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United Nations Environment Programme (UNEP), Questions and Answers about the Effects of Ozone Depletion, UV Radiation, and Climate on Humans and the Environment. Supplement of the 2022 Assessment Report of the UNEP Environmental Effects Assessment Panel

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Abstract

This collection of Questions & Answers (Q&As) was prepared by the Environmental Effects Assessment Panel (EEAP) of the Montreal Protocol under the umbrella of the United Nations Environment Programme (UNEP). The document complements EEAP's Quadrennial Assessment 2022 (https://ozone. unep.org/science/assessment/eeap) and provides interesting and useful information for policymakers, the general public, teachers, and scientists, written in an easy-to-understand language.

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Questions and Answers about the Effects of Ozone Depletion, UV Radiation, and Climate on Humans and the Environment

Supplement of the 2022 Assessment Report of the UNEP Environmental Effects Assessment Panel

UN environment programme | ozone secretariat

Montreal Protocol on
Substances that
Deplete the Ozone Layer

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Cover image: View from Tahquitz Peak, Southern California, towards the West. Radiation from the setting Sun is attenuated by smoke and haze from a wildfire, illustrating the effect of aerosols on UV and visible radiation. Photo by Germar H. Bernhard

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Introduction

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The Montreal Protocol is an international treaty with the goal to protect the Earth's ozone layer, which guards life on our planet from harmful ultraviolet (UV) radiation from the Sun. The treaty has been agreed upon by all member states of the United Nations and aims to limit the release of chemical substances into the Earth's atmosphere that harm the ozone layer. These chemicals are called "ozone depleting substances" or simply ODSs. As part of the Montreal Protocol, several advisory bodies were established to annually assess important new scientific information on changes in the ozone layer and how these may affect life on Earth, as well as to evaluate alternative technologies that would allow elimination of the ODSs. The EEAP is one of these advisory bodies and assesses the various environmental effects of ozone layer depletion.

The Q&As discuss the importance of UV radiation for life on Earth and consider both harmful and beneficial effects. They also describe changes in UV radiation that have occurred in the past and are predicted to take place during the 21st century. Some of these changes are also linked to climate change. The Q&As focus on consequences from changes in ozone on human health and life on land, lakes, and the oceans.

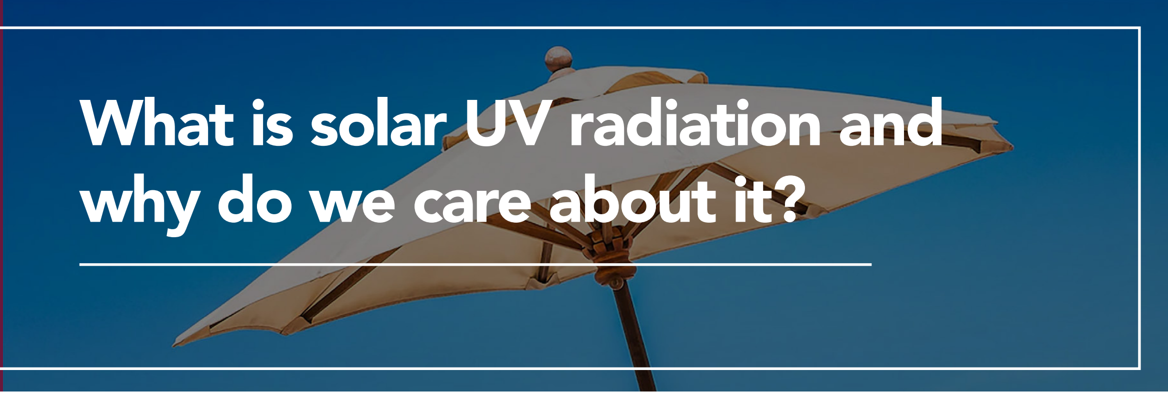
You will find that the scope of the Q&As reflect the links among many important issues influencing life. Aside from the atmospheric and biological roles, UV radiation, ozone, and climate change play a part in the quality of the air we breathe. The last two Q&As discuss the effects of UV radiation on materials used for buildings and other applications and the role of UV radiation in plastic pollution on land and in the oceans.

Taken together, the Q&As highlight the crucial role of the Montreal Protocol in protecting life on Earth and are aimed at increasing our understanding so that we can continue to pursue innovative ways to maintain environmental sustainability and quality of life.

Janet F. Bornman
Co-Chair, Environmental Effects Assessment Panel

Q1

What is solar UV radiation and why do we care about it?



Solar ultraviolet (UV) radiation is part of the electromagnetic radiation originating from the Sun. In contrast to visible light, which we can see, UV radiation is invisible and more energetic. Because of its higher energy, UV radiation can break chemical bonds of molecules, including those of DNA, which is the molecule that contains the genetic code of most organisms. Damage to this molecule can result in multiple health effects, including skin cancers. UV radiation can also adversely affect agricultural and aquatic productivity as well as air quality. It can also reduce the effective lifespan of materials such as plastics and paints. However, some UV radiation is beneficial for human health as it produces vitamin D in the skin and can kill pathogens.

There are different types of UV radiation. UV radiation is divided into UV-C, UV-B, and UV-A. UV-C is the most energetic type and exposure to it is particularly dangerous to all life forms. Fortunately, UV-C radiation is entirely absorbed by oxygen and ozone molecules high up in the Earth's atmosphere (**Figure Q1-1**). Most of UV-B radiation emitted by the Sun is also absorbed by the ozone layer; however, some of it reaches the Earth's surface. In humans, exposure to UV-B radiation causes sunburn, increases the risks of skin cancer and cataracts, and suppresses the immune system (see **Q4**). Excessive exposure to UV-B radiation can also damage terrestrial plants, including agricultural crops (see **Q6**), aquatic ecosystems (see **Q7**), and materials used for construction and textiles (see **Q11**). UV-A radiation is the least energetic type and is only weakly absorbed by the ozone layer but can still cause some adverse health effects such as premature aging of the skin.

The UV Index is a measure of the amount of harmful UV radiation to human health. The intensity of solar UV radiation relevant to human health is typically quantified with the UV Index, which is a measure of the amount of UV radiation causing sunburn (also called "erythema"). Solar UV-B and UV-A radiation make up about 90% and 10% of the UV Index, respectively. The UV Index is an internationally recognised number and was introduced to increase public awareness about the detrimental effects of UV radiation on human health and to emphasize the need for using personal protective measures (**Figure Q1-2**). For example, when the UV Index is moderate or high, the World Health Organization's advice is to "seek shade, slip on a shirt, slop on sunscreen, and slap on a hat". When the UV Index at noon is very high or extreme, the advice is to either avoid being outside during midday hours or seek shade at all times, wear a shirt and hat, and apply sunscreen with an appropriate protection factor.

EXPOSURE CATEGORY	UV RANGE
🟩 LOW	< 2
🟨 MODERATE	3 TO 5
🟧 HIGH	6 TO 7
🟥 VERY HIGH	8 TO 10
🟪 EXTREME	11 +

Figure Q1-2. Relationship between exposure categories and ranges for the UV Index.

Several factors affect the intensity of UV radiation. On days without clouds, the main parameters that determine the intensity of UV radiation at the Earth's surface are the

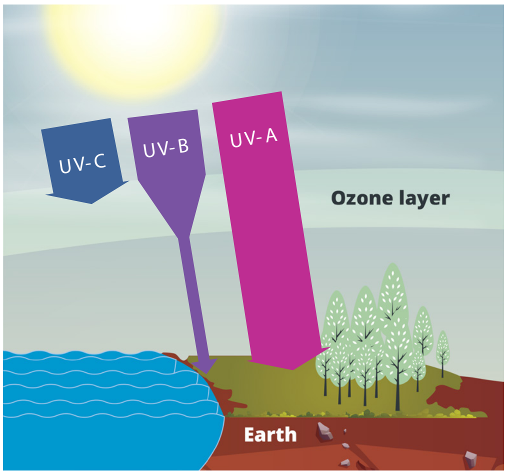


Figure Q1-1. The ozone layer in the stratosphere protects the Earth's surface from harmful UV radiation. *The ozone layer surrounds the entire Earth and is mainly located between 15 and 40 km from the ground, within the Earth's stratosphere. UV-C radiation is entirely absorbed within the ozone layer, UV-B is only partially absorbed, while UV-A and other wavelengths such as visible light and infrared radiation are only weakly absorbed. Depletion of the ozone layer primarily increases the amount of UV-B radiation that reaches the Earth's surface. Preventing excessive ozone depletion that would increase human exposure to UV-B radiation is a principal objective of the Montreal Protocol (see* ***Q2****). UV radiation is part of the electromagnetic radiation originating from the Sun. Scientists classify the three types of UV radiation in terms of their wavelength, measured in nanometre (nm): UV-C ranges from 100 to 280 nm, UV-B from 280 to 315 nm, and UV-A from 315 to 400 nm (1 nanometre equals one billionth of a metre).*

elevation of the Sun above the horizon and the amount of ozone in the atmosphere above the specific location. Consequently, the intensity of UV radiation is highest in the tropics, where the Sun is sometimes directly overhead at noon and where the amount of ozone is less than at middle latitudes. UV radiation is also attenuated by particles suspended in the atmosphere such as dust, smoke, soot, and sea salt, collectively called aerosols (see **Q9**). Measures to curb air pollution in cities and industrial regions reduce aerosols, thereby restoring UV radiation levels to those of a cleaner atmosphere (see also **Figure Q2-2**). UV radiation is also influenced by altitude, seasonal changes in Sun-Earth separation (the Earth is closest to the Sun in December and January and farthest away in June and July), and the reflection of the ground (**Figure Q1-3**). For example, fresh snow reflects upward more than 90% of the incoming UV radiation and some of this radiation is scattered back towards the ground. Under these conditions, the UV Index can be up to 60% greater over snow-covered than snow-free ground. Clouds can reduce UV radiation by more than 90% but the reduction is less than for visible radiation. Thin clouds, such as cirrus, have little effect on the intensity of UV radiation at the Earth's surface. UV radiation may therefore cause sunburn on overcast days even when the sky looks relatively dark. On the other hand, clouds that surround the Sun but do not block the Sun can lead to increases in UV radiation that can exceed the UV radiation under cloud-free skies. The intensity of UV radiation under water can still be high and depends on the clarity of the water, which is greatly affected by dissolved organic matter (see **Q7**).

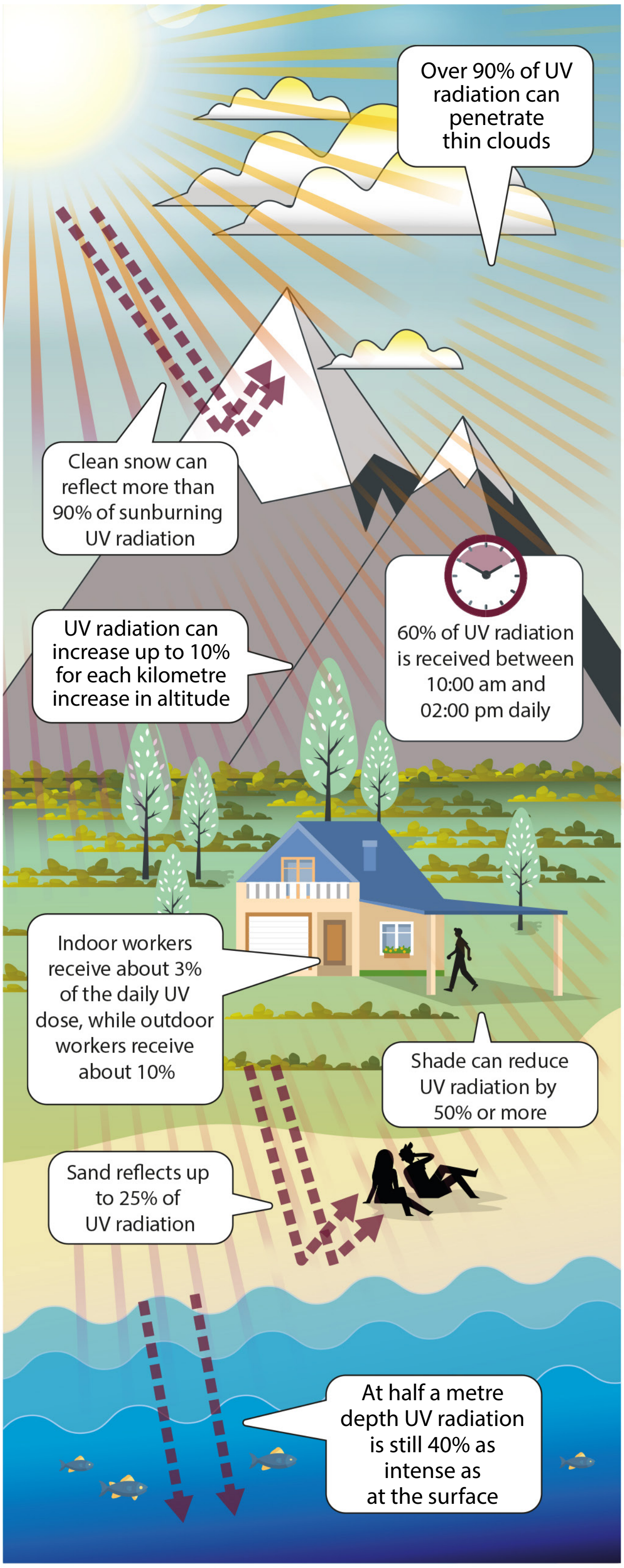


Figure Q1-3. Factors determining the intensity of UV radiation at the Earth's surface.

Decreases in ozone lead to increases in the UV Index. For a given solar elevation, the UV Index depends greatly on the amount of ozone in a vertical column extending from the Earth's surface to the top of the atmosphere (**Figure Q1-4**). This column is referred to as "total ozone" and is reported in Dobson Units (DU). One DU corresponds to a hypothetical layer of pure ozone with a thickness of 0.01 millimetre when compressed to the pressure at the Earth's surface. Averaged over the Earth's surface and over the year, total ozone is about 300 DU, which relates to a layer of pure ozone that is three millimetres thick (the height of a stack of two common coins).

