The UV Index: Definition, Distribution and Factors Affecting It

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ABSTRACT

The UV Index was introduced in Canada in 1992 in response to growing concerns about the potential increase of ultraviolet (UV) radiation due to ozone depletion. The index was adopted as a standard indicator of UV levels by the World Meteorological Organization and World Health Organization in 1994. This survey article gives an overview of the UV Index and the main features of its geographical distribution.

UV index values are determined from measurements made by ground-based spectrometers, broad-band filter radiometers and multi-filter radiometers. Radiative transfer models are used to estimate UV Index values from other types of geophysical observations, primarily column ozone and cloud thickness. UV Index values can also be retrieved from satellite measurements of atmospheric ozone and cloud cover. Forecasts of UV Index values are now widely available and are intended to be used by the public as a guide to avoid excessive exposure to UV radiation.

Over the US and Canada, mean noontime UV Index values in summer range from 1.5 in the Arctic to 11.5 over southern Texas and can be as high as 20 at high elevations in Hawaii. The UV Index is also often used to quantify UV levels in studies investigating the impact of UV on other biological and photochemical processes. Factors affecting the UV Index, such as the sun elevation, total amount of ozone in the atmosphere, cloud cover, reflection from snow and local pollution, are also discussed.

Since its introduction in 1992, the UV Index has become a widely used parameter to characterize solar UV. Information about it can be useful for helping people avoid excessive levels of UV radiation.

Key words: UV Index; ozone; solar UV; UV radiation

The UV Index was introduced in Canada in 1992 in response to growing concerns about the potential increase of ultraviolet (UV) radiation due to ozone depletion and was later adopted as a standard indicator of UV levels by the World Meteorological Organization and World Health Organization in 1994. The UV Index was designed to represent erythemally weighted UV radiation in a simple form, as a single number. The goal of this survey article is to provide an overview of the UV Index, the factors affecting it and the main features of its geographical distribution. The overview briefly covers a wide range of topics related to the UV Index and provides references where more in-depth information can be found.

Solar UV radiation at the earth's surface passes through the atmosphere, where many complicated absorption and scattering processes occur. UV radiation is classified as UV-A (315-400 nm), UV-B (280-315 nm) and UV-C (200-280 nm). Atmospheric gases absorb very little UV-A radiation. Atmospheric oxygen and ozone absorb all UV-C radiation and prevent it from reaching the troposphere and the earth's surface. Absorption by ozone increases rapidly with decreasing wavelength in the UV-B range and causes surface radiation to fall off sharply with decreasing wavelength (Figure 1).

The fractions of solar energy above the atmosphere in the UV-B and UV-A ranges are approximately 1.5% and 7% respectively. Radiation at progressively shorter wavelengths in the UV range increases energetically and becomes increasingly harmful to most biological species. An action spectrum for a particular biological effect expresses the effectiveness of radiation at each wavelength as a fraction of the effectiveness at a certain standard wavelength.

The UV Index is based on the erythemal (skin reddening) action spectrum (Figure 1), since this has the most immediate short-term impact on humans. The UV Index was designed to represent erythemally weighted UV radiation in a simple form, as a single number. The UV Index is an irradiance scale computed by multiplying the erythemal irradiance, in watts m^{-2}, by 40.

UV measurements and estimates

There are several ways to obtain information on UV radiation at the surface. It can be measured by spectrophotometers (i.e., instruments that measure the UV intensity at individual wavelengths). These instruments yield accurate spectral data, but they are relatively expensive, and their operation and maintenance can be complex. There are only nine sites in Canada where such measurements are carried out on a regular basis by Canadian-designed Brewer spectrophotometers.[1] Filter instruments are less expensive, but they measure UV intensity weighted over a broad spectral interval. The weighting function is determined by the filter characteristics that can mimic, for example, erythemal response. Filter instruments are less stable than spectrophotometers and have various systematic errors.[2]

