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PERSPECTIVE

Ozone depletion and climate change: impacts on UV radiation

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The Montreal Protocol is working, but it will take several decades for ozone to return to 1980 levels. The atmospheric concentrations of ozone depleting substances are decreasing, and ozone column amounts are no longer decreasing. Mid-latitude ozone is expected to return to 1980 levels before mid-century, slightly earlier than predicted previously. However, the recovery rate will be slower at high latitudes. Springtime ozone depletion is expected to continue to occur at polar latitudes, especially in Antarctica, in the next few decades. Because of the success of the Protocol, increases in UV-B radiation have been small outside regions affected by the Antarctic ozone hole, and have been difficult to detect. There is a large variability in UV-B radiation due to factors other than ozone, such as clouds and aerosols. There are few long-term measurements available to confirm the increases that would have occurred as a result of ozone depletion. At mid-latitudes UV-B irradiances are currently only slightly greater than in 1980 (increases less than ~5%), but increases have been substantial at high and polar latitudes where ozone depletion has been larger. Without the Montreal Protocol, peak values of sunburning UV radiation could have been tripled by 2065 at mid-northern latitudes. This would have had serious consequences for the environment and for human health. There are strong interactions between ozone depletion and changes in climate induced by increasing greenhouse gases (GHGs). Ozone depletion affects climate, and climate change affects ozone. The successful implementation of the Montreal Protocol has had a marked effect on climate change. The calculated reduction in radiative forcing due to the phase-out of chlorofluorocarbons (CFCs) far exceeds that from the measures taken under the Kyoto protocol for the reduction of GHGs. Thus the phase-out of CFCs is currently tending to counteract the increases in surface temperature due to increased GHGs. The amount of stratospheric ozone can also be affected by the increases in the concentration of GHGs, which lead to decreased temperatures in the stratosphere and accelerated circulation patterns. These changes tend to decrease total ozone in the tropics and increase total ozone at mid and high latitudes. Changes in circulation induced by changes in ozone can also affect patterns of surface wind and rainfall. The projected changes in ozone and clouds may lead to large decreases in UV at high latitudes, where UV is already low; and to small increases at low latitudes, where it is already high. This could have important implications for health and ecosystems. Compared to 1980, UV-B irradiance towards the end of the 21st century is projected to be lower at mid to high latitudes by between 5 and 20% respectively, and higher by 2–3% in the low latitudes. However, these projections must be treated with caution because they also depend strongly on changes in cloud cover, air pollutants, and aerosols, all of which are influenced by climate change, and their future is uncertain. Strong interactions between ozone depletion and climate change and uncertainties in the measurements and models limit our confidence in predicting the future UV radiation. It is therefore important to improve our understanding of the processes involved, and to continue monitoring ozone and surface UV spectral irradiances both from the surface and from satellites so we can respond to unexpected changes in the future.

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Introduction

The amount of ultraviolet radiation (UV)† received at Earth's surface has important implications for human health, terrestrial and aquatic ecosystems, biogeochemical cycles, air quality, and damage to materials, which are assessed in subsequent papers of this thematic issue. Research into these topics was stimulated by the realisation, more than 30 years ago, that the stratospheric ozone layer was at risk, and that there would be consequent increases in UV-B (280–315 nm) radiation. Increases in UV-B due to decreasing ozone amounts were observed during the 1980s and 1990s, particularly at high latitudes (>~60°), where ozone depletion was more pronounced. However, because of the success of the Montreal Protocol‡ in reducing the ozone-depleting substances (ODSs), ozone is no longer decreasing and at unpolluted sites, unaffected by changes in cloud cover, the increases in UV have not continued in recent years. Based on our current understanding (which may be incomplete), a gradual recovery of ozone is expected in the decades ahead. Changes in other factors, such as clouds, air pollution (including aerosols), and surface albedo, are sometimes more important for changing UV radiation, and may also lead to future differences on urban and regional scales. For the forest and aquatic environments, respectively, the UV transmission of canopy foliage and water must also be considered.

By the end of the 21st century, amounts of ozone in most regions are expected to be greater than they were before ozone depletion began prior to 1980. Therefore, in the absence of changes in other factors, UV-B would be expected to decrease. However, at some locations it is possible that UV will remain elevated due to decreasing extinctions by clouds and aerosols, particularly if the combustion of fossil fuels is significantly reduced by that time. In some regions, such as at high latitudes, where increases in cloud cover and reduction of the area of snow or ice are projected as a consequence of climate change, decreases in UV at the surface may be expected.

It is well known that UV radiation can have harmful effects on human health (*e.g.*, skin cancer and eye damage), terrestrial and aquatic ecosystems and materials. However, UV radiation also has beneficial effects, for example by stimulating the production of vitamin D in humans and other animals (adverse and beneficial effects are discussed in detail in Norval *et al.*[1]). At mid- and high-latitudes, wintertime UV is very low, and human populations may be at risk from insufficient vitamin D, a risk which may increase further if ozone increases in the years ahead and if the current trend toward indoor living continues.

Here the past changes and projected future changes in UV are assessed, focusing on the effectiveness of the Montreal Protocol implementation and the effects of interactions between ozone depletion and climate change. Although brief progress reports[2–4] have been published in the last three years, this paper summarises changes in our understanding of these factors in the period since the last full assessment report in 2007.[5] To put this work into context, we include a brief discussion of changes in stratospheric ozone, which is described in greater detail in the WMO Scientific Assessment of Ozone Depletion.[6]

Past changes in UV

Despite the paucity of corroborative long-term measurements of UV radiation, studies and theory have established a clear inverse relationship between column ozone and UV-B radiation reaching the surface of Earth. It is therefore generally accepted[5,7] that, during the period of declining column ozone starting prior to 1980 and continuing through the 1990s, UV would have increased by a few percent at mid-latitudes (*i.e.*, latitudes ~30–60° in both hemispheres), so that the UV experienced there since the late 1990s probably exceeds that at any time in the last century. However, this assumes that changes in cloud cover and aerosols have been small – an assumption which at many locations is not valid. Further, over timescales of hundreds of years or longer, it is unknown whether the current UV levels are particularly severe. Better proxy methods are needed to estimate these effects reliably and to better understand the severity of the present situation in a longer historical context.

Estimates of UV from periods prior to modern instruments

Changes in UV over timescales of centuries have been estimated from records of sunspot number, an index of solar activity. Increased solar activity leads to increased UV-C (100–280 nm) radiation in the upper atmosphere, which in turn enhances the photochemical formation of ozone and hence the absorption of UV-B radiation. Therefore an inverse relationship between solar activity and UV-B irradiance at the surface is expected. For example, the 11-year solar activity cycle is responsible for increases in UV-C irradiance of a few percent between minimum and maximum. These increases lead to enhanced production of stratospheric ozone, which in turn reduces UV-B transmitted to Earth's surface by a few percent between solar minima and solar maxima in recent solar cycles. It has been further suggested that long-term changes in UV-C exceed these variations by a factor of two, and that during quieter periods (low number of sunspots), such as the Maunder minimum in the 17th century, surface UV-B irradiance may have been significantly higher than in the modern epoch.[8]

Over much longer timescales, before the appearance of man, UV irradiances may have been much greater than at present, due to differences in the composition of the atmosphere. For example, a recent modelling study estimated that about 4 billion years ago, UV-B radiation may have been several orders of magnitude higher than at present.[9] Another modelling study suggested that about 250 million years ago the UV-B levels may also have been elevated, mainly at higher latitudes.[10] Historic changes in UV-B, their causes, and methods to probe them have recently been reviewed.[11]

For the more recent past, on timescales of a century or so, attempts have been made to estimate UV irradiances using information about daily sunshine duration. For example, daily totals of solar UV radiation back to 1893 were reconstructed for Central Europe.[12] The estimated annually averaged erythemal

† For ease of reading, we use "UV" as an abbreviation of "UV radiation" or "amount of UV radiation". The term "UV irradiance" means the measured quantity of UV radiation (usually in units of W m^{-2}) incident on a horizontal surface. See the glossary for further details, including definitions of UV-A, UV-B and UV-C.

‡ Here we take the Montreal Protocol to include its subsequent amendments and adjustments.

irradiances (UV-Ery)§ in this region were found to be only weakly dependent on ozone amounts. Thus, assuming that any ozone changes prior to 1980 were no larger than those since 1980,[14] this new information extends our knowledge of historical changes in UV irradiance to the period before direct measurements were available. However the uncertainty in the reconstruction is typically 10–20% for annual means.

