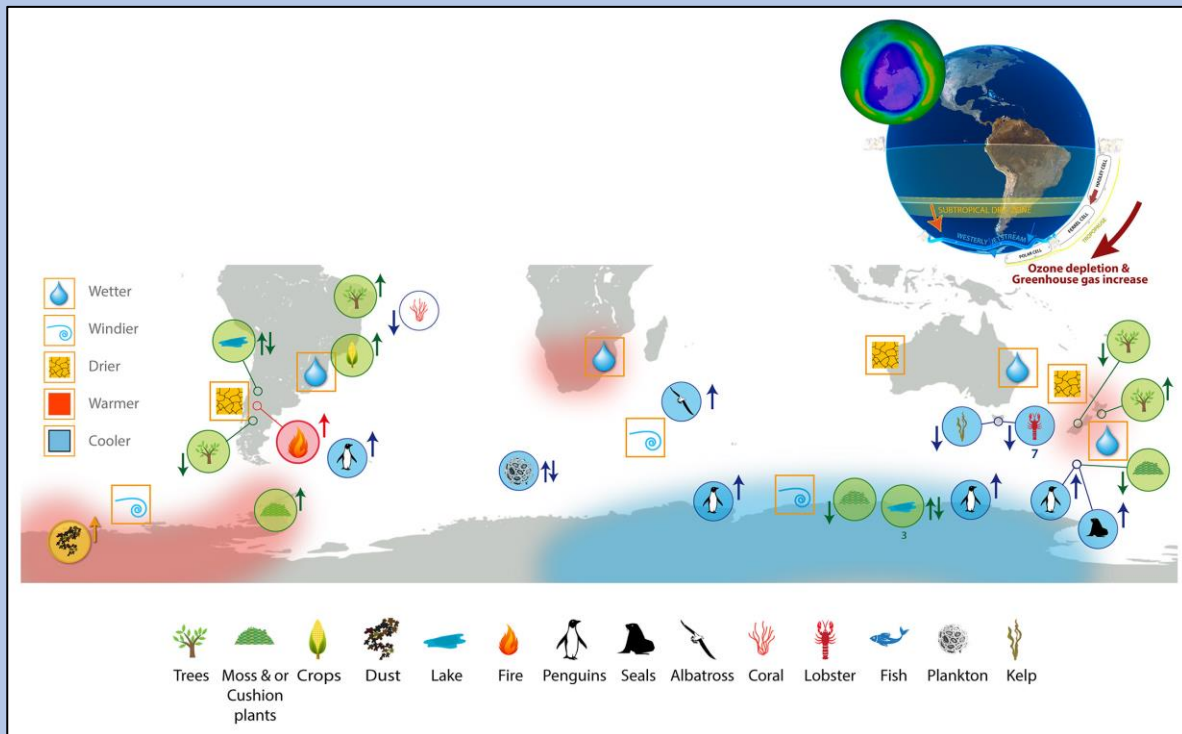
Stratospheric ozone depletion has been a dominant driver of changes in Southern Hemisphere summer climate over the later part of the 20th Century, moving the winds and associated latitudinal bands of high and low rainfall further south[23-30,34] (inset globe). As a result, aquatic and terrestrial ecosystems, 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.

332   *3.3.2 Impacts on agriculture and food production*

333   There is little evidence to suggest that modest increase in solar UV radiation by itself has

334   had any substantial negative effect on crop yield and plant productivity[31]. It is unclear how food

335   production would have been impacted by the large increases in solar UV radiation in the

336   absence of the Montreal Protocol. One analysis, based on data from a number of field studies

337   conducted in regions where stratospheric ozone depletion is most pronounced (i.e., high

338   latitudes), concluded that a 20% increase in UV radiation equivalent to about a 10% reduction in

339   stratospheric ozone has only reduced plant production by ca. 6% (i.e., a 1% reduction in growth

340   for every 3% increase in UV radiation)[66]. To what extent this relationship would hold for levels of

341   UV radiation >2-fold higher than present (i.e., the 'World Avoided' scenario; Box 2[11]) is

342   uncertain, but would be an obvious major concern under such a scenario.

