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Executive summary

Decreased quantities of total-column ozone are now observed over large parts of the globe, permitting increased penetration of solar UV-B radiation (280–315 nm) to the Earth's surface. The present assessment deals with the possible consequences. The Atmospheric Science Panel predicts that the ozone layer will be in its most vulnerable state during the coming two decades. Some of the effects are expected to occur during most of the next century. Recent studies show that the effects of ozone depletion would have been dramatically worse without the protective measures taken under the Montreal Protocol.

The assessment is given in seven papers, summarized as follows:

1. Changes in ultraviolet radiation

• **Stratospheric ozone levels are near their lowest points since measurements began, so current UV-B radiation levels are thought to be close to their maximum.** Total stratospheric content of ozone-depleting substances is expected to reach a maximum before the year 2000. All other things being equal, the current ozone losses and related UV-B increases should be close to their maximum. Increases in surface erythemal (sunburning) UV radiation relative to the values in the 1970s are estimated to be:

– about 7% at Northern Hemisphere mid-latitudes in winter/spring;

– about 4% at Northern Hemisphere mid-latidudes in summer/fall;

– about 6% at Southern Hemisphere mid-latidudes on a year-round basis;

– about 130% in the Antarctic in the spring; and

– about 22% in the Arctic in the spring;

• **The correlation between increases in surface UV-B radiation and decreases in overhead ozone has been further demonstrated and quantified by ground-based instruments under a wide range of conditions**. Improved measurements of UV-B radiation are now providing better geographical and temporal coverage. Surface UV-B radiation levels are highly variable because of sun angle, cloud cover, and also because of local effects including pollutants and surface reflections. With a few exceptions, the direct detection of UV-B trends at low- and mid-latitudes remains problematic due to this high natural variability, the relatively small ozone changes, and the practical difficulties of maintaining long-term stability in networks of UV-measuring instruments. Few reliable UV-B radiation measurements are available from pre-ozone depletion days.

• **Satellite-based observations of atmospheric ozone and clouds are being used, together with models of atmospheric transmission, to provide global coverage and long-term estimates of surface UV-B radiation**. Estimates of long-term (1979–1992) trends in zonally averaged UV irradiances that include cloud effects are nearly identical to those for clear-sky estimates, providing evidence that clouds have not influenced the UV-B trends. However, the limitations of satellite-derived UV estimates should be recognized. To assess uncertainties inherent in this approach, additional validations involving comparisons with ground-based observations are required.

• **Direct comparisons of ground-based UV-B radiation measurements between a few mid-latitude sites in the Northern and Southern Hemispheres have shown larger differences than those estimated using satellite data**. Ground-based measurements show that summertime erythemal UV irradiances in the Southern Hemisphere exceed those at comparable latitudes of the Northern Hemisphere by up to 40%, whereas corresponding satellite-based estimates yield only 10 to 15% differences. Atmospheric pollution may be a factor in this discrepancy between ground-based measurements and satellite-derived estimates. UV-B measurements at more sites are required to determine whether the larger observed differences are globally representative.

• **High levels of UV-B radiation continue to be observed in Antarctica during the recurrent spring-time ozone hole**. For example, during ozone-hole episodes, measured biologically damaging radiation at Palmer Station, Antarctica (64°S) has been found to approach and occasionally even exceed maximum summer values at San Diego, USA (32°N).

• **Long-term predictions of future UV-B levels are difficult and uncertain. Nevertheless, current best estimates suggest that a slow recovery to pre-ozone depletion levels may be expected during the next half-century**. Although the maximum ozone depletion, and hence maximum UV-B increase, is likely to occur in the current decade, the ozone layer will continue to be in its most vulnerable state into the next century. The peak depletion and the recovery phase

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could be delayed by decades because of interactions with other long-term atmospheric changes, e.g., increasing concentrations of greenhouse gases. Other factors that could influence the recovery include non-ratification and/or non-compliance with the Montreal Protocol and its Amendments and Adjustments, and future volcanic eruptions. The recovery phase for surface UV-B irradiances will probably not be detectable until many years after the ozone minimum.

