# Environmental effects of ozone depletion: 2006 assessment: interactions of ozone depletion and climate change
# Executive summary†

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## Ozone and UV changes

**• The Montreal Protocol is working. The concentrations of ozone depleting substances in the atmosphere are now decreasing**

Outside Polar Regions, the decline of ozone seen in the 1980s and 1990s has not continued. In Polar Regions, there is much higher variability. Each spring, large ozone holes continue to develop in Antarctica and less severe regions of depleted ozone continue to develop in the Arctic. There is evidence that some of these changes are driven by changes in atmospheric circulation rather than being solely attributable to reductions in ozone-depleting substances, which may indicate a linkage to climate change. Global ozone is still less than in the 1970s. Changes in ozone directly influence UV-B radiation, so elevated UV-B radiation due to reduced ozone is expected to continue.

**• The future evolution of atmospheric ozone remains uncertain. It is expected to increase slowly in the decades ahead, but it is not known whether it will return to higher, similar, or lower levels than those prior to the onset of ozone depletion**

Current chemical models are unable to reproduce accurately all of the observed ozone variability, the rates of future increases in greenhouse gases are not yet established, and interactions between ozone depletion and climate change are not yet fully understood. Current models predict that ozone will have recovered from the effects of man-made ozone-depleting gases by mid-century at mid-latitudes, and about 1–2 decades later at polar latitudes.

**• Long term responses in UV-B radiation caused by ozone changes have been observed**

Increases in UV-B irradiance have occurred over the period of ozone depletion. At unpolluted sites in the Southern Hemisphere, there is some evidence that UV-B irradiance has diminished since the late 1990s. Because of improvements in the availability and temporal extent of UV data we are now able to evaluate the changes in recent times compared with those estimated since the late 1920s, when ozone measurements first became available. The increases in UV-B radiation from about 1980 to the end of the 20th century have been larger than the long-term natural variability.

**• The effects of aerosols and air pollutants on long-term variations in UV-B irradiance may be comparable with those due to changes in ozone**

At some sites in the Northern Hemisphere, UV-B radiation may continue increasing because of the continuing reductions in the attenuation by aerosols since the 1990s despite the cessation of ozone depletion.

**• Interactions between ozone depletion and climate change are complex and can be mediated through changes in chemistry, radiation, and atmospheric circulation patterns**

The changes are in both directions: ozone changes affect climate, and climate changes affect ozone. Contrary to what was predicted from some models in previous assessments, more recent models and the observational evidence suggest that stratospheric ozone (and therefore UV-B radiation) has responded relatively quickly to changes in ozone depleting substances, implying that climate interactions have not delayed these responses.

**• There is greater uncertainty about future surface UV-B radiation than future ozone, since UV-B radiation will be additionally influenced by climate change**

Climate change can also affect UV-B radiation through changes in cloudiness, aerosols and surface reflectivity, without involving ozone. The rate of climate change is accelerating. Temperature changes over the 21st century are likely to be about 5 times greater than in the past century. This will affect future cloud, aerosol and surface reflectivity. Consequently, unless strong mitigation measures are undertaken with respect to climate change, profound effects on the biosphere and on the solar UV radiation received at the Earth's surface can be anticipated.

## Health

**• In addition to cortical cataract, nuclear cataract has been found to be associated with solar UV radiation**

Numerous studies have implicated exposure to solar UV radiation as a causative factor in the development of cortical cataract. Several reports now confirm an association between nuclear cataract and UV exposure. In addition, higher ambient temperatures may increase the risk of nuclear cataract development. In contrast,

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there is insufficient evidence to infer a causative role for solar UV radiation in the induction of posterior subcapsular cataract.

**• Exposure to sunlight is a significant risk factor for pterygium on the surface of the eye**

Pterygium is an inflammatory, proliferative and invasive lesion of the human cornea that can severely impair vision. It is induced, in part, by the intracellular damage caused by UV-B exposure. Genetic factors and the degree of long-term exposure to sunlight are important parameters for the development of pterygia in populations of all skin colours.

