SUMMARY

OZONE SCIENCE: A CANADIAN PERSPECTIVE ON THE CHANGING OZONE LAYER

The tenth anniversary of the 1987 signing of the Montreal Protocol is an event to be celebrated because the protocol has been the basis of a successful effort by the international community to control and greatly reduce the emission of ozone-depleting substances into the atmosphere. A serious threat to the global environment has been addressed and appropriate measures have been taken. This report provides a brief overview of the state of ozone science 10 years after the signing. Compiled by Canadian scientists, it draws on both Canadian and international research to outline our current understanding of ozone depletion and its effects. It also highlights Canadian results and data, where appropriate, and emphasizes items of special Canadian concern, such as ozone depletion in the Arctic and the impacts of UV changes on forests and freshwater ecosystems.

THE DISTRIBUTION OF OZONE AND OZONE-DEPLETING SUBSTANCES IN THE ATMOSPHERE AND OBSERVED CHANGES

The main features of the climatology of total ozone were discovered by G.M.B Dobson by 1930. These were the dependence on latitude and season and the day-to-day changes that are associated with meteorological conditions. A more extensive climatology extending from the ground to all levels in the stratosphere is now available as a result of the use of many new techniques. These measure the distribution of ozone with altitude as well as the total amount both from the ground and from a variety of platforms, including balloons, aircraft, rockets, and satellites. The severe depletion in the Antarctic during the spring, known as the ozone hole, was discovered in 1985, and a few years later midlatitude depletion was recognized. A significant and developing depletion in the Arctic spring has also been observed during the last few years. Atmospheric concentrations of ozone-depleting substances have been measured for some decades and now show definitive evidence of the effect of the Montreal Protocol.

- Canada began total ozone measurements at five stations in the early 1960s and has been operating twelve ground-based ozone observing stations equipped with Brewer spectrophotometers since 1992. The total ozone data are used for trend studies, for forecasting ozone and UV radiation, and for characterization and calibration of satellite measurements.
- The four-station Canadian ozonesonde network was initiated in the mid-1960s. Currently sondes are flown at least weekly from six locations. All the sonde and ground-based data are available from the World Ozone and Ultraviolet Radiation Data Centre (WOUDC) which Environment Canada operates for the WMO.
- The Stratospheric Ozone Observatory at Eureka (80°N, 86°W), which is part of the WMO/UNEP Network for Detection of Stratospheric Change(NDSC), was opened

in 1992. It houses lidars for measuring ozone and aerosols, Fourier transform spectrometers, and other spectrometers for measuring stratospheric composition. The Ontario Institute for Space and Terrestrial Physics and the Japanese Meteorological Agency and Communications Research Laboratory are partners with Environment Canada in conducting these experiments.

- Annual average ozone values over Canadian stations have declined by about 6% from pre-1980 averages. The decline is greatest in spring and least in the fall. Sonde measurements show that the main loss is in the lower stratosphere.
- Sonde measurements over Canada have shown that free (i.e., unpolluted) tropospheric air has suffered a similar loss of ozone to that in the stratosphere during the past 15 years. However, European sonde data show some increases during the 1980s.
- The ozone values in 1993 were lower than in any other year over southern Canada and over the midlatitudes in general. The decline, which is attributed to the effects of the eruption of Mt. Pinatubo in 1991, occurred in the lower stratosphere and, at least over Canada, throughout the troposphere.
- Ground and balloon-based measurements over the Canadian Arctic from the Eureka NDSC observatory, Resolute, and Alert, as well as satellite measurements, show the development of strong depletion during the past few years, especially in the spring of 1997. However, the lowest Arctic ozone values are still much higher than the low values in the Antarctic.
- The Canadian Meteorological Centre's daily forecast of the total ozone field over Canada is based on measurements of total ozone by the twelve Canadian Brewer spectrophotometers and the output from the Numerical Weather Prediction model. The forecast, based on statistical relationships, has a very low error.
- Measurements show that atmospheric concentrations of CFC-11 at Alert and Point Barrow have begun to decline and that the rate of increase in CFC-12 is much reduced.

The Influence of Dynamical Processes on Ozone Abundance.