2. Effects on human and animal health

• **Recent estimates suggest that the increase in the risk of cataract and skin cancer due to ozone depletion would not have been adequately controlled by implementation of the Montreal Protocol (1987) alone but can be achieved through implementation of its later provisions**. Risk assessments for the USA and northwestern Europe indicate large increases in cataracts and skin cancers under either the 'no Protocol' or the early Montreal Protocol scenarios. Under scenarios based on the later amendments, Copenhagen (1992) and Montreal (1997), increases in cataracts and skin cancer attributable to ozone depletion return almost to zero by the end of the next century.

• **The increases in UV-B radiation associated with ozone depletion are likely to lead to increases in the incidence and/or severity of a variety of short-term and long-term health effects, if current exposure practices are not modified by changes in behavior**.

• **Adverse effects on the eye will affect all populations irrespective of skin color**. Adverse impacts could include: more cases of acute reactions such as 'snowblindness'; increases in cataract incidence and/or severity (and thus the incidence of cataract-associated blindness); and increases in the incidence (and mortality) from ocular melanoma and squamous cell carcinoma of the eye.

• **Effects on the immune system will also affect all populations but may be both adverse and beneficial**. Adverse effects include depressed resistance to certain tumors and infectious diseases, potential impairment of vaccination responses, and possibly increased severity of some autoimmune and allergic responses. Beneficial effects could include decreases in the severity of certain immunologic disease/conditions such as psoriasis and nickel allergy.

• **Effects on the skin could include increases in photoaging, and skin cancer with risk increasing with fairness of skin**. Increases in UV-B are likely to accelerate the rate of photoaging, as well as increase the incidence (and associated mortality) of melanoma and non-melanoma skin cancer, basal cell carcinoma, and squamous cell carcinoma.

• **Research is generating much new information that is being used to help reduce the uncertainties associated with the current risk estimates**. Evaluation of the impact of susceptibility genes is helping to identify highly susceptible populations so that their special risk can be assessed. Examination of the impacts of behavior changes, such as consuming diets that are high in antioxidants, avoiding sun exposure during the four hours around solar noon, wearing covering apparel, e.g., hats, sunglasses, is beginning to identify important exposure patterns as well as possible mitigation strategies.

• **Quantitative risk assessments for a variety of other effects, such as UV-B-induced immunosuppression of infectious diseases, are not yet possible**. New information continues to confirm the reasonableness of these concerns, but data adequate for quantitative risk assessment are not yet available.

3. Effects on terrestrial ecosystems

• **Increased UV-B can be damaging for terrestrial organisms including plants and microbes, but these organisms also have protective and repair processes**. The balance between damage and protection varies among species and even varieties of crop species; many species and varieties can accommodate increased UV-B. Tolerance of elevated UV-B by some species and crop varieties provides opportunities for genetic engineering and breeding to deal with potential crop-yield reductions due to elevated UV-B in agricultural systems.

• **Research in the past few years indicates that increased UV-B exerts effects more often through altered patterns of gene activity rather than damage**. These UV-B effects on regulation manifest themselves in many ways including changes in life-cycle timing, changes in plant form, and production of plant chemicals not directly involved in primary metabolism. These plant chemicals play a role in protecting plants from pathogens and insect attack, and affect food quality for humans and grazing animals.

• **Terrestrial ecosystem responses to increased UV-B are evident primarily in interactions among species, rather than in the performance of individual species**. Much of the recent experimentation indicates that increased UV-B affects the balance of competition among higher plants, the degree to which higher plants are consumed by insects, and susceptibility of plants to pathogens. These effects can be mediated in large part by changes in plant form and chemistry, but effects of UV-B on insects and microbes are also possible. The direction of these UV-B-mediated interactions among species is often difficult to predict based only on single-organism responses to increased UV-B.

• **Effects of increased UV-B radiation may accumulate from year to year in long-lived perennial plants and from generation to generation in annual plants**. This effect has been shown in a few recent studies, but the generality of this accumulation among species is not presently known. If this phenomenon is widespread, this would amplify otherwise subtle responses to UV-B seen in a single growing season, for example, in forest trees.