UV-B irradiance can also be reconstructed from long-term records of other geophysical parameters, primarily total ozone and charac-
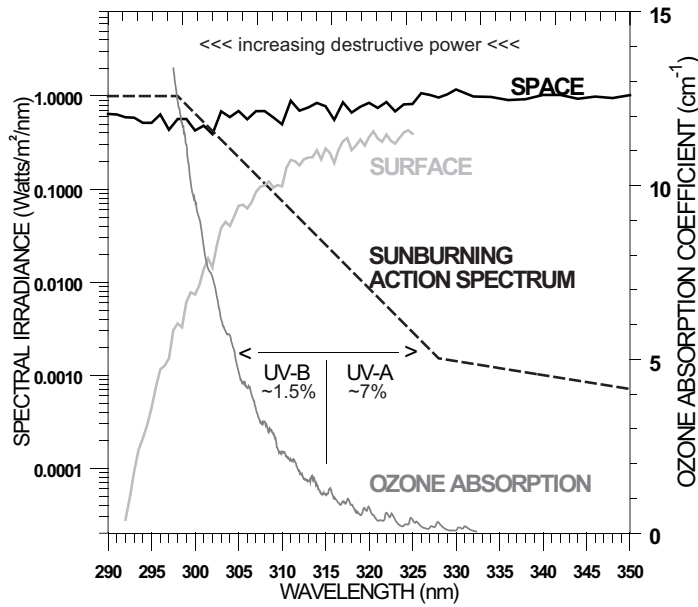
Figure 1. Ultraviolet radiation measured from space and on the ground at noon during the summer

Absorption by stratospheric ozone is the main cause for the decrease by several orders of magnitude with decreasing wavelength. Also shown is the erythemal action spectrum illustrating that sunburning potential increases with decreasing wavelength. In general, most biological species show increasing sensitivity with decreasing wavelength in the UV-B range.

Figure 2. UV Index plots based on Brewer spectrophotometer observations

The actual 2006 measurements are indicated by the dots. Estimates of the UV Index for clear sky, no-snow conditions and "normal" pre-1980 total ozone values are shown by the solid black line. Estimates of the UV Index for clear sky, no-snow conditions and each actual day's total ozone values are shown by the grey line.

teristics of cloud cover. Ground-based and satellite total ozone measurements are the sources of ozone data. Global solar radiation (i.e., total radiation in the entire spectral range from UV to infrared) is often used to quantify cloud effect.[3] Cloud cover or measurements of sunshine duration are also used for UV reconstruction.[4]
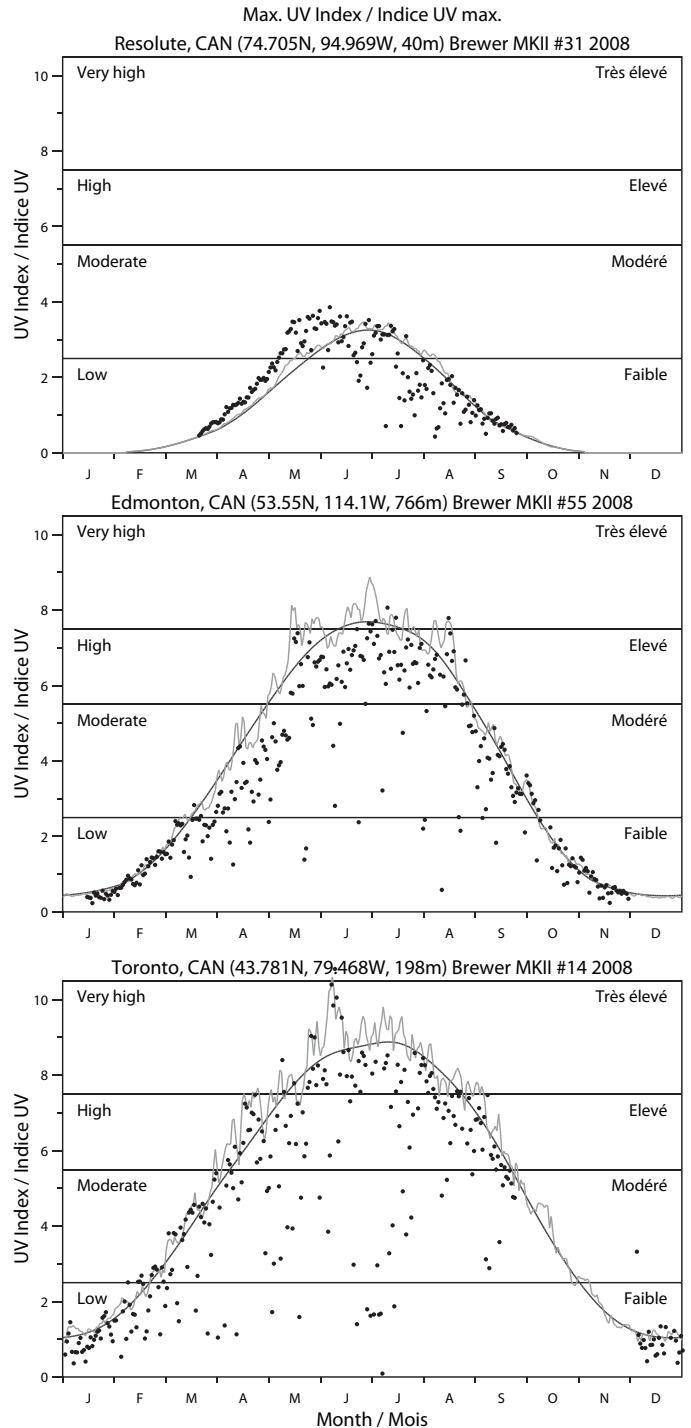
Cloud reflectivity measured from satellites is also used as a source of information about cloud cover for UV estimates. Some satellite instruments can measure both cloud reflectivity and column ozone. For example, total ozone mapping spectrometer (TOMS) observations made it possible to produce global UV maps starting from 1978.[5] There are, however, certain problems with these estimates: they produce systematically higher UV irradiance values (by typically 10%-15% but as much as 60% in extreme cases) than ground-based measurements,[6,7] because of absorption by aerosols in the boundary layer, and up to 60% lower values when snow is on the ground.[8]