A 1% decrease in the total ozone leads to an increase in the UV Index of about 1.2%. However, for larger changes in ozone (for example, for the large decreases experienced under the

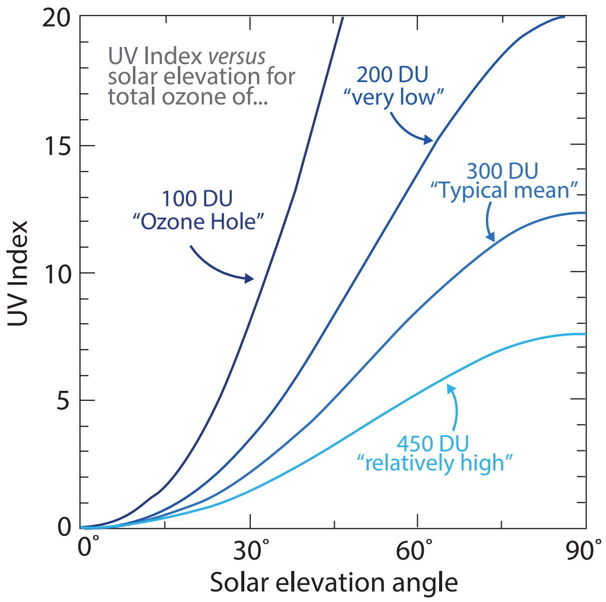


Figure Q1-4. Effect of solar elevation and total ozone on the UV Index. *The UV Index is plotted against the Sun's elevation above the horizon for different amounts of total ozone. Total ozone as low as 100 DU has only been observed under the Antarctic ozone hole. The typical mean ozone column at mid-latitudes is 300 DU, while a high ozone column of 450 nm may be observed during spring at mid-latitudes.*

Antarctic ozone hole), increases in the UV Index are much larger. For example, a 50% reduction in the total ozone results in more than a doubling of the UV Index (**Figure Q1-5**).

UV radiation is unevenly distributed around the globe. Figure Q1-6 illustrates the maximum UV Index across the globe. In the tropics, the UV Index can exceed 16 at sea level and reach 25 at high altitudes like the Altiplano region in Chile. The UV Index has significantly higher summer maxima in the Southern Hemisphere compared with corresponding latitudes in the Northern Hemisphere because of differences in total ozone and Sun-Earth separation. Generally, peak UV Index values decrease with increasing latitude. However, the Antarctic region, which is affected by the Antarctic ozone hole, is a notable exception. There, the maximum UV Index can be comparable to that in the tropics (see also **Figure Q2-1**). Outside the protective Earth's atmosphere, the UV Index exceeds 300.

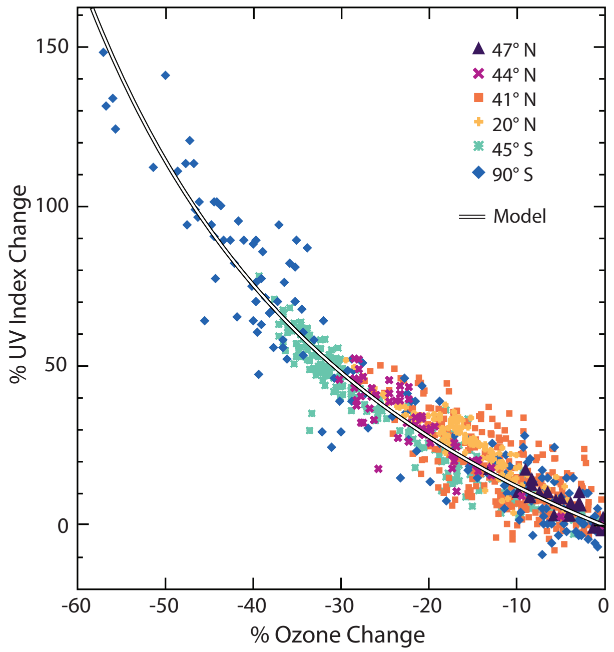


Figure Q1-5. The relationship between changes in total ozone and the UV Index. *Symbols illustrate this relationship using data of total ozone and the UV Index measured at six sites at different latitudes. The dependence of the UV Index on total ozone was also calculated theoretically and is shown by the smooth curve labelled "Model".*

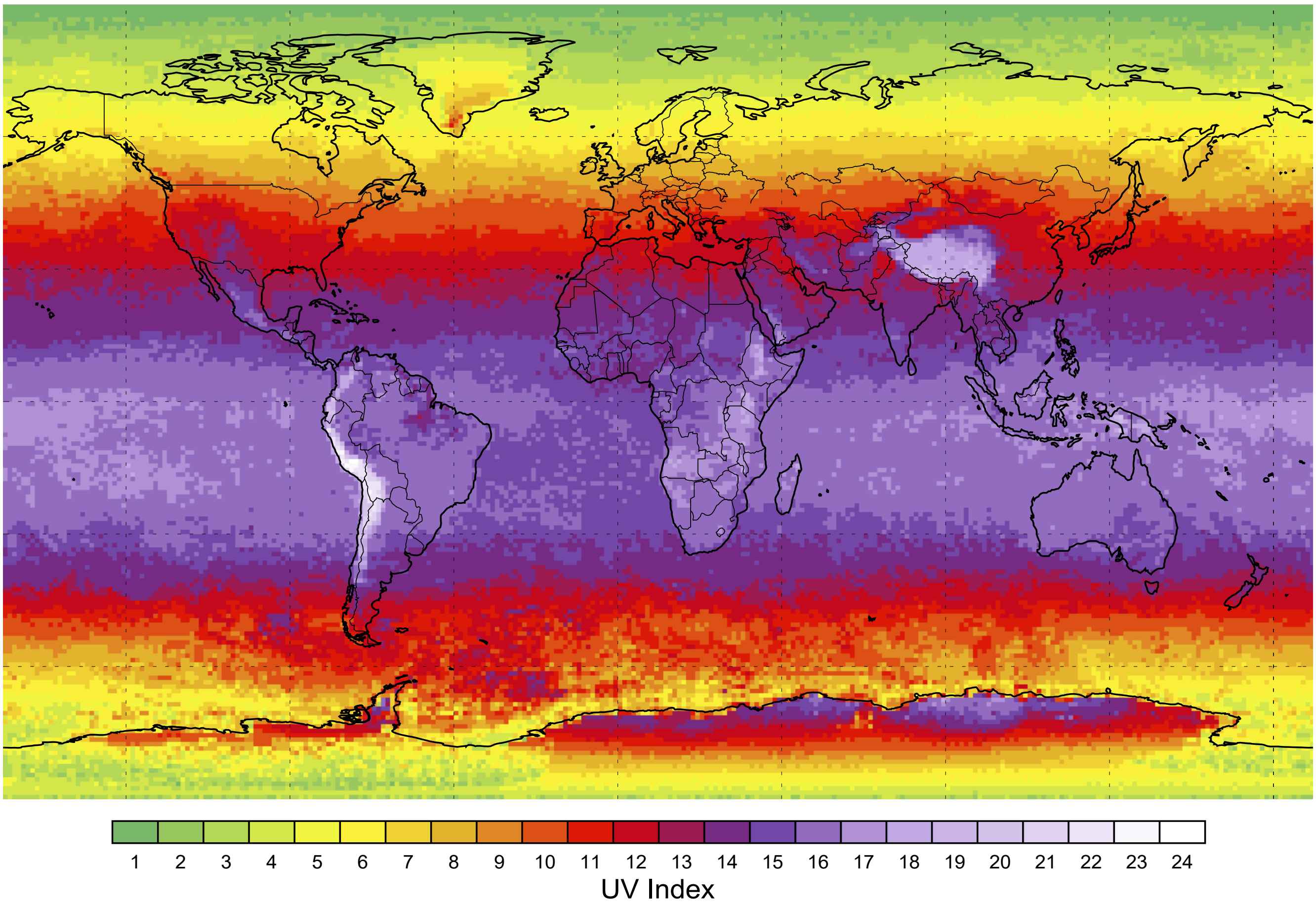


Figure Q1-6. The maximum UV Index at the Earth's surface derived from satellite measurements. *The highest UV Index on Earth is observed near the equator at high-altitude sites. Because of the ozone hole, the UV Index at the coast of Antarctica can sometimes be as high as in the tropics.*

Q2

How has solar UV radiation changed in the past and what changes are predicted for the future?

Reductions in stratospheric ozone between the 1970s and the early 1990s, which were caused by manufactured ozone-depleting substances (ODSs) such as chlorofluorocarbons, have led to increases in UV radiation by a few percent at middle latitudes and by much larger amounts in Antarctica. These ODSs caused the Antarctic ozone hole, which has been observed over the South Pole every spring since the 1980s. Without the Montreal Protocol and its Amendments, the depletion of stratospheric ozone and the consequent increases in UV radiation would have continued. Because of the successful implementation of this international treaty, the ozone layer is now starting to recover. Levels of UV radiation during the last ~25 years have not increased at most locations and are now mainly affected by variations in clouds and aerosols.

UV radiation increased above normal levels between the 1970s and the early 1990s. Long-term changes in UV radiation have been calculated using data from ground-based radiometers and instruments installed on satellites. Unfortunately, systematic monitoring of UV radiation on the ground started only in the early 1990s. For this reason, estimates of UV radiation levels at the Earth's surface prior to this date rely mostly on satellite observations, which started in the 1970s, or on reconstructions using total ozone measurements and other data such as sunshine duration for characterising long-term changes in cloudiness. These observations and reconstructions indicate that UV radiation at middle latitudes (25–50°) of both hemispheres increased by about 3–5% between the early 1980s and the early 1990s. However, increases under the Antarctic ozone hole were much larger. The maximum UV Index at Palmer Station, a research station on the Antarctic coast, has more than doubled compared to the 1970s before the ozone hole had developed (**Figure Q2-1**). In recent years, the UV Index at Palmer Station has occasionally exceeded UV Index maxima in San Diego, a mid-latitude city near the border of the United States and Mexico, despite the much lower latitude of San Diego compared to Palmer Station. In contrast, significant increases in UV radiation have not been observed over the tropics. Because UV radiation is also affected by aerosols and clouds (see **Q1** and **Q6**), changes in UV radiation in some regions were more driven by changes in clouds and air pollutants than by changes in the amount of stratospheric ozone (**Figure Q2-2**). For example, the rapid economic development of East Asia, which started

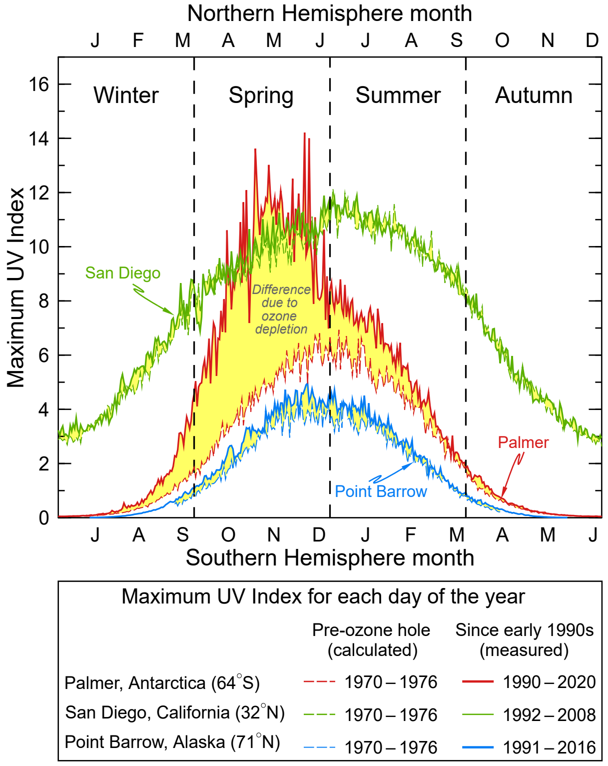


Figure Q2-1. Differences in the UV Index at different latitudes and times of the year. *The figure compares the highest UV Index ever measured for each day of the year at Palmer Station (a station on the Antarctic coast), San Diego (a city near the border of the United States and Mexico), and near Point Barrow (the northern-most point in Alaska) for two periods: before the ozone hole had formed (1970 – 1976, broken lines) and the contemporary period starting in the early 1990s, during which the ozone hole has been fully developed (solid lines). The yellow shades indicate the difference between the two periods. Historically, the maximum UV Index at Palmer Station was well below that at San Diego. Because of the ozone hole's influence, the highest UV Index measured at Palmer Station has more than doubled since the 1970s and may nowadays occasionally exceed maxima observed at San Diego. In contrast, peak UV Indices at Barrow are considerably smaller than those at Palmer Station and have changed only modestly (18% on average) between the two periods. This relatively small increase can be explained by the weaker spring-time ozone depletion in the Arctic compared to Antarctica. At San Diego, historical and contemporary data are almost indistinguishable. On average, UV Indices increased only by about 3% since the 1970s.*

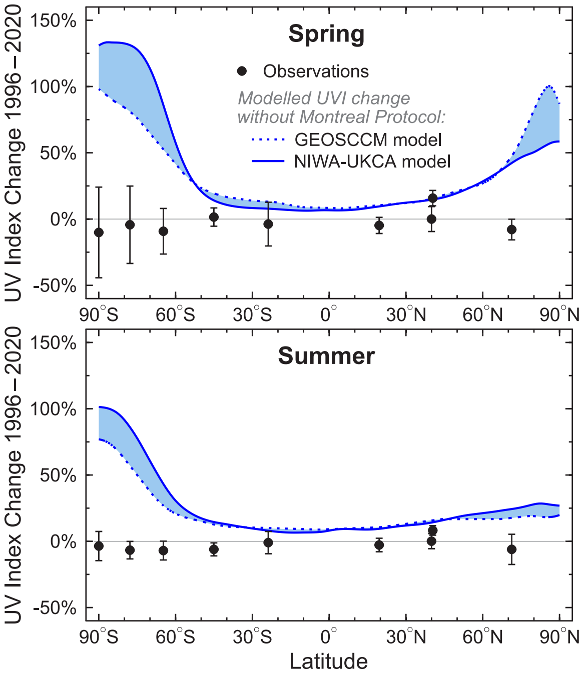


Figure Q2-2. Comparison of observed changes in the UV Index between 1996 and 2020 and estimated changes without the Montreal Protocol. *Circles and vertical bars indicate the best estimates and their plausible range for changes in the UV Index that have occurred between 1996 and 2020. These estimates were derived from observations at mostly unpolluted sites (nine ground stations ranging in latitude from the South Pole (90° S) to Barrow (71° N), Alaska) for spring (top) and summer (bottom). The solid and dotted blue lines are the results of simulations using two different chemistry-climate models that assume a world without the Montreal Protocol, where emissions of ozone-depleting substances would not be controlled. Without the Montreal Protocol, the UV Index would have increased by 10–20% at middle latitudes and more than doubled at the South Pole in spring. Except for one urban site at 41° N (Thessaloniki, Greece), observed changes in the UV Index have been small at all sites and smaller than the scenarios predicted by the two climate models. These observations confirm that the Montreal Protocol has prevented large increases in UV radiation, in particular at southern latitudes higher than 60° S. The relatively large increases in the measured UV Index at Thessaloniki (8% for summer and 16% for spring) are mostly caused by reductions in atmospheric aerosols resulting from measures to control air pollution at this urban site, showing the importance of factors other than ozone in determining UV radiation levels at the Earth's surface (see* ***Q1****).*

in the early 1980s, led to large increases in atmospheric aerosols. In some regions, this caused a decrease in UV radiation of more than 25% compared to pre-industrial times.

