

1 Towards an Understanding of the Implications of Changing Stratospheric Ozone, Climate and UV Radiation

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Introduction

Changing profiles of ultraviolet radiation

The stratospheric ozone layer, located *c.* 10 to 50 km above the Earth's surface (Fig. 1.1), makes up approximately 90% of the world's ozone. The remaining ozone is located in the troposphere closest to Earth. Although ozone is an effective filter against transmission of ultraviolet (UV) radiation to the Earth's surface, even a small amount of the short wavelengths can have environmental effects. UV radiation is conventionally defined as UV-C (< 280 nm), UV-B (280–315 nm) and UV-A (315–400 nm). About 97–99% of UV radiation in the wavelength range of 200–300 nm is absorbed by ozone with little or no filtering effect on UV-A radiation (NASA, 2016). Thus, as the UV radiation passes through the atmosphere to Earth, all UV-C radiation and most of the UV-B radiation is absorbed. Other factors influencing the amounts of UV radiation reaching the Earth's surface include altitude, latitude, sun angle, clouds, aerosols, ground reflectivity, depth and quality of water bodies, as well as climate-induced changes.

More than 40 years ago scientists contemplated the likely cause of a decreasing

stratospheric ozone layer (Molina and Roland, 1974) and the consequent threat of increased amounts of UV radiation. Thirty-two years ago, the Antarctic 'ozone hole' was discovered (Farman *et al.*, 1985). Research has since shown that substances used in many applications such as air conditioners, fire extinguishers, refrigerators, foams, aerosol sprays and agricultural fumigants as well as certain solvents, were ozone-depleting substances (ODS). Most were also contributors to the warming greenhouse effect. These ODS include chlorofluorocarbons, methyl bromide, methyl chloroform, halons, hydrochlorofluorocarbons, and carbon tetrachloride. Subsequently, several of the substances used as substitutes for the ODS have also been found to add to global warming. The Montreal Protocol and its Amendments have successfully controlled further production of the ODS, preventing catastrophic exposures to UV radiation (Newman *et al.*, 2009; Newman and McKenzie, 2011; Chipperfield *et al.*, 2015; United Nations Environment Programme Environmental Effects Assessment Panel, 2016). These evolving events and human activities demonstrate the intricate interrelationship of ozone dynamics, UV radiation and climate change,

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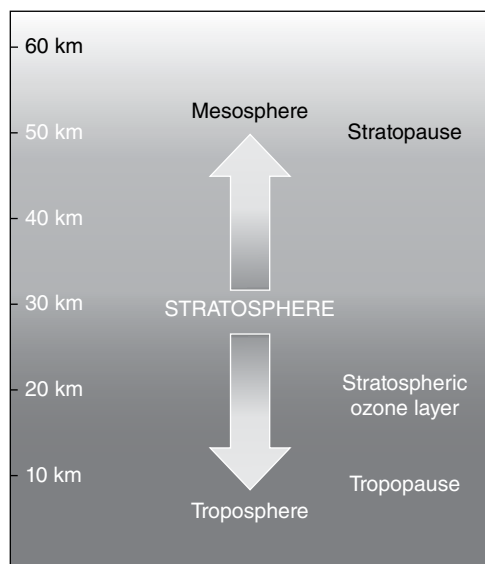


Fig. 1.1. Diagrammatic sketch of the stratosphere and its boundaries.

which in turn affect the environment and life on Earth in complex ways.

Environmental and health implications

Projections involving the dynamics of UV radiation, climate and ozone have important implications for the environment and human health. In areas with reduced UV radiation, vitamin D levels may drop below the recommended concentrations, and the positive effects of the UV radiation on certain autoimmune diseases, cancers and infections (Lucas *et al.*, 2015) may become lessened. However, behavioural patterns towards sun exposure among diverse population groups will largely determine the amount of UV radiation and levels of vitamin D acquired. At the same time, reduced levels of UV radiation would mean decreased incidences of skin cancers and cataracts. In natural ecosystems and agricultural systems, low exposure to UV radiation may favour pathogens and herbivores as a consequence of decreased levels of UV-induced phenolic compounds, which would otherwise function as deterrents against attack.