**• Adverse photobiological effects of UV radiation on the eye can be enhanced by the presence of clouds and are thus affected by climate change**

Although direct sunlight does not play a major role in acute solar photokeratitis (sunburn of the eye), or in cataract formation, scattered and reflected UV-B radiation contribute to these disorders. Under conditions of cloud cover and with lower light levels, the natural defence mechanisms of the eye are relaxed, permitting greater exposure of the anterior surface of the eye and its internal structures. At the same time, the effective UV-B exposure of the eye can be increased during cloud cover due to scatter.

**• The incidence of squamous cell carcinoma (SCC), basal cell carcinoma (BCC) and melanoma continues to rise**

Approximate doublings in the incidence of all three types of skin cancer have been projected in the Netherlands for the years 2000 to 2015 and in many other countries with predominantly fair-skinned populations. The major increase in melanoma incidence has been for thin (early) melanomas that have high survival rates. In children, the incidence of melanoma is still rising and has been positively correlated with environmental UV radiation exposure.

**• Susceptibility to skin cancer is increasingly recognised as being linked with subtle variations in genes that code for proteins involved in prevention and repair of DNA damage**

Such proteins function in defensive mechanisms that are crucial to the prevention of skin cancers. The relevance of certain gene variations differ between skin cancer types and these variations provide clues regarding the types of DNA damage and repair that are important in each of the skin cancer types. Thus, there is a wide range in the occult genetically determined susceptibility in a population. In the future, gene profiling may accurately identify high-risk individuals.

**• UV-induced immunosuppression is a crucial factor in the generation of skin cancers. In some subjects, this immunomodulation may lead to viral reactivation and a reduction in vaccine efficacy**

The lack of repair of UV-induced DNA damage decreases the resistance to skin cancers and is a significant factor in the generation of such tumours. By effects both on the virus itself and on suppression of immunity, solar UVR exposure can induce the reactivation of latent herpes simplex virus leading to the re-emergence of cold sores and can act as a co-factor in the development of some skin cancers and conjunctival squamous cell carcinomas in association with human papillomavirus infection. Limited evidence indicates that UV radiation exposure can reduce the efficacy of vaccination, at least in genetically predisposed individuals.

**• Vitamin D, formed by exposure of the skin to UV-B (with subsequent hydroxylation to the active vitamin), may play a protective role against the development of several internal cancers, autoimmune and some other diseases**

A number of studies link low solar UV exposure with a higher risk of some internal cancers, such as colorectal and prostate, and autoimmune disease, such as multiple sclerosis and type 1 diabetes. As lack of exposure to the UV-B in sunlight leads to suboptimal vitamin D levels, vitamin D has been proposed as the protective factor in helping to prevent these diseases. The evidence to support the protective role of solar UV-B exposure and whether this is mediated through vitamin D is not definitive.

**• Personal strategies to protect the eye and skin from the adverse effects of high solar UVR exposure are being adopted increasingly by the general public**

Health campaigns in several countries such as Australia, Canada, UK, and USA have raised the awareness of the general public regarding protection from the sun. Broad-spectrum sunscreens, in widespread use in mid-latitudes by fair-skinned individuals, minimise the erythemal effects of high sun exposure. UV-absorbing soft contact lenses covering the entire cornea provide excellent protection from solar UV-B for the eye, and are superior to some tinted sunglasses as the soft contact lenses shield against UV radiation entering from the side or below.

**• It is not feasible to give a single recommendation for optimal solar UV-B exposure to allow sufficient vitamin D synthesis while not increasing the risk of skin cancer**

The solar UV-B dose experienced by an individual varies greatly depending on time of the day, latitude, altitude, season of the year, cloud cover, physical activity and type of clothing worn. Skin colour, age and genetic background are other critical factors in determining the positive or negative outcome of the exposure. Therefore the message regarding "safe" sun exposure depends on the individual and place of residence.

**• The interaction between ozone depletion and global climate change may adversely affect human health**

At present, it is impossible to predict how global warming might alter the behaviour of people, especially those living in mid-latitudes, with respect to the amount of time spent outdoors in sunlight. If temperatures rise, then personal solar UV radiation exposure might be greater than at present. This would then have detrimental effects on the incidence of skin cancer and cataract and on the immune system, although benefiting vitamin D status.