Satellite estimates of UV

Estimates of surface UV irradiance are available from satellite measurements for the period since the late 1970s. Changes in UV at different spectral bands over the period 1979 to 2008 for the entire globe have been derived from a series of polar orbiting satellite instruments, as summarised for UV-Ery in Fig. 1.[15] Although satellite observations are available to higher latitudes, the latitude range in this study is limited to 55°S to 55°N to avoid large solar zenith angle effects and seasonal bias caused by missing data during polar nights. The reduced latitude range also helps to reduce the effects of uncertainties in the retrieval associated with distinguishing reflections from clouds or snow.[16,17] Over this time period, UV increased significantly at all latitudes except the equatorial zone. Over the shorter period from 1979 to 1998, the increase was caused by decreases in ozone amount, but after 1998, ozone amounts and UV irradiance in the northern mid-latitudes have been approximately constant. The annual average UV increase due to ozone changes is partially offset by an increase in clouds and aerosols which led to a decrease in transmission of UV to the surface (*i.e.*, a "dimming"), especially at higher latitudes in the southern hemisphere. For clear skies, the largest increases in estimated UV-Ery were in the southern hemisphere (about 8% at 50°S for clear-sky conditions compared to 5% at 50°N). At lower latitudes, the increases were smaller. It should be noted that the effects of absorbing aerosols have not been included in this analysis because the satellite sensors do not adequately probe the lower-most regions of the atmosphere. Thus, the estimates are insensitive to changes in pollution in the boundary layer (approximately the lower-most kilometre) of the atmosphere. This means that, while the results are applicable for zonal averages, they may not be applicable in regions where there are heavy concentrations of absorbing aerosols and air pollutants that change with time. Furthermore, in some regions there can be large longitudinal variations in ozone trends,[18] which would in turn affect the longitudinal variability in UV trends. Consequently, the changes in Fig. 1 may not apply in specific regions, particularly urban areas.

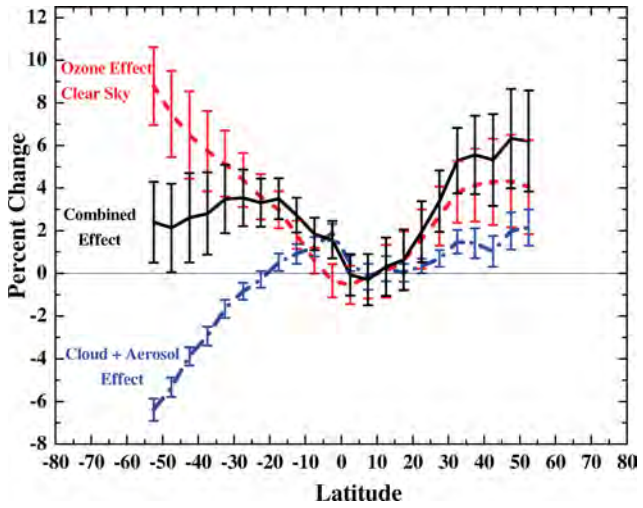

Fig. 1 Change in erythemal irradiance as a function of latitude between 55°S and 55°N (negative values of latitude for southern hemisphere) over the 30-year period from 1979 to 2008, estimated from satellite data. The red line (dashed) represents the change in clear-sky irradiance due to decreases in ozone; the blue line represents the change due to changes in clouds and non-absorbing aerosols, and the black line represents the combined effect. Adapted from ref. 15.

§ Erythemally-weighted UV (*i.e.*, "sunburning" irradiance, UV-Ery) is the irradiance weighted by the erythema action spectrum (see Fig. 6). This is often reported to the public in terms of the UV Index (UVI) where UVI = 40 × UV-Ery (W m^{-2}). For clear skies it can be approximately estimated[13] from UVI = 12.5(cos(SZA))$^{2.42}$(O_3/300)$^{-1.23}$, where O_3 is the total ozone column amount in DU and SZA is the solar zenith angle.

In the above study, as in most other studies of this type, estimates of UV irradiance are based on data from polar-orbiting satellites, which typically have only one overpass per day. As a result, no information on diurnal variability is provided, and there are significant uncertainties in the estimated daily doses (integrated UV irradiance during a day). Following earlier attempts to use data from geostationary satellites to estimate effects of clouds in Europe,[19] a new algorithm has been developed to estimate diurnally-varying spectral irradiance of UV at the surface over North America based on information (*e.g.*, cloud, surface albedo and aerosol data) from such satellites.[20] The results show reasonable agreement between the satellite data and ground-based observations from the US Department of Agriculture UV-monitoring network (bias within ±3.5% and root mean square differences of between 14 and 25%). The use of detailed information on cloud cover from geostationary satellites will improve the estimation of daily doses of UV, which are more relevant for effects that depend on accumulated UV.

Ground-based studies

There were few long-term records of UV radiation from ground-based instruments prior to the era of satellite measurements. The first co-ordinated ground-based networks were established in the 1970s,[21] but their geographical coverage was limited during the period of most-rapid depletion of ozone prior to the 1990s. Furthermore, in some cases, the wavelength response of the instruments was such that they were not particularly sensitive to changes in the amount of ozone, and the UV irradiances were more strongly affected by changes in other factors, such as clouds and aerosols. Consequently, the expected increase in UV radiation attributable to ozone depletion was not well established by direct measurements of surface UV radiation. Significant increases in UV irradiance have been observed from the United States National Science Foundation's UV spectroradiometer network in Antarctica,[22] where ozone depletion has been substantial. However, because ozone depletion had started well before the deployment of these instruments, the full extent of the changes in UV-B could not be fully documented. Model calculations suggest that in some cases, the peak UV-B irradiances would have doubled since the pre-1980 era, and current values in spring are

approximately twice as large as corresponding values in the Arctic where ozone depletion has been less severe.[6,23]

Long-term changes in observed UV irradiance at the surface vary geographically, and are not always in response to ozone changes alone. In some locations, the response of UV radiation to the beginning of an ozone recovery is apparent, but in other places UV radiation is still increasing. Since the mid 1990s, mean annual changes in UV-Ery within the United States Department of Agriculture's UV Network ranged from –0.5% to +0.2% per year,[24] although in most of these cases the trends for individual months were not statistically significant. Over the measurement period of about one decade, there was a general increase in ozone, suggesting that changing cloud, aerosol, air pollution and snow conditions were also important determinants of variability in surface radiation in addition to ozone changes. At Belsk, Poland, although an increase in column ozone occurred between 1995 and 2006, UV-B did not decrease, but instead tended to level off.[25] Such variations could arise from differences in the changes in clouds and aerosols among the measurement sites, as discussed further below. The results of UV measurements and reconstructions have been compared in a comprehensive study in Europe. Eight sites were involved, and the study included an attribution of the changes in UV to ozone and clouds.[26] At some sites, records of UV were reconstructed from the 1960s to the present. Upward trends in UV were observed from 1980 to mid-1990s for most sites. However, UV irradiances in the 1980s, before ozone depletion became apparent at these sites, were also low compared with the long-term average. Year-to-year variability was also large, but there was a strong commonality in the long-term changes between the sites, indicating that widespread regional effects are important. Attribution of the observed changes between ozone and cloud effects shows that the low irradiances in the 1980s were primarily a cloud/aerosol effect. The largest effects from ozone generally occurred in the 1990s (see Fig. 2). The eruption of Mt

