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# Understanding the factors that affect surface ultraviolet radiation

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**Abstract.** Spectral measurements of solar ultraviolet (UV) radiation have been made at several ground-based locations and for more than 10 yr at some sites. These measurements are important for two main reasons. First, the measurements combined with results of radiative transfer models contribute toward our understanding of the many complicated radiative transfer processes in the atmosphere and at the Earth's surface. These processes include absorption of radiation by atmospheric gases such as ozone and sulfur dioxide, scattering by atmospheric aerosols and clouds, and scattering from the earth's surface. Knowledge of these processes is required for operational applications such as the estimation of surface UV radiation from satellite data and the forecasting of the UV index. Also, our ability to estimate UV climatology in the past, as well as in the future, requires thorough knowledge of the UV radiative transfer processes. The second reason for making systematic ground-based measurements of UV radiation is to determine whether long-term changes are occurring as a result of ozone depletion or climate change and to identify specific causes. Examples of how long-term ground-based data records have contributed to our understanding of surface UV radiation are presented.
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## 1 Introduction

Ultraviolet (UV) radiation falling on the earth's surface originates from the sun and passes through the atmosphere, where many absorption and scattering processes occur. The near-UV radiation at wavelengths just shorter than visible light is classified as UV-A (315 to 400 nm). Radiation at progressively shorter wavelengths is more energetic and is classified as UV-B (280 to 315 nm) and UV-C (200 to 280 nm). Atmospheric gases absorb very little UV-A radiation. Absorption by atmospheric oxygen and ozone prevent all UV-C radiation from reaching the troposphere and the earth's surface. The intensity of UV-B reaching the ground and the short wavelength cutoff of solar radiation at about 290 nm are strongly influenced by atmospheric ozone.

Knowledge of the environment of UV radiation at the earth's surface is important for several reasons. The evolution and growth of most aquatic and terrestrial life forms, including human beings, are influenced by many environmental variables, including the intensity of UV radiation present at the Earth's surface or underwater. In human beings, excessive accumulated exposure can cause skin cancer, eye cataracts, or suppression of the immune system. Most biological systems respond to UV radiation with effects that generally become more detrimental with decreasing wavelength. The sensitivity of a particular life form to UV radiation is quantified by an action spectrum such as the erythema (skin reddening) for human beings,[1] plant damage,[2] and DNA damage.[3] In addition, materials such as plastics are sensitive to exposure to UV radiation, and significant research is being carried out to develop UV resistant materials intended for outdoor use. UV radiation also drives photochemical reactions in the atmosphere and is therefore an important consideration for studies of tropospheric pollution.

The environment of UV radiation at the earth's surface and underwater depends on many complicated absorption and scattering processes that occur in the atmosphere, at the earth's surface, and below water. Radiation at the earth's surface that is absorbed by a particular atmospheric gas can have structured wavelength dependence with features that are similar to the absorption spectrum of the constituent. The most significant absorption at UV-B wavelengths is by stratospheric ozone. Absorption by airborne aerosols such as smoke from forest fires or biomass burning generally has less wavelength-dependent structure and absorption usually increases with decreasing wavelength. Scattering processes in the atmosphere include molecular (Rayleigh) scattering and scattering by larger particles that comprise clouds and aerosols. Downwelling UV radiation is also enhanced by increased albedo, which returns radiation upward to the atmosphere. In general, the albedo for UV radiation on most surfaces is quite small (about 4%), but when snow is on the ground or when clouds are present below an observation site, the effects of increased albedo become significant.

The use and release of man-made chlorfluorocarbons (CFCs) into the atmosphere was suggested[4] as a possible threat to the ozone layer in the early 1970s. It was proposed that the removal of these stable chemicals occurs only at high altitudes where the harsh UV radiation required for

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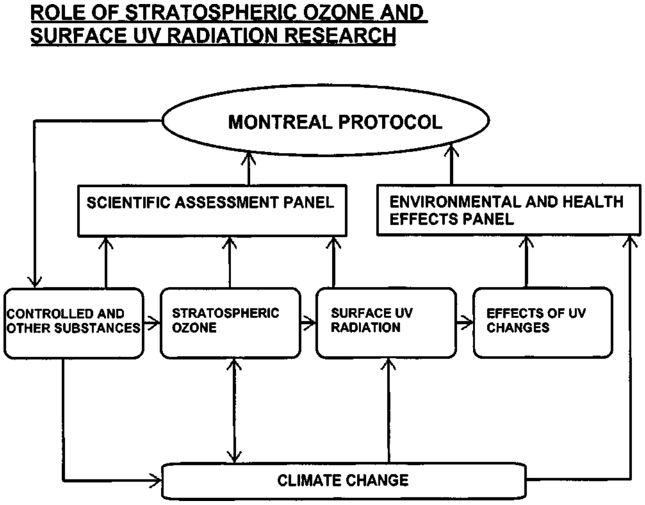

