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Environmental effects of ozone depletion and its interactions with climate change: 2014 assessment

Executive summary†‡

Ozone depletion and climate change

• The Montreal protocol continues to be effective

The Scientific Assessment Panel of the Montreal Protocol on Substances that Deplete the Ozone Layer concludes that the atmospheric abundance of most controlled ozone-depleting substances (ODSs) is decreasing. There are several indications that the global ozone layer is beginning to recover from ODS-induced depletion. However, the variability of the atmosphere and the influence of climate change have hindered a definitive attribution of the observed global ozone increases since 2000 to the concomitant ODS decreases. In Antarctica, large ozone depletion continues to occur each year. In the Arctic, ozone depletion is generally less pronounced than in Antarctica but more variable: the very high stratospheric ozone concentrations observed in the spring of 2010 were followed by record-low concentrations in spring 2011.

• As a result of the success of the Montreal Protocol in limiting ozone depletion, changes in UV-B irradiance measured at many sites since the mid-1990s are due largely to factors other than ozone

Increases in UV-B irradiance (280–315 nm) ranging from 5 to 10% per decade have been reported for several northern mid-latitude sites, caused predominantly by reductions in cloudiness and aerosols. However, at some northern high latitude sites, UV-B irradiance has decreased during that period mainly due to reduction in snow- or ice-cover. Because of the large natural variability, any responses of UV-B irradiance to stabilisation of the concentrations of stratospheric ozone and possible beginning of a recovery are not yet detectable in the measurements.

• Large short-term increases in UV-B irradiance have been measured at some locations in response to episodic decreases of ozone at high latitudes

For example, the low ozone in spring 2011 in the Arctic increased the erythemal (sunburning) dose averaged over the duration of the low-ozone period by 40–50% at several Arctic and Scandinavian sites. Corresponding increases over Central Europe were estimated to be about 25%.

• Future levels of UV-B irradiance at high latitudes will be determined by the recovery of stratospheric ozone and by changes in clouds and reflectivity of the Earth's surface

In Antarctica, reductions of up to 40% in mean noontime UV Index (UVI) are projected for 2100 due to the continuing recovery of ozone. These reductions are comparable in magnitude with the increases in UVI that occurred in the past due to ozone depletion. Because of the anticipated increases in cloud cover, the UVI is projected to decrease by up to 7% at northern high latitudes. Reductions in surface reflectivity due to ice-melt will continue to contribute to reductions in UVI by up to 3% in the margins of the Antarctic continent and by up to 10% in the Arctic, but confidence in the magnitude of these effects is low.

• With continued effective implementation of the Montreal Protocol, future changes in UV-B irradiance outside the Polar regions will likely be dominated by changes in factors other than ozone

By the end of the 21st century, the effect of the recovery of ozone on UV-B irradiance will be very small, leading to decreases in UVI of between 0 and 5%. Additional decreases of up to 3% in the UVI are projected due to the anticipated increases in cloud cover. Future changes in UVI would be likely dominated by decreases in aerosols, resulting in increases in the UVI, particularly in densely populated areas. For example,

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increases in the UVI of up to 40% are projected for parts of Asia, reversing the large reductions in UVI that have probably occurred in this region during the second half of the 20th century. The confidence in these effects of aerosols is very low due to uncertainties in the projected amounts and optical properties of aerosols, as well as in future policy on emission controls.

Human health

- **Changing behaviour with regard to sun exposure by many fair-skinned populations has probably had a more significant effect on human health than increasing UV-B irradiance due to ozone depletion**

The increase in holiday travel to sunny climates, wearing clothing that covers less of the body, and the desire for a tan are all likely to have contributed to higher personal levels of exposure to UV-B radiation than in previous decades. Such changes in behaviour have both adverse and beneficial consequences for health.

- **Immediate adverse effects of excessive UV-B irradiation are sunburn of the skin and inflammation of the eye (photoconjunctivitis or photokeratitis). Long-term regular low-dose or repeated high-dose exposure to the sun causes melanoma and non-melanoma (basal and squamous cell) carcinomas of the skin and cataract and pterygium (a growth on the conjunctiva) of the eye**

The incidence of each of these skin cancers has risen significantly since the 1960s in fair-skinned populations, but has stabilised in recent years in younger age groups in several countries, perhaps due to effective public health campaigns. Cataract is the leading cause of blindness worldwide.