Depending on the amount of UV radiation received, crop quality may be affected due to changes in the amounts and profiles of plant phenolics (many of which are effective antioxidants), nutritional composition, general plant fitness and morphology (Wargent and Jordan, 2013; Bornman *et al.*, 2015; Robson *et al.*, 2015). These patterns of change also offer opportunities in crop management (Raviv and Antignus, 2004; Paul *et al.*, 2005; Wargent and Jordan, 2013).

Complexities of Ozone Dynamics, UV Radiation and Climate Change

Shaping of the current and future environment

Annual ozone depletions are still occurring in the polar regions, especially in Antarctica because of the long atmospheric lifetimes (close to 100 years) of some of the ODS such as chlorofluorocarbons (CFCs; 'freons') and halons containing chlorine and bromine. Substantially smaller ozone depletions occur also at mid-latitudes, with periodic large depletions due to volcanic eruptions and the resultant sulphate emissions, which enhance activation of chlorine that in turn catalyses the loss of ozone. Over the tropics, the stratospheric ozone layer is always naturally thinner than in other regions, and variations in the concentration of the ozone layer here are so far small.

There now appear to be indications of initial recovery (Fig. 1.2) of the stratospheric ozone layer (Solomon *et al.*, 2016) as a consequence of the regulations put in place by the Montreal Protocol and its Amendments. However, predicting future changes in the ozone layer is difficult because of the confounding influence of rapid climate change. The Montreal Protocol has been instrumental in stimulating research and production of substitutes for many of the ODS. Among these substitutes are the typical hydrofluorocarbons (HFCs), which are used in refrigeration and air conditioning. However, HFCs have a large global warming potential and long atmospheric lifetimes (Hurwitz

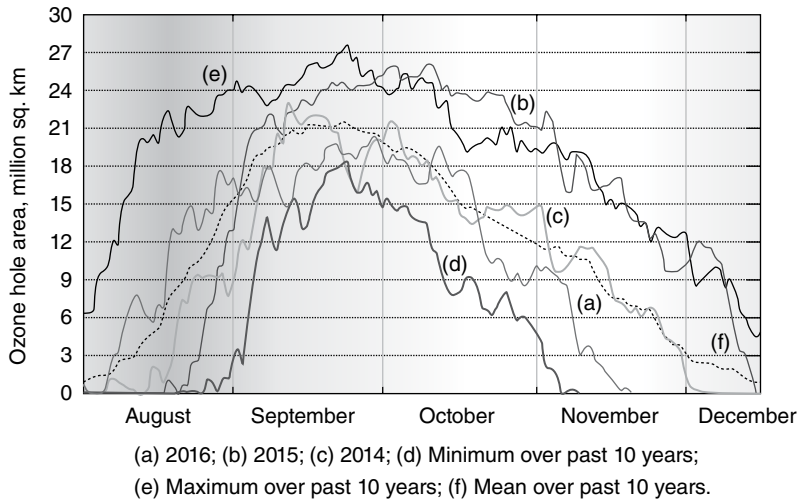


Fig. 1.2. Progression of the ozone ‘hole’ area in millions of sq. km. The shaded area during August depicts decreasing uncertainty in the size of the ozone ‘hole’ as the polar region becomes sunlit. (NASA Ozone Hole Watch.)

et al., 2016). For example, HFC-23 has a lifetime of *c.* 228 years, and a global warming potential thousands of times greater than carbon dioxide (Chipperfield, 2015). Despite their potential to contribute to global warming, HFCs did not come under the Montreal Protocol since they have a negligible effect on the ozone layer. However, because they were produced as a result of the agreements to phase out the major ODS under the Protocol, much effort finally culminated in a decision by 197 countries in Kigali, Rwanda (Kigali Amendment, 2016) to phase out the use of HFCs. This is expected to have profound and positive effects on mitigating climate warming.