The Montreal Protocol helped the ozone layer to recover. The Montreal Protocol and its Amendments have been very successful in reducing the atmospheric abundance of ozone-depleting substances (ODSs). These substances include halogen gases such as chlorofluorocarbons (CFCs) released by human activities. Because the Montreal Protocol was ratified by all 198 member states of the United Nations, the production and consumption of ODSs are now controlled worldwide. As a consequence, the amount of ODSs released in the atmosphere is now decreasing and the stratospheric ozone layer is starting to recover. However, the recovery process is slow, as the rate at which ODSs get removed from the atmosphere is three to four times slower than the rate at which they were emitted in the 1980s. It will therefore take several decades until the ozone layer has fully recovered. Furthermore, concentrations of stratospheric ozone will also depend on future emissions of greenhouse gases such as carbon dioxide, which cool the stratosphere. Current climate models predict that this cooling will lead to increases in ozone. Stratospheric ozone at the end of the 21st century will therefore likely be higher compared to the 1970s when ozone depletion started.

The intensity of UV radiation has changed very little between the 1990s and today. Since ozone recovery is a slow process, UV radiation levels observed between the 1990s and today have been essentially constant at unpolluted sites (**Figure Q2-2**). At most sites, year-to-year changes in UV radiation are more driven by variations in aerosols and clouds than stratospheric ozone. Conversely, climate models suggest that without the Montreal Protocol and its Amendments, the UV Index would have increased by 10–20% at middle latitudes between 1996 and 2020. At the South Pole, ozone depletion would have continued and the UV Index in spring would have more than doubled over that period (**Figure Q2-2**).

Greenhouse gases and aerosols influence the prediction of UV radiation levels throughout the 21st century. Estimates of future total ozone, aerosols, and clouds are obtained from "chemistry-climate" models. The results of these calculations are then used as inputs in other models (called radiative transfer models) that calculate changes in UV radiation over time. Results from the latest simulations suggest that the rising concentration of greenhouse gases will impact total ozone (and thus, the UV Index) in the future. For simulations where the amount of atmospheric aerosol remains fixed at current levels, the UV Index at mid-latitudes is projected to decrease slightly from 2015 to 2090 (3% in the Northern Hemisphere and 6% in the Southern Hemisphere). Decreases predicted for high latitudes are larger as both the Antarctic ozone hole and Arctic ozone depletion will decline. No significant changes in the UV Index are projected over the tropics. In regions that are currently affected by air pollution, the UV Index is projected to increase if emissions of air pollutants are curtailed in the future. The magnitude of this increase depends greatly on policy decisions. For this reason, we cannot reliably predict changes in UV intensities in regions that are currently greatly affected by air pollution.

Q3

Has depletion of ozone changed climate and weather?

While stratospheric ozone depletion is not the principal cause of climate change, it has contributed to changes in climate and weather in certain regions of the Earth. The greatest effect has been observed in the Southern Hemisphere outside the tropics. Ozone depletion and climate change intertwine because both ozone and most substances that deplete the ozone layer are greenhouse gases. Variations in their concentrations therefore lead to changes in the air temperature near the Earth's surface. Furthermore, the Antarctic ozone hole has led to a southward shift of climate zones in the Southern Hemisphere with effects on climate, weather, and the environment.

Ozone-depleting substances contribute to global warming. The ozone-depleting substances (ODSs) regulated under the Montreal Protocol (see **Introduction**) are also strong greenhouse gases. Thus, they warm the air near the surface of the Earth by trapping heat. Over the second half of the 20th century, the combined effect of all ODSs was the second largest contributor to global warming after carbon dioxide, the most important greenhouse gas. By reducing the emissions of ODSs the Montreal Protocol has already prevented warming between 0.5 to 1.0 °C (0.9 to 1.8 °F) over mid-latitude regions of Africa, North America, and Eurasia, and by as much as 1.1 °C (2.0 °F) in the Arctic. Between 1955 and 2005, ODSs were responsible for about one-third of warming globally, and for about half of the warming in the Arctic. However, these estimates are expected to be slightly revised in the future. Because ozone is also a greenhouse gas, the depletion of ozone caused by ODSs tends to cool the Earth's surface. The magnitude of this cooling response is still not well understood.

Stratospheric ozone depletion influences climate and weather. While ODSs warm the atmosphere near the Earth's surface, they exert a cooling effect up in the stratosphere. This cooling is most pronounced inside the Antarctic ozone hole and leads to changes in winds circling Antarctica at high altitudes (the stratospheric polar vortex). These changes in winds also affect lower layers of the atmosphere and have caused a southward shift of climate zones in the Southern Hemisphere. As a result, precipitation near Antarctica has increased, and the subtropical dry zone has moved south in summer during the last decades of the 20th century. This correlates with large increases in rainfall during summer in northern Argentina, Uruguay, southern Brazil, Paraguay, and subtropical regions of eastern Australia, while southern

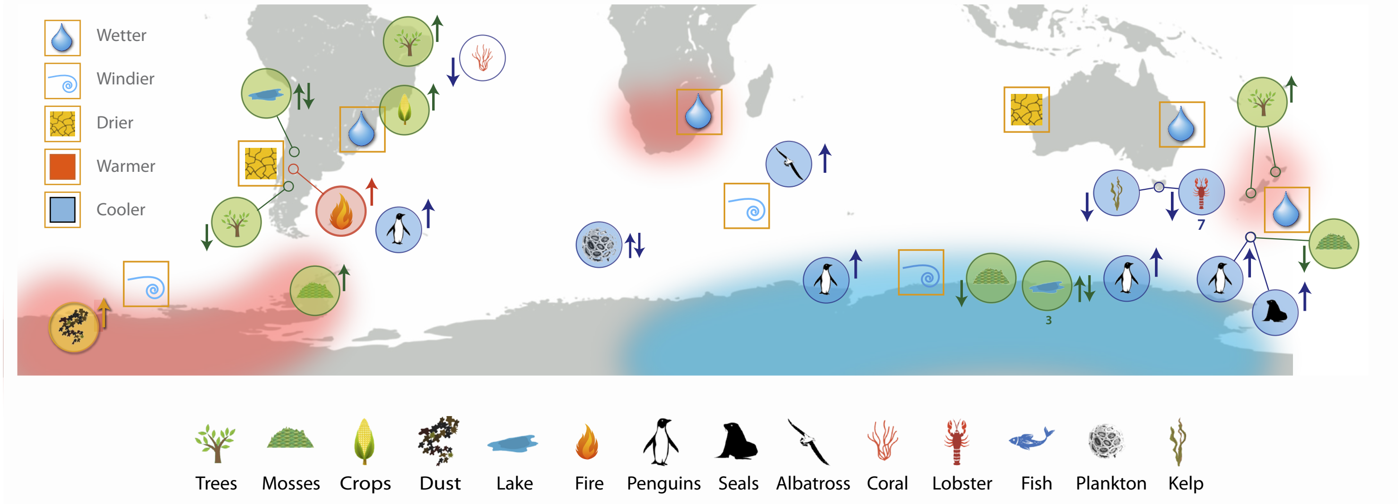


Figure Q3-1. Map of the Southern Hemisphere showing how stratospheric ozone depletion may have affected climate and environment, and the effects of these changes on terrestrial ecosystems and populations. *The map shows associations between stratospheric ozone depletion and effects on the environment. Symbols show types of organisms, ecosystems or entities affected (see legend below the figure). Arrows indicate direction of effects on biodiversity; up = positive, down = negative effect. Two-way arrows indicate changed biodiversity. Red and blue shading indicate regions that became warmer or cooler, respectively. Areas that became wetter, windier, and drier are indicated with the respective symbols. The mechanisms by which ozone depletion mediates these various changes have not yet been established for all environmental indicators.*

South America became drier (**Figure Q3-1**). Observed changes in temperature and precipitation also correlate with the abundance and distribution of plants and animals, such as penguins and seals, and affect ecosystems in the Southern Hemisphere. Year-to-year changes in the depth and size of the Antarctic ozone hole are strongly dependent on the strength and size of the polar vortex, which is also influenced by changes in weather outside the polar regions, for example, the temperature of the Pacific Ocean. Because of the many links between the factors that drive changes in climate, it is difficult to distinguish the effect of ozone depletion from other factors. Therefore, the effect of ozone depletion on changes in regional weather patterns in the Southern Hemisphere is still not completely understood.

Ozone recovery reverses climate and weather trends. Models suggest that the expected recovery of stratospheric ozone over the first half of the 21st century would reverse the shift of climate zones towards the poles, leading instead to an equatorward movement. However, this reversal is countered by the expected increase in greenhouse gases such as carbon dioxide. If atmospheric concentrations of greenhouse gases continue to rise, the poleward movement of climate zones is then likely to endure. In the second half of the 21st century — when ODSs will be mostly removed from the atmosphere and the seasonal ozone hole will no longer occur — the effects from greenhouse gases will dominate, and climate zones will shift further towards the poles. It is still unclear how this shift would affect weather patterns in South America, South Africa, and Australia because of the many climate feedbacks (for example, changes in sea ice and ocean temperatures) that may develop over the next 50 years.

Stratospheric ozone depletion has been less severe in the Arctic than in the Antarctic. For this reason, the effect of Arctic ozone depletion on weather in the Northern Hemisphere is less well established. However, there is evidence that the exceptionally large Arctic ozone depletion in March–April 2020 contributed to abnormally high temperatures across Asia and Europe in the months that followed the event. For example, the temperature in the Siberian town of Verhojansk set a new record of 38 °C (100 °F) on 20 June 2020, which is the highest temperature ever documented near the Arctic Circle.

Q4

What are the harmful effects of sun exposure on human health?

Exposure to UV radiation causes damage to the skin and eyes. Exposing the skin to UV radiation causes sunburn, skin ageing, skin cancer, and inflammatory skin conditions. Exposing the eyes causes conditions such as cataract and pterygium. The risks are particularly high for people with light skins living in areas where the intensity of UV radiation is very high, such as in Australia and New Zealand.

Exposing the skin to sunlight can cause sunburn and skin cancer. Acute overexposure of the skin to solar UV radiation causes sunburn, which presents as redness in people with light skin, and can cause pain, blistering and peeling. Repeated exposure to sunlight exposure can lead to skin aging and skin cancers.

There are three common skin cancers caused by exposing the skin to UV radiation. These are melanoma, squamous cell carcinoma and basal cell carcinoma. Squamous and basal cell carcinomas are collectively called keratinocyte cancers. Melanoma is the most fatal type of skin cancer. It affects approximately 325,000 people worldwide each year and causes around 57,000 deaths. It has been estimated that between 62% and 96% of melanomas are caused by exposing the skin to the Sun, depending on the intensity of UV radiation in a specific country and on the method used to calculate this percentage. Keratinocyte cancers can cause significant disfigurement, particularly when they occur on the face, but they are rarely fatal. However, they can be deadly in some people, particularly those that have received an organ transplant or are on drugs that suppress their immune system. Because they occur so frequently in some countries, keratinocyte cancers are a major burden on health systems. For example, in Australia these are the most expensive of all cancers, costing around AUD $1.3 billion per year.

Sun exposure causes skin cancer by damaging DNA and suppressing the immune system. Exposing the skin to UV radiation causes skin cancer through multiple mechanisms (**Figure Q4-1**). UV-B radiation directly damages the DNA within the cells. UV-A and, to a lesser extent, UV-B radiation can also indirectly damage DNA through the production of reactive oxygen species generated by adjacent molecules. Most DNA damage is repaired. However, if repair does not occur before the cell divides, the mutation persists and is passed to the two new cells that are created during cell division. Each of these newly created cells can undergo further DNA damage and pass these additional mutations to their daughter cells. If the accumulation of DNA mutations continues, cells eventually lose control of cellular division and become cancerous. The immune system plays a critical role in recognising and destroying cancerous cells, but unfortunately exposure to UV radiation suppresses the immune system. Thus, UV radiation causes both the damage that drives cells to become cancerous and stops the immune system from finding and destroying the cancerous cells.

It has been estimated that the Montreal Protocol will have prevented approximately 11 million melanomas and 432 million keratinocyte cancers that would have otherwise occurred in the United States in people born between 1890 and 2100.

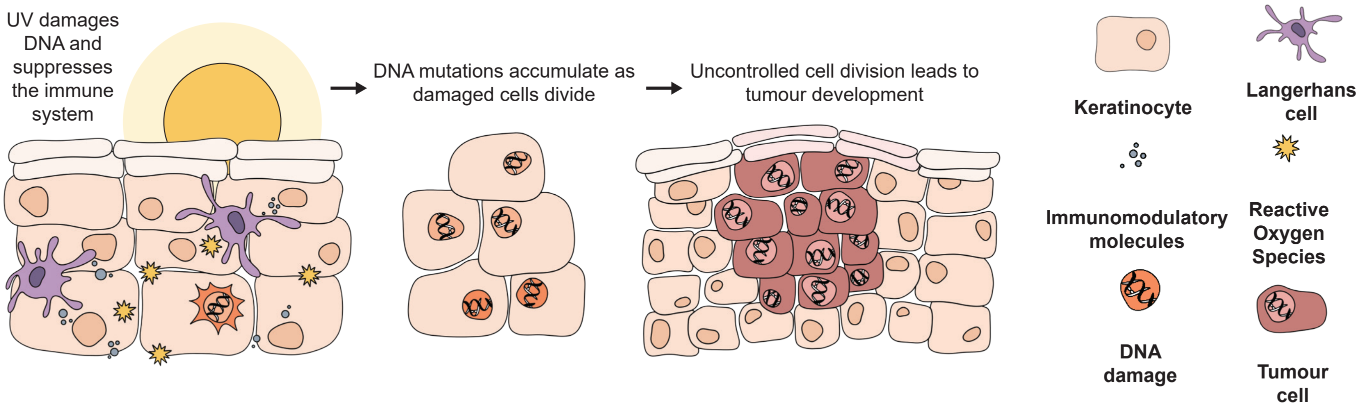


Figure Q4-1. UV radiation causes skin cancer through a variety of mechanisms. *These mechanisms include direct DNA damage, indirect damage through production of reactive oxygen species, and immune suppression. Keratinocytes are cells in the top layer of our skin (the epidermis). Most of the cells in the epidermis are keratinocytes. Langerhans cells are immune cells that reside within the skin. Immunomodulatory molecules are chemicals that are up- or down-regulated by UV radiation, influencing the immune system's response to mutated cells.*

The incidence of skin cancer varies across the world. Skin cancers are more frequent in countries where the intensity of UV radiation is high, and where there are many people with light skin. The incidence is highest in Australia and New Zealand, and lowest in countries where most people have highly pigmented skin (**Figure Q4-2**). The incidence of melanoma in Australia is 228 times higher than in Equatorial Guinea, the country with the lowest incidence in the world.