Factors affecting surface UV

The absolute intensity of UV irradiance at the earth's surface at all wavelengths is directly proportional to that of the solar spectrum. The intensity of solar UV-C radiation is about 6%-9% higher when solar activity is at a maximum than at a solar minimum.[9] However, the variability in UV-A and UV-B radiation has been found to be relatively small (<1%) over the 11-year solar cycle. The earth is closest to the sun in early January and farthest from the sun in early July. The difference in intensity of solar radiation between the January maximum and the July minimum is nearly 7% at all wavelengths.

The intensity of UV radiation falling on a horizontal surface decreases with an increase in the zenith angle (i.e., the angle between the local zenith and the line of sight to the sun). This is caused by two effects. First, the intensity of down-welling solar irradiance is proportional to the cosine of the solar zenith angle. Second, the relative path length of direct irradiance passing through the atmosphere increases with increasing zenith angle, so any absorption by atmospheric gases or aerosols is enhanced by the increased path length through the atmosphere. For a particular site at the earth's surface, the solar zenith angle depends on latitude,

Figure 3. Maps of mean UV Index values at noon (11 a.m.-1 p.m. local solar time) for the US and Canada in March and July[22]

March

July
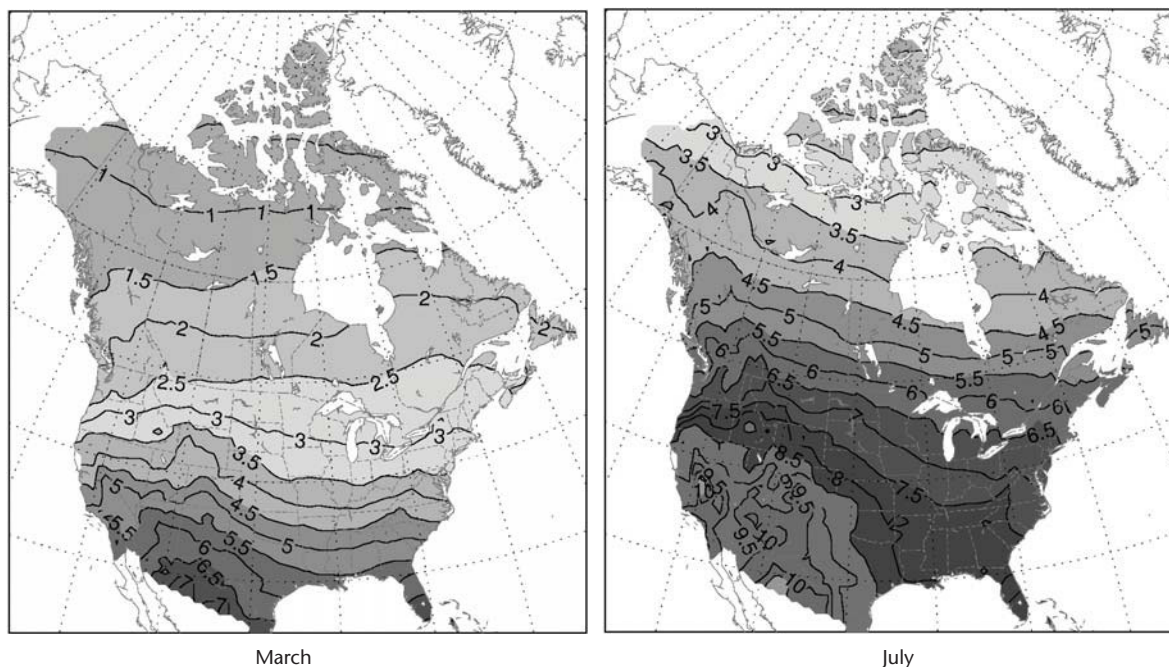
time of day and season. Changes of the noon solar zenith angles are responsible for the annual cycle in noon UV Index, as illustrated by Figure 2.

Several trace atmospheric gases absorb solar radiation at UV-B wavelengths. The most significant absorber is stratospheric ozone, which allows less than 3% of erythemal radiation to reach the lower troposphere and earth's surface. A 1% decline (or increase) in column ozone yields about a 1.2% increase (or decline) in UV Index. Day-to-day fluctuations in the estimated clear sky UV Index (the grey line in Figure 2) with the amplitude up to 20% are caused by natural fluctuations in column ozone. Over northern midlatitudes, column ozone is higher in spring and lower in autumn, although ozone variability is also higher in spring.[10]