- **The major known beneficial effect of exposure of the skin to solar UV radiation is the synthesis of vitamin D**

Vitamin D is critical in maintaining blood calcium levels and is required for strong bones. People vary in how efficiently their skin makes vitamin D from sun exposure and perhaps in their physiological needs for this vitamin. Vitamin D deficiency might increase the risk of an array of diseases such as cancers, autoimmune diseases and infections. At present it is not clear if the low level of vitamin D is a cause of these diseases, occurs as a consequence of them, or is a marker of other factors that predispose to ill-health.

- **Strategies to avoid over-exposure to solar UV radiation include staying indoors, seeking shade, wearing protective clothing, brimmed hats and sunglasses, and applying sunscreens. These methods should aim to balance the harmful and beneficial effects of sun exposure**

Such a balance may be difficult to achieve in practice as the recommended time outdoors will differ between individuals, depending on personal factors such as skin colour, age, and clothing as well as on environmental factors such as location, time of day, and season of year. Current uncertainties centre on defining an optimal level of vitamin D and the amount and pattern of sun exposure required to achieve the optimum in different individuals. Thus, devising appropriate health messages for the public at the present time is not straightforward.

- **Climate change may affect personal sun-exposure behaviour, but the impact is likely to vary according to season and location**

For example, increasing temperatures may lead to decreased time outdoors in climates where it is already hot, but more time outdoors in cooler climates.

Terrestrial ecosystems

- **The effects of UV-B radiation on plants are influenced by various abiotic and biotic factors in ways that can have both positive and negative consequences on plant productivity and functioning of ecosystems**

Ozone depletion, increased exposure to ultraviolet-B radiation, and climate change affect biological systems, resulting in intricate feedbacks and complexity. In mid-high latitudes of the Southern Hemisphere plant productivity has likely decreased slightly due to the increased UV radiation as a result of the ozone depletion. On the other hand, exposure to UV-B radiation can promote plant hardiness, and enhance plant resistance to herbivores and pathogens. It can also improve the quality, and increase or decrease the yields of agricultural and horticultural products, with subsequent implications for food security.

- **Exposure to UV-B radiation can increase or decrease rates of decomposition of dead plant matter (litter), depending on prevailing climate and the chemistry and structure of the litter**

In arid and semi-arid ecosystems (grasslands, savannas and deserts), photodegradation generally increases rates of decay of plant litter and is now being considered as an important driver of decomposition, although uncertainty exists in quantifying its regional and global biogeochemical significance. Changes in the decomposition of plant litter from exposure to UV-B and also UV-A (315–400 nm) and visible radiation have potential consequences for the cycling and storage of carbon and other nutrients.

- **Solar UV radiation has the potential to contribute to climate change *via* its stimulation of emissions of carbon monoxide, carbon dioxide, methane, and other volatile organic compounds from plants, plant litter and soil surfaces**

Mechanisms and sources of emissions of trace gases have been identified in plants and ecosystems. UV radiation together with other abiotic factors, in particular temperature, stimulates these emissions. The magnitude, rates and spatial patterns of the emissions remain highly uncertain at present. These UV radiation processes could increase emissions of trace gases that affect the atmospheric radiation budget (radiative forcing) and hence changes in climate.

• While UV-B radiation does not penetrate into soil to any significant depth, it can affect a number of belowground processes through alterations in aboveground plant parts, microorganisms, and plant litter

These include modifications of the interactions between plant roots, microbes, soil animals and neighbouring plants, with potential consequences for soil fertility, carbon storage, plant productivity and species composition.

• Terrestrial ecosystems in the Southern Hemisphere are being affected by the Antarctic ozone 'hole'

Resultant changes in precipitation patterns have been correlated with ecosystem changes such as increased tree growth in Eastern New Zealand and expansion of agriculture in Southeastern South America. Conversely, in Patagonia and East Antarctica, declining tree and moss bed growth have been linked to reduced availability of water. A full understanding of the effects of ozone depletion on terrestrial ecosystems in these regions should therefore consider both UV radiation and climate change.