**Fig. 1** Role of research on stratospheric ozone and UV radiation in the development of the Montreal Protocol.

their breakup is available. The active chlorine released by the photolysis of CFCs would then react catalytically to destroy stratospheric ozone, leading to an increase in surface UV-B radiation.

## 2 Importance of Research on Ozone and UV Radiation

Research on stratospheric ozone and surface UV-B radiation plays an important role in the overall scientific assessment of the ozone layer and the development of regulations for controlling ozone-depleting substances (ODSs). Figure 1 summarizes some of the activities involved in the formulation of the Montreal Protocol, which is the international process to govern the protection of the ozone layer. Information required for making informed decisions for amending or adjusting the Montreal Protocol comes from three sources: the Scientific Assessment Panel, the Environmental Effects Panel, and the Technology and Economic Assessment Panel (not shown in Fig. 1).

Research on the effects of changes in surface UV radiation provides input for the Environmental and Health Effects Panel report. The effects of UV radiation on human health include the sensitivity of erythemal reaction to sunlight, the occurrence of malignant melanoma related to accumulated UV radiation exposure, the occurrence of eye cataracts with sun exposure, and suppression of the immune system. Effects of UV radiation on terrestrial biological systems include the productivity of agricultural crops and forestry, which both have economic impacts. Effects of UV radiation on marine life such as phytoplankton and fish stocks are also extensively studied. UV radiation also affects the degradation of materials and the photochemistry of urban tropospheric pollution.

Results of research on the ODSs, atmospheric ozone, and UV radiation provide input to the Scientific Assessment Panel. Atmospheric measurements of ODSs quantify the temporal changes of regulated or other known ODSs, thereby validating the atmospheric lifetimes of the substances and indicating the effectiveness of the control regulations. Laboratory research identifies new potential ODSs and quantifies how effectively a particular ODS acts as a greenhouse gas.

Past research on atmospheric ozone has led to the conclusion that stratospheric ozone has decreased over the last 25 yr, has quantified the spatial and temporal distributions of the decrease, and has attributed the observed decrease to increases in ODSs. Currently, research on atmospheric ozone focuses on the detection of the anticipated recovery of the ozone layer and on quantifying links between climate change and ozone depletion.

Research on UV radiation has identified the negative correlation between atmospheric ozone and surface UV radiation. Significant effort has also been made in understanding and quantifying all factors, including atmospheric ozone, that affect surface UV radiation.

### 2.1 *Research on Stratospheric Ozone*

Atmospheric ozone research began in the mid 1920s with measurements made by Dobson at Oxford University. Shortly after, a network of instruments was used to make measurements of total ozone at six sites in Western Europe. These measurements led to discovery that column ozone is strongly correlated to weather patterns.[5–7] A special scientific campaign in the late 1920s measured total ozone at six sites around the world, and results of this study were used to determine the basic geographical and annual behavior of total ozone.[8]

Routine measurements of total ozone on a global scale began around the International Geophysical Year (IGY) in 1958. At this time, about 100 instruments commenced the measurement of total ozone on a daily basis and many of these instruments are still operating today. The main motivation for taking these systematic long-term records was to investigate the potential use of total ozone data in improving weather forecasts.

With the suggestion that the ozone layer could be threatened by anthropogenic activities,[4,9] the primary objective for stratospheric ozone measurements shifted in the early 1970s from the application to weather forecasting to the detection of long-term changes. Evidence for long-term changes over polar regions appeared with the 1985 discovery of the Antarctic ozone hole,[10] which was observed to develop every austral spring (October) and was observed to be increasing in severity between the mid-1970s to the mid-1980s. This discovery of the Antarctic ozone hole was a major driving force for the ratification of the Montreal Protocol for the protection of the ozone layer in 1987.