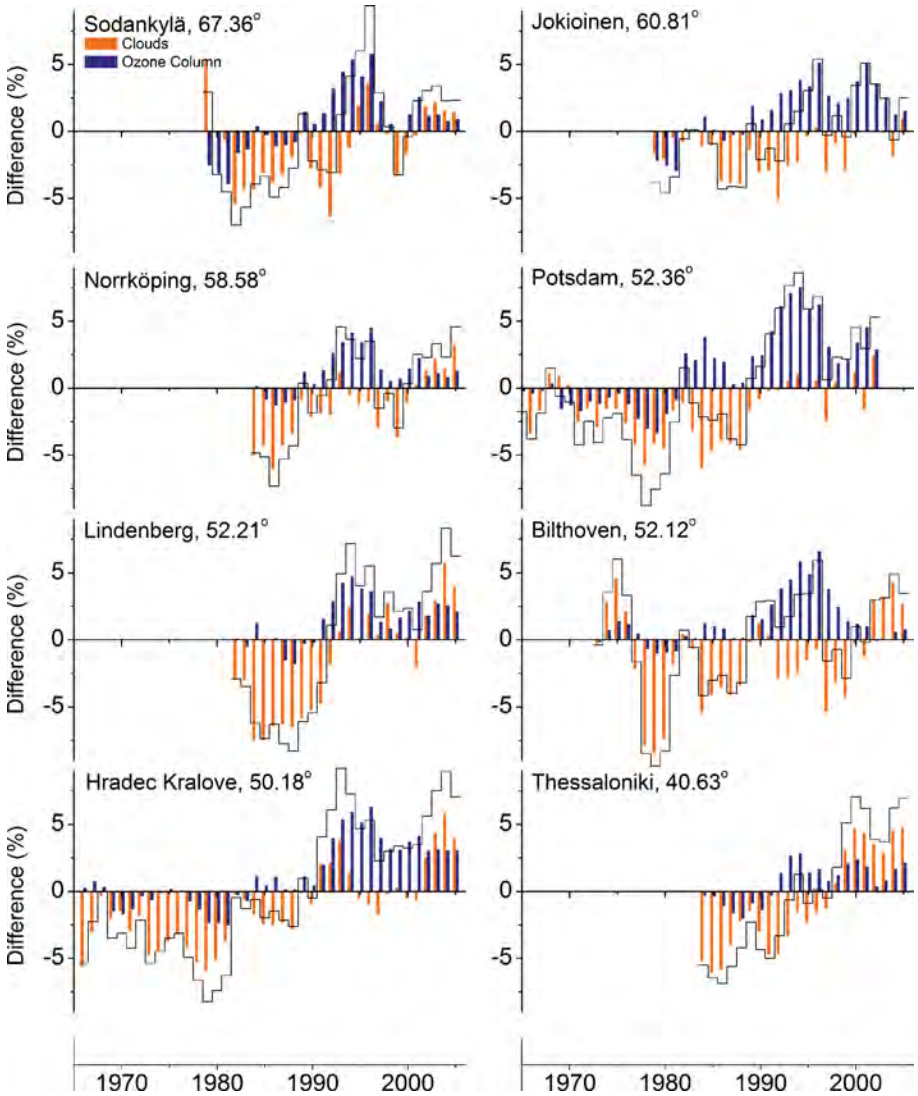

Fig. 2 The long-term impacts of ozone and clouds (including aerosols) on UV-Ery have been estimated separately at eight European sites by comparing the UV-Ery derived from measurements at each site with that derived from model calculations using the climatological ozone record. The step lines show the combined effect of clouds and ozone on UV-Ery. All estimates, expressed as differences from the long-term mean over the period of observations at each site, have been smoothed first by a three-year running average. Adapted from ref. 26.

Pinatubo in 1991 had an important contribution to the changes in the mid-1990s, through reducing the ozone amounts (tending to increase UV) and increasing aerosol extinctions (tending to decrease UV). As discussed further below, these results for Europe cannot be extrapolated to other regions, as there are strong regional differences in the patterns in long-term changes in cloud cover.[27]

Biological proxies to measure UV

In the absence of direct measurements over longer periods, attempts have been made to use biological proxies to estimate past changes in UV radiation. For example, changes in the concentration of compounds in plant spore walls have been used to estimate changes in UV at several sites over a wide range of latitudes since 1960,[28] and studies are in progress to determine whether similar changes in fossilized plants and in pollen can be used to estimate past UV.[29] However, the ratio between two UV protective substances, as a proxy for UV-B, showed no correlation with either sunspot activity or volcanic eruptions.[30] In another study, the concentrations of a different UV-protective substance in herbarium samples of a liverwort (a moss-like plant) were investigated as a proxy for UV-B. However, no trend was found over the years 1850–2006.[31]

Further studies have been carried out to investigate the association between UV radiation and the concentration of protective compounds (flavonoids) in Antarctic mosses.[32] Measurements taken since the 1970s, spanning periods before and after the onset of Antarctic ozone depletion, reveal significant negative correlations between measured ozone amounts and the concentration of flavonoids, suggesting that these herbarium specimens may reveal historical UV-B radiation. However, factors other than ozone, such as changes in cloud cover and distribution in the locations of samples, may have had a significant influence on the UV exposures received.

A spore dosimetry method has been used to investigate relationships and trends of biologically effective doses of solar UV radiation in Asia, Europe and South America from 1999 to 2007.[33] However, the changes in UV deduced using these dosimeters is much larger than expected from changes in ozone over the same period, suggesting that there may be other factors that are not yet accounted for properly.

Effects on UV of air pollution, aerosols and clouds

Regional effects

Cloud cover and transmission can vary appreciably as a function of geography and topography, leading to significant differences in UV for sites at similar latitudes.

Large reductions in surface UV irradiance have been observed at polluted locations compared to pristine locations, caused by aerosols in the boundary layer, by differences in the profile of ozone, and by interactions between ozone and aerosols in the lower atmosphere.[34–36] Naturally-occurring aerosols (*e.g.*, Saharan dust, aerosols from wild fires or emissions of volatile organic compounds) have been shown to cause substantial reductions in UV-B radiation, far from their source regions.[37]

In urban areas, the effects of pollution on UV can be large. A recent study quantified the contributions to differences in UV irradiances between a site with pristine conditions (Lauder, New Zealand) and a megacity (Tokyo, Japan).[36] For a given solar elevation, irradiances were much greater at the pristine site, particularly in the summer months. Parts of the differences are attributable to well-known effects, including seasonal differences in Sun–Earth separation, and differences in stratospheric ozone. Blocking of solar radiation by buildings was also significant in the city, as was, on some occasions, absorption of UV-A by NO_2 and of UV-B by SO_2. Significant reductions in UV radiation by NO_2 have also been observed in Moscow.[38] Co-located measurements of UV-B irradiance and aerosol optical characteristics in a relatively polluted environment, in Pune, western India, revealed a reduction in UV-B by ~50% per unit increase in the aerosol optical depth¶ measured at 0.4 μm.[39]

These effects on UV radiation of aerosols and pollutants in the boundary layer air can seriously compromise the accuracy of retrieval of surface UV radiation from satellite-based measurements, which generally use back-scattered solar ultraviolet radiation. A large part of the radiation that is back-scattered near the surface and contains information on absorption from aerosols cannot reach the satellite sensor. These instruments therefore tend to overestimate the UV irradiance at the surface under polluted conditions.[34,40,41] A new approach for correction of satellite-derived UV irradiance estimates, using climatological fields of aerosol absorption optical depth from a global ground-based network and a model, has recently been reported.[42] Although the corrected values are in better agreement with measurements, a significant bias remains.

Global dimming and brightening effects

In addition to local pollution effects, UV irradiances are affected at regional or even global scales by effects such as "global dimming and brightening". Widespread deployment of instruments to measure broad-band global irradiance began in the mid 20th century, and has resulted in valuable data on decadal changes in solar radiation. Recent analysis has made it clear that many regions experienced reductions in global irradiance up to the 1980s, followed by a reversal thereafter.[43,44] The causes of these changes may vary from region to region and may include long-term changes in extinctions from aerosols (from anthropogenic pollution[45,46]), volcanic eruptions,[47] or cloud cover.[43] Changes in clouds and aerosols may themselves be influenced by climate change, as discussed further below.

In the northern hemisphere, apart from some regions in Asia,[46,48] there has been widespread brightening in recent decades, due to reductions in air pollutants, aerosols and clouds, but this tendency has been less pronounced since 2000. Analysis of satellite data over Europe also shows an increase in transmittance of solar radiation between 1987 and 2002.[49]

The effects of both dimming and brightening are likely to be larger at UV wavelengths. Long-term increases in the concentrations of aerosols since pre-industrial times probably contributed

¶ The optical depth of aerosols (AOD) is a measure of the reduction in direct beam irradiance due to the presence of the aerosols, and depends on the wavelength. If the AOD at a given wavelength is unity (1), then the direct beam is attenuated by the factor $1/e = 0.368$.

to reductions in UV radiation at the surface in more densely populated regions (*e.g.*, Europe) from well before the time when UV measurements were routinely available. It has been estimated that the aerosol optical depth, at wavelength 550 nm, has increased by about 20% since pre-industrial times,[50] which could have led to significant decreases of UV-B radiation. Another study has estimated that there may have been a reduction in annual mean UV of up to 20% since 1750 in some industrialized regions.[51]

Changes in UV radiation due to changes in aerosol optical depth observed in Thessaloniki, Greece, over the period 1997–2005, have been consistent with the broad trends.[52] A recent update[53] reported a decrease of ~7% per decade in aerosol optical depth and an increase of ~9% per decade in UV-B irradiance over the period 1991–2006. At another site (Moscow) the weak spectral dependence observed in the changes of UV irradiance implies that they are due to changes in clouds and aerosols rather than ozone.[54] If those recent trends in atmospheric transmittance continue, that would imply that the UV radiation in these regions may not yet have reached its peak.

The longer term reductions in UV from anthropogenic pollution prior to the 1980s are probably larger than any increases due to the more recent depletion of stratospheric ozone. Effects from aerosols in the future are uncertain. Significant increases in the background optical depth of stratospheric aerosols have been observed over the past two decades from Mauna Loa Observatory in the remote Pacific.[55] These have been ascribed to increased pollution originating in Asia, but the changes in aerosol extinctions have not yet had a significant impact on UV irradiances at that site.

