Questions and Answers about the Environmental Effects of the Ozone Layer Depletion and Climate Change: 2014 Update

Environmental Effects Assessment Panel: 2014

United Nations Environment Programme

Pieter J Aucamp & Robyn Lucas

Coordinating Authors

This document provides some answers to commonly asked questions about the environmental effects of ozone depletion

This document has been compiled by the following representatives of the Environmental Effects Assessment Panel:

Pieter J. Aucamp

Robyn Lucas

David J. Erickson III

Richard L. McKenzie

Mary Norval

Sharon Robinson

Keith Solomon

Craig E. Williamson

We gladly acknowledge the cooperation and contributions of several of the members of the Environmental Effects Assessment Panel.

Cover page photo by Dr Pieter J Aucamp with the question***: UV exposure has a major effect on the human eyes. How does it affect the eyes of animals?***

FREQUENTLY ASKED QUESTIONS ABOUT THE ENVIRONMENTAL EFFECTS OF OZONE DEPLETION

Contents

Abbreviations/acronyms used in this document

Abbreviation/ Acronym	Full name
CDOM	Coloured Dissolved Organic Matter
CDR	Carbon Dioxide Reduction
CFC	Chlorofluorocarbon
DOM	Dissolved Organic Matter
DU	Dobson Unit, for measuring total column of ozone in the atmosphere
EESC	Equivalent Effective Stratospheric Chlorine
GHG	Greenhouse gas
GWP	Global Warming Potential
HCFC	Hydrochlorofluorocarbon
HFC	Hydrofluorocarbon
ODS	Ozone depleting substance
PFC	Perfluorocarbon
SAM	Southern Annular Mode
SRM	Solar Radiation Management
sza	Solar Zenith Angle
TOMS	Total Ozone Mapping Spectrometer (satellite-based instrument designed to measure total ozone amount)
UV	Ultraviolet
UV-A	UV radiation in the wavelength range from 315 to 400 nm
UV-B	UV radiation in the wavelength range from 280 to 315 nm
UV-C	UV radiation in the wavelength range from 100 to 280 nm
UVI	UV Index

INTRODUCTION

In the mid-1970s it was discovered that some man-made products destroy ozone molecules in the stratosphere. Ozone filters out damaging solar ultraviolet (UV) radiation. The destruction of stratospheric ozone thus leads to higher levels of UV radiation at the surface of the Earth and this can cause damage to ecosystems and to materials such as plastics. It may cause an increase in the risk of some human diseases, for example, skin cancers and cataracts.

The discovery of the role of the synthetic ozone-depleting chemicals, such as the chlorofluorocarbons (CFCs), stimulated increased research and monitoring. Computer models predicted a disaster if nothing was done to protect the ozone layer. Based on this scientific information, the nations of the world took action in 1985 with the Vienna Convention for the Protection of the Ozone Layer, followed by the Montreal Protocol on Substances that Deplete the Ozone Layer in 1987. The Convention and Protocol have been amended and adjusted several times since 1987 as new knowledge has become available.

The Meeting of the Parties to the Montreal Protocol appointed three Assessment Panels to regularly review research findings and progress. These panels are the Scientific Assessment Panel, the Technological and Economic Assessment Panel and the Environmental Effects Assessment Panel. Each panel covers a designated area with a natural degree of overlap. The main reports of the Panels are published every four years, as required by the Meeting of the Parties. All three reports have an executive summary that is distributed more widely than the entire reports. It has become customary to add a set of questions and answers – mainly for non-expert readers – to these executive summaries. This document contains the questions and answers prepared by the experts of the Environmental Effects Assessment Panel. They refer mainly to the environmental effects of ozone depletion and its interactions with climate change, based on the 2014 report of this Panel, but also on information from previous assessments and from the 2014 report of the Scientific Assessment Panel[1]. Readers who need further details on any question should consult the full reports for a more complete scientific discussion. All of these reports can be found on the UNEP website: http://ozone.unep.org .

1 Reference: Twenty Questions and Answers about the Ozone Layer 2014 Update, Scientific Assessment of Ozone Depletion 2014, United Nations Environment Programme, Nairobi.

1. HOW IS OZONE PRODUCED AND DESTROYED?

The ozone molecule (O_3) contains three atoms of oxygen and is mainly formed by the action of UV radiation from the sun on oxygen molecules (diatomic oxygen, O_2) in the upper part of Earth's atmosphere (called the stratosphere). Ozone is also produced locally near Earth's surface (in the troposphere) from the action of UV radiation on some air pollutants.

About 90% of all ozone molecules are found in the stratosphere, a region that begins about 10-20 kilometres above Earth's surface and extends up to about 50 kilometres. Most of this ozone is found in the lower stratosphere in what is commonly known as the "ozone layer." The stratospheric ozone layer protects life on Earth by absorbing most of the harmful UV radiation from the Sun. The remaining 10% of ozone is in the troposphere, which is the lowest region of the atmosphere, between Earth's surface and the stratosphere.

The concentration of ozone varies from about 12 parts per million in the stratospheric ozone layer to about 20 parts per billion near Earth's surface.

Figure 1.1 illustrates the production and destruction of stratospheric ozone. Atomic oxygen (O) is formed when UV radiation in sunlight interacts with oxygen molecules (O_2). Atoms of O react with molecules of O_2 to form an ozone molecule (O_3). Ozone is destroyed naturally in the upper stratosphere by the UV radiation from the sun. These reactions are most important in the stratosphere above tropical and middle latitudes, where UV radiation is most intense. For each ozone molecule that is destroyed, an oxygen atom and an oxygen molecule are formed. Some of these recombine to produce ozone again. These naturally occurring reactions of destruction and production of ozone are balanced so that the ozone amount in the stratosphere remains constant.

Ozone is a very strong oxidising agent and reacts with many chemicals including organic substances. In addition to the processes described above, human activities and natural processes can emit large amounts of gases containing chlorine (Cl), bromine (Br) and fluorine (F) that eventually reach the stratosphere. When exposed to UV radiation from the Sun, these halogen-containing gases are converted to more reactive gases, such as chlorine monoxide (ClO) and bromine monoxide (BrO). These reactive gases participate in "catalytic" reaction cycles that efficiently destroy ozone in the stratosphere (Figure 1.1).

The destruction of ozone by halogens involves two separate chemical reactions. The net or overall result is that atomic oxygen (O) and ozone (O_3) are combined, to form two oxygen molecules (O_2). In Figure 1.1, the cycle begins with ClO or Cl. Cl reacts with (and thereby destroys) ozone and forms ClO. This then reacts with O to generate O_2 and regenerate Cl. Because Cl or ClO is reformed each time an ozone molecule is destroyed, chlorine is considered to be a catalyst for ozone destruction. Similar reactions occur with bromine derivatives and other compounds such as nitrogen oxides.

The relative potency of the different halogens depends largely on the stability of the compounds. Hydrogen fluoride (HF) is very stable, so fluorocarbons have no known impact on ozone. The atmospheric lifetimes of the iodine compounds are extremely short and they do not play an important role in the ozone destruction processes.

Chlorine-containing compounds from natural sources, such as volcanic eruptions, are usually "washed out" of the atmosphere before they can reach the stratosphere. They can however destroy ozone in the troposphere.

The total amount of ozone above any point on Earth is measured in Dobson Units (DU). An ozone column amount of 300 DU, which is a typical global average, corresponds to a 3 mm layer of pure ozone. Ozone column amounts vary seasonally and with latitude, and can sometimes reach values nearly twice as large as the global average. During the springtime Antarctic Ozone "Hole", ozone amounts of less than 100 DU may occur.

Most of the atmospheric column of ozone is in the stratosphere (see Box 1), where the intensity of UV radiation is greater than closer to Earth's surface. At any location, between 5 and 10% of the ozone column is in the troposphere, where it may be harmful to human and ecosystem health. For example, high concentrations of ozone can lead to respiratory problems and decreased crop productivity. In polluted environments, ozone production in photochemical smog can lead to increases from its background levels of ~25 ppb (parts per billion) to in excess of 100 ppb. For this reason, in many large cities, ozone is routinely measured, and health warnings are issued whenever the concentration exceeds 100 ppb.

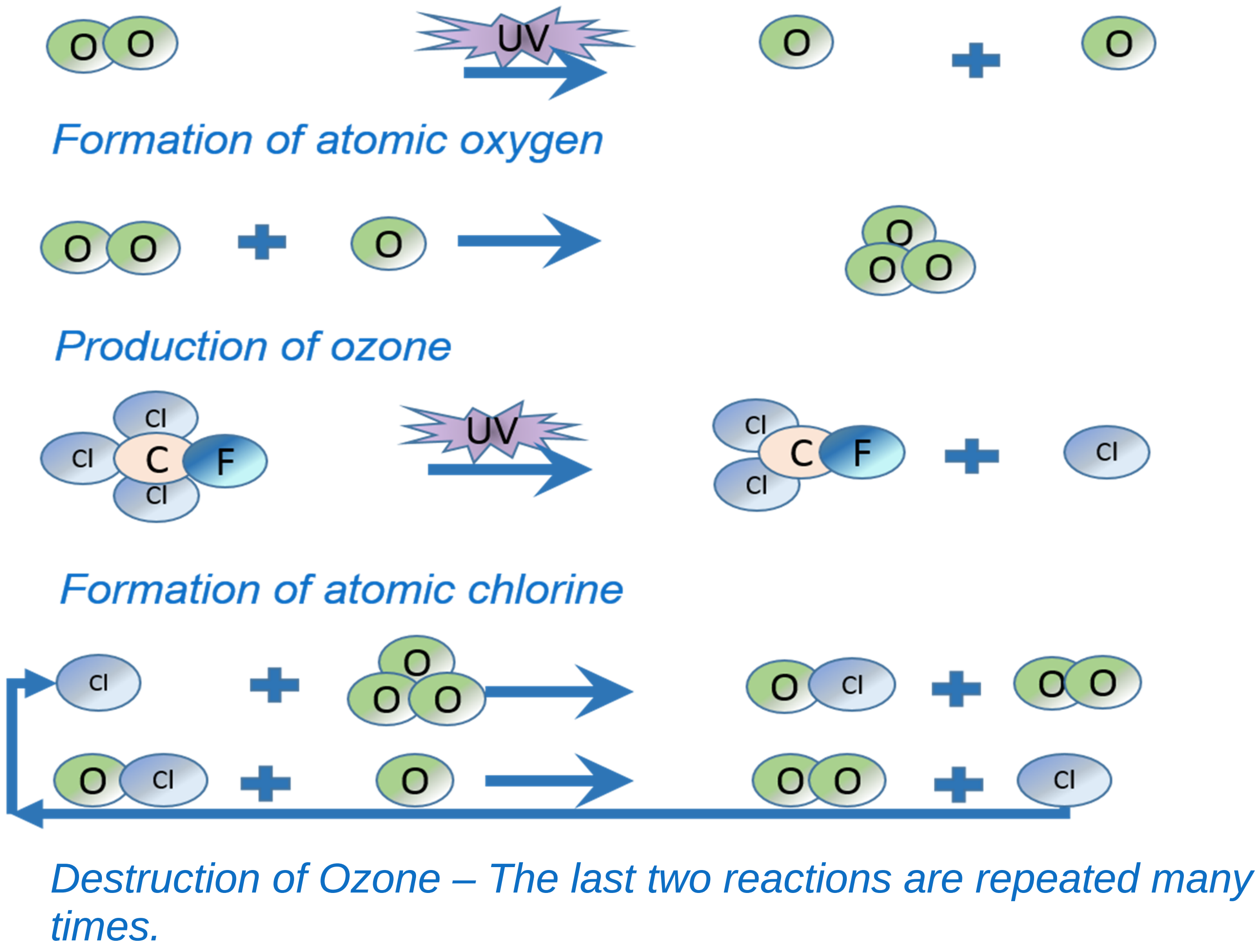

Figure 1.1: Formation and destruction of ozone

Box 1. Troposphere *versus* Stratosphere

The troposphere is the region of the atmosphere extending from the surface of the Earth to an altitude of approximately 15 km, but ranging from less than 10 km in Polar Regions to about 20 km in the tropics. Temperature decreases with altitude in the troposphere typically at a rate of approximately 6°C/km. This promotes turbulent mixing so that any gases there are uniformly mixed. The upper limit of the troposphere is called the tropopause, which is the altitude at which temperature no longer decreases with altitude. At altitudes above this point, absorption by ozone of incoming sunlight (especially UV radiation), and of outgoing infrared radiation from Earth's surface cause the temperature gradient to stabilise or to show an increase in temperature with increasing altitude. Such temperature gradients inhibit the vertical mixing, resulting in a layered (or "stratified") structure. In this region of the atmosphere, gases are no longer uniformly mixed. Peak ozone amounts occur at altitudes near 25 km, and the stratosphere extends to an altitude of about 50 km (Figure 1.2).

The maximum altitudes of clouds, of jet aircraft flight paths, and of the highest mountains are all approximately 10 km. Turbulent mixing in the troposphere leads to convective motion, condensation and cloud formation, and precipitation.

Annual Mean Atmospheric Profiles: Lauder, New Zealand (45 degrees South)

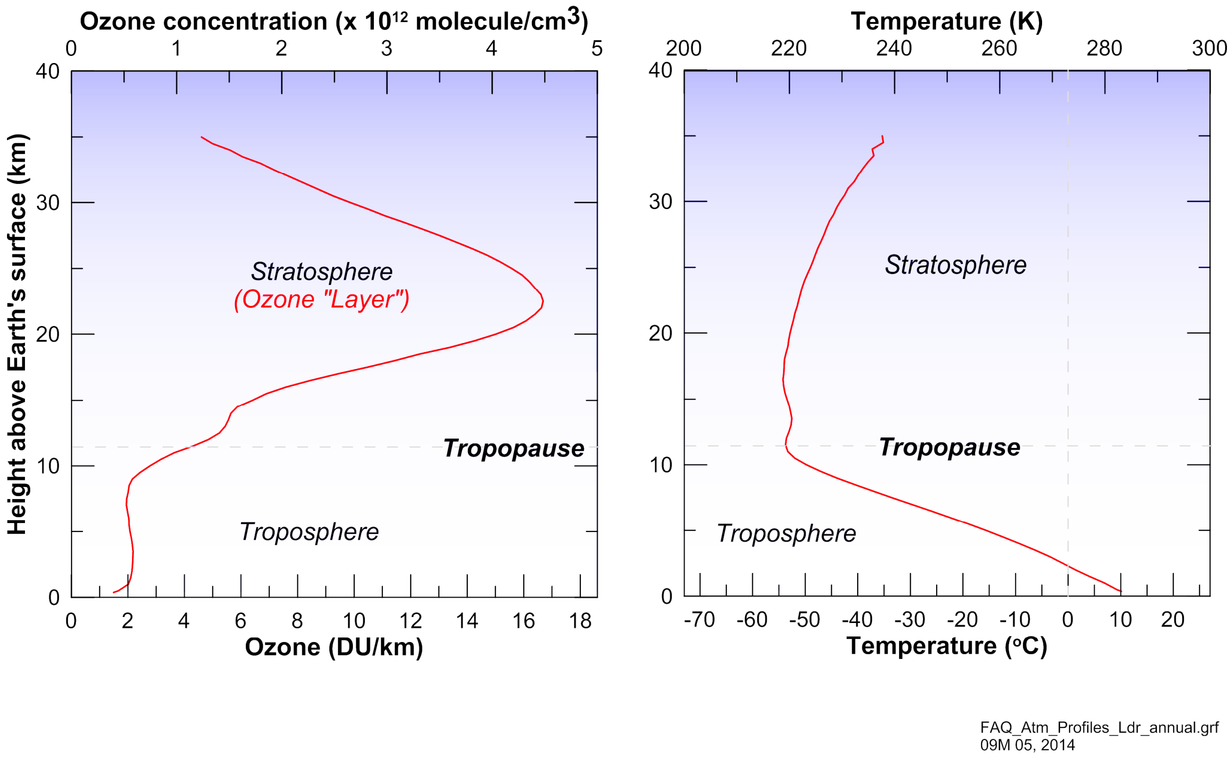

Figure 1.2: Atmospheric profiles of ozone and temperature measured with instruments carried by balloons. Figure provided by Dr R McKenzie.

2. ARE THERE INTERACTIONS BETWEEN OZONE AND CLIMATE CHANGE?

The relationship between ozone and climate change is complex as depicted in Figure 2.1 and explained on the next pages.