Less severe ozone declines over midlatitudes were reported[11,12] in the early 1990s, and these developments led to the strengthening of the Montreal Protocol with subsequent adjustments and amendments to advance phase-out schedules and to include the regulation of additional ODSs.

### 2.2 *Research on UV Radiation*

Research on UV radiation includes the measurement of UV radiation at the earth's surface, from airborne platforms (including aircraft, balloons, and satellites), or underwater. Ground-based instruments generally measure the intensity of radiation falling on a diffuse horizontal surface. The in-

**Table 1** Summary of instruments and methods of observing UV radiation indicating advantages and disadvantages.

| Measurement Type | Advantages | Disadvantages |
|---|---|---|
| Spectroradiometer | Specific processes identified by full spectra | |
| | Straightforward absolute calibration | |
| Scanning spectroradiometer | Stray light can be minimized | Subject to changes during scan |
| Array detector | Reduced effects of variability during scan | More consideration of stray light required |
| Group scan | Reduced effects of variability during scan | Limited wavelength range |
| Broadband filter radiometer | Easy and economical operation | No knowledge of cause of variations |
| | Continuous measurement | Complicated absolute calibration |
| Narrowband multifilter radiometer | Easy and economical operation | Complicated absolute calibration |
| | Near continuous operation | Analysis requires model simulation |

struments are usually designed so that the angular response is closely matched to the cosine of the zenith angle of incident radiation.

Long-term data records can be used to detect long-term changes in UV-B radiation that may be attributed to changes in atmospheric ozone. In addition, research is carried out using radiative transfer models. Combining the measurements with the model simulations contributes to the understanding of the absorption and scattering processes involved in the transfer of radiation through the atmosphere and at the earth's surface. Combining the UV measurements with those of other variables such as total ozone, cloud cover, aerosol optical depth, surface albedo, or reflectivity (from space-based satellite data) enables the development of statistical relationships that establish the dependence of UV on absorption and scattering processes.

Three main types of instruments are used for measuring UV radiation: spectral, broadband, and multifilter narrowband. The applications, advantages, and disadvantages for all of these instrument types are summarized in Table 1 and comparisons between various standard instruments have been made.[13]

Spectral instruments measure the intensity of UV irradiance as a function of wavelength with a full width at half intensity (FWHI) less than 1 nm. The spectra are measured with either a single detector that samples the individual components of the spectra using a wavelength-scanning mechanism[14–18] or more recently developed multidetector diode arrays.[19] The scanning measurements generally take a few minutes to complete, so there is a possibility that measured spectra are subject to changing conditions (e.g., cloud or haze) during the course of the scan. The array detectors sample simultaneously by wavelength so any rapid changes during the sample period have much smaller impact on the shape of the spectrum and spectral features of the order of 0.1% can be identified. In addition, a new ''group scan'' method has been developed that combines the traditional mechanical scanning operation with the multisample method to reduce the effects of changing conditions during the course of the scan.[20] The spectral scan data are useful to quantify and distinguish between the various absorption and scattering processes that occur in the atmosphere or at the Earth's surface. Also, the spectral measurements are relevant for all effects studies since the spectra can be weighted by any desired action spectrum.

The broadband instruments take measurements through a filter that transmits radiation with a wavelength response (FWHI>10 nm) made to approximate a particular action spectrum. In most cases the instruments simulate the erythemal action spectrum (see Fig. 2). These measurements quantify the intensity of a single variable as a function of time throughout the day and are used to establish the dependence of specific biological systems on UV radiation weighted to maximize the effects. The main advantage of this type of instrument is that it is easy to use. The disadvantages include the fact that only one absolute measurement is retrieved, so distinguishing between different causes (e.g., ozone, clouds, haze) of variability cannot be done. Also the bandpass of the instrument must be accurately known to make an absolute calibration, and the transmission of the filter must remain stable with time.