Transport of ozone by the Brewer-Dobson circulation from its main source region in the equatorial midstratosphere to its regions of greatest abundance, in the lower stratosphere at middle and high latitudes, is a key determining factor in establishing the observed distribution of ozone. The height of the tropopause is also a determining factor for the total ozone amount, since the tropopause is ozone poor while the stratosphere is relatively ozone rich. These are dynamical factors that affect the ozone directly. Different scales of mixing affect concentrations of ozone and other constituents; modelling of chemical reactions may be inaccurate if the spatial resolution of the model is not fine enough to capture the smaller scale effects.

Dynamics act indirectly on the chemistry of ozone by causing changes in temperature, which affect the rates of most chemical reactions (some more than others). Of particular importance is the effect of temperature on the formation of polar stratospheric clouds, and the enhancement that these cause of chlorine concentration and ozone destruction. Understanding of atmospheric dynamics has developed through advances in numerical modelling coupled with increasingly detailed measurements of ozone and other trace constituents, but a number of problems remain.

- The spatial structure of the tropopause directly affects the total abundance and latitudinal distribution of ozone, but our understanding of how this structure is established is mostly qualitative and our ability to characterize, let alone predict, interannual variability and trends is extremely limited.
- Although we have a basic understanding of the origin of the Brewer-Dobson circulation and its seasonal cycle, significant theoretical gaps remain, especially with respect to the tropics. There is considerable potential for interannual variability and decadal-scale trends in the Brewer-Dobson circulation associated with corresponding variability in the driving mechanisms. Such variability places a major limitation on our predictive capability.
- It has recently become evident that the transport and mixing characteristics of the tropics are qualitatively different from those of the midlatitudes. To a first approximation, the tropical stratosphere regime comprises a large-scale systematic upwelling modified by mixing across a permeable subtropical transport barrier. Adequate characterization is not yet possible because of the difficulty in determining the upwelling rate and the current lack of accurate wind measurements in the tropics.
- The lowest part of the tropical stratosphere appears to be a particularly complex region of the atmosphere which plays a critical role in determining the global structure of stratospheric transport and mixing , yet it is a region that remains poorly understood. For example, most current conceptual models completely ignore the effect of longitudinal asymmetries such as the monsoon circulation.
- There is now a good understanding of why wintertime polar ozone depletion is much less and more variable from year-to-year in the Arctic than in the Antarctic. Quantita-

tive evaluation is limited by uncertainties in the cause and magnitude of the polar downwelling (which affects polar temperatures) and in our understanding of planetary wave drag.

- It has been shown recently that simulation of the amount of ozone destruction in the Arctic winter is highly sensitive to an adequate representation of small-scale structure in chemical fields. Similar considerations presumably apply to midlatitudes and represent a major challenge for quantitative modelling.
- The laminae seen in ozonesonde profiles have been clearly linked to filamentation processes associated with planetary wave breaking at the edge of the polar vortex. Dynamical lifetimes of these filaments/laminae are estimated to be at least two weeks, comparable to estimated chemical lifetimes of ozone filaments in midlatitudes.

Ozone Chemistry: Simulation and Depletion

Stratospheric ozone originates almost entirely as a result of the action of sunlight on normal diatomic oxygen molecules, mostly at altitudes above about 25 km and in the tropics. Ozone is also produced through reactions involving volatile organic compounds(VOCs) and nitrogen oxides, but these are mainly of significance in the troposphere. The reaction of atomic oxygen with ozone was once thought to be the only ozone loss mechanism in the stratosphere. However, various anthropogenic and natural long-lived gases such as N_2O, CFCs, halons, and methyl bromide and chloride are dissociated in the stratosphere into products that are effective catalytic destroyers of ozone molecules. These reactive molecules include NO and NO_2, Cl and ClO, OH and HO_2, and Br and BrO. Their concentrations are limited by the formation of reservoir species, such as HNO_3, $ClONO_2$, and HCl, that may dissociate, but not necessarily quickly, to give back the reactive molecules. The relative concentrations of the reactive molecules and the reservoir species which do not destroy ozone determine the effectiveness of ozone destruction. They are strongly influenced by polar stratospheric clouds (PSCs), which facilitate the conversion of reservoir species to reactive halogens as, to a lesser degree, do sulphate aerosols in the midlatitudes. Adequately representing the properties and behavior of PSCs and sulphate aerosols is therefore an important challenge for simulation models. Types of models that are in use range from the zero-dimension, chemistry-only, box models to modified atmospheric general circulation and numerical weather prediction models (AGCMs and NWPs) that incorporate interactive ozone photochemistry. Models serve as tools to diagnose the processes that are occurring in the atmosphere and can be used to make predictions, provided that they are validated and their characteristics are consistent with the known properties of the atmosphere.