• **Effects of increased UV-B must be taken into account together with other environmental factors including those**

associated with global change. Responses of plants and other organisms to increased UV-B are modified by other environmental factors such as CO_2, water stress, mineral nutrient availability, heavy metals, and temperature. Many of these factors also are changing as the global climate is altered.

4. Effects on aquatic ecosystems

• **Recent studies continue to demonstrate that solar UV-B and UV-A have adverse effects on the growth, photosynthesis, protein and pigment content, and reproduction of phytoplankton, thus affecting the food web**. These studies have determined biological weighting functions and exposure–response curves for phytoplankton, and have developed new models for the estimation of UV-related photoinhibition. In spite of this increased understanding and enhanced ability to model aquatic impacts, considerable uncertainty remains with respect to quantifying effects of ozone-related UV-B increases at the ecosystem level.

• **Macroalgae and seagrasses show a pronounced sensitivity to solar UV-B**. They are important biomass producers in aquatic ecosystems. Most of these organisms are attached and so cannot avoid being exposed to solar radiation at their growth site. Effects have been found throughout the top 10–15 m of the water column.

• **Zooplankton communities as well as other aquatic organisms including sea urchins, corals, and amphibians are sensitive to UV-B**. There is evidence that for some of these populations even current levels of solar UV-B radiation, acting in conjunction with other environmental stresses, may be a limiting factor, but quantitative evaluation of possible effects remains uncertain.

• **UV-B radiation is absorbed by and breaks down dissolved organic carbon (DOC) and particulate organic carbon (POC) and makes the products available for bacterial degradation and remineralization**. The degradation products are of importance in the cycling of carbon in aquatic ecosystems. Because UV-B breaks down DOC as it is absorbed, increase in UV-B can increase the penetration of both UV-B and UV-A radiation into the water column. As a consequence, the quantity of UV-B penetrating to a given depth both influences and is influenced by DOC. Warming and acidification result in faster degradation of these substances and thus enhance the penetration of UV radiation into the water column.

• **Polar marine ecosystems, where ozone-related UV-B increases are the greatest, are expected to be the oceanic ecosystems most influenced by ozone depletion**. Oceanic ecosystems are characterized by large spatial and temporal variabilities that make it difficult to select out UV-B-specific effects on single species or whole phytoplankton communities. While estimates of reduction in both Arctic and Antarctic productivity are based upon measurable short-term effects, there remain considerable uncertainties in estimating long-term consequences, including possible shifts in community structure. Reduced productivity of fish and other marine crops could have an economic impact as well as affect natural predators; however, quantitative estimation of the possible effects of reduced production remain controversial.

• **Potential consequences of enhanced levels of exposure of aquatic ecosystems to UV-B radiation include reduced uptake capacity for atmospheric carbon dioxide, resulting in the potential augmentation of global warming**. The oceans play a key role with respect to the budget of greenhouse gases. Marine phytoplankton are a major sink for atmospheric carbon dioxide and they have a decisive role in the development of future trends of carbon dioxide concentrations in the atmosphere. The relative importance of the net uptake of carbon dioxide by the biological pump and the possible role of increased UV-B in the ocean are still controversial.

5. Effects on biogeochemical cycles

• **Effects of increased UV-B on emissions of carbon dioxide and carbon monoxide (CO) and on mineral nutrient cycling in the terrestrial biosphere have been confirmed by recent studies of a range of species and ecosystems**. The effects, both in magnitude and direction, of UV-B on trace-gas emissions and mineral nutrient cycling are species specific and operate on a number of processes. These processes include changes in the chemical composition in living plant tissue, photodegradation (breakdown by light) of dead plant matter, including litter, release of carbon monoxide from vegetation previously charred by fire, changes in the communities of microbial decomposers, and effects on nitrogen-fixing micro-organisms and plants. Long-term experiments are in place to examine UV-B effects on carbon capture and storage in biomass within natural terrestrial ecosystems.

• **Studies in natural aquatic ecosystems have indicated that organic matter is the primary regulator of UV-B penetration**. Enhanced UV-B can affect the balance between the biological processes that produce the organic matter and the chemical and microbial processes that degrade it. Changes in the balance have broad impacts on the effects of enhanced UV-B on biogeochemical cycles. These changes, which are reinforced by changes in climate and acidification, result from clarification of the water and changes in light quality.