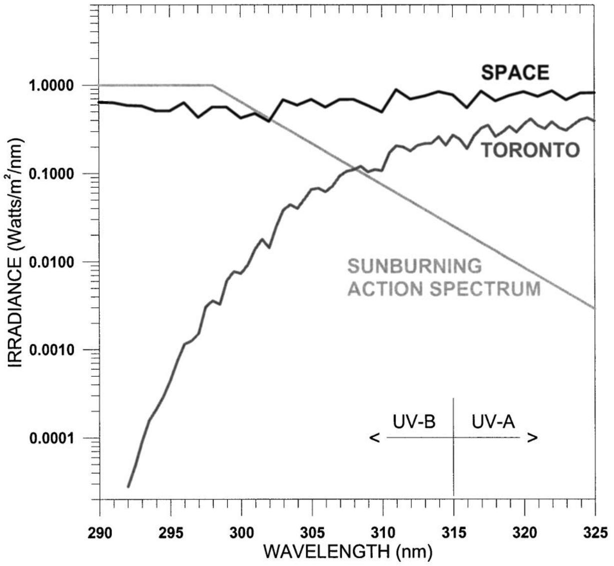

**Fig. 2** Space- and ground-based spectral measurements of UV radiation. Absorption by atmospheric ozone causes the sharp cutoff of the ground-based spectrum of global irradiance around 290 nm. The erythemal action spectrum is also shown to illustrate the significance of the lower intensity at shorter wavelengths (<310 nm) compared with the larger intensity at longer wavelengths (>320 nm).

The multifilter narrowband instruments take measurements at a FWHI resolution of about 2 to 5 nm at several wavelengths[21] in the UV. The signals from each filter are sampled sequentially in rapid succession thereby minimizing effects of changing conditions during the measurement. Detailed design and calibration considerations for these instruments and examples of what kind of information is obtained from the data have been reported.[22] The measurements from the sampled wavelengths can be combined with a radiative transfer model to estimate the complete spectrum. Advantages of these instruments include the fact that they are relatively inexpensive compared with spectral radiometers and that measurements can be made rapidly and nearly continuously. The main disadvantage is that the bandpass and transmission of the individual filters must be accurately known and remain stable with time. Wavelength shifts of less than ±0.04 nm over a period of 1 yr have been reported for filters in 30 operational UV multifilter rotating shadowband radiometers.[23]

Routine measurements of spectral UV radiation began[14–16] at only a few sites in the late 1980s. Several factors make the routine measurement of UV radiation on an absolute scale a challenging task, especially over a long time period. One reason for the difficulty is the reliability of the absolute reference against which the spectral instruments are calibrated. The operational calibration reference is usually a tungsten halogen quartz lamp whose emission in the UV is traceable to a national standards laboratory. The incandescent output of the lamps in the UV is very sensitive to the power supplied to the lamp. Significant effort has been required to develop accurate and well-regulated power supplies for the lamps. In addition, the lamps degrade with time, usually at different rates from one lamp to another, so periodic replacements with newly calibrated lamps are required.

Another technical difficulty for obtaining good-quality long-term spectral data is the question of instrument stability. Spectral instruments must be designed to be stable with time. In addition, the instrumental response to other variables such as instrument temperature or humidity must be known so that appropriate corrections can be made to minimize erroneous systematic, diurnal, or seasonal dependencies.

The shape of the UV-B spectrum at the earth's surface plays a major role in defining the requirements for making accurate measurement. Absorption by atmospheric ozone causes the intensity of radiation to decrease by several orders of magnitude over a relatively narrow wavelength region (~25 nm) below 320 nm. This is illustrated in Fig. 2, which shows the solar spectrum as measured by satellite and a ground-based spectrum measured on a summer day in Toronto. The absorption by atmospheric ozone is quite apparent. Figure 2 also shows the erythemal action spectrum, which increases by more than two orders of magnitude over the same wavelength range. Thus, even though the radiation at 300 nm is roughly 1% of the radiation at 320 nm in this example, the impact of radiation at 300 nm relevant to sunburning potential is 100 times that of radiation at 320 nm. This means that the accuracy of measurements made at shorter wavelengths, where there is smaller signal, is just as critical as measurements made at longer wavelengths, where there is a relatively large signal.

The sharp gradient of radiation at UV-B wavelengths leads to an important requirement for spectral radiometers. The instruments must be capable of making accurate measurements over a wide dynamic range. For most single-grating spectrometers, the radiation at nearby wavelengths registers as a false "stray light" signal. For example, the relatively strong radiation at 320 nm adds to the measurement at 295 nm. In some cases, the additional stray light signal integrated over all nearby wavelengths exceeds that of the actual radiation at the targeted wavelength.