## Terrestrial ecosystems

**• Field studies, in which solar UV-B radiation is either augmented or attenuated, report many effects on**

**higher plants and on bacteria, fungi and other microbes**

Although photosynthesis of higher plants and mosses is seldom affected in field studies by UV-B radiation, growth and morphology (form) of higher plants and mosses are often changed. This can lead to small reductions in shoot growth and changes in the competitive balance among species. Fungi and bacteria are generally more sensitive to damage by UV-B radiation than are higher plants. However, the species differ in their UV-B sensitivity to damage. This can lead to changes in species composition of microbial communities with subsequent influences on processes such as litter decomposition. Changes in plant chemical composition are commonly reported from experiments using enhancement or attenuation of UV-B radiation in sunlight.

**• Enhanced UV-B often leads to substantial reductions in consumption of plant tissues by insects**

In some cases this is because of altered insect behaviour, but changes in plant chemical and physical characteristics induced by UV-B radiation usually account for the reduced herbivory. Such modifications affect many interactions of plants with other organisms, both above and below ground. More is now understood about the mechanisms of these interactions.

**• Although sunlight does not penetrate significantly into soils, the biomass and morphology of plant root systems can be affected to a much greater degree than plant shoots**

Root mass can exhibit large declines with enhanced UV-B radiation. Also, UV-B-induced changes in soil microbial communities and biomass, as well as altered populations of small invertebrates have been reported and these changes have important implications for processing of mineral nutrients in the soil. Many of these ecosystem-level phenomena appear to be the result of systemic changes in chemical and physical properties of plants and in the nature of root exudates.

**• UV-B radiation and other environmental factors that are undergoing changes such as temperature, $CO_2$, moisture and available nitrogen over large areas may interact to produce a complex plant response**

In several studies, plant growth was augmented by higher $CO_2$ levels, while on the other hand many of the effects of UV-B radiation were usually not ameliorated by the elevated $CO_2$. UV-B radiation often increases both plant frost tolerance and survival under extreme high temperature conditions. Conversely, extreme temperatures sometimes influence the UV-B sensitivity of plants. Plants that are drought tolerant are likely to be more tolerant of high UV-B flux. Furthermore, UV-B radiation has been reported to alleviate some symptoms of water stress. Biologically available nitrogen is exceeding historical levels in many regions due to human activities. Studies show that plants well supplied with nitrogen are generally more sensitive to UV-B radiation.

**• Many new developments in understanding the underlying mechanisms mediating plant response to UV-B radiation have emerged**

UV-B radiation results in an activation of as yet uncharacterised receptor molecules. These initial events engage signalling pathways that result in altered plant gene expression and response. Exposure to UV-B induces some signals that are UV-B-specific and some that have elements in common with those elicited by other environmental factors. The use of shared signalling elements generates overlapping patterns of gene expression and functional responses. This new information is helpful in understanding common responses of plants to UV-B radiation, such as diminished growth, acclimation to elevated UV radiation, and interactions of plants with plant consumer organisms. It also helps in interpreting the interaction of various environmental stresses on plant growth and function.

**• Technical issues concerning the use of biological spectral weighting functions (BSWFs) have been further elucidated**

The BSWFs are multiplication factors assigned to different wavelengths giving an indication of their relative biological effectiveness. They are critical to the proper conduct and interpretation of experiments in which organisms are exposed to UV radiation, both in the field and in controlled environment facilities. The characteristics of BSWFs vary considerably among different plant processes, such as growth, DNA damage, oxidative damage and induction of changes in secondary chemicals. Thus, use of a single BSWF for plant or ecosystem responses is not appropriate.

## Aquatic ecosystems

**• Recent field studies continue to show that even current solar UV-B radiation can adversely affect aquatic organisms**

Reductions in productivity and impaired reproduction and development have been shown for phytoplankton, fish eggs and larvae, zooplankton and other primary and secondary consumers exposed to UV-B radiation. UV-B-related decreases in biomass productivity can be transferred through all levels of the food web, as well as cause changes in species composition and structure and function of ecosystems. Decreases in primary production would result in reduced sink capacity for atmospheric carbon dioxide, with its related effect on climate change.

