

Title	Ozone depletion, ultraviolet radiation, climate change and prospects for a sustainable future
Authors	Barnes, Paul W.;Williamson, Craig E.;Lucas, Robyn M.;Robinson, Sharon A.;Madronich, Sasha;Paul, Nigel D.;Bornman, Janet F.;Bais, Alkiviadis F.;Sulzberger, Barbara;Wilson, Stephen R.;Andrady, Anthony L.;McKenzie, Richard L.;Neale, Patrick J.;Austin, Amy T.;Bernhard, Germar H.;Solomon, Keith R.;Neale, Rachel E.;Young, Paul J.;Norval, Mary;Rhodes, Lesley E.;Hylander, Samuel;Rose, Kevin C.;Longstreth, Janice;Aucamp, Pieter J.;Ballaré, Carlos L.;Cory, Rose M.;Flint, Stephan D.;de Gruijl, Frank R.;Häder, Donat-P.;Heikkilä, Anu M.;Jansen, Marcel A. K.;Pandey, Krishna K.;Robson, T. Matthew;Sinclair, Craig A.;Wängberg, Sten-Åke;Worrest, Robert C.;Yazar, Seyhan;Young, Antony R.;Zepp, Richard G.
Publication date	2019-06-24
Original Citation	Barnes, P. W., Williamson, C. E., Lucas, R. M. et al. (2019) 'Ozone depletion, ultraviolet radiation, climate change and prospects for a sustainable future', Nature Sustainability, 2, pp. 569–579 (2019). https://doi.org/10.1038/s41893-019-0314-2
Type of publication	Article (peer-reviewed)
Link to publisher's version	10.1038/s41893-019-0314-2
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Download date	2025-07-31 16:13:24
Item downloaded from	https://hdl.handle.net/10468/15373



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This document is the accepted manuscript version of the following article: Barnes, P. W., Williamson, C. E., Lucas, R. M., Robinson, S. A., Madronich, S., Paul, N. D., ... Zepp, R. G. (2019). Ozone depletion, ultraviolet radiation, climate change and prospects for a sustainable future. Nature Sustainability, 2(7), 569-579. https://doi.org/10.1038/s41893-019-0314-2

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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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- 5 6 Paul W. Barnes^{1*}, Craig E. Williamson², Robyn M. Lucas³, Sharon A. Robinson⁴, Sasha 7 Madronich⁵, Nigel D. Paul⁶ [Lead Authors], Janet F. Bornman⁷, Alkiviadis F. Bais⁸, Barbara 8 Sulzberger⁹, Stephen R. Wilson¹⁰, Anthony L. Andrady¹¹, Richard L. McKenzie¹², Patrick J. 9 Neale¹³, Amy T. Austin¹⁴, Germar H. Bernhard¹⁵, Keith R. Solomon¹⁶, Rachel E. Neale¹⁷, Paul J. 10 Young¹⁸, Mary Norval¹⁹, Lesley E. Rhodes²⁰, Samuel Hylander²¹, Kevin C. Rose²², Janice Longstreth²³, Pieter J. Aucamp²⁴, Carlos L. Ballaré²⁵, Rose M. Cory²⁶, Stephan D. Flint²⁷, Frank 11 R. de Gruijl²⁸, Donat-P. Häder²⁹, Anu M. Heikkilä³⁰, Marcel A.K. Jansen³¹, Krishna K. Pandey³², 12 T. Matthew Robson³³, Craig A. Sinclair³⁴, Sten-Åke Wängberg³⁵, Robert C. Worrest³⁶, Seyhan 13 Yazar³⁷, Antony R. Young³⁸, and Richard G. Zepp³⁹ 14 15 16
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¹Department of Biological Sciences and Environment Program, Loyola University New Orleans, 18 New Orleans, Louisiana, 70118, USA; ²Department of Biology, Miami University, Oxford, Ohio, 19 45056, USA; ³National Centre for Epidemiology and Population Health, The Australian National 20 21 University, Canberra, Australia; ⁴Centre for Sustainable Ecosystem Solutions, School of Earth, 22 Atmosphere and Life Sciences & Global Challenges Program, University of Wollongong, 23 Wollongong, NSW 2522, Australia; ⁵National Center for Atmospheric Research, Boulder, 24 Colorado, 80307, USA; ⁶Lancaster Environment Centre, Lancaster University, Lancaster LA1 25 4YQ, UK; ⁷College of Science, Health, Engineering and Education, Murdoch University, Perth, 26 WA, Australia; ⁸Laboratory of Atmospheric Physics, Aristotle University of Thessaloniki, 54124 27 Thessaloniki, Greece; ⁹Swiss Federal Institute of Aquatic Science and Technology (Eawag), 28 CH-8600 Dübendorf, Switzerland; ¹⁰Centre for Atmospheric Chemistry, School of Earth, 29 Atmosphere and Life Sciences, University of Wollongong, Wollongong, NSW 2522, Australia; 30 ¹¹Department of Chemical and Biomolecular Engineering, North Carolina State University, 31 Raleigh, NC 27695-7901, USA; ¹²National Institute of Water & Atmospheric Research, NIWA, Central Otago 9352, New Zealand: ¹³Smithsonian Environmental Research Center, Edgewater, 32 33 MD 21037, USA: ¹⁴University of Buenos Aires, Faculty of Agronomy and IFEVA-CONICET,