- The development of techniques and computer hardware during the past decade has resulted in the ability to carry chemical reaction sets that were once tractable only in box or 1D models into higher dimensional models.
- 3D chemical transport models (CTMs) are models in which the chemical constituents are carried by winds that are generated in AGCMs or NWP models. They do not include feedback from chemical composition to the dynamics. Several advanced AGCMs, including the Canadian Middle Atmosphere Model (CMAM), now incorporate chemistry interactively, so that the feedback from chemistry to dynamics is included.
- NWP models, which are similar to ACGMs but have finer resolution, can also now include interactive chemistry. The Canadian NWP, the Spectral Finite Element Model (SEF), is now carrying gas phase chemistry and heterogeneous reactions are being added. The SEF model, with the addition of new data assimilation methods that are being developed for chemical constituents, is the ideal tool for simulating the Arctic spring stratosphere.
- Current models reproduce the behaviour of atmospheric ozone quite well, but loss rates in the upper stratosphere are overestimated. Also, discrepancies between modelled and observed ratios of active to reservoir chlorine have not yet been resolved.
- Most current models underestimate the ozone loss in the lower stratosphere, which is the major component of the change in total ozone. Some models that give reasonable simulations of the observed loss in total ozone do not reproduce the vertical profile satisfactorily.
- The eruption of Mt. Pinatubo provided a unique opportunity to study the role of sulphate aerosols in ozone chemistry. It is believed that the thermal effects of the enhanced aerosol concentrations may have altered transport patterns so as to enhance ozone destruction and that the conversion of N_2O_5 to HNO_3 on the aerosol surfaces perturbed the chemistry so as to enhance depletion by halogens.
- Simulation of the Antarctic spring depletion by current models appears satisfactory and is somewhat insensitive to the details of the heterogeneous conversion chemistry; this insensitivity is related to the ozone loss being nearly complete in substantial parts of the stratosphere.

- Simulation of the Arctic spring depletion is less satisfactory, the calculated loss being approximately 60% of the observed value according to one recent simulation. The discrepancy may be due to the model's inability to capture small-scale mixing effects. As well, the winter stratospheric temperatures that are used in these simulations may be in error by small amounts that are nevertheless significant for PSC formation.
- Aircraft that fly in the stratosphere and upper troposphere can affect the chemistry there through their emission of nitrogen oxides (NO_x) and water. Both of these will tend to increase the prevalence of PSCs and so enhance ozone destruction. NO_x itself can increase both the loss rate and the production of ozone, and adequate estimation of these competing processes requires characterization of the transport between and within the stratosphere and troposphere of a quality that is not yet available.
- The increased UV-B (290–315 nm) radiation in the troposphere resulting from the depletion of stratospheric ozone could increase tropospheric concentrations of OH. Such an increase would, in turn, increase removal rates for several greenhouse gases, such as methane, CO, and the CFCs. The effects of increased UV-B on tropospheric ozone are complex and uncertain. Ozone concentrations might increase in populated areas with higher concentrations of VOCs and NO_x while decreasing in the less polluted background air.
- The cooling of stratospheric temperatures that is associated with global warming may make PSCs more numerous and thereby counteract the expected recovery of ozone as the amount of stratospheric halogens declines. Evidence of decreasing trends in stratospheric temperatures has been questioned, but in the past few Arctic winters ozone values and stratospheric temperatures have been particularly low. The loss of ozone may itself have augmented the low temperatures and caused the vortex breakup to be delayed.
- Important factors that are not yet treated effectively in atmospheric modelling are: gravity waves and their effect on the middle atmosphere circulation, detailed transport processes in the upper troposphere and lower stratosphere, microphysical aerosol processes that are involved in heterogeneous chemistry in both the troposphere and the stratosphere, and the effects of aerosols on climate through radiation and the formation of clouds.
- It is assumed that, as stratospheric chlorine begins to decline in the next decade, ozone amounts will begin to recover, albeit slowly, shortly thereafter. It is imperative to continue monitoring to determine whether this scenario unfolds in this manner.