**• Experiments in large enclosures show that changes in community structure may be more ecologically important than effects of enhanced UV-B on overall algal biomass**

These mesocosm experiments allow the experimenter to control the level of UV radiation on plankton communities to simulate various levels of ozone depletion. Growth was inhibited by ambient UV radiation in fixed-depth experiments but not in mesocosms where vertical mixing exposed planktonic organisms to variable radiation regimes. A synthesis model simulating mesocosm experiments suggests that enhanced UV-B could cause a shift from primary producers to bacteria at the community level. Shifts in community structure could have important consequences for carbon dioxide concentration in oceanic surface waters.

**• Recent studies have expanded our understanding of UV-B protection mechanisms for aquatic organisms**

UV radiation impairs photosynthesis, nitrogen fixation and damages DNA, but most phytoplankton have developed mitigating measures including UV-absorbing substances, repair enzymes and reactive oxygen species scavenging systems. However, protection is not complete. Picoplankton cyanobacteria do not produce absorbing substances but rely on fast cell division; these organisms have recently been found to be ubiquitous and to contribute more than 50% to the productivity in aquatic habitats. Solar UV controls the vertical position of macroalgae in the tidal zone. Organisms in the upper tidal zone have developed effective screening and repair mechanisms.

**• UV-B-related decreases in primary-producer biomass have a negative effect on the growth and survival of consumers, which form the higher levels in the aquatic food web**

Specific, direct UV-B effects have been identified in a wide variety of consumers, including copepods and other zooplankton, corals and sea urchins.

**• In their natural habitat, zooplankton face conflicting selection pressures, including exposure to UV-B radiation and factors of global climate change**

Invertebrate predators cause an upward movement of the zooplankton during daylight hours, exposing them to high levels of UV radiation at the surface. Besides vertical migration and UV screening, zooplankton rely on photorepair of UV-B-induced DNA damage. Increases in water temperature resulting from climate change are expected to increase enzymatic activity, which would enhance photorepair.

**• Primary causes for a decline in fish populations are predation and poor food supply for larvae; however, exposure of the larvae to enhanced UV-B radiation may further contribute to this decline**

Other major factors are overfishing, increased water temperature due to global climate change, pollution, and disease. Imprecisely defined habitat characteristics and the naturally high mortality rates of fish larvae render quantitative assessment of specific UV-B effects difficult.

**• The concentration and chemical composition of dissolved organic matter in aquatic ecosystems govern the penetration of UV radiation in the water column**

UV radiation affects the species composition of plankton communities and thus the concentration of DOM. There is a strong link between early succession of zooplankton communities and terrestrial plant communities within watersheds, which in turn are affected by climate change. Consequently, climate change and UV radiation have the potential to affect species composition in lakes and also to increase the invasion potential by imported species.

## Biogeochemical cycles

**•Climate-related changes can alter the transfer of organic matter from terrestrial to freshwater and coastal ecosystems and thereby influence UV radiation penetration into water bodies, with major consequences for aquatic biogeochemical processes**

These changes are particularly prevalent in high latitude systems. Dissolved organic matter leaching from or running off terrestrial ecosystems enters streams, rivers, lakes and, ultimately the oceans. The coloured part of dissolved organic matter controls the penetration of UV radiation into water bodies, but is also photodegraded by solar UV to release small inorganic molecules, mainly $CO_2$.

**• Future increases in the temperature of surface waters will enhance stratification of lakes and the ocean, which will intensify effects of UV-B radiation on biogeochemistry in the surface layer**

This important effect is manifested by the extensive increase in transparency of the water to UV-B radiation in the upper layer of stratified aquatic environments. These effects of climate change increase the impacts of UV-B radiation on biogeochemical cycles in the upper layer of aquatic systems, thus partially offsetting the beneficial effects of an ozone recovery.