Ozone itself absorbs heat and, therefore, decreases or increases in ozone concentration can have a cooling or warming effect. This effect also depends on altitude. Since ozone absorbs heat at relatively low altitudes, it cools the lower stratosphere over Antarctica (Thompson and Solomon 2002; Hartmann *et al.*, 2013; Bais *et al.*, 2015), contributing favourable conditions for the formation of polar stratospheric clouds that form a catalytic ice crystal surface for ozone-depleting chlorine free radicals.

As the environment changes, so too will the levels of exposure to UV radiation and the ecosystem’s responses to the interactive

effects of multiple climate factors (Bornman *et al.*, 2015; Robinson and Erickson, 2015), including temperature, water availability and soil nutrients. Thus the effects of ozone depletion on climate change – and impacts of climate change events less directly dependent on ozone dynamics – will very probably continue to further modify the amount of UV radiation reaching the Earth. Some of these UV-modifying conditions due to climate change include variations in cloud cover, UV-absorbing tropospheric gases, and changes in reflectivity from melting snow and ice as temperatures increase (Bais *et al.*, 2015). In regions outside the polar areas, cooling of the middle and upper stratosphere from increasing amounts of greenhouse gases is predicted to decrease the catalytic destruction of ozone and reduce levels of UV radiation outside the tropics (Eyring *et al.*, 2007; Shepherd, 2008; Waugh, *et al.*, 2009; Bais *et al.*, 2015). However, this may be partly offset by the highly reactive nitrogen oxides (NO_x) from nitrous oxide (N_2O) that catalyse the destruction of the upper stratospheric ozone. Emissions of N_2O come from biomass burning, industry, agriculture and also natural sources (e.g. soils) but human activity is set to account for substantially increased emissions by the middle of the 21st century unless mitigating actions

are taken (Ravishankara *et al.*, 2009; Davidson and Kanter, 2014; Revell *et al.*, 2015). In contrast to regions outside the tropics, UV radiation in the tropics is likely to increase slightly because of large-scale circulation changes in the upper atmosphere brought about by the increase in greenhouse gases (Butchart, 2014; Bais *et al.*, 2015).

Ozone affects climate and vice versa

There is further emerging evidence of the way in which stratospheric ozone is influencing climate change and vice versa (Thompson and Solomon, 2002; Shepherd, 2008; Nowack *et al.*, 2015; Iglesias-Suarez *et al.*, 2016), and how these two factors modify the amount of UV radiation received by ecosystems, humans and other animals (Williamson *et al.*, 2014). Thus several consequences of current and future climate change are becoming apparent through both observation and modelling. One such example is the effect on climate by ozone depletion in the Southern hemisphere (Thompson *et al.*, 2011; Turner *et al.*, 2014; Bais *et al.*, 2015). It is predicted that the cooling of the lower stratosphere will intensify, and that stronger winds (Li *et al.*, 2016; Gent, 2016) will increase the meridional overturning – a circulation system of deep ocean and surface currents resulting in the transport and storage of large quantities of water, heat and carbon – thus playing a major role in climate change and in modifying the environment.

Ozone level variation and increasing climate change are highly dynamic processes, and consequently there is some uncertainty in the way in which they will play out as the Earth's climate evolves and as research unravels more interacting factors. Global climate is perturbed by stratospheric ozone through temperature changes from radiative forcings (Myhre *et al.*, 2013) and also by changes in tropospheric and stratospheric circulations (WMO, 2015). Radiative forcing refers to the changes in the radiative or energy balance from differences between incoming solar radiation and outgoing infrared radiation, which can modify climatic

conditions. Since ozone is itself a greenhouse gas, where increases occur, there is a warming effect (positive radiative forcing), and consequently a depletion in ozone generally results in a cooling effect (negative radiative forcing). Therefore, after 2050, projected climate change will probably become the dominant driver of future stratospheric ozone dynamics, affecting also the UV radiation environment, as the amounts of ozone depleting substances gradually decrease (Eyring *et al.*, 2007; IPCC, 2013).