Important differences in cloud effects between northern hemisphere and southern hemisphere sites have been identified from measurements of UV spectral irradiance. For example, it has been shown, using data from multiple sites, that the effects of cloud cover on UV are smaller in New Zealand than at corresponding latitudes in Europe.[56] However, based on global satellite data (including the oceans) the southern hemisphere appears to be generally cloudier overall, with a reduced frequency of clear-sky occurrences, than corresponding northern hemisphere locations.[57]

The Montreal Protocol

Past successes and expectations for the future

The Montreal Protocol continues to be effective in protecting the stratospheric ozone layer. However, the timing of the return to pre-1980 ozone and UV values cannot yet be predicted precisely. The concentrations of ODSs are decreasing, and the concentrations of replacement chemicals are increasing.[58,59] Stratospheric ozone is no longer decreasing and in some cases there is evidence for an increase. A European study[60] showed that at mid-latitudes in the northern hemisphere and in the Arctic there was an almost monotonic negative trend in ozone from the late 1970s to the mid 1990s followed by an increase, as expected from the changes in ODSs, which peaked in 1997. Improved models that include better estimates of atmospheric circulation predict a slightly faster ozone layer recovery at mid latitudes, and a slightly slower recovery at high latitudes compared with results from earlier models.[61] Unfortunately, few high-quality long-term measurements are available to monitor the effectiveness of the Montreal Protocol in terms of UV radiation received at Earth's surface.

Attribution of changes in ozone to the Montreal Protocol

In the past it has been argued that at least part of the recently-observed reductions in the decline of ozone may in fact be the result of changes in atmospheric circulation,[60] rather than the result of reductions in the concentrations of ODSs due to the Montreal Protocol. Although the slowdown of ozone depletion may be statistically significant at northern mid-latitudes, it was argued that the attribution of the levelling off of ozone column amounts due to reductions of chlorine and bromine in the stratosphere has not yet been verified.[62] However, it has recently been shown, using ground-based measurements of ozone vertical profiles, that the increases in ozone detected at higher regions in the stratosphere (above 40 km) – where chemical effects outweigh dynamical effects – are consistent with changes in ODSs resulting from the Montreal Protocol.[63]

In most regions, any recovery in total ozone column amounts is not yet statistically significant. The recovery should be detectable earlier at southern middle- and high-subpolar latitudes where changes are larger, and the natural ozone variability is smaller.[64] A study of ozone variabilities in the Antarctic vortex region, where ozone is affected by both chemical and dynamical processes,[65] reported that, in this region at least, decreases in the concentrations of stratospheric halogens are the primary cause of the recent reduction in the rate of decline of ozone amounts.

In the northern temperate zone, the long-term globally averaged trends in total ozone derived from 50–60 stations range from about –2% per decade in the late 1980s to around +1% per decade by the start of the 21st century.[66] Analysis of height-resolved data showed that nearly half of the increase in total ozone is due to increases in the lower stratosphere, with the troposphere contributing only about 5% of the decadal change, which is consistent with expectations based on the Montreal Protocol.

Full attribution of changes in total ozone or in ozone profiles to changes in ODS abundances resulting from the Montreal Protocol remains problematic due to observational uncertainty and natural variability as discussed in the Science Assessment.[6]

Effect on global warming

In addition to its effectiveness in the reduction of ODSs, the Montreal Protocol has also reduced global warming. This arises because the Global Warming Potential (GWP = 1 for CO_2) of the replacements is less than that of the original CFCs. For example, the GWPs of CFC-11 and CFC-12 are 3800 and 8100, respectively, while the GWP for HCFC-22 (a major replacement), is 1500.[67] Model calculations indicate that the climate protection already achieved through the Montreal Protocol alone is larger than the reduction target of the first commitment period of the Kyoto Protocol (ending 2012).[68] In fact, without the Montreal Protocol, the radiative forcing due to increasing chlorofluorocarbons (CFCs) over the period 1990 to 2020 would have been comparable with that due to increasing GHGs. The reduction in radiative forcing from the phase-out of CFCs far exceeds that from the measures taken under the Kyoto protocol for the reduction of emissions of GHGs. It has been estimated that the cooling effect at Earth's surface due

to the phase-out of ODSs is approximately equal to the warming effect due to increasing GHGs at least through the first two decades of the 21st century.[68] Thus, the Montreal Protocol has succeeded not only in reducing the content of chlorine in the atmosphere, but has also reduced global warming. The replacement halocarbons now in use are also GHGs, so they continue to add to global warming but to a lesser extent than the ODSs they replaced.[69] At polar latitudes in both hemispheres, climate feedback effects from ozone depletion could have led to a warmer surface by up to ~1 °C in some locations,[70] but a cooler surface in others.[71] Within the atmosphere substantial regional differences would have occurred at different altitudes due to changes in circulation: some regions would have warmed up to 3 °C (middle stratosphere over Antarctica), while others would have cooled up to 6 °C (upper stratosphere over mid latitudes).[70]

The world avoided

A future scenario in which ODSs were not regulated and production grew at an annual rate of 3% in a study of the "world avoided" was simulated by the success of the Montreal Protocol.[72] By 2020, 17% of the globally-averaged column ozone in 1980 would have been destroyed, with depletion increasing to more than 60% by 2060 (Table 1). Decreases in stratospheric ozone due to increasing CFCs would have led to a marked increase in UV irradiance, with the UV index (UVI, see glossary) at northern mid-latitude summer tripling by 2065 (see Fig. 3). 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, including in the summer months. However, this simulation did not include tropospheric chemical processes and, in case of the large ozone depletions predicted, the increased penetration of UV into the troposphere could have resulted in an increase in ozone in that region (*i.e.*, the so-called "self-healing" effect), which could have ameliorated some of these projected decreases.

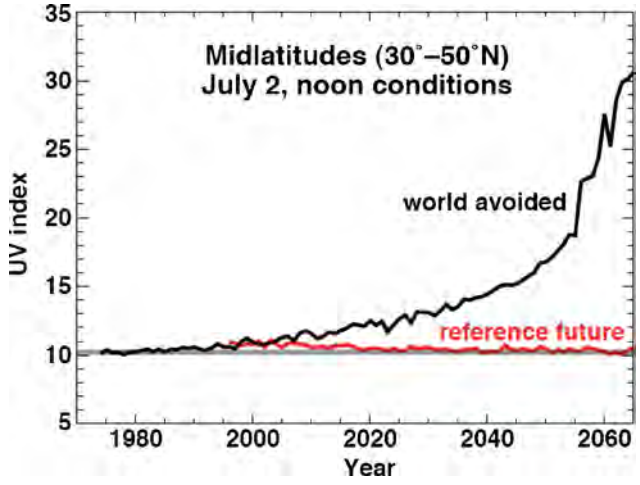

Fig. 3 UV index for clear skies predicted by a climate-chemistry model *versus* year for two future scenarios: (black curve) the "world avoided" by implementing the Montreal Protocol, and (red curve) a "reference future", calculated using the observed and currently predicted chlorine concentrations. The UV index is calculated using the July 30–50°N zonal-mean ozone, and for local noon on 2 July. The horizontal grey line shows the 1975–1985 average from the fixed chlorine simulation. Adapted from ref. 72.

Table 1 Estimated ODS concentrations (EESC, defined in glossary), annual global mean column ozone, and the peak UV index at 40°N that would have occurred in 1980, 2020, 2040 and 2065 if the Montreal Protocol had not been implemented.[72]

	1980	2020	2040	2065
EESC (ppbv)	2	11.5	20	40
O_3 (DU)	310	250	220	100
UVI_{max}	10	12.5	15	30

Future uncertainties

The largest uncertainties in estimating future ozone result from interactions with climate change, as discussed in more detail below. Other uncertainties include the continued political will to comply with the Montreal Protocol, unexpected volcanic eruptions, and unexpected developments in our understanding of the atmospheric processes involved.

The precise quantitative contribution of very short-lived bromine compounds to lower stratospheric ozone depletion also remains uncertain.[73] Furthermore, larger amounts of ODSs than previously estimated are now thought to be contained in existing storage banks (*i.e.*, repositories for CFCs), and a large proportion of these ODSs may eventually be released into the atmosphere, where they will continue to destroy ozone.[74]

Ozone depletion from anthropogenic oxides of nitrogen is also likely to be more important in the future as the concentrations of atmospheric chlorine decline.[75] The ozone depletion potential of N_2O, a greenhouse gas that is emitted from soils, was recently estimated. It was shown that by the middle of the 21st century, N_2O will be the major ozone-depleting gas.[76]

Thus, although the Montreal Protocol has succeeded in controlling most of the ODSs, remaining uncertainties in threats to the ozone layer and climate change mean that potential changes in surface UV radiation are still a matter of concern.