The Influence of Ozone and Other Factors on Surface Radiation.

Atmospheric ozone is important as it interacts both with solar radiation and with the thermal radiation that is emitted by the earth's surface and the atmosphere. It screens the surface from solar UV radiation that would otherwise prove harmful to living organisms, causes heating in the stratosphere, and acts as a "greenhouse" gas. The depletion of ozone during the past two decades has allowed more UV-B radiation to reach the ground than would otherwise have happened. The extent of this increase and the variability of ground-level UV radiation and its causes are the focus of current research, since estimation of the biological effects of ozone depletion may require knowledge of both these factors. The effects of UV on people are largely determined by behaviour, and public awareness programs can help people avoid excessive exposure. Ozone-depleting substances are also greenhouse gases, and their presence in the atmosphere and the recent changes in atmospheric ozone affect global warming.

- Changes in the UV are usually expressed as trends in monthly or seasonal averages, although certain biological effects may depend more on peak values during critical stages in life cycles than on the total irradiation. Also, for biological effects that are more complex than skin reddening, there may be problems in representing the effectiveness of UV radiation by simple action-spectra weighted integrals.
- About 100 station years of UV irradiance data can be accessed from the World Ozone and Ultraviolet Radiation Data Centre (WOUDC). Most of the stations have more than five years of data.
- The dependence of clear-sky UV irradiance on ozone is well established. When the sky is overcast, the irradiance throughout the spectral range 300–325 nm is reduced by approximately the same amount at all wavelengths, provided that the transmision is greater than about 15%. Consequently, the ozone amount can be easily derived from the spectrum. The accuracy of one technique developed for this purpose is 3% for daily averages of total ozone.
- With heavily overcast skies, the transmitted spectrum carries the signature of a greater amount of ozone. This is consistent with the enhancement of ozone absorption in the cloud by multiple scattering. Apparent ozone amounts up to 1000 DU have been observed when the cloud transmission is down to about 1%.

- Sulphur dioxide absorbs strongly in the UV-B region. High amounts of absorption by SO_2 are often evident in the UV irradiance spectra from Kagoshima in Japan. This is caused by the plume from the nearby volcano, Sakurajima. The SO_2 absorption associated with the plume can reduce the UV Index by as much as 25%. However, throughout the year the average reduction is only 1–2%. No other stations in the WOUDC exhibit significant absorption by SO_2.
- The effect of ground reflectance on UV radiation has been investigated at seven Canadian locations by comparing data with and without snow on the ground. It was found that the enhancement due to snow cover varies from 8% at Halifax to 39% at Resolute. The range of results reflects differences in terrain around these stations.
- An eleven-year time series of the accumulated spectral irradiation during summer has been derived from spectral irradiance measurements at Toronto that were started in 1986. The irradiation at 324 nm shows a small downward trend, while at 300 nm there is an upward trend of about 1% per year. The ratio of the irradiation at 300 nm to that at 324 nm closely follows the average summer ozone values. This suggests that the main cause of the upward trend at 300 nm is ozone depletion.
- There has been considerable progress in simulating UV irradiance from related atmospheric variables and satellite measurements. These developments should be useful in extending the current climatology of UV and in constructing past climatology.
- The downward thermal radiation at the earth's surface from ozone and several ozone-depleting gases has been measured in southern Canada. The results confirm that ozone-depleting substances are making a significant contribution to global warming.
- The UV Index program, which produces daily forecasts of UV radiation and is designed to help people avoid excessive exposure, was started in Canada in 1992. Similar programs are now operated in several other countries. The Ozone Watch program, also started in 1992, provides Canadians with weekly information on the ozone layer.

UV-B Effects

Increased UV flux to the earth's surface has properly heightened concerns over the impact on human health, given that it is well-known to cause a variety of skin cancers, eye conditions, and other problems. Although the potential health impacts are serious, many aspects of the epidemiology and pathology of UV exposure are relatively well understood; however, the situation with respect to non-human biota is more complex. Ecosytems and biomes have adapted over long periods to a particular range of UV-B, and any change in the regimen must *a priori* influence their stability, geographical range, and possibly survival. Whether changes wrought by an increase in UV flux will be profound or subtle, minor or dramatic, beneficial or inconsequential depends on many factors, most of which are poorly understood. There is, therefore, a pressing need to measure, monitor, and understand the effects of enhanced UV-B irradiance on biological communities if we are to be able to predict the impacts that will occur in the next 30–40 years and manage the consequences.