The incidence of skin cancer has changed over time. In every country where trends have been documented, the incidence of skin cancer has increased over the past four decades (**Figure Q4-3**). This trend is most likely attributable to changes in sun exposure habits through the middle of the 20th century. People born between around 1950 and 1980 were encouraged to obtain a tan, and sun protection was not widely promoted. As these people reach middle-to-older age, the number of skin cancers that they experience is markedly increasing. However, in some countries there is a plateau, or even a decline, in younger age groups (**Figure Q4-3**). This may be due to public health campaigns that have led to increased use of sun-protective strategies, such as sunscreen, hats, and clothing.

Exposing the skin to the Sun causes inflammatory skin conditions. In some people, exposing the skin to UV radiation causes an over-reaction of the immune system that leads to an inflammatory skin condition called photodermatosis. There are multiple different types of photodermatoses. The symptoms of each condition vary, but classical symptoms are pain in the skin within a few minutes of sun exposure, severe itching, redness, blistering, and scarring. These conditions can negatively impact people's quality of life, both because of the symptoms directly, and because people have to markedly limit their outdoors activities. It is not clear how common these conditions are because they are not routinely documented in registries.

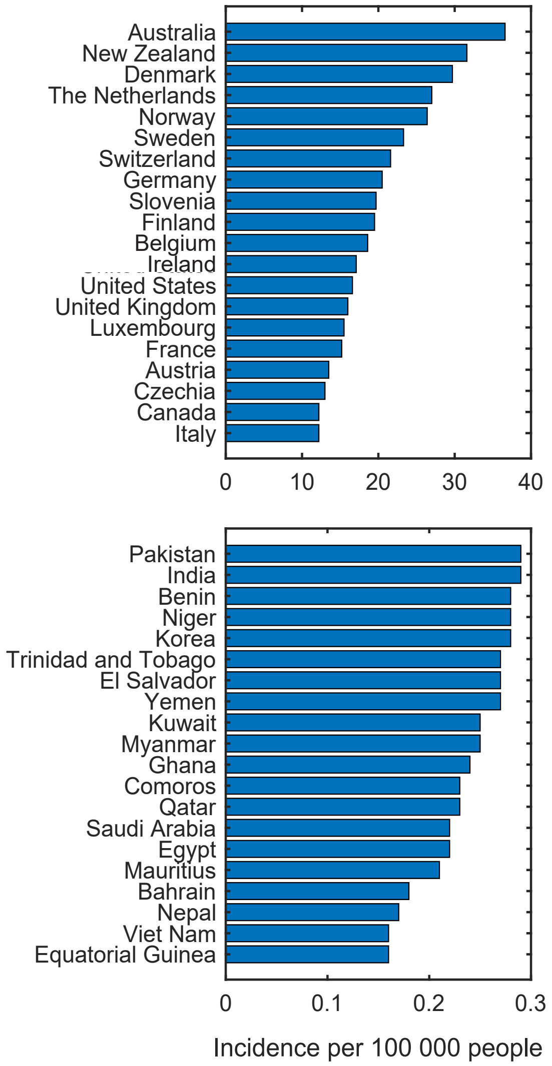


Figure Q4-2. Incidence of melanoma (standardised by age to the world standard population) in the 20 countries with the highest (top) and lowest (bottom) incidence rate. *Data are expressed as number of cases per 100,000 people per year.*

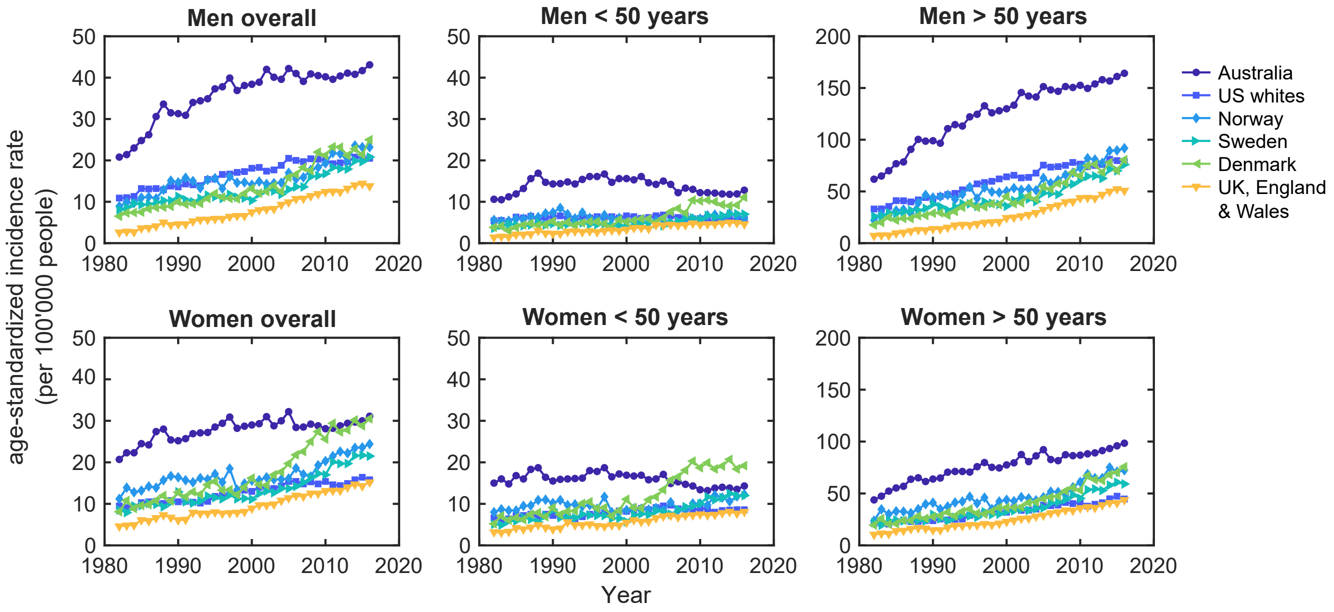
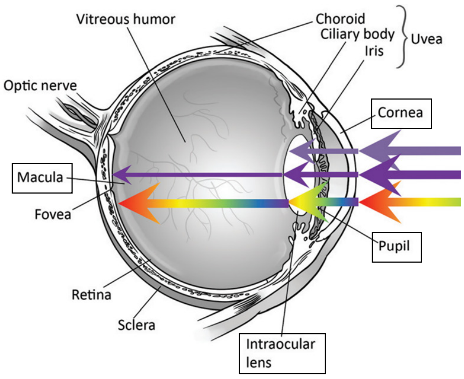


Figure Q4-3. Incidence of melanoma in six countries with predominantly light-skinned populations according to sex and age between 1982 and 2016. *The y-axis indicates the number of cases of melanoma per 100,000 people per year (age standardised to the world standard population). Note that the two graphs on the right (men and women > 50 years) have a different y-axis.*

Sun exposure causes harm to the eyes. There are a number of eye conditions caused by exposing the eyes to the Sun, as shown in **Table 1**. Melanomas occurring inside the eye, macular degeneration (which affects the retina at the back of the eye and causes vision loss), and glaucoma (increased pressure in the eye) are additional conditions that may also be influenced by exposing the eyes to sunlight, but this is not yet proven.

Cataract is the most common cause of vision loss. It is readily treatable by removing the cloudy lens and replacing it with an artificial lens. Nevertheless, it is the leading cause of blindness worldwide; in 2015 it accounted for 35% of the total blindness. Between 1990 and 2019, the global burden of disability due to cataract almost doubled. There are some countries in East Asia, South-East Asia, and Sub-Saharan Africa where the proportion of moderate to severe vision impairment caused by cataract was estimated to be higher than the average for the world. This may be due to the high intensity of UV radiation in these countries, combined with low access to surgical treatment.

***Table Q4-1**. **Eye conditions caused by exposing the eyes to the Sun.** The figure on the upper right shows a schematic of the eye's anatomy. The arrows show the different penetrations of UV-B, UV-A, and visible radiation (top to bottom) into the eye*



Condition	Definition
Cataract	Opacity of the lens, leading to impaired vision.
Pterygium	A fleshy overgrowth of thickened conjunctiva (the membrane lining the inside of the eyelids and the eye socket) that grows across the cornea. If it grows across the pupil, a pterygium can cause impaired vision.
Squamous cell carcinoma of the cornea or conjunctiva	Squamous cell carcinoma is like a skin cancer but occurring on the surface of the eye.
Photokeratitis / photoconjunctivitis	These painful temporary eye conditions are akin to having a sunburn of the eyes. Photokeratitis, also called "snow blindness", affects the cornea (the surface of the eye), whereas photoconjunctivitis affects the conjunctiva.
Pinguecula	A pinguecula is a small, raised, white- or yellow-coloured growth that is limited to the conjunctiva; it can occur on the inner or outer side of the eye.

Q5

What are the benefits of spending time in the Sun?

Exposing the skin to UV radiation leads to the production of vitamin D, which is needed to maintain adequate levels of calcium in the blood stream. Low vitamin D causes soft bones and influences the risk of developing fractures. Vitamin D may play a role in health more broadly. Other possible benefits of Sun exposure include reduced risk of autoimmune diseases (e.g., multiple sclerosis), high blood pressure, short-sightedness, and depression.

Although exposing the skin and eyes to UV radiation causes significant harms (see **Q4**), spending time in the Sun also has important benefits (**Figure Q5-1**). Some of these are mediated by UV radiation and others by longer wavelengths such as visible light. Because the wavelengths that cause many of the harms and benefits overlap it can be difficult to find the optimum balance.

Exposure to UV radiation leads to production of vitamin D. Production of vitamin D is the best-known benefit of exposing the skin to UV-B radiation. When UV-B radiation strikes the skin, 7-dehydrocholesterol, a chemical compound present in the skin, gets converted to pre-vitamin D_3 (**Figure Q5-2**). This compound then transforms to vitamin D_3, which is transported in the blood stream to the liver. In the liver, vitamin D_3 is converted into another chemical called 25-hydroxyvitamin D (or 25(OH)D for short). 25(OH)D has minimal activity in the body, but it stays in the blood stream for a long time and is a good indicator of the body's vitamin D store. This chemical is what doctors and scientists measure to determine people's vitamin D status. 25(OH)D is transported to the kidney where it is converted to the active form of vitamin D, also called calcitriol (**Figure Q5-2**). Calcitriol circulates in the blood stream and is particularly important for maintaining the correct amount of calcium in the blood. Calcitriol enables calcium to be absorbed from food, and reduces its secretion in urine. Lack of adequate vitamin D leads to soft bones. In children, this condition is called rickets; in adults, it is called osteomalacia.

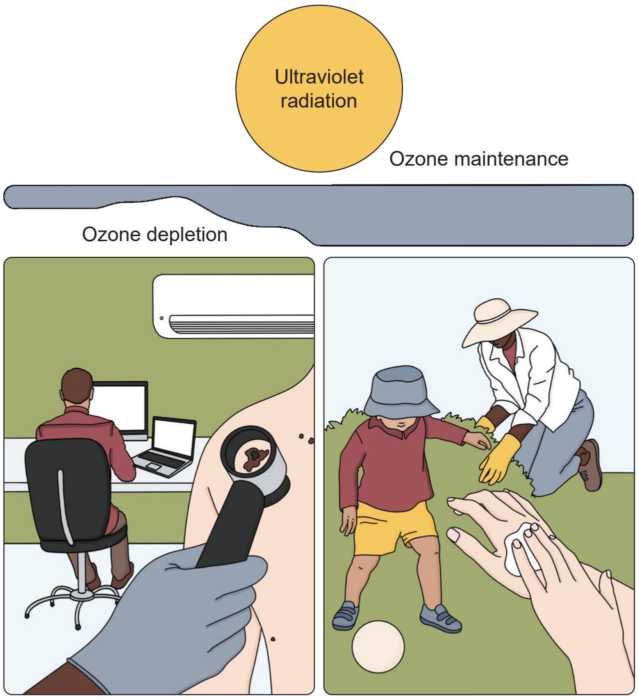


Figure Q5-1. The Montreal Protocol and its Amendments have prevented excessive increases in the intensity of UV radiation. *This allows people to spend time outdoors, obtaining the many benefits of sunshine that may not otherwise have been possible.*

Vitamin D keeps us healthy. In addition to maintaining stable calcium levels and having important effects on bones and muscles, vitamin D plays additional important functions in our body — it controls the way in which cells reproduce or die, it influences the pathways that control blood pressure, and it modulates the immune system. Increasing evidence suggests that vitamin D plays a role in cancer, infectious diseases, and autoimmune conditions such as multiple sclerosis.