Aquatic ecosystems

• Climate change and UV radiation affect phytoplankton productivity and species composition of marine ecosystems

Phytoplankton (primary producers) are decreasing along the West side of the Antarctic Peninsula due to increased solar UV-B radiation and rapid regional climate change. Changes in ice phenology as well as light and nutrient availability may affect species composition. Organisms mitigate UV-B radiation-induced damage by repair mechanisms or by producing UV-absorbing compounds.

• Interactions between climate change and UV radiation are having strong effects on aquatic ecosystems that will change in the future due to feedbacks between temperature, UV radiation and greenhouse gas concentrations

Higher air temperatures are increasing the surface water temperatures of numerous lakes and oceans, with many large lakes warming at twice the rate of air temperatures in some regions. Species composition and distribution of many marine ecosystems may change with warmer oceans. For others, such as corals, the warming may alter their tolerance to other stressors. This warming can also shift the thermal niche of organisms towards the pole and causes changes in community structure.

• Warming of the ocean results in stronger stratification that decreases the depth of the upper mixed layer

The decrease in the depth of the upper mixed layer exposes organisms that dwell in it to greater amounts of solar visible and UV radiation which may overwhelm their capability for protection and repair. Enhanced stratification also reduces upward transport of nutrients across the thermocline from deeper layers. In the polar waters, increasing temperature results in explosions of phytoplankton growth under the ice and around the ice edges.

• Increased concentrations of atmospheric CO_2 are continuing to cause acidification of the ocean, which alters marine chemical environments with consequences for marine organisms

Acidification interferes with the calcification process by which organisms, such as phytoplankton, macroalgae and many animals including mollusks, zooplankton and corals, produce exoskeletons protecting themselves from predators and solar UV radiation. Consequently, they become more sensitive to UV radiation, so that they calcify even less and decrease their production of biomass.

• Climate change-induced increases in concentrations of dissolved organic matter (DOM) in inland and coastal waters reduce the depth of penetration of UV radiation

Increased extreme precipitation events and enhanced growth of terrestrial vegetation produce greater fluxes of UV-absorbing DOM from the landscape. This creates a refuge for UV-sensitive organisms including some invasive species. Decreased penetration of UV radiation also reduces the natural disinfection of surface water containing viruses, pathogens, and parasites.

Biogeochemical cycles

• Climate change modulates the effects of solar UV radiation on biogeochemical cycles in terrestrial and aquatic ecosystems resulting in UV-mediated positive or negative feedbacks on climate

For example, where photochemical priming plays an important role, changes in continental runoff and ice melting, due to climate change, are likely to result in enhanced UV-induced and microbial degradation of dissolved organic matter (DOM) and the release of carbon dioxide (CO_2). Such positive feedbacks are particularly pronounced in the Arctic resulting in Arctic amplification of the release of CO_2 (see next point).

• Solar UV radiation is driving the production of substantial amounts of carbon dioxide from Arctic waters

The production is enhanced by the changes in rainfall, and melting of ice, snow and permafrost, which lead to more organic material being washed from the land into Arctic rivers, lakes and coastal oceans. Solar UV radiation degrades this organic material, which stimulates CO_2 and CO emissions from the water bodies, both directly and by enhanced microbial decomposition. New results indicate that up to 40% of the emissions of CO_2 from the Arctic may come from this source, much larger than earlier estimates.

• The changes in climate associated with the Antarctic ozone 'hole' include changes to wind patterns, temperature and precipitation across the Southern Hemisphere

More intense winds lead to enhanced wind-driven upwelling of carbon-rich deep water and less uptake of atmospheric CO_2 by the Southern Ocean, reducing the oceans' potential to act as a carbon sink (less sequestering of carbon). These winds also transport more dust from drying areas of South America into the oceans and onto the Antarctic continent. In the oceans this can enhance iron fertilisation resulting in more plankton and increased numbers of krill. On the continent the dust may contain spores of novel microbes that increase the risk of invasion of non-indigenous species. The ozone 'hole' has also helped to keep East Antarctica cold, but conversely has helped to make the Maritime Antarctic region one of the fastest warming regions on the planet. These climate-related impacts of ozone depletion on ecosystems may also interact with changing UV radiation, leading to tipping points.

• The carbon cycle is strongly influenced by interactions between droughts and the intensity of UV-radiation at the Earth's surface

Increased aridity due to climate change and severity of droughts will change the amount of plant cover, thereby increasing UV-induced decomposition of dead plant matter (plant litter). These increased losses could have large impacts on terrestrial carbon cycling in arid ecosystems.