343   It is likely that by contributing to the mitigation of climate change, the Montreal Protocol

344   and its Amendments have reduced the vulnerability of agricultural crops to rising temperatures,

345   drought, and extreme weather events. However, on a regional scale, changes in southern

346   hemisphere rainfall, driven by ozone depletion and climate change, have been linked to both

347   increases and decreases in plant productivity (Box 3) and these effects may reverse as the

348   ozone 'hole' recovers. Exposure to UV radiation can also modify how climate change factors,

349   including drought, high temperatures, and rising carbon dioxide levels, influence plants, but

350   effects are complex and often contingent on growth conditions. For example, in some cases

351   increased UV radiation can reduce the stimulatory effects of elevated carbon dioxide on plant

352   growth[67]. In other cases, exposure to UV radiation can increase tolerance of plants to drought[68].

353   Increases in ground-level ozone resulting from reduced UV radiation resulting from the recovery

354   of stratospheric ozone could also negatively affect crop yields[42]. Understanding these, and other

355   UV-climate change interactions can inform growers and breeders about agricultural practices

356   that could aid in maintaining crop yields in the face of evolving environmental change.

357   UV radiation can also have beneficial effects on plants as mediated by specific

358   photoreceptors that regulate plant growth and development[69]. These non-damaging effects

359   include alterations in plant chemistry, leading to changes in the nutritional quality of food[70] and

360   increased plant defenses against pests and pathogens[71]. Consequently, conditions that

361   decrease the exposure of crop plants to UV radiation (e.g., climate change, ozone recovery,

362   shifting planting dates or increased sowing densities), could reduce plant defenses and thereby

363   affect food security in ways other than just the direct effects on yield[72]. For certain vegetable

364   crops grown in greenhouses and other controlled-environments, UV radiation from lamps is

365 increasingly being used to manipulate plant hardiness, food quality and, in certain cases,

366 resistance to pests[73].

367

368 *3.3.3 Impacts on water quality and fisheries*

369   Climate change is altering the mixing patterns in the water column of lakes and oceans,

370 with deeper mixed layers in some regions and shallower mixed layers in others. These changes

371 are altering the UV exposure and fundamental structure of aquatic ecosystems and

372 consequently their ecosystem services (e.g., water quality, productivity of fisheries) in regionally

373 specific ways[32]. The sensitivity to damage induced by UV radiation for the transparent larvae of

374 many commercially important fish species, combined with the distribution of these larvae in high

375 UV surface waters, have the potential to reduce juvenile population sizes and subsequent

376 harvest potential for fisheries[74]. In contrast, reductions in the transparency of clear-water lakes

377 to UV radiation may increase the potential for invasions of UV-sensitive warm-water species

378 that can negatively affect native species[75].

379   Climate change-related increases in heavy precipitation and melting of glaciers and

380 permafrost are increasing the concentration and color of UV-absorbing dissolved organic matter

381 and particulates[32,43]. This is causing the "browning" of many inland and coastal waters, with

382 consequent loss of the valuable ecosystem service in which solar UV radiation disinfects

383 surface waters of parasites and microbial pathogens[59]. Region-specific increases in the

384 frequency and duration of droughts have the opposite effect, increasing water clarity and

385 enhancing solar disinfection, as well as altering the depth distribution of plankton that provide

386 critical food resources for fish[44,51].

387

388 *3.3.4 Impacts on biogeochemical cycles, climate system feedbacks and biodiversity*

389   Solar UV radiation inhibits primary production in the surface waters of the oceans by as

390 much as 20%, reducing carbon fixation rates in one of the most important biogeochemical

391 cycles on Earth[76,77]. Exposure to solar UV and visible radiation can also accelerate the

392 decomposition of natural organic matter (e.g., terrestrial plant litter, aquatic detritus, and

393 dissolved organic matter) through the process of photodegradation, resulting in the emission of

394 greenhouse gases including carbon dioxide and nitrous oxide[78,79]. Climate change-driven

395 increases in droughts, wildfires, and thawing of permafrost soils have the potential to increase

396 photodegradation[43,80], thereby fueling a positive feedback on global warming; however, the

397 scale of this effect remains an important knowledge gap.