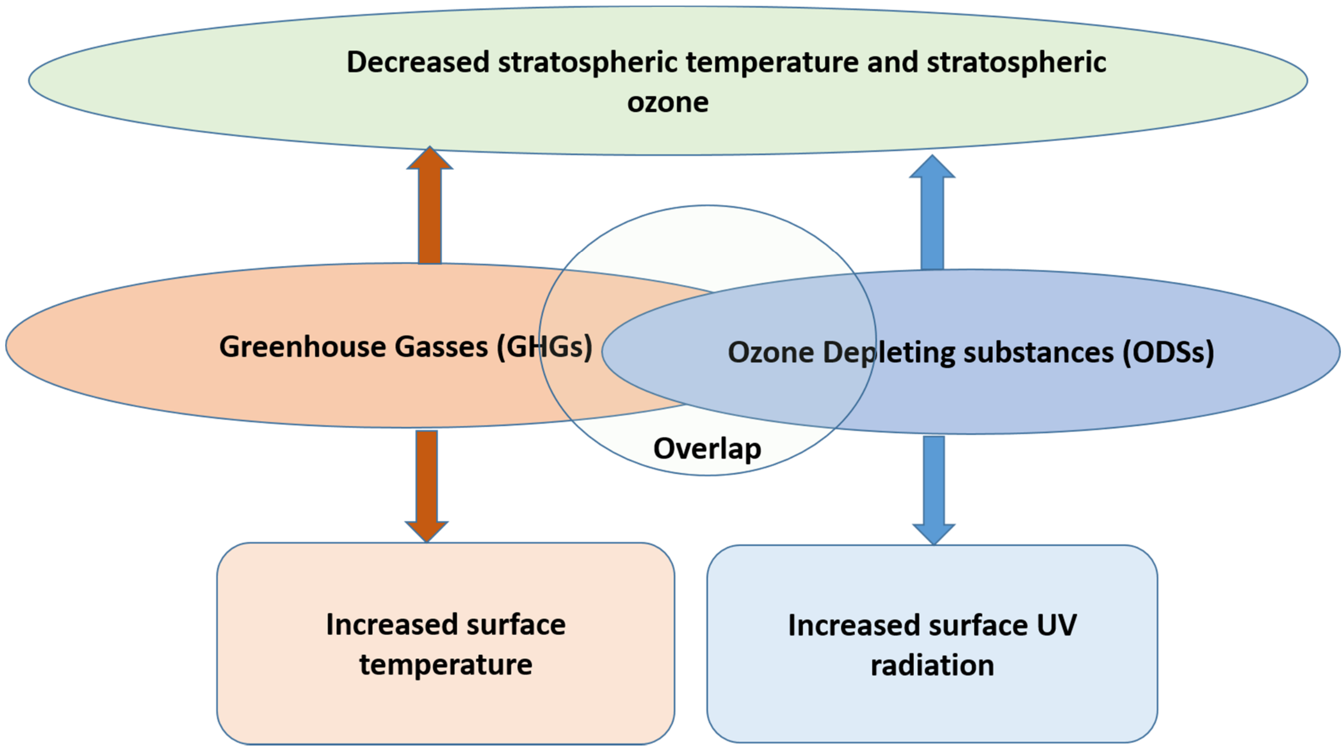

Figure 2.1. Schematic of ozone focused stratospheric chemistry-climate interactions. Links between components of the chemistry-climate system are indicated with arrows.

a. Is ozone depletion affected by climate change?

Climate change will affect ozone depletion through changes in atmospheric conditions that alter the chemical production and loss of stratospheric ozone. The interactions are complex. Climate change is expected to decrease temperatures and water vapour abundances in the stratosphere.

Ozone, the chlorofluorocarbons (CFCs), and their substitutes, are greenhouse gases (GHGs) that have a relatively small (± 13%) contribution to climate change. Several other gases that are involved in the chemistry of ozone depletion are also active greenhouse gases. They include water vapour, methane, and nitrous oxide. Increases in these gases will ultimately lead to increases in stratospheric gases that destroy ozone. Changes in solar output and future volcanic eruptions (the latter through injection into the atmosphere of particulates and gases that form an active surface for ozone depletion) will influence both climate change and ozone depletion.

While recent ozone depletion has been dominated by chlorine and bromine in the stratosphere, in the longer term (~100 years) it seems likely that the impact of climate change will dominate, through the effects of changes in atmospheric circulation and chemistry. Increases in GHGs over the first half of the current century may contribute to a colder stratosphere, leading to a decrease in the rate of destruction of ozone outside Polar Regions. In Polar Regions however, the lower temperatures may lead to some increases in polar stratospheric clouds that can lead to exacerbation of ozone depletion. The temperature changes are also leading to changes in atmospheric circulation. These changes may aid the mixing of long-lived CFCs from the troposphere to the stratosphere that will increase their rate of photochemical destruction. This can lead to more severe ozone depletion in the short term but will contribute to faster ultimate recovery of ozone. Changes in polar ozone can also lead to changes in circulation patterns in the lower atmosphere, which in turn affect surface climate. The effects of climate change on UV radiation are twofold: those that influence total ozone directly, and those that depend on changes in other variables (such as clouds, aerosols or snow cover) that influence solar UV indirectly. This is further complicated by the notion that decreasing the water vapour in the stratosphere will cause cooling of the Earth's surface, competing with the present warming.

b. Has stratospheric ozone depletion had an influence on climate change?

Stratospheric ozone depletion has an influence on climate change since both ozone and the compounds responsible for its depletion are active greenhouse gases.

Halocarbons such as CFCs have contributed to positive direct radiative forcing and associated increases in global average surface temperature. Ozone depletion due to increasing concentrations of ozone depleting substances (ODSs) has an indirect cooling effect. Warming due the existence of ODSs and cooling associated with ozone depletion are two distinct climate forcing mechanisms that do not simply offset one another. Bromine-containing gases currently contribute much more to cooling than to warming, whereas CFCs and hydrochlorofluorocarbons (HCFCs) contribute more to warming than to cooling. Hydrofluorocarbons (HFCs) and perfluorocarbons (PFCs) contribute only to warming. The indirect cooling effect of ODSs is projected to cease upon ozone layer recovery.

Actions taken under the Montreal Protocol resulted in the replacement of CFCs with HCFCs, HFCs, and other substances or methods of fulfilling their main uses, e.g. as coolants. Because these replacement chemicals/compounds generally have lower global warming potentials (GWPs), and because total halocarbon emissions have decreased due to the Montreal Protocol and its amendments and adjustments, their contribution to climate change has been reduced. Ammonia and those hydrocarbons used as halocarbon substitutes are very likely to have a negligible effect on global climate.

Substitutes for ODSs in air conditioning, refrigeration, and foam blowing, such as HFCs, PFCs, and other gases such as hydrocarbons, are not expected to have a significant effect on global tropospheric chemistry.

c. How is ozone depletion influencing Southern Hemisphere climate?

Ozone depletion changes the distribution of atmospheric heat resulting in distinct alterations to Southern Hemisphere atmospheric circulation and climate factors such as precipitation and temperature.

Stratospheric ozone depletion and resultant cooling over Antarctica has caused the tropopause to lift allowing the polar westerly jet stream to shift southwards (Figure 2.2). The speed of both the polar jet and the westerly winds has also increased, keeping most of Antarctica cold as the rest of the world warms. This shift in the westerly's and their increased strength has changed atmospheric and oceanic circulation throughout the Southern Hemisphere by creating a more positive phase of the Southern Annular Mode (SAM). The SAM index describes the difference in sea-level pressure between the latitudes of 40˚S and 60˚S. Over the past century, increasing greenhouse gases and then ozone depletion over Antarctica have both pushed the SAM towards a more positive phase and the SAM index is now at its highest level for at least 1000 years. Positive SAM anomalies are characterised by stronger sub polar westerly winds positioned further south over the continental landmass, colder Antarctic temperatures and low atmospheric pressure over the icecap. As a result, high latitude precipitation has increased and the mid-latitude dry zone has moved south as shown (Figure 2.2). The resultant changes to precipitation and temperature and some of their ecosystem impacts are just emerging. In addition to increased wind across the Southern Ocean and colder temperatures across Antarctica, these include warmer and wetter summers in Southern Africa, SE South America, SE Australia and E New Zealand and warmer drier summers in Patagonia. In southernmost South America these drier conditions have been linked to slower growth of trees, while in New Zealand the wetter summers have led to increased tree growth.

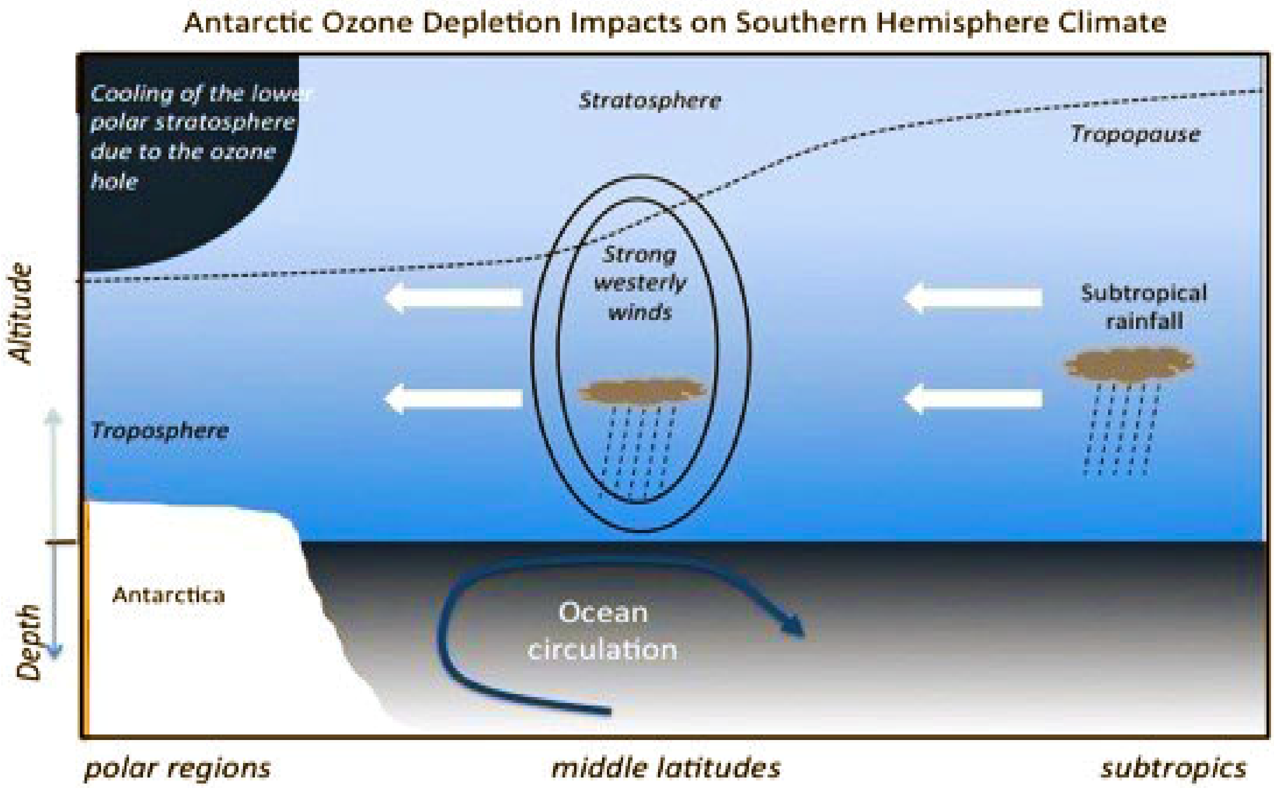

Figure 2.2 Schematic illustration of Southern Hemisphere climate impacts in the austral summer associated with Antarctic ozone depletion. This ozone depletion has cooled the Antarctic stratosphere, shifting the mid-latitude westerly jet pole ward with associated rainfall impacts (shown by the white arrows). These changes in rainfall have been observed in Australia, New Zealand, Africa and South America. The wind changes have also strengthened the subtropical rotating ocean currents and overturning circulation in the ocean (shown by the blue arrow). Figure provided by David J. Erickson III and Sharon Robinson.

3. WHAT IS THE RELATIONSHIP BETWEEN OZONE AND SOLAR UV RADIATION?

There is an inverse relationship between the concentration of ozone and the amount of UV radiation transmitted through the atmosphere since ozone absorbs some of the UV radiation. The main benefit of ozone is that it absorbs UV radiation from sunlight so that the intensity of UV radiation at Earth's surface is dramatically lower than at the top of the atmosphere. If there were no ozone present, the intensities of UV-B radiation at ground level would be increased by orders of magnitude, leading to substantial harmful environmental impacts.

Only a small fraction of the radiation emitted by the Sun is in the UV range. This range extends from 100 to 400 nm and is divided into three bands: UV-A (400 – 315 nm), UV-B (315 – 280 nm) and UV-C (280 – 100 nm). As the Sun's radiation passes vertically through the atmosphere, all the UV-C and approximately 90% of the UV-B is absorbed by ozone and oxygen molecules in the stratosphere. UV-A radiation is less affected by the atmosphere. Therefore, the UV radiation reaching Earth's surface is composed mainly of UV-A with a small UV-B component (Figure 3).

The amount and variability of the UV-B component depends on the solar elevation angle, which defines the path-length through the atmosphere, and also on the amount of ozone. A decrease in the concentration of ozone in the atmosphere results in increased UV-B radiation at the surface of the Earth. UV-B radiation is much more biologically active than UV-A radiation and can have either beneficial or detrimental effects on living organisms. Changes in the amount of UV-B radiation (for example due to stratospheric ozone depletion) are very important for ecosystems, materials and humans.

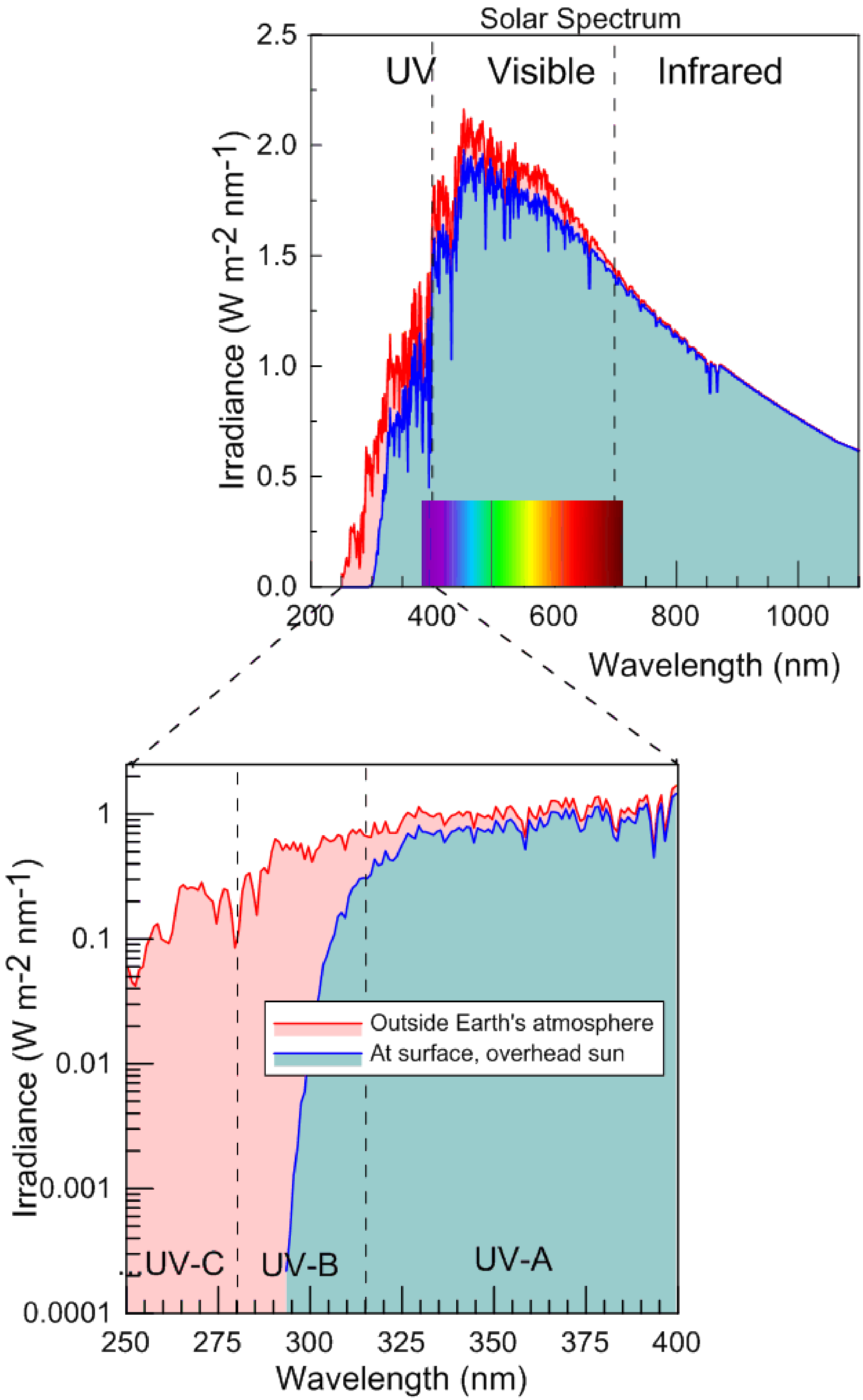

Figure 3: Absorption of UV radiation by ozone. The blue curve shows that ozone absorption increases rapidly at shorter wavelengths so that at wavelengths less than 300 nm, less than 1% of the radiation is transmitted. Figure provided by Dr R McKenzie.