34 Buenos Aires, Argentina; ¹⁵Biospherical Instruments Inc., San Diego, CA 92110-2621, USA; 35 ¹⁶School of Environmental Sciences, University of Guelph, Guelph, ON, N1G 2W1 Canada; 36 ¹⁷QIMR Berghofer Medical Research Institute, Herston, Queensland, 4006, Australia; 37 ¹⁸Lancaster Environment Centre, Lancaster University, Lancaster, LA1 4YQ, UK; ¹⁹Biomedical 38 Sciences, University of Edinburgh Medical School, Edinburgh EH8 9AG, UK; ²⁰Centre for 39 Dermatology Research, The University of Manchester and Salford Royal NHS Foundation Trust, 40 Manchester M6 8HD, UK; ²¹Centre for Ecology and Evolution in Microbial Model Systems, 41 Linnaeus University, SE-39182 Kalmar, Sweden; ²²Department of Biological Sciences, 42 Rensselaer Polytechnic Institute, Troy, New York, 12180, USA; ²³The Institute for Global Risk Research, Bethesda, Maryland 20817, USA; ²⁴Ptersa Environmental Consultants, Faerie Glen, 43 0043, South Africa; ²⁵IFEVA, Faculty of Agronomy and CONICET, University of Buenos Aires, 44 C1417DSE Buenos Aires. Argentina: ²⁶Department of Earth and Environmental Sciences. 45 46 University of Michigan, Ann Arbor, Michigan, 48109, USA; ²⁷Department of Forest, Rangeland, and Fire Sciences, University of Idaho, Moscow, Idaho, 83844-1135, USA: ²⁸Department of 47 48 Dermatology, Leiden University Medical Centre, NL-2300 RC Leiden, The Netherlands; 49 ²⁹Friedrich-Alexander University, Erlangen-Nürnberg, Germany; ³⁰Finnish Meteorological Institute R&D/Climate Research, 00101 Helsinki, Finland; ³¹School of Biological, Earth and 50 Environmental Sciences, University College Cork, Cork, Ireland; ³²Institute of Wood Science 51 52 and Technology, Bengaluru-560003, India: ³³Organismal and Evolutionary Biology, Vikki Plant 53 Science Centre, 00014 University of Helsinki, Finland; ³⁴Cancer Council Victoria, Melbourne, 54 Australia: ³⁵Department of Marine Sciences, University of Gothenburg, SE-405 30 Göteborg, 55 Sweden; ³⁶CIESIN, Columbia University, New Hartford, Connecticut, 06057-4139; USA; 56 ³⁷Centre for Ophthalmology and Visual Science, University of Western Australia, Perth, WA, 57 6009, Australia; ³⁸St. John's Institute of Dermatology, King's College London, London SE1 9RT, UK; ³⁹United States Environmental Protection Agency, Athens, Georgia, 30605-2700, USA. 58 59 60 ^{*}Author for correspondence: Email: pwbarnes@loyno.edu; ORCID: 0000-0002-5715-3679 61 62 63 64 Author contributions: All authors helped in the development and review of this paper. P.W.B, C.E.W., R.M.L., S.A.R., S.M., and N.D.P. played major roles in conceptualizing and writing the 65 66 document; P.W.B. organized and coordinated the paper and integrated comments and revisions