**• Climate change and changes in UV-B radiation influence the concentration of halogen-containing compounds that are involved in ozone chemistry in the atmosphere**

Emissions of halogen-containing compounds, for example, methyl bromide from higher plants, increase with increasing air temperature. Recent observations indicate that methyl bromide concentrations in the atmosphere are decreasing at a rate of 2.5–3.0% per year but future global warming may reduce the current rate of decline. Bromine and other halogen radicals are also generated in UV-B radiation induced reactions of halogen-containing compounds both in atmospheric aerosols present in the marine boundary layer and in surface waters. These halogen-containing compounds may be transported by convection to the upper troposphere where the bromine radical participates in ozone destruction.

**• UV-B can alter the biological availability and toxicity of metals in aquatic environments**

Although many trace metals are essential trace nutrients, all metals are toxic above a certain concentration. In sunlit surface waters, however, they often exist in forms that are biologically not available. Increased UV-B can alter the chemical form of metals to produce forms that are available to aquatic organisms. For example, the UV-induced oxidation of elemental mercury results in the formation of precursors to methyl mercury that can adversely affect human health through bioaccumulation in aquatic food webs.

**• UV radiation drives photoreactions involved in cycling of marine sulfur, leading to the production of atmospheric aerosols and cloud formation**

Oceanic emissions of dimethylsulfide (DMS) produce atmospheric aerosols that influence atmospheric radiation and temperature. UV radiation induced transformation is an important sink of DMS in the upper ocean. Carbonyl sulfide, another important sulfur compound in the upper ocean, is produced in UV-B radiation induced reactions involving chromophoric DOM.

**• In terrestrial systems UV-B radiation can affect cycling of carbon and nutrients through changes in decomposition and soil biology**

Exposure to solar UV-B radiation causes direct photodegradation of dead plant material, especially in arid climates. When plants are exposed to UV-B radiation, changes in plant root exudation and/or the chemistry of dead plant material influence soil organisms and biogeochemistry. Changes in carbon and nutrient cycling induced by UV-B radiation can interact with responses to climate change and so may influence long-term ecosystem carbon budgets.

## Air quality

### • Models and measurements suggest that ozone transport from the stratosphere to the troposphere may have decreased by approximately 30% in the last 30 years

Ozone concentrations near the ground are a key indicator of air quality. Tropospheric ozone concentrations are affected by UV-B radiation, local weather systems, and pollutant concentrations. Stratospheric ozone depletion has increased the rate of ozone production in the troposphere due to enhanced UV-B radiation but reduced the amount of ozone transported from the stratosphere to the troposphere.

### • The predicted future increase in stratospheric ozone may increase tropospheric temperature and concentrations of ozone in the atmospheric boundary layer

Models predict that ozone concentrations in the atmospheric boundary layer will increase globally by 33 to 100% during the period 2000 to 2100 due to the combined effects of climate change, atmospheric pollution, and increases in stratospheric ozone. The impact of this increase on climate is difficult to quantify as tropospheric ozone concentrations are very variable, both in space and time.

### • Changes in the concentration of tropospheric hydroxyl radical caused by changes in UV-B radiation are now much better quantified

Tropospheric hydroxyl radical (OH) is one of the major oxidizing agents in the atmosphere, destroying trace gases that are involved in ozone depletion, climate change, and urban air pollution. The globally averaged OH has been observed to change on short time scales (months–years) but not in the longer term. Recent measurements in a relatively clean location over 5 years showed that OH concentrations can be predicted by the intensity of solar ultraviolet radiation. If this relationship is confirmed by further observations, this approach could be used to characterize the oxidation efficiency of the troposphere in different chemical regimes using UV radiation measurements, thus simplifying assessment of air quality.

### • Confidence in models estimating the impact of ozone change on the oxidation capacity of the atmosphere has improved for unpolluted locations

Measurements of UV radiation and chemical composition, including OH in the lower atmosphere, now normally agree with chemical models to within the measurement accuracy in unpolluted air both for clear skies and uniform cloud cover. However, in moderately and heavily polluted urban regions or forested environments, models and measurements disagree. These model uncertainties underline the importance of local measurements of tropospheric ozone, especially in areas where air may be polluted.