4. WHY IS THERE CONCERN ABOUT UV RADIATION?

The high photon energies at UV-B wavelengths are capable of breaking molecular bonds in DNA, which is the building block of life. Damage to this molecule can result in multiple health effects, including skin cancers. UV radiation can adversely affect agricultural and aquatic productivity as well as air quality. It can also reduce the effective lifespan of materials such as plastics and paint products. Some UV radiation is however beneficial for human health such as in the production of vitamin D and for killing pests and pathogens.

UV-B radiation makes up only a small proportion of the UV radiation reaching Earth's surface, because it is largely absorbed by stratospheric ozone. However, UV-B radiation is the most biologically damaging as the high photon energies are sufficient to break molecular bonds. The longer wavelength UV-A is less damaging, but is implicated in some adverse effects, including skin damage. Ozone has only a minor effect on UV-A radiation.

For many, but not all, environmental effects and biological processes, the damaging effect of UV radiation increases as the wavelength decreases (and hence the energy per individual photon increases).

Table 4. Approximate contributions (Wm^{-2}) to solar energy from UV-A and UV-B radiation at selected ozone amounts for overhead sun (sza=0) and for sza=60 °. All for an Earth-Sun separation of 1 Astronomical Unit (the mean distance between the Earth and the Sun i.e., close to the equinoxes), cloudless skies, no aerosols, and assuming a value for the solar constant of 1365 W m^{-2}. (See also Question 6 for an explanation of sza).

Solar zenith angle (sza)	**Ozone levels (Dobson Units)**	**Solar Energy Contribution (Wm^{-2})**	
		UV-B (280-315 nm)	**UV-A (315-400 nm)**
Extra-terrestrial		20.8	85.1
Earth surface, sza= 0	300	3.82	65.1
Earth surface, sza=60,	450	0.60	26.3
Earth surface, sza=60	300	0.90	26.7
Earth surface, sza=60	100	1.89	27.2

5. WHAT IS THE UV INDEX?

The UV Index (UVI) describes the level of solar UV radiation at the Earth's surface relevant to sunburn in humans (erythema).

Information about the intensity of UV radiation is provided to the public in terms of the internationally adopted UVI colour-scale, along with appropriate health warnings, as shown in Table 5. The colours corresponding to the various ranges are standardised throughout the world.

The UVI can be measured directly with instruments designed specifically to measure sun burning UV radiation. For clear-sky conditions, the UVI can be calculated approximately from knowledge of the ozone and the solar zenith angle (also known as solar elevation angle; see Question 6 for more detail). However, the UVI at a specific location and time depends strongly on the cloud cover and on the amount of aerosols. Other influential factors include the seasonally varying Sun-Earth separation, the altitude, and surface reflection. When the surface is snow-covered, the UVI can be up to 60% greater than for snow-free surfaces. Several countries provide daily forecasts of the UVI that take predicted changes in ozone and cloud cover into account. Further details about the UVI can be found at *www.unep.org/PDF/Solar_Index_Guide.pdf*

Table 5: The UV Index and related colours as used by the World Health Organization

Exposure Category	UVI Range
Low	**< 3**
Moderate	**3 to 5**
High	**6 to 7**
Very High	**8 to 10**
Extreme	**>11**

6. WHEN AND WHERE SHOULD THERE BE CONCERN ABOUT EXPOSURE TO UV RADIATION?

The effects of UV radiation depend on how much is received. Therefore it is important to understand how exposure to UV radiation varies, due to both variation in levels at Earth's surface and to human activities.

The main determinants of surface UV radiation are the elevation of the Sun above the horizon – known as the solar zenith angle (sza) (Figure 6.1), and the amount of ozone in the atmosphere. Consequently, the highest UVI values occur in the tropics, where ozone amounts are at their lowest (apart from the Antarctic "ozone hole"), and where the sun is directly overhead at noon. UV radiation is also influenced by seasonal changes in Sun-Earth separation (closest in Dec/Jan), altitude, and surface reflection (albedo). The variation in the UVI as a function of the solar zenith angle and the ozone amount is illustrated in Figure 6.2.

In addition to this variation in estimated clear-sky UVI, there are a range of modifiers of the UVI at Earth's surface. Clouds and aerosols can reduce levels of UV radiation by more than 50%; and on average they block about 30% of the clear-sky radiation. However, scattering from clouds that are in the direct beam of the sunlight, but which do not obscure it, can lead to significant shorter term enhancements in levels of UV radiation. For aquatic systems, the transmitted UV radiation also depends on the clarity of water, with coloured dissolved organic matter (CDOM) being an important attenuator.

Most organisms that are exposed to UV radiation have their own means of blocking it to reduce the dose received (e.g., melanin in human skin, or flavonoids in some plant species).

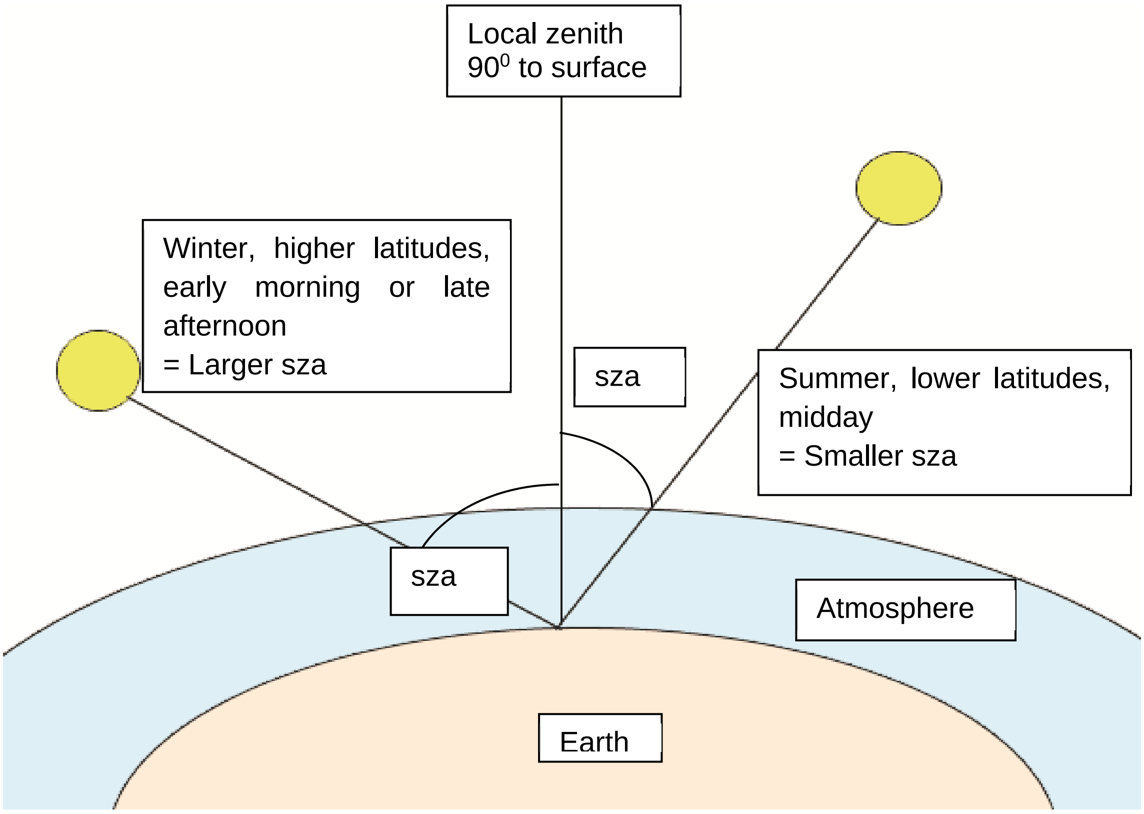

Figure 6.1: The solar zenith angle (sza) is the angle between the theoretical perpendicular position of the Sun and the incoming rays from the Sun

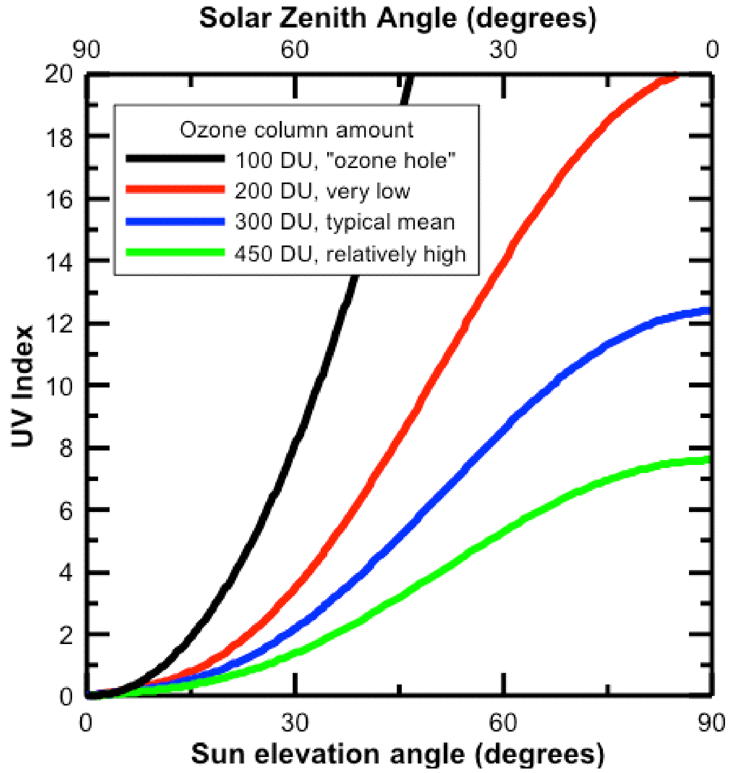

Figure 6.2: Variation of the clear-sky UVI in relation to solar elevation. The coloured lines represent different ozone concentrations, measured in Dobson Units (DU), Figure provided by Dr R L McKenzie, NIWA.

The maximum UVI for any location on the globe is illustrated in the map below (Figure 6.3). The UVI has significantly higher summer maxima in the Southern Hemisphere compared with corresponding latitudes in the Northern Hemisphere. In the tropics at sea level the UVI can exceed 16 and a peak terrestrial value of 25 has occurred at high altitudes e.g. Altiplano region of South America (Figure 6.3). Recently a value of 35 has been measured in Chile. Generally, peak UVI values decrease with increasing latitude and in Polar Regions; UVI values tend to be much lower, and are zero during the polar winter night. However, the Antarctic region, which is affected by the Antarctic “ozone hole”, is a notable exception. Peaks there can exceed an UVI of 16. Outside the protective layer of Earth’s atmosphere (altitude > 50 km), the UVI can exceed 300.

The higher the UVI, the greater the potential for damage, and the less exposure time it takes for harm to occur. For fair-skinned individuals a UVI of more than 10 can cause sunburn from an exposure of about 15 minutes.

High levels of UV radiation can have a wide range of environmental impacts. For any particular process, the impact depends on the difference in absorption of the different wavelengths. For example, effects on human skin erythema (sunburn) will be proportional to the dose of erythemally active UV radiation.

In humans, high levels of exposure to UV radiation can lead to skin-damage (e.g., sunburn) skin cancer and eye damage (e.g., cataract). However, some exposure to UV radiation is required to maintain adequate levels of vitamin D. UV radiation can also affect other animals, plants, aquatic organisms, and whole ecosystems. It influences air quality through the production of photochemical smog, and the degradation rates of materials such as paints and plastics. These are discussed further in subsequent FAQs.

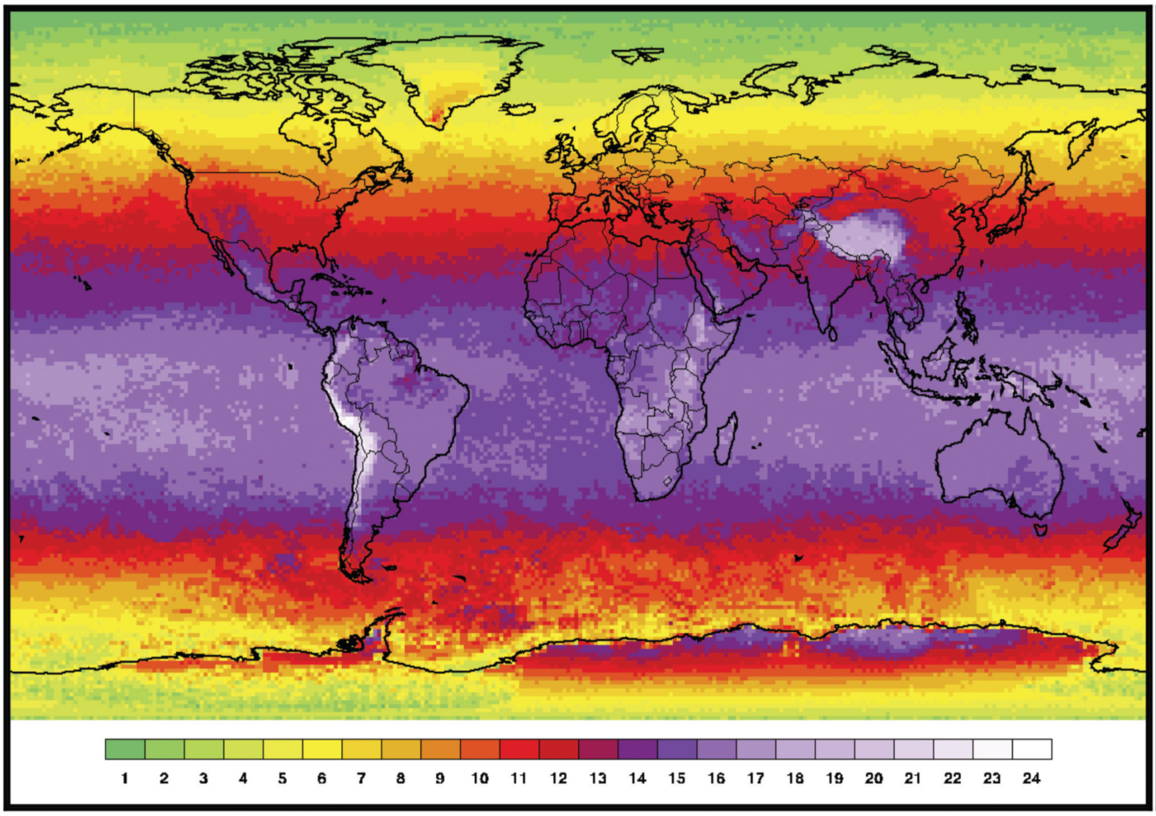

Figure 6.3: Average values for the maximum UVI at each point on the globe derived from the total ozone monitoring satellite (TOMS) measurements over several years. Figure provided by Ben Liley, NIWA Lauder (note that the colours used to depict the UVI here are different to those provided in Table 5)

7. HOW IS UV RADIATION EXPECTED TO CHANGE IN THE FUTURE?

Due to the combined effects of ozone recovery, and changes in cloud cover induced by increasing greenhouse gases, relatively modest changes in UV radiation are expected in the future.

In the Antarctic region, significant reductions in mean noontime UVI values are expected due to the continuing recovery of ozone, especially during the springtime "ozone hole" period. By the end of the 21st century, these future reductions in UVI due to projected ozone increases will be comparable with the increases that occurred due to ozone depletion in the past, as shown in the bottom panels of Figure 7. Other changes in UVI induced by climate change effects are also potentially important. For example, projected increases in cloud cover and reductions in surface reflectivity due to ice-melt in the Arctic, and in the margins of the Antarctic continent, are expected to continue to contribute to reductions in UVI (see middle panels of Figure 7). However, there is only low confidence in these estimates of effects. Outside Polar Regions, future changes are likely to be dominated by changes in aerosol extinctions, particularly in densely populated areas. For example, large increases in UVI are projected for parts of Asia, to counterbalance the large reductions in UVI that probably occurred there over the past few decades (see upper panels of Figure 7). Because of uncertainties in both the projected amounts of aerosols, and their optical properties, these aerosol effects are uncertain. For that reason, we do not provide an estimate of the sum of the individual effects.