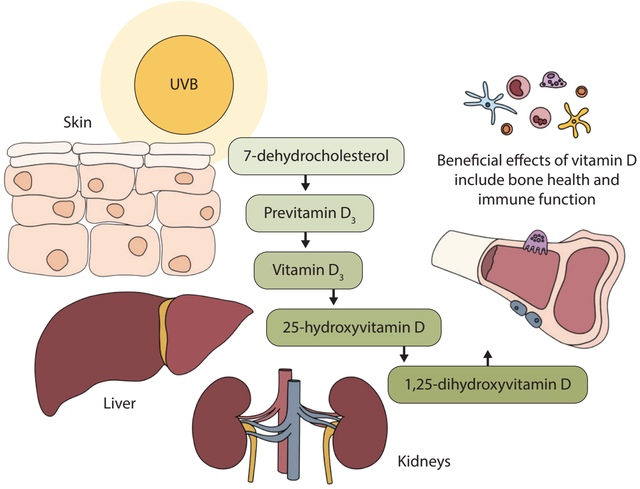


Figure Q5-2. Production of vitamin D in the skin and formation of the active product in the liver and kidneys. *Solar UV radiation converts 7-dehydrocholesterol to pre-vitamin D_3 in the skin.*

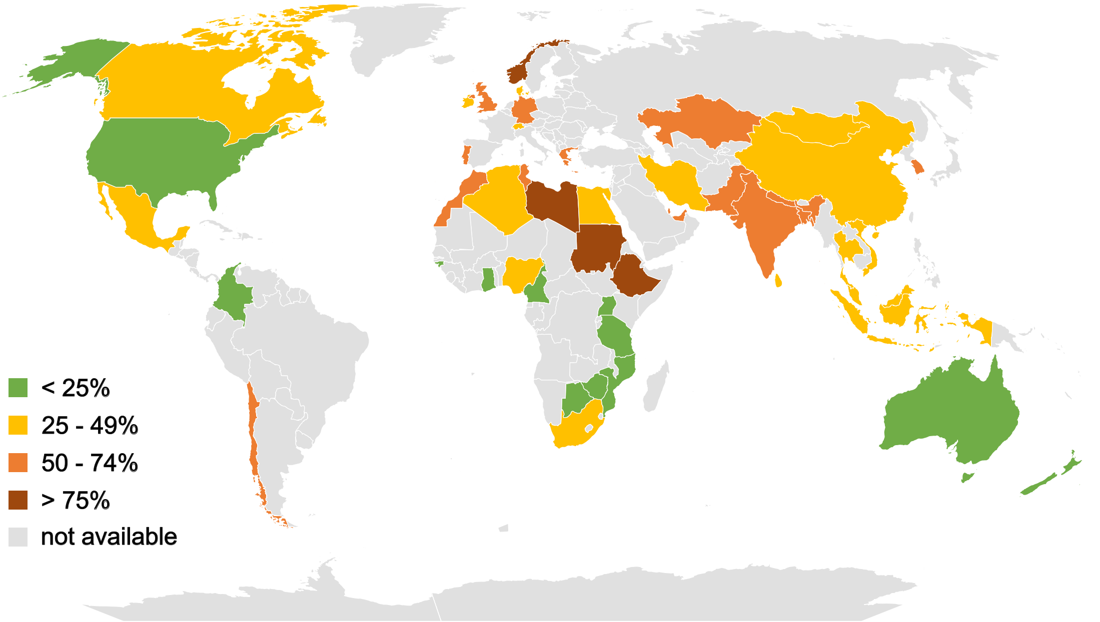


Figure Q5-3. Prevalence of vitamin D deficiency across the world. *The numbers indicate the percentage of population with reported vitamin D deficiency (25(OH)D < 50 nmols per litre).*

Since the emergence of the COVID-19 pandemic, there has been a lot of research focused on a possible role of vitamin D in the risk or severity of COVID-19. The evidence is still inconsistent but, considering the reasonably strong evidence for a positive role in other respiratory tract infections and the effect on immune cells in mouse studies and the laboratory, it is prudent to avoid vitamin D deficiency at times when the infection risk is high.

There is a certain amount of 25(OH)D needed in the blood stream. It is still unclear how much 25(OH)D is needed to maintain optimal health. This is partly because the laboratory tests used to measure 25(OH)D have been inaccurate and imprecise. For bone health, many experts consider that a concentration of 50 nanomoles of 25(OH)D per litre is sufficient to avoid harms to the bones. If 25(OH)D is below this threshold, one is considered to be vitamin D deficient. Most evidence emerging from different types of studies suggest that this concentration is also sufficient to prevent other possible negative health conditions.

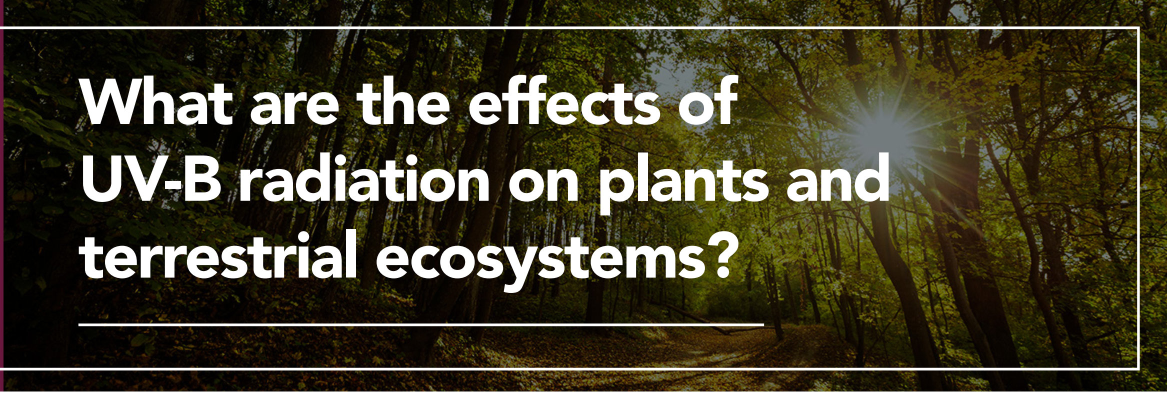
The prevalence of vitamin D deficiency varies around the world, with some countries having more than 75% of their population in a state of vitamin D deficiency (**Figure Q5-3**). However, in most countries there have not been high-quality surveys.

Adequate vitamin D status can be mantained by spending time outdoors. Human skin makes vitamin D very efficiently. A small dose of UV-B radiation is all that is needed to meet the body's requirements, provided sufficient skin is exposed (e.g., wearing a short-sleeved shirt and shorts). Importantly, studies show that regular sunscreen use does not prevent us from making the vitamin D we need. However, the time required to obtain the dose of UV-B radiation needed to maintain adequate vitamin D varies markedly according to skin colour, geographic location, season, and time of day. In tropical and subtropical locations, people with light skins can produce sufficient vitamin D all year round with a small amount of time outdoors (less than 15 minutes) between 8:00 and 16:00. In locations further from the equator it may not be possible to manufacture sufficient vitamin D in winter, as extended time outdoors with plenty of skin exposed would be required and weather conditions make this difficult for most people. However, vitamin D can remain in the body for several months, so it may be possible to meet requirements through winter by obtaining sufficient sunlight exposure in other seasons. For example, in the United Kingdom people with fair skin can maintain sufficient vitamin D status all year long by spending 10 minutes outdoors every day around noon between March and September (with lower legs and forearms uncovered from June to August, and only hands and face uncovered from March to May and in September). People with dark brown or black skin need more time outdoors (1.5 to 3 times more, although this number is uncertain) to meet their vitamin D requirements through sunlight as compared to people with light skin.

There are other benefits of exposing the skin to solar radiation beyond vitamin D production. Exposing the skin to UV radiation is beneficial for our health separately from vitamin D. Some of these benefits are mediated by the positive effects that UV radiation has on the immune system as a whole. In particular, UV radiation suppresses pathways in the immune system that lead to autoimmune diseases such as multiple sclerosis and type 1 diabetes mellitus. There is also some evidence that UV radiation may release chemicals in the skin that can reduce the risk of high blood pressure and metabolic conditions, such as obesity and type 2 diabetes mellitus. However, these benefits have yet to be proven.

Spending time outdoors enables people to gain other benefits that are mediated by wavelengths of solar radiation other than UV radiation. Visible light helps to maintain circadian rhythm, which is important for sleep, mood, and concentration. There is also an association between time outdoors and the development of short-sightedness (myopia) in children, with more light exposure leading to lower rates of myopia.

Q6



What are the effects of UV-B radiation on plants and terrestrial ecosystems?

Depending on the amount a plant is exposed to, UV-B radiation has both positive and negative impacts on plant productivity, agricultural crop production and quality, and biodiversity in terrestrial ecosystems. The interactions between climate change and depletion of stratospheric ozone significantly affect how plants respond to UV-B radiation, with implications for ecosystem health and services, and food security.

UV-B radiation has various effects on plants. Plants require sunlight for growth and reproduction, but this also means they are exposed to significant amounts of UV-B radiation over their lifetimes. High levels of UV-B radiation, as would have occurred without the Montreal Protocol, can damage important molecules (like DNA, proteins, and lipids) and inhibit photosynthesis, growth, and reproduction (**Figure Q6-1**). These effects would have likely reduced the ability of plants to remove carbon dioxide (CO_2) from the atmosphere through photosynthesis, resulting in more severe climate change. At the current levels of UV-B radiation, agricultural productivity and food security are likely not at risk because most plants have protective mechanisms to tolerate UV-B radiation.

Plants adapt to changing levels of UV-B radiation. Plants are protected from the deleterious effects of UV-B radiation through several mechanisms. One of the most common is the production and accumulation of sunscreen pigments in their epidermal tissue (i.e., their "skin"), which minimises the amount of UV-B radiation that reaches sensitive molecules like DNA. The quantity of sunscreens increases with exposure to UV-B radiation, and some plants can rapidly adjust the production of these pigments in response to daily and seasonal variations in UV-B radiation (**Figure Q6-2**). Additional protective mechanisms include increasing leaf thickness and efficient repair of DNA damage.

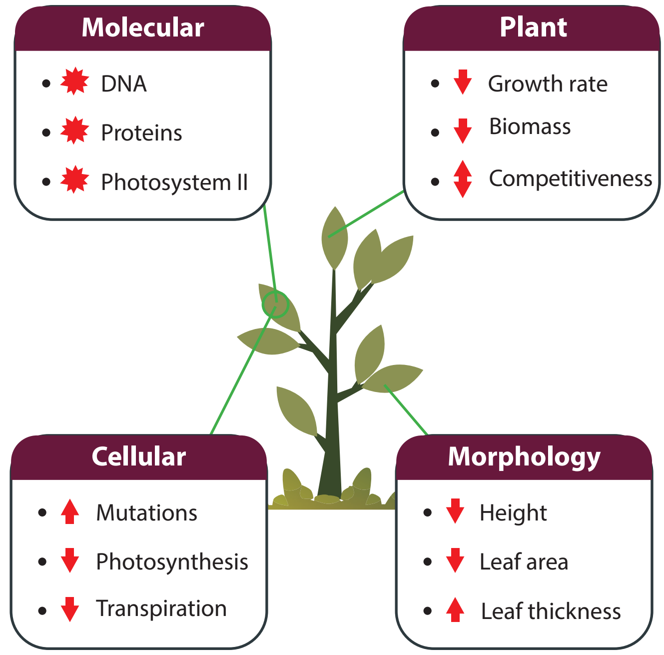


Figure Q6-1. Potential effects of high levels of UV-B radiation on plants*. Red explosion icon indicates UV damage on DNA, proteins, and photosystem II. Red arrows indicate decreased and increased effect on plant traits or process.*

Figure Q6-2. Rocks encrusted in mosses and lichens near Casey Station in East Antarctica. *In early summer, Antarctic mosses emerge from under the snow and can be exposed to high levels of UV-B radiation. When mosses first emerge, they are bright green. Those in protected areas, such as under melt water or in small depressions, will remain green; however, mosses on exposed ridges quickly accumulate protective sunscreen pigments, as evident from the redbrown colour in this photograph.*

UV-B radiation has both adverse and beneficial effects on agricultural crops. UV-B radiation affects the chemical composition of various plant organs. These changes can alter the food quality of crops and the pharmaceutical content of medicinal plants. Some of these variations in chemistry are beneficial for people and livestock, whereas others reduce the digestibility of plants (**Figure Q6-3a**). For example, in some crops, UV-B radiation can increase the quantity of flavonoids, which are beneficial to health because of their antioxidant properties. These variations in chemical composition can strengthen the tolerance of plants to drought and extreme temperatures and heighten their defences against pests and pathogens. These are important

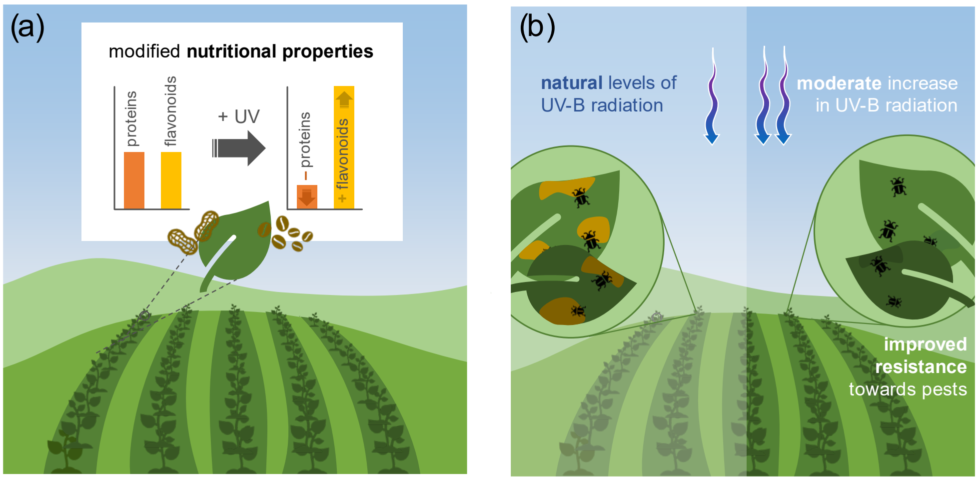


Figure Q6-3. Beneficial effects of UV radiation on agricultural crops. *(a) UV radiation modifies the nutritional properties of crops and (b) can improve their resistance towards pests.*

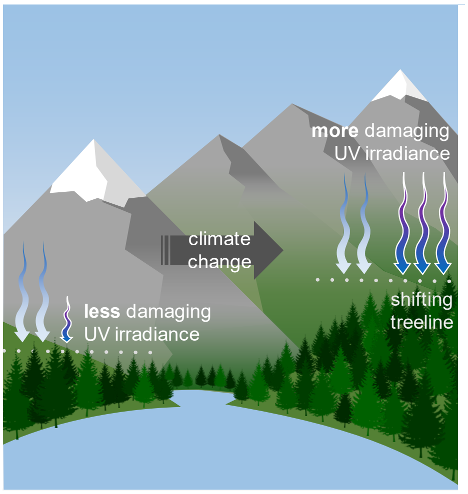


Figure Q6-4. Effects of UV radiation on species distributions and ecosystems. *Increasing temperatures resulting from climate change cause plants to move to higher elevations, where levels of UV-B radiation are higher.*

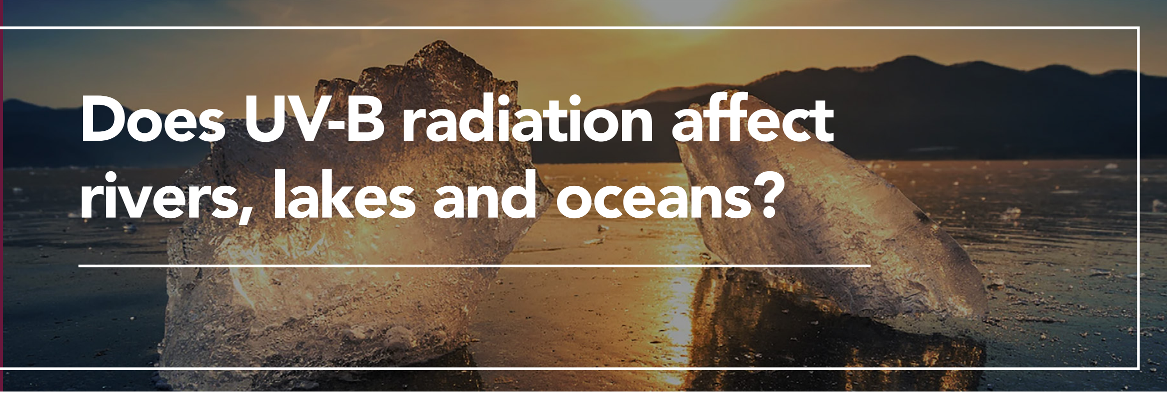
indirect defences to UV-B radiation in agricultural ecosystems (**Figure Q6-3b**).