Ecological consequences of ozone depletion

Only recently has attention turned to considering the consequences for ecosystems of the impact of the dynamics of ozone depletion *per se* on climate change (Villalba *et al.*, 2012; Bornman *et al.*, 2015; Gutt *et al.*, 2015; Robinson and Erickson, 2015). There are already indications that the complex events arising from ozone depletion are altering ecosystems in the Southern hemisphere through changes in precipitation, wind circulation patterns and wind speed, leading in some instances to increased aridity, thereby impacting plant habitats (Clarke *et al.*, 2012) and altering growth response of, for example, forest ecosystems (Villalba *et al.*, 2012).

Nitrous oxide and the future

One of the intriguing conundrums is the idea that future environmental change may require consideration of some policy intervention with respect to the ozone-depleting nitrous oxide (N_2O) (Butler *et al.*, 2016), to prevent what has been termed 'super recovery' of stratospheric ozone. If CO_2 and methane (CH_4) levels continue to increase, they will contribute to ozone recovery due to the temperature effects in the stratosphere of these greenhouse gases (GHGs). On the other hand, curbing CO_2 and CH_4 would also have obvious beneficial environmental effects with respect to global warming.

However, if N_2O is reduced against a background of rising CO_2 and CH_4 , stratospheric ozone is projected to increase beyond its historical values – i.e. the so-called super recovery (Portmann and Solomon, 2007; Iglesias-Suarez *et al.*, 2016; Maycock, 2016). As a consequence, a reduction in UV radiation exceeding pre-1980s values would intuitively be a positive outcome for some human diseases such as skin cancer and cataracts, but may be detrimental for other diseases, e.g. where UV-induced vitamin D is involved, as well as for other health conditions benefitting from appropriate exposure to UV radiation (Lucas *et al.*, 2015). Ecosystems and plant development would be affected by a lowered UV radiation regime which would probably also decrease plant tolerance to pathogen and insect attack (see below: *UV radiation: environmental stress or regulatory factor?*).

A significant reduction in UV radiation reaching Earth as a result of ozone super recovery also has implications for the chemical composition of the atmosphere, since it would result in reduced action by UV radiation in ‘cleaning’ or oxidising the troposphere through the generation of hydroxyl radicals ($\cdot\text{OH}$) (Levy, 1971; Madronich *et al.*, 2015). These radicals control atmospheric lifetimes of many pollutants such as nitrogen oxides, methane, halocarbons, and sulphur dioxide (Madronich *et al.*, 2015), which have consequences for climate change, ozone concentration and possible further reductions in UV radiation reaching the Earth’s surface. Some of these effects may be partly counterbalanced by global measures to reduce air pollutants (McKenzie *et al.*, 2011; Watanabe *et al.*, 2011), which would result in higher levels of UV radiation reaching the Earth’s surface. Thus, trends in air quality, important for ecosystems and health, will be modulated by UV radiation. Post-2050, it is likely that we will see CO_2 and N_2O becoming progressively important in determining the future of the ozone layer (Stolarski *et al.*, 2015) and the UV radiation environment. It is therefore becoming very clear that increasing climate change will influence the recovery of stratospheric ozone and modulate the penetration

of UV radiation to the Earth’s surface. It is also becoming apparent that apart from the effects of ozone on climate, and vice versa, climate changes can modify exposure to UV radiation, independently of ozone. By way of human adaptation strategies and opportunism, these rapidly changing environmental conditions can also be exploited for practical purposes, as reviewed by Wargent and Jordan (2013), to improve the nutritional quality of agricultural crops through UV-induced enhancement of antioxidants and other health-promoting compounds (see above).

UV Radiation: Environmental Stress or Regulatory Factor?