.
.

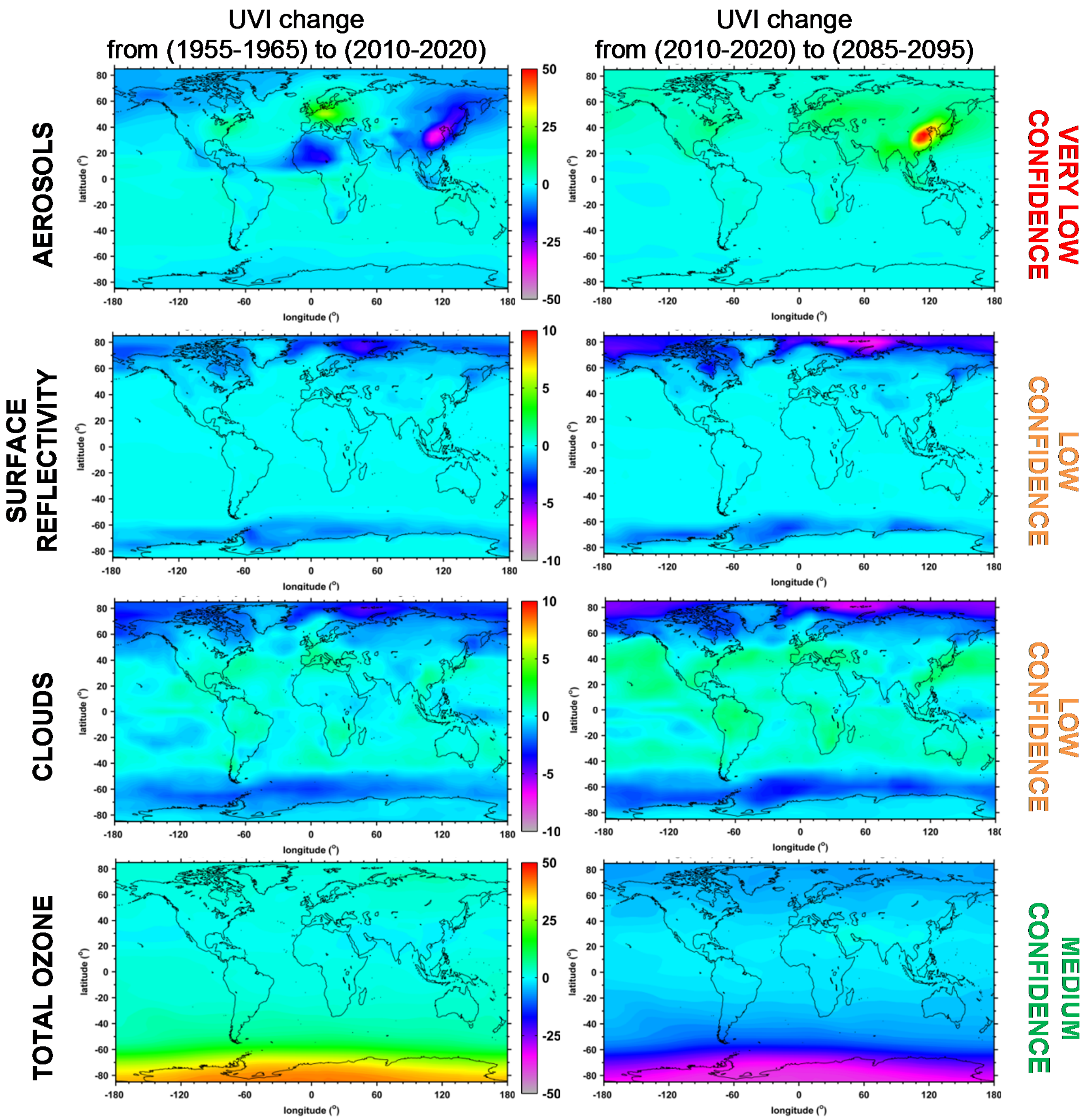

Figure 7. Calculated percentage changes per year in noontime UVI relative to the "present" (i.e., 2010-2020). The left column shows simulated changes since 1955-1965. The right column shows the simulated changes expected from the present to the period 2085-2095. Effects of aerosols, surface reflectivity, cloudiness and total ozone on UVI are shown in each row, with our assessment of the confidence in the UVI projections. Note the different colour-scales for each row.

8. HOW IS UV RADIATION BAD FOR MY HEALTH?

Exposure to solar UV radiation damages the skin and eyes. These effects can be acute after intense exposure or chronic after long-term exposure.

Sunburn is the major immediate (acute) outcome in the skin of over-exposure to sunlight. The dose of solar UV-B radiation required to induce sunburn varies considerably from one individual to another, largely depending on the pigment in their skin. Six categories of skin type are commonly used to describe sensitivity to sunlight (see Table 8).

Exposure of the unprotected eye to intense UV-B radiation causes sunburn of the superficial layers of the eye or the inner surface of the eyelids, resulting in photoconjunctivitis, or affecting the cornea, resulting in photokeratitis. This can cause pain and blindness for a few hours to a day or two. Protection of the eye is needed under conditions of high ambient UV radiation or where there are highly reflective surfaces, such as snow or white sand. Sunburn occurs because energy from UV radiation damages DNA and other molecules in the skin or eyes.

The inflammatory response that occurs to manage this damage includes increased blood flow to the area and release of chemicals that stimulate nerve fibres, leading to redness and pain, respectively. Damage to the DNA of skin cells can result in their destruction; peeling of the skin may occur if DNA damage is severe and affects a large number of skin cells.

Exposure to UV radiation suppresses the generation of cell-mediated immune responses (Box 8). Higher exposure to UV radiation around the time of vaccination may result in a lower immune response, at least in some individuals. UV irradiation can cause immune suppression that allows the reactivation of some viruses. For example sun exposure can trigger the reactivation of latent herpes simplex virus infection and the reappearance of vesicles (cold sores or fever blisters) in the skin (Figure 8.1).

Table 8: Skin types commonly used to categorise sensitivity of the skin following exposure to UV radiation.

Skin phototype	Sun sensitivity	Sunburn/tan
I	Extremely sensitive	Always burns, never tans
II	Very sensitive	Burns readily, tans slowly and with difficulty
III	Moderately sensitive	Can burn after high exposure, tans slowly
IV	Relatively tolerant	Burns rarely, tans easily
V	Variable	Can burn easily, difficult to assess as pigment is present already
VI	Relatively insensitive	Rarely burns

The major harmful effect of chronic (long-term) exposure of the skin to sunlight, and/or intermittent episodes of sun burning, is the development of skin cancers, including non-melanoma skin cancers and melanoma (Figure 8.2). Repeated DNA damage from exposure to UV radiation results in mutations in specific tumour-related genes, including those required for DNA repair. Immune suppression induced by exposure to UV radiation (Box 8) allows the abnormal tumour cells to develop and form skin cancers.

The non-melanoma skin cancers are divided into squamous cell carcinoma and basal cell carcinoma (Figure 8.2), and are the most common cancers in many countries. Incidence is highest in fair-skinned populations living in sunny climates, and increases with increasing age. The majority of these tumours are found on the face and head - the sites most consistently exposed to the sun. Non-melanoma skin cancers are generally readily treatable and are rarely fatal but both the tumours and the treatment may be disfiguring. The number of new cases of non-melanoma skin cancer occurring each year has increased significantly in many countries over the past 40 years or so, particularly in fair-skinned populations.

Melanomas of the skin (Figure 8.2) are much more dangerous than the non-melanoma skin cancers, with a significant risk of death if not treated at an early stage. They arise from the cells that form the pigment (melanin) that determines skin colour. While non-melanoma skin cancers predominantly occur in older adults, melanoma can develop in people of all ages. For example, it is the most commonly reported cancer in women age 17-33 years in Australia. Melanoma occurs mainly in fair-skinned populations, and, while high levels of sun exposure at any age increase the risk of melanoma, high dose exposure and/or sunburn in childhood may be particularly important. In people with fair skin, melanoma occurs most frequently on the back in men and on the legs in women. In people with dark skin, melanoma is more common on the soles of the feet than on the sun-exposed areas of the body. The incidence of melanoma has increased in many countries in recent decades, but current figures indicate a levelling-off or even a decrease in younger age groups in countries with strong sun protection programs.

Over the long term, sun exposure also causes photoageing of the skin, seen as wrinkling and freckling of the skin and the development of moles (naevi), brown spots (solar lentigines) and crusty lesions of the skin called actinic keratoses. UV radiation in both the UV-A and UV-B wavelengths are responsible, causing mutations in DNA and loss of the elastic fibres in the skin. Some of these changes, particularly actinic keratoses and numerous moles, are associated with an increased risk of skin cancers.

Chronic exposure of the eye to UV radiation increases the risk of pterygium (surfer’s eye) and cataract, both of which are irreversible. Pterygium is an invasive growth on the surface of the eye that may impair vision and require surgery (sometimes repeatedly). Cataracts are extremely common in older people and are at least partly caused by chronic exposure of the eye to UV radiation. Clouding of the lens of the eye progresses slowly and painlessly, leading to an increasing loss of vision and eventually blindness, if not treated surgically.

Immune suppression resulting from chronic exposure to UV radiation may underlie the involvement of certain human papillomavirus types (that typically cause warts) in the formation of squamous cell carcinomas.

Box 8: UV-induced immune suppression

When UV radiation reaches the skin, it is absorbed by specific molecules called chromophores. These initiate a cascade of events affecting the immune system that result in a decreased ability to respond to "foreign" challenges, such as invading microorganisms or tumour proteins, encountered within a short period of the exposure. The production of a range of immune mediators is altered, and specialised lymphocytes called T regulatory cells are induced. All of these changes lead to long-term suppression of immune responses to the specific challenge.

Figure 8.1: Cold sores caused by reactivation of latent herpes simplex virus following exposure to solar UV-B radiation. Photograph supplied by Professor M. Norval (University of Edinburgh, Scotland).

Squamous cell carcinoma | Basal cell carcinoma | Cutaneous malignant melanoma

Figure 8.2: Examples of the 3 major types of skin cancer. Photograph supplied by Professor M. Norval (University of Edinburgh, Scotland).

9. HOW WILL CLIMATE CHANGE AFFECT EXPOSURE OF HUMANS TO UV RADIATION?

The effects of climate change on the amount of UV radiation reaching Earth's surface will be small. However warming temperatures and changes in precipitation patterns may affect the amount of time people spend outdoors and their use of sun protection, and thus the dose of UV radiation to which they are exposed.

The risk of developing skin cancers, eye diseases and immune suppression depends on the dose of UV radiation reaching the relevant tissues. This in turn depends on the amount of UV radiation reaching Earth's surface and on the sun exposure behaviour of the individual: time spent in the sun and use of sun protection such as clothing, hats, sunscreen and sunglasses. As noted in previous sections, the effects of climate change on the amount of UV radiation reaching Earth's surface will be small. The major uncertainty is whether people will spend more or less time outdoors in the sun, and expose more or less skin to the sun, as temperatures rise, but humidity, storms, floods and droughts also increase. Trends in fashion, holiday locations and leisure activities will also be important in determining the amount of exposure to UV radiation that people receive in future years. There is some evidence that skin cancers develop more rapidly when ambient temperatures are higher, but the relevance of this finding to health effects of climate change is unclear at present.

Altered levels of immune suppression, due to changes in the received dose of UV radiation may change vulnerability to infectious diseases and allergic diseases that also have changed in geographic and/or seasonal distribution as a result of climate change. At this time, the direction and magnitude of any such effects are highly speculative.

10. HOW IS UV RADIATION GOOD FOR MY HEALTH?

The best known benefit of exposure to solar UV radiation is production of vitamin D in the skin. In most regions of the world, humans obtain most of their vitamin D requirements from sun exposure. Many health benefits have been proposed for vitamin D. Exposure to UV radiation may also have beneficial effects through non-vitamin D pathways. Solar UV radiation can kill viruses, bacteria, and protozoan parasites in surface waters, making them safer to drink.

Vitamin D is the precursor of a hormone that is essential in humans for the maintenance of good health, particularly of the musculoskeletal and immune systems. Although the diet of humans contains some items rich in vitamin D, such as oily fish and eggs, most vitamin D in the majority of people is produced by exposure of the skin to solar UV radiation (Figure 10). Vitamin D is synthesised most effectively when the sun is at its height in the summer months and in the middle of the day; little or none is synthesised in the early morning and late afternoon, or in mid-winter at latitudes higher than about 40 degrees (for example, Boston, USA 42°N; Madrid, Spain 40°N; Christchurch, New Zealand 43°S). Individuals with dark skin usually require more sun exposure than those with fair skin to make the same amount of vitamin D, and the production is less efficient in older people.

It is important for many aspects of human health to maintain a sufficient level of vitamin D in the body. An assessment of this can be made by measuring the concentration of a vitamin D metabolite [25-hydroxyvitamin D, 25(OH)D] in the blood. There is considerable controversy around the optimal blood level of 25(OH)D, although a level of more than 50nmol/L (20ng/ml) is commonly recommended.

The active form of vitamin D is required in the body to maintain blood levels of calcium within a narrow range. The bones are a major store of calcium; vitamin D deficiency can result in release of calcium from the bones to maintain blood calcium levels, leading to defects in the bone that result in the diseases of rickets in children and osteomalacia in adults. There is controversial evidence currently that vitamin D deficiency may also increase the risk of a range of non-skeletal disorders. These include some internal cancers such as colorectal cancer, autoimmune diseases such as multiple sclerosis and type 1 diabetes, infections such as tuberculosis and influenza, and cardiovascular diseases such as hypertension. While some reports indicate that vitamin D supplementation decreases the risk of fractures, and possibly colorectal cancer, it has yet to be confirmed that increased exposure to solar UV-B radiation, affecting vitamin D status, can modulate the risk of these diseases.

In addition to the possible protective effect of higher vitamin D status on the development of some autoimmune diseases, there is emerging evidence that sun exposure itself may have beneficial effects through non-vitamin D pathways. In some autoimmune diseases, there is over-activity of certain T lymphocytes in the immune system against specific elements of the body's own tissues. Through the immunosuppression pathways, sun exposure and vitamin D may reduce this response, thus providing protection.

UV-B radiation is a potent disinfectant and naturally sterilises surface waters that may contain pathogenic microorganisms. Many people rely on surface waters for their drinking supplies, and the safety of these may depend on the dose of UV-B radiation (see also Question 14).

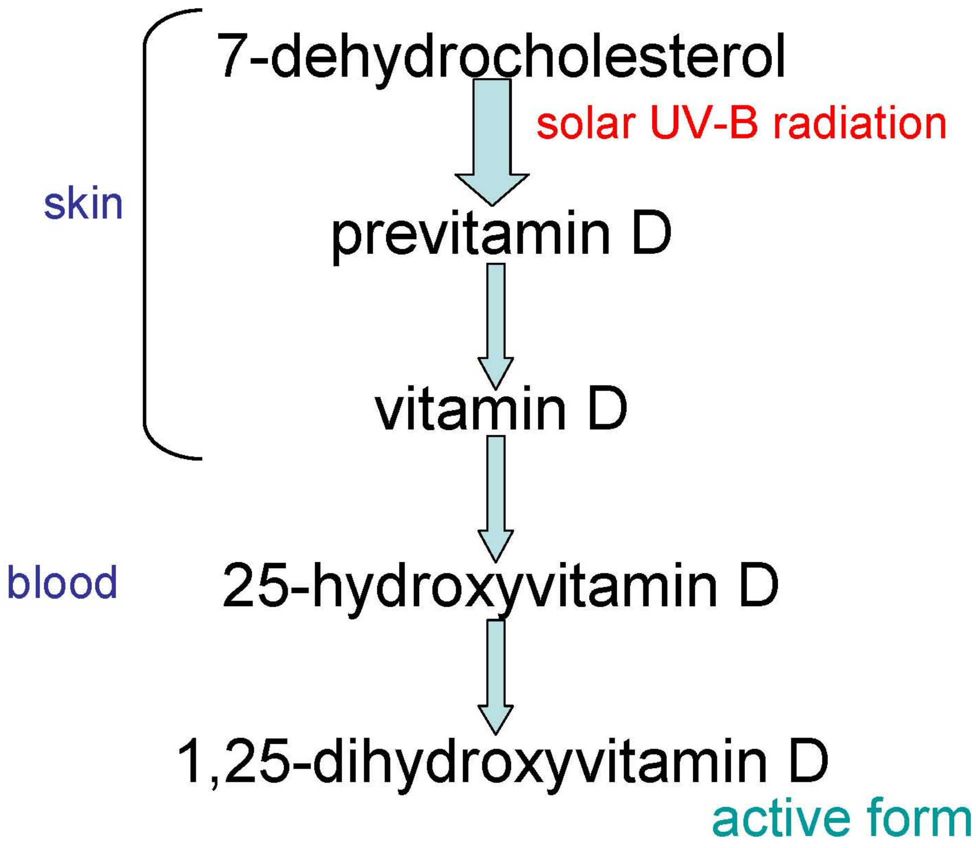

***Figure 10.** Simplified metabolic pathway leading to production of the active form of vitamin D which binds to receptors on target cells, thus initiating a variety of genetic and cellular responses.*

11. HOW MUCH EXPOSURE TO SOLAR UV RADIATION SHOULD I HAVE?

Optimal sun exposure maximizes the beneficial effects and minimizes the adverse effects of exposure to UV radiation. Levels of UV radiation vary according to location (latitude, altitude and environment), season, time of day, cloudiness and levels of air pollution. People vary in their sensitivity to UV radiation, for both the beneficial and adverse effects of sun exposure, through differences in skin colour and a range of other genetically determined factors. There is no "one-size-fits-all" recommendation, but some guidance is given below.

The intensity of UV-B radiation from the sun is highest at low latitude, in summer and during the hours around noon (about 11 am until 3M). Many news outlets and government websites report the daily UV Index (UVI) and issue alerts when high values are predicted.

If you are outside, it is most important to avoid sunburn. The time taken to reach this point depends on many factors, including your ability to tan in response to exposure to the sun. The face is the most common place for skin cancers to develop, so when outside for more than brief casual exposures, wear a hat and protect your eyes. Hats with brims more than 10 cm wide are recommended for head and neck protection, and can reduce exposure of the eyes by up to 50%. The hood of a jacket and headwear with side-flaps can provide protection from UV-B irradiation to the side of the face and eyes. Wrap-around sunglasses are better at protecting the entire eye than conventional sunglasses with open sides (see Figures 11.1 and 11.2).

Vitamin D is made most efficiently in the middle of the day, but this is also the time when UV radiation is most intense and there is the greatest risk of sunburn. Brief casual exposures during the central hours of the day may not require sun protection; however sun protection is recommended when outside for longer periods, including during the middle of the day, if the forecast UVI is 3 or greater. Some textiles are highly effective at blocking the penetration of UV rays, but others are less so. If you can easily see through the fabric when you hold it up to the light, it is likely to be less effective at screening UV radiation. Sunscreens are effective but need to be applied at the stated concentration and re-applied frequently, especially after swimming. Often they are applied too sparingly. It is advisable to use a sunscreen with a SPF (sun protection factor) rating of at least 15 which provides protection against the sunburn caused by UV-B radiation, and which also includes protection against UV-A radiation (graded by up to 5 stars). It is particularly important to protect children from sunburn, episodes of which could lead to increased risk of skin cancer development in adulthood. People with darker skin need higher exposure to UV-B radiation to develop sunburn, and also to make vitamin D, than people with fairer skin.

.

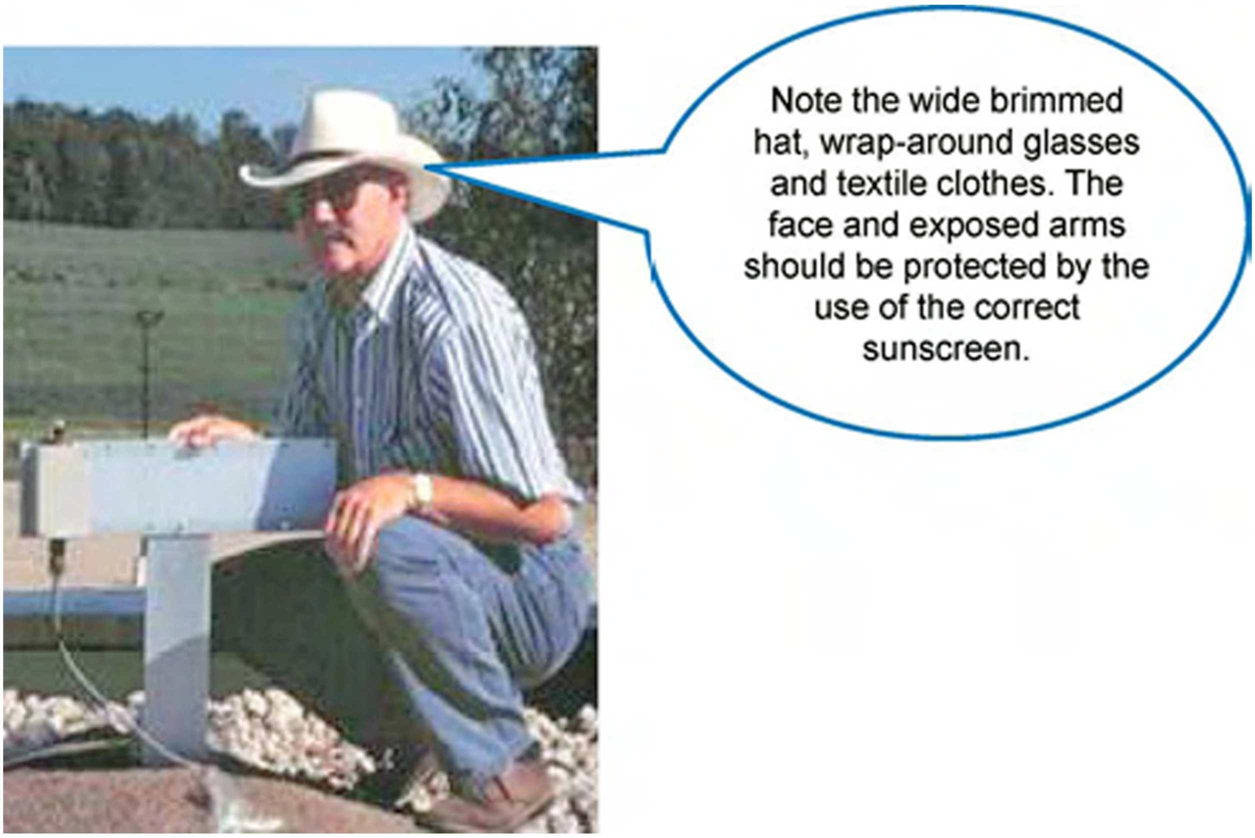

Figure 11.1. Wearing the correct clothing and the use of sunscreen can protect against UV radiation. (Photograph supplied by Dr A. Cullen, University of Waterloo, Canada.)

Figure 11.2. Wearing the correct clothing and the use of sunscreen can protect against UV radiation. (Photograph supplied by Mary Norval)

12. ARE THE REPLACEMENTS FOR OZONE DEPLETING SUBSTANCES SAFE FOR HEALTH AND THE ENVIRONMENT?

The replacements for ozone depleting substances (ODSs) are tested for safety to health and the environment before they are approved for use and so far few problems have been found. Originally CFCs were thought to be safe for the environment, so there is always the possibility that safety issues could emerge the longer a product is used, the greater the volume that is produced, the more uses that are found, or with new findings about the environment. For example, when HFCs were proposed as substitutes for CFCs, the global warming potentials of such compounds were only just being conceptualized. Once such properties were recognized, it was realised that these compounds could only be a short-term solution and that they too would need to be replaced. Thus, there is a requirement to avoid complacency and to manage these substances responsibly.

The Significant New Alternatives Program (SNAP) of the U.S. Environmental Protection Agency (EPA) evaluates alternatives for ozone depleting substances prior to their use. Anyone planning to market or produce a substitute in the U.S. must provide notice to EPA of their intent, as well as providing health and safety information, before introducing it. Normally the health and safety information will include information on chemical and physical properties, flammability and basic toxicological information, and more recently, global warming potential. The SNAP program reviews the information in the context of the proposed use and issues one of four decisions: acceptable; acceptable subject to use conditions; acceptable subject to narrowed use limits; and unacceptable. The information on a particular compound is continually updated so that compounds may be proposed for additional uses or additional information may be added to the portfolio for a particular use and this could change the decision originally issued by the SNAP program.

The HFCs and HCFCs that are replacements for the CFCs have a smaller effect on the ozone layer. The HFCs and HCFCs are largely degraded before reaching the stratosphere. HFCs and HCFCs break down relatively rapidly into several products including the persistent substances such as trifluoroacetic acid (TFA) and chlorodifluoroacetic acid. These compounds are washed from the atmosphere by precipitation and reach surface waters, along with other chemicals washed from the soil. In locations where there is little or no outflow and high evaporation (seasonal wetlands and salt lakes), the concentrations of these products are expected to increase over time. The effects of increased concentrations of naturally occurring mineral salts and other materials is likely to be greater and more biologically significant than those of breakdown products of the HFCs and HCFCs.

TFA, a final degradation product of some HFCs and HCFCs, is very resistant to breakdown, and amounts deposited in flowing surface water will ultimately accumulate in the oceans. Based on estimates of current and future use of HFCs and HCFCs, additional inputs to the ocean will add only fractionally (less than 0.1%) to amounts already present from natural sources such as undersea vents and volcanic activity (Figure 12).

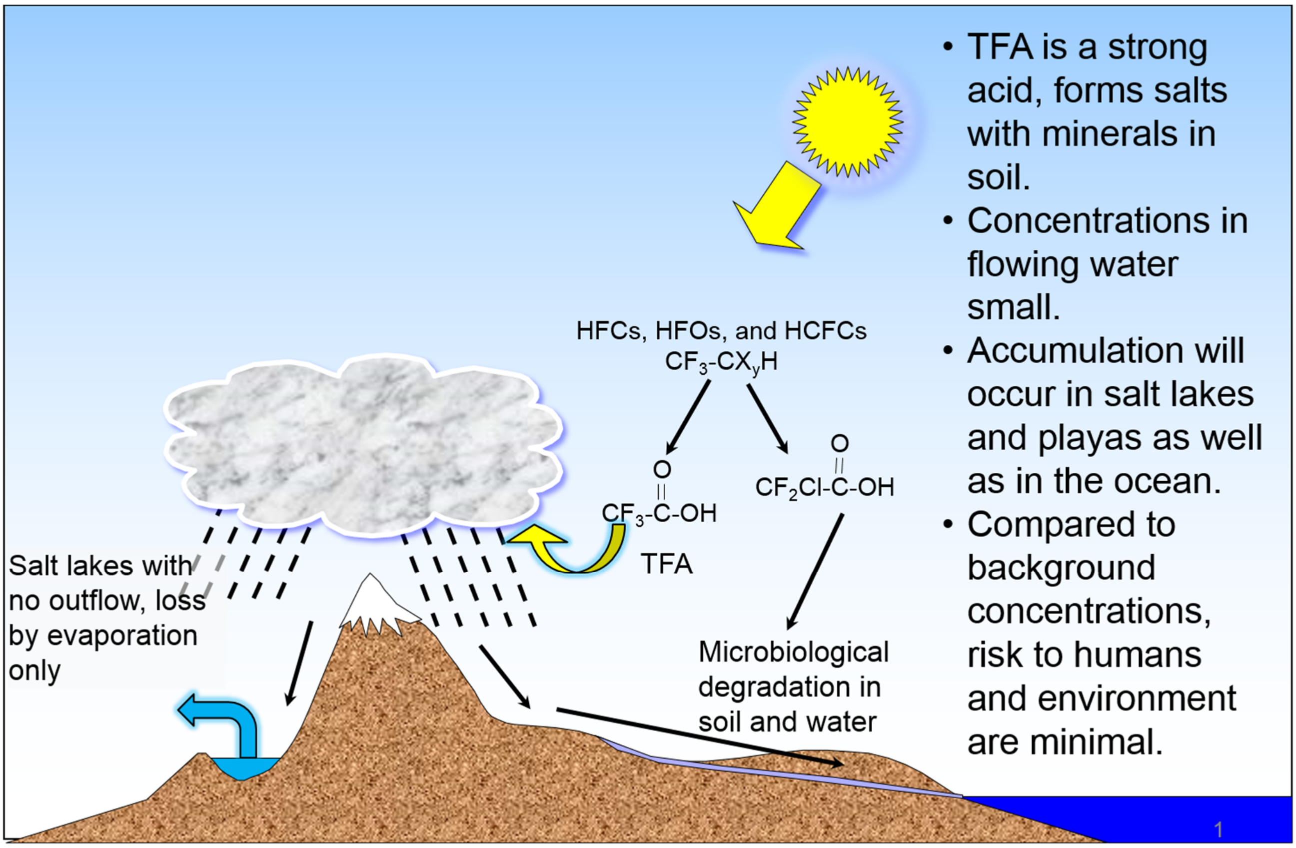

Figure 12. Illustration of the formation of trifluoroacetic acid (TFA) from HFCs and HCFCs in the lower atmosphere and the movement of the TFA into surface waters and the oceans. Figure provided by Keith Solomon.

13. WHAT EFFECTS DOES UV-B RADIATION HAVE ON NATURAL TERRESTRIAL ECOSYSTEMS, CROPS AND FORESTS?

UV-B radiation causes a wide range of responses in terrestrial ecosystems. Animals can move to avoid UV-B radiation but plants cannot. However, most plants (including agricultural and forest species) have mechanisms that provide some shielding from UV radiation. In some cases, increases in UV radiation are detrimental, for example, reducing production. However, some plant species have increased resistance to insect feeders when exposed to UV radiation, with a net result of decreased feeding on agricultural plants and greater productivity.

a. How do plants protect themselves from UV-B radiation?

Only a small portion of the UV-B radiation striking a plant penetrates into the inner tissues. The outer surface of the plant can be protected by light coloured hairs or waxes that reflect the UV-B radiation (Figure 13.1). Thicker leaves and stems (e.g. in succulents) also reduce the proportion of inner tissues exposed to UV-B radiation. In the majority of plant species tested, UV-B radiation induces the synthesis of compounds that act as sunscreens and prevent UV-B radiation from reaching sensitive biological components within the leaves. These protective screening compounds can be found inside the cells or bound to the cell walls (Figure 13.1). Even where screening of UV radiation is incomplete, plants have several mechanisms for repairing damage to vital biomolecules such as DNA, including one that uses sunlight to drive the repair reactions. This suite of protective mechanisms means that in general plants are able to protect themselves from increases in UV-B radiation especially if the plants are native to high radiation environments such as the tropics or high mountains (Figure 13.2).

The present rate of global change is so rapid, however, that evolution may not keep up with it, particularly in high latitudes where temperature and UV-B radiation have increased dramatically over recent decades. In Antarctica and the southern tip of South America, plants adapted to environments with relatively low levels of UV-B radiation have been affected by the increased levels of UV-B radiation due to ozone depletion (see Figure 13.1). Although the negative impact of UV-B radiation on plant productivity is usually relatively small (about 6%), some species are more affected than others. Over time, these differences between species may lead to changes in terrestrial ecosystems, especially in regions like Antarctica where UV-B radiation is likely to remain elevated for many more decades (Figure 13.2).

Another group of plants that may be more sensitive to UV-B radiation are agricultural plants that humans have moved from areas of low UV-B to high UV-B radiation e.g. from temperate to tropical regions. This is analogous to light-skinned humans moving to high radiation environments and becoming susceptible to higher rates of sun damage (see Question 8) or light skinned cattle being moved to tropical areas and being affected by UV-induced eye damage. Some varieties of these crops are UV-B-sensitive and produce reduced yields following an increase in UV-B radiation. It is possible to breed and genetically engineer UV-B tolerant crops so that crop losses are reduced.

.

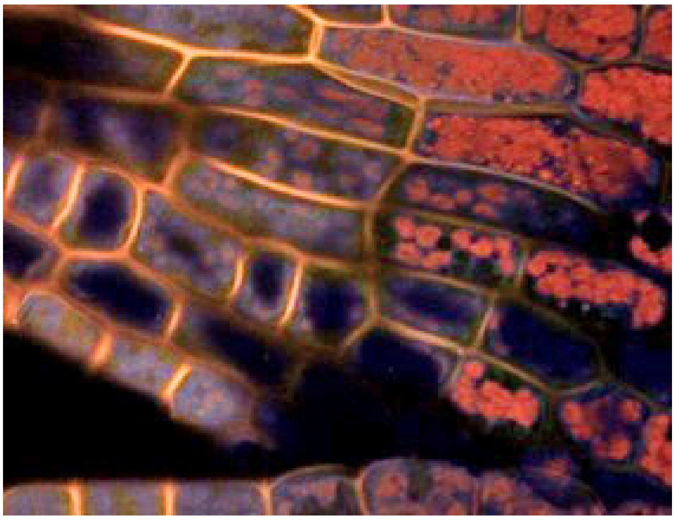

Figure 13.1 Wax on the surface of cabbage plants protects the underlying leaf from high UV radiation (left). If UV radiation penetrates the leaf it can be removed by sunscreen compounds bound to the cell walls, highlighted in orange in this micrograph (right). Photographs Prof. S. Robinson and Dr L. Clarke, University of Wollongong, Australia.

Figure 13.2: Impacts of UV-B radiation on terrestrial ecosystems. Ozone depletion has led to higher UV fluxes over Antarctica with negative effects on some species of Antarctic plants, such as the mosses seen growing along this icy stream (RH panel). An example of the chemical structure of protective molecules produced by plants in response to UV radiation is shown in the centre. These compounds include the red pigments seen in lettuces (top left panel), while those shielded from UV are mostly green. Similarly, Antarctic mosses (bottom left) shielded by small stones are green (centre), while the plants around them produce protective red pigments. These compounds can be important components of our foods. (Photograph of lettuce from Prof. N. Paul, University of Lancaster, UK, others Prof. S. Robinson, University of Wollongong, Australia).

b. How is UV-B radiation beneficial to agriculture and food production?

Some protective molecules produced by plants in response to natural UV-B radiation, are important in our food and medicinal plants. They can enhance the colour and flavour of food and increase its antioxidant activity. Such compounds are increasingly important to the food industry and horticulturalists often seek to enhance production by ensuring plants are exposed to sufficient UV-B radiation.

Some of these changes in plant biochemistry induced by UV- B radiation can have further effects in agriculture, for example by influencing the interactions between crop plants and herbivorous insects. Under enhanced UV-B radiation, sunscreen compounds both protect the plant from the UV-B radiation directly and deter insects from eating the plant (herbivory). The change in biochemical composition can make the plant less attractive as food for herbivores (including for insect pests). The negative effect of UV-B radiation on the food supply of plant-eating insects can be substantial. Some of the reduced consumption is due to direct effects of UV-B radiation on insects and some due to the changes in plant tissues induced by the UV-B radiation. This means that if UV-B radiation is higher, insects generally eat less plant material. In an agricultural context this may mean less insecticide is needed to deter agricultural pests. These effects on palatability also impact the food supply of animals at an ecosystem level.

Another example of positive effects of UV radiation in the environment is UV vision which is used extensively by a wide range of invertebrates and vertebrates, including birds, fish, insects, spiders, and other taxa, for critical life processes including mate selection and location of food resources. Some invertebrates are specifically able to detect and respond to UV-B radiation under natural conditions.

.

c. How far does UV penetrate - does it affect soil processes

In addition to changing the palatability of plants, UV-induced compounds alter the speed at which leaf litter is broken down in the soil and thus the recycling of nutrients in the soil. Therefore UV radiation has impacts that go beyond individual plants and can affect ecosystem processes. Changes to plant composition, induced by UV-B radiation, have impacts on the animals and microbes (bacteria and fungi) that rely on plant matter for food.

Sunscreen compounds and structural alterations, which allow leaves to withstand UV-B radiation while attached to the plant, can make leaves more fibrous and tougher to break down once they form leaf litter. UV-B radiation changes the composition of the microbes in the soil and this can also influence how easily leaf litter is broken down. When plant litter is directly exposed to sunlight, it is degraded photochemically (photodegradation).

The changes that occur at the plant level can influence underground decomposition. Decomposition of dead plant material (leaf litter) is a vital process, since it recycles carbon and nutrients making them available to growing plants. UV radiation affects decomposition indirectly via changes to leaf biochemistry and microbial diversity and directly through photodegradation.

Changes to both microbial and photodegradation breakdown processes have important consequences for future carbon sequestration and nutrient cycling.

14. WHAT ARE THE INTERACTIVE EFFECTS OF UV RADIATION AND CLIMATE CHANGE ON AQUATIC ECOSYSTEMS AND ORGANISMS?

UV radiation can affect aquatic ecosystems and the metabolism of aquatic organisms both through direct exposure and via secondary effects from photochemical changes of nutrients and organic matter. Many of these effects interact with the changes induced by climate change.

In the open water, the incoming solar radiation is attenuated and thus the part of the ecosystem that is affected is close to the surface. Most aquatic systems are stratified with an upper mixing layer where the photosynthesis occurs. Here the biomass is increasing and nutrients are consumed. In the layers below are organisms and organic matter that are consumed and nutrients are mineralised. This results in an upper sun-exposed, low-nutrient layer and a lower dark layer high in nutrients. The exchange between the layers is limited, depending on the strength of the temperature or salinity difference that separates the layers.

As planktonic organisms circulate within the layers, the intensity of UV radiation to which the organisms are exposed will depend on the depth of the upper layer and the UV attenuation. Both these factors are affected by climate change.

Increased temperature and increased fresh water inflow from melting glaciers and sea ice reduce the depth of the upper layer and thus the plankton organisms will be exposed to more UV radiation. It also makes the stability of the separation of the layers stronger, reducing the transport of nutrient to the upper layer.

On the other hand, climate change will increase the runoff of UV-absorbing dissolved organic matter (DOM) from land, reducing the UV intensity in lakes and in coastal waters. In addition, climate change reduces the area covered by sea ice in polar areas, and reduces the thickness of the ice. Still another consequence from increased concentration of CO_2 in the atmosphere is that more CO_2 will dissolve in water and acidify it. One important consequence is that production of calcified outer scales, which protect the inner parts of some organisms from UV radiation, will be harmed. These functions show that interactions between UV radiation and climate change are numerous and not yet fully understood.

Different organisms have different sensitivity for UV radiation, either through inherent differences in basic metabolism or through differences in their UV protection capacity (production of screening pigments or mechanisms to repair lesions). Thus exposure to UV radiation will change the species composition. This might propagate through higher levels in the food chain. Typically smaller organisms will be more susceptible than larger ones. Many protections against UV radiation are not constant but are induced and produced when organisms are exposed. Organisms living under low-UV conditions (for example in coastal areas with high concentration of DOM) are more sensitive than organisms from off-shore that are acclimatised to higher levels of UV radiation.

Temperature increases and changes in nutrient concentration as a result of climate change might modify both the repair rate and the production of UV-absorbing compounds. This is because some of them, such as mycosporine-like amino acids (MAA), contain nitrogen, which commonly is a limiting nutrient in marine waters.

15. WHAT ARE THE INTERACTIVE EFFECTS OF UV RADIATION AND CLIMATE CHANGE ON WATER QUALITY?

Climate change, involving increases in temperature and the frequency and intensity of precipitation, is altering ice and snow cover as well as the UV transparency and mixing regimes of inland and oceanic waters. These changes are influencing the exposure of aquatic organisms to UV radiation, altering the structure and function of aquatic food webs, and decreasing the ability of solar UV radiation to disinfect pathogens and parasites of humans and wildlife.

Most groups of aquatic organisms are susceptible to the negative sub lethal as well as lethal effects of solar UV radiation. In addition, there is increasing recognition that parasites and pathogens of humans and wildlife are sensitive to damage by solar UV radiation. Thus UV radiation in natural sunlight has the beneficial effect of disinfecting surface waters by killing free-living stages of parasites and pathogens (Figure 15.1). Exposure to sunlight can decrease viral infections in Atlantic salmon by many orders of magnitude, as well as decrease fungal infections in both amphibians and important zooplankton grazers. Thus aquatic food webs are being altered by both direct UV damage and by solar UV disinfection of parasites and pathogens.

Climate change is leading to a warmer and wetter world on average, though extreme events and regional variation that result in extreme droughts and floods are major concerns. Increasing concentrations of the tea-coloured dissolved organic matter (DOM), washed in from terrestrial ecosystems, can also decrease the UV transparency of surface waters following rain and runoff events (Fig. 15.2). Heavy precipitation events also wash more parasites and pathogens into surface waters and drinking water supplies. The outbreaks of infectious diseases that often follow extreme precipitation events are likely related to these increases in runoff as well as to decreases in water transparency. Higher concentrations of DOM in many regions of Europe and North America are leading to an increase in the cost of water purification as treatment facilities often have to be upgraded.

Both warmer and wetter conditions associated with climate change are increasing the strength of vertical temperature gradients, or "thermal stratification" in lakes and oceans. Reductions in winter snow cover, later freeze dates in early winter and earlier ice-out dates in freshwater and marine environments are causing longer periods of exposure to solar UV radiation as well as more intense thermal stratification. The surface temperatures of large lakes and oceans are getting warmer, and deeper waters in lakes are often getting cooler. The wind-mixed warmer surface waters are also often shallower as a result of the increased thermal stratification. In regions where the shallower mixed layer are caused by increases in DOM and subsequent decreases in water transparency, the effectiveness of disinfection by solar UV irradiation is reduced. Good examples include reductions in the viability of human parasites such as *Cryptosporidium* as well as decreases in potentially lethal fungal pathogens of both amphibians and zooplankton with increasing UV exposure (Figure 15.1). The reductions in light levels at deeper depths will, at the same time, also lead to oxygen depletion and larger and more frequent "dead zones". In contrast, in regions where the shallower mixed waters are caused by warming air temperatures, water transparency is increasing (Figure 15.2), natural solar disinfection is more effective, and oxygen depletion is less likely. These changes in thermal stratification, UV exposure, and oxygen depletion, are influencing the frequency and intensity of harmful algal blooms (HABs), the distribution and abundance of fish species, and the plankton and other species that comprise the critically important lower levels of the food web.

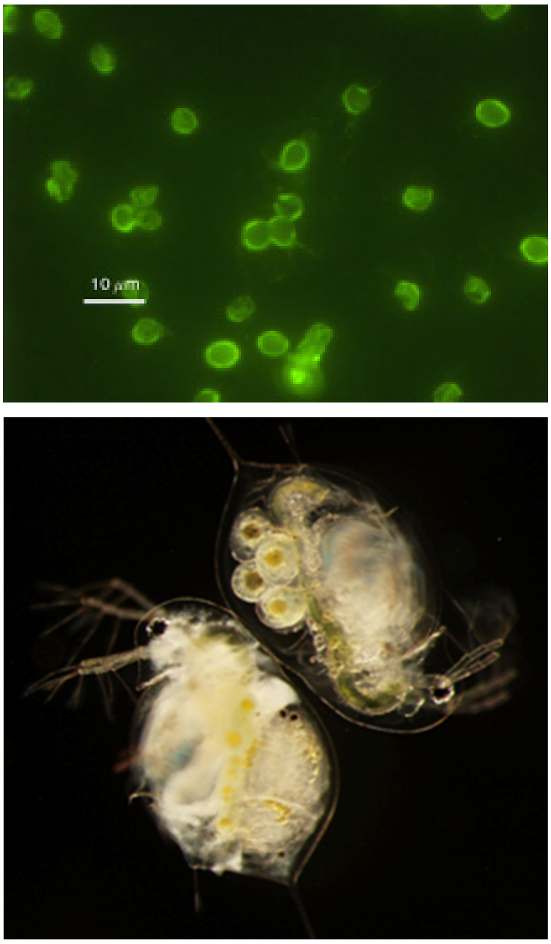

Figure 15.1 Microphotographs of two parasites that are sensitive to disinfection by solar UV radiation. Cryptosporidium parvum (top) is a protozoan parasite of humans, and Metschnikowia bicuspidata (bottom) is a fungal parasite seen here inside of its host, the important freshwater zooplankton grazer Daphnia (body length ~ 1 mm). The Daphnia on the lower left is parasitized while that on the upper right is healthy and not parasitized. (Photo credits: Cryptosporidium by Sandi Connelly, Metschnikowia by Meghan Duffy)

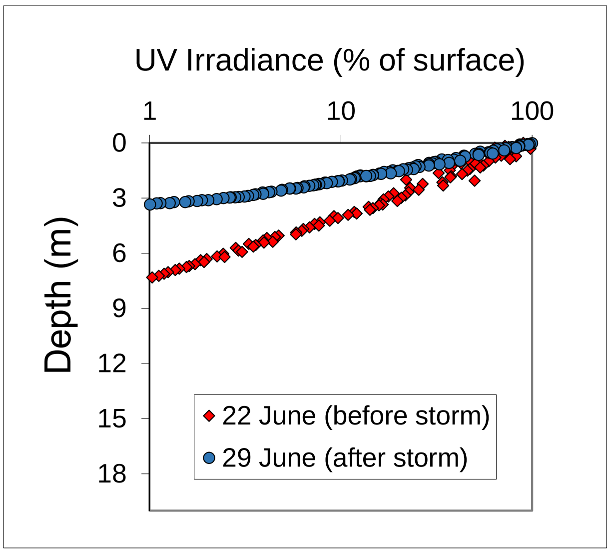

Figure 15.2. An example of the reduction in underwater UV transparency following a heavy precipitation event. This event in June, 2006 dropped 200 mm of rain in the vicinity of Lake Giles in eastern Pennsylvania within a week. Figure adapted from Rose et al. 2012. Limnology and Oceanography 57: 1867.

16. DOES EXPOSURE TO SOLAR UV RADIATION ALTER THE USEFUL LIFETIME OF BUILDING MATERIALS?

Solar UV radiation decreases the useful lifetime of some plastics and wood materials used in building construction.

The useful life of wood, plastic and wood-plastic composite products used in the exterior of buildings is determined primarily by degradation caused by exposure to solar UV radiation. The affected products include structural and decorative wood products as well the cladding (siding), exposed plastic pipes, plastic roofing membranes and plastic glazing. Figure 16.1 shows the cross-section of a PVC plastic window frame used in residential buildings. These plastics are easily degraded by UV-B radiation resulting in uneven discoloration, surface release of fillers or 'chalking', reduced impact strength and development of surface cracks. Acceptable lifetimes are possible only because very efficient UV-stabilizers are incorporated as additives.

Wood used in building applications undergoes UV-induced degradation of the cellulose, rendering the surface increasingly hydrophilic. This encourages colonization of the surface by fungal species that can break down the wood. (Figure 16.2). Absorbed water can stress and damage the wood during freeze-thaw cycles. Wood used in outdoor applications is either chemically treated or surface coated with polymer-based paints to mitigate this problem. The coatings themselves deteriorate and have to be replaced several times during the service life of the wood. This is also true of the wood-plastic composites where the wood fraction is photolabile.

The photodegradation processes in wood and plastic progress faster at higher levels of UV-B radiation and at higher temperatures. Therefore, the 2 - 6°C increase in surface temperatures suggested by the climate models will shorten their service lives even further. Possible synergistic effects of the combination of UV radiation and higher temperatures are not fully understood for both plastics and wood materials. The effects will be most severe in places with high rainfall and high air pollution, both of which tend to accelerate the degradation.

Any increase in UV-B radiation as a result of a decrease in the stratospheric ozone layer will increase the rates of degradation, shortening the service lifetime. However, with both wood and plastics, this can be compensated for by either using higher amounts of UV-stabilizer levels or using better UV-resistant alternatives. Even taking into account the potential for a few degrees increase in ambient temperatures, available high-efficient stabilizers should be able to maintain service lifetimes at the present levels. (Figure 16.3). Dark-coloured plastics exposed to sunlight reach a much higher bulk temperature under present conditions compared to white or light-coloured plastics, but can still be effectively stabilized. There are also classes of plastics, varieties of wood and better surface coatings available that can be substituted for existing materials as well.

There is invariably a cost associated with mitigating the effects of increased levels of solar UV radiation and/or increased temperature due to climate change. In such situations the cost of some plastic and wood products in construction will rise.

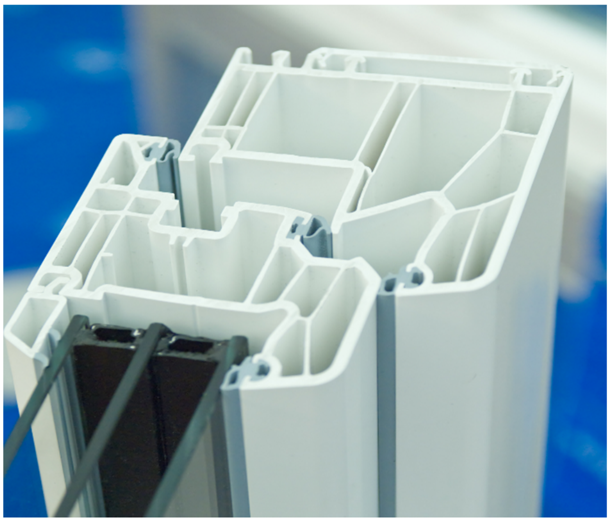

Figure 16.1. Cross-section of a rigid PVC window frame used in residential building. PVC is the most-used plastic in building construction where it is used in residential siding, pipes, window frames and gutters. Rigid PVC meant for outdoor use has rutile titanium dioxide mineral powder incorporated in it. This oxide absorbs solar UV radiation and helps reduce the light-induced yellowing, chalking and weakening of the plastic material. Picture supplied by Anthony L. Andrady.

Figure 16.2. Unprotected wood surfaces that are damaged by solar UVR can easily undergo biodegradation by wood-rot fungi. The light induced damage renders the surface more hydrophilic making it easier for bacteria and fungi to degrade the material. Coating the wood can often control the deterioration of wood by solar radiation. Adding UV stabilizers to the coating can make it even more effective in protecting the wood. Picture supplied by Anthony L. Andrady.

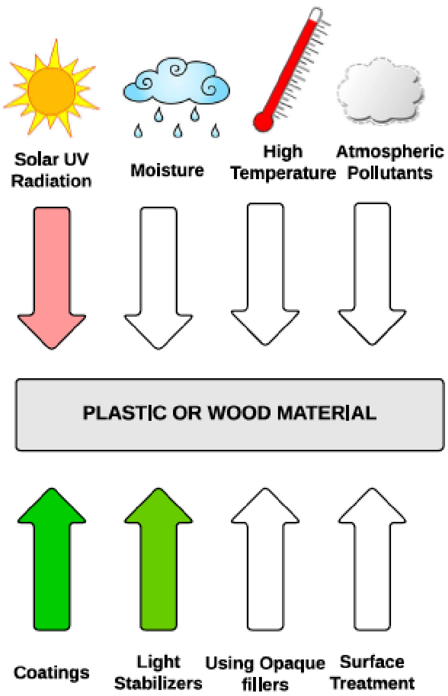

Figure 16.3. The main agencies that promote the environmental degradation of materials used outdoors are shown in the upper part of the figure. The most important of these is solar UV Radiation. The techniques used to mitigate these effects are shown in the lower part of the figure with the two primary strategies of using light-stabilizers and coatings highlighted as they are the most effective in protecting the wood.

17. WILL THE USEFUL OUTDOOR SERVICE LIFETIME OF A MATERIAL AT ONE LOCATION BE APPLICABLE FOR ITS USE AT A DIFFERENT LOCATION?

Generally, any estimate of the service lifetime of a material used outdoors, determined for one geographical location, will not be the same at a different location. This is because the levels of UV radiation and temperature the major determinants of service lifetime are different at different locations.

Damage induced by UV radiation to outdoor materials, such as plastics and paints, is primarily governed by the cumulative dose received over the course of their lifetimes. As previously noted, solar UV radiation at Earth's surface is primarily UV-A with a small proportion of UV-B, and the annual dose of UV radiation depends on location. Thus, latitudes within the tropics, where the noon solar elevation gets close to the zenith throughout the year, receive much higher annual doses of UV radiation than high latitude sites, where winter doses of UV radiation are small compared with summer doses. Generally, the closer the site is to the equator, the greater the annual dose of UV radiation, and therefore the shorter the serviceable lifetime of the material. This may be exacerbated if damage is accelerated at higher temperatures.

Figure 17 shows a compilation of UV-A and UV-B data (and their ratios) from a selection of sites where the highest quality UV measurements are available.

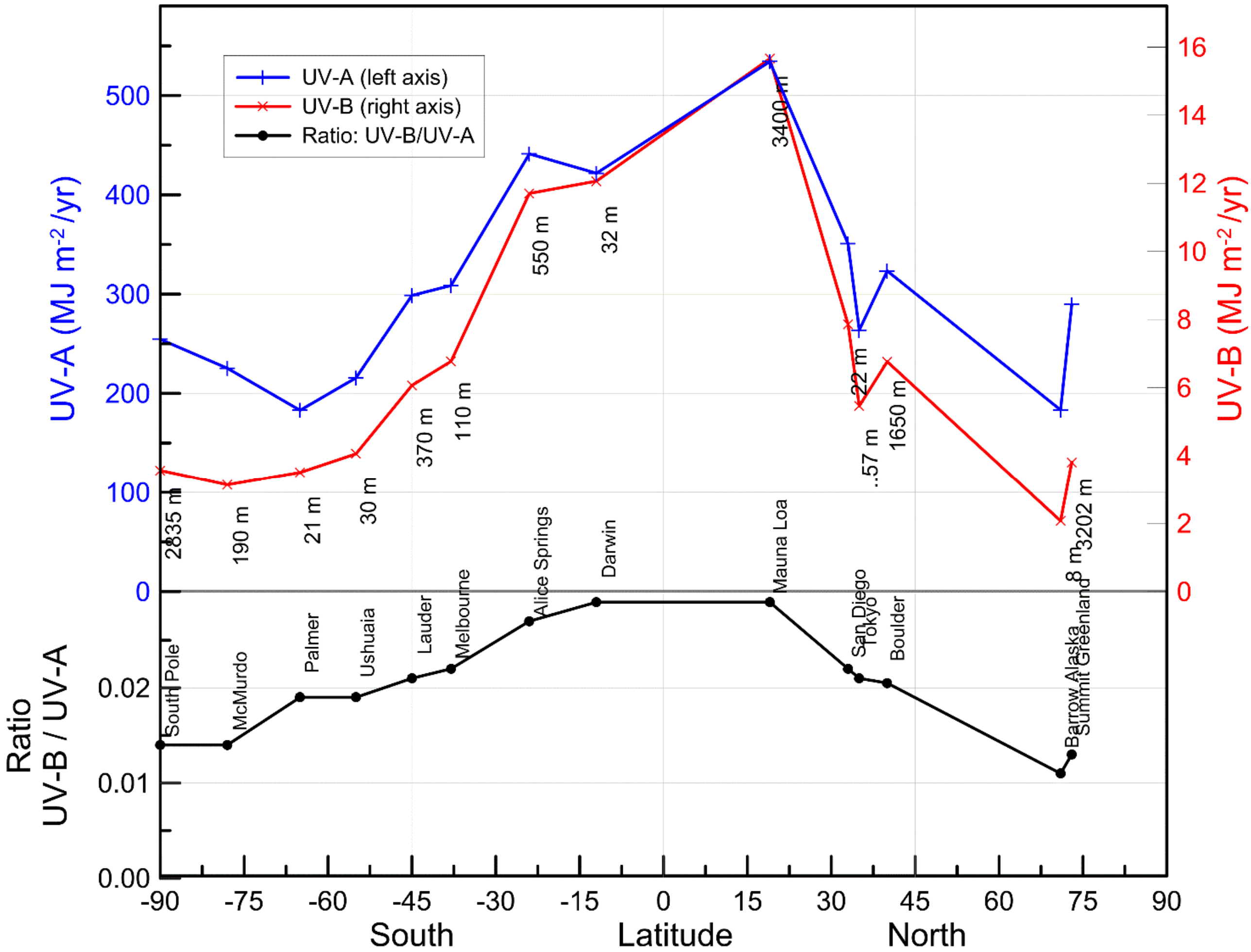

Figure 17. Latitudinal variability in UV-A and UV-B radiation. Altitudes of locations are shown. Although doses of UV radiation are larger in the Southern Hemisphere (SH) than at corresponding latitudes in the Northern Hemisphere (NH), the difference is much less marked than for the peak irradiances, which can be 40% greater in the SH compared with the NH. Generally, the annual dose decreases with latitude, with stronger latitudinal gradients in the UV-B region than in the UV-A region, even allowing for differences in altitude between these sites, which can account for differences of approximately 5% per 1000m (i.e., 15% more UV at Mauna Loa and 10% more at Boulder). Most of these sites are relatively clean, but aerosol extinctions have a significant effect at some, such as Tokyo. These results imply that UV doses in the latitude greater than 30° in each hemisphere generally are significantly less than for sites within the latitude range from 30° S to 30° N, a range which corresponds to half the area of the globe.

18. TO WHAT EXTENT IS UV RADIATION TRANSMITTED THROUGH MATERIALS?

Solar UV-B radiation is blocked by glass as well as by most fabric materials but UV-A is transmitted to varying extents.

About 5% of the solar radiation reaching Earth's surface is within the UV wavelengths. Protecting ourselves, and objects of value, from the damaging effects of the UV radiation is important. Some materials effectively block the UV radiation and provide such protection.

All types of glass very effectively screen out the UV-B radiation, the most damaging spectral region in sunlight. The same is not true of UV-A; different grades of glass transmit UV-A to different degrees. Laminated glass in double-glazed laminated glass windows or used in vehicles as windshields or windows is most effective, allowing less than 2% of the UV-A radiation to pass through. Clear glass or tinted glass windows allow 20-53% of UV-A radiation to pass through depending on the type and thickness.

Fabrics are also good filters of UV radiation depending on how tightly woven they are and the textile type. A tighter weave results in less free space through which UV rays can pass. Generally, cotton (grey or bleached) offers more protection than synthetic fibres at the same tightness of weave. Wet fabrics where the interstices are filled with water are less protective.

Fabrics can be dyed or made of particle-filled synthetic fibres to obtain even better protection from both UV-A and UV-B radiation.

19. HOW DOES OZONE DEPLETION AFFECT AIR POLLUTION AND VICE VERSA?

Variations in stratospheric ozone and climate change will modify concentrations of pollutants in the atmosphere, which play a significant role in the health of both humans and Earth's environment.

Globally, outdoor air pollution is estimated to lead to 850,000 premature deaths each year, mostly from respiratory and cardiovascular diseases. The cost of crop damage in the U.S. from air pollution is estimated to be 6.1 billion dollars annually. In some locations, air pollution is made worse by interactions between UV radiation and changes in climate. These problems are expected to continue and worsen in the future, thus increasing risks to humans directly and to the supply of food.

Variations in stratospheric ozone and climate change are important drivers of changes in the production and fate of air pollutants. Solar UV radiation provides the energy for many of the chemical transformations that occur in the atmosphere. Solar UV irradiation changes the chemistry or breaks down a number of important atmospheric gases, e.g., nitrogen dioxide, formaldehyde, and ozone. These processes will be altered by anything that changes the amount of UV radiation such as attenuation by clouds and particulate pollutants in the air, both of which will be affected by changes in climate. Decreased stratospheric ozone and increasing temperature from climate change are expected to lead to greater concentrations of ozone close to the surface of the Earth in polluted regions, resulting in an increased mortality rate that could exceed that resulting from climate-related increases in storms and flooding. The quality of the air in less-polluted areas is expected to improve but will not fully offset the damage in polluted regions, in terms of human disease burden.

20. WHAT IS GEOENGINEERING?

Geoengineering is described as technologies that aim to alter the climate system in order to counter climate change.

The Intergovernmental Panel on Climate Change (IPCC) set up a panel to investigate geoengineering in 2011 with the results detailed in the latest IPCC report. The technologies can be divided into two groups (Figure 20):

Carbon Dioxide Reduction (CDR) that would result in slower, or even reverse, projected increases in future CO_2 concentrations by accelerating the natural removal of atmospheric CO_2 and increasing the storage of carbon in reservoirs. The main removal methods are:

A. Ocean fertilization: Adding nutrients to the ocean which increases oceanic productivity in the surface ocean and transports a fraction of the resulting biogenic carbon downward,

B. Alkalinity addition to the ocean: Adding alkalinity from solid minerals to the ocean, which causes more atmospheric CO_2 to dissolve in the ocean,

C. Accelerated weathering: Increasing the weathering rate of silicate rocks and transporting the dissolved carbonate minerals to the ocean,

D. Direct air capture: Capturing atmospheric CO_2 chemically, and storing it either underground or in the ocean,

E. Biomass energy with carbon capture: Burning biomass at electric power plants with carbon capture, and the captured CO_2 is stored either underground or in the ocean, and

F. Afforestation: Capturing CO_2 through afforestation and reforestation to be stored in land ecosystems.

Solar Radiation Management (SRM) that would counter the warming associated with increasing greenhouse gasses by reducing the amount of sunlight absorbed. The main methods are:

G. Deployment of space mirrors: Placing reflectors into space to reflect solar radiation,

H. Stratospheric aerosol injection: Injecting aerosols in the stratosphere, e.g. sulphur dioxide,

I. Marine cloud brightening: Seeding marine clouds to make them more reflective,

J. Ocean brightening with microbubbles: Producing microbubbles at the ocean surface to make it more reflective,

K. Crop brightening: Growing more reflective crops, and

L. Whitening rooftops: Painting roofs and other built structures in light colours.

The CDR methods will not influence the surface UV radiation but the SRM methods will, depending on the specific method used. The first three should reduce the amount of solar radiation reaching Earth's surface but the last three will increase the UV radiation received by an object by reflecting radiation to the sides of the object.

Stratospheric sulphate aerosols from volcanic eruptions and natural emissions deplete stratospheric ozone. Stratospheric aerosols introduced for SRM are expected to have the same effect and the resulting ozone depletion will increase the amount of UV radiation reaching the surface of the Earth, with potential damage to terrestrial and marine ecosystems and to human health.

The IPCC evaluation of geoengineering came to the following conclusion: "*CDR methods have biogeochemical and technological limitations to their potential on a global scale. There is insufficient knowledge to quantify how much CO_2 emissions could be partially offset by CDR on a century timescale. Modelling indicates that SRM methods, if realizable, have the potential to substantially offset a global temperature rise, but they would also modify the global water cycle, and would not reduce ocean acidification. If SRM were terminated for any reason, there is high confidence that global surface temperatures would rise very rapidly to values consistent with the greenhouse gas forcing. CDR and SRM methods carry side effects and long-term consequences on a global scale.*"

Figure 21: Overview of some proposed geoengineering methods that have been suggested.

Reference: Summary for Policymakers, The Physical Science Basis, Working Group I Contribution to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change, 2013.

21. WHAT WOULD HAVE HAPPENED WITHOUT THE MONTREAL PROTOCOL?

Without the successful and continued implementation of the Montreal Protocol and its subsequent amendments and adjustments, stratospheric ozone would have continued to decline globally, and levels of UV-B radiation would have consequently continued to increase dramatically, leading to severe environmental effects.

The objective of the Montreal Protocol is the protection of the ozone layer through control of the global production and consumption of Ozone Depleting Substances (ODSs). Projections of the future quantities of ODSs expressed as equivalent effective stratospheric chlorine (EESC) values are shown below (Figure 21.1) for the mid-latitude stratosphere for the scenarios of no Protocol and the 1987 Montreal Protocol and its subsequent amendments and adjustments. EESC is a relative measure of the potential for stratospheric ozone depletion that combines the contributions of chlorine and bromine from surface observations of concentrations of ODSs in the stratosphere. Without the Protocol, EESC values have been projected to increase significantly in the 21st century (Black curve). Only with the Copenhagen (1992) and subsequent Amendments and Adjustments did projected and measured EESC values show a long-term decrease.

Since there is an inverse relationship between the amount of ozone and the amount of UV radiation reaching Earth's surface one can expect the levels of UV radiation on the surface to decline as is illustrated in figure 21.2 using the UVI as indicator.

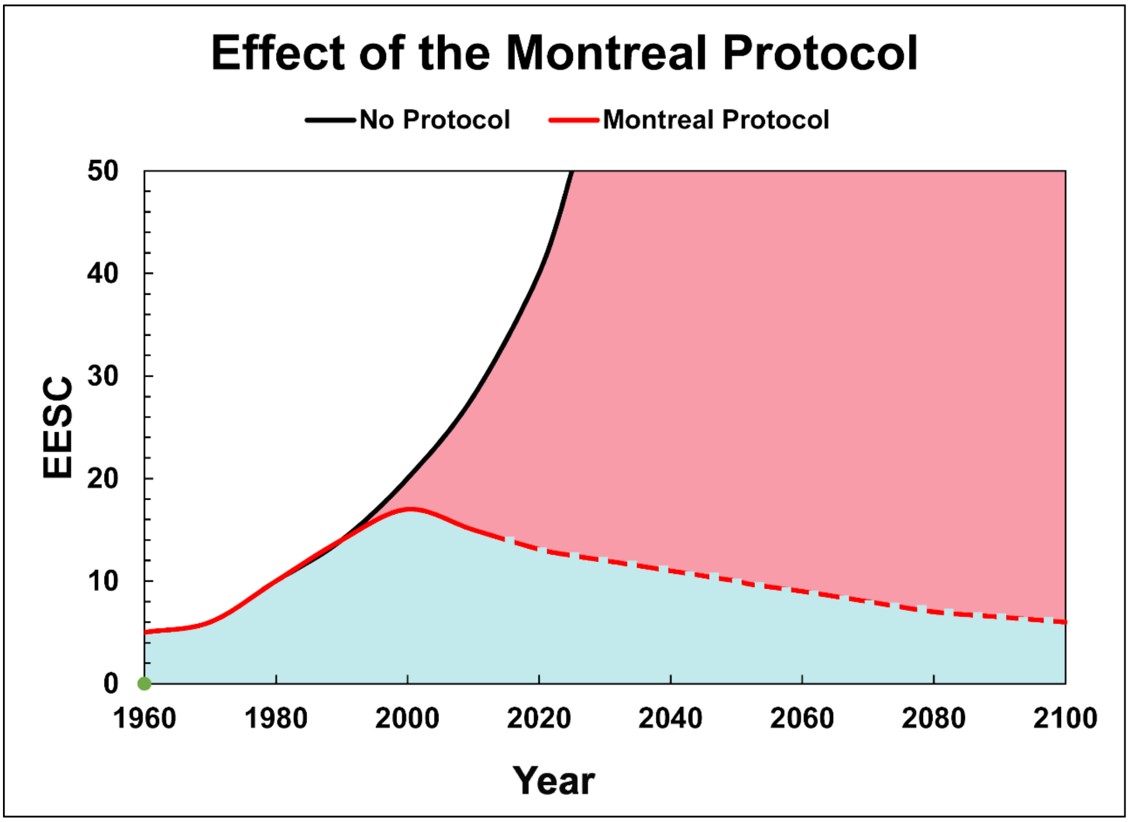

Figure 22.1: The observed (solid red line) and predicted (dashed red line) effects of the Montreal Protocol and its amendments and adjustments. The black line is a projection of the situation without the Montreal Protocol. (Figure provided by Dr P J Aucamp based on the 2014 report of the Scientific Assessment Report)

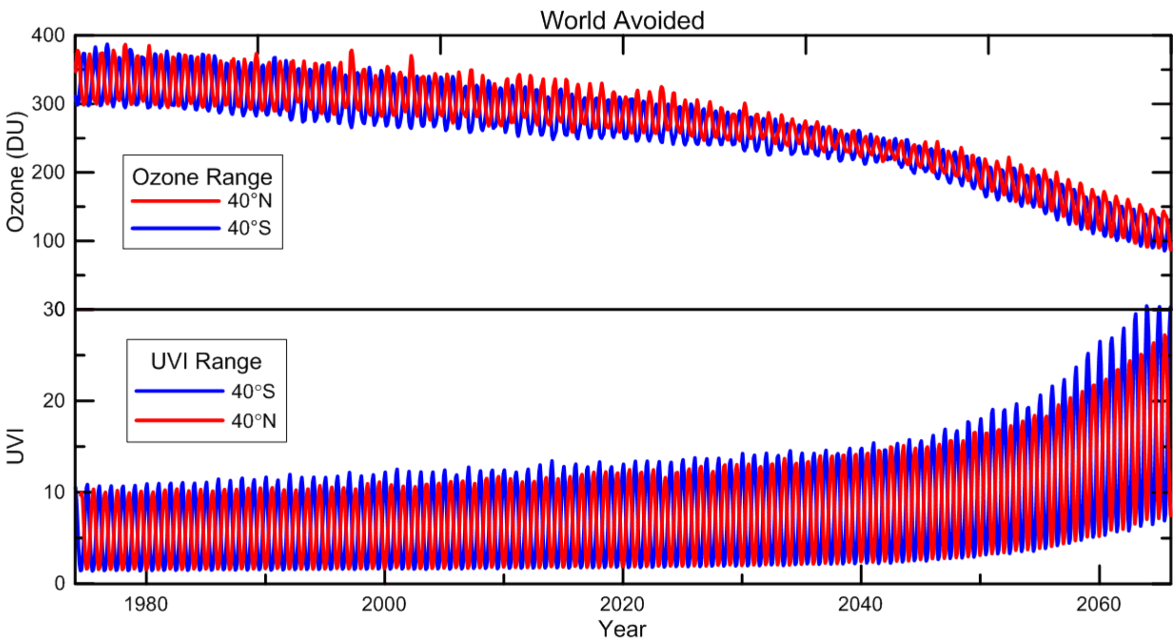

Figure 21.2: The observed (to 2014) and predicted effects of the Montreal Protocol and its amendments and adjustments. In 2065, the summer UVI would have increased to three times the 1975 values, and the wintertime UVI in 2065 would have been comparable to summertime UVI in 1975.

22. ARE THE CONTROL MEASURES IN THE MONTREAL PROTOCOL WORKING? WHAT IS THE WORLD WE AVOIDED?

a. Has the phase-out of ODSs changed levels of UV radiation?

The Montreal Protocol has been very successful.

The Montreal Protocol for the Protection of the Ozone Layer is the most successful environmental international agreement to date. It has been ratified by all of the 197 countries of the UN. All the CFCs have been phased out since January 2010. The phase-out of the HCFCs is on schedule and has been advanced.

The detail of the phase-out achieved and the predictions of future halocarbon concentrations in the stratosphere can be found in the Scientific Assessment Panel's 2014 report. Stratospheric ozone is no longer decreasing and is predicted to return to pre-1980 values before 2050 at mid-latitudes and a few years later at high latitudes. Concentrations of the ODSs have been decreasing for over ten years, and are expected to continue to decrease in the future (Figure 22.1 and 22.2).

A future scenario in which ODSs were not regulated and production grew at an annual rate of 3% was simulated in a study of the "world avoided" by the success of the Montreal Protocol. By 2020, 17% of the globally-averaged column ozone in 1980 would have been destroyed, with depletion increasing to more than 60% by 2060 (Figure 22.2). Decreases in stratospheric ozone due to increasing CFCs would have led to a marked increase in UV radiation, with the UV Index possibly trebling at mid-latitudes by 2065. In view of what is known about the effects of excess UV radiation exposure, this would have had serious environmental consequences. In Polar regions, substantial ozone depletion would have become year-round rather than seasonal, resulting in large increases in surface UV radiation, including during the summer months.

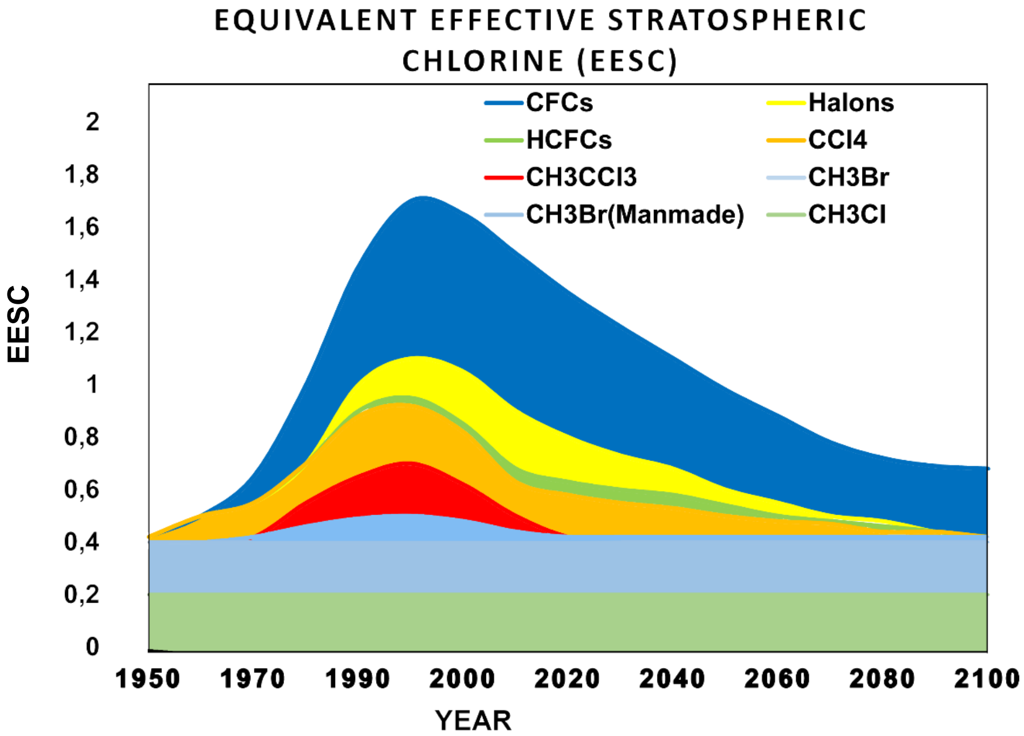

Figure 22.1: The past and predicted future concentrations of halocarbons in the stratosphere (Figure provided by Dr P J Aucamp based on the 2014 report of the Scientific Assessment Report)

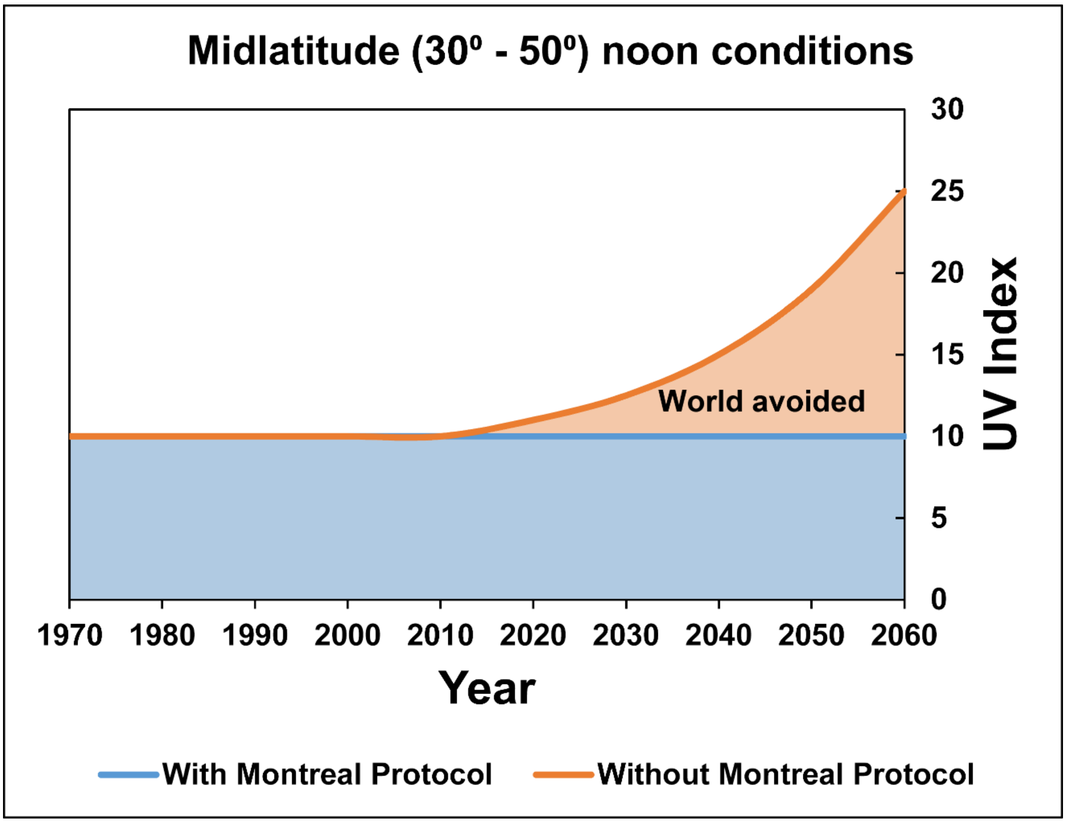

Figure 22.2: Prediction of the UVI indicating what could have happened in the absence of a Montreal Protocol (Adapted from Figure 5.11 Scientific Assessment of Ozone Depletion: 2010).

b. What effect has the phase-out of ODSs had on the climate?

As a result of the phase-out schedules of the Montreal Protocol, the global production and use of chlorofluorocarbons (CFCs) and halons has decreased significantly. However, the sustained growth in demand for refrigeration, air-conditioning and insulating foam products in developing countries has led to an increase in the consumption and emissions of hydrofluorocarbons (HFCs). Consequently the use of HCFCs and HFCs as replacements for CFCs and halons has increased. The HCFCs are low-ozone-depletion-potential substitutes for high-ozone-depletion-potential substances, particularly CFCs and halons, and were classified under the Protocol as "transitional substitutes" for the time it takes to commercialize new ozone-safe alternatives and replacements. Ultimately, HCFCs will be phased out globally under the Montreal Protocol leaving much of the application demand for refrigeration, air conditioning, heating and thermal-insulating foam production to be met by HFCs, HFOs and other replacement products. The demand for HCFCs and/or HFCs in many applications is expected to increase. HFCs do not deplete the ozone layer but, along with CFCs and HCFCs, are greenhouse gases that contribute to the radiative forcing of climate. Thus, the transition away from ozone depleting substances (ODSs) has implications for future climate. HFCs are in the "basket of gases" regulated under the 1997 Kyoto Protocol, a global treaty to reduce emissions of greenhouse gases by developed countries.

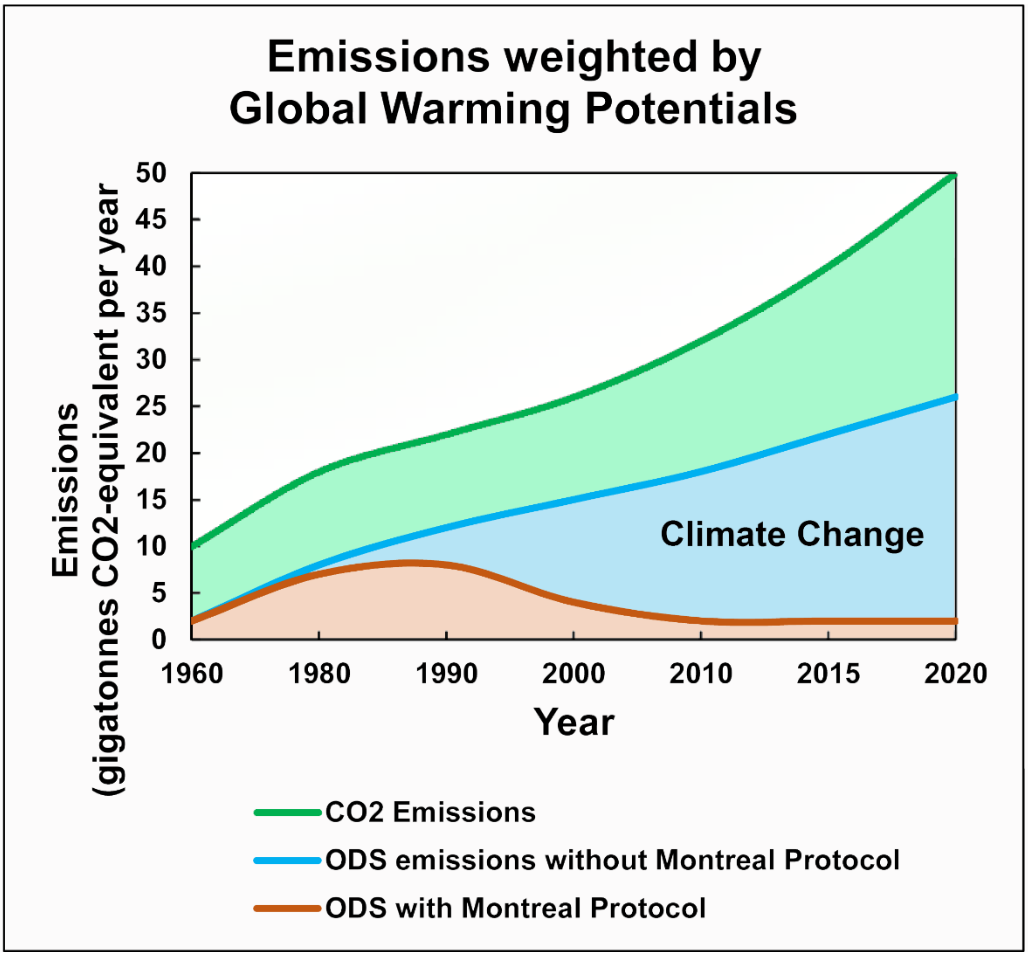

Figure 22.3: Montreal Protocol protection of ozone and climate (Based on: Twenty Questions and Answers about the Ozone Layer 2014 Update, Scientific Assessment of Ozone Depletion 2014, United Nations Environmental Programme, Nairobi.).

23. WHERE CAN I GET MORE INFORMATION ABOUT THE SCIENCE AND EFFECTS OF OZONE DEPLETION?

There are several websites that contain information on ozone, UV radiation, environmental effects and related topics. The sites mentioned below belong to dependable organizations and contain reliable information. Most of these sites contain links to other sources of information.

UNEP .... http://www.ozone.unep.org

WMO .... http://www.wmo.ch

WHO .... http://www.who.int

IPCC .... http://www.ipcc.ch

NOAA .... http://www.noaa.gov/climate.html

EPA .... http://www.epa.gov/ozone.html

NASA .... http://ozonewatch.gsfc.nasa.gov

NIWA .... http:// www.niwa.co.nz/UV-ozone

WOUDC .... http://www.woudc.org

Environment Canada .... http://www.ec.gc.ca