UV-B radiation impacts ecosystems with potential negative effects on biodiversity. The amount of UV-B radiation to which crops and wild plants are exposed is not only due to stratospheric ozone, but also to climate change. In response to increased temperatures, many plant species are moving to higher elevations (thus, to an environment with higher levels of UV-B radiation (**Figure Q6-4**)); or to higher latitudes (where, on the other hand, levels of UV-B radiation are lower). These changes in the distribution of plant species across ecosystems can alter plant chemistry and growth patterns, affect the way plants and insects interact, and change the vegetation structure. When considered together, these changes may reduce biodiversity.

Most organisms can adapt to high levels of UV-B radiation, but climate change may challenge their survival. Polar regions, high-elevation mountains, and the tropics are the most likely ecosystems to be negatively impacted by variations in UV-B radiation induced by climate change. Due to high natural levels of UV-B radiation, plants living in the latter environments have evolved protective mechanisms against UV radiation. However, the combined effect of UV-B radiation and climate change may pose significant threats to their survival by overwhelming mechanisms of acclimatation and adaptation to changing conditions. For example, climate change is resulting in less snowfall at high latitudes and high elevations. This leaves certain plants vulnerable to UV-B radiation (as they are not protected by a "blanket" of snow) and unfavourable environmental conditions (as snow maintains stable soil temperatures) at times of the year when they may be ill-equipped to acclimate to these changes. This phenomenon is evident, for example, in some areas of the high Arctic tundra and in Antarctica.

Q7

Does UV-B radiation affect rivers, lakes and oceans?



UV-B radiation in sunlight can penetrate river, lake and ocean waters where it affects many organisms and chemicals. There are enormous variations in underwater exposure to UV radiation that are controlled by factors such as latitude, altitude, depth, ice cover, and water clarity. The net effect of UV-B radiation depends on both the amount of exposure to UV radiation, the sensitivity of the organism or chemical and the mechanisms that organisms have developed to protect against damage caused by UV-B radiation. Climate change modifies the penetration of UV radiation into water by regulating ice cover, mixing, and water clarity.

UV-B radiation penetrates through water. Colour and clarity control the penetration of UV radiation through water and can differ enormously across different types of waterbodies (e.g., rivers, lakes, and oceans). The concentration of dissolved organic matter is often the single largest factor controlling water clarity. High concentrations of dissolved organic matter impart a brown hue to water bodies, much like the colour of tea or coffee. The concentration of dissolved organic matter can be high in lakes, ponds, and coastal zones surrounded by abundant forests and wetlands, where UV-B radiation often penetrates less than a metre underwater. In clearer water, where the concentration of dissolved organic matter is low, UV-B radiation can penetrate to substantial depths, sometimes tens of metres or more. For most waters, the concentration of dissolved organic matter and the depth to which UV-B radiation penetrates is somewhere between those extremes and varies seasonally and with the amount of snow or rainfall.

UV-B radiation affects aquatic organisms and water chemistry. When organisms are exposed to high levels of UV-B radiation, important cell components such as proteins, DNA, and lipids can be harmed. In turn, this process can reduce growth and reproduction, or in severe cases lead to death. For example, the development of sea urchin embryos can be severely affected causing abnormal development (**Figure Q7-1**). High amounts of UV-B radiation can also reduce the virulence of pathogens and parasites or kill them. Single-celled or small organisms that lack a shell or skin structures are especially vulnerable. Fish eggs and young (larval) fish can also be sensitive to UV radiation (both UV-B and UV-A). Meanwhile, adult fish are usually not sensitive to UV damage, but some can develop skin cancer in high UV environments. Organisms living in waters with low underwater levels of UV radiation (such as coastal zones) are often more sensitive to UV radiation than those living offshore that are adapted to higher levels of UV radiation.

Organisms have evolved for billions of years and have a wide range of tools to adapt to UV-B radiation. Some aquatic organisms can see UV radiation and avoid areas where UV damage is high. Moreover, some organisms can make or consume pigments that protect them from UV damage, similar to how human skin can darken when exposed to sunlight (due to the production of melanin). These attributes and responses help many types of aquatic organisms adapt to levels of UV radiation that could otherwise harm them.

Similar to how UV radiation can fade the colour of materials left outside (see **Q11**), exposure to UV radiation breaks down substances and alters the chemistry of the natural world. Underwater, UV radiation leads to the decay of dead plant and animal matter (termed "organic matter"). UV radiation can also break down oil pollutants. This break-down process often releases carbon dioxide to the air. It can also stimulate bacteria to further decompose organic matter, thereby releasing more carbon dioxide.

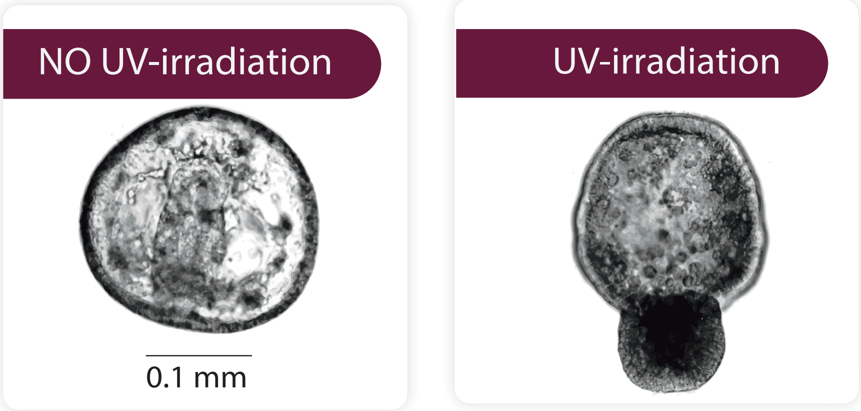


Figure Q7-1. Effect of exposure to UV radiation on embryos of the green sea urchin Strongylocentrotus droebachiensis. *The left photo shows a normal embryo (not exposed to UV radiation), while the embryo on the right has abnormal development following exposure to UV radiation.*

Q8

Does climate change modify the effects of UV-B radiation on the aquatic environment?

Increasing temperatures and shifts in weather patterns due to climate change affect how UV-B radiation impacts aquatic environments. Scientists have discovered that this occurs in several ways, including changes in ice cover, in water circulation in oceans and lakes, and in the transparency of water to UV-B radiation.

Ice-cover is decreasing on lakes and oceans. When present, ice-cover shields water from exposure to UV radiation. However, ice cover has been declining in the polar oceans and in many lakes that have historically frozen over at least seasonally. For example, the annual minimum in ice cover decreased from 63% to 41% of the Arctic Ocean between 1996 to 2022. The present coverage is 25% below the long-term median (**Figure Q8-1**). Higher temperatures also mean that more ponds form on the ice surface, which increases the penetration of UV radiation through the remaining ice, further amplifying underwater levels of UV radiation.

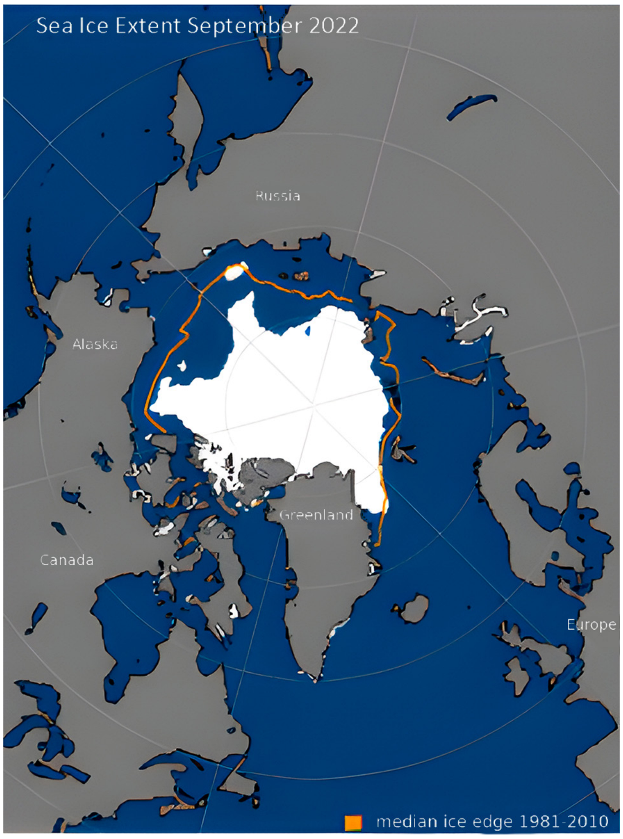


Figure Q8-1. Decrease in Arctic sea-ice. *Map of ice cover at the seasonal minimum in September 2022 (white area) compared to the median ice edge in September for the years 1981 – 2010 (orange line). UV-B radiation now penetrates into the Arctic Ocean in areas previously protected from it.*

The depth of the mixed layer is changing. Wind mixes the surface waters of most water bodies. This layer of water is referred to as the "mixed layer". Organisms and substances free-floating in this zone are mixed regularly and are exposed to UV-B radiation when they pass near the surface (**Figure Q8-2**). Deeper mixing results in lower exposure to UV-B radiation (on average), while shallower mixing increases exposure to UV-B radiation. Climate change has been altering the depth of the mixed layer in many water bodies, thereby altering the exposure to UV-B radiation. For example, in the oceans, the mixed layer has been getting deeper in many regions, thereby reducing the average exposure to UV-B radiation in the layer.

Concentrations of dissolved organic matter are increasing. Over the last two decades, concentrations of dissolved organic matter have been increasing in many water bodies in regions such as the Northeast United States and Northwestern Europe, thereby decreasing the penetration of UV radiation and underwater exposure to UV radiation. Regional increases in precipitation (e.g., rainfall), warming temperatures, and extreme events such as severe storms amplify inputs of dissolved organic matter and other light absorbing substances to rivers, lakes, and coastal zones. Ongoing changes in climate are likely to further reduce underwater UV radiation in coming years to decades.

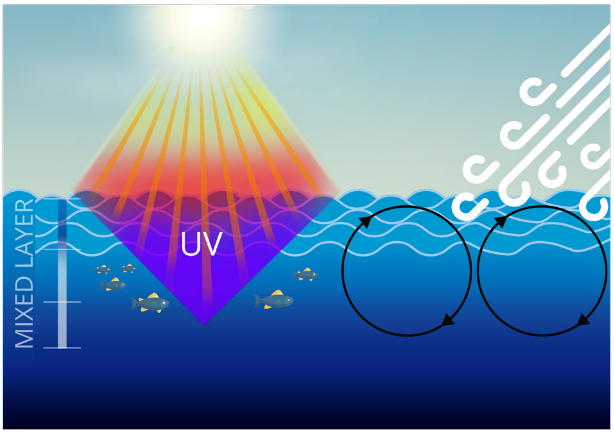
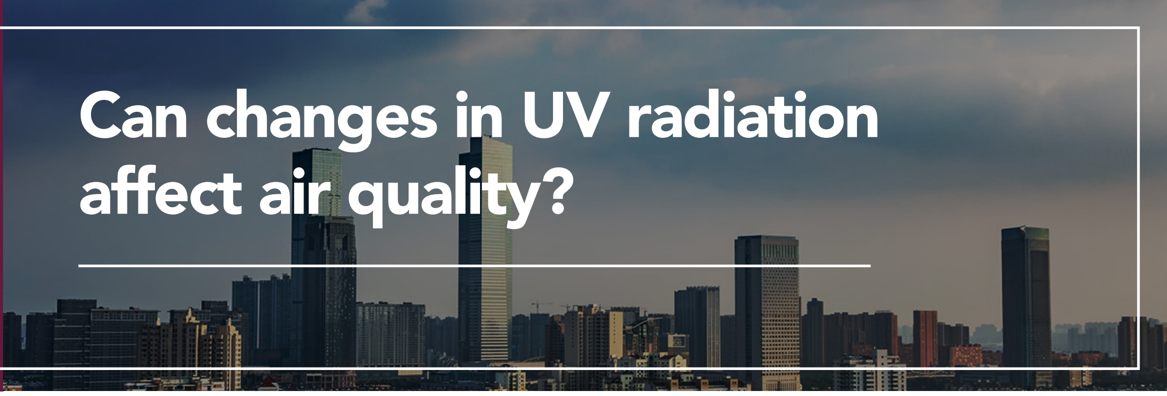


Figure Q8-2. Diagram of a lake or ocean water column. *Black circles indicate the depth to which wind mixes the water. Winds have been increasing over the oceans, and in many regions the ocean surface waters now mix deeper than they did decades ago.*

Q9

Can changes in UV radiation affect air quality?