There are three methods for dealing with the stray light issue. The usual solution is to use double spectrometers. Here the stray light is reduced to the square of that in a single spectrometer. For example, if the out-of-band rejection from one wavelength to another nearby wavelength is $10^{-4}$ for a single spectrometer, then the out-of-band rejection is $10^{-8}$ for the double spectrometer. Another method to reduce stray light is the use of a filter that blocks longer wavelengths and transmits the shorter wavelengths. Stray light can also be corrected if the stray light characteristics of the instrument are measured and applied to the measured spectra.[20]

## 3 Factors Affecting Surface UV Radiation

The understanding of factors that affect surface UV irradiance is important for several products that are being developed for useful operational applications. These products include the forecast of the UV index,[24–26] the estimation of surface UV irradiance from space,[27–29] and the estimation of UV penetration underwater from space-based measurements.[30] A good understanding of the factors that affect surface irradiance is also important for extending measurement records of spectral UV irradiance to times prior to measurement periods, using satellite data[31] and other ground-based records,[32] for estimating past spatial distribution of surface UV radiation,[33] and for estimating future UV radiation, using expectations of future changes in atmospheric ozone and other variables.[34]

The absolute intensity of UV irradiance at the earth's surface as a function of wavelength is proportional to the solar spectrum. Other factors that affect the intensity and angular distribution of surface UV irradiance are geometrical and geophysical variables. The geometrical variables are the distance between the earth and sun and the solar zenith angle of the sun at a specific time and location on the earth's surface. Geophysical variables include atmospheric constituents that absorb or scatter radiation as it passes through the atmosphere or scatter radiation at the earth's surface. The absorbing variables include ozone, nitrogen dioxide, sulfur dioxide, and absorbing aerosols and the scattering variables include clouds, nonabsorbing aerosols, and snow or ice at the Earth's surface.

### 3.1 *Solar Spectrum*

Solar radiation is of paramount importance for nearly all studies regarding the earth's geophysical properties and biological behavior. The solar spectrum is used as input for radiative transfer, dynamical, and photochemical models that simulate the real atmosphere.[35] The absolute intensity of surface UV irradiance at a given wavelength is proportional to the radiative output from the Sun at the same wavelength. Therefore, spectral features of the solar spectrum are present in surface UV irradiance, as illustrated in Fig. 2, which compares space-based measurements of the solar spectrum with ground-based measurements of surface UV irradiance.

Traditionally, the method for measuring the solar spectrum outside the earth's atmosphere has been the ground-based Langley plot method.[36] However, this method is limited by the fact that there is no radiation at the earth's surface for wavelengths shorter than 290 nm, and the uncertainty in the measured extraterrestrial value for wavelengths less than about 300 nm is quite large because of the small signal. Radiation below 300 nm is important for driving many atmospheric photochemical processes.

More recently, space-based measurements from satellite instruments have measured the absolute intensity of the solar spectrum.[37] Comparison of the solar spectrum measured from different satellite instruments agree to within ±3%, a value that is similar to results of comparisons between direct space-based measurements and ground-based Langley plot measurements.[38,39]

### 3.2 *Earth-to-Sun Distance*

The intensity of solar radiation just outside the earth's atmosphere at all wavelengths, including the UV, is proportional to the inverse square of the distance between the earth and the sun. The earth is closest to the sun in early January and farthest from the Sun in early July. The difference between the intensity of solar radiation at the maximum in January and the minimum in July at all wavelengths is nearly 7%. This asymmetry has consequences with the geographical distribution of UV radiation since the maximum occurs during summer in the Southern Hemisphere and winter in the Northern Hemisphere, whereas, the minimum occurs during winter in the Southern Hemisphere and summer in the Northern Hemisphere.

### 3.3 *Solar Zenith Angle*

There are two reasons why the intensity of radiation falling on a horizontal plane at the earth's surface decreases as the solar zenith angle (SZA) increases. The first is the fact that incident radiation falling on a surface is proportional to the cosine of the angle between the direction of radiation and the normal to the surface. Both the direct component of surface UV radiation and the diffuse component are subject to the cosine effect. Diffuse surface UV radiation is scattered from layers in the atmosphere, which are generally horizontal and therefore illuminated by radiation from a direction defined by the SZA. The second reason why surface UV radiation decreases with increasing SZA is the fact that the relative path length ($\mu$=slant path/vertical path) of direct radiation passing through the atmosphere increases as the Sun becomes lower in the sky. For a plane Earth atmosphere, $\mu$ is proportional to the secant of the SZA. For a spherical Earth, the enhancement is slightly smaller than the sec(SZA) for smaller angles (i.e., SZA<70 deg). As the SZA increases to 90 deg the departure of $\mu$ from sec(SZA) diverges significantly. Therefore, enhanced attenuation of the direct solar beam by both scattering and absorption processes in the atmosphere increases with increasing SZA.