on all the drafts. C.E.W., R.M.L., J.F.B., A.F.B., B.S., S.R.W., and A.L.A. provided content with

- the assistance of S.M., S.A.R., G.H.B., R.L.M., P.J.A., A.M.H., P.J.Y. (stratospheric ozone
- 69 effects on UV and ozone-driven climate change), R.E.N., F.R.G., M.N., L.E.R., C.A.S., S.Y.,
- A.R.Y. (human health), P.W.B., S.A.R., C.L.B., S.D.F., M.A.K.J., T.M.R. (agriculture and
- 71 terrestrial ecosystems), P.J.N., S.H., K.C.R., R.M.C., D.P.H., S-Å.W., R.C.W. (fisheries and
- 72 aquatic ecosystems), A.T.A., R.G.Z. (biogeochemistry and contaminants), K.R.S., J.L. (air
- 73 quality and toxicology), and K.K.P. (materials). R.L.M. conducted the UV simulation modelling.

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 time: however, the Montreal Protocol will continue to have far-reaching benefits for human well-85 86 being and environmental sustainability.

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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
Antarctica³ with smaller, but more widespread erosion of stratospheric ozone found over much
of the rest of the planet⁴. Subsequent studies clearly linked these ozone losses to the
emissions of CFCs and other ozone-depleting substances⁵ and, at least over Antarctica, unique
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 layer⁸. 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
- 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
- 114 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).

- 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
- surface UV-B radiation⁹⁻¹² (Box 2). Concentrations of chlorine and bromine from long-lived
- 120 ozone-depleting substances have been declining in the stratosphere since the late 1990s¹².
- 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 2001-2013¹². Global mean total ozone has
- been projected to recover to pre-1980 levels by about the middle of the 21st century, assuming
- 125 full compliance with the Montreal Protocol¹². 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 simulation¹¹ 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 tropics¹¹, 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 McKenzie¹¹. 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 Agency¹³ 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.

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While carbon dioxide (CO₂), methane (CH₄) and nitrous oxide (N₂O) 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 warming¹⁴. 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 131 ozone-depleting substances alone¹⁵. The adoption of the Kigali Amendment to the Montreal 132

Protocol in 2016 limits the production and consumption of hydrofluorocarbons (HFCs), which are non-ozone depleting substitutes for CFCs¹⁶. 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 century¹⁷. 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 date¹⁸⁻²⁰.

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.

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 change²¹, 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 elsewhere²². 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 Change²³ 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/

167 3. Key findings and highlights

168 3.1 Stratospheric ozone, climate change and UV radiation at Earth's surface

169 Stratospheric ozone depletion and climate change interact via several direct and indirect 170 pathways that can have consequences for food and water security, human well-being and 171 ecosystem sustainability (Figs. 1, 2). Climate change can modify depletion of stratospheric 172 ozone by perturbing temperature, moisture, and wind speed and direction in the stratosphere 173 and troposphere²⁴; and certain greenhouse gases (e.g., N₂O and CH₄) can affect ozone levels.¹² 174 Conversely, it is now clear that ozone depletion in the southern hemisphere is directly 175 contributing to climate change by altering regional atmospheric circulation patterns in this part of 176 the globe²⁵ which affects weather conditions, sea surface temperatures, ocean currents, and the 177 frequency of wildfires²⁶⁻³⁰. These ozone-driven changes in climate are currently exerting significant impacts on the terrestrial and aquatic ecosystems in this region³¹⁻³⁴ (Box 3). In the 178 179 northern hemisphere similar, but smaller effects of ozone depletion on climate may exist³⁵, but 180 year-to-year variability in the meteorology is greater than in the southern hemisphere, and there 181 are no reports as yet linking these changes to environmental impacts.