Interactions with climate change

Scientifically, and at political and policy levels, there are strong links between the depletion of ozone and climate change. The Kyoto Protocol on climate change has similarities with the successful Montreal Protocol. However, addressing climate change is much more complicated than the phase-out of ODSs.[67]

There has been an increased focus on understanding physical interactions between ozone depletion and climate change. These are more complex than previously thought (see also Ballaré *et al.*,[77] Häder *et al.*,[78] Zepp *et al.*,[79] and Tang *et al.*[78]). They can work in both directions: changes in ozone can induce changes in climate, and *vice versa*. Changes in climate can also induce changes in UV radiation without affecting ozone. Thus, the return of ozone (or UV) to its value at any particular date in the past should not necessarily be interpreted as a recovery from the effects of ODSs.[80]

Impacts of ozone depletion on climate change

As noted earlier,[68] the Montreal Protocol has helped to mitigate effects caused by the increases in the main GHGs (*i.e.*, CO_2, CH_4

and N_2O). However, on the negative side, future reductions in GHGs arising from this Montreal Protocol "windfall" will be slower, leading to more rapidly increasing climate impacts from the main GHGs in the future. Further, the concentrations of hydrofluorocarbons (HFCs), which are replacements for CFCs and are also GHGs, are increasing rapidly. By 2050, the increased climate forcing from these HFCs will exceed the reduction in climate forcing due to the phase-out of CFCs.[81] It has been suggested that rapid action to curb further emissions of HFCs may be among the most effective means of limiting climate change in the next few decades.[82]

In recent decades, increases in Antarctic temperatures may have been suppressed by changes in stratospheric ozone affecting wind patterns even at locations in the northern hemisphere,[83] so that melting of the west Antarctic ice sheet may proceed faster in future decades, as stratospheric ozone recovers.[84] The effects of changes in stratospheric chemistry and circulation associated with ozone recovery have not been included in all models used in previous assessments of climate change,[85] although these effects have been investigated together in the most recent Scientific Assessment of Ozone Depletion.[6] Improved predictions of climate change should be achieved by extending the upper boundary of climate models to include the stratosphere.

For accurate prediction of future changes in climate, all forcing agents must be included, rather than the principal GHGs alone. These forcing agents should include changes in ozone with altitude[86] and longitude,[87] changes in the mixtures and concentrations of ODSs,[88] and changes in aerosols.[89] For example, climate models that include stratospheric chemistry predict that the observed increase in westerly winds at southern high latitudes will not continue, as previously thought, but will decrease in the next few decades as ozone recovers.[90]

Impacts of climate change on stratospheric ozone and UV radiation

Changes in different components of the earth-atmosphere system due to global warming may affect ozone and UV radiation. The changes in UV may be a direct consequence of the changes in ozone, or they may be due to changes in other factors such as changes in aerosols, clouds, or surface reflectance. The extent of sea-ice in the Arctic is decreasing rapidly due to global warming and models suggest that ice cover in summer will disappear within the next few decades.[91,92] The reduced surface albedo may have important implications for future climate by increasing the fraction of solar energy that is absorbed at Earth's surface. Furthermore, organisms that were once living below the ice will be exposed to increased doses of UV, but organisms living above the surface will receive lower doses of UV due to the reduced reflectivity. It has been postulated that reductions in Arctic sea-ice resulting from climate change could also lead to significant reductions in ozone and associated increases in UV due to changes in atmospheric circulation.[93]

As discussed further elsewhere,[6] increases in GHGs are expected to influence future changes in ozone. For example, as noted previously,[5] outside polar regions, decreased stratospheric temperatures that result from climate change are expected to slow down the rate of chemical destruction of ozone, and so aid ozone recovery. However, in polar regions the decreased stratospheric temperatures can lead to increased areas of polar stratospheric clouds, which provide surfaces for rapid ozone loss, and therefore inhibit ozone recovery.[94] Most models also predict that by the end of the 21st century ozone amounts will be significantly greater than they were in 1980, before the onset of anthropogenic depletion of ozone.[80,95] However, changes in atmospheric circulation resulting from climate change can induce regional differences in ozone, leading to increases in UV in some regions and reductions in other regions.[96]

It has been suggested that global warming could be counteracted by injection of sulfur compounds directly into the stratosphere to produce aerosols that reflect incoming solar radiation back to space. A secondary effect of this strategy would be the direct reduction of UV radiation reaching the surface due to extinction by these aerosols. However, this geo-engineering strategy would increase Arctic ozone depletion during the 21st century and delay Antarctic ozone recovery by 30 to 70 years.[97] Other geo-engineering schemes have also been suggested. However, because the atmosphere is a complex system, any deliberate interventions should be treated with great care as they may have unanticipated adverse effects.

Future changes in UV

Changes in UV radiation in the future are estimated by model simulations that are based on the projected changes in ozone and clouds, which are the most important factors that are known to influence UV. Because of the complex interactions between ozone depletion and climate change, particularly with regard to future changes in clouds and aerosols, continued monitoring of ozone and UV radiation will remain important. In particular, it will be necessary to maintain an extensive ground-based UV measurement capability to enable us to confirm whether the measures taken under the Montreal Protocol continue to be effective, and whether the model predictions for the future are consistent with observations.

Projected changes in clear-sky UV

New simulations have been carried out using coupled Chemistry-Climate Models (CCM), incorporating projected changes in total ozone columns and vertical profiles of ozone and temperature. One such study[98] reported that clear-sky surface erythemal irradiance would decrease over mid-latitudes by 5 to 15% over the 21st century, while at southern high latitudes the decrease would be twice as much. Surface erythemal irradiance was projected to decrease globally at somewhat higher rates in the first half of the 21st century and more slowly later on. This decreasing tendency would be more pronounced over latitudes where stratospheric ozone depletion was largest.[99] Another simulation[98] for the period 1980–2080 found that a reduction of UV to values similar to those in 1980 would be achieved before the mid-century at most latitudes, but because of the continued increase of ozone thereafter, UV would continue to decrease. By 2080, erythemally-weighted irradiances would be on average 25% lower at high latitudes and 10% lower at mid-latitudes. These estimates have appreciable uncertainties, ranging from about 3% at mid latitudes to about 5% at high latitudes. For some weighting functions (*e.g.*, DNA-damage) the changes are larger.

Fig. 4 shows the projected annually averaged changes in clear-sky UV-Ery from 1960 to 2100 relative to 1980,[6,100] based on projected changes in ozone from 15 models. These new simulations show that UV-Ery is projected to return to its 1980 values in the early 2020s at northern latitudes, with a slower return in the southern hemisphere, especially over Antarctica. These return dates are significantly earlier than reported in the previous assessment. UV-Ery is projected to continue to decrease thereafter, except at low latitudes where a small increase is projected. However, there is a wide range in return dates between the models. These studies do not take into account the potentially important changes in cloudiness, surface reflectivity, and tropospheric aerosol loading due to or additional to climate change. The projected return date for annual mean UV to 1980 levels occurs a few years earlier than for ozone, which is projected to return to its 1980 levels earlier for the summer months when UV high, than for the winter months when UV is low.

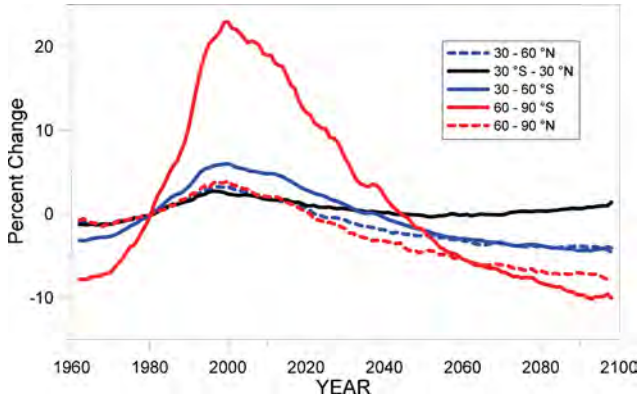

Fig. 4 Time series of projected changes in annual mean of noon-time clear-sky erythemally-weighted UV over the period 1960 to 2100, relative to 1980, smoothed with a five-year running mean. Results are zonal means for several latitude belts. Updated from ref. 5 and 96.

Another atmospheric chemistry-climate model has been used to isolate the effects of climate change from those of ozone depletion and recovery on clear-sky UV-Ery.[96] Under the "moderate" emissions scenario (designated AB1) of the Intergovernmental Panel on Climate Change,[67] tropospheric ozone increases markedly between 1965 and 2095 as a result of changes in atmospheric circulation induced by climate change. The overall change varies with location and season. The predicted decrease in UV-Ery of 9% in northern high latitudes is a much larger effect than that due to stratospheric ozone recovery alone. In the tropics, clear-sky UV-Ery is predicted to increase by 4%; and in southern high latitudes in late spring and early summer by up to 20%. The latter increase is equivalent to nearly half of that generated by the Antarctic 'ozone hole'. The results suggest that climate change will alter the tropospheric ozone budget and UV radiation at the surface, with consequences for tropospheric temperatures, air quality, and human and ecosystem health.