Globally, outdoor air pollution is estimated to cause over 4 million premature deaths each year. Air pollution also damages crops, leading to estimated reduction in yield of up to 10%. The danger posed by air pollution depends on the nature and quantities of the compounds that are emitted into the atmosphere as well as their interaction with UV radiation and changes in climate. The net impact on air quality depends on changes in all these factors.

Poor air quality is a significant global risk for human health. The air we breathe contains a complex mixture of compounds that can be affected by UV radiation. These compounds include chemicals released directly to the atmosphere such as nitrogen oxides (NOx) from combustion, and volatile organic compounds (VOCs) from sources as diverse as plants and paints. Other chemicals, like ozone (O_3) and oxidised VOCs are formed in the atmosphere in processes powered primarily by solar UV radiation (**Figure Q9-1**). Variations in stratospheric ozone and climate change impact the production and fate of these air pollutants.

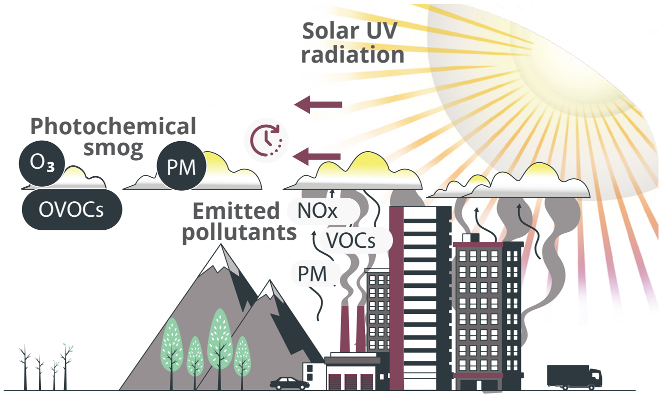


Figure Q9-1. What is air quality? *Air quality is a way of summarising how healthy the air is that we breathe. Human activities release numerous chemicals into the atmosphere, including volatile organic compounds (VOCs), nitrogen oxides (NOx), and particulate matter (PM). In the atmosphere, solar UV radiation can transform them into a range of other compounds, including additional hazardous particulate matter, oxidised VOCs (OVOCs) and ozone (O_3). Ultimately, solar radiation removes the atmospheric pollutants, although it can take a long time.*

Tiny particulate matter ($PM_{2.5}$, particles smaller than 2.5 µm) is considered to pose the greatest threat to human health from polluted air. Recent estimates found that in the United States more than half the mass of these particles is generated during processes driven by solar UV radiation.

In addition to forming particulate matter, solar UV radiation triggers many other chemical reactions that are involved in the formation of smog, most notably the generation of ground-level ozone (also called tropospheric ozone), which also significantly impacts human and plant health. UV-B radiation is also involved in the destruction of ground-level O_3, a process that generates hydroxyl radicals, the major cleaning agent of the troposphere. Hydroxyl radicals react with compounds such as VOCs, NOx, and sulfur dioxide in reactions that often regenerate ozone. This complex cycle is altered by any factor that influences the amount of UV radiation such as clouds and stratospheric O_3.

Expected changes in ground-level ozone resulting from the Montreal protocol. Increases in the concentration of stratospheric O_3 resulting from the implementation of the Montreal Protocol and climate change are expected to lower the concentration of ground-level ozone in polluted regions, tending to improve air quality. On the other hand, air quality in less-polluted areas is expected to worsen due to an increase in ground-level ozone. **Figure Q9-2** shows the expected changes in ground-level ozone in the western United States caused by a 5% increase in stratospheric O_3. While these are not negligible, larger changes are possible by reducing emissions of NOx and VOCs.

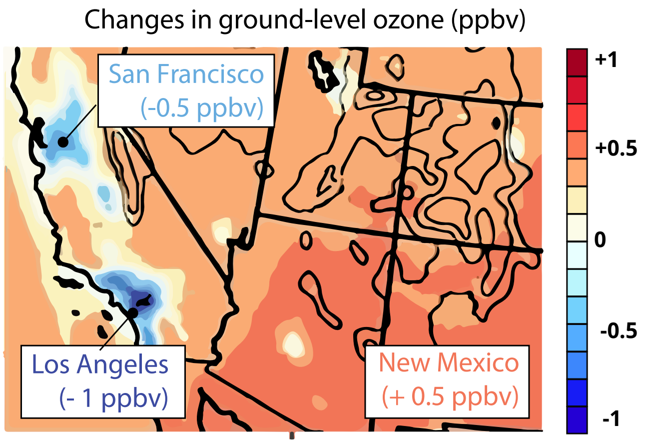


Figure Q9-2. Expected change in ground-level ozone resulting from the recovery of stratospheric ozone. *Increasing stratospheric ozone (O_3) will reduce UV-B radiation at the Earth's surface, altering the production and destruction of O_3 at ground level. The figure shows that in the western United States, ground-level O_3 (in parts per billion by volume, ppbv) is expected to decrease in large urban areas and increase elsewhere as a result of a 5% increase in stratospheric O_3.*

Q10 Will chemicals that replace existing ozone-depleting substances bring new environmental problems?

New replacements for ozone-depleting substances are tested for safety to humans and the environment before they are approved for use and few problems have been observed so far. However, we must avoid complacency and apply responsible management of these substances.

Ozone-depleting substances and their replacements have an effect on climate and the environment. Originally, chlorofluorocarbons (CFCs) and halons, which were widely used as refrigerants and for a variety of other purposes, were thought to be safe for the environment, but that proved not to be the case. Once in the stratosphere, these substances release chlorine and bromine, which destroy stratospheric ozone. In addition, CFCs are greenhouse gases and contribute to global warming. When hydrofluorocarbons (HFCs) were proposed as substitutes for CFCs in the 1980s as a response to the Montreal Protocol, the global warming potential of these chemicals was only just being thought about. Once their global warming potentials were recognised, it was clear that HFCs could only be a short-term solution.

Breakdown products of ozone-depleting substances and their replacements can accumulate in the environment. The current replacements for CFCs (such as hydrocarbons and hydrofluoroolefins) have less effect on the stratospheric ozone layer and on climate than HFCs. This is because they are degraded before reaching the stratosphere and have a low global warming potential. However, trifluoroacetic acid (TFA), the ultimate atmospheric breakdown product of several of these chemicals (**Figure Q10-1**,①), has caused concerns because of its persistence in the environment. TFA is very water soluble and is washed from the atmosphere by precipitation (**Figure Q10-1**,②-③). When it reaches the land, TFA combines with minerals in soil and water to form TFA salts (**Figure Q10-1**,④), which run off into surface waters on land and into the oceans (**Figure Q10-1**,⑤). In locations where there is little or no water outflow and high evaporation (oceans and salt lakes), the concentration of TFA salts will increase over time. However, for lakes and oceans, the effects of increased concentrations of naturally occurring mineral salts, such as sodium chloride, and other water-soluble minerals are greater and more biologically significant than those caused by TFA salts. Salts of TFA in soil are taken up by plant roots and concentrate in the leaves, where they appear to have no effects. If animals eat the leaves, TFA is rapidly excreted and does not accumulate in their bodies or in the food chain.

Based on current knowledge, breakdown products do not pose environmental concerns. Based on estimates of current and future use of HFCs and other replacements for CFCs, additional inputs of TFA to the ocean will only slightly (less than 0.5% per year) increase the amounts that have been present historically. Now and in the distant future, predicted TFA concentrations in surface waters and terminal basins are thousands of times less than thresholds of concern for human or environmental health. However, TFA is also produced by the breakdown of many other human-made products such as plastics, pesticides, and pharmaceuticals. As it does persist in the environment, these additional sources underscore the need for ongoing monitoring of concentrations of TFA and consideration of potential environmental effects.

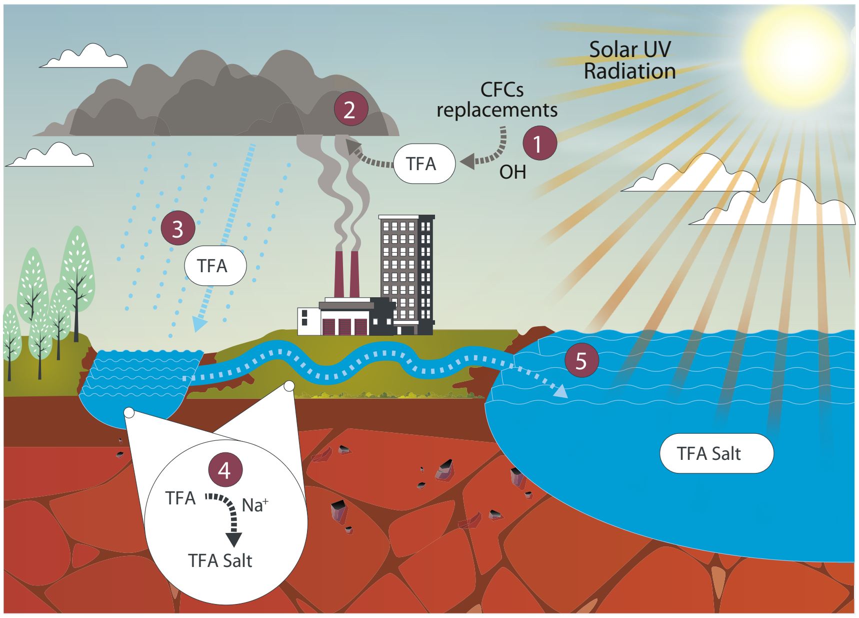
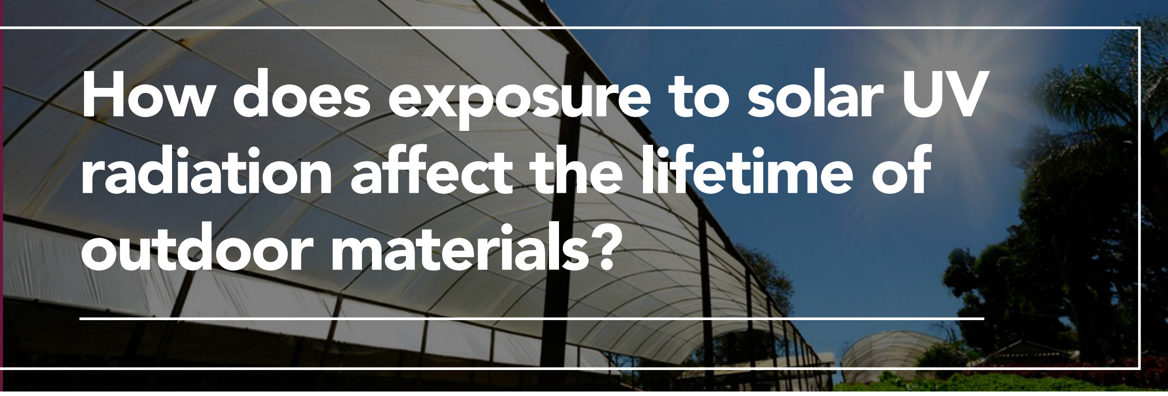


Figure Q10-1. Where does trifluoroacetic acid (TFA) come from, and where does it go? *TFA is formed by the destruction of a range of fluorinated gases in the atmosphere (①). Once formed, it rapidly dissolves in cloud water (②) and reaches the Earth's surface through rain or snow (③). After contact with soil or natural waters, it forms salts with metal ions such as sodium (④). These then flow with surface water until reaching a terminal basin (e.g., salt lakes) or the ocean (⑤). Concentrations of TFA salts are lowest in precipitation and flowing surface waters, slightly greater in oceans, and greatest in smaller terminal basins where they collect along with other mineral salts.*

Q11

How does exposure to solar UV radiation affect the lifetime of outdoor materials?



Materials commonly used in building construction, transportation, the energy industry, and textiles are routinely exposed to solar UV radiation during their lifetime. Often the loss in their useful properties (such as mechanical strength) or surface characteristics (such as colour and roughness) caused by exposure to solar UV radiation determines their service lifetimes outdoors. Available strategies to control UV-induced degradation include surface coatings or incorporation of very low concentrations of chemical compounds that act as "sunscreens". Although effective in controlling degradation by UV radiation under various exposure conditions, these additives increase the overall lifetime cost of materials designed for routine outdoor use. In addition, some of these additives may leach out of the materials during use or after disposal and can harm the ecosystem due to their toxicity.

Materials can degrade when exposed to sunlight. Some materials used in construction and textiles are carbon-based polymers that can degrade when they absorb solar UV radiation. These polymeric materials include wood and paper products, synthetic polymers such as plastics and rubber, and textiles like wool and polyester. These polymers have specific chemical groups (called chromophores) that can absorb solar UV radiation and trigger their degradation. In materials like wood, chromophores are part of the polymer structure, whereas other materials, such as polyethylene plastic, contain chemical impurities that absorb solar UV radiation.

Absorption of solar UV radiation triggers chemical reactions that often lead to the degradation of the material by disrupting the polymer's long chain-like structure. Since the materials' strength and desirable properties (such as appearance and surface characteristics) rely on the presence of long and intact polymer chains, absorption of UV radiation compromises the useful properties like durability and appearance of wood and plastics used outdoors. Furthermore, in applications such as photovoltaic modules, building construction, and protective organic coatings, this reduction in service life requires faster replacement, increasing the cost of use.

Fading, yellowing, and embrittlement are signs of photochemical degradation. When materials are exposed to solar radiation, three signs can indicate their degradation. These are fading, yellowing, and surface cracking (**Figure Q11-1**).

Fading. Fading is a change of colour caused primarily by exposure to UV radiation, even though heat and visible light can also contribute to this phenomenon. Fading is observed in paints, coatings, wood products, textiles, and plastics. UV-B radiation is more energetic but less intense in the solar spectrum than other wavelengths. However, fading of fabric and coatings caused by UV-B radiation is common and often limits their useful service life. UV-A radiation is less energetic than UV-B, but at the Earth's surface, solar radiation has a higher proportion of UV-A compared to UV-B radiation. For this reason, UV-A radiation is the primary cause of fading.

Yellowing. When exposed to solar radiation, plastics may yellow over time, a process that generally requires oxygen

Figure Q11-1. Signs of sunlight-induced degradation of materials.

(thus, air) to take place. Yellowing occurs because oxidation of polymers by UV radiation forms chemical species that are yellow in colour — which is why the yellow hue is indicative of degradation. PVC polymers undergo yellowing during outdoor use affecting their useful service life. Yellowing of PVC can occur even without oxygen.