398   Species of aquatic and terrestrial organisms differ in their tolerances to UV radiation and

399   these differences can lead to alterations in the composition and diversity of ecological

400   communities under conditions of elevated UV radiation[31,32]. UV radiation also modifies herbivory

401   and predator-prey interactions, which then alters trophic interactions, energy transfer, and the

402   food webs in ecosystems[81]. Presently, ozone-driven changes in regional climate in the southern

403   hemisphere are threatening the habitat and survival of a number of species. These include

404   plants growing in the unique high-elevation woodlands of the South American Altiplano[82] and

405   moss and other plant communities in Antarctica[33]. At the same time, the ozone-driven changes

406   in climate are enhancing reproductive success of some marine birds and mammals[31,32](Box 3).

407   To what extent the Montreal Protocol has specifically contributed to the maintenance of

408   biodiversity in ecosystems is unknown, but losses in species diversity in aquatic ecosystems are

409   known to be linked to high exposure to UV radiation which can then lead to a decline in the

410   health and stability of these systems[44].

411

412   *3.3.5 Impacts on contaminants and materials*

413   Solar UV radiation plays a critical role in altering the toxicity of contaminants[32,43].

414   Exposure to UV radiation can increase the toxicity of contaminants such as pesticides and

415   polycyclic aromatic hydrocarbons (PAHs) to aquatic organisms but, more commonly, results in

416   the formation of less toxic breakdown products. For example, UV-B radiation transforms the

417   most toxic form of methyl mercury to forms that are less toxic, reducing the accumulation of

418   mercury in fish[83]. Although the degradation of many pollutants and water-borne pathogens by

419   solar UV radiation is affected by changes in stratospheric ozone, other factors such as dissolved

420   organic matter are more important in regulating penetration of UV radiation into water, and

421   hence photodegradation of these pollutants[43]. Advances in modeling approaches are allowing

422   improved quantification of the effects of global changes on the fate of aquatic pollutants.

423   Sunscreens are in widespread use, including in cosmetics, as part of the suite of

424   approaches to UV protection for humans. It is now recognized that sunscreens wash into

425   coastal waters, with potential effects on aquatic ecosystems. The toxicity of artificial sunscreens

426   to corals[84], sea urchins[85], fish[86], and other aquatic organisms, has led Palau, the State of

427   Hawaii, USA, and the city of Key West in Florida, USA, to ban the use of some sunscreens.

428   Similar legislation is under consideration by the European Union[87].

429   Microplastics (defined as plastic particles < 5mm) are now ubiquitous in the world's

430   oceans and pose an emerging serious threat to marine ecosystems with many organisms now

431   known to ingest them[88]. Microplastics are formed by the UV-induced degradation and

432 breakdown of plastic products exposed to sunlight. Microplastic pollutants occur in up to 20% or

433 more of fish marketed globally for human consumption[89]. Although the toxicity of microplastics is

434 unknown, higher temperatures and increased exposure to UV radiation accelerate the

435 fragmentation of plastics, potentially threatening food security.

436 Until very recently, plastics used in packaging and building materials were selected and

437 optimized on the basis of durability and performance[90]. However, the present focus on

438 increased sustainability with the trend towards 'green' buildings, now requires such choices to

439 be environmentally acceptable as well. This includes the increased use of wood, which can be

440 renewable, carbon-neutral, and low in embodied energy, in place of plastics. Many of the

441 materials used are vulnerable to accelerated aging when exposed to UV radiation. At present,

442 industrial activities are aimed at identifying and developing novel, safer, effective, and 'greener'

443 additives (colorants, plasticizers, and stabilizers) for plastic materials and wood coatings, but

444 continued research and development is required to further combat harsher weathering resulting

445 from climate change.

446 Some compounds being used as substitutes for CFCs, such as

447 hydrochlorofluorocarbons (HCFCs), HFCs, and hydrofluoroolefins (HFOs), are known to

448 degrade to trifluoroacetic acid (TFA) in the atmosphere. TFA is a strong acid, and in sufficiently

449 large concentrations could produce damage to organisms. Because no sinks in the atmosphere

450 or in surface soils and waters have been identified, concern has been raised about its potential

451 accumulation over time in sensitive environments (e.g., salt lakes, wetlands, vernal pools).

452 Large natural sources of TFA have been invoked to explain high TFA concentrations in deep

453 oceanic waters[91] that have no contact with atmospheric gases for several millennia.

454 Anthropogenic sources include pesticides, pharmaceuticals, and industrial reagents. Current

455 estimates indicate that any incremental TFA burden from the CFC substitutes would be minor

456 compared to the other natural and anthropogenic sources, and the overall TFA concentrations

457 (from all sources) are expected to remain well below levels harmful to the environment[92].