• **Increased UV-B has positive and negative impacts on microbial activity in aquatic ecosystems that can affect carbon and mineral nutrient cycling as well as the uptake and release of greenhouse and chemically reactive gases**. Photoinhibition of surface aquatic micro-organisms by UV-B can be partially offset by photodegradation of dissolved organic matter to produce substrates, such as organic acids and ammonium, that stimulate microbial activity.

• **Modeling and experimental approaches are being developed to predict and measure the interactions and feedbacks between climate change in UV-B-induced**

changes in marine and terrestrial biogeochemical cycles. These interactions include alterations in the oxidative environment in the upper ocean and in the marine boundary layer and oceanic production and release of CO, volatile organic compounds (VOC), and reactive oxygen species (ROS, such as hydrogen peroxide and hydroxyl radicals). Climate-related changes in temperature and water supply in terrestrial ecosystems interact with UV-B radiation through biogeochemical processes operating on a wide range of time scales.

6. Effects on air quality

- **Increased UV-B will increase the chemical activity in the lower atmosphere (the troposphere)**. Troposphere ozone levels are sensitive to local concentrations of nitrogen oxides (NOx) and hydrocarbons. Model studies suggest that additional UV-B radiation reduces tropospheric ozone in clean environments (low NOx), and increase tropospheric ozone in polluted areas (high NOx).
- **Assuming other factors remain constant, additional UV-B will increase the rate at which primary pollutants are removed from the troposphere**. Increased UV-B is expected to increase the concentration of hydroxyl radicals (OH) and result in faster removal of pollutants. Increased concentrations of oxidants such as hydrogen peroxide and organic peroxides are also expected. The effects of UV-B increases on tropospheric ozone, OH, methane, carbon monoxide, and possibly other tropospheric constituents, while not negligible, will be difficult to detect because the concentrations of these species are also influenced by many other variable factors (e.g., emissions).
- **No significant effects on humans or the environment have been identified from trifluoroacetic acid (TFA) produced by atmospheric degradation of HCFCs and HFCs**. Numerous studies have shown that TFA has, at most, moderate short-term toxicity. Insufficient information is available to assess potential chronic, developmental, or reproductive effects. The atmospheric degradation mechanisms of most substitutes for ozone-depleting substances are well established. HCFCs and HFCs are two important classes of substitutes. Atmospheric degradation of HCFC-123 (CF_3CHCl_2), HCFC-124 (CF_3CHFCl), and HFC-134a (CF_3CH_2F) produces TFA. Reported measurements of TFA in rain, rivers, lakes, and oceans show it to be a ubiquitous component of the hydrosphere, present at levels much higher than can be explained by currently reported sources. The levels of TFA currently produced by the atsmopheric degradation of HFCs and HCFCs are estimated to be orders of magnitude below those of concern and make only a minor contribution to the current environmental burden of TFA.

7. Effects on materials

- **Physical and mechanical properties of polymers are negatively affected by increased UV-B in sunlight**. Increased UV-B reduces the useful lifetimes of synthetic polymer products used outdoors and of biopolymer materials such as wood, paper, wool, and cotton. The reduction in service life of materials depends on the synergistic effect of increased UV-B and other factors, especially the temperature of the material during exposure to sunlight. Even under harsh UV exposure conditions, the higher temperatures largely determine the extent of increased UV-induced damage to photostabilized polyethylenes. However, accurate assessment of such damage to various materials is presently difficult to make due to limited availability of technical data, especially on the relationship between the dose of UV-B radiation and the resulting damage of the polymer or other material.
- **Conventional photostabilizers are likely to be able to mitigate the effects of increased UV levels in sunlight**. More effective photostabilizers for plastics have been commercialized in recent years. The use of these compounds allows plastic polymer products to be used in a wide range of different UV environments found worldwide. It is reasonable to expect existing photostabilizer technologies to be able to mitigate these effects of an increased UV-B on polymer materials. This, however, would increase the cost of the relevant polymer products, surface coatings, and treated biopolymer materials. However, the efficiencies of even the conventional photostabilizers under the unique exposure environments resulting from an increase in solar UV-B have not been well studied.