### • An analysis of surface-level ozone measurements in Antarctica suggests that there has been a significant change in the chemistry of the atmospheric boundary layer in this region as a result of stratospheric ozone depletion

Measurements of ozone concentrations in the atmospheric boundary layer show a recent (since 1990) increase in surface ozone concentrations consistent with more UV radiation reaching the Earth's surface during ozone hole episodes, and the enhanced production of nitrogen oxides from the ice. Thus, the Antarctic lower atmosphere is estimated to be more oxidizing now than before the development of the ozone hole, which may have adverse consequences through changing bioavailability of metals.

### • The tropospheric concentration of HFC-134a, a potent greenhouse gas and the main known anthropogenic source of trifluoroacetic acid, is increasing rapidly

The increase is in agreement with the known usage and atmospheric loss processes. Observations in both hemispheres between 1998 and 2002 show that the concentration of HFC-134a has been increasing by up to 12% per year. The good agreement between observations and known sources and sinks gives increased confidence in predictions of the environmental build-up of trifluoroacetic acid. The increasing concentration of HFC-134a may contribute to an acceleration of climate change.

### • Risks to humans and the environment from substances produced by atmospheric degradation of hydrochlorofluorocarbons (HCFCs) and hydrofluorocarbons (HFCs) are considered minimal

These include trifluoroacetic acid (TFA) and chlorodifluoroacetic acid. Recent studies reinforce the conclusion of small environmental and human health risks from current environmental loadings in fresh- and salt-water. Although the amounts of these compounds are expected to continue to increase in the future because of climate change and continued use of HCFCs and HFCs, current information suggests that this is not an issue of great importance.

### • Perfluoropolyethers, substances proposed as HCFC substitutes, have very large global warming potential and show great stability to chemical degradation in the atmosphere

These compounds are commonly used as industrial heat transfer fluids. It is not known whether these substances will contribute significantly to global warming and its interaction with ozone depletion. Their risks should be further evaluated.

## Materials damage

### • Plastics and wood exposed to solar UV radiation undergo degradation losing their useful properties over a period of time

This damage is dose-dependent and limits the outdoor lifetimes of most materials. The damage is exacerbated by higher ambient temperatures, higher humidity levels, and atmospheric pollutants. Light stabilizers and surface coatings are generally used to control the solar-UV induced damage to materials. Higher UV levels will require higher levels of stabilizers resulting in higher cost of materials used outdoors.

**• Several novel UV stabilizers and product fabrication techniques that improve UV-resistance have been reported**

New variants of effective light stabilizers, such as stabilizer compounds that bind to the polymer and are therefore less likely to be lost by leaching, have been reported recently. Mechanisms of synergistic effects of stabilizer blends have been further elucidated and will contribute to the design of new light-stabilizer blends. Continued research on this topic will facilitate the development of strategies that are better able to protect materials exposed to solar UV-B radiation.

**• An emerging trend towards the use of nanoscale fillers may improve the UV stability of plastics formulations**

These nanoscale fillers have smaller average particle sizes and often yield better mechanical properties than conventional fillers. Initial data suggest some of the nanoscale fillers may also act as good light stabilizers and extend the service life of products exposed to outdoor UV radiation. However, potential interference of these fillers with the effects of conventional light stabilizers or other additives such as antioxidants or flame retardants has not yet been fully evaluated.

**• Using powdered wood as a filler in plastics is continuing to be explored, and the effect of these fillers on UV-stability depends on the type of wood**

Powdered wood and other plant materials are used as low-cost natural fillers in some plastics products intended for outdoor use. Recent research indicates that several of these plant-derived fillers can either enhance the photodamage or act as a photostabilizer for the plastic material, depending on the source of the natural filler material and processing method used with the material. However, the lignin content in wood filler absorbs solar UV-B radiation and promotes photodamage of the polymer component. Identifying sources and processing technologies for these bio-based fillers without compromising light stability of filled polymers can lead to low-cost UV-stable plastics products for certain outdoor applications.