### 3.4 *Molecular Scattering*

The simplest case for determining surface radiation is when there is a clean atmosphere with no absorption, no particulate scattering (i.e., clouds and haze), and no reflection from the ground (i.e., albedo=0). In this case, the only consideration is that of molecular (Rayleigh) scattering. Rayleigh scattering for air is accurately known,[40] and radiation at the earth's surface can be well defined in radiative transfer models.[41] The main variables for calculating surface UV in a Rayleigh atmosphere are the solar zenith angle and the surface pressure, which is an important consideration at elevated sites.

### 3.5 *Absorption by Atmospheric Gases*

Atmospheric gases that absorb UV-B radiation include ozone, sulfur dioxide, and nitrogen dioxide. Both the direct and diffuse component of surface UV radiation are absorbed by these gases. The direct component is reduced in accordance with Beer's law, which is inversely proportional to the exponent of the absorption coefficient at a given wavelength times the secant of the SZA, as discussed in Sec. 3.3. The diffuse component is reduced by absorption that occurs in the optical path both before and after the radiation is scattered. Multiple scattering enhances the amount of absorption because the path length of radiation through the absorber is increased.

The negative correlation between spectral UV-B radiation and total ozone has been well documented.[14,42–44] With all other variables (e.g., cloud cover, snow) remaining constant, there is a clear signature of the ozone absorption coefficient in the reduction of UV radiation as a function of wavelength. The decrease in total ozone over the Antarctic during the past 2 decades is the main cause of the observed increase in UV-B radiation, particularly during the period of the ozone hole in spring.[44,45]

Surface UV radiation also depends on the vertical distribution of an absorbing gas. This becomes evident when considering the extreme cases. With all of the absorption occurring at the top of the atmosphere the absorption of surface UV radiation is proportional to $\mu$ because all of the radiation passes through the layer with the direct Sun, whose path length through the absorption is $\mu$. With all of the absorption occurring at the bottom of the atmosphere (e.g., a thin layer of pollution), the absorption process is more complicated. For a $\mu$ value of 1 (i.e., the Sun directly overhead), the path length of diffuse UV radiation reaching the surface is always greater than the direct vertical path, so the overall enhancement is greater than $\mu$. At a larger SZA (and $\mu$), the direct path becomes larger than the diffuse path, so the effective enhancement is less than $\mu$. Note that there is a value of SZA where the effective path length enhancement is equal to $\mu$. For the real atmosphere, where the absorption is distributed in the vertical, the effective enhancement would generally fall between the two extremes. In addition to the height of an absorbing layer, the behavior of enhanced path length as a function of SZA also depends on wavelength (i.e., absorption coefficient), amount of the absorber, and thickness of the absorbing layer.

### 3.6 *Scattering by Clouds*

One of the most important geophysical variables that affects surface radiation at all wavelengths, including the UV-B, is cloud cover. There are several cloud types and the different types can have significantly different impact on the intensity and angular distribution of surface UV radiation. The geometrical thickness of the cloud, the cloud height, the cloud composition, and the spatial homogeneity of the clouds are all factors that must be considered.

Surface UV irradiance can be reduced by more than 95% under heavy cumulonimbus clouds at wavelengths that are not significantly absorbed by atmospheric ozone.[46] Under thin clouds, surface UV radiation is usually reduced provided the clouds are distributed uniformly in the horizontal. With overcast conditions, clouds always reduce surface UV irradiance,[47] and under broken cloud conditions, reduction is significant if the Sun is obscured.[48,49] However, if the Sun is not obscured, the reduction is small and there can also be enhancements of up to 25% if there are bright clouds in the field of view.[50] The broken cloud situation also poses problems for comparisons between ground-based measurements and satellite estimates of surface UV irradiance since the satellite views an extensive area with a spatially averaged cloud cover and the ground-based measurement is made at a single point, which may or may not be obscured by the Sun. To understand the effects of broken clouds on surface UV, 3-D models are required.[29] Another effect of clouds is the enhancement of absorption of an absorbing gas such as ozone from the increase in the optical path length through the absorber by multiple scattering.