Projected effects of cloud changes on UV

Although clouds have large effects on UV, there has been only limited progress in forecasting future cloud prevalence or characteristics, or in calculating the detailed radiative effects of realistic cloud situations. It is uncertain whether the radiative effects of clouds in the future will be greater or less than at present. A recent modelling study suggests that, in response to climate change, cloud cover will increase at high latitudes by up to 5% but will decrease at low latitudes (<~30°) by up to 3%.[101] If this prediction is correct, there could be important implications for human health, the local ecosystems, biogeochemical cycles and air quality, since UV radiation would increase at low latitudes where it is already high, but decrease at high latitudes where it is already low. The already large latitudinal gradients in UV radiation will become even larger. However, these modelled cloud effects have not yet been verified against observed effects, and large uncertainties remain.

New simulations with 15 different CCMs have provided more robust predictions of ozone, and 4 of these models also provided estimates of future surface solar irradiance both under clear-skies and for cloud-affected conditions.[102]

When the effects of projected changes in clouds are included, a further reduction in UV-Ery of about 2% is calculated for mid-latitudes. In the tropics, UV is projected not to return to its levels in 1980. Although UV is projected to decrease at all latitudes during the 21st century, in the tropics this decrease is smaller and lasts only until the middle of the century. Thereafter, low latitude UV-Ery increases in response to the projected decreases in ozone due to the acceleration of the large scale atmospheric transport (specifically, the 'Brewer–Dobson' circulation).[88] Although the magnitude of this increase due to ozone is small (on average 2%) compared to the changes projected for the higher latitudes, the inclusion of clouds in the calculations results in an additional increase in UV-Ery of between 3 and 6% at low latitudes (see Fig. 5). This additional increase in a region where UV-Ery is already high would increase the risk of adverse effects on ecosystems and human health.

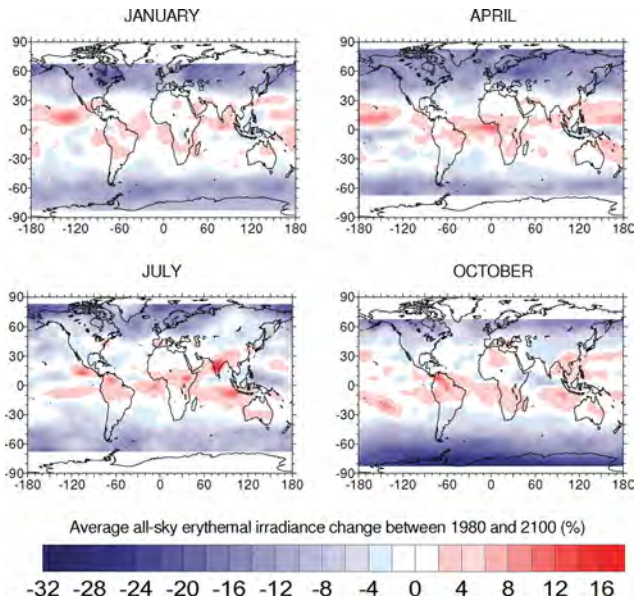

Fig. 5 Multi-model average changes in surface erythemal irradiance from 1980 (1975–1985) to 2100 (2089–2099) under all-sky conditions for four months, calculated with a radiative transfer model using projections of ozone, cloudiness, temperature and solar radiation from 15 different CCM runs. Updated from ref. 99 and 100. Note the seasonally-dependent bands of missing data at high latitudes.

At high latitudes, especially in the Arctic spring, increasing cloudiness is expected to further reduce the UV irradiance at the surface. While changes in ozone are responsible for a reduction in UV-Ery of up to ~10%, the increases in cloud cover predicted by the models produce a further reduction in UV-Ery of ~10%. Reduced surface albedo due to decreases in the extent of sea ice during the 21st century will further amplify these reductions in UV at the surface (but increase UV below the sea surface that was formerly covered by ice). We note that the differences in the estimates among models are large, reducing confidence in these results. More work is needed to simulate future cloud changes with confidence.

The changes described in Fig. 4 and 5 are for erythemally-weighted UV irradiances. For other environmental effects, the influence of ozone differs, as described further below. However, the influences of changing cloud cover are similar for most environmental effects.

Biological relevance of ozone changes

Sensitivity of UV radiation to ozone changes

The damaging or beneficial effects of UV radiation often have a strong wavelength dependence, the effect being generally larger at shorter wavelengths. These effects are quantified using weighting functions, also called 'action spectra', which typically increase towards shorter wavelengths in the UV-B region. Examples of action spectra, illustrating their huge diversity, are shown in Fig. 6. Action spectra express the relative response at different wavelengths. To calculate physical effects, they are combined with a response in relevant units at the normalisation wavelength.

The relationship between change in total column ozone (O_3) and change in biologically effective UV irradiance (E) can be quantified in terms of the 'Radiation Amplification Factor' (RAF). For *small* changes in ozone, the RAF is defined as the relative fractional change in effective UV irradiance with fractional change in total column ozone: $\mathrm{RAF} = -(\Delta E/E)/(\Delta O_3/O_3)$where ΔE and ΔO_3 are the respective changes of UV irradiance (E) and ozone (O_3). For example, RAF = 1.5 means that a 1% decrease in ozone will lead to a 1.5% increase in effective UV. Processes with steeper action spectra are more sensitive to changes in ozone, and have larger RAFs (see Fig. 6). An earlier assessment[103] included a comprehensive list of RAFs for various action spectra available at that time. Since then, several new action spectra have become available. An updated list of RAFs for these, and for some commonly-used older action spectra, is tabulated below (Table 2). Note that uncertainties in the weighting functions can be large and these uncertainties propagate through to these RAFs. Therefore, differences in the RAFs, shown in Table 2, should not be over-interpreted.

As the effect of ozone on UV is non-linear, for larger changes in ozone, the power form should be used:[104]

$$E^+/E^- = (O_3^-/O_3^+)^{\mathrm{RAF}}$$

where the superscripts (+ and –) refer to the cases with higher or lower ozone amounts, respectively.

While the concept of RAF is a good approximation, it cannot generally be applied as a single value under all circumstances. It depends on all factors that may alter the shape of the irradiance

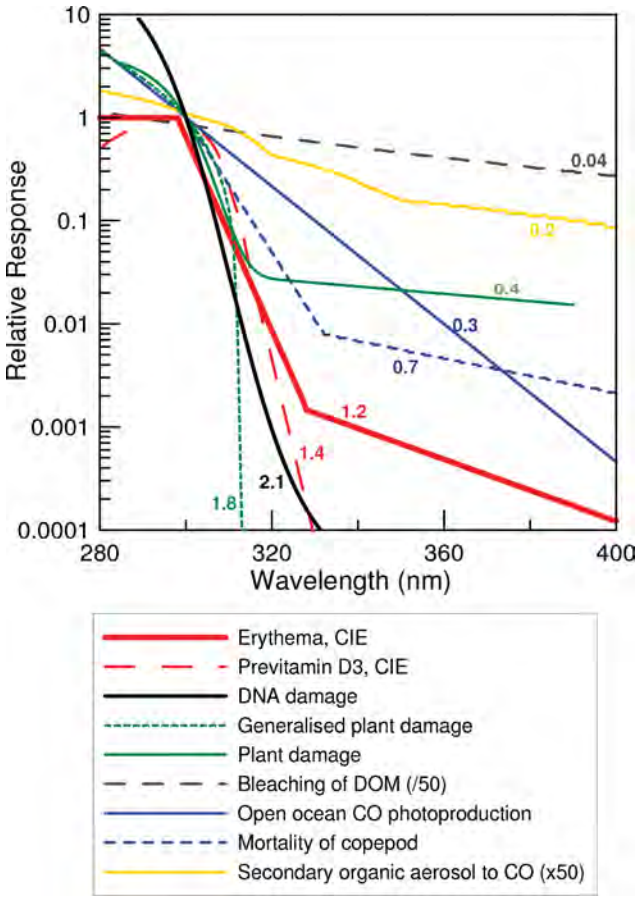

Fig. 6 Weighting functions for several of the UV-induced effects listed in Table 2. Curves are labelled by their summertime RAF and colour-coded according to the nature of the effect (*e.g.*, health effects in red). Note that the action spectra for bleaching of dissolved organic matter (DOM) and secondary organic aerosols have been scaled by 1/50 and 50, respectively, to bring their normalisation at 300 nm close to unity.

spectrum, the solar zenith angle (SZA) and the ozone column amount being particularly important. This dependency for the erythemal action spectrum is illustrated in Fig. 7. For SZAs

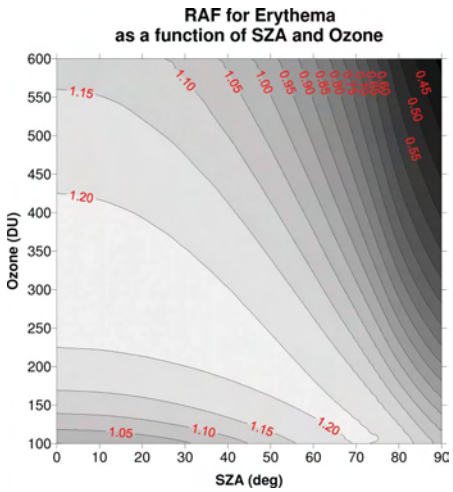

Fig. 7 The RAF for erythema,[105] calculated as a function of solar zenith angle and total ozone column amount.