Early on, it was recognised that UV radiation was part of the environmental cue for plants and fungi that shaped their morphology (Kumagai, 1988; Ensminger, 1993; Kim *et al.*, 1998; Paul and Gwynn-Jones, 2003), growth and biochemistry (Klein, 1978). Early work also raised the question whether UV-B radiation posed a threat to photosynthesis. The finding was that inhibition was generally only seen at high UV-B irradiances and that even these could be compensated for by acclimation mechanisms (Allen *et al.*, 1998). However, in the wake of increasing evidence of ozone depletion, most of the research quickly centred around damage, giving in many instances an unbalanced interpretation due to unrealistic experimental conditions of UV radiation and visible light (Searles *et al.*, 2001). This trend has slowly reversed and consequently our understanding has broadened regarding the diversity of response in an increasingly complex and rapidly changing environment (assessed in Ballaré *et al.*, 2011; Jansen and Bornman, 2012; Williamson *et al.*, 2014; Bornman *et al.*, 2015). It has also highlighted the need for a strong interdisciplinary approach in order to gain a comprehensive, whole-systems perspective of the plant environment. Similarly, evaluation of the role of UV radiation at plant and ecosystem levels, under multi-environmental conditions (e.g. water availability, temperature,

CO₂, and soil nutrients (assessed in Caldwell *et al.*, 2007; Ballaré *et al.*, 2011; Bornman *et al.*, 2015)) is important for obtaining realistic outcomes and determining potential interacting effects.

Increasingly, more information on the regulatory and acclimatory role of UV radiation has been facilitated by molecular studies that have demonstrated some of the mechanisms underlying plant genetic, biochemical, physiological and morphological modifications. These mechanistic studies have included investigation of the way in which UV-B radiation is perceived by the plant through the UV-B photoreceptor, UV RESISTANCE LOCUS8 (UVR8), which mediates photomorphogenic response to UV-B radiation (Jenkins, 2009, 2014).

Research on some of the indirect responses to UV radiation, in particular, UV-B radiation, of individual plants and terrestrial ecosystems has also contributed to the shift in focus from UV radiation as mainly a stress issue to one of a modifying or regulatory factor. The indirect effects are often manifested by a response not directly induced by a current stressor, but through a series of interactions (Paul and Gwynn-Jones, 2003; Miller and TerHorst, 2012). Typical indirect effects are exemplified by changes in plant chemistry leading to plant tolerance against pathogens and herbivores due to UV-induced plant polyphenolics (Ballaré *et al.*, 2011; Ferreyra *et al.*, 2012) at toxic concentrations or at levels that deter pathogen or herbivore attack. These polyphenolics, e.g. flavonoids, function as chemical defence compounds and also contribute to antioxidant activity. Other indirect modifications

by UV radiation occur below the soil surface, although penetration by UV is minimal. Rather, the response appears to be mainly mediated through flavonoids in plant root exudates as a result of exposure to UV radiation of the above-ground plant parts (Zaller *et al.*, 2002; Avery *et al.*, 2003; Caldwell *et al.*, 2007; Cesco *et al.*, 2010; Bornman *et al.*, 2015).

Although the research emphasis on damaging effects of UV radiation on plants and ecosystems has lessened, potential deleterious effects can still occur under certain environmental situations. These effects are largely dependent on genotype, co-occurring stress factors, regional location, season and duration of the stress(es). Importantly, in light of the projected changes in the UV radiation environment (as a consequence of the diverse interactive effects of changes in ozone and climate, compounded by human activities) detrimental modifications may increase if plant defence systems become less effective under harsh conditions (Williamson *et al.*, 2014).

Conclusions

Thus, although stratospheric ozone levels are projected to recover or super-recover, future exposure to UV radiation will be strongly influenced by the interactive processes involving ozone dynamics and climate change, either singly or together. With the projected increase and complexity of climate change, ozone dynamics and land-use changes, research on the effects of UV radiation will continue to be relevant.

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