It has been demonstrated that clouds have a wavelength-dependent effect on surface UV irradiance[51] such that radiation at shorter wavelengths is less affected by the presence of a cloud than that at longer wavelength. This suggests that the presence of clouds makes global surface UV irradiance ‘‘bluer.’’ Qualitatively, this is likely due to the fact that clouds cause less blue (more white) radiation scattered back to space, leaving more blue radiation transmitted to the surface.

### 3.7 *Scattering and Absorption by Aerosols*

In general, atmospheric aerosols have two optical processes that affect surface UV irradiance: scattering and absorption. As a result aerosols are referred to as either nonabsorbing or absorbing. The effects of these two processes are quantified by values for aerosol optical depth (AOD) and single scattering albedo (SSA). AOD equals the log of the ratio of direct solar radiation without to that with the aerosols in the path divided by the path length and is the sum of the absorption and scattering processes (i.e., $\mathrm{AOD} = \mathrm{AOD}_{\mathrm{absorption}} + \mathrm{AOD}_{\mathrm{scattering}}$). The SSA is the ratio of $\mathrm{AOD}_{\mathrm{scattering}}$ to AOD.

Global surface irradiance is the sum of direct and diffuse irradiance, and two measurements are required to determine the two parameters (AOD and SSA). Shadowband instruments measure global and block the direct from the Sun with a shadowband.[19,21] Brewer instruments measure direct radiation for routine ozone measurements that have been applied[20,38,52] to measurements of AOD in the UV-B. Determination of the SSA requires models that relate SSA as functions of AOD and the ratio of direct-to-diffuse irradiance.[53] Values of the SSA have been reported recently from measurements with a UV multifilter rotating shadowband radiometer.[54]

Both the scattering and absorption components of AOD are wavelength dependent. The AOD is generally assumed to be proportional to $\lambda^{-\alpha}$, where $\lambda$ is the wavelength, and $\alpha$ is the Angstrom coefficient, which quantifies the strength of the wavelength dependence. In general, absorbing aerosols have stronger wavelength dependence, which increases with decreasing wavelength. Significant absorption by aerosols has been observed under desert dust[55] and smoke from biomass burning[56] or forest fires.[46] Significant progress has been made in interpreting the difference between absorbing and nonabsorbing aerosols using satellite data.[29] This understanding has been applied to space-based measurements that estimate surface UV irradiance and detect desert dust and smoke from forest fires on a global scale.

### 3.8 *Surface Albedo*

Surface UV irradiance increases with surface albedo, which scatters radiation upward to the atmosphere. The main cause for variability of surface albedo in the UV is snow cover, which depends on both time and space. The effect of snow has been clearly demonstrated and quantified.[57] Also, the enhancement by snow is site dependent since snow-covered terrain is more uniform, and thus ‘‘whiter,’’ at some sites (e.g., Arctic) than it is at other sites (in cities or near open water). The concept of ‘‘regional’’ or site-specific albedo is required for comparisons of measurements with models when there is snow on the ground.

Snow on the ground also affects the estimates of surface UV from satellite data. The increased reflectivity from snow can lead to lower estimates of surface irradiance, since the increased reflectivity could be interpreted as cloud cover. The satellite estimates would therefore be reduced instead of increased. The situation becomes more complex with a mixture of cloud cover and snow. The use of ancillary information, such as snow cover, at specific sites improves the estimates significantly, however, this ancillary information is not available daily on a global scale.[28]

### 3.9 *Angular Dependence of UV*

The traditional measurement of surface radiation, including the UV, is the intensity incident on a horizontal surface. This is a sensible measurement for studies involving the transfer of radiation through the atmosphere and at the earth’s surface. However, in many applications, there is more interest in radiation falling on surfaces that are not plane horizontal. For example, it is more pertinent for some biological studies, including those of human beings, to have knowledge of radiation falling on a surface that approximates a vertical cylinder. Other studies, such as photochemical modeling, are interested in the actinic flux of radiation, which is radiation equally weighted from all directions, both downward and upward.