Other naturally occurring absorbers of UV-B radiation include sulfur dioxide (SO_2) and nitrogen dioxide (NO_2). Large eruptions from volcanoes can emit enough SO_2 to cause significant absorption of up to 50% of erythemal UV.[11] However, the overall effect of absorption of erythemal UV by SO_2 and NO_2 is small.

Clouds can substantially reduce UV and visible solar radiation although they do not significantly absorb UV radiation. In the UV-A range, irradiance can be reduced by a factor of more than 100 under heavy thunderclouds compared with that of clear sky conditions, and the reduction can be even stronger in UV-B. UV Index values in Figure 2 that are much lower than those expected under a clear sky are caused by cloud effects.

Atmospheric aerosols are nongaseous particles that are suspended in the atmosphere. There are many sources of atmospheric aerosols, both natural and manmade, and a wide variety of aerosol types. Sources include volcanoes, forest fires[3] and deserts,[12] as well as emissions from power plants, factories, biomass burning,[13] automobiles and aircraft. Absorption by aerosols under typical urban conditions reduces UV by 10%-15%, although this can be substantially higher over heavily polluted sites.

The intensity of radiation falling on a horizontal sensor can be enhanced with an increase in the reflectivity of the earth's surface, even when the earth's surface is not in view of the sensor. This is the result of the sky being brighter because of higher surface albedo. For water and most land surfaces the albedo is generally quite low (<5%) in the UV range.[14,15] Sand surfaces can have higher albedo.[16] In general, spatial differences in land type have little optical effect on surface UV radiation.

The main cause for variable UV albedo is snow or ice on the earth's surface.[17,18] UV enhancements due to snow cover vary significantly from site to site. For example, a smooth terrain covered by snow in the Arctic (Churchill) causes an enhancement of about 36%, whereas snow at an urban site (Halifax) causes an enhancement of only 7%.[10] An abrupt decline in UV Index values at Resolute in May, shown in Figure 2, is related to the melting of snow.