Table 2 RAFs for action spectra calculated on the basis of daily integrals for latitude 30°N. This is an update of Table 1.1 in ref. 103

Effect	RAF Jan. (290 DU)	RAF July (305 DU)	Reference
Exponential decay (14 nm per decade)	1.00	1.01	—
UV-B (280–315 nm)	1.25	0.99	—
UV-A (315–400 nm)	0.03	0.02	—
Erythema (CIE, standard reference)	1.1	1.2	105
Erythema (from tuneable laser)	1.6	1.5	129
Squamous skin cancer in humans (SCUP)	1.2	1.2	130
US Industrial Safety Standard (ACGIH)	1.4	1.5	131
Cataract using whole pig lens	1.3	1.1	132
Visual sensitivity in insect	0.1	0.1	133
Previtamin D3 (CIE)	1.7	1.4	106
DNA damage (Setlow)	2.2	2.1	134
DNA damage in alfalfa	0.5	0.6	135
Generalised plant damage (Caldwell, truncated at 313 nm)	2.2	1.8	136
Plant damage (extended to 390 nm)	0.3	0.4	137
Phytoplankton *Phaeodactylum*	0.3	0.3	138
Phytoplankton *Prorocentrum*	0.4	0.4	138
Phytoplankton	0.8	0.8	139
Inhibition of photosynthesis in phytoplankton	0.3	0.3	140
Damage to freshwater cladoceran (*Daphnia*)	0.72	0.74	141
Bleaching of dissolved organic matter (DOM)	0.04	0.04	142
Baltic Sea photoammonification	0.2	0.2	143
Photoproduction of CO from tropical savanna litter	0.3	0.3	144
Coastal ocean biologically labile photoproduction	0.2	0.2	145
Open ocean CO photoproduction	0.3	0.3	146
Mortality of copepod *Boeckella gracilipes*	0.6	0.7	147
DNA damage in embryos of sea urchin	0.1–0.2	0.1–0.2	148
Inhibition of hypocotyl growth in *Arabidopsis*	1.6	1.3	149
Inhibition of photosynthesis in kelp (depth dependent)	0.1–0.4	0.1–0.4	150
Secondary organic aerosol to carbon monoxide	0.2	0.2	151
Secondary organic aerosol to formic acid	0.2	0.2	152
Material: PVC, 2.5% TiO_2, approximated as $\exp(-0.058\lambda)$	0.3	0.3	153
Material: Rigid sheets, approximated as $\exp(-0.082\lambda)$	0.4	0.4	154
Material: Mechanical pulp, approximated as $\exp(-0.110\lambda)$	0.08	0.08	155
$O_3 \rightarrow O_2 + O(^1D)$	1.5	1.4	156
$H_2O_2 \rightarrow 2OH$	0.3	0.3	156
$NO_2 \rightarrow NO + O(^3P)$	0.02	0.02	156
$HNO_3 \rightarrow OH + NO_2$	0.8	0.8	156
$NO_3^-(aq) \rightarrow NO_2(aq) + O^-$	0.6	0.5	156
$CH_2O \rightarrow H + HCO$	0.5	0.4	156
$CH_2O \rightarrow H_2 + CO$	0.2	0.1	156
$CH_3COCH_3 \rightarrow CH_3CO + CH_3$	1.5	1.5	156

between 0° and 50°, the RAF is 1.1 ± 0.1, but for larger than 50° SZA and large total ozone column amounts, resulting in strong absorption of radiation, the RAF for erythema gradually decreases. Limitations of the RAF and its application to other action spectra have been discussed in more detail elsewhere.[104]

Attempts to quantify the risks and benefits of UV radiation

Assessments prior to 2006[5] emphasized the risks of increased UV radiation, and gave little attention to benefits. However, in recent years there has been increased awareness of possible benefits. Therefore, future reductions in UV irradiance as the ozone layer recovers may not necessarily be beneficial in some regions, particularly if ozone returns to higher levels than prior to the 1980s. Significant reductions in UV could have implications for human health, and possibly other environmental effects. For human health, the main beneficial effect of UV radiation is through inducing the synthesis of vitamin D in the skin. Balancing the risks and benefits of solar UV radiation has become a challenge for policy-makers and health advisors.

The most important determinant of UV radiation at Earth's surface is the path length of the radiation through the atmosphere. Consequently, differences in sun angle are responsible for large latitudinal and seasonal variations in both beneficial and harmful UV. These changes differ in magnitude, depending on the relevant weighting functions. Compared with the action spectrum for erythema[105] which is used to calculate the UVI, the action spectrum for vitamin D production[106] is confined more to the UV-B region (see erythema and pre-vitamin D curves in Fig. 6). This affects the seasonal and diurnal variability. Thus at mid latitudes, the UVI at noon in winter is typically 1, which is only about 10% of its summer value. On the other hand, vitamin D-weighted UV radiation shows a summer/winter contrast that is approximately twice as large as that for UVI. In each case, the weighted irradiances decrease at higher latitudes, and the ratio between summer and winter values increases rapidly. Daily doses show more marked seasonal variations than peak noon values due to the longer daylight periods in summer and shorter daylight periods in winter.

Because of the success of the Montreal Protocol, increases in UV-B radiation due to ozone depletion have been modest in most populated regions of the world (*i.e.*, outside the regions affected by

the Antarctic ozone hole). Thus wintertime deficiencies in vitamin D production in mid and high latitude regions are unlikely to have been ameliorated (see Norval *et al.*[1]). Monthly climatological maps of the mean vitamin D-weighted UV radiation incident on a horizontal surface, and various other biological weightings, are now available,[27] and methods have been devised to estimate vitamin D-weighted UV from measurements of erythemal irradiance.[107,108] In many cases the biologically-relevant dose may differ appreciably from that on a horizontal surface. For non-horizontal surfaces the winter dose is increased significantly compared to horizontal surfaces, particularly under conditions of high surface albedo.[109] It should also be noted that the action spectra for the production of vitamin D and erythema published to date have large uncertainties, and may require revision in the future.[110] Both of these weighting functions include an arbitrary normalisation, so their magnitudes should not be interpreted in terms of direct health consequences.

The effective dose of vitamin D-weighted UV over 60 min around local noon has been calculated from spectral measurements at three European stations.[111] Seasonal and latitudinal differences between sites are very large (see Fig. 8). In summer, these noon doses at the lower latitude sites can be up to 250 times higher than in winter at higher latitudes. For some skin types, optimal vitamin D production is impractical for some months, especially at the high latitude sites. We emphasise that there is large uncertainty in determining the thresholds shown in Fig. 8 (shaded area). These uncertainties will likely be resolved as results from new studies become available.

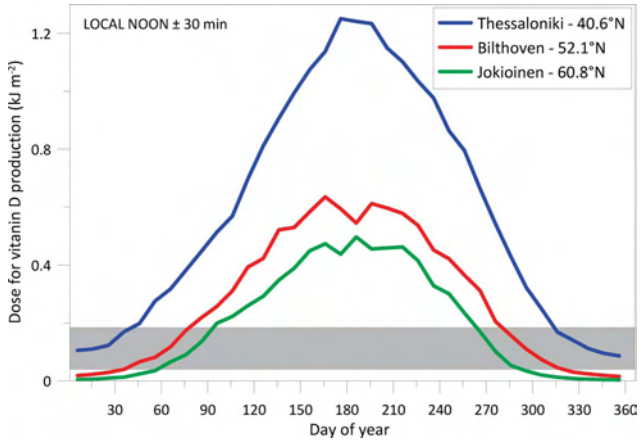

Fig. 8 Average vitamin D-weighted UV dose received on a horizontal surface exposed for 60 min centred at local noon at three sites. The shaded area represents the range of thresholds equivalent to 1000 IU vitamin D production for 25% of skin exposed according to ref. 157 for the full range of Fitzpatrick skin types (I–VI).[158] Adapted from ref. 111.