Human Health

Within Canada, most UV effects research has centred on skin cancer and eye damage, but only minimal effort has been devoted to studies of immune suppression and infectious diseases.

- Recent Australian and Canadian research has shown that members of lower socioeconomic occupations with substantial outdoor exposure have a lower risk of malignant melanoma and basal cell carcinoma than those engaged in indoor, professional, managerial, and technical occupations, who receive only intermittent exposure to the sun.
- Squamous cell carcinoma appears to be related to cumulative exposure.
- Acquired (non-congenital) skin moles (nevi) are an indicator of elevated risk for malignant melanoma. Australian and Canadian researchers have shown a direct relationship between mole density and solar UV exposure. Generally, the risk of melanoma increases with mole density.
- Persons with light skin colour, red hair, and a propensity to burn in the sun are at greater risk of basal and squamous cell carcinoma.
- UV radiation may suppress the human immune response, increasing the risk of skin cancer and bacterial and viral infection (including the re-activating of smallpox and herpes lesions).
- Acute, long-term, and chronic eye conditions may become more prevalent if UV exposure increases.
- Avoidance of the sun, use of sun screens, and wearing UV-protective glasses are important prophylactic measures.

Ecosystems

Alterations in UV irradiance can affect primary production in all ecosystems, terrestrial and aquatic, natural, managed or exploited with a potential cascade of effects. Current understanding of these processes does not enable confident prediction of the impacts.

There has been little systematic research on the impact of enhanced levels of UV-B on Canadian flora and fauna. A few studies of some agricultural and commercial forest species provide limited insight into the problem, but it is difficult to extrapolate from these to predict impacts on whole ecosystems.

It is important that the effects of both chronic increases in irradiance leading to cumulative doses, and also episodic peaks or events that may coincide with critically vulnerable stages in life cycles, be evaluated. Further, the influence of ozone depletion must also be considered in conjunction with the effects of other stressors such as global warming, acidification, and the presence of toxic chemicals, making it essential that UV-B impact studies be integrated with existing ecological research, monitoring, and assessment programs.

Agriculture

- Ultraviolet radiation damages DNA, cell membranes, and organelles (e.g., chloroplasts). Plants have a capacity to repair damaged DNA, and some can protect themselves by synthesizing UV-absorbing pigments and by modifying key metabolic enzymes. Harm occurs when the radiation dose causes damage beyond a plant's capacity for repair and protection.
- Crop damage is manifest as a decline in yield, reduced fertility with fall in seed and fruit production, drop in marketable quality, and ecological effects such as changes in crop-weed interactions and pasture mixtures.
- While the extrapolation from controlled environments to field conditions remains an issue, research is consistent in identifying that individual varieties differ in their sensitivity to UV-B, as measured by changes in photosynthesis, growth, yield, and reproduction. Most Canadian crops have low or intermediate sensitivity to moderate increases in UV-B radiation. Impacts on forage and vegetable crops have been equivocal. Of over 100 varieties of 12 important crop species, 40% were unaffected by UV-B equivalent to a 20% decrease in the ozone layer and 60% were affected in some fashion. Soybean, tomato, and canola losses may be expected, possibly totalling hundreds of millions of dollars annually. Maize does not appear to be vulnerable to anticipated increases in UV.
- UV-B may accelerate the rate of decomposition of straw and chaff, with potentially beneficial effects in arid environments and under minimum-till conditions.

Forests

- Although forests are of major economic, social, and natural importance, little is known about their susceptibility to enhanced UV-B radiation.
- Trees are long-lived and will be exposed to increased UV-B over decades. Short-term effects have been reported, and there is some indication of cumulative, chronic impacts. Multiyear experiments with long-lived species are desirable.
- The impacts of UV radiation appear to be less serious on species native to high elevations and adapted to greater irradiance.
- Impacts of enhanced UV radiation should be considered in conjunction with the effects of other stressors such as climate change and acidification. Studies of the interactive effects of UV-B and CO_2 enrichment on the growth and physiology of conifer seedlings suggest that future conifer seedling growth and competitive ability will be altered by the changing environment.
- The only field study to have been done so far on UV-B effects on trees in North America attributed sun-scalding of white pine foliage in Ohio and Ontario to elevated ambient UV-B levels. Recent research has also shown that epicuticular wax chemical composition in certain conifer species is affected by UV-B exposure in a manner that inhibits photosynthesis.
- The 50-year window of significant ozone depletion has sufficient potential to affect Canadian forest productivity on a large scale, with far-reaching consequences that are not yet apparent.