182 Depletion of stratospheric ozone leads to increased UV-B radiation at Earth's surface³⁵ 183 and the resultant changes in UV-B can directly affect organisms and their environment. 184 Because of the success of the Montreal Protocol, present-day increases in UV-B (quantified as 185 clear sky UV Index) due to stratospheric ozone depletion have been negligible in the tropics, 186 small (5-10%) at mid-latitudes, and large only in Antarctica. As stratospheric ozone recovers 187 over the next several decades¹², the clear-sky noon-time UV Index is expected to decrease 188 (e.g., by 2-8% at mid-latitudes depending on season and precise location, and by 35% during 189 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 (400700 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 cloudy³⁹. Increased cloud cover generally tends to reduce UV radiation at Earth's surface, but 204 effects vary with type of clouds⁴⁰ and their position relative to that of the sun⁴¹. Aerosols (solid 205 and liquid particles suspended in the atmosphere⁴²) 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 which are affected by climate change^{35,43,44}. In heavily polluted areas (e.g., southern and 208 eastern Asia), improvements in air quality resulting from measures to control the emissions of 209 210 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 areas³⁵. 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.

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220 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 <u>or</u> 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 population⁴⁵, 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 sunscreens³⁸. Warmer
 temperatures and changing precipitation patterns resulting from climate change will

- alter patterns of exposure to the sun in humans⁴⁶, 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 waters⁵¹⁻⁵⁴. 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 organisms⁵⁷.
- 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 regions⁵⁸. 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 increasing³².
- 261

262 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 Assessment²². 268

269 <u>3.3.1. Impacts on human health and air quality</u>

270 Higher exposure to solar UV radiation increases the incidence of skin cancers and other 271 UV-induced human diseases, such as cataracts and photosensitivity disorders³⁸. While 272 increases in the incidence of skin cancer over the last century appear largely attributable to 273 changes in behavior that increase exposure to UV radiation, these changes highlight how 274 susceptible some human populations would have been to uncontrolled depletion of 275 stratospheric ozone. Skin cancer is the most common cancer in many developed countries with 276 predominantly light-skinned populations³⁸. Melanoma accounts for less than 5% of skin cancers, 277 but has a much higher mortality than other skin cancers and accounts for approximately 60,000 278 deaths worldwide each year. Exposure to UV radiation accounts for 60-96% of the risk of 279 developing cutaneous malignant melanoma in light-skinned populations; globally, ca.168,000 280 new melanomas in 2012 were attributable to 'excess' exposure to UV radiation (above that of a 281 historical population with minimal exposure) corresponding to 76% of all new melanoma 282 cases⁶⁰. To date, stratospheric ozone depletion is expected to increase these numbers by a few 283 percent⁶¹ when integrated over a lifetime of exposure. Much larger increases in skin cancer 284 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 unclear³⁸.

291 Concern about high levels of UV-B radiation as a consequence of stratospheric ozone 292 depletion was an important driver for the development of programs for sun protection in many 293 countries. These programs focus on promoting changes in people's behavior, supported by 294 structural and policy-level interventions⁶³. Sun protection programs have been shown to be 295 highly cost effective in preventing skin cancers⁶⁴. Behavioral strategies need to be informed by 296 the real-time level of ambient UV radiation (provided by the UV Index) and include controlling 297 time outdoors together with using clothing, hats, sunscreen and sunglasses to reduce exposure 298 to UV radiation. Behavioral changes can be facilitated by providing shade in public spaces such 299 as parks, swimming pools, sports fields and playgrounds, and access to sunscreen⁶³.