Surface UV radiation increases with altitude so, in general, sites at higher elevation receive more UV radiation than those near sea level. Radiation increases with decreasing pressure, since there is less scattering. UV-absorbing gases that are often present in the troposphere, particularly near urban regions, reduce surface UV radiation. Also, there can be absorbing or non-absorbing aerosols that reduce UV radiation at the surface. In general, measurements show that erythemal UV increases between 7% and more than 15% per kilometer of altitude.[19,20]

UV Index climatology

Over the US and Canada, mean noontime UV Index values in summer range from 1.5 in the Arctic to 11.5 over southern Texas near sea level; in countries such as Australia they often reach values of 15-16. In Canada, the highest UV index values (about 10.5) were measured in Toronto. The highest UV Index values in the world occur at high altitude sites in the tropics (e.g., values of about 20 have been observed at Mauna Loa observatory, Hawaii[21,22]), and satellite-based estimates of the UV Index have exceeded 25 in the Altiplano area of Peru.[23]

Figure 3 shows maps of the mean UV Index values at solar noon for spring (March) and summer (July).[24] Maps for other months are

available from http://exp-studies.tor.ec.gc.ca/e/ozone/uv.htm. As one would expect, UV Index values are typically higher at low latitudes owing to the lower solar zenith angle there than those at high latitudes. However, the latitude is clearly not the only factor affecting UV. For example, mean UV Index values for July are higher over Colorado, located at 40°N, than over southern Florida (26°N) owing to the difference in altitude, cloud conditions and, perhaps, absorbing aerosols. There are also longitudinal differences. Summer values over the west Coast are typically higher than the values over the east coast at the same latitudes.

Long-term changes

Since the UV Index depends on multiple factors, long-term changes of these factors yield long-term changes in the UV Index. Long-term decline in column ozone over northern midlatitudes is about 2% in summer and 4% in winter-spring, yielding a 2.5% and 5% increase in UV Index respectively. Long-term changes in cloud cover can also affect UV Index values. Analyses of reconstructed data sets over central and eastern Europe since the 1960s indicate a ~10% change in UV Index due to variations in cloud cover.[25,26] Local trends in absorbing aerosols can also have a noticeable effect on the UV Index. For example, a more than 10% increase in UV-B at Thessaloniki, Greece, is likely due to a decrease in aerosols.[27,28]

Figure 4 shows long-term fluctuations in mean daily erythemal UV doses for Toronto calculated from actual spectral UV measurements and reconstructed from global solar radiation and ozone. The somewhat elevated UV level in the 1990s and 2000s is related to the ozone decline, and the large year-to-year fluctuations are caused by natural fluctuations in cloud cover and ozone.

Forecasts and public awareness program

Environment Canada issues the UV Index in its weather forecasts[29] in order to increase awareness of the harmful affects of UV radiation, support the education of the public on UV risks and encourage people to take action for protection. Comparisons of forecasted UV Index values with measurements show that the overall agreement between predicted and observed values is about ±1.4 Index units. Dividing the comparison into various weather conditions indicates that agreement is best under sunny or mainly sunny conditions (±0.7 units). In general, the agreement degrades (>1.5 units) under other conditions, such as partial clouds, overcast skies or precipitation.

Environment Canada introduced a renewed UV Index program in February 2004 based on the recommendations contained in the World Health Organization's *Global Solar UV Index Practical Guide* of 2002.[30] The UV Index is categorized into low (less than 2), moderate (3 to 5), high (6 and 7), very high (8 to 10) and extreme (11 and above), as shown in Figure 2.

Media coverage of the UV Index varies considerably by region. Most newspapers, many TV and some radio stations carry the daily UV Index forecast. It is available from Environment Canada in the public weather forecasts whenever the maximum value is expected to reach 3 or higher. Newspapers extract the forecast from a bulletin that is available all year, and so they generally cover it year-round. However, TV and radio obtain the UV Index from public forecast bulletins and hence report when values are 3 or more. Many stations still choose to report it on a seasonal cycle, typically from at least May through August. The frequency of coverage varies substantially from outlet to outlet.