Freshwater and Wetland Ecosystems

- Shallow freshwater ecosystems are particularly vulnerable to enhanced levels of UV radiation, showing changes in primary productivity, nutrient cycling, community structure, and modification to the transport and speciation of toxic chemicals in the food-chain.
- UV penetration of surface waters is attenuated by the presence of dissolved organic carbon (DOC), and changes in DOC levels have a greater effect on the vulnerability of freshwaters to UV than changes in stratospheric ozone. In boreal lakes, where global warming and lake acidification have caused a sharp decline in DOC, UV-B penetration into the water column has increased between 22% and 60%.
- Even at current ambient levels, UV-B inhibits some species of zooplankton from frequenting their preferred position in the water column.
- Under experimental conditions, enhanced levels of UV radiation depressed algal production but affected the zooplankton that fed on the algae to a proportionately greater extent. As a result, the accumulated algal biomass increased, even though primary production was reduced. Because a key link in the food chain had been weakened, less production was transferred to higher trophic levels. The implications for aquatic ecosystems are disturbing.
- Concern has been expressed over synergisms between UV-B, climate change, lake acidification, fungal infections, and toxic chemicals that could affect amphibia. However, Ontario amphibians do not seem to have been affected by current levels of radiation, despite the apparent vulnerability of eggs and larvae.

Marine ecosystems

- Direct impacts of UV-B on microbial processes and higher trophic levels have been demonstrated, but the cumulative effects of ozone depletion on marine ecosystems are, as yet, unpredictable. Potential responses include changes in species composition, shifts in food webs (with collateral impacts on fisheries), and possibly climatic changes.
- Increases in UV-B alter the growth, survival, and biogeochemical activities of many microbes, plants, and animals in the sea. Damage to DNA directly influences survival, but UV-B also affects spatial orientation (and hence vertical migration) of phytoplankton, nitrogen metabolism, photosynthesis, larval mortality, and processes ranging from viral infection to hatching success in fish eggs.
- The sensitivity of physiological processes to solar UV-B requires a biological weighting function (BWF, also called an action spectrum) to quantify the effective irradiance. BWFs need to be determined for a greater number of biological functions and estimates need to be made of the range in variation of BWFs for each process, as these appear to be highly variable between species.
- Biological effects of UV-B have been detected tens of metres into the water column, most notably the inhibition of short-term photosynthesis in Antarctic phytoplankton. Quantitative estimates of the inhibition of photosynthesis by UV radiation are converging as research continues.
- Some toxic dinoflagellates show UV-photoprotective mechanisms that might give them a competitive edge, perhaps leading to a greater dominance of toxic or nuisance algae.
- Increases in UV-B may favour species of phytoplankton that produce dimethyl sulphide (DMS), a gas involved in cloud formation, and thus contribute to climate change.
- Interpretations of UV effects in Canadian waters require recognition of the fundamental differences that exist between the Antarctic and waters of the northern hemisphere, including the Arctic. Consequently, basic research on marine ecosystems in Canadian waters is essential.

Materials

UV radiation causes significant and deleterious changes to many materials used in outdoor applications. Any increase in UV flux to the earth's surface will degrade infrastructure and so generate significant costs for repair and replacement.

- Canadian research has addressed the effects of UV on polymers, wood and paper, building materials, paints and coatings, and textiles and clothing, although the main thrust has been on the evaluation of radiation resistance of materials used in outer space and of clothing materials.
- UV-B radiation damages synthetic polymers and other materials, but the mechanisms are not well understood at the molecular level and the combined impacts of both short and long wavelength radiation and other environmental variables adds further complexity to the issue.
- Bleached pulp and paper products made by inexpensive processes are discoloured by UV radiation. Canadian researchers have made significant advances in understanding how this occurs. The ability to reduce discolouration could greatly expand the market for this class of paper.
- Non-plastic building materials such as roofing membranes and outdoor sealants are currently being studied with respect to their resistance to UV but not specifically in the context of enhanced, ozone-related irradiance.