Measurements of spectral irradiance have been used to estimate the exposure times to optimize beneficial effects of UV while minimizing risks (see Fig. 9).[112] These calculations are for radiation falling on a horizontal surface. For more realistic surface geometries, the exposure times would tend to be longer at high UVI values (when the sun is high in the sky), and shorter at lower UVI values (when the sun is lower in the sky). Generally, there is a wide margin between UV insufficiency and damage; however, this is not the case for low UVI when little skin is exposed. Based on these

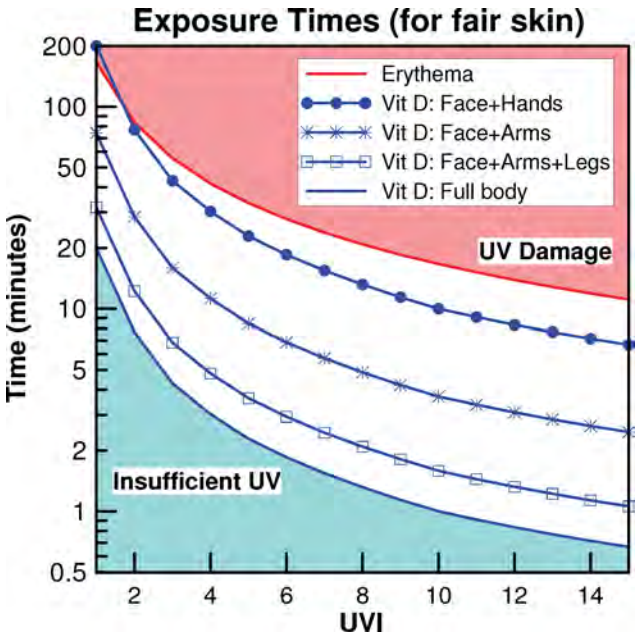

Fig. 9 Indicative exposure times for skin damage or for sufficient vitamin D production as functions of UVI, where 'sufficient' vitamin D production is taken as the time required to receive a dose equivalent to 1000 IU. The latter times depend on the area of skin exposed and both depend on the skin type. The curves are for fair skin (for which it has been assumed that 1 Minimum Erythemal Dose (MED) = 250 J m^{-2}). For highly susceptible individuals, the times for erythema could be shorter, while for darker skins these times could be up to ~5-times longer. Adapted from ref. 112.

calculations, for the present wintertime UV irradiances at mid-latitudes (~45°N or S), sufficient vitamin D should be produced in less than 1 h of full body exposure. However, this result is inconsistent with earlier findings that no vitamin D is produced at mid-latitudes in winter[113] and therefore suggests that there may be a problem with the currently accepted action spectrum for the production of vitamin D. The sensitivity of the vitamin D assay method for the earlier study[113] was rather low compared with modern techniques and more work is needed to resolve these inconsistencies. See Norval *et al.*[1] for further discussion on the vitamin D issue.

Personal exposure to UV radiation

The exposure of an individual to UV (personal exposure) can far exceed the thresholds recommended by health agencies, especially during summer vacation periods when the available daily dose received at mid-latitudes on a horizontal surface can exceed 70 standard erythemal doses (SED).[114] Even in Antarctica, where the sun elevation is smaller than at lower latitudes, UV exposures can approach that value. This is partly because of low ozone amounts and partly because of the long length of day and high surface albedo. A study of UV exposures of expeditioners on Antarctic resupply voyages was performed using polysulfone dosimetry over the summer, including the period of the springtime Antarctic 'ozone hole'. The median measured daily exposure was 3.2 SED and about 80% of the workers received more than the occupational exposure limits. At one of the sites (Casey, 66°S), peak UVI values sometimes exceeded 12. Some workers also reported mild erythema.[115]

The UV radiation received by an individual may be expressed in terms of the exposure ratio (ER) of erythemally-weighted dose received by a given part of the body and the available ambient dose incident on a horizontal surface. These ratios are usually expressed as percentages:

$$ER = 100\% \times ED_p/ED_a$$

where ED_a is the ambient erythemal dose, in SED, received on a horizontal surface (1 SED = 1 Standard Erythemal Dose = 100 J m^{-2} of erythemally-weighted irradiance),[116] and ED_p is the personal dose received by an individual, based on a measurement at a representative anatomical site. While this is a valid quantity for assessing skin damaging effects such as erythema, in other cases (*e.g.*, for assessing vitamin D production), a further scaling would be necessary to account for the proportion of uncovered skin.

Exposure ratios depend on lifestyle, but are usually very small. This may be beneficial for preventing skin damage, but may be detrimental for maintaining optimal vitamin D status.

A comprehensive study in Germany using polysulfone UV dosimeter badges concluded that the ER varies greatly between the anatomical body sites tested, but is typically ~2%.[117] In two studies in New Zealand using electronic dosimeters, an ER of ~5% was measured for primary school children,[118] and only reached ~20% for the population subset of outdoor workers.[119] Another study in Denmark using electronic personal UV dosimeters[120] appears to refute the widespread belief that most of our lifetime cumulative UV dose is received during childhood.[121]

However, in some population groups, exposure ratios can be much larger. A recent study, using polysulfone UV dosimeter badges, reported no significant differences in solar UV exposure on a specific anatomical site (chest) among three groups of Italian sunbathers: (1) healthy suntanned people, (2) healthy non-suntanned people and (3) people affected by abnormally high sensitivity to solar exposure.[122] The mean ER reported in the study was ~20%, and ranged from ~10 to ~40%. Another study, by the same group, on skiers at a high albedo alpine site found even higher ER values on the forehead, with a median ER of 60%, and sometimes even exceeding 100%.[123] However, large ER values are the exception rather than the rule for the wider population.

Prior to the industrial revolution, and especially before the widespread introduction of glass windows, these exposure ratios would have been much larger. For the glass material used in typical windows, the transmission falls below 10% for wavelengths less than 310 nm. Consequently, only 5–10% of sun-burning UV radiation and an even smaller fraction of vitamin D-weighted UV radiation are typically transmitted. However, the resulting reductions in UV exposure may have been negated by changes in clothing habits and the fashion to be tanned. In recent years, there has been a further trend towards more indoor vocational and recreational activities in everyday life, punctuated with only occasional exposures to high UV irradiances, for example during vacations.[124] To circumvent the difficulties in monitoring UV exposures, attempts have been made to develop behavioural models for estimating exposure to UV radiation for different population types.[125]

Gaps in our knowledge

At the present time, there are few reliable satellite-based measurements of atmospheric ozone, which are needed to estimate global patterns and variability in UV radiation. A continuation of reliable measurements – without gaps – is vitally important. Most current satellite sensors for estimating surface UV radiation do not adequately probe the lower troposphere (altitudes below ~5 km), so the method for deriving surface UV radiation is rather insensitive to changes in pollution in the boundary layer of the atmosphere.

Despite the few attempts to reconstruct past UV records, there is a large gap in our knowledge of past changes in UV on a global scale, and in particular the changes resulting from decreasing ozone over the latter part of the 20th century, especially prior to the satellite era.

Projections of future changes in UV radiation are uncertain, due mainly to the complexity in the projections of cloud and aerosol changes. It is therefore important to maintain a geographically wide-spread network of high-quality ground-based UV spectral measurements to determine if the measures taken under the Montreal Protocol are effective in moderating UV radiation, and if future model predictions are consistent with observations. Our ability to predict future changes in UV is limited by our inability to accurately predict future changes in clouds and pollution. Even if we were confident about changes in cloud cover, we are still limited in our ability to model their effects realistically. The inclusion of stratospheric processes (chemistry and circulation) in climate models would lead to more accurate predictions.

Knowledge about the ranges of both beneficial and detrimental effects of UV radiation is still incomplete. For many biological processes, including skin cancer or vitamin D production in humans, our ability to assess biological impacts is limited by incomplete knowledge of the relevant action spectra and the geometric conditions of exposure. Even the widely-used action spectrum for erythema is an idealization which may be inappropriate in many cases.

Finally, although the main focus of this assessment is on the long-term effects of ozone depletion, it is noted that ozone can also change over much shorter time scales,[126–128] and the biological impacts of the corresponding changes in UV may also be important. It is not known whether the frequency and severity of these events will change in future as a result of climate change. In many cases (including erythema and vitamin D production), threshold effects, recovery times, repair mechanisms, and linearities of the effects are not well established. Knowledge of reciprocity of effects is incomplete. For example, is the effect from an exposure to UV for a given period always equivalent to that from a UV source of one tenth the strength with an exposure period 10 times as long?

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