• Lignin present in all terrestrial vegetation plays a significant role in the carbon cycle, sequestering atmospheric carbon into the tissues of perennial vegetation

Although it is well known that lignin is one of the components of dead vegetation most resistant to biotic decomposition, new results have shown that lignin is readily decomposed with exposure to solar UV radiation. Consequently, UV-induced degradation of plant litter is correlated with its lignin content, reducing long-term storage of carbon in terrestrial systems.

Air quality

• UV radiation is an essential driver for the formation of photochemical smog, which consists mainly of ground-level ozone and particulate matter. Recent analyses support earlier work showing that poor outdoor air quality is a major environmental hazard

Greater exposures to these pollutants have been linked to increased risks of cardiovascular and respiratory diseases in humans and are associated globally with several million premature deaths per year. Ozone also has adverse effects on yields of crops, leading to loss of billions of US dollars each year. These detrimental effects may also alter biological diversity and affect the function of natural ecosystems.

• Future air quality will depend mostly on changes in emission of pollutants and their precursors; changes in UV radiation and climate will also contribute

Significant reductions in emissions, mainly from the energy and transportation sectors, have led to improved air quality in many locations. Air quality will continue to improve in those cities/states that can afford controls, and worsen where the regulatory infrastructure is not available. Future changes in UV radiation and climate will alter the rates of formation of ground-level ozone and some particulate matter and must be considered in predictions of air quality and consequences for human and environmental health.

• Decreases in UV radiation associated with the recovery of stratospheric ozone will, according to recent global atmospheric model simulations, lead to increases in ground-level ozone over large geographic scales

If correct, this would add significantly to future ground-level ozone trends. However, the spatial resolution of these models is insufficient to inform policy, especially for urban areas.

• UV radiation affects the atmospheric concentration of hydroxyl radicals, $^{\bullet}OH$, which are responsible for the self-cleaning of the atmosphere

Recent measurements confirm that on a local scale, $^{\bullet}OH$ radicals respond rapidly to changes in UV radiation. However, on large (global) scales, models differ in their predictions by nearly a factor of two, with consequent uncertainties for estimating the atmospheric lifetime and concentrations of greenhouse gases and key air pollutants. Projections of future climate need to consider these uncertainties.

• No new negative environmental effects of the substitutes for ozone depleting substances or their breakdown-products have been identified

However, some substitutes for ozone depleting substances will continue to contribute to global climate change if concentrations rise above current levels.

Materials

• A trend towards environmentally sustainable materials in building has increased the use of wood and wood–plastic composites

Despite this trend, the use of rigid PVC, the most-used plastic in building, will continue to be popular at least in the medium term. Improvements are being developed that make PVC easier to process and environmentally friendly. The effects of solar UV radiation and climate change on the lifetime of PVC building products continue to be a concern.

• The role of solar UV radiation in creating microplastics debris in the oceans from the weathering of plastic litter on beaches is an emerging environmental issue

These microplastic particles concentrate toxic chemicals dissolved in seawater and are ingested by zooplankton, thus providing a potential mechanism for the transfer of pollutants into the marine food web. While the process has not been studied in any great detail, the production of microplastics will likely increase at high solar UV-B radiation levels and/or elevated temperatures.

• Nanoscale inorganic fillers can provide superior stability against solar UV irradiation relative to conventional fillers in coatings and plastics

Nanoparticle fillers in coatings, especially those in clear-coatings on wood or fibre-coatings of textiles, also provide enhanced stability. With nanoparticles that absorb UV radiation, such as the mineral rutile, the stabiliser effect is particularly evident. The benefits of nanofillers in bulk plastics, however, are less clear and more information is needed to assess their efficacy. Nanofillers may provide a low-cost means of stabilising some polymer and wood-based products and help increase service lifetimes in the face of variations in UV radiation or climate change.

• Clothing and glass can provide protection against exposure to solar UV radiation

Textile fabrics block personal exposure to solar UV radiation, whereas glass usually blocks mainly UV-B radiation. The effectiveness of specific fabrics depends on the weave characteristics but can be further improved by surface-treating the fibres with a UV absorber. Glazing for windows is being developed to further improve their thermal properties and also results in increased filtering of the UV radiation with benefits to the health of humans and indoor components of buildings and artwork.