458

459 **4. Conclusions and Knowledge Gaps**

460 The Montreal Protocol has prevented the global depletion of stratospheric ozone and

461 consequently large-scale increases in solar UV-B radiation. Changes in the ozone layer over the

462 next few decades are expected to be variable with increases and decreases in different

463 regions.[12] The return of column ozone to 1980 levels is expected to occur in the 2030s and

464 2050s respectively over northern- and southern-hemisphere mid-latitudes and around the 2060s

465 in Antarctica[12,93,94]. Thus, because of the Montreal Protocol, we have averted a "worst-case"

466   scenario of stratospheric ozone destruction, prevented the resultant high levels of UV-B at

467   Earth's surface, and so avoided major environmental and health impacts (Box 2).

468   We are confident in our qualitative predictions of the environmental effects that have

469   been avoided as a result of the implementation of the Montreal Protocol. However,

470   quantification of many of the environmental benefits resulting from the success of the Montreal

471   Protocol remains a challenge. The same knowledge gaps that constrain modelling of most

472   environmental effects in the 'World Avoided' scenario also constrain quantification of the

473   potential impacts of any current or future threats to the ozone layer. At present, no quantitative

474   estimates are available on the effects of the recently reported unexpected increases in

475   emissions of CFC-11[95] on stratospheric ozone, UV radiation or the environment. However,

476   were such unexpected emissions to persist and increase in the future, or new threats emerge,

477   environmental and health impacts could be substantial. New threats to the integrity of the

478   stratospheric ozone layer include 'geoengineering' activities proposed for combating warming

479   caused by greenhouse gases, which could have consequences for UV radiation. In particular,

480   proposals to inject sulfate aerosols into the stratosphere to reduce solar radiation at Earth's

481   surface[96] would likely reduce stratospheric ozone at most latitudes. The combined effect of

482   increased scattering by the aerosols and reduced absorption by ozone would then lead to

483   complex net changes in surface UV-B radiation[35,97-99].

484   Meeting the challenge of improving quantification of the environmental effects of future

485   changes in stratospheric ozone requires addressing several significant gaps in current

486   knowledge. First, we need a better understanding of the fundamental responses of humans and

487   other species to UV radiation, particularly how organisms respond to the different wavelengths

488   of UV radiation. Second, we need to better understand the full scope of not only the adverse

489   (e.g., skin cancer, impaired vision and unfavorable ecosystem changes), but the beneficial

490   effects (e.g., vitamin D, defense against plant pests and purification of surface waters) of UV

491   radiation on humans and other organisms. Third, we need long-term, large-scale field studies to

492   better understand how changes in UV radiation, together with other climate change factors,

493   including extreme events, affect intact ecosystems[100]. Taken together, all three would increase

494   our ability to develop models that could be used to quantify effects of UV radiation on living

495   organisms and materials on scales ranging from individuals to ecosystems and the planet.

496   As a consequence of rapid climate change, many organisms, including humans, are

497   being exposed to novel and interactive combinations of UV radiation and other environmental

498   factors. These environmental changes will continue into the future and will result in alterations in

499   the structure and composition of ecological communities[101], which will then indirectly affect the

500   growth, reproduction, and survival of many species. How humans and ecosystems respond to

501   changes in UV radiation against this backdrop of simultaneous, multi-factor environmental

502   change remains a major knowledge gap. Quantifying these effects is extremely challenging,

503   where many of the outcomes are contingent upon human behavior and societal responses that

504   are difficult to predict or measure (Fig. 2).

505   The focus of concern regarding increased exposure to UV radiation has historically been

506   on human health. However, terrestrial and aquatic ecosystems provide essential services on

507   which human health and well-being ultimately depend. In addition to being critical for human

508   health and well-being, environmental sustainability and the maintenance of biodiversity are also

509   important at a higher level if we are to maintain a healthy planet[102]. The topics covered by the

510   UNEP EEAP Quadrennial Assessment Report embrace the full complexity and inter-relatedness

511   of our living planet, and the outcomes of the Montreal Protocol (and Amendments and

512   Adjustments) demonstrate that globally united and successful actions on complex

513   environmental issues are possible.

514

515   **5. Acknowledgements**

529

530   **6. References**

531

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