The angular distribution of UV irradiance depends on many factors. Under a clear sky, global radiation comes directly from the sun as well as diffusely from the sky. The angular distribution depends on SZA, wavelength, total ozone, and the vertical distribution of ozone. As the optical depth of clouds or nonabsorbing aerosols increases, the angular distribution of down-welling radiation becomes more isotropic. Radiation scattered upward from the surface increases significantly with snow cover on the ground or ice. Research that quantifies the angular dependence of surface UV radiation uses radiative transfer models and ancillary data.[58]

## 4 Understanding the Factors that Affect Surface UV Radiation

A major goal for carrying out research on UV radiation is to determine accurately the wavelength dependence and angular dependence of UV at the earth's surface and underwater on a continuous basis and on a global scale. Clearly, measuring the UV environment everywhere all the time at a resolution pertinent to local biological systems is an impossible task. Advances toward this goal can only be achieved with a thorough understanding of the factors that affect surface UV radiation. This understanding is achieved by collectively considering results from all research involving measurements, modeling, and data analysis and interpretation.

Our knowledge of the dependence of spectral surface radiation on the variables listed in Sec. 3 has been advanced through the use of several tools, which include ground-based measurements, satellite irradiance measurements, radiative transfer models, and statistical models. The quantity and quality of ground-based spectral irradiance measurements has increased significantly over the last 10 yr. Comparisons of satellite retrievals and radiative transfer computer models with the ground-based data have uncovered problems with the measurements, the interpretation of the data, and with the models. Ancillary information such as total ozone, AOD, humidity, or snow cover have been used to develop statistical models that quantify the dependence of surface UV irradiance on geophysical variables.

Currently, important applications of our understanding include

1. the routine daily forecasting of the UV index.[24–26]
2. global or regional estimates of surface UV irradiance using satellite irradiance and reflectivity data.[27–29]
3. global estimates of the penetration of UV irradiance into natural waters.[30]
4. the extension of spectral UV irradiance estimates in space using ancillary data.[33] These measurements have been used to determine surface UV irradiance values averaged over several years for large areas of land.
5. the extension of spectral surface UV irradiance records into the past using satellite[31] data records. Satellite estimates indicate that surface UV increased from mid to high latitudes between 1979 and 1992.
6. the extension of spectral surface UV irradiance back to the 1960s using ground-based total ozone data with pyranometer global radiation measurements, humidity, and snow cover information.[32] These results indicate that there have been decadal increases in surface UV irradiance, but the changes are due to causes other than ozone at some sites.

A number of questions remain in our knowledge of the dependence of surface UV radiation on geophysical variables. Comparisons of satellite retrievals with ground-based measurements indicate that the satellite data is generally between 0 and 40% higher than the ground-based measurements,[57,59] with better agreement at cleaner sites. This observation suggests that there are some gaps in our knowledge of radiative transfer through aerosols, particularly for nonabsorbing aerosols. The combined effect of an absorbing gas within a cloud or haze layer, or the combined effect of snow and clouds, can lead to errors in satellite estimates. Also, the effects of nonhomogeneous scattering (e.g., clouds, snow cover) or absorbing (e.g., local pollution) processes are difficult to quantify since these situations require 3-D radiative transfer models.

## 5 Summary

There are two main goals for carrying out research on surface UV irradiance. The first is to understand thoroughly the complicated scattering and absorption processes involved in the transfer of solar radiation through the atmosphere. With the understanding of the processes, it is possible to estimate the environment of surface UV irradiance without having to measure it. The second goal is to determine the short-term and long-term variability and long-term changes in surface UV irradiance as a function of geographic location. Results of the research are important for studies on the effects of UV on plants; animals, including human beings; atmospheric photochemical processes; and material degredation.

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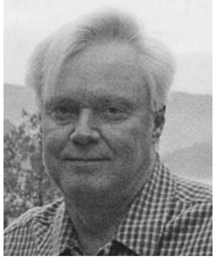

**James Kerr** recently retired as a senior research scientist with the Meteorological Service of Canada and continues his research as a scientist emeritus of Environment Canada. His research interests center on stratospheric ozone and ultraviolet radiation. He is co-inventor of the Brewer ozone spectrophotometer, the standard, ground-based instrument for measuring atmospheric ozone and UV radiation. He also developed the Canadian UV Index. Both the Brewer instrument and the UV Index are in widespread use throughout the world. His scientific achievements include demonstrating the critical link between ozone depletion and increased UV radiation. He has also made significant contributions as coauthor and lead author of international scientific assessments on the ozone layer and climate change.