Weakening and embrittlement. When exposed to UV radiation, plastics undergo chemical changes that can break the long chain-like polymer molecules into smaller fragments. Alternatively, these reactions can create new chemical bonds among polymer chains making the material stiffer over time. Both processes weaken the polymer, which tends to snap and break instead of bend and spring back when subjected to mechanical stress. The weakening of materials exposed to solar radiation causes a marked reduction in mechanical strength and flexibility over time. For plastics, extended exposure to solar radiation causes them to fall into pieces on handling. The material is then said to be embrittled, a phenomenon that contributes to the generation of microplastics in the environment (see **Q12**).

Several strategies exist to protect materials from UV radiation. Several strategies to mitigate the damage that UV radiation causes to wood, plastics, and textile fibres are available. The three most common are shielding, stabilising, and scavenging.

Shielding. Shielding involves the presence of an additive in the plastic that physically blocks UV radiation from entering the material. The most common additives for plastics are carbon black and titanium dioxide. For wood, a common way to reduce damage caused by sunlight and moisture involves the use of surface coating products. These coatings consist of an opaque film containing an inorganic pigment (like titanium dioxide) that prevents UV radiation from reaching the underlying wood.

Stabilisers. A second way to protect plastics and wood is by using UV stabilisers. A stabiliser can be a compound that strongly absorbs UV radiation and thus reduces the amount of light available to degrade the material. UV stabilisers are effective at very low concentrations, typically less than 0.1% of the material weight. Stabilisers mitigate the harmful effect of UV radiation on materials and, in most cases, can maintain the service life of products even under extended exposure to UV radiation. However, these additives again add to the cost of the material and can cause environmental contamination when they leach out of the material or coating.

Scavengers. A third approach is to stop the progress of degradative chemical reactions using a scavenger. UV radiation typically initiates free-radical reactions, which can create more oxidative damage to the material. Scavengers are molecules that can trap these free radicals, thereby stopping the oxidative chain of reactions and preventing damage to polymer chains. The most-used group of scavengers for polyolefin plastics are hindered amine light stabilisers.

Q12

What is the relationship between microplastics and solar UV radiation?

Microplastics are small pieces of common plastics. They are formed by fragmentation of large plastic litter through a variety of processes including solar UV-driven weathering. These small (less than 5 mm) plastic particles are widespread in the environment, and there is considerable concern about potential effects on living organisms.

Microplastics are ubiquitous in the environment. Microplastics are small pieces of plastic materials, typically defined as particles of less than 5 mm in one dimension. Recent studies have demonstrated that microplastics are ubiquitous in fresh and marine waters, air, soil, and living organisms, even in remote areas such as the Arctic and deep-sea sediments. Even more concerning are recent findings of microplastics in drinking water, salt, and even human blood. Consequently, there is considerable concern about the potential impacts of microplastics on organisms, particularly human beings.

UV radiation is a key environmental factor responsible for the formation of microplastics. There are two key questions concerning microplastics in the environment: How do they form? How long will they last? Most of the microplastic particles found in the environment are thought to form through the fragmentation of larger plastic litter such as disposed beverage bottles, food wrappers, and shopping bags. This breakdown starts with the weathering of plastics, a process that is mediated primarily by solar UV radiation. UV radiation initiates surface degradation, cracking, and pitting of large plastic debris (see **Q11**). These cracks propagate into the bulk of the material, making it prone to fragmentation. Fragmentation also requires exposure of degraded plastic to a mechanical force such as wave turbulence in seas and oceans, chewing by organisms, or abrasion by sand (**Figure Q12-1**). Particularly significant is the 'slush' zone of beaches where waves break churning water, sand, and any plastic debris, resulting in the formation of microfragments. While solar UV radiation is a key driver of the weathering and subsequent fragmentation of large plastic litter, climate change impacts the rates of this process by modifying the amount and spectral composition of UV radiation, distribution of plastics, and mechanical forces such as wave movement and energy.

Photochemical degradation of plastics can release carbon dioxide. Solar UV radiation does not just drive the breakdown of large plastic objects into smaller fragments. Laboratory studies have also indicated that some types of plastics are fully broken into carbon dioxide after exposure to UV radiation. However, the environmental relevance of this process remains to be established, since it may be too slow to meaningfully reduce the large amounts of plastic litter in the environment. Thus, on the one hand, the implementation of the Montreal Protocol and related legislation may have reduced the formation of microplastic by decreasing the amount of UV radiation available for this process. On the other hand, it may also have decreased the final removal of this littering material from the environment because lower amounts of UV radiation mean that less microplastic debris is transformed into carbon dioxide. At present, there is insufficient data to quantify the relative contribution of these opposing processes and their overall impact on the environment.

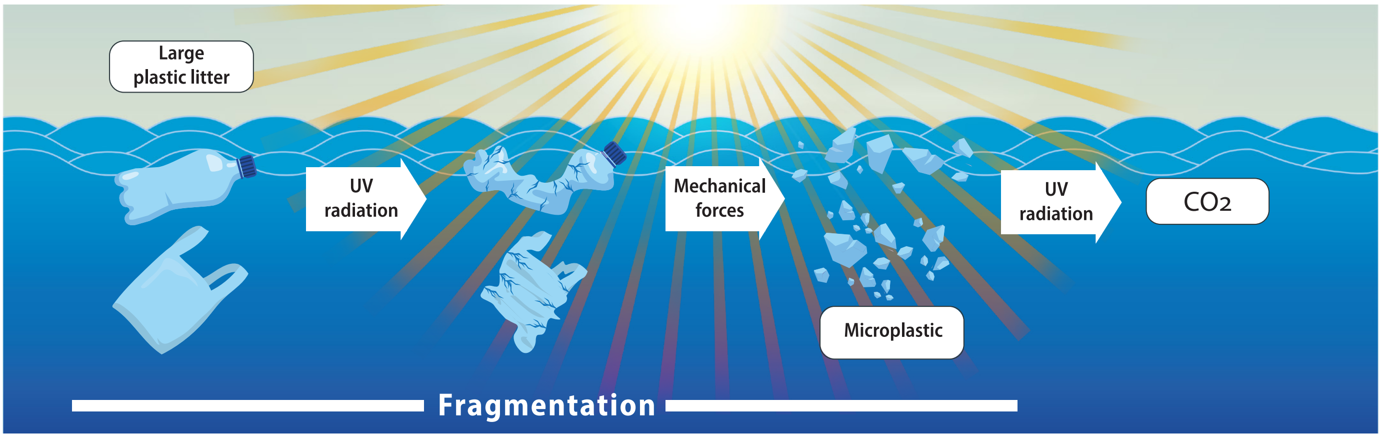


***Figure Q12-1. Solar UV radiation can drive the photo-oxidation of plastics**, causing plastic weathering and making plastics prone to fragmentation, a process that may result in the formation of microplastic particles. The relevance of the degradation of plastics to carbon dioxide in the natural environment remains to be established. Climate impacts photo-oxidation through a variety of different routes, including direct effects on solar UV radiation, plastic dispersal, and by creating the mechanical forces that drive the actual fragmentation.*

Source of figures

Q1-2	Reproduced from WHO, 2002: Global Solar UV Index: A Practical Guide. WHO/SDE/OEH/02.2, 28 pp., https://apps.who.int/iris/handle/10665/42459
Q1-3	Updated from WHO, 2002: Global Solar UV Index: A Practical Guide. WHO/SDE/OEH/02.2, 28 pp., https://apps.who.int/iris/handle/10665/42459
Q1-5	Reproduced from 20 Questions & Answers About the Ozone Layer 2022 Update, avaialble at https://ozone.unep.org/science/assessment/sap. The document is a component of the WMO/UNEP Scientific Assessment of Ozone Depletion: 2022 report. Figure provided by Chelsea R. Thompson, NOAA Chemical Sciences Laboratory
Q1-6	Provided by J. Ben Liley, National Institute of Water and Atmospheric Research, New Zealand
Q2-1	Adapted from Bernhard, G.H., McKenzie, R.L., Lantz, K. et al. Updated analysis of data from Palmer Station, Antarctica (64° S), and San Diego, California (32° N), confirms large effect of the Antarctic ozone hole on UV radiation. Photochem Photobiol Sci 21, 373–384 (2022). https://doi.org/10.1007/s43630-022-00178-3
Q3-1	Updated from Bornman, Janet F., Paul W. Barnes, T. Matthew Robson, Sharon A. Robinson, Marcel AK Jansen, Carlos L. Ballaré, and Stephan D. Flint. "Linkages between stratospheric ozone, UV radiation and climate change and their implications for terrestrial ecosystems." Photochemical & Photobiological Sciences 18, no.3 (2019): 681-716. https://doi.org/10.1039/C8PP90061B. Figure provided by Sharon A. Robinson, University of Wollongong, Australia
Q6-2	Provided by Sharon A. Robinson, University of Wollongong, Australia
Q7-1	Adapted from Figure 1 of Adams, N. L., Campanale, J. P., & Foltz, K. R. (2012). Proteomic responses of sea urchin embryos to stressful ultraviolet radiation. Integrative and Comparative Biology, 52(5), 665-680. https://doi.org/10.1093/icb/ics058. Used with permission of Nikki L. Adams.
Q8-1	Provided by National Snow and Ice Data Center, United States

Figures not listed in this table were either drawn specifically for this Q&A report or reproduced from the 2022 Assessment Report of the UNEP Environmental Effects Assessment Panel, available at https://ozone.unep.org/science/assessment/eeap

List of acronyms

CFC	chlorofluorocarbon
CO_2	carbon dioxide
DNA	deoxyribonucleic acid
EEAP	Environmental Effects Assessment Panel
HFC	hydrofluorocarbon
nm	nanometre
NOx	nitrogen oxides
O_3	ozone
ODS	ozone-depleting substance
PM	particulate matter
$PM_{2.5}$	particles smaller than 2.5 micrometres
ppbv	parts per billion by volume
PVC	polyvinyl chloride
TFA	trifluoroacetic acid
UNEP	United Nations Environment Programme
UV	ultraviolet
UV-A	ultraviolet A
UV-B	ultraviolet B
UV-C	ultraviolet C
VOC	volatile organic compound

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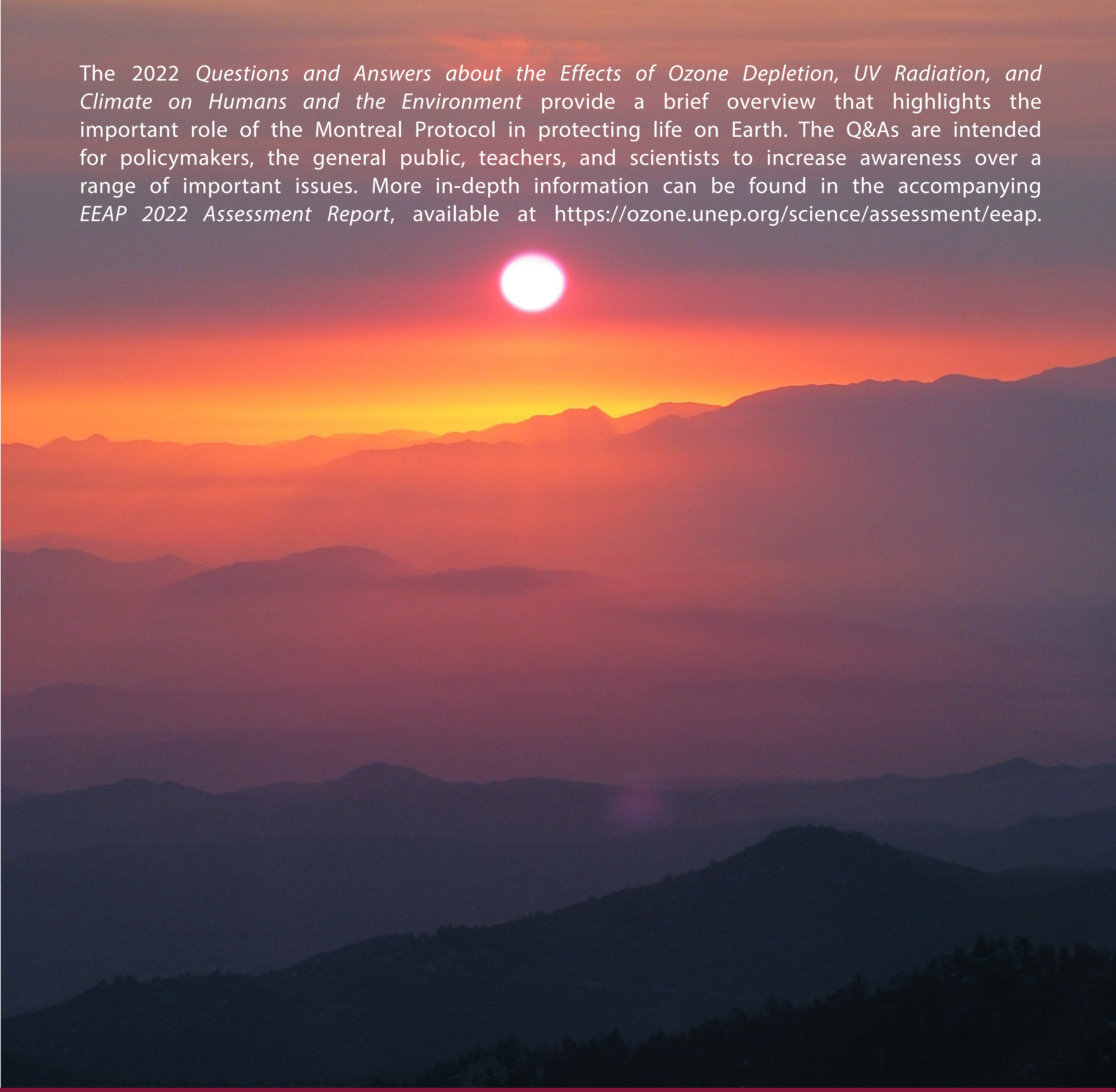

The 2022 *Questions and Answers about the Effects of Ozone Depletion, UV Radiation, and Climate on Humans and the Environment* provide a brief overview that highlights the important role of the Montreal Protocol in protecting life on Earth. The Q&As are intended for policymakers, the general public, teachers, and scientists to increase awareness over a range of important issues. More in-depth information can be found in the accompanying *EEAP 2022 Assessment Report*, available at https://ozone.unep.org/science/assessment/eeap.

Questions and Answers about the Effects of Ozone Depletion, UV Radiation, and Climate on Humans and the Environment

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Montreal Protocol
on Substances
that Deplete the
Ozone Layer