Figure 4. Time series of summertime (May-August) mean daily erythemal irradiance for Toronto showing ground-based measurements and reconstructed data
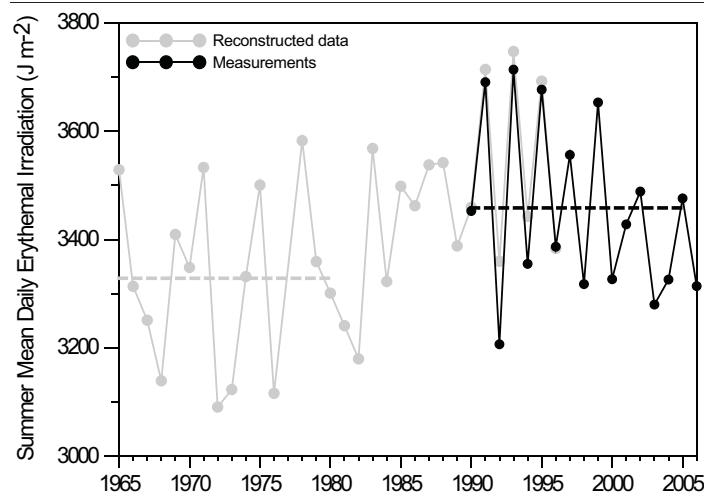
The overlap period for measurements and reconstructed data shows good agreement. The mean levels for the 1965-1980 and 1990-2005 periods are shown by the grey and black dashed lines respectively.

SUMMARY

The UV Index program was developed with the goal of providing information on surface UV radiation to the general public. In the early 1990s, concerns had arisen regarding the implications of reduced ozone levels, which had become more evident to scientists and more prominent in the media. In response to these concerns, Environment Canada developed the UV Index program in 1992 to quantify levels of UV radiation at the surface. It was later adopted as a standard indicator of UV levels by the World Meteorological Organization and World Health Organization in 1994. The goal was to provide an easily understood number that would be forecast to quantify UV levels expected for the following day. Since its introduction in 1992, the UV Index has become a widely used parameter to characterize solar UV radiation. Information about it can be useful in helping people avoid excessive levels of UV radiation. More information about the UV Index can be found in survey articles,[22,31] as well as in the World Meteorological Organization/United Nations Environment Programme ozone assessments.[28]

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RÉSUMÉ

L'indice UV (ultraviolet) a été institué au Canada en 1992 en réponse aux préoccupations croissantes suscitée par l'augmentation possible des rayons ultraviolets avec l'amincissement de la couche d'ozone. Cet indice a été adopté par l'Organisation météorologique mondiale et l'Organisation mondiale de la santé en 1994 comme indicateur standard des niveaux de rayons UV. Notre article donne un aperçu de l'indice UV et des principaux attributs de sa répartition géographique.

Les valeurs de l'indice UV sont déterminées à partir des mesures prises par des spectromètres au sol, des radiomètres à large bande et des radiomètres multifiltres. Au moyen de modèles de transfert radiatif, on estime ces valeurs à partir d'autres types d'observations géophysiques, principalement la colonne d'ozone et l'épaisseur des nuages. On peut aussi les obtenir à partir des mesures satellitaires de l'ozone atmosphérique et de la couverture nuageuse. Les prévisions de l'indice UV sont maintenant largement diffusées; on veut que le public s'en serve pour éviter les expositions excessives aux rayons ultraviolets.

Pour les États-Unis et le Canada, l'indice UV moyen à midi en été varie entre 1,5 dans l'Arctique et 11,5 pour le Sud du Texas et peut atteindre 20 dans les hauteurs d'Hawaï. L'indice UV sert aussi souvent à chiffrer les niveaux de rayonnement ultraviolet dans les études portant sur l'incidence des rayons UV sur d'autres processus biologiques et photochimiques. Les facteurs qui influent sur l'indice UV, comme la hauteur du soleil, la quantité totale d'ozone dans l'atmosphère, la couverture nuageuse, la réflexion des rayons sur la neige et la pollution locale, sont également abordés.

Depuis son adoption en 1992, l'indice UV est devenu un paramètre très utilisé pour caractériser les ultraviolets solaires. L'information à ce sujet peut être utile pour aider les gens à éviter les niveaux d'exposition excessifs aux rayons ultraviolets.

Mots clés : indice UV; ozone; ultraviolets solaires; rayons ultraviolets