301 Changes in UV radiation and climate can further impact human health by influencing air 302 quality⁴². A number of recent international assessments have concluded that poor air quality is 303 the largest cause of deaths globally due to environmental factors⁴². 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 ozone⁴². 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 elsewhere⁶⁵. 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 myopia³⁸. 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.



Trees Moss & or Crops

Cushion plants Dust

Lake

Fire

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 Brazil³². 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 drying³³. 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 Erickson³⁴ 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.

Penguins Seals Albatross Coral

Lobster

Fish

Plankton

Kelp

332 <u>3.3.2 Impacts on agriculture and food production</u>

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 productivity³¹. 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 2¹¹) 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 growth⁶⁷. In other cases, exposure to UV radiation can increase tolerance of plants to drought⁶⁸. 353 Increases in ground-level ozone resulting from reduced UV radiation resulting from the recovery 354 of stratospheric ozone could also negatively affect crop yields⁴². 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 development⁶⁹. These non-damaging effects 359 include alterations in plant chemistry, leading to changes in the nutritional quality of food⁷⁰ and 360 increased plant defenses against pests and pathogens⁷¹. 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 yield⁷². For certain vegetable 364 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,

366 resistance to pests⁷³.

367

368 <u>3.3.3 Impacts on water quality and fisheries</u>

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 ways³². 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 374 375 UV surface waters, have the potential to reduce juvenile population sizes and subsequent 376 harvest potential for fisheries⁷⁴. 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 species⁷⁵.

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 pathogens⁵⁹. 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 <u>3.3.4 Impacts on biogeochemical cycles, climate system feedbacks and biodiversity</u>

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 ecosystems⁸¹. 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 Altiplano⁸² and 405 moss and other plant communities in Antarctica³³. 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 systems⁴⁴.

411

412 <u>3.3.5 Impacts on contaminants and materials</u>

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 fish⁸³. 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 pollutants⁴³. 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

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 corals⁸⁴, sea urchins⁸⁵, fish⁸⁶, 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.

428 Similar legislation is under consideration by the European Union⁸⁷.

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 them⁸⁸. 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 consumption⁸⁹. 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 performance⁹⁰. 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 waters⁹¹ 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 environment⁹². 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"

scenario of stratospheric ozone destruction, prevented the resultant high levels of UV-B atEarth'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-11⁹⁵ 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 surface⁹⁶ 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 complex net changes in surface UV-B radiation^{35,97-99}. 483

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 ecosystems¹⁰⁰. 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

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 communities¹⁰¹, 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
- 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 important at a higher level if we are to maintain a healthy planet¹⁰². The topics covered by the 509 510 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**

516 This work has been supported by the UNEP Ozone Secretariat and we are grateful to T. 517 Birmpili and S. Mylona for their guidance and assistance. Additional support was provided by 518 the U.S. Global Change Research Program (P.W.B., C.E.W., and S.M.), the J.H. Mullahy 519 Endowment for Environmental Biology (P.W.B.), The U.S. National Science Foundation (Grants 520 DEB 1360066 and DEB 1754276 to C.E.W.), The Australian Research Council (DP180100113 521 to S.A.R.) and the University of Wollongong's Global Challenges Program (S.A.R.). We 522 appreciate the contributions from other UNEP EEAP members and co-authors of the EEAP 523 Quadrennial Report, including: M. Ilyas, Y. Takizawa, F.L. Figueroa, H.H. Redhwi, and A. 524 Torikai. Special thanks to A. Netherwood for his assistance in drafting and improving figures. 525 This paper has been reviewed in accordance with the U.S. Environmental Protection Agency's 526 (U.S. EPA) peer and administrative review policies and approved for publication. Mention of 527 trade names or commercial products does not constitute an endorsement or recommendation 528 for use by the U.S. EPA.

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