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# The Montreal Protocol and Human Health

How global action protects us from the ravages of ultraviolet radiation

United Nations Environment Programme

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# Executive Summary

The successful implementation of the Montreal Protocol sends out the powerful message that the world can come together to avert a common threat to humanity. Since its adoption in 1987, the treaty to phase out the substances that deplete the stratospheric ozone layer has resulted in significant benefits to human health worldwide. This has been achieved primarily by the prevention of large increases in ultraviolet (UV) radiation in most inhabited parts of the globe.

Ozone depletion increases the UV radiation reaching the Earth's surface. Intensive scientific research over the past years has resulted in a clearer understanding of how ozone depletion affects not only human health but also food production and life-supporting ecosystems.

The world would have been a very different place without the Montreal Protocol. Summarising current understanding of how changes in UV radiation affect human health, this booklet also presents a picture of what the world would have been like, had we failed to control ozone depleting substances. There would have been a collapse of stratospheric ozone by the middle of the 21st century, resulting in large increases in UV radiation in all parts of the world, from the poles to the tropics.

The effects of the outstanding implementation of the Montreal Protocol on human health are beginning to be quantified with at least 100 million cases of skin cancer expected to have been avoided by the end of this century. A recent model suggests the prevention of over 300 million skin cancers in the USA alone. Many millions of extra cases of cataracts will have been prevented by 2100, one estimate suggesting tens of millions of cases in the USA alone.

Exposure to UV radiation can also affect the human immune system and, by limiting ozone depletion, the Montreal Protocol is expected to have avoided all measurable impact of UV rays on human immune function. The decrease in UV radiation, as the ozone layer recovers, is also not expected to affect the amount of time people need to spend in the sun in order to synthesise Vitamin D, which is crucial to human health.

Increased UV radiation could affect crop production and damage some economic fish species as well as marine life-supporting ecosystems vital for fisheries. The Montreal Protocol has thus benefited human health by protecting food security. Another benefit is the phase-out of commonly used toxic chemicals, such as methyl bromide. Finally, by eliminating ozone depleting substances that are also powerful greenhouse gases, the Protocol has helped reduce health risks related to climate change.

The scale of the damage to health had we failed to protect the ozone layer is clear. The health and well-being of hundreds of millions of people, many yet to be born, have been protected by the concerted action of the Parties since 1987.

# Contents

# Foreword

Human health has always been at the forefront of protecting the ozone layer. In 1985, the very first lines in the preamble of the Vienna Convention for the Protection of the Ozone Layer leave no doubt that the Parties to the Convention were *"...aware of the potentially harmful impact on human health and the environment through modification of the ozone layer....".* Two years later, in 1987, this position is re-affirmed in the preamble to the Montreal Protocol which begins *"...mindful of their obligation ...to take appropriate measures to protect human health and the environment against adverse effects resulting or likely to result from human activities which modify or are likely to modify the ozone layer".*

We now look back at those statements after thirty years during which the Parties to the Vienna Convention and Montreal Protocol have invested immense efforts to protect the ozone layer. The protection of human health has been implicit in every action of the Parties. Yet, perhaps, in our detailed discussions of the use and replacement of ozone depleting substances, the complexity of stratospheric processes and so on, we have sometimes overlooked what protecting the ozone layer really means to the health and well-being of every person living on the planet. It is that "human face" of protecting the ozone layer that this booklet explores.

The booklet summarises current understanding of how changes in the ozone layer affect human health, not only in the world we live in but also in the 'World Avoided'. That is the world we would have lived in had we failed to control ozone depleting substances. By examining the 'World Avoided' we clearly see, to echo the words of the Vienna Convention, the magnitude of the "*harmful impact on human health and the environment*" that we have prevented through the effective implementation of the Montreal Protocol.

The Montreal Protocol is widely heralded as a success story both in terms of achieving its direct aims in ODS phase-out targets and the resultant curbs in ozone depletion, and consequent environmental and health benefits.

The considerable quantified public health benefits of reductions in UV radiation are of particular significance in demonstrating the success of the Protocol and the contribution to the Millenium Development Goals (MDGs), «ensuring environmental sustainability and combatting diseases».

It is our wish that this publication will serve the National Ozone Units and other stakeholders to raise the visibility, awareness and education of the Montreal Protocol. "*Education is the most powerful weapon which you can use to change the world*" '(Nelson Mandela). Let us work together to educate on the protection of our environmental common, the precious ozone layer.

We are grateful to Professor Nigel Paul for taking this highly scientific subject and converting it to an easy read for all stakeholders. We also thank all the reviewers for their voluntary contributions to the publication.

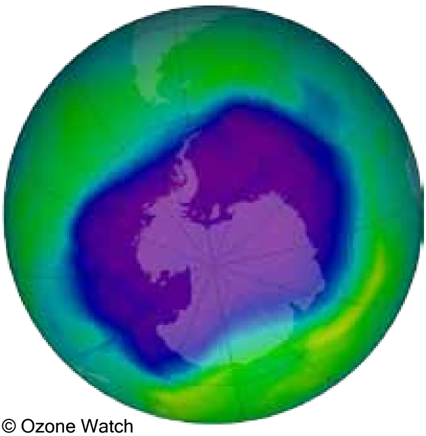
**Shamila Nair-Bedouelle**
Head of OzonAction

# Introduction

**"The example of the Montreal Protocol sends a powerful message that action on major global challenges is not only possible, but that the financial and human benefits invariably outweigh the costs."**

*United Nations Secretary General Ban Ki-Moon*

Secretary General Ban Ki-Moon is not alone in seeing the Montreal Protocol as a pinnacle in global efforts to protect our planet. The success of the Montreal Protocol is surely beyond dispute. Since it was signed in 1987 the release of the major ozone depleting substances has been first reduced and now almost halted. We can now be confident that the stratospheric ozone layer is beginning to recover. Through the combined efforts of all 197 signatories to the Protocol we have succeeded in 'fixing the hole in the ozone layer'.



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When most of us think about stratospheric ozone, the first thing that comes to mind may well be an image of the 'Antarctic ozone hole'. Images like this have become icons of environmental protection, but may also create the impression that ozone depletion is confined to a remote, unpopulated continent. Many would argue for the inherent value in protecting Antarctica and the animals that live there, but is that the only reason for protecting the ozone layer?

What about human health, crops or ecosystems? Of course, protecting the ozone layer does protect all those things, but how? How can ozone, a tiny fraction of the atmosphere (less than one part per million), almost all of it present many kilometres high in the atmosphere, really affect people and other life on the Earth's surface?

Intensive research over several decades (see Box 1) has clarified how stratospheric ozone might change the environment at the Earth's surface, and how that would affect human health.

The major link between human health and stratospheric ozone depletion is the increase in ultraviolet (UV) radiation at the Earth's surface that results from ozone depletion.

We now understand that the UV component of sunlight has multiple effects on human health. With the levels of UV that humans have been exposed to over millions of years there is a balance between the different damaging effects of too little and too much UV (Figure 1).

However, we are now beginning to have a clearer understanding of the run-away destruction of the ozone layer that would have occurred without a successful Montreal Protocol. With that knowledge we can assess how such changes might have affected human health.

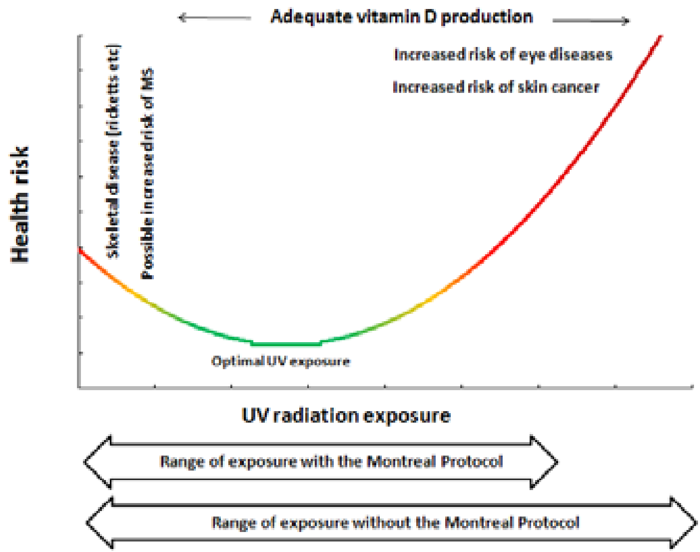


Figure 1. The "U-shaped" relationship between UV and health. With current UV exposure there are risks of under-exposure (e.g. high latitudes in winter) as well as of over-exposure (e.g. due to seeking the sun in summer, especially at low latitudes). Risks of under-exposure include increases in some bone diseases and, perhaps, in some auto-immune diseases like multiple sclerosis (MS). The large increases in UV that would result from uncontrolled ozone depletion would greatly increase the risks of excess UV exposure, including skin cancers and eye disease. These topics are covered in detail later in this booklet.

## Box 1 UNEP's Environmental Effects Assessment Panel (EEAP)

Since 1987, UNEP's Environmental Effects Assessment Panel (EEAP) has provided the Parties to the Montreal Protocol with up-to-date, expert assessments of developments in research into the effects of ozone depletion. EEAP assesses the full range of potential effects of ozone depletion and increased UV [1] on aquatic [2] and terrestrial ecosystems [3], environmental cycles [4], air quality [5] and construction materials [6]. The effects of ozone loss on human health have always been a major area of concern for the Parties, and hence a primary focus for EEAP's assessment [7]. This booklet makes extensive use of EEAP's most recent assessment published in 2015 [1-7].

# Ultraviolet Radiation: The Key Link between Stratospheric Ozone and Human Health

Ultraviolet radiation is the link between changes in ozone high in the atmosphere and changes at the Earth's surface, the environment we all live in. The light we see- the colours of the rainbow from red to violet (Figure 2)- is just a small part of the spectrum of radiation that makes-up sunlight. The sun emits a whole range of radiation from radio-waves (long wavelength/low energy) to gamma rays (short wavelength /high energy). The ultraviolet radiation in sunlight ranges from wavelengths only just too short to be seen by the human eye to much shorter wavelengths.

The shortest ultraviolet wavelengths are called ultraviolet C (often abbreviated to UVC). The UVC that is present in sunlight in space is completely absorbed by the atmosphere, and so does not reach the Earth's surface.

The Earth's atmosphere does not greatly affect the longest ultraviolet wavelengths, ultraviolet A (UVA). UVA is not absorbed substantially by ozone or other gases in the atmosphere, and so it reaches the Earth's surface. Many animals can see the UVA, and it plays an important part in their behaviour. There are hints that human babies may also be able to see UVA, but it is invisible to adults. However, we are aware of it through its effects on our skin. It is mostly the UVA in sunlight that stimulates tanning in pale skin. In the longer term, UVA can cause skin ageing, and contribute to other skin damage.

The narrow band of ultraviolet between UVA and UVC is known as ultraviolet B (UVB). UVB radiation is strongly absorbed by ozone, so damage to the ozone layer allows more UVB to reach the Earth's surface. As individuals, we become aware of UVB because it is the part of sunlight that causes sunburn. Sunburn develops within a few hours of short periods of exposure to high UVB. **Exposure to too much UVB over a long period can lead to much more severe health problems.**


Figure 2. The light that we see as the colours of the rainbow is just part a small part of radiation that is emitted from the sun. If we could see beyond the colours of the rainbow then shorter wavelength radiation, like ultraviolet, would be extra bands below the violet band in the rainbow. If humans had such "UV vision" then ultraviolet A (UVA) would appear as another colour-band immediately below the violet. Many birds and insects do see UVA, so they really do see an extra colour in the rainbow, one that is invisible to us. Seen in that way, ultraviolet B (UVB) would be another band below UVA. If we could see UVB as a colour, then we might even be able to see ozone depletion in the rainbow. Ozone depletion would cause the UVB band, but not other colours, to get brighter as more UVB penetrates to the surface.

# UV radiation and human health: environment, biology and behaviour

To understand the effects of the ultraviolet radiation in sunlight on human health we need to consider not just environmental factors, like the ozone layer, but also biology (e.g. how different UV wavelengths affect biological molecules) and human behaviour.

## Environment

For UV to affect human health it must penetrate the atmosphere to reach the Earth's surface.

UVC radiation does not reach the Earth's surface, even with extreme ozone depletion, so UVC is not a factor in human health (although it is very damaging when emitted from artificial sources like welding systems or specialist lamps). UVA and UVB both penetrate to the Earth's surface, so they do have the potential to affect human health.

## Biology

The effects of UVA and UVB on human health are linked to their ability to be absorbed by and cause major changes to biological molecules. The chemical nature of molecules that are essential for life, including DNA and proteins, means that they can absorb UVA and/or UVB. This is often, but not always, damaging to their function (see Box 2). UV damage to the basic molecules of life can ultimately affect human health but, of course, not everyone responds to sunlight in the same way. Darkly pigmented skin provides some protection against UV damage, but that protection is certainly not total [7].

## Behaviour

We can all make choices about how we behave in response to the sun. It is stating the obvious that UV radiation cannot affect our health unless we are exposed to sunlight. If we choose to stay indoors or in the shade, especially around mid-day when UV is most intense, then we minimise the risk of diseases associated with excessive UV exposure, including skin cancers and cataracts. On the other hand, if we deliberately seek out the sun, aiming for a suntan for example, we inevitably increase our risk of over-exposure to UV. Other choices, like protecting our skin with clothes and eyes with a hat are also major factors in determining risk.

## Box 2: The biological targets for UV damage

DNA is probably best known as the "genetic code" that we pass from generation to generation. However, DNA is also the "instruction manual" that allows every cell in our body to carry out its proper function. If the instruction manual is damaged then cells may die or function incorrectly, and that is exactly what can happen when a cell is exposed to the UV in sunlight, especially UVB. Some of the chemical building blocks of DNA absorb UVB radiation. When this happens, the light energy can break or distort the structure of the DNA, damaging its function.

Sometimes the DNA damage caused by UVB is so great that the cell dies: but our bodies can replace dead cells quickly. However, the DNA damage can be repaired (our cells have various ways of doing that), and the cell continues to function normally. The greatest threat to health comes when cells survive but the DNA damage is not properly repaired. Depending on the exact damage, this does not always cause immediate problems. However, if the cell's DNA is damaged again, perhaps by more exposure to UV or other physical or chemical factors, the cumulative damage can be enough to trigger the changes in cell function that ultimately cause cancers.

If DNA is the cell's "instruction manual" then proteins are vital as either the tools by which the instructions are carried out, or the building blocks from which the cell is constructed. The effect of UV on skin ageing is due to direct damage to the proteins that help maintain skin structure. Cataracts are also the result of UV damage to proteins, in this case the proteins in the lens of the eye.

Finally, UV absorbed by our skin drives the chemical reactions by which we produce vitamin D. This is why vitamin D has been called "the sunshine vitamin". While we can obtain vitamin D from some food (like oily fish), and some food has vitamin D added during manufacture, for most people around the world it is the effect of sunlight on our skin that provides most of the vitamin D that we need for good health.

"Each year between two and three million new cases of skin cancer are diagnosed around the world"

# Skin Cancer as a Global Health Challenge

Skin cancer is not a single disease, but the majority of cases are one of three types: basal cell carcinoma, squamous cell carcinoma (known together as non-melanoma skin cancers) and malignant melanoma (see Box 3 for more information). Each year between two and three million new cases of skin cancer are reported around the world. That means that skin cancers account for around a third of all new cancer cases. In some pale-skinned populations skin cancers are the most common cancers.

Very substantial increases in these diseases have been observed in recent decades. The increase in skin cancers is a global phenomenon, especially in people with lightly pigmented skin. The incidence of non-melanoma skin cancers has more than doubled in several countries since the 1960s. The increase in malignant melanoma (which is generally better recorded in public health data) is even clearer. **Incidence of malignant melanoma in fair skinned people has broadly doubled every 10 to 20 years since the 1960s [7].**

The startling increases in malignant melanoma raise serious questions about the underlying causes.

## Skin cancers and UV radiation

The link between UV radiation and the development of malignant melanoma and non-melanoma skin cancers is clear from several lines of evidence [7].

- The risk of malignant melanoma and non-melanoma skin cancers in fair-skinned populations increases at lower latitudes, where the sun's UV is most intense.
- Some forms of non-melanoma skin cancers occur most often on the face, neck and forearms, parts of the body most likely to be exposed to the sun over a lifetime.
- In young people, malignant melanoma is most likely to occur on body extremities and on the torso. The increase in malignant melanoma in fair skinned populations in recent decades has also been most pronounced on the torso.

These observations point to intermittent exposure to intense solar UV being a significant risk factor for malignant melanoma. Intermittent exposure to high UV may also be significant in some non-melanoma skin cancers.

Box 3: Major skin cancers

Malignant melanoma

Only about 4-5 per cent of all skin cancers are malignant melanoma (Figure 3), and with early diagnosis it can be treated very successfully. However, if it is left untreated malignant melanoma can spread to other parts of the body. As a result, malignant melanoma, although it corresponds to 5 per cent of cases, causes about 75-80 per cent of all the deaths due to skin cancer. Although malignant melanoma is far more common among people with a pale skin, it does occur in people with darker skin. Data for the USA shows that malignant melanoma is approximately 20 times lower in black-skinned Americans compared with white-skinned Americans. But the early signs of melanoma are harder to identify in darker skins, the disease is more likely to be at an advanced stage when it is diagnosed, reducing the chances of successful treatment.

Figure 3. Illustrative image of malignant melanoma

Basal cell carcinoma and squamous cell carcinoma

About 95 per cent of all skin cancers are "non-melanoma skin cancers", the collective name for basal cell carcinomas and squamous cell carcinomas. Basal cell carcinoma is 3-4 times more common than squamous cell carcinoma. Although far more common than malignant melanoma, non-melanoma skin cancers are less likely to cause death. Even so, non-melanoma skin cancers can spread locally, leading to disfiguring tumours, loss of quality of life and significant ill-health. Surgery to remove non-melanoma skin cancers is painful and can be disfiguring. As with malignant melanoma, non-melanoma skin cancers are less common in dark skinned populations. However, non-melanoma skin cancers tend to be diagnosed far later in dark-skinned people, leading to greater ill health and a greater risk of death.

Sun exposure sufficient to cause severe sunburn, particularly during childhood, seems to be a particular risk factor for malignant melanoma later in life. This highlights a key aspect in the link between UV and skin cancer. **There is a time-lag of years or even decades between the initial UV damage and the onset of skin cancer.** In other words, malignant melanoma developing now is not a function of UV exposure a year or two ago, but of exposure that may have occurred as long as twenty years or more ago. The time-lag is crucial in understanding the increase in skin cancer in recent decades [7].

## Skin cancer in relation to recent changes in UV levels and sun-related behaviour

With the successful implementation of the Montreal Protocol increases in UV due to ozone depletion have been small. In fact, apart from a few short episodes, increases in UV in most inhabited parts of the globe have been hard to measure against the background variation in UV that is caused by clouds and other factors [1].

The world would have been a very different place without the Montreal Protocol (see below). However, given its success we cannot explain increases in skin cancers on the scale these have happened as being caused by uncontrolled ozone depletion. So what has caused the increase in skin cancers reported in recent decades?

Part of the increase may be due to greater public awareness of skin cancers, leading to increased reporting. The high media profile of ozone depletion has contributed to that increased awareness, and probably saved lives through earlier diagnosis and treatment.

However, it is clear that increases in skin cancers are far more than just changes in reporting. There has been a real increase in the frequency of these cancers. The major factor affecting the incidence in skin cancers in recent decades has been changes in the way many people choose to behave in the sun [7]. Over the last half century several linked changes in behaviour have led to increased sun exposure including:

- preference for a suntan among fair-skinned populations that are most vulnerable to sun damage;
- changing fashions, in the style of clothing and hats, leading to more skin being exposed more often;
- changing leisure patterns leading to more time spent in the sun, including "sunshine holidays" in regions with intense UV.

All these changes combined lead to increased personal exposure to UV and hence the risk of skin cancer. While public health campaigns have succeeded in increasing knowledge of sun protection, this does not always lead to altered behaviour. **The need for sustained efforts to change attitudes and behaviour (see Box 4) remains an urgent public health priority, regardless of future changes in the ozone layer.**

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## Box 4: The United Nations INTERSUN programme

In the early 1990s, understanding of the threat to the ozone layer and evidence for substantial increases in skin cancers led by the World Health Organisation (WHO) and others to establish the INTERSUN programme. The goals of the INTERSUN programme are as follows:

- to provide information, practical advice and sound scientific predictions on the health impact of UV exposure;
- to encourage countries to take action to reduce UV-induced health risks; and
- to provide guidance to national authorities and other agencies about effective sun awareness programmes.

Even with the success of the Montreal Protocol in preventing major increases in UV radiation, the work of INTERSUN remains an international priority. Individual choices about how to behave are vital in relation to exposure to the sun, so information and education are key objectives.

The INTERSUN programme promotes the use of the UV Index as a widely available measure of the health risk of excess UV that is readily understood by the public (Box 7). The UV Index has a simple 1-12 scale (now being expanded to 1-15 to account for the high UV levels in the mountains of the tropics). Variation in the UV component of sunlight with time of day and season, and with latitude or due to cloud can be readily expressed using the UV Index. This provides a basis on which individuals can make informed choices about how much time to spend in the sun, the use of protective clothing or sunscreens, etc.
Helping people to make the best decisions on their exposure to the UV in sunlight depends on effective education. INTERSUN especially prioritises educational programmes for children since over-exposure to UV early in life is a major risk factor for malignant melanoma and some non-melanoma skin cancers. Examples include innovative approaches that target children themselves, teachers, health professionals and those, like life guards, who are on the “frontline” of sun exposure behaviour.

# The Montreal Protocol and the Future of the Ozone Layer: The World We Live in and the World Avoided

In 2014, UNEP announced that the ozone layer was beginning to recover [8]. We can begin to look ahead to the progressive recovery of the global ozone layer over the 21st century [1,8]. With the continued effective control of ozone depleting substances, changes in climate are likely to become the dominant factor influencing the ozone layer. It is possible that we may even see a 'super-recovery' at mid-latitudes, with future ozone increasing above the levels that existed in the 1960s and before [1,8].

Of course, this future, the one we will live in, was not the only future that was possible when ozone depletion was first recognised. The same atmospheric and climate models that allow us to predict the future of the ozone layer as it is now also allow us to model what would have happened to ozone without the Montreal Protocol: the 'World Avoided'.

In fact, there are a number of published models of the ozone layer in the 'World Avoided' [1]. Each uses slightly different methods and assumptions but all highlight the severity of changes that would have occurred without the successful control of ozone depleting substances. All point to progressive loss of ozone that would have accelerated over time and extended to affect the entire planet (Figure 4). The predicted changes over the tropics are particularly dramatic, especially from the current perspective, where major ozone loss is principally a polar phenomenon. **Models predict that ozone over the tropics would have remained relatively stable until the mid-century, but then suffered a rapid collapse.**

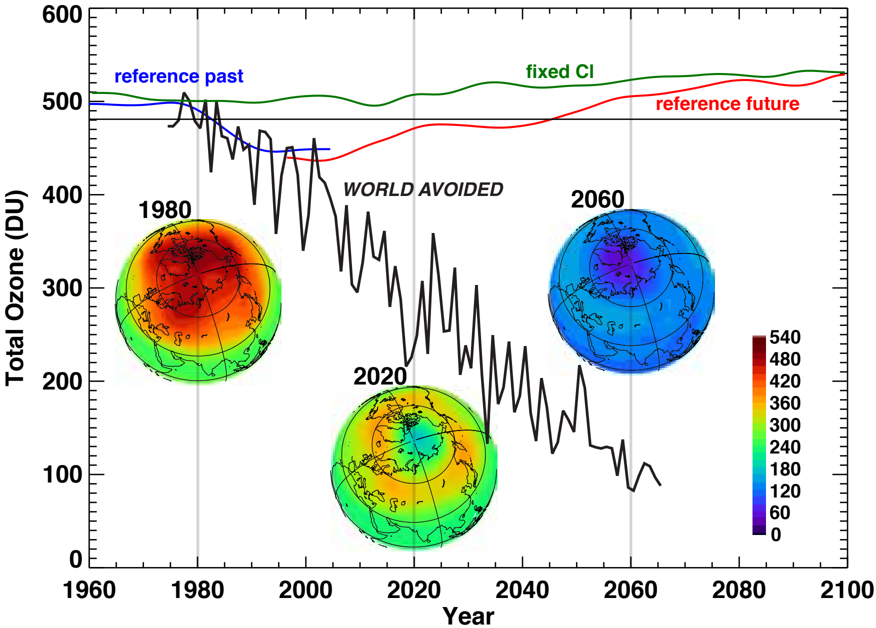
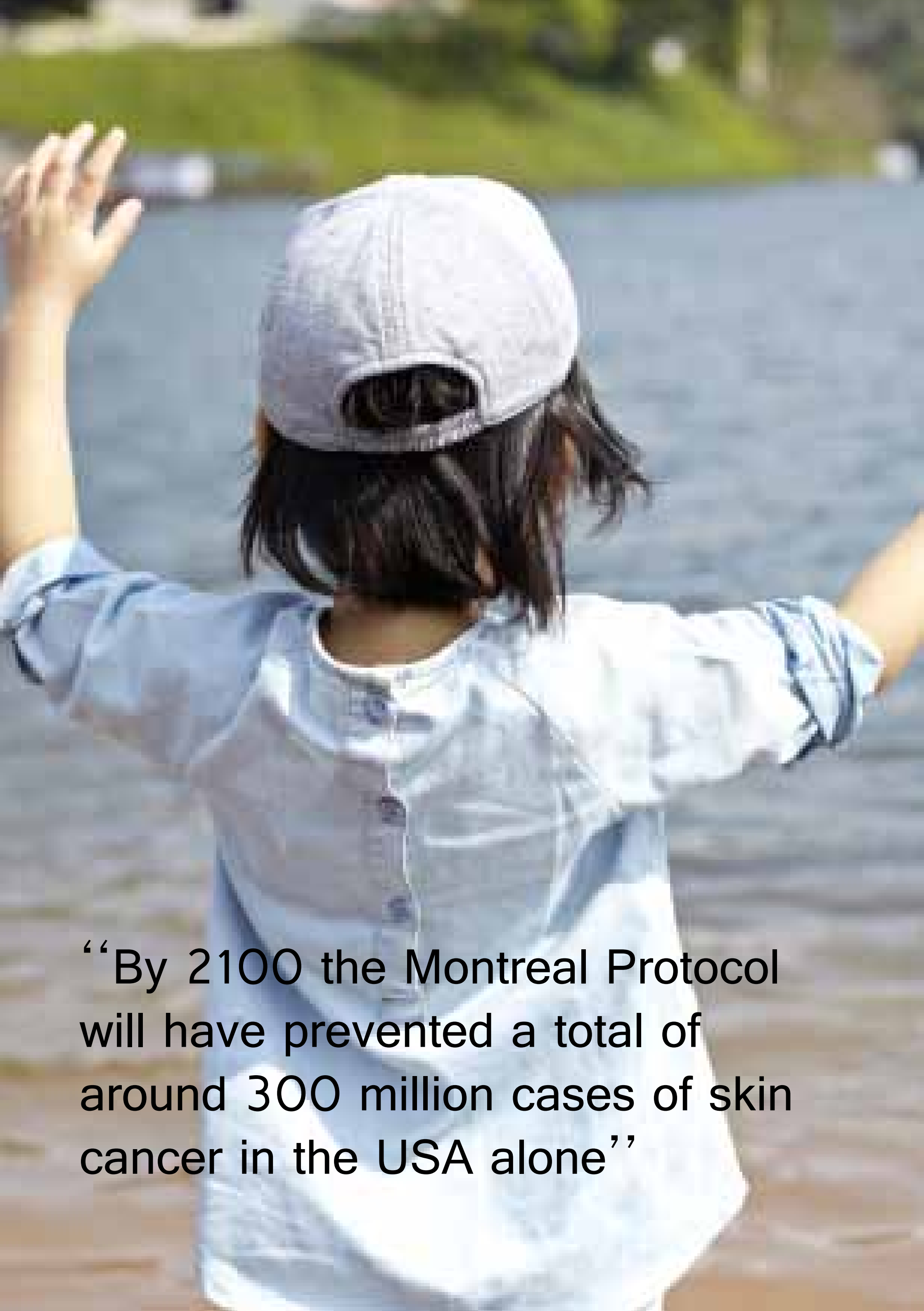



Figure 4. Ozone depletion over the course of the 21st century in the 'World Avoided' scenario.The data are simulations for April in the northern hemisphere in the 'World Avoided', i.e. without the successful implementation of the Montreal Protocol (shown in black), and for a future in which the Montreal Protocol is successfully implemented (show in red). The two additional lines simulate ozone between 1960 and 2005 (blue) and a world in which ozone depleting substances never rose above 1960 levels (green). The false colour images show the geographical distribution of ozone in 1980, 2020 and 2060 (the scale is in Dobson units). Note the global collapse of stratospheric ozone by 2060. Reproduced with permission from Newman *et al*, 2009 [9].



"By 2100 the Montreal Protocol will have prevented a total of around 300 million cases of skin cancer in the USA alone"

The consequences of this collapse in global ozone on UV would have been profound. Using the UV Index as a useful 'short-hand' (see Box 7) the range of UV that we experience now over most parts of the planet is in the range 0-12. At high altitude in the tropics, for example in the Andes, the UV Index may reach 15. In such locations, the UV Index may, under exceptional conditions, reach values as high as 25 for short periods. The World Health Organisation defines any UV Index above 10 as meaning an "extreme risk of harm from unprotected skin exposure". This is often accompanied by warnings that "unprotected skin and eyes can burn in minutes". That current range provides a useful context for the predictions of the 'World Avoided' models

Without the Montreal Protocol, **values of UV Index above the current extreme of 25 would have become commonplace over almost all inhabited areas of the planet** (Figure 5). Over the lowlands of the tropics, UV Index would have exceeded 50, which is more than four times the UV Index that is considered 'extreme'. It seems likely that these extreme values of the UV Index that would have occurred without the Montreal Protocol are beyond anything that humans have ever experienced over our evolutionary history. What is certainly becoming clearer is how these unprecedented UV indices in the 'World Avoided' could have affected skin cancers and other aspects of human health.

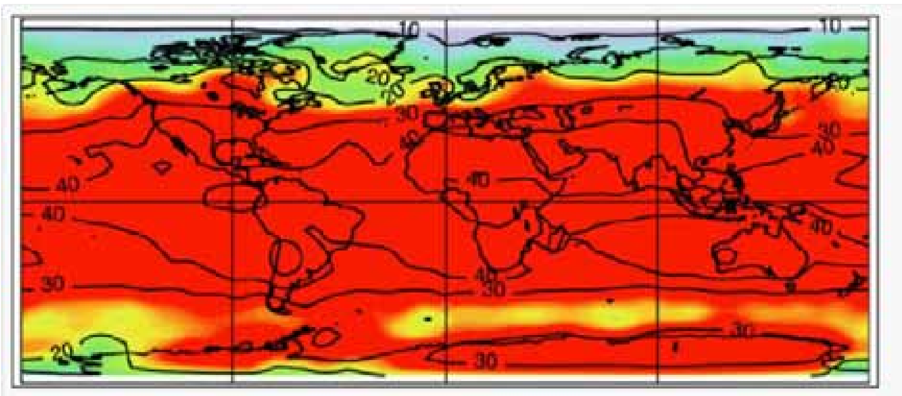


Figure 5. UV Index in the 'World Avoided'. The data are UV Index (see Box 7) for 2090 in the 'World Avoided', i.e. without the successful implementation of the Montreal Protocol. Note that regions shown in red exceed the maximum UV Index currently experienced on Earth (approximately 25, which occurs only under exceptional conditions at high altitude in the Andes). Reproduced with permission from Egorova *et al*, 2013 [10]

# Skin Cancers in the World Avoided

There are now an increasing number of models of how stratospheric ozone and UV Index would have changed in the world without the Montreal Protocol [1,8]. Since the 1990s these models have been combined with an understanding of the links between exposure to excessive UV radiation and the risk of skin cancers, to provide quantitative estimates of the incidence of skin cancer in the 'World Avoided'.

One recent model [11], led by the Netherlands National Institute for Public Health and the Environment and built on previous models by the same institute, considered how rates of skin cancers would have changed world-wide in the 'World Avoided' (Figure 6). The headline figure from this research [11] is that **the successful implementation of the Montreal Protocol will be preventing about two million skin cancers world-wide every year by 2030.** This model does not look beyond 2030 but if we make a very conservative assumption that effects on skin cancer later in the century are no worse than those predicted for 2030 we arrive at a total figure of around 150 million skin cancers prevented by 2100.

However, there is a delay of years or decades between the initial skin damage by UVB and the development of visible

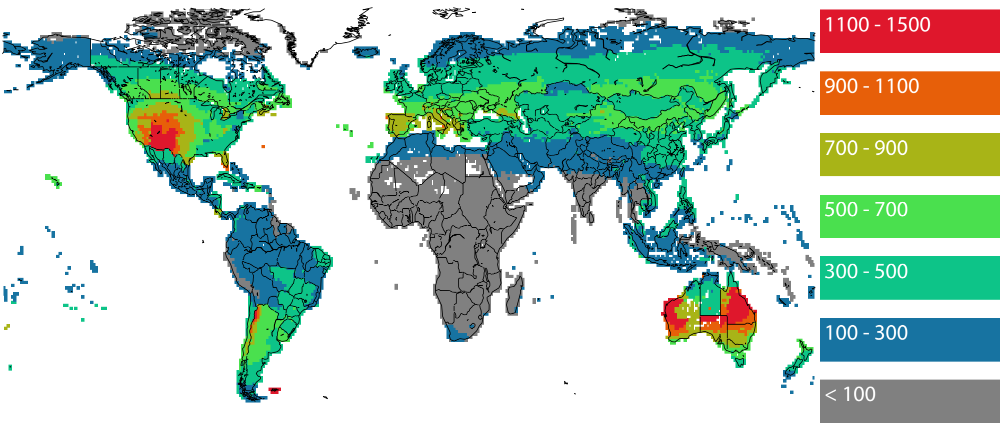



Figure 6. Modelled estimates of skin cancers avoided by the Montreal Protocol in the year 2030. Data are new cases per million people per year. Reproduced with permission from van Dijk *et al.* 2013 [11].

skin cancer (see above). That means that the increase in skin cancer by the 2030s would be largely the result of UV exposure in the late 1990s or the first few years of the 21st century. That is before the major ozone depletion expected for the middle of the century in the 'World Avoided'.

Other models have estimated the long-term benefits of the Montreal Protocol in reducing skin cancers, but only for some parts of the world. The first model of this type was published as early as 1996 [12]. This research considered changing patterns of skin cancer until 2100, focusing just on the USA and north-western Europe. The model predicted that without effective ozone protection the incidence of skin cancer would increase progressively. Increases would be relatively small in the early decades of the century, but then accelerate rapidly (Figure 7). **Effective implementation of the Montreal Protocol was predicted to prevent around two million additional skin cancer cases a year by 2100, just in the USA and northwestern Europe.**

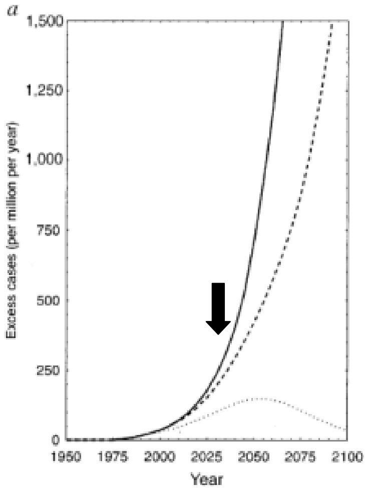



Figure 7. Modelled estimates for the increase in skin cancers in (a) USA and (b) northwest Europe in the 'World Avoided', i.e. without the successful implementation of the Montreal Protocol, compared a baseline with full implementation. The arrows indicate 2030, the date used in the global model of skin cancers avoided (see Figure 6). Modified from Slaper *et al.* 1996 [12].

Models produced by the US Environmental Protection Agency (EPA) also provide insight into the longer-term health benefits of the Montreal Protocol in terms of skin cancers in the 'World Avoided'. Their models, the first in 2006 [13], then updated in 2015 [14], consider the incidence of skin cancers in the USA only, for people born between 1980 and 2100. The 2015 EPA report [14] estimates that the Montreal Protocol and its amendments will have prevented a total of 275-330 million cases of non-melanoma skin cancers in the USA alone, and 8-10 million cases of malignant melanoma. Even with the high level of medical treatment available in the USA these additional skin cancers would have led to more than one and a half million additional deaths. The 2006 EPA report [13] highlighted that most of these additional skin cancers cases would have occurred in the later part of the century. More than 80 per cent of the additional cancers would have been suffered among those born after 2015 [13].

None of these models claim to make exact quantitative predictions of the future incidence of skin cancer. All assess the limits of their own methods and acknowledge the uncertainties associated with their predictions (see Box 5). Nonetheless, all the existing models point to the same "ball park" prediction that by 2100 the Montreal Protocol will have avoided at least a hundred million cases of skin cancers, and probably far more.

## Box 5: Methods and limits in modelling health in the World Avoided.

All the models of skin cancer incidence in the 'World Avoided' have taken great care to consider the limits on their predictions. As with any aspect of understanding the effects of ozone depletion on human health, modelling future incidence of skin cancer needs to account for environmental factors, the underlying biology of disease and human behaviour.

Of the three, the smallest uncertainties are probably associated with the environmental variables, i.e. future changes in ozone and UV radiation. However, as models have been refined over time they have incorporated new understanding of future trends in ozone depleting substances and ozone itself, including the effects of climate on stratospheric ozone. The way that models deal with cloud and other factor affecting ultraviolet radiation have also been refined.

Biological uncertainties include the effects of different wavelengths of ultraviolet radiation on the major skin cancer types, their different mortality rates, the relative importance of different patterns of UV exposure, and the protective effects of different skin pigmentation. The effect of a growing and ageing population also needs to be considered. The 2006 USA EPA report [13] suggested that biological factors might give an uncertainty of 60 per cent in its estimate of skin cancers in the USA. Extending modelling to the global population clearly tends to further increase such uncertainties.

The greatest unknowns in predicting future skin cancer incidence relate to behaviour. In a world without the Montreal Protocol people would surely have become acutely aware of the threat posed by UV. By choosing to avoid the sun they might have prevented some of the increase in skin cancers predicted by current models. The necessary behavioural changes remain unclear. Living in the 'World Avoided' would have meant living with UV levels several times greater than those currently described as meaning that "unprotected skin and eyes can burn in minutes". The changes in individual behaviour needed to cope in such a world are hard to imagine.

‘‘The greatest unknown in predicting future skin cancer incidence relates to behaviour’’

# Skin Cancers in the Future We Expect

As noted above, by limiting ozone depletion, the Montreal Protocol has prevented large increases in UV radiation. Given continued implementation of the Montreal Protocol it is currently predicted that stratospheric ozone will increase over the remainder of the 21st century. This increase will be greatest at high latitudes in the Southern hemisphere, reversing the large ozone depletion that has occurred there since the 1970s. Changes in UV radiation around the Antarctic will mirror these changes in ozone. UV radiation will begin to return towards the levels that existed before significant ozone depletion. In other parts of the globe the potential super-recovery of ozone (see p.20) may lead to UV levels falling below those experienced in the past [1,8]

However, these ozone-related changes in UV exposure at lower latitudes are likely to be relatively small. Other changes in the environment may have greater effects on future UV exposure. These include changes in cloud cover that are expected as the global climate changes [1]. In large cities, changes in air quality have a major effect on UV exposure because air pollutants such as particulates and ground-level ozone absorb UV radiation [1,5]. The improvement in urban air quality that is expected in many developing countries will mean lower levels of these air pollutants, and this is expected to substantially increase UV Index locally, compared with current values [1,5].

The strong links between UV exposure and skin cancers demands continued vigilance of these future changes in UV. Assessments of the effects of the small increases in UV radiation that have occurred since the 1970s, even with the Montreal Protocol, suggest that there may be some additional skin cancers, with a peak between 2040 and 2060 [12,13]. However, **it is likely that human behaviour will have the greatest influence on the future incidence of skin cancers.** While there are signs that rates of malignant melanoma may be stabilising in a few countries, these remain the exception. There are even hints that in some countries the level of public awareness of the risk of excessive sun exposure is lower than a few years ago [15].

Effective public health and education programmes, like INTERSUN (see Box 4) will remain essential. Without them, the prevention of skin cancers due to the success of the Montreal Protocol may be compromised by a failure to change public attitudes to the sun.


"Uncontrolled ozone depletion would have been a major threat to eyesight around the world"

# Ozone Depletion, UV Light and Eye Diseases

For us to see, light must pass through the eye to the light sensitive cells in the retina. In humans UVB and UVA are both absorbed before reaching the retina. While this protects the retinal cells, parts of the eye that absorb UV can be damaged, leading to eye disease.

In the short term, exposure to intense UV can damage the layers at the front of the eye (the cornea or conjunctiva: Figure 8).

A well-known example is snow-blindness. The combination of highly reflective snow and intense mountain sunlight causes very high UV exposure that demands very effective eye protection.  Similar damage can occur as the result of artificial sources of intense UV radiation. For example, 'arc-eye' is caused by the UVC produced by welding equipment.

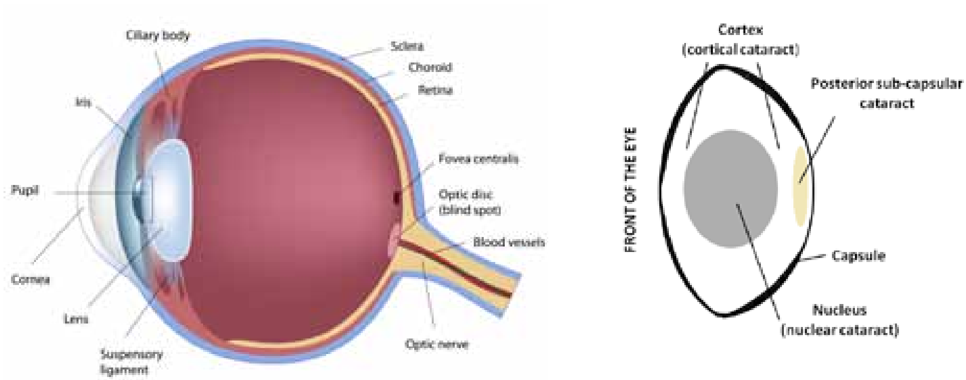



Figure 8. The structure of the human eye. The diagram on the left illustrates the main structures of the eye in cross-section. The diagram on the left is an enlarged illustration of the lens, showing the location of the three main types of cataract. UV radiation appears to be especially important in the development of cortical cataract.

In the longer term, exposure to UV is linked to a number of important eye diseases. These include cancers of the eye, which are comparable to the skin cancers caused by UV, but are much rarer. Probably the most important long- term effect of UV on the eye is the increased risk of cataracts. According to WHO figures, about 51 per cent of blindness world-wide is caused by cataracts. Every year around 16 million people suffer loss of sight due to the development of cataracts.

## UV and cataracts

Cataracts occur when the lens of the eye becomes cloudy (Figure 8). In its early stage a cataract causes blurred vision. Without treatment, changes in the lens progress and loss of vision becomes severe. Cataracts are classified according to which part of the lens is affected. The link between cataracts and exposure to the UV in sunlight is clearest for one type of cataract - cortical cataract. UVB appears to have a greater effect than UVA [7].

As with skin cancers, the US Environmental Protection Agency has published research which allows some estimation of how the incidence of cataracts would have changed in a world if the Montreal Protocol had not been successfully implemented [14,16]. The 2015 EPA report [14] concluded that, by 2100, **failure to effectively control ozone depletion would have led to a total of between 45 and 50 million additional cataract cases, just in the USA.**

As with models used to forecast the incidence of skin cancer, modelling can provide only broad estimates of the future incidence of cataracts in the 'World-Avoided'. The report's authors assess the uncertainties in their model, and note that they treat all cataracts together, while UV seems to affect only one type [16]. Even if the methods used by the EPA tend to over-estimate the US figures, that needs to be balanced by the key role of cataracts in causing blindness world-wide, not just in the USA. No global 'World-Avoided' model has been published for cataracts, but based on available evidence it is reasonable to suggest that by 2100 the Montreal Protocol will probably have avoided many tens of millions of cases of cataracts world-wide.

# Ozone Depletion, UV Radiation and the Immune System

Humans, like all organisms, are constantly being attacked by organisms that can cause disease. Our bodies are protected against such attack by a range of mechanisms that together form our immune system (see Box 6). In recent decades it has become clear that UV radiation can affect the human immune system, but these effects are complex. UVB and UVA both have independent effects on immune functioning, and these effects may interact. Different components of the immune system respond in different ways (see Box 6).

In animal studies, exposure to UV has been shown to increase the severity of some infectious diseases. There is also evidence that increased exposure to the sun can increase the severity of herpes simplex infections (cold sores) in humans and, perhaps, reduce the effectiveness of vaccinations [7].

Auto-immune diseases include conditions such as type 1 diabetes, multiple sclerosis, rheumatoid arthritis and inflammatory bowel disease. The frequency or severity of several of these diseases varies across the globe, especially with latitude [7]. This has led to suggestions that auto-immune disease may be affected by exposure to UV. The strongest evidence that variation in UV has significant effects on auto-immune disease comes from multiple sclerosis [7]. The balance of evidence is that the incidence and severity of multiple sclerosis decreases at lower latitudes, at least in fair-skinned populations. Experimental evidence suggests that UV exposure early in childhood, or even during pregnancy, may be particularly important in affecting future risk of multiple sclerosis [7].

As with other health effects, the success of the Montreal Protocol in limiting ozone depletion means that the small changes in UV that have occurred since the 1970s, and those predicted over the 21st century, are unlikely to have measurable effects on human immune function. However, the response of the immune system to variation in UV exposure, due to where one lives, or personal choices about how to behave in the sun, remain relevant to understanding a number of diseases.

## Box 6: The immune system and mechanisms of response to UV light

The human immune system brings multiple mechanisms into action to protect us from attack by microorganisms and chemicals. The *innate* immune system is a relatively generalised and immediate response, based on mechanisms including inflammation, a range of defensive chemicals (e.g. anti-microbial peptides) and some types of white blood cells (phagocytes). In contrast to the innate immune system, the acquired immune system is highly specific and long-lasting. Acquired immunity involves the production of antibodies and a range of white blood cells which are specific for each foreign molecule. Vaccination provides long-lasting acquired immunity against several common *infections*

UV can affect the immune system through effects on multiple target molecules (the 2015 EEAP report lists five [7]). Despite this underlying complexity, it seems that exposure to UV radiation generally increases the activity of the innate immune system but tends to decrease the activity of the acquired immune system.

# Ozone Depletion, UV Radiation and Vitamin D

The last few decades have seen a major re-examination of how UV in the sunlight may affect health through its role in vitamin D production in the skin [7].

Bone deformities, like rickets, have been recognised for centuries. With increased understanding of the role of vitamins in human health it became clear that rickets was caused by a lack of vitamin D. By the 1920s it was understood that humans could synthesise vitamin D in the skin if it was exposed to sunlight. It is now known that it is the UVB component of sunlight that drives most vitamin D synthesis.

A few foods, such as oily fish are natural sources of vitamin D, and some foods may contain added vitamin D, but for most people the main source of vitamin D is synthesis in the skin. As a result, vitamin D deficiency can develop when the skin is unable to synthesise adequate vitamin D.

## UV radiation and vitamin D deficiency

Vitamin D production in the skin depends on exposure to sunlight. At high latitudes during winter the UVB component in sunlight can become too low for adequate vitamin D synthesis [1]. Winter clothing that leaves little skin exposed to sunlight, and spending less time outdoors in winter further reduce the potential for vitamin D synthesis. The pigments that protect our skin from UV damage may also reduce vitamin D synthesis, so people with darker skin are more commonly deficient in vitamin D than fairer skinned people living at the same latitude [7].

Many studies have shown that the concentration of vitamin D in the body is reduced during winter at high latitudes. It is less clear just how low vitamin D needs to fall to be considered as vitamin D deficiency and how deficiency might affect health [7].

## Vitamin D deficiency and disease

In recent years it has been suggested that vitamin D has a much wider role in human health than just preventing bone disease [7]. Vitamin D deficiency has been linked with an increased risk of a range of diseases [7]. These include infections like tuberculosis, autoimmune diseases, notably multiple sclerosis, and a number of internal cancers (e.g. cancers of the colon, breast, uterus, and prostate).

These wider effects of vitamin D on human health are the subject of considerable debate [7]. This is partly because some of the evidence of vitamin D effects is based on variations in disease incidence at different latitudes. Such variation is readily correlated with variation in the intensity of UV radiation. However, UV radiation effects that are independent of vitamin D, for example on the immune system, may also explain this geographical variation in some diseases [7].

It is now clear that, whether mediated by vitamin D alone, or by a range of mechanisms, **some exposure to the UV in sunlight is beneficial to health.** That poses a difficult question for individuals and for those responsible for public health. How can we get the UV we need but avoid getting too much? Beyond that, will future changes in the ozone layer change the balance between the 'good' and 'bad' effects of UV radiation?

Unfortunately, there is no hard and fast rule about the 'right amount' of sun exposure. Individuals differ in their vulnerability to UV damage and the amount of UV they need to make the vitamin D they require. Latitude also has a major effect with higher UV at low latitudes reducing the risk of vitamin D deficiency while increasing the risk of UV damage.

The decreases in UV expected as the ozone layer recovers over the coming decades are probably too small to greatly alter the time required for either sunburn or adequate vitamin D synthesis. For example, a recent model considering both these aspects of UV effects suggests that the time needed for a fair-skinned individual to suffer a slight sunburn, or to produce vitamin D, will increase by only a few minutes between now and 2100 (Figure 9). The time required for the skin to produce sufficient vitamin D remains less than the time needed to cause sunburn [17].

The message that excess UV poses a long-term threat to health, especially through increased risk of skin cancer, remains unchanged. Programmes like INTERSUN (Box 4) will remain an important element of public health education.

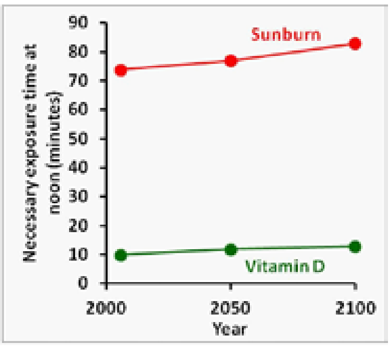



Figure 9. Predicted changes in the time necessary to suffer a slight sunburn or synthesise vitamin D given expected changes in UV radiation over the 21st century. The exposure times are for a latitude of 52°N in the spring and assume an individual with fair skin that is sensitive to the effects of UV radiation (skin type II). The time required for the synthesis of 1000 International units of vitamin D assumes that an individual exposure of face, arms and hands. Modified from Correa *et al* (2013) [17].

# Other Potential Effects of Ozone Depletion on Human Health

The prevention of large increases in skin cancers and cataracts are examples of how protecting the ozone layer has directly benefited human health. We can even begin to make quantitative estimates of the scale of these benefits of the successful implementation of the Montreal Protocol.

However, the Montreal Protocol has had other benefits on health. Some ozone depleting substances, for example methyl bromide, are toxic to humans. Replacing toxic ozone depleting substances with less toxic technologies will have reduced the health threat to users. Some ozone depleting substances, notably CFCs, are also very potent greenhouse gases. By replacing these CFCs with chemicals that contribute less to the greenhouse effect, the Montreal Protocol has made a significant contribution to protecting the climate. In turn, this will contribute to reducing the threats to health associated with increased temperature and other elements of climate change.

Focusing on UV radiation, the effects of increased UV in the 'World Avoided' would not have been confined to humans. The effects of uncontrolled ozone depletion on other organisms and ecosystems, and on environmental processes, would have had many knock-on consequences for human health.

Our understanding of the mechanisms of these indirect effects of ozone depletion, on air and water quality or on food production, shows that there would not be major time-lags between changes in ozone and the response. This contrasts with the lags of years to decades that occur with direct health effects, such as skin cancer. So these indirect changes might have been the first to become apparent in the 'World Avoided', much earlier than changes in skin cancers or cataracts. These "indirect" changes would have affected everyone on the planet. Everyone needs adequate and nutritious food, and everyone needs clean drinking water and clean air.
It is not yet possible to be precise about the scale or timing of these indirect effects of ozone depletion on health. Despite the uncertainties about the indirect effects they are surely worth including in any assessment of the benefits of the Montreal Protocol for people and communities all around the world.

## Changes due to the effects of ozone depletion on climate

Research into the environmental impacts of ozone depletion have focused almost entirely on effects caused by changes in UV. In the last few years it has become clear that ozone depletion can also have major impacts on climate [1,3,8] and that this can have knock-on effects on people. Even with the successful

implementation of the Montreal Protocol, the Antarctic ozone hole is causing changes in climate over large parts of the southern hemisphere, including changes in temperature and rainfall [3,8].

## Changes in water quality

The UV naturally present in sunlight can kill disease-causing micro-organisms in water bodies and thus reduce the burden of water-borne disease [2]. UV may also increase the rate of degradation of organic pollutants [4]. In the 'World Avoided' these cleansing effects of UV radiation would have increased. However, any resulting positive effects on human health would likely have been very small compared with the negative effects.

## Changes in food security

Many crops respond to the normal variation in UV due to season but these effects are rarely damaging to crop production or quality [3]. On the other hand, there is good evidence that as UV, especially UVB, increases above the current range then it can begin to threaten crop yields and quality [3].

The relationships between increased UVB and food production in the "World Avoided" cannot currently be quantified.

This is partly because each crop will respond differently and few have been studied in detail. An additional factor is the range of UV treatments used in field studies of crops. For example, a pioneering overview of crop responses in the field treated anything more than 20 per cent of ozone loss as "high levels of ozone depletion " [18]. That was probably an accurate assessment of a world with a partly successful Montreal Protocol but it is conservative compared with the predictions of ozone depletion in the 'World Avoided'. Those predictions approach 80 per cent ozone loss in some cases. The same overview of crop responses [18] showed "higher" ozone depletions (mostly 20-30 per cent) reduced plant biomass an average of about 16 per cent. That figure includes most of the world's major food crops and gives some insight into the potential scale of the effects of uncontrolled ozone depletion on agricultural production.

It is clear that some economic fish species can be damaged by UV either as adults or during development [2]. UV can also damage the plankton that form the basis of marine food webs, and ultimately the productivity of fisheries [2]. However, the challenges of experimental studies of UV in aquatic, especially marine, systems mean that is hard to estimate the magnitude of the effects of uncontrolled ozone depletion on fisheries.

In summary, we cannot yet quantify the scale of the indirect effects of ozone depletion on human health. However, we can say that uncontrolled ozone depletion would have added to global food insecurity, with all the associated effects on human health.

# The Bottom Line: The Economic Value of the Health Benefits of the Montreal Protocol

There have been several estimates of the financial value of the Montreal Protocol. The most recent of those estimates [19] suggest that health benefits represent about 80 per cent of the total economic benefit of the Montreal Protocol, estimated to be US$1.8 trillion by 2060 (Figure 10). A part of this benefit comes from avoiding the health-care costs associated with treating the greater numbers of non-lethal skin-cancers and cataracts expected in the 'World Avoided'. A much greater financial benefit comes from the lives saved by avoiding large increases in skin cancers, especially malignant melanoma. This represents around 50 per cent of the total economic benefit of the Montreal Protocol. It is worth noting that, due to the lag between UV exposure and the development of skin cancer (see above) these financial estimates do not include the effects of the collapse in the global ozone layer that the 'World Avoided' models predict for the middle of the 21st century (see p.21).

In the 'World Avoided', this ozone collapse around 2050 would have caused very large UV increases in the second half of the century. The resulting impacts on global health have yet to be quantified (see above). However, it seems likely that the positive economic gains of the Montreal Protocol by the end of the century will substantially exceed the estimates for financial gains until 2060.

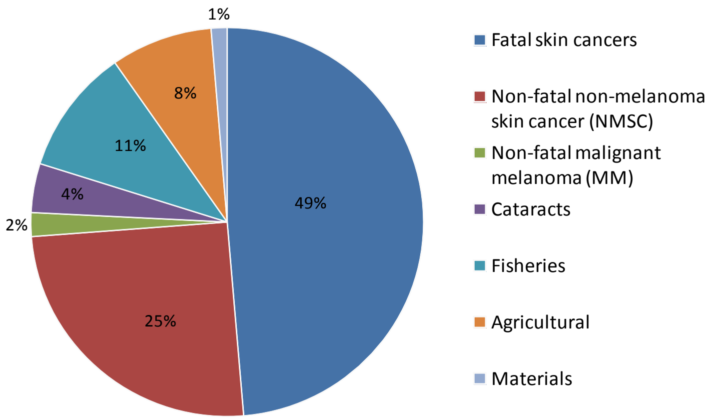



Figure 10. The estimated financial benefits of the Montreal Protocol to 2060. The figures are absolute value in billions of US dollars at 1997 values. Based on Markandya & Dale (2012) [19]

# Concluding Remarks

Much of this booklet has considered how human health might have changed in a future where the Montreal Protocol had not been successfully implemented. The models of the 'World Avoided' provide our best current insight into a world that, fortunately, will not be the one that we, and our children and grand-children, live in. Those models, combined with great advances in understanding the biology of UV effects on human health, have confirmed the threat to human health that was recognised by the Parties when they first signed the Montreal Protocol in 1987.

Our understanding of life in the 'World Avoided' will continue to become clearer and deeper. Models of ozone and UV radiation in the 'World-Avoided' are increasingly robust. We are, perhaps, moving to a position where we can adopt an "ensemble" approach using a larger number of models to support more robust predictions. This may help fill existing gaps in the knowledge that currently prevent us from assessing the full benefits of the implementation of the Montreal Protocol. For example, we cannot currently begin to quantify how ozone depletion late in this century would have affected health in the 'World Avoided' beyond 2100. The limits on existing models also prevent us from quantifying indirect effects, like those on food production, in any detail.

However, the scale of the damage to health had we failed to protect the ozone layer is already clear. The health and well-being of hundreds of millions of people, many not yet born, have been protected by the concerted action of the Parties since 1987. Can there be a better answer to any questions about the reasons for protecting the ozone layer, or any better reason to celebrate the benefits that have resulted from the success of that protection?

# Box 7: Measuring UV Radiation: the UV Index

The UV radiation that reaches the earth's surface is conveniently divided into UVA and UVB. These two parts of the UV spectrum are defined in terms of their wavelength. UVB is between 290 and 315nm, UVA between 315 and 400nm.

It is often possible to make broad generalisations about the effects of UVA and UVB, for example "UVB is more damaging than UVA". However, this is rarely sufficient to fully understand the effects of UV on human health. Every target for UV effects, whether that is a molecule like DNA or a process like cancer development, has a specific pattern of response to different UV wavelengths.

By using these characteristic wavelength responses we can account for the changes in the balance of different UV wavelengths in sunlight. Those changes occur with latitude and season as well as with ozone depletion.

For human health the wavelength response of sunburn is used as a convenient "short-hand" for a range of responses. Researchers often express UV in terms of this sun-burning UV (known technically as "erythemal UV"). It is this same sun-burning UV that forms the basis of the UV Index.

The UV Index translates sun-burning UV in to a simple, standardised scale that can be used in weather forecasts and other public information. It provides a "snap-shot" which allows individuals to make sensible choices about their exposure to the sun.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# About the UNEP DTIE OzonAction Programme

Under the Montreal Protocol on Substances that Deplete the Ozone Layer, countries worldwide are taking specific, time-targeted actions to reduce and eliminate the production and consumption of man-made chemicals that destroy the stratospheric ozone layer, the shield that protects human health and all life on Earth from the damaging effects of extreme UV radiation

The objective of the Montreal Protocol is to phase out ozone depleting substances (ODS), which include CFCs, halons, methyl bromide, carbon tetrachloride, methyl chloroform, and HCFCs. One hundred ninety seven governments have joined this multilateral environmental agreement and are taking action.

The UNEP DTIE OzonAction Branch assists developing countries and countries with economies in transition (CEITs) to enable them to achieve and sustain compliance with the Montreal Protocol. With our programme's assistance, countries are able to make informed decisions about alternative technologies, ozone-friendly policies and enforcement activities.

OzonAction has two main areas of work:

- Assisting developing countries in UNEP's capacity as an Implementing Agency of the Multilateral Fund for the Implementation of the Montreal Protocol, through a Compliance Assistance Programme (CAP).
- Specific partnerships with bilateral agencies and Governments.

UNEP's partnerships under the Montreal Protocol contribute to the realisation of the Millennium Development Goals and implementation of the Bali Strategic Plan.

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The UNEP Division of Technology, Industry and Economics (DTIE) helps governments, local authorities and decision-makers in business and industry to develop and implement policies and practices focusing on sustainable development.

The Division works to promote:

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> the efficient use of renewable energy,
> adequate management of chemicals,
> the integration of environmental costs in development policies.

### The Office of the Director, located in Paris, coordinates activities through:

**> The International Environmental Technology Centre** - IETC (Osaka), which implements integrated waste, water and disaster management programmes, focusing in particular on Asia.
**> Sustainable Consumption and Production** (Paris), which promotes sustainable consumption and production patterns to contribute to human development through global markets.
**> Chemicals** (Geneva), which promotes sustainable development by catalysing global actions and building national capacities for the sound management of chemicals and the improvement of chemicals safety worldwide.
**> Energy** (Paris), which fosters energy and transport policies for sustainable development and encourages investment in renewable energy and energy efficiency.
**> OzonAction** (Paris), which supports the phase-out of ozone depleting substances in developing countries and countries with economies in transition to ensure implementation of the Montreal Protocol.
**> Economics and Trade** (Geneva), which helps countries to integrate environmental considerations into economic and trade policies, and works with the finance sector to incorporate sustainable development policies.

***UNEP DTIE activities focus on raising awareness, improving the transfer of knowledge and information, fostering technological cooperation and partnerships, and implementing international conventions and agreements.***

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Multilateral Fund
for the Implementation of the Montreal Protocol

This booklet summarises how the successful implementation of the Montreal Protocol has protected human health. It describes how ozone depletion would have led to increases in UV radiation and, based on current understanding of the mechanisms by which UV affects biological processes, how that would have led to a dramatic increase in skin cancers, cataracts and affected human health in other ways. It also covers recent progress in understanding the 'World Avoided' – that is the world we would have lived in without a successful Montreal Protocol